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Power Management Strategies for a Wind Energy Source in an Isolated Microgrid and Grid Connected System

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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POWER MANAGEMENT STRATEGIES FOR A WIND ENERGY SOURCE IN AN ISOLATED MICROGRID AND GRID CONNECTED SYSTEM

(Thesis format: Monograph)

by

Devbratta Thakur

Graduate Program in Electrical and Computer Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Abstract

This thesis focuses on the development of power management control strategies for a direct drive permanent magnet synchronous generator (PMSG) based variable speed wind turbine (VSWT). Two modes of operation have been considered: (1) isolated/islanded mode, and (2) grid-connected mode.

In the isolated/islanded mode, the system requires additional energy sources and sinks to counterbalance the intermittent nature of the wind. Thus, battery energy storage and photovoltaic (PV) systems have been integrated with the wind turbine to form a microgrid with hybrid energy sources. For the wind/battery hybrid system, several energy management and control issues have been addressed, such as DC link voltage stability, imbalanced power flow, and constraints of the battery state of charge (SOC). To ensure the integrity of the microgrid, and to increase its flexibility, dump loads and an emergency back-up AC source (can be a diesel generator set) have been used to protect the system against the excessive power production from the wind and PV systems, as well as the intermittent nature of wind source. A coordinated control strategy is proposed for the dump loads and back up AC source.

An alternative control strategy is also proposed for a hybrid wind/battery system by eliminating the dedicated battery converter and the dump loads. To protect the battery against overcharging, an integrated control strategy is proposed. In addition, the dual vector voltage control (DVVC) is also developed to tackle the issues associated with unbalanced AC loads.

To improve the performance of a DC microgrid consisting wind, battery, and PV, a distributed control strategy using DC link voltage (DLV) based control law is developed. This strategy provides simpler structure, less frequent mode transitions, and effective coordination among different sources without relying on real-time communication.

In a grid-connected mode, this DC microgrid is connected to the grid through a single inverter at the point of common coupling (PCC). The generated wind power is only treated as a source at the DC side for the study of both unbalanced and balanced voltage sag issues at a distribution grid network.
The proposed strategy consists of: (i) a vector current control with a feed-forward of the negative-sequence voltage (VCCF) to compensate for the negative sequence currents; and (ii) a power compensation factor (PCF) control for the VCCF to maintain the balanced power flow between the system and the grid. A sliding mode control strategy has also been developed to enhance the overall system performance. Appropriate grid code has been considered in this case.

All the developed control strategies have been validated via extensive computer simulation with realistic system parameters. Furthermore, to validate developed control strategies in a realistic environment in real-time, a microgrid has been constructed using physical components: a wind turbine simulator (WTS), power electronic converters, simulated grid, sensors, real-time controllers and protection devices. All the control strategies developed in this system have been validated experimentally on this facility.

In conclusion, several power management strategies and real-time control issues have been investigated for direct drive permanent magnet synchronous generator (PMSG) based variable speed wind turbine system in an islanded and grid-connected mode. For the islanded mode, the focuses have been on microgrid control. While for the grid-connected mode, main consideration has been on the mitigation of voltage sags at the point of common coupling (PCC).

**Keywords**

Battery storage, Converter, DC microgrid, Distributed control, Distribution network, Hybrid system, Induction motor, Permanent magnet synchronous generator (PMSG), Power management, Photovoltaic (PV), Wind turbine (WT), Renewable energy sources, Sliding mode controller, Variable speed wind turbine (VSWT), Vector current control, Vector torque mode (VTM), Voltage sag, Wind turbine, Wind turbine simulator (WTS)
Dedication

To my parents (Tirth Nath and Rekha), my wife (Richa), and my son (Rishaan).
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sequence $d-q$ axis currents (e) DC link voltage, and (f) Extracted system frequency – omega (rad/s).
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CMLP</td>
<td>Claudette Mackay-Lassonde Pavilion</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DCL</td>
<td>Direct Current Link</td>
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<tr>
<td>DCM</td>
<td>DC Motor</td>
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<tr>
<td>DG</td>
<td>Distributed Generation</td>
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<tr>
<td>DGN</td>
<td>Distributed Grid Network</td>
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<tr>
<td>DLV</td>
<td>DC Link Voltage</td>
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<tr>
<td>DVCC</td>
<td>Dual Vector Current Control</td>
</tr>
<tr>
<td>DVVC</td>
<td>Dual Vector Voltage Control</td>
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<tr>
<td>EPS</td>
<td>Electric Power System</td>
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<tr>
<td>GSC</td>
<td>Grid Side Converter</td>
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<tr>
<td>IM</td>
<td>Induction Motor</td>
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<tr>
<td>LV</td>
<td>Low Voltage</td>
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<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
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<tr>
<td>NSC</td>
<td>Network Side Converter</td>
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<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
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<tr>
<td>PCF</td>
<td>Power Compensation Factor</td>
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<tr>
<td>PE</td>
<td>Power Electronic</td>
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<tr>
<td>PEC</td>
<td>Power Electronic Converter</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PMSG</td>
<td>Permanent Magnet Synchronous Generator</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>PWT</td>
<td>Physical Wind Turbine</td>
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<tr>
<td>RES</td>
<td>Renewable Energy Source</td>
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<tr>
<td>SMC</td>
<td>Sliding Mode Controller</td>
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<tr>
<td>SOC</td>
<td>State of Charge</td>
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<tr>
<td>SRF</td>
<td>Synchronous Reference Frame</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
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<tr>
<td>SSWT</td>
<td>Small Scale Wind Turbine</td>
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<tr>
<td>UWO</td>
<td>University of Western Ontario</td>
</tr>
<tr>
<td>VCCF</td>
<td>Vector Current Control with Feed-forward</td>
</tr>
<tr>
<td>VRO</td>
<td>Voltage Regulation Operating Mode</td>
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<tr>
<td>VSWT</td>
<td>Variable Speed Wind Turbine</td>
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<tr>
<td>VTM</td>
<td>Vector Torque Mode</td>
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<tr>
<td>WES</td>
<td>Wind Energy Source</td>
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<tr>
<td>WPS</td>
<td>Wind Power System</td>
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<tr>
<td>WT</td>
<td>Wind Turbine</td>
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<tr>
<td>WTS</td>
<td>Wind Turbine Simulator</td>
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Nomenclature

\begin{align*}
m & \quad \text{Mass} \\
\theta & \quad \text{Wind velocity} \\
\rho & \quad \text{Air density} \\
C_p & \quad \text{Power coefficient} \\
P_m & \quad \text{Turbine mechanical power} \\
\gamma & \quad \text{Tip speed ratio} \\
\omega_m & \quad \text{Rotor angular speed} \\
\omega_e & \quad \text{Electrical rotor angular speed} \\
\beta & \quad \text{Pitch angle} \\
T_m & \quad \text{Turbine mechanical torque} \\
T_e & \quad \text{Turbine electrical torque} \\
T & \quad \text{Motor torque} \\
k_{pm} & \quad \text{Magnetic strength} \\
\lambda_m & \quad \text{Flux linkage} \\
J_t & \quad \text{Moment of inertia of the wind turbine} \\
J_g & \quad \text{Moment of inertia of the generator} \\
J & \quad \text{Moment of inertia of the motor} \\
V_{dc} & \quad \text{DC link voltage} \\
i_{mpp} & \quad \text{Current at the maximum power point} \\
i_w & \quad \text{Wind current} \\
i_{bat} & \quad \text{Battery current} \\
i_{dc} & \quad \text{DC link output current} \\
s_b & \quad \text{Switching signal to DC-DC converter} \\
i_{pabc} & \quad \text{abc currents at primary side of a transformer} \\
V_{pabc} & \quad \text{abc voltages at primary side of a transformer} \\
s_{1-6} & \quad \text{Switching signal to Inverter (full bridge)} \\
C_{in} & \quad \text{Input capacitor in front of a DC-DC converter} \\
P_{opt} & \quad \text{Optimal (maximum) wind turbine power}
\end{align*}
$P_t$ Total power losses from turbine to DC-DC converter

$P_{m_{pp}}$ Wind power at the maximum power point

$P_e$ Electrical/generator output power

$V_{(d,q)p}$ d-q axis positive sequence reference voltages

$V_{(d,q)p}$ d-q axis positive sequence voltages

$V_{(d,q)n}$ d-q axis negative sequence reference voltages

$V_{(d,q)n}$ d-q axis negative sequence voltages

$i_{(d,q)p}^*$ d-q axis positive sequence reference voltages

$i_{(d,q)p}$ d-q axis positive sequence voltages

$i_{(d,q)n}^*$ d-q axis negative sequence reference voltages

$i_{(d,q)n}$ d-q axis negative sequence voltages

$\delta$ Rotating angle of the d-q synchronous reference frame

$i_{abc}$ abc currents at the inverter side

$V_{abc}$ abc voltages at the inverter side

$i_{out}$ Source output current

$\eta_{opt}$ Optimal tip speed ratio

$V_{pv}$ PV array output voltage

$I_{pv}$ PV array output current

$V_o$ Source converter output DC voltage

$I_{out}$ Source converter output DC current

$i_p$ Current at the primary side of a transformer

$k_{opt}$ Optimal constant value in MPPT block

$m_{d,q}$ Control input of inverter in d-q axes

$V_i$ Inverter pole/terminal voltage

$V_p$ Voltage at the primary side of a transformer

$V_s$ Voltage at the secondary side of a transformer

$\omega$ Angular grid frequency
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$abc$</td>
<td>Stationary $abc$ axes</td>
</tr>
<tr>
<td>$d, q$</td>
<td>Synchronous $d-q$ axis</td>
</tr>
<tr>
<td>$pdp$</td>
<td>Primary side $d$-axis positive-sequence</td>
</tr>
<tr>
<td>$pqp$</td>
<td>Primary side $q$-axis positive-sequence</td>
</tr>
<tr>
<td>$pdn$</td>
<td>Primary side $d$-axis negative-sequence</td>
</tr>
<tr>
<td>$pqn$</td>
<td>Primary side $q$-axis negative-sequence</td>
</tr>
<tr>
<td>$d_c$</td>
<td>Duty cycle</td>
</tr>
<tr>
<td>$i_{ind}$</td>
<td>Inductor current</td>
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Chapter 1

1 Introduction

1.1 General Introduction and Benefits

Many power electric utilities around the world have been forced to change their way of operation from vertically integrated mechanisms to open market systems during the nineties, which is referred to as the “Deregulation of Power Industry”. The deregulation of power industry is motivated by bringing competition among utility companies, new choices for customers, and economic benefits. Competition brings innovation, higher efficiency and lower costs, which is a win-win situation for both suppliers and consumers. Some other critical forces that drive power industry into deregulation are: the global economic crisis, more demanding environmental issues, and managerial inefficiency in regulated companies [1].

Therefore, two major driving forces: deregulation and environmental concerns, bring interest in distributed generation (DG). DG is defined as a small size electric power source connected directly to the distribution network or on the customer site of the meter [1]. Compared to the conventional centralized power plants, DGs are sustainable, are smaller, and can be installed closer to customers. Many DGs can be installed on or close to the customers to deliver power rather than the conventional way of transmitting power from centralized power plants over transmission and distribution lines. Due to steady progress in power industry deregulation, and tight constraints imposed on the construction of new transmission lines for long distance power transmission, DGs are expected to increase in the future.

DGs with controllable energy resources such as microturbines, fuel cells, diesel generators and small hydro units are dispatchable, whereas DGs with uncontrollable energy resources, such as renewable energy sources like wind and PV are non-dispatchable [2]. Many DGs are flexible in several aspects: operation, size and expandability. However, non-dispatchable DGs require a proper control strategy to cope
with all attractive features of DGs such as peak power saving, reliability and power quality improvement, alternative to expansion of the grid network and grid support.

Non-dispatchable DGs, such as wind and PV, are renewable energy based sources which inherently lack the capability of dispatching due to the weather dependency. However, the penetrations of these sources have increased drastically in the last few decades due to advancements in technology, free cost of energy, increasing energy consumption, soaring cost, exhaustible nature of fossil fuel, and cost reduction [3]. The wind energy source (WES) is the dominant renewable energy source (RES) compared to PV around the world.

In Canada nearly 1,600 MW wind energy source was installed in 2013, ranking 5th globally for newly installed capacity. The total installed wind capacity in 2013 was 7,802.72 MW—supplying approximately 3% of Canada’s electricity demand with enough power to meet the needs of over 2 million Canadian homes. The dominating Canadian provinces in wind energy projects were Prince Edward Island, Nova Scotia, Quebec, Ontario, British Columbia and Saskatchewan. Ontario is leading from the front with a total installed capacity of 2,500 MW at the end of 2013 [4]. The installed capacity of RES for Ontario province keeps increasing, as shown in Figure 1.1.

![Figure 1.1: Ontario long term energy plan [5]](image-url)
According to the Ontario Ministry of Energy, the RES will grow to 46% of Ontario’s generating capability by 2025. The renewable energy penetrations considering only wind and solar were 8% in 2013, which will become 23% in 2025. This shows the rising of these non-dispatchable RESs in the power industry.

These RES based DGs can be used in different structures under different control strategies. Some non-dispatchable DGs can be used as a standalone or a hybrid system, which is either grid connected or islanded. A standalone power system is defined as an off-grid system, which operates independently without a grid support. Similarly, a standalone RES is defined in this thesis as a single source which is operated individually without any support systems, such as storage or back up source to counteract the stochastic nature or weather dependency.

Due to the intermittent nature of RESs, the standalone wind and PV normally require energy storage devices such as battery, super-capacitor, super magnetic energy storage (SMES), flywheel, and so on. However, some RESs based DGs can complement each other. For example, PV output is high during the day whereas wind output is high during the night and vice versa; therefore, these two sources together can provide the required stable and reliable power to customers, which is referred to as a hybrid system. Similarly, a local grid consisted of dispersed loads and different DGs: dispatchable and non-dispatchable, along with or without energy storage is referred as a ‘microgrid’, which may operate in a grid connected or Islanded for small communities [6].

The concept of microgrids or many DGs at the customer’s end is mainly focused on generating an amount of power in multiple locations instead of generating a lot of power in one center; therefore, it defers the expansion of a long distance high voltage transmission line which is very expensive [7]. Furthermore, the microgrid provides the potential benefits to the customer from reliability and power quality point of view [8]. However, proper coordination is required between the sources and loads to utilize all of its useful benefits [9].

As of now, the importance and benefits of DGs have been identified and justified for the existing power system. However, the use of these intermittent nature of RESs in a
standalone or hybrid, or in a cluster such as a microgrid are still challenging tasks because there is no prominent standard specified for control and power management, especially during islanded conditions or off-grid mode. However, IEEE 1547 does provide the universal standard for interconnecting all kinds of DGs in an electric power system (grid). It provides requirements relevant to performance, operation, testing, safety and maintenance of the interconnection. But the evolution of new DGs and the different nature of the grid around the world, along with the lack of a concrete national standard, is still a challenge to the implementation of new DGs project [10].

The advancement in power electronics brings a lot of flexibility in the control strategies of non-dispatchable DGs such as wind and PV [11]. The intelligent power electronic based interfacing unit between the RES based DG and grid is changing the basic characteristics of these DGs from being an energy source to be an active power source for the grid [12]. The grid has now started demanding power at its given time from these RESs. Therefore, power management strategies for these DGs are essential to cope with all of the grid requirements. The increasing penetrations of these RESs in the grid are not only expected to increase their reliability and stability for the sake of their revenues, but also to support the grid during adverse conditions [13].

Some of the sophisticated and sensitive loads in the industries are semiconductor manufacturing, textile mills, paper mills and plastic injection molding, etc. whereas smaller commercial sensitive loads such as modern digital appliances, VCRs, microwave ovens, computers, electronic data processing equipment, and so on, are all demanding a stable and reliable power supply [14]. Nowadays, many loads are powered by RESs [15]. Therefore, even a standalone or hybrid RESs based power system requires a proper power management control strategy to meet the load demand.

Due to lack of standard control strategies and insufficient information regarding newly established form of power supply, existing microgrids around the world ensures reliability by using the generation capability far more than the load demand. Some of the applications of existing microgrids are remote area power supply systems, military base camps, shipboard power systems, remote telecommunication rely stations, data centers,
and industrial/commercial power systems. Since these microgrids are not operated optimally, the energy cost and the footprint are higher than they have to be. Therefore, the current research work is mainly focused on developing control strategies for hybrid and microgrid systems with possibly reduced number of components but still maintained the same level of performance if not higher.

In summary, the deregulation of power industry, advancement in technologies, constraint in the construction of new transmission lines, customer demand for stable and highly reliable power and environmental concerns encourage to use clean and RESs, such as wind and PV in different structures such as a standalone system, hybrid system and microgrid either in islanded or grid connected mode. The intermittent nature of these RESs and non-specified standard in a hybrid and microgrid system require proper power management control strategies to meet the load demand with stable and reliable power.

1.2 Motivations

The non-dispatchable DGs such as renewable energy sources, wind and PV are utilizing broadly nowadays due to the advancement in technology, free of energy cost, less dependence on fossil fuels, and cost reductions in last few years. However, the power management control strategy for RESs is still challenging due to their weather dependency, high stability and reliable power demand and grid requirements. The advancement in power electronics provides flexibility in control, whereas increasing penetration of RESs brings issues in a grid. Similarly, increasing islanded (off-grid) applications of RESs especially with a rapidly growing DC system realizes challenges in power management. In addition, the lack of optimum control strategy for the concerned issues increase the overall cost of the system with lower efficiency. The RESs are still costly in comparison to conventional energy sources, such as gas, and diesel. Therefore, the RESs demand the cost effective system structure and control strategy to reduce the overall cost.

1.2.1 Advancement in Power Electronics

Among RESs, the wind energy source along with its power electronic based interfacing unit which is referred to here as a wind power system (WPS) plays a dominant role in the
overall power generation. Although large wind farms are still being constructed all over the world, the last few years have seen increasing focus given to small scale wind turbines (< 500 kW) due to their lower impact on landscapes, lower noise levels, and their capability to operate separately from the grid in islanded communities [16]. These advantages, in turn, stem from advancements in power electronics, including improvements in the ability to cope with the intermittent nature of wind energy to meet the grid requirements. The variable speed wind turbines (VSWT) equipped with permanent magnet synchronous generators (PMSG) and full-scale power electronics-based converters are an excellent example of such advancements.

### 1.2.2 Grid Connected Mode

These small scale RESs are flexible in control and operation which can be used as a standalone, hybrid system or a microgrid. The standalone operation of RESs such as WPS brings lots of challenges in a grid connected and off-grid mode. In a grid connected mode, the WPS is supposed to intact with the grid at the point of common coupling (PCC) even during the adverse conditions of the grid such as fault, voltage sag and imbalanced loads etc. In the first place, the WPS should be disconnected during any ill effect at the PCC. If the increasing penetrations of these WPSs in the grid disconnects at once, then it affects the stability of the grid and could cause the catastrophic collapsing of the grid. Therefore, the grid code is designed for these RESs to be connected in the grid. The small WPS which is not sufficient itself to cure the grid problem is also asked to remain in the grid even during worst conditions at PCC. Therefore, these WPSs require a control strategy which can get rid of the effect of grid problems and remain in the grid for the specified period, according to the grid code during grid disturbances [13].

### 1.2.3 Islanded (Off-grid) Mode

In an islanded (off-grid) mode, WPS can be operated in a hybrid system or in a microgrid. However, the stochastic nature of wind and fluctuating loads make the operation of WPS more challenging than in a grid connected application [17]. The random variation of wind speed leads to a fluctuation in torque and output power of the wind turbine. As a result of the fluctuation, there is a variation in the voltage and
The integration of energy storage with the standalone operation of WPS improves the voltage and frequency responses in the presence of fluctuating wind speed and varying load demand [19]. Energy storage is capable of supplying large amounts of energy to balance power during abnormal conditions such as wind gusts and sudden load variations [20]. Battery storage is one of the best suited storage technologies for wind power applications, due to its high energy density levels [21]. The off-grid WPS demands a cost effective and smaller footprint system with high level of power quality and reliability.

Microgrids can be perceived to use DC or AC voltage in the local grid, hence they can be classified into the DC and AC microgrid [22]. The DC microgrid is gaining popularity due to its attractive features such as low cost, easy control with no reactive power concern, higher energy conversion efficiency with less electronic components, modular and scalable, and recently various applications [23]-[24]. Therefore, a proper power management control strategy is required in the DC microgrid to maintain a stable and reliable power supply by considering all of its attractive features.

1.3 Problem Statement

The renewable energy source, such as a wind source, cannot operate satisfactorily within the operating limits and meet the load demand due to its intermittent nature. Some additional sources and sinks are required in order to counterbalance the fluctuating nature of the wind. With the rapid development of renewable energy and power electronics technology, cost reduction in energy storage and wider applications of the microgrid system, different control strategies and power management systems have been proposed for wind integration [163].

The battery is one of the commonly used energy storage to counterbalance the intermittent nature of wind source. However, the optimal size of battery has its own operating limits, which provides the operating constraints for the wind source to operate in all system conditions. Therefore, the dump load is introduced to activate during overcharging battery constraints while the backup AC source (can be a diesel generator set) is integrated to activate during over-discharging battery constraints. As a result, the
power is balanced within the system in all conditions and the stability of the system is also maintained by regulating the DC link voltage within the operating limits of the DC microgrid.

In contrast to the diesel generator based microgrid system in the literature where the generator is contributed constantly throughout the operation in order to counterbalance the intermittent nature of renewable sources, the developed control strategy operates the diesel generator occasionally in the presence of the battery. The proposed control strategy utilizes the local power sources owned by the community as a microgrid at maximum by deactivating the local grid. In addition, the diesel generator is activated only during abnormal (extreme) conditions, such as low battery energy storage or maintenance requirements. This strategy provides the following advantages: (i) The maximum use of local power reduces the electricity bill from the grid; and (ii) The reduction of frequent operation of the diesel generator, which cuts down the operating cost of the microgrid.

In Chapter 5, the conventional structure maintains the stability and reliability of the hybrid system by regulating the DC link voltage within the operating limits and balancing the power flow in the system irrespective of fluctuating weather and load conditions. In addition, it gives the flexibility of control, but at high structural cost. The hybrid system which is controlled with lesser power electronic components or devices not only reduces the cost, but also reduces the failure rate and maintenance period. The possible structure elements that can be removed without affecting the system performance as shown in Chapter 5, are the battery converter and a dump load. However, the challenges exist in control which requires an intelligent power management scheme to maintain the same level of power stability, and reliability of the system, which is presented in Chapter 6.

In the literature, the battery is directly interfaced to the DC link and the wind source is operated as a voltage source. The issue in such a configuration is the protection of a battery charging against the high current. The wind system which is operated as a voltage source charges the battery at a continuously high current. As a result, the life cycle of the battery is deteriorated or, in a worst condition (high inrush current), the battery may be damaged. In the proposed control strategy, the wind source is operated as a current
source. Therefore, the battery is charging through a regulated current value. Furthermore, the battery is charging smoothly without a high inrush current.

Therefore, the proposed control strategy in the hybrid system, presented in Chapter 6, features a power management strategy that does not require a converter for the battery, eliminates the need of a dump load and provides simple integration to the distribution network, if required, compared with a set of two standalone systems. Thus, the integration of a PMSG based VSWT in a standalone hybrid system is expected to be cost-effective and efficient.

However, the issues of balanced power flow, stable DC link voltage (DLV) within operating limits, and protection against battery overcharging and over discharging in the microgrid, cannot be solved by the integrated control strategy proposed in Chapter 6. Therefore, a distributed control strategy using a DLV based control law is proposed for a DC microgrid in Chapter 7, considering the same system configuration features: no dedicated battery converter and a dump load.

In the literature, the centralized-master/slave control, and decentralized-droop control power management strategies for a DC microgrid are commonly considered. Centralized control involves performing control action in a control center and then sending control signals to the different sources through real time high bandwidth communication links [68]. Therefore, the failure in communication links can degrade the system reliability. This issue is avoided by a decentralized control. Decentralized control refers to control action performed autonomously based on local measurements [69]. Nevertheless, this improvement is at the cost of both inaccurate power sharing or poor voltage regulation and circulating current due to the mismatch in the parallel converter’s output voltages. These issues are tackled in a droop control mechanism using a low bandwidth communication link.

The alternative solution for centralized and decentralized control is a distributed control based power management strategy. In this thesis, distributed control refers to control action which is distributed throughout the network, without centrally focused [76]. For example, instead of a single secondary control in a decentralized-droop control, a
distributed control for each source is incorporated. A typical distributed control strategy applied to DC microgrid is the average current sharing. This algorithm requires the average current of each source to set the voltage reference. The complexity rises with increasing number of sources. Therefore, a distributed control strategy using DLV based control law is proposed. The proposed strategy provides the following features to improve issues occurring in the literature:

(i) Unlike in a droop control, the renewable sources are operated in a current mode under the MPPT scheme as long as the source is not assigned to participate in regulating the DLV. In droop control, the sources are operated under voltage control mode to regulate the DLV together. The sources are out of MPPT scheme most of the time.

(ii) Under the proposed strategy, one source at a time is operated in the voltage regulation mode unlike in a droop control: therefore, the issues of inaccurate power sharing or poor voltage regulation and circulating current do not exist.

(iii) The proposed strategy operated in a distributed manner with local information therefore, it does not require a real time communication link as in the centralized controller.

(iv) The offline communication link is used to update the set values for sources when it requires, such as the integrating of a new sources and the revising of priority level. As a result, the renewables are at their maximum power output without frequent switching from one operating mode to another which can create a less transient effect in the system.

In addition, the sources are considered close to the DC link in a DC microgrid. As a result, the line resistance is ignored in the literature. However, the stability of the system becomes affected beyond a certain line length. Some reasons are: (i) the voltage drop increases in proportion to the line resistance, which weakens the source to the farthest DC link; and (ii) the non-ideal power electronic converter has its own constraints such as delay time, gate drive circuitry, signal noises, switching and power losses which limits the operating conditions. Therefore, the stability analysis with the line resistance is performed in designing the control strategy.
The issues related to DC link are studied in Chapters 5, 6, and 7 for a wind source as a hybrid system and a DC microgrid. In previous chapters, the developed control strategies are used to coordinate the sources in order to regulate the DC link voltage and maintain the DC link stability. The same concept is implemented in Chapter 8, as well, but with a grid connected wind source only. The generator side converter or DC-DC converter is used to regulate the DC link voltage and maintain the DC link stability. Therefore, issues related to the network side converter or inverter at AC link in the presence of voltage sag at the PCC is the primary focus of this chapter. The PMSG-based VSWTs that are integrated with the grid have the following issues during voltage sag:

(i) Conventionally, the controller output of the DC link voltage determines the flow of the active power, making the active power flow inaccurate to the reference.

(ii) The negative-sequence currents flow from the inverter to the grid, causing unacceptable oscillation at twice the system frequency during unbalanced voltage sags at the PCC [80]. This oscillation creates instability in the system.

(iii) The imbalanced power flow occurs between the generator and the grid side inverter, causing the DC link voltage to rise abruptly with ripple during balanced voltage sags at the PCC [80], and

(i) The inverter output current can rise drastically during voltage sags.

These issues potentially may cause damage to the DC link capacitor, and the power electronic components which, in turn, forces the WPS to disconnect from the grid.

If the voltage sag issue at the PCC is not considered while developing a control strategy for a WPS, then the WPS may be disconnected from the grid or damaged during the voltage sag. In addition, the grid code is mandatory for WPS to support the grid, such as active filters or shunt/series inverters [81]. Unfortunately, this solution may not be suitable for small scale wind turbines, SSWTs (< 300 kW) in the low voltage (LV) distribution network.

Based on the issues discussed above, the following control objectives are set for PMSG-based VSWT:

(i) The DC-DC converter regulates the DC link voltage.
(ii) The inverter control performs the following functions, depending on the conditions of the grid:

- Achieving maximum power point tracking (MPPT).
- Regulating the negative-sequence currents to zero.
- Maintaining that the inverter output currents are symmetrical and at the pre-disturbance amplitude irrespective of grid disturbances.
- Balancing the active power between the generator and the grid side inverter during grid voltage sags.

This configuration decouples the control objectives, allowing for the separation of control dynamics at both the generator and the grid side converter. This leads not only to the accurate flow of active power due to the direct power control, but also permits independent control of DC link voltage, and active and reactive power under the vector control strategy. An additional advantage of this control strategy is that it allows the system to ride through grid disturbances without the need to add additional components, such as a chopper to the system. Therefore, the proposed control strategy enables the wind turbine (WT) system to be optimally designed without the need for oversized converters, a large DC link capacitor and a crowbar circuit, which reduces the overall cost of the system.

However, this research work argues, if a large number of SSWTs disconnect from the LV distributed grid network (DGN) within a short period time, then the grid may also encounter instability issues. This is a foreseen condition considering the increasing penetration of SSWTs at the LV DGN. Unlike HV grid network, the LV DGN has a resistive dominant line impedance ($R/X > 1$), which demands more active power than reactive power to support the voltage sag [188]. Therefore, the PCF based control strategy is proposed to control the active power injection to remain in a grid during the voltage sag so that the MPPT power level can be maintained right after the fault clearance.

The WES is a non-linear system, which requires a non-linear and robust controller to perform satisfactorily, as presented in Chapter 9. The classical proportional-integral ($PI$) linear controller is used commonly in WES, which performs well under small
disturbances, but may not be effective in the presence of large disturbances, such as transient disturbances [96]. This is because PI controllers are designed based on linearized small signal models. These models become invalid under large disturbances [97]. In addition, SSWTs at the distributed grid network (DGN) are highly exposed to inherent transient disturbances, such as frequent weather fluctuations, variations in dynamic loads, and temporary faults. The reason could be the close proximity of such wind turbines (WTs) to the loads and surroundings, such as trees and buildings. These transient disturbances create stress on the PEC [184], where a large amplitude transient can shorten the life span of the components and lead to premature failures [11],[185].

In the literature, the non-linear controllers have been used in PEC such as adaptive control, hysteresis control, intelligent control, and modern control theory based controllers such as state feedback controllers and self-tuning controllers. However, most of the nonlinear controls are application dependent and difficult to design and implement, whereas sliding mode control (SMC) is an exception, as it is straightforward to design and easy to implement. Furthermore, the conventional control strategy for the grid side converter (GSC) is to carry out maximum power point tracking (MPPT) schemes, whereas the power flow in the network side converter (NSC) is determined by the DC link voltage regulation [57]. This conventional control strategy has two issues:

(i) The power flow is not accurate to the reference as the controller output of the DLV regulation determines the power flow;

(ii) The complexity arises for the implementation of SMC [103]. The number of differentiations of the output function required for the input to appear explicitly is called the relative degree of the system [186], which becomes 2 for the NSC.

With the proposed control strategy the DLV, active power, and reactive power control are decoupled, so that a separate sliding surface for each variable with a relative degree of 1 is considered. As a result, all variables are regulated independently with smooth transient effects and no complexity. Therefore, the SMC approach based control strategy is proposed under a grid code, considering the line impedance, $R/X<1$, and is performed the following tasks: (i) GSC- DLV regulation; and (ii) NSC- power injection strategy:
(i) The reactive power is injected based on the grid code during the voltage sag to support the voltage at the grid.

(ii) The active power is the difference between the MPPT power and reactive power, so that the amplitude of converter current is maintained within the safe limits.

(iii) The VCCF in the positive synchronous reference frame (SRF) is proposed to regulate the negative sequence currents to zero during unbalanced voltage sag.

The control strategy achieved the same performance, as shown in Chapter 8, in the presence of unbalanced voltage sag at PCC, in addition to the suppressed transient effect and robustness to the parameter variations. Unlike Chapter 8, the proposed strategy is operated under the grid code (reactive power supply). In addition, the loops for feed forward terms in the control strategy proposed in Chapter 8 are eliminated with SMC approach. The complexity of the control structure is reduced.

Therefore, the power management control strategy for a WES in different power system structures: hybrid, microgrid and distribution grid, are developed to actively participate in the operation of the system with improved performance.

1.4 Objectives of the Research

The primary objectives of the research are to develop different control strategies for a WES under different structures and operating modes: islanded (hybrid/microgrid) and distribution grid network in order to maintain stable and reliable operation in the system. Thus the objectives are:

(a) To design and develop a physical hardware system in order to evaluate the developed control strategies for a power management scheme.

- The wind turbine simulator (WTS) is developed to mimic the steady and dynamic characteristics of a real physical 1.0 kW wind turbine on the roof of the Claudette Mackay-Lassonde Pavilion (CMLP) building at the University of Western Ontario (UWO).
- The power electronic converters such as AC-DC and DC-DC of 1.2 kW with a real time controller are developed to interface the WTS to the existing inverter as the PMSG based VSWT.
• The DC and AC link buses are also developed to interface different energy sources and storage in the laboratory.

(b) To develop a comprehensive model for renewable energy sources: wind and PV, and battery energy storage system to study the power management control strategies in an islanded microgrid and a grid connected system. Furthermore, the simulation model is validated by the real physical system developed in the laboratory.

(c) To develop a power management control strategy for a wind power system along with a battery energy storage in the presence of a dedicated bidirectional converter as a hybrid system. The focus is on regulating the DC link voltage and balancing the power flow irrespective of fluctuating weather conditions and load demands. In addition, the dump loads and a diesel generator (emulated as an AC source) are also considered to protect the battery against the SOC limitations.

(d) To develop a power management control strategy for a wind power system along with battery energy storage as a hybrid system without a battery converter and a dump load. The focus is on regulating the DC link voltage and balancing the power flow irrespective of fluctuating weather conditions and load demands. In addition, the regulation of the amplitude and frequency of its terminal voltage for unbalanced load conditions is also performed.

(e) To develop a power management control strategy for a DC microgrid consists of wind, PV, battery energy storage and loads. The focus is on regulating DC link voltage and balancing the power flow irrespective of weather conditions and load demands. The control strategy is developed without a dedicated converter for battery and a dump load to increase the efficiency and reduce the cost.

(f) To develop a control strategy for a low voltage distribution grid connected WPS during voltage sag at PCC due to faults or unbalanced loads.

(g) To design a sliding mode controller for the WPS to enhance the performance during unbalanced voltage sag under the grid code. Furthermore, the comparison with a classical PI controller is also performed to show the effectiveness of the controller.

(h) To validate all the developed control strategies in the laboratory based experimental configuration using different real time controller platform, such as National Instrument LabVIEW, Texas Instrument C2000 microcontroller, and dSPACE.
1.5 Scope of the Research

The focus in this thesis is on developing power management control strategies for a permanent magnet synchronous generator based variable speed wind turbine, a non-dispatchable DG, in different structural forms: (i) Isolated/Islanded mode as a hybrid system and a microgrid; and (ii) Grid connected mode, as illustrated through a tree diagram in Figure 1.2.

![Tree Diagram](image)

**Figure 1.2:** Scope of the thesis using tree diagram

The objective of the considered structures and the developed power management control strategies broadly define the scope of this research, which are briefly introduced as follows:

(i) Islanded hybrid system and microgrid: The system structure is considered with and without a dedicated bidirectional battery converter and a crowbar circuit, in order to operate the system with both conventional and proposed (possibly minimum power electronic components) ways. However, the control strategies in the hybrid system and a microgrid become a challenge in the absence of a battery converter. The existing control strategies cannot operate the system satisfactorily within the operating limits. Therefore, the power management control strategies are developed for both hybrid system and microgrid that can operate with a battery interfaced directly to the DC link. The sources and loads are connected at DC link; thus, DC microgrid is considered for the study. However, the AC loads are connected to the system through a DC-AC converter.
(ii) Grid connected wind system: The wind system is considered to connect at the distribution grid network. Therefore, the control strategy is developed for common distribution grid disturbance- balanced and unbalanced voltage sag. However, the voltage swell which is also a problem with RES, has not been considered in this thesis. The control strategies are developed for a WES at a distribution grid with a line impedance, \( R/X > 1 \) (highly resistive). In addition, the same control strategy using SMC approach is also operated under a grid code (for a low \( R/X \) ratio).

1.6 Contributions of the Thesis

The main contributions of the thesis can be summarized as:

(a) The physical hardware systems are designed and developed to validate the developed control strategies. The WTS is developed to mimic the static and dynamic characteristics of a real physical wind turbine on the roof of the Claudette Mackay-Lassonde Pavilion (CMLP) building at the University of Western Ontario. Furthermore, the design and development of power electronic based interfacing unit for a WTS, such as AC-DC converter, DC-DC converter (buck), and DC link bus, which can be interfaced to the existing DC-AC converter (inverter) in the laboratory as a PMSG based VSWT system (type IV).

(b) The coordinated control strategy for power management in the system consisting of wind, battery with a dedicated bidirectional converter, dump loads and back up diesel generator (emulated as an AC source) as an islanded hybrid system in a DC microgrid is proposed, to balance the power flow within the system irrespective of fluctuating weather conditions and load demands. The status of DC link voltage (DLV) and state of charge (SOC) of the battery are used to activate the sources and sinks autonomously. The battery storage is used to regulate the DC link voltage by consuming excess power and supplying deficit power. In addition, the dump load is used to consume the excess power in the microgrid during fully charged battery condition. Furthermore, the diesel generator is activated only during the discharging of the battery below the minimum operated voltage and SOC thresholds. The proposed control strategy utilizes the local power sources owned by the community as
a microgrid at maximum, by deactivating the grid. Moreover, the diesel generator is activated only during abnormal (extreme) conditions such as low battery energy storage or maintenance requirements. This strategy provides the following advantages: (i) Maximum use of local power reduces the electricity bill from the grid; and (ii) Reduce the frequent operation of the diesel generator, which cuts down the operating cost of the microgrid.

(c) The power management control strategy is proposed for a PMSG based VSWT along with lead acid battery energy storage as a hybrid system in an islanded (off-grid) mode. The control strategy controls the wind and battery through the same DC-DC converter and without the dump load; thus, it is referred to as an integrated control strategy. The objective of the integrated control strategy is to regulate the DC link voltage within the specified limit in order to balance the power flow irrespective of fluctuating wind speed and varying load demands and to protect the battery from overcharging. A dual vector voltage control (DVVC) strategy is also proposed at the AC side to regulate the amplitude and the frequency of AC link voltage during the unbalanced loads for an islanded hybrid system.

(d) The distributed control for power management in a DC microgrid using a DC link voltage (DLV) based control law is proposed. The operational strategy is based on the established dynamic control law which decides the operating modes: maximum power point (MPP) or voltage regulation operating (VRO) mode of the sources. The cost effective control strategy is proposed for a microgrid system (renewable dominated), which protects the battery storage against overcharging without a dedicated battery converter. Therefore, this work explains the control structure, strategy and the implementation of the distributed dynamic control law. The notable features of the proposed control strategy are: (i) straightforward implementation; (ii) less frequent mode transition; (iii) no real time communication link; and (iv) potential for plug and play. In addition, the stability analysis of the control strategy with respect to the line resistance is also performed.

(e) The power management control strategy is proposed for a PMSG based VSWT at a LV distribution grid network during both balanced and unbalanced voltage sags. The
work first analyzes the adverse effects of voltage sags on VSWT systems and then outlines a control strategy. The strategy consists of: (i) a vector current control with feed-forward of the negative-sequence voltage (VCCF) in order to eliminate the effect of negative-sequence components during unbalanced voltage sags; and (ii) a power compensation factor (PCF) control for the VCCF, which maintains the balanced power flow from the VSWT to the grid irrespective of voltage sag. The latter also works to keep the VSWT system’s output currents within safe limits to avoid potential damage to electronic components in the inverter. Unlike the conventional control strategy, the proposed one allows the VSWT system to use optimally sized converters without the need for large DC link capacitors and crowbars.

(f) The control strategy for a PMSG based VSWT at a grid network is further enhanced by using a non-linear sliding mode controller. The strategy not only takes care of the effect of unbalanced voltage sags, but also reduces the effect of sudden changes in the unhealthy grid by suppressing the transient effects and providing robustness to the system. In addition, the control strategy is operated under a grid code to support the voltage sag by injecting reactive power, considering line impedance, $R/X<1$. As a result, the VSWT remains on line without harming itself and supports the grid.

(g) The real time experiments for the hybrid, microgrid and grid connected system are performed to validate the proposed power management control strategies with the physical systems. The closed loop control algorithms are translated into versions that can operate in real-time control platforms. Different real time control platforms such as National Instrument LabVIEW, Texas Instrument (TI) C2000 microcontroller and dSPACE are used for different applications: LabVIEW is used for the control of WTS, TI microcontroller is used for the control of DC-DC converter and dSPACE is used for the control of DC-AC converter. The dSPACE is also used to gather data in real time during experiments.

1.7 Literature Review

Chapters 2, 3, and 4 of this thesis focus on energy sources modeling, design and implementation of the real system (experimental set up) and validation of the model. The
design and development of wind turbine simulator is performed in the laboratory to support the research on wind energy sources.

1.7.1 Wind Turbine Simulator

The concept of a WTS is not new, and different universities and research institutions have developed various WTSs to meet their own research needs. For example, Illinois Institute of Technology (IIT) installed the 8kW Viryd lab based wind turbine drive train system, which is used extensively for research and education [25]. In almost all WTSs, electric motors are used to realize the characteristics of the wind turbine under consideration. As a result, different types of motors lead to different WTS properties.

Three types of motors are commonly used, namely direct current motors (DCM), permanent magnet synchronous motor (PMSM), and induction motors (IM). A DCM is relatively large in size for a given power rating, expensive, and requires more frequent maintenance. However, DC motors are easy to control in order to generate the complex dynamic behavior of a physical wind turbine. A permanent magnet motor is reliable and has good power density, but it is relatively expensive. An IM is robust, inexpensive, has good power density, and low maintenance costs. However, to achieve the desired response, a more complex control system has to be used to deal with its inherent nonlinear characteristics.

A review of wind turbine simulators prior to 2000 was made in [26]. It was based on the performance of three WTS categories according to the intended use. The categories are as follows: (i) a simulator of a particular structure without specified dynamic behavior, (ii) a simulator with specific dynamic behavior, and (iii) a simulator with a general structure. The following section will review existing WTSs in the literature based on the type of motors used.

**WTS Based on DC Motor**

The DC motors are dominant choices for WTSs due to their simplicity in control. The development can be chronologically summarized as follows:
A DCM with a separate excitation and controlled by a microcomputer was used to develop a WTS at the Federal University of Santa Maria in 1995 [27]. A wind turbine emulator, another name for a WTS, was designed based on a dual digital signal processing (DSP) system at Universidad Nacional de La Plata in Argentina. It was used for developing and testing new control strategies for a wind energy conversion system [28]. A wind turbine emulator was developed to investigate the effect of oscillating torque on power quality due to wind shear and tower shadow. Both stall and pitch controlled wind turbines were emulated at Universidad Carlos III de Madrid [29].

A permanent magnet DC motor (PMDCM) driven by a thyristor based AC-DC converter was used to investigate tower shadow and inertia effects [30]. Control algorithms and implementation issues have been presented for realistic emulation of the variable characteristics of wind and rotor blades using a hardware-in-the-loop simulation concept [31]. A WTS was developed to create a controlled test environment for drive trains of wind turbines [32].

A 300 W prototype wind turbine emulator was developed in Centro Nacional de Investigacion y Desarrollo Tecnologico in Mexico to study wind energy conversion systems [33]. A wind turbine emulator was designed and implemented, with consideration given to the different requirements for the development and testing of control strategies in a doubly-fed wind power generating system [34]. The operating principles and torque characteristics of the wind turbine and DC motor were analyzed to imitate the wind turbine characteristics based on a DC motor [35].

The varying aerodynamic power of a wind turbine due to furling actions, as well as the resulting changes in dynamics were incorporated in the simulator reported on by Arifujjaman et al [36]. A novel torque sensorless inertia compensation algorithm was developed to simulate the dynamical behavior of a physical wind turbine in real time [37]. A novel emulator for a fixed pitch wind turbine was presented and the simulator consisted of a series coupling of a DC voltage source, a power resistor, and a DC motor. The adjustment of the DC voltage input had the same effect as variations in wind speed in a fixed pitch wind turbine [38]. A hardware-in-the-loop (HIL) based simulator was
developed with discussion of the design, construction, error evaluation, and performance assessment [39].

**WTS based on Permanent Magnet Synchronous Motor**

In practice, very few WTSs use PMSM because they lack both the simple controls of a DC motor system and the maintenance-free features of an IM. However, the PMSM does offer high-power density. A WTS based on a PMSM was developed to model the torque oscillations caused by wind shear and tower shadow effect [40]-[41]. Both open-loop and closed-loop control systems were implemented to emulate the wind turbine using a PMSM motor and vector control based on the rotor magnetic field orientation. Ke et al, also compare and analyze the characteristics of the WTS against a PMSM [42].

**WTS based on Induction Motor**

A WTS using an IM and a variable speed drive inverter was developed to support the design, evaluation, and implementation of a physical wind turbine controller [43]. The mechanical shaft of the wind turbine was emulated using a standard IM that was controlled by a variable frequency inverter operated in an open-loop torque control mode to test different control strategies [44]. A WTS was also developed to support the design, evaluation, and testing of physical wind turbine drive trains, including generators, transmission, power electronic converters and controllers in [45]. Turbulence and tower effects on wind turbine systems were also examined using a WTS [46]. A research platform for a wind energy system was also developed based on a space vector pulse width modulation (PWM) algorithm, an insulated gate bipolar transistor (IGBT) inverter, and an IM [47].

In the literature, the DCM based WTS is found to be the dominant one because of its smooth transient effects and close to zero steady state error. In addition, most of the papers in Table 1 operated the WTS at deterministic wind speeds (step changes), which is good to test the controller in the system, rather than the system performance. The realistic wind speeds with turbulence effects are considered in the literature; however, they are only verifying mathematical models with hardware, without considering any specific PWT [29]-[33], [48], [49]. Recently, a few papers have been published that consider the
PWT [50]-[51]. The turbine dynamics including the gearbox is designed using a single mass model in [50], which does not represent the accurate dynamics of a MW wind turbine. The simulator was not protected against higher realistic wind conditions in [51]. In practice, the simulator was not designed for a large wind profile (size limitations to reduce cost). Therefore, the simulator components should be protected against higher real wind profile, otherwise the simulator can be damaged.

A unique WTS with an IM using vector torque mode (VTM) control is proposed. This proposed structure and control not only enhance the performance close to that of a DC motor (thanks to vector control technique), but also provide the inherent features of IM such as inexpensive, good power density, and low maintenance costs. The control allows testing of the simulator under the measured real wind profile. In addition, the WTS in the literature is analyzed alone without considering the complete wind system interfacing units. The control of WTS can be affected by the addition of interfacing units and their control. The performance would be degraded by not following the features of the PWT. Therefore, the WTS with its complete interfacing unit has been tested in a microgrid environment. The major existing wind turbine simulators discussed in the literature are summarized in Table 1.1.

Table 1.1: Existing wind turbine simulators

<table>
<thead>
<tr>
<th>Machine</th>
<th>Drive/Control</th>
<th>Focuses/features</th>
<th>Organizations</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCM</td>
<td>Fully controlled 3 phase thyristor bridge</td>
<td>Independent excitation control</td>
<td>Federal University of Santa Maria, Brazil</td>
<td>[27]</td>
</tr>
<tr>
<td>DCM</td>
<td>Phase controlled AC/DC converter</td>
<td>Dual DSP processor</td>
<td>UNLP, Argentina</td>
<td>[28]</td>
</tr>
<tr>
<td>IM</td>
<td>GBT Inverter-variable speed drive</td>
<td>Model of motor, controller design</td>
<td>University of New Brunswick, Canada</td>
<td>[43]</td>
</tr>
<tr>
<td>IM</td>
<td>Commercial frequency inverter</td>
<td>Open loop torque control</td>
<td>Aalborg University, Denmark</td>
<td>[44]</td>
</tr>
<tr>
<td>DCM</td>
<td>Commercial DC drive</td>
<td>Tower shadow &amp; wind shear effect</td>
<td>Universidad Carlos III de Madrid, Spain</td>
<td>[29]</td>
</tr>
<tr>
<td>IM</td>
<td>IGBT inverter</td>
<td>Motor model, controller design</td>
<td>University of New Brunswick, Canada</td>
<td>[45]</td>
</tr>
<tr>
<td>PMSM</td>
<td>3 phase Voltage Source Converter</td>
<td>Tower shadow, wind shear &amp; inertia effect</td>
<td>University of Toronto, Canada</td>
<td>[40]</td>
</tr>
<tr>
<td>PMDCM</td>
<td>3 phase thyristor rectifier</td>
<td>Tower shadow &amp; inertia effect</td>
<td>Concordia University, Canada</td>
<td>[30]</td>
</tr>
<tr>
<td>DCM</td>
<td>Single phase thyristor converter</td>
<td>Tower shadow &amp; inertia effect</td>
<td>Chonbuk National University, Korea</td>
<td>[31]</td>
</tr>
<tr>
<td>PMSM</td>
<td>IGBT inverter</td>
<td>Motor &amp; wind turbine comparison</td>
<td>The Southeast University, China</td>
<td>[42]</td>
</tr>
</tbody>
</table>
### 1.7.2 Hybrid System

In Chapter 5, the power management control strategy in a wind/battery hybrid system with a conventional structure: a dedicated battery converter, dump loads and a backup AC source-diesel generator is presented. In contrast to the grid connected wind system in the literature where the grid is constantly regulated the DC link voltage [52]-[54], the developed control strategy operates the wind system in the presence of battery storage and diesel generator in an islanded mode. In the literature, the diesel generator is contributed constantly throughout the operation of the hybrid system (wind/diesel/battery) in order to counter balance the intermittent nature of renewable sources [55]. The same structure shown in [55] is considered in this study; however, the developed coordinated control strategy operates the diesel generator occasionally during abnormal (extreme) conditions such as low battery energy storage or maintenance requirements.

In Chapter 6 the control strategy for the power management of an islanded hybrid system consists of wind energy source and battery energy storage system is presented. The control strategy is focused on a cost effective and efficient one in an off-grid system without a dedicated converter for battery storage and inefficient dump load.
Extensive research has been done on grid connected VSWT such as low voltage ride through capability, faulty conditions, unbalanced/non-linear loads and grid support [56]–[61]. However, very little attention has been made on standalone operation of wind turbines, which is now gaining attention for various applications. Some energy storage technologies integrated with wind power system requires a suitable geographical site such as hydrogen [62], compressed-air [63] and pumped hydro [64]. A standalone wind energy system using a PMSG has been developed in [52]-[54], [65]. In [65], the paper does not discuss the use of an energy storage, which is required to balance the power during varying wind speed and load demand.

Similarly, the effect of an unbalanced load which is a common phenomenon for standalone operation is not mentioned in [52], [66]. In [53], authors compared the standalone operation of two variable speed wind turbines: PMSG and DFIG; however, these studies require the presence of a dump load and also do not consider unbalanced load conditions. The standalone operation of PMSG based wind turbine along with battery storage and a fuel cell is presented in [54]. The unbalanced study is also performed in [54]. However, a peak detection method is employed for unbalanced load conditions, which is sensitive to small frequency variations as well as harmonics. The sensitivity of the detection is reduced by using multiple low pass filters which require proper design to eliminate oscillations. The control strategy in [54] considers an additional converter for battery storage and dump load.

1.7.3 DC Microgrid

In Chapter 7, the control strategy for power management in an islanded DC microgrid is proposed. A distributed control strategy for power management in a DC microgrid based on dynamic control law without a real time communication link is proposed which improves the voltage regulation and power flow performance of the system unlike the conventional droop control.

The power management strategies for a DC microgrid can be generally classified as centralized, decentralized, and distributed manner [67]. The centralized control such as master-slave is acquired information by a central control to perform the operation, which
is highly relying on the communication link [68]. The failure in communication links can degrade system reliability. This issue is avoided by a decentralized control such as droop control, which is based on the local information measurements [69]. Nevertheless, this improvement is at the cost of inaccurate power sharing or poor voltage regulation and circulating current, due to mismatch in the parallel converter’s output voltages [70]. This constraint of droop control method is improved by several techniques in the literature.

The issues of conventional droop control are improved by using a low bandwidth communication (LBC) link. This algorithm enhances the droop performance; however, the effect of line resistance was not considered [71]. An improved droop control using LBC link and considering the line resistance is discussed in [72]. However, the issues such as reliability and performance constraints still exist with a new LBC link. The improved droop control is proposed in [73] without a communication link. The algorithm requires an estimation of line resistance during grid connected mode. This estimated line resistance value is used to update the droop value during islanding mode. Therefore, the flexibility in the microgrid operating modes is limited by the mandatory connection to the grid, at first. A co-operative algorithm with a voltage regulator and current regulator is presented in [74]. In this algorithm, the current regulator compares local current with the neighbor’s currents and, accordingly, adjusts the droop virtual impedance to balance the supplied currents. A droop index is determined using current sharing differences and losses in the output side of the converters [75]. This strategy raises the complexity of the microgrid control for more than two sources.

The alternative solution for centralized and decentralized control is a distributed control based power management strategy. Instead of single secondary control, distributed control is incorporated in each source. A typical distributed control strategy applied to a DC microgrid is the average current sharing [70]. This algorithm requires the average current of each source to set the voltage reference. The complexity rises with increasing the number of sources. The other distributed control strategy is based on the DC link voltage (DLV) information [76]. The DLV is used to determine the operation modes of converters according to the predefined voltage thresholds. The overall system redundancy can be maintained, as only voltage information is required. However, some extreme
conditions in [76] such as over current/voltage charging and fully charging/undercharging for storages are not considered. The DLV information is extended to control a grid coupling DC microgrid in [77]. Different bus voltage levels are predefined to distinguish different system operation modes and switching between stand-alone and grid connected modes. The DC voltage variation based autonomous control of DC microgrid is proposed in [78]. This DLV information based distributed control strategy has one drawback. The number of sources and storages within the microgrid is restricted by the number of voltage levels, which cannot be divided unlimitedly due to the DLV tolerance. This issue has not been emphasized in [76]-[78]. In addition, the voltage levels are selected arbitrarily.

The DC voltage based distributed control is implemented using a bidirectional battery converter, which protects the battery against overcharging and discharging in [78]. However, the overall cost also rises—especially when the energy cost (renewable) is high. The battery without converter can be controlled through proper power management scheme of the system [79] at the same performance level. Therefore, the proposed control strategy which is motivated by an economic system control, considers the battery protection against overcharging without the dedicated converter. Furthermore, it regulates the DLV within the operating range.

In order to provide a cost effective, simple structure and reliable DC microgrid with less information exchange, a distributed control strategy based on dynamic control law is proposed in this thesis.

1.7.4 Grid Connected Wind System

In Chapter 8, the control strategy for a PMSG based VSWT integrated at a low voltage distributed grid network in the presence of voltage sag at the point of common coupling (PCC) is presented. The objective of this control strategy is to protect the wind power system (WPS) from any detrimental effect of balanced or unbalanced voltage sag at PCC and remains on line to support grid stability. The control strategy is further enhanced by introducing the non linear and robust sliding mode controller (SMC).
The literature contains some previous work on the active power control of power electronic converters (or inverters) and PMSG-based WTs when connected to a grid [80] and [57],[81]-[87]. In, [80] different techniques for creating current references under unbalanced grid voltage have been studied. However, the paper does not consider the impact on the DC side during abnormal conditions. In addition the peak current is not limited to the pre-disturbed level. Similarly, the approaches in [57], [81]-[84] fail to take grid disturbances into consideration. The dual vector current controller (DVCC) is developed in [85], which uses two current controllers for positive and negative SRFs. Unfortunately, this system leads to a complex control structure and can potentially produce asymmetrical phase currents.

A current controller with positive-sequence grid voltage is used in the positive synchronous reference frame (SRF) [86], but does not completely solve the issue of voltage imbalances. Controlling each phase separately using the peak detection method (PDM) is also proposed as a compensation scheme for unbalanced voltage [87], but such a strategy is hampered by PDM’s sensitivity to low frequency fluctuations and harmonics. The feed-forward power compensation technique is implemented in [88]-[91]. In [88], sinusoidal balanced currents are obtained at the expense of DLV oscillation and a large DC link capacitor. The control to suppress the rise in grid current due to unbalanced voltage sag has not been emphasized in [88]-[91], which could damage the power electronic components of the converter or the oversized converters can suppress the effect. In addition, the control strategy requires a real time calculation for compensating power, which is complex to implement and creates a further delay in addition to the time required for sequence extraction.

For balanced voltage sag, additional sources and sinks are used to compensate for the voltage sag at the PCC. Such solutions include a braking chopper, a crowbar, storage and even a STATCOM [92]-[94], but all serve to further increase the total cost of the WPS.

In Chapter 9, the performance of the control strategy proposed in Chapter 8 is enhanced by using non-linear sliding mode controller. The WES is a non-linear system, which requires a non-linear and robust controller to perform satisfactorily. The classical PI
linear controller is used commonly in WES, which performs well under small disturbances, but may not be effective in the presence of large disturbances, such as transient disturbances [95]. This is because PI controllers are designed based on linearized small signal models. These models become invalid under large disturbances [96].

A nonlinear controller may outperform a linear controller under certain circumstances. Some of these controllers have been used in PEC such as adaptive control [97], hysteresis control [98], intelligent control [99], and modern control theory based controllers such as state feedback controllers [100] and self-tuning controllers [101]. However, most of the nonlinear controls are application dependent and difficult to design and implement, whereas sliding mode control (SMC) is an exception, as it is straightforward to design and easy to implement.

The non-linear SMC has been implemented to enhance the control performance by suppressing the transient effect and bringing robustness to the system [102]-[105]. The SMC is implemented for an ideal grid without any disturbances and the results are compared with PI based vector current control (VCC) [102]. In [103] the voltage, sag effect has been eliminated using the SMC approach however unbalanced conditions are not considered, which are common and responsible for distorted imbalanced output current. The WT is supposed to inject the distorted free balanced sinusoidal currents to the grid according to IEEE 1547 and IEEE 519, which is the primarily focus in [91], [104]-[107]. However, the rise in current amplitude due to the voltage sag is not emphasized. The hard switch limit would further distort the current. The SMC based direct power control (DPC) is implemented for the fast dynamics during an unbalanced voltage sag [104],[105]. However, the SMC control does not guarantee zero steady state error for all disturbances because the integral function is missing in the sliding surface. In [108], the integral function is considered. The SMC based direct power control is normally implemented in a two coordinate stationary reference frame, which has sinusoidal functions. Therefore, to achieve satisfactory performance the compensator must be of high order. In addition, the closed loop bandwidth must be adequately larger.
than the frequency of the reference command. Thus, the control design is not straightforward.

This thesis proposes the vector current control with feed-forward of negative sequence voltage (VCCF), including the current limiting strategy under the SMC approach at the NSC, and SMC based DC link voltage regulation at the GSC. The linear controller based voltage feed-forward strategy without considering the NSC’s injected current amplitude has been studied in [109].

1.8 Organization of the Thesis

The thesis is organized into the following chapters:

In Chapter 2, the modeling, structure and control of energy sources are considered. The detailed model of PMSG based VSWT including the aerodynamic and generator model was performed. The model of PMSG was developed by synchronously rotating $d-q$ reference frame. The photovoltaic (PV) and lead acid battery were also modeled considering their characteristics. Furthermore, the chapter also reports the structure of these sources utilized in different applications, so that the corresponding control strategy can be developed. The control strategy was varied depending upon the structure of the system where these energy sources were implemented.

In Chapter 3, the design, development, and implementation of a physical system as an experimental test bed for the energy sources with their power electronic based interfacing (PEBI) units are presented. The WTS was designed and developed in a laboratory, which mimics the steady and dynamic characteristics of a real physical wind turbine installed on the roof of engineering building (CMLP) at the University of Western Ontario. The PEBI units were also designed and implemented for energy sources to interface with DC and AC system. The PEBI units include a converter such as AC-DC, DC-DC, DC-AC, DC link (bus) and AC bus respectively. The commercial systems used in the test bed are also presented. The real time control platform such as TI microcontroller, dSPACE and LabVIEW are also introduced and used for various applications.
In Chapter 4, the model of energy sources are validated against the real physical system. The WTS coupled with PMSG validates the model of PMSG based VSWT. Similarly, the real data collected through the roof top PV installed on the engineering building (CMLP) validated the model of PV. The lead acid battery model is validated through a commercial lead acid battery data, and the paper published on the model of real lead acid battery of same features.

In Chapter 5, the power management control strategy for a wind/battery hybrid system in a DC microgrid with a conventional structure: a dedicated battery converter, dump loads and a backup AC source –diesel generator is presented. The coordinated control strategy between the sources and sinks in the system is performed, so that the power flow is balanced with a stable DC link voltage.

In Chapter 6, the control strategy for power management in an islanded hybrid system consists of PMSG based VSWT and battery energy storage is developed. This chapter explains the cost effective and efficient structure of the hybrid system along with the control strategy. The control strategy is validated on the experimental test bed.

In Chapter 7, the control strategy for power management in an islanded DC microgrid consists of PMSG based VSWT, PV, battery energy storage, and dispersed loads is proposed. This chapter explains the proposed power management control strategy for the DC microgrid. The control strategy is validated in the experimental test bed.

In Chapter 8, the control strategy for a PMSG based VSWT integrated at a low voltage distributed grid network in the presence of both balanced and unbalanced voltage sag is developed. The control structure of the system is explained in detail followed by the control strategy. The control strategy is developed to deal with the most common disturbance phenomenon at distribution network-voltage sag at the PCC in order to remain in the grid without affecting the stability of the system. The control strategy is validated by the experimental test bed.

In Chapter 9, the performance of the proposed control strategy in Chapter 8 is enhanced by using non-linear sliding mode controller. The effectiveness of SMC has been justified
by comparing it with the linear $PI$ controller. In addition, the experiment is performed to validate the control strategy with sliding mode controller under a grid code (supplying reactive power).

The conclusions of the thesis and suggestions for the future work constitute Chapter 10, followed by bibliography and appendices.
Chapter 2

2 ENERGY SOURCES: MODEL, STRUCTURE AND CONTROL

This chapter presents the model, general structure, and control of energy sources considered in the study. The detailed model of PMSG based VSWT including the aerodynamic and generator model along with photovoltaic and lead acid battery were performed in PSCAD and MATLAB softwares. Furthermore, the chapter also reports the general structure and control of these sources utilized in different applications so that the improved control strategy can be developed. The control strategies for these sources were varied depending upon the structure of the system.

2.1 Wind Energy Source

The wind energy source has been used for many centuries. In early years, wind energy (which is in the form of mechanical energy) could be used directly or converted into other forms of energy such as electrical energy. The pumping of water and grain grinding were the most common applications of wind energy. The other possible application of wind energy could be the producing of hydrogen from the electrolysis of water. Hydrogen, which is a clean fuel, can be used for electricity generation employing fuel cells. It can also be used as a fuel for producing heat or running internal combustion engines.

Nowadays, the wind energy source is becoming extremely popular for generating electricity. It can be used as a standalone hybrid system for a small community or in a microgrid with other energy sources. Due to the advancement of wind energy technology, the wind energy source is also used as an active power source in a power system utility. However, the basic fundamentals of generating power from a wind energy source are the same irrespective of new technology. Therefore, the following sections explain the wind power production along with different energy conversion systems. Finally, the modeling of wind energy source based on the latest conversion system technology is presented.
2.1.1 Wind Power Production

Wind energy is basically the kinetic energy of large masses of air moving over the earth’s surface. The blades of the wind turbine receive this kinetic energy from the air, which in turn rotate the wind turbine. The generator which is coupled with the turbine directly or indirectly through a gearbox also rotates in the same direction. As a result, the generator produces the electromotive force or electricity based on its operating principle. Hence, the kinetic energy is converted into mechanical energy and mechanical energy is finally converted into electrical energy. When a stream of air with mass \( m \) moves with a velocity \( \theta \), its kinetic energy \( E \) is given by

\[
E = \frac{1}{2} m \theta^2 \tag{2.1}
\]

During a time period \( t \), the mass \( m \) of air passing through a given area \( A \) at a velocity \( \theta \) is given as

\[
m = \rho A \theta t \tag{2.2}
\]

where \( \rho \) is the air density. Hence, energy per unit time, that is the power \( P_{av} \) in the wind stream available for the rotor can be expressed using (2.1) and (2.2) as

\[
P_{av} = \frac{1}{2} \rho A \theta^3 \tag{2.3}
\]

The theoretical power available in wind is given by (2.3). However, the extracted or actual power \( P_m \) of a wind turbine depends on its design and the structure. Therefore, power coefficient \( C_p \) of the rotor or rotor efficiency determines the actual wind power, which is the ratio of actual power developed by the rotor to the theoretical power available in the wind.

\[
C_p = \frac{P_m}{P_{av}} \tag{2.4}
\]

Therefore, the actual power which is also a mechanical power \( P_m \) of a wind turbine is expressed as

\[
P_m = \frac{1}{2} \rho A C_p \theta^3 \tag{2.5}
\]

The theoretical optimum power that can be extracted from available power is 59\%, which was discovered by Betz in 1926, which is why this is also called Betz law. In practical
designs, maximum achievable power coefficient is between (40 -50) % for a three bladed horizontal axis wind turbine [110].

The power coefficient is based on the design of the wind turbine and also the function of tip speed ratio ($\gamma$) and pitch angle ($\beta$) respectively. The tip speed ratio is defined as the ratio of linear speed of the blade’s outermost tip to the free upstream wind velocity, which is given as
\[
\gamma = \frac{\omega_m \times r}{\theta}
\]  
(2.6)

where $\omega_m$ and $r$ are the rotor angular speed (rad/s) and rotor radius respectively. The power coefficient is now expressed in the form of tip speed ratio and pitch angle for three bladed horizontal axis wind turbine as given below [110]:
\[
C_p(\gamma, \beta) = c1 \left( c2 \left( \frac{1}{\gamma + 0.08\gamma} - \frac{0.035}{(\beta^3 + 1)} \right) - c3\beta - c4 \right) \\
\exp \left( -c5 \left( \frac{1}{\gamma + 0.08\gamma} - \frac{0.035}{(\beta^3 + 1)} \right) \right) + \frac{c6}{\gamma}
\]  
(2.7)

where, $c1$, $c2$, $c3$, $c4$, $c5$ and $c6$ are the constants which relies on the aerodynamic design of the particular wind turbine.

Table 2.1: Aerodynamic constants of a considered wind turbine

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c1$</td>
<td>0.22</td>
</tr>
<tr>
<td>$c2$</td>
<td>116</td>
</tr>
<tr>
<td>$c3$</td>
<td>0.4</td>
</tr>
<tr>
<td>$c4$</td>
<td>5</td>
</tr>
<tr>
<td>$c5$</td>
<td>12.5</td>
</tr>
<tr>
<td>$c6$</td>
<td>0</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.225 kg/m³</td>
</tr>
<tr>
<td>$r$</td>
<td>1.2 m</td>
</tr>
</tbody>
</table>

Therefore the mechanical power ($P_m$) and torque ($T_m$) developed by the wind turbine are finally expressed as
\[
P_m = \frac{1}{2} \rho AC_p(\gamma, \beta) \theta^3
\]  
(2.8)
2.1.2 Wind Energy Conversion System

In the last few decades, the wind energy cost has been creeping down due to the advancement of technology. As a result, different wind configurations or topologies have been analyzed and fitted in the system. However, the great interest at the present time is how light a turbine can be and still survive the desired amount of time. Thus, wind turbine configuration can be classified in various ways based on different factors such as:

- Rotor axis orientation: horizontal and vertical
- Rotor position: upwind or downwind of tower
- Rotational speed: constant or variable
- Rotor power control: pitch, stall and active stall

Beside the above classification of topology, the wind turbine can be also classified based on number of blades, hub, yaw etc. The wind energy source which is stochastic by nature requires some form of conversion system to fit into the electric power system without disturbing the stable voltage and frequency. Therefore, the more general classification of wind turbine topology is based on rotational speed with different power control, which is classified into four types – Type I, Type II, Type III and Type IV, respectively.

2.1.2.1 Type I- Constant Speed

The wind turbine rotor speed is constant regardless of wind speed and determined by the frequency of the supply grid, the gear ratio, and the generator design. Type I configuration consists of a wind turbine coupled with a squirrel cage induction generator (SCIG) through a gear box as shown in Figure 2.1. The soft starter and capacitor bank are also present for smoother grid connection and reactive power compensation.
The configuration is simple, robust, reliable and well proven; however, it has some limitations such as uncontrollable reactive power consumption, mechanical stress, and limited power quality control.

2.1.2.2 Type II- Variable Speed

The configuration is similar to Type I except the wound rotor induction generator (WRIG) and the variable resistance are incorporated, as shown in Figure 2.2. The resistance, which can be changed by an optically controlled converter mounted on the generator shaft, controls the generator typically in the range of 0-10% above the synchronous speed.

The Type II configuration brings flexibility in the generator control with variable resistance; however, the control range is very limited.
2.1.2.3 Type III- Variable Speed with Partial-Scale Frequency Converter

The configuration is similar to Type II except with some modifications to the control and structure. The stator windings are directly connected to the constant frequency three phase grid and the rotor windings are mounted to a bidirectional back to back voltage source converter (VSC), hence both stator and rotor induced voltage on the system, which is why it is called variable speed with partial scale frequency converter as shown in Figure 2.3. Sometime, it is also referred to as a doubly fed induction generator (DFIG).

![Figure 2.3: Type III wind system configuration](image)

The VSC performs reactive power compensation and smoother grid connection beside speed control. It has a wider range of dynamic speed control, typically in the range of -40% to +30% of synchronous speed.

2.1.2.4 Type IV- Variable Speed with Full-Scale Frequency Converter

The configuration consists of either an induction generator or a synchronous generator (with excitation winding or permanent magnet) which is connected to the electric power system (EPS) through a full scale frequency converter, as shown in Figure 2.4. The configuration can be a gearless especially with permanent magnet synchronous generator (PMSG) with large number of poles. The frequency converter passes all of the generating power from the wind generator to the load, hence it is referred as a full scale frequency converter, as shown in Figure 2.4.
The stator frequency is completely decoupled with the EPS frequency; hence, the configuration provides lots of flexibility in the control to meet the strict regulation of the EPS.

In this thesis, the Type IV wind system configuration with PMSG is studied and its control strategy has been developed.

### 2.1.3 Wind Turbine Model

The Type IV wind system configuration consists of wind turbine, PMSG and power electronic based converter (PEC). The PECs are modeled using average linearized techniques such as a small signal model. However, the wind turbine and generator requires a detailed model to mimic the realistic behavior of a system. In addition, the control strategy should incorporate the wind power system dynamics and its impact on the electric power system, which is not possible without the adequate model of the wind system.

The wind turbine characteristics are explained in Section 2.1.1. The steady state characteristics of wind power production is shown in (2.8) which requires the tip speed ratio and power coefficient at the particular wind speed. The tip speed ratio depends on the wind speed and rotor angular speed, as shown in (2.6), whereas the power coefficient in (2.7) relies on tip speed ratio. Therefore, both parameters of wind turbine vary with wind speed. By maintaining the power coefficient at maximum (optimum) value irrespective of fluctuating wind speed, the wind turbine can operate at maximum power point tracking (MPPT) scheme.
The dynamic characteristics of the wind turbine are modeled using a single mass model of a drive train. The drive train complexity varies with the objective of the study. For example, the study related with mechanical dynamics or torsional fatigue requires two or more sophisticated mass model. However, when the study is focused on the interaction of WPS with the electric power system, especially Type IV where the dynamics of the generator and grid side are decoupled then the drive train is treated as one lumped mass model for the sake of time efficiency and acceptable precision [111],[112]. In addition, the drive train is modeled by assuming that the switching of the proposed converters does not affect the mechanical dynamics of the wind turbine. The switching periods of the converters are very fast in the millisecond range compared to seconds for the mechanical time constant. The effect of converter switching on the mechanical dynamics is thus neglected. The damping and friction are also neglected. Therefore, the first order equation is adequate to model the dynamics of the wind turbine which is given as [113]:

\[
J \frac{d\omega_m}{dt} = T_m - T_e
\]  

(2.10)

where \(J\) is the inertia of the drive train, \(\omega_m\) is the rotor angular speed, \(T_m\) is the mechanical torque and \(T_e\) is the electrical torque respectively.

2.1.4 Permanent Magnet Synchronous Generator (PMSG)

The machine model is analyzed in a single phase assuming that the three phases are balanced. Each phase of machine can therefore be modeled as shown in Figure 2.5.

![Figure 2.5: Per phase model of PMSG](image)

The stator resistance \((R_s)\) is the resistance of the windings of the machine which is relatively small. The synchronous inductance \((L_s)\) of the machine comes from the
inductance of the windings and is composed of the air gap inductance, the slot leakage inductance and the end turn inductance respectively. The back electromotive force (emf, \( E_f \)) is produced through the flux linkage in the windings from the rotating magnetic field in the machine. Lastly, \( V_s \) is the stator terminal voltage. Therefore, the induced emf or back emf is expressed as [114]

\[
E_f = k_{pm}\lambda_{pm}\omega_e
\]  

(2.11)

where \( k_{pm} \) is the magnetic strength, \( \lambda_m \) is the permanent magnet flux linkage and \( \omega_e \) is the electrical rotor angular speed. The back emf can also be expressed from Figure 2.5 as

\[
E_f = k_{pm}\lambda_m\frac{p}{2}\omega_m = V_s - i_sR_s - L_s\frac{di_s}{dt}
\]  

(2.12)

where the electrical rotor speed is related with mechanical rotor speed as

\[
\omega_e = \frac{p}{2}\omega_m
\]  

(2.13)

The terminal stator voltage of the PMSG can be described by the following expression:

\[
V_s = i_sR_s + L_s\frac{di_s}{dt} + k_{pm}\lambda_m\frac{p}{2}\omega_m
\]  

(2.14)

The rate of change of total flux linking with each stator winding (\( \lambda_s \)) is given as

\[
\frac{d\lambda_s}{dt} = L_s\frac{di_s}{dt} + k_{pm}\lambda_m\frac{p}{2}\omega_m
\]  

(2.15)

Substituting (2.15) into (2.14), so that the final terminal voltage equation of PMSG can be written as

\[
V_s = i_sR_s + \frac{d\lambda_s}{dt}
\]  

(2.16)

Assuming zero sequence quantities are not present and applying Park’s transformation, (2.16) may be written in synchronous rotor reference or \( d-q \) frame as [115]. The \( abc \) and \( d-q \) equivalent windings of PMSG is shown in Figure 2.6, where the \( d \)-axis is aligned by an angle \( \theta_m \) with \( a \)-axis.
The machine model voltage equations in $d-q$ rotating reference frame where $d$-axis is fixed to the permanent magnet rotor flux direction are expressed as:

$$V_s = v_{sd} + jv_{sq}; \quad i_s = i_{sd} + ji_{sq} \quad (2.17)$$

$$v_{sd} = R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_m \lambda_{sq} \quad (2.18)$$

$$v_{sq} = R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_m \lambda_{sd} \quad (2.19)$$

where subscripts ‘$d$’ and ‘$q$’ represent axes of the $d-q$ reference frame.

$$\lambda_{sd} = L_{sd} i_{sd} + \lambda_m \quad (2.20)$$

$$\lambda_{sq} = L_{sq} i_{sq} \quad (2.21)$$

Substituting (2.20) and (2.21) in (2.18) and (2.19) respectively

$$v_{sd} = R_s i_{sd} + L_{sd} \frac{di_{sd}}{dt} - \omega_m L_{sq} i_{sq} \quad (2.22)$$

$$v_{sq} = R_s i_{sq} + L_{sq} \frac{di_{sq}}{dt} + \omega_m L_{sd} i_{sd} + \omega_m \lambda_m \quad (2.23)$$

In the generating mode, the power flows in a reversed direction in Figure 2.5. Therefore, the sign conversion should be considered in the generator model. As a result the stator terminal voltage of PMSG in $d-q$ reference frame is finally expressed as

$$v_{sd} = -(R_s i_{sd} + L_{sd} \frac{di_{sd}}{dt}) + \omega_m L_{sq} i_{sq} \quad (2.24)$$

$$v_{sq} = -(R_s i_{sq} + L_{sq} \frac{di_{sq}}{dt}) - \omega_m L_{sd} i_{sd} + \omega_m \lambda_m \quad (2.25)$$
The electrical torque \((T_e)\) is expressed in (2.26) where \(p\) is the number of pole pairs [117]:
\[
T_e = 1.5p(\lambda_{sd}i_{sq} - \lambda_{sq}i_{sd}) \tag{2.26}
\]
Substituting (2.20) and (2.21) in (2.26), the torque equation becomes
\[
T_e = 1.5p(\lambda_{m}i_{sq} + (L_{sd} - L_{sq})i_{sd}i_{sq}) \tag{2.27}
\]
The considered PMSG is a surface mounted generator (non-salient), therefore the air gap is uniform. In addition, there is no variation in \(d-q\) axes inductances. Therefore, the torque expression becomes
\[
T_e = 1.5p\lambda_{m}i_{sq} \tag{2.28}
\]

2.2 Photovoltaic (PV) Energy Source

The photovoltaic (PV) source is the other rising renewable energy technology. The PV system is a complex system and its performance depends on the internal characteristics of PV material to external meteorological parameters, such as the solar irradiance and the ambient temperature [118]. Investigating control strategies in a microgrid system requires a reasonable model which can accurately represent the PV system.

The PV cells are fabricated by semiconductor materials. These materials are exposed to sunlight rays in order to lose the electrons which move in the external circuit and, hence, generate the DC current. Therefore, an ideal PV can be considered as a current source which is parallel to one or two diodes depending upon the semiconductor materials and manufacturing technology [119]. The real characteristics of PV exhibit the need of series and parallel resistances in the model [119]. The circuit model of PV is shown in Figure 2.7. Based on this model, the current \((I)\)-voltage \((V)\) characteristics of a cell can be represented as:
\[
I = N_p \left[ I_{ph} - I_s \left( \exp \left( \frac{q}{AKT} \left( V \frac{1}{N_s} + I \frac{R_s}{N_s} \right) \right) - 1 \right) - \frac{V}{N_s + \frac{I}{N_p} R_s} \right] \tag{2.29}
\]
where

- \(I_{ph}\) = Photo generated current
- \(I_s\) = Saturation current of the diode
$R_s =$ Cell series resistance
$R_p =$ Cell shunt resistance
$A =$ Diode quality factor
$T =$ Cell operating temperature in Kelvin
$q =$ Electronic charge, $1.6 \times 10^{-19} C$
$k =$ Boltzmann’s constant, $1.38 \times 10^{-23} J/K$
$N_p =$ Number of cells connected in parallel
$N_s =$ Number of cells connected in series

![Circuit model for a PV cell](image)

**Figure 2.7:** Circuit model for a PV cell

The PV electrical model depends upon five parameters as shown in (2.29): $I_{ph}, I_s, R_s, R_p$ and $A$ which are regarded hereafter as model parameters. These parameters can either be estimated from the data provided on the datasheet or obtained through the experimentation. The model parameters are non-uniform which varies based on the weather conditions: solar irradiance and temperature. Therefore, the effects of solar irradiance and temperature on PV parameters should be taken into account. The widely used approach, proposed in the literature, is considered which is to mathematically formulate the relationship between model parameters and solar irradiance and temperature [120], [121].

Accordingly, the photo generated current related to solar irradiance and temperature is given as:

$$I_{ph} = \frac{E}{E_n} I_{ph(n)} \left(1 + k(T - T_0)\right)$$

(2.30)

where $I_{ph(n)}$ is the photo generated current at the standard condition ($25^\circ C$ and $1000 W/m^2$). $T$ and $T_0$ are the cell actual and standard temperature ($^\circ K$), respectively. Similarly, $E$ and $E_n$ are the actual and standard irradiance levels ($W/m^2$) on the PV surface. The
diode saturation current has a non-linear dependence on temperature, unlike photo generated current; however, it is not considerably affected by solar irradiance [120],[121].

\[ I_s = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{kTAN_{s}}\right) - 1} \]  

(2.31)

where \( I_{sc} \) is the short circuit current and \( V_{oc} \) is the open circuit voltage of the PV which are calculated at specific operating condition instead of the nominal one, unlike in [119].

The nominal open circuit voltage \( (V_{oc}) \) can be also formulated as:

\[ V_{oc} = V_{oc(n)} + k(T - T_0) \]  

(2.32)

where \( V_{oc} \) is the nominal open circuit voltage and \( k \) is a constant. The other two parameters \( R_s \) and \( R_p \) are normally kept at nominal values irrespective of weather conditions. They do, however, vary with solar irradiance and temperature, thus, the relationship can be developed as:

\[ R_s = k_1 + \frac{k_2}{E} + k_3T \]  

(2.33)

\[ R_p = R_{p(n)}e^{-k_4T} \]  

(2.34)

where \( k_1-k_4 \) are constants and \( R_{p(n)} \) is the nominal parallel resistance at the standard condition \((1000W/m^2 \text{ and } 25^\circ C)\).

The model parameters are determined through experiments which were performed in a single PV module under various solar irradiance and temperature as detailed in [122].

2.3 Battery Energy Storage

The lead acid battery is considered as an energy storage in this study because the lead acid battery is still the most common energy storage device for renewable energy sources with high power density [123]. Several inputs are considered for the modeling of this battery such as battery current, capacity, state of charge and temperature. All these parameters are varied with the operating conditions and affected the capacity of battery to charge or discharge. The battery terminal voltage is considered as an output of the model.

The CIEMAT (Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas) model is the most detailed and accurate model which is considered in this study [124],[125].
The voltage equations based on this model are represented as:

\[
V_d = n \times [1.965 + 0.12 \times SOC] - n \times \frac{|I_{bat}|}{C_{10}} \\
\quad \times \left[ \frac{4}{1 + |I_{bat}|^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02 \right] \times [1 - 0.007 \times \Delta T] \\
(2.35)
\]

\[
V_c = n \times [2 + 0.16 \times SOC] + n \times \frac{|I_{bat}|}{C_{10}} \\
\quad \times \left[ \frac{6}{1 + |I_{bat}|^{0.88}} + \frac{0.48}{(1 - SOC)^{1.2}} + 0.036 \right] \times [1 - 0.025 \times \Delta T] \\
(2.36)
\]

\[
V_{oc} = n \times V_g + n \times (V_{ec} - V_g) \times \left[ 1 - \exp \left( \frac{t - t_g}{\tau_g} \right) \right] \\
(2.37)
\]

\[
V_{ec} = n \times \left[ 2.45 + 2.011 \times \ln \left( 1 + \frac{I_{bat}}{C_{10}} \right) \right] \times [1 - 0.002 \times \Delta T] \\
(2.38)
\]

\[
V_g = n \times \left[ 2.24 + 1.97 \times \ln \left( 1 + \frac{I_{bat}}{C_{10}} \right) \right] \times [1 - 0.002 \times \Delta T] \\
(2.39)
\]

\[
\tau_g = \frac{1.73}{1 + 852 \times \left( \frac{I_{bat}}{C_{10}} \right)^{1.67}} \\
(2.40)
\]

where \( n \) is the number of battery cells, \( SOC \) is the state of the charge of the battery, \( I_{bat} \) is the battery current, \( C_{10} \) is the battery capacity at the constant current during ten hours \( (C_{10} = 10 \times I_{10}) \) which can be also determined for different time periods such as \( C_{32} \) for 32 hours, \( \Delta T \) is the temperature variation with respect to nominal value \( (25^\circ C) \), \( V_d \) and \( V_c \) are the voltages across the battery terminal while the battery are discharging and charging, \( V_{oc} \) is the over-charge voltage of the battery after reaching a so called gassing voltage \( (V_g) \) during the charging process, \( \tau_g \) is the time constant which is inversely proportional to charge current, \( t \) is the time period, \( t_g \) is the time when the gassing voltage formed, \( V_{ec} \) is the ending charge voltage, \( C_{bat} \) is the battery capacity, \( Q_d \) is the charge delivered at the time of interest and \( I_{10} \) is the discharge current corresponding to \( C_{10} \). Therefore, the \( SOC \) is calculated theoretically as in (123).

\[
SOC = 1 - \frac{Q_d}{C_{bat}} \\
(2.41)
\]
\[ \frac{C_{bat}}{C_{10}} = \frac{1.67}{1 + 1.67 \times \left( \frac{l_{bat}}{l_{10}} \right)^{0.9}} \times [1 + 0.005 \times \Delta T] \]  

(2.42)

According to (2.42) if the discharge mean current \( l_{bat} \) of the battery decreases, the capacity of the battery increases. In other words if the battery discharges with high current, the actual capacity of the battery will decrease. Therefore, for the better utilization of the battery, the battery output current is controlled in a way that the discharge mean current remains at minimum.

2.4 Structure and Control of Renewable Energy based Power System

Some of the new renewable energy technologies under non-dispatchable DGs, such as PMSG based VSWT (Type IV wind system), and PV are primarily based on full scale power electronic interfacing units or converters, which allow different structure and control without being dominantly advantageous to one another. These renewable energy sources are connected to the electric power system with other complimentary sources or storage within close vicinity, to increase the overall stability and reliability of the system. Therefore, these sources can be operated in a standalone, hybrid, and microgrid as a cluster of sources and local loads which may be in a grid connected or islanded (off-grid) mode. The typical structures and the corresponding controls are reviewed as follows:

2.4.1 Standalone System

**Structure**

The RES is connected differently to the electric power system (EPS) depending upon the overall system structure. A standalone power system is defined as an off-grid system, which operates independently without a grid support. Similarly, a standalone RES is defined in this thesis as a single source which is operated individually without any support systems, such as storage or back up source to counteract the stochastic nature or weather dependency. Such a standalone RES cannot be operated effectively and efficiently in an islanded (off-grid) system; thus, it is always operated in a grid connected mode to maximize its optimal use and credentials, as shown in Figure 2.8.
The RES is connected to a grid at the point of common coupling (PCC) through a series of power electronic interfacing units as shown in Figure 2.8. The fluctuating wind speed has impact on the output power which also varies irrespective of load demands. The mismatch power between the RES and loads are compensated through a grid. In other words, the deficit and abundance power supply from RES is supplied and consumed by a grid to balance the power flow in order to maintain the stability and reliability of the system, which is not possible for a standalone RES in an islanded mode.

**Control**

The RES is normally operated under power or current control mode, where the active and reactive power are controlled based on the reference voltage and frequency (say 170 V rms line to line and 60 Hz) at the PCC of the grid. The power electronic (PE) I interfacing unit or DC-DC converter is controlled under maximum power point tracking (MPPT) scheme whereas PE III interfacing unit or inverter is used to regulate the DC link voltage in order to generate the power flow to the grid [126].

**2.4.2 Hybrid Systems**

**Structure**

A hybrid system, in this thesis, is defined as a combination of different kinds of energy sources and energy storage systems. For example, if a wind source is combined with a storage element or a complementary source e.g. PV or a dispatchable source, such as diesel generator can all be referred as a hybrid system. The hybrid system has a great potential to provide higher quality and more reliable power to customers. This hybrid
system can be operated either on a grid connected mode or in an islanded (off-grid) mode. Hybrid system can be of different combinations utilizing mainly RESs. The two most popular RESs are wind and PV. The combination between these two sources can also form one of the suited hybrid systems because wind and PV can complement each other meteorologically. Similarly, any RESs: standalone, wind, or PV can combine with dispatchable DG such as a diesel generator or energy storage such as a battery to form another type of hybrid system. Different hybrid systems can be formed with the combination of different dispatchable and non-dispatchable DGs and energy storage.

In this thesis, standalone wind is combined with battery energy storage to form a hybrid system which operates in an islanded mode. The energy storage such as battery storage has a capability of supplying and consuming power to balance the power flow between RESs and loads. Battery storage can also be used as short term energy storage to supply fast transient and ripple power. Therefore, this hybrid system can be used in many applications in rural or urban areas as an islanded and grid connected system. Thus hybrid energy systems are becoming popular in the EPS world. A typical hybrid wind and battery energy storage structure is shown in Figure 2.9.

![Figure 2.9: A typical RES based hybrid system](image)

The wind energy source is connected to the point of common coupling (PCC) through a series of power electronic interfacing units or converters. Similarly, battery energy storage is also connected to DC link through a PE II interfacing unit to match the voltage level with a separate controller. However, battery energy storage can be connected to a DC link without a PE II interfacing unit by matching the voltage level and combined control strategy. This hybrid system can be operated either in a grid connected mode or in
an islanded mode as shown in Figure 2.9. The purpose of battery energy storage is to counteract the effect of the stochastic nature of wind energy source.

**Control**

In a grid connected mode, the PE I interfacing unit of wind energy source is controlled to extract the maximum power under different wind speed whereas the PE III interfacing unit is operated under power or current control mode similar as in the case of standalone system. In this control mode, the voltage and frequency at the PCC of the grid are considered as given references, whereas the active and reactive powers are controlled in a stable and reliable manner [57]. The battery energy storage is inactively floating or charging depending upon the control strategy or can actively participate for short term transient conditions or to regulate the DC link voltage to form a dispatchable wind energy source [127].

In an islanded mode, the PE I interfacing unit of wind energy source is operated under maximum power point tracking (MPPT) scheme, whereas PE III interfacing unit is operated under voltage control mode. In this control mode, the amplitude and the frequency of AC link voltage are regulated at the given reference values (say 170 V rms line to line and 60 Hz) irrespective of wind speed fluctuations. In other words, the power flow is the output of the AC link voltage regulation. The PE II interfacing unit of battery energy storage is used to regulate the DC link voltage [53].

**2.4.3 Microgrid**

The microgrid is becoming popular, nowadays, because of the following reasons: (i) full use of free cost renewable energy sources; (ii) no need for long transmission lines thus reduces the heavy cost and issues of right of ways; (iii) provision of higher quality and more reliable power supply to the customers; (iv) community ability to sell the excess energy back to the grid; and (v) ability to easily incorporated in a smart grid for optimal use of energy and price. The microgrid provides greater reliability and stability in the EPS compared to the hybrid system comprising of two sources. Microgrids can be perceived to use DC or AC voltage in the local grid, hence it can be classified into DC and AC microgrid [22].
2.4.3.1 DC Microgrid

Structure

A typical DC microgrid is shown in Figure 2.10.

In a DC microgrid, all energy sources and storage are connected to the DC link through PE interfacing units. Therefore the common local voltage is DC voltage. The prime objective is to regulate the DC link voltage in order to balance the power flow within the system. The DC microgrid can supply the power to both the DC loads and the AC loads. The AC loads require additional PE interfacing unit to convert DC power to AC power, which can be operated in both grid connected and islanded mode.

Control

In a DC microgrid, different control strategy can be used at DC side to operate multiple sources and storage in a stable and reliable manner [71]. The (PE I # 1 – PE I # n) interfacing units can be controlled either in a current or a voltage mode depending upon the control strategy. However, in a current control mode, the interfacing units are usually controlled under MPPT scheme, whereas in a voltage control mode, the interfacing units are used to regulate the DC link voltage. The PE II interfacing unit is always controlled...
under voltage mode to regulate the DC link voltage. The PE II interfacing unit is operated either in parallel to (PE I # 1-PE # n) interfacing units using droop control or alone in a voltage mode while others are operated in a current mode [128].

The PE III interfacing unit is used to convert DC power into AC power so that the power can be delivered to the AC loads. In a grid connected mode, PE III interfacing unit is operated under power control mode as explained in the previous section on hybrid systems. In some control strategies, the PE III interfacing unit acts as a bidirectional converter where the power flow can be either sides depending upon the conditions. For example the battery storage can be charged through a grid. In an islanded mode, PE III interfacing unit is operated under voltage control mode where the amplitude and frequency of the AC link voltage are regulated to the reference values [7].

2.4.3.2 AC Microgrid

Structure

A typical AC microgrid is shown in Figure 2.11.

![Figure 2.11: A typical AC microgrid system](image-url)
In an AC microgrid, all energy sources are usually connected to the AC link. The source has either its own DC link or shares it with storage or other sources as a hybrid system within the microgrid. Therefore the common local voltage is the AC voltage, which can operate in both grid connected and islanded mode.

**Control**

In a grid connected mode, the (PE I #1-PE I # n) interfacing units are normally operated under the MPPT scheme, current control mode. In addition, the (PE III #1- PE III #n) interfacing units are used to regulate the DC link voltage in order to control the power flow to the grid and AC loads [129]. The PE II interfacing unit operates in a similar manner as explained in the section on hybrid systems.

In an islanded mode, the (PE I # 1 – PE I # n) interfacing units are normally controlled in a voltage mode. In a current control mode, the interfacing units are controlled under MPPT scheme, whereas in a voltage control mode, the interfacing units are used to regulate the DC link voltage. The PE II interfacing unit is always controlled under voltage mode. The (PE III # 1-PE III # n) and PE II interfacing units are operated in a voltage control mode under droop control strategy to regulate the amplitude and frequency of AC link voltage to the reference values (say 170 V rms line to line and 60 Hz) [130].

### 2.5 Conclusions

In this chapter, the modeling of energy sources is carried out. The modeling is performed to test the proposed control strategy before validating in a physical hardware system. The wind system types are briefly explained in order to highlight the advantages of Type IV wind system, which is considered in the research. The static and dynamic characteristics of Type IV wind system are presented. Furthermore, the permanent magnet synchronous generator is modeled in the $d-q$ synchronous reference frame. In addition, the PV source and lead acid battery are also modeled. The widely used approach for PV source is considered, which is to mathematically formulate the relationship between model parameters and solar irradiance and temperature. The CIEMAT model for the lead acid battery, which is the detailed and accurate model, is considered in this study. The most
common structures and controls of renewable energy based power system are also reviewed in order to highlight the contributions of the work.
Chapter 3

3 Design and Development of Physical Systems: Experimental Set Up

This chapter presents the design and development of the physical hardware system along with their real time control platform. The simulator for non-dispatchable energy sources, such as PMSG based VSWT and PV, is used in the thesis. The wind turbine simulator is designed and developed in the laboratory while the commercial PV simulator is considered. In addition, the real physical lead acid battery is used in the experiment. The power electronic interfacing units or converters, such as AC-DC converter (rectifier), DC-DC converter, DC bus, and DC-AC converter (inverter) are also designed and developed in the laboratory. Different converters are controlled by three different real time controller platform such as NI LabVIEW for wind turbine simulator (WTS), Texas Instrument (TI) C2000 microcontroller for DC-DC converter and dSPACE for inverter respectively.

3.1 Wind Turbine Simulator (WTS)

This section deals with the design and development of the WTS. The purpose of this WTS is to perform the wind research work without relying on the weather conditions outside the environment.

3.1.1 Introduction

Wind power systems are a cost-effective renewable-energy technology, and have expanded globally at a rate of 25% to 35% annually over the last decade [131]. To increase the penetration of wind energy at the distribution level, wind power systems are often integrated with other forms of energy generating or storage systems, such as solar and batteries to create a small power grid (known as a microgrid). Research in this area requires access to a physical wind turbine for testing and validation; however, it is often impractical to rely solely on a physical wind turbine (PWT) for research purposes because it is dependent on the weather. It is, therefore, useful to use a wind turbine simulator (WTS) which can faithfully mimic the characteristics of a PWT under various
wind conditions in a lab environment.

Most existing WTSs are not designed and evaluated for the conditions of a microgrid environment, which requires complete interfacing units with smooth and accurate control dynamic interactions. Furthermore, the analysis of wind turbine control strategies, such as protection against high wind speed and maximum power point tracking schemes, are not considered for most WTSs in the literature, as they are running under controlled wind speeds. This narrows down the operating range of WTSs, resulting in a lack of full consideration of PWTs. This thesis presents the results of work: (i) to develop a new method for WTS implementation; and (ii) to demonstrate it in a microgrid in order to validate its performance as a variable speed direct drive (VSDD) wind system.

The first objective involves designing a WTS that is able to simulate a range of wind turbines with minimal error under realistic weather conditions. Therefore, the WTS must have a wide dynamic range. It is important to consider the desired dynamic range of the PWT when selecting components in the design of a WTS. Several researchers have developed WTSs to study the effects of tower shadows, wind shear, and turbine control mechanisms, which will be briefly discussed in Section 2. These have used different types of motors, controllers, and other components, resulting in a wide variety of WTS structures.

A new structure for a WTS is developed using an induction motor with a vector torque mode (VTM) control. The reference torque signal in the WTS changes frequently due to changes in the wind speed, so it has a wide dynamic spectrum. The VTM has a superior dynamic performance along with an accurate steady state operation even at low speeds [132], [133]. Therefore, a motor controller in the vector torque mode is used in the current WTS. Instead of relying on universal and theoretical formulas for wind turbines, real physical experiments have been performed in the Boundary Layer Wind Tunnel (BLWT) at the University of Western Ontario (UWO) to obtain practical turbine data [134]. The MPPT scheme and the simulator protection against a high real wind profile are also considered in the development of this WTS. The results demonstrate that the
The proposed WTS can meet the design specifications of a PWT to produce nearly the same characteristics.

The second objective involves integration of the developed physical WTS with other energy sources, as shown in Figure 3.1, in the form of a microgrid to investigate the coordinating control strategies using WTS as a wind source.

![Figure 3.1: An experimental microgrid](image)

A cost-effective interfacing unit for a VSDD PMSG based wind energy system (WTS+PMSG) is developed using power electronic based converters, AC-DC and DC-DC, as shown in Figure 3.1. A rooftop photovoltaic array is also interfaced to the common DC link through a DC-DC converter. Such integration poses several unique challenges [135]. The DC link voltage is regulated by the battery storage. This DC microgrid is interfaced to the AC loads and campus grid through a DC-AC converter to form an AC microgrid, which requires a smart coordination between the energy sources [136].
Section 3.1.1 provides the issues of existing WTSs, and the unique features of the proposed simulator. Section 3.1.2 presents a structure and design of the proposed WTS. Sections 3.1.3 and 3.1.4 provide a detailed analysis of the modeling and control system design for the proposed WTS, including its connections to a microgrid. Section 3.1.5 presents the experimental evaluations of the WTS.

3.1.2 Structure and Design of the WTS

The performance of the WTS should be measured from both dynamic and steady state points-of-view. The dynamics of the WTS should be as close as possible to the response of the PWT that it tries to mimic, while its steady state behavior is assessed by the magnitude of mismatches between the reference and the emulated variables, such as torque and power output.

3.1.2.1 Structure of a WTS

The proposed structure of the WTS is shown in Figure 3.2.

![Figure 3.2: Proposed structure of the WTS](image)

The structure consists of two feedback loops: an inner control torque loop and an outer speed feedback loop. The outer feedback loop is used to generate the reference torque signal based on the features of the PWT in the LabVIEW software. This reference torque signal sends to the motor controller through national instrument data acquisition chassis.
(NI cDAQ 9172). The inner loop is used to determine the motor torque based on the stator current and the voltage, which is compared with the reference torque signal. A proportional-integral-derivative (PID) controller is used to stabilize the torque control loop and to minimize the torque error. In the current implementation, the motor torque is estimated rather than measured to reduce cost.

### 3.1.2.2 Design Specifications of the WTS

The objective of the proposed WTS is to simulate the behavior of any physical wind turbine below a certain size and power limit. Based on realistic weather conditions, the specifications of the proposed WTS are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Range</td>
<td>$\leq 1.0$ kW</td>
</tr>
<tr>
<td>Rotor Speed</td>
<td>$(0 - 900)$ rpm</td>
</tr>
<tr>
<td>Time constant</td>
<td>$\geq 0.315$ s</td>
</tr>
<tr>
<td>Pitch control response time</td>
<td>$10$ / s</td>
</tr>
</tbody>
</table>

Once the above design specifications are met, the proposed WTS will be able to emulate the behavior of any wind turbine up to 1.0 kW, with a response equal to or more than 0.315 s.

### 3.1.2.3 Selection of Hardware Components

Selection of properly sized components is one of the most important tasks in the development of a WTS. The components should be chosen with full knowledge of the characteristics of the PWT that the WTS is intended to simulate. The dynamics of the wind turbine will determine the power rating of the motor, as well as the associated control systems.

#### Physical Wind Turbine (PWT) as a Reference

A 1.0 kW, three bladed horizontal axis wind turbine from True North Power Inc., with a rotor diameter of 2.0 m, was used as the reference turbine. This was installed on the roof of the Engineering Building [137]. Its output is directly accessible to the research lab. The $C_p - TSR$ characteristics of this turbine at different pitch angles are shown in Figure
3.3. These curves are obtained by wind turbine tests carried out in the BLWT at UWO [134].

![Figure 3.3: Power coefficient curve of the actual wind turbine](image)

**Motor and Motor Controller**

Based on the design specifications and the characteristics of the reference PWT, a 2.2 kW induction motor was selected to account for the transient power peaks of the wind turbine. The motor also satisfied the specification for a rotor speed with a response time shorter than 87 ms. A 2.2 kW motor controller (or AC drive) was also selected to control the motor. The motor controller was chosen based on the maximum current requirements under peak torque demands, and operates in a vector torque mode.

**3.1.3 Modeling and Controller Design**

The closed-loop control of the IM with the reference determined by the static and dynamic characteristics of a PWT, drives the WTS as a close resemblance of a real PWT. Therefore, the characteristics of the PWT are captured through the modeling in the LabVIEW software. In addition, the modeling of IM and motor controller are also performed to determine the motor torque.

**3.1.3.1 Physical Wind Turbine (PWT)**

**Static Characteristic**

The static characteristics of a PWT are described in [138], and depend on the blade design coefficients, size, and environmental conditions. The power coefficient represents the efficiency of the wind turbine under different wind conditions. Therefore, the wind
speed and the turbine rotor characteristics are the key parameters to be considered in the design of a wind turbine simulator.

**Dynamic Characteristics**

The dynamic characteristic of any rotational machine can be represented by the dynamic equation of motion. The equation is the relationships between the turbine torque \( T_t \) and the generator torque \( T_g \). Generator torque is the electrical torque which depends on the electrical load connected to the generator output.

A pictorial representation of turbine dynamics with a motor-generator (M-G) set is shown in Figure 3.4, where \( T, J_t, J_g, J \) and \( \omega \) represent the torque, moment of inertia of the reference wind turbine, moment of inertia of the generator, moment of inertia of the motor, and the angular speed, respectively. With negligible friction losses and under the unity gear ratio assumption, the torque equation of a PWT can be expressed as follows [31]:

\[
T_t - T_g = (J_t + J_g) \frac{d\omega}{dt}
\]  
(3.1)

Similarly, the dynamic equation of the motor-generator (M-G) set can be represented as follows:

\[
T - T_g = (J + J_g) \frac{d\omega}{dt}
\]  
(3.2)

**Figure 3.4:** Representation of turbine dynamics using (a) PWT and (b) M-G set
Substituting (3.1) in (3.2),

\[ T = T_t - (J_t - J) \frac{d\omega}{dt} \]  

(3.3)

The term \((J_t - J) \frac{d\omega}{dt}\) is the compensated torque and represented by \(T_{\text{comp}}\). Hence, (3.3) becomes

\[ T_{\text{comp}} = T_t - T \]  

(3.4)

Equation (3.4) can be implemented in the model of a PWT to match the dynamics of the WTS with a PWT as shown in Figure 3.5.

![Figure 3.5: Block diagram of WTS with the compensated torque](image)

The wind turbine model block in Figure 3.5 consists of both static and dynamic characteristics of PWT, which determines the turbine torque based on the input wind speed \((\theta)\) and feedback angular speed \((\omega)\). The turbine torque is then compensated to match the dynamics with a physical motor. The compensated torque is the command signal to the controller. The controller consists of the motor controller and the PI compensator, which is tuned using the refined Ziegler-Nichols rule [139]. The controller drives the IM with the same static and dynamic features as the PWT.

3.1.3.2 Induction Motor

The dynamic properties of the induction motor can be described by a set of nonlinear differential equations linking the stator and the rotor currents and voltages with the torque, speed, and angular position. The model is established under the following assumptions:

- The air gap is uniform
• The flux density is radial in the air gap
• The stator windings are identical, and
• The magnetic saturation is not considered.

The modeling process is performed in the stator flux coordinate frame. The flux linkage in the stator and the rotor windings can be represented as

\[
\frac{d\lambda_s}{dt} = \vec{V}_s - R_s \vec{i}_s \\
\frac{d\lambda_r}{dt} = \vec{V}_r - R_r \vec{i}_r
\]  

(3.5)

(3.6)

where \(\lambda\), \(\vec{V}\), \(R\) and \(i\) are the flux linkage, voltage, resistance and current with subscripts \(s\) and \(r\) representing stator and rotor, respectively. The fundamental fluxes in an AC induction machine can be expressed as a function of the stator and rotor currents [140].

\[
\lambda_s = L_m [(1 + \sigma_s)\vec{i}_s + e^{j\theta_r} \vec{i}_r] \\
\lambda_r = L_m [(1 + \sigma_r)\vec{i}_r + e^{-j\theta_r} \vec{i}_s]
\]  

(3.7)

(3.8)

where, \(\sigma_s = \frac{L_s}{L_m} - 1\) and \(\sigma_r = \frac{L_r}{L_m} - 1\)

\(L\) and \(\theta_r\) represent inductance and rotor angle respectively. The subscript \(m\) and \(img\) stand for magnetizing and imaginary. The developed torque of the motor can be expressed by

\[
T = \frac{3}{2} L_m \, \text{img} \{\vec{i}_s (\vec{i}_r e^{j\theta_r})^*\}
\]  

(3.9)

where \(T\) is an electromechanical torque. A detailed description of (3.6), (3.9) and (3.11) is given in [141],[142]. The term within the square brackets in (3.7) represents a fictitious magnetizing current in the stator flux coordinates, that is

\[
\vec{i}_{ms} = (1 + \sigma_s)\vec{i}_s + e^{j\theta_r} \vec{i}_r \quad \text{and} \quad \vec{i}_{ms} = \vec{i}_{ms} e^{j\delta}
\]  

(3.10)

where \(\delta\), \(\vec{i}_{ms}\) and \(\vec{i}_{ms}\) represent flux rotating angle, fictitious magnetizing current, and its magnitude in vector form, respectively. All other variables are represented in phasor form. From (3.10), one can obtain

\[
e^{j\theta_r} \vec{i}_r = \vec{i}_{ms} e^{j\delta} - (1 + \sigma_s)\vec{i}_s
\]  

(3.11)

Substituting (3.11) into (3.9), the torque produced can be expressed by

\[
T = \frac{3}{2} L_m \, \text{img} \{\vec{i}_s (\vec{i}_{ms} e^{j\delta} - (1 + \sigma_s)\vec{i}_s)^*\}
\]
\[= \frac{3}{2} L_m \text{img}\left\{i_s \left( i_{ms} e^{-j\delta} - (1 + \sigma_s) i_s^* \right) \right\} \]
\[= \frac{3}{2} L_m \overline{i_{ms}} \text{img}(i_s e^{-j\delta}) \]
\[= \frac{3}{2} L_m \overline{i_{ms}} i_{sq} \quad (3.12) \]

where, \(i_s e^{-j\delta} = i_{sd} - j i_{sq}\)

The final torque equation as shown in (3.12) demonstrates that the mechanical torque of the motor can be controlled by the quadrature axis of the stator current \((i_{sq})\), provided that the magnetizing current remains constant. Hence, the motor controller which operates in vector torque mode (VTM) provides the controlled stator current based on the reference torque signal.

### 3.1.3.3 Motor Controller in VTM

The dynamics of an electric machine are affected by two quantities: torque and speed, either of which can be used to control the machine. In the torque control mode, the torque is used as a controlled variable and the speed is determined by loads. Vector control decouples the flux from the torque, which can be controlled in two independent loops as expressed in (3.12), where the torque is controlled independently from the flux by controlling the quadrature axis of the current.

A motor controller in a VTM has the potential to produce superior dynamic performance, as it relies on independent torque control. Under VTM control, the motor controller tracks the reference torque signal with fast dynamics and accurate steady state operation [133]. The reference torque signal in the WTS can be subject to abrupt changes due to variations in the wind speed. In addition, it can also have a wide dynamic spectrum. Hence, a motor controller in the vector torque mode is adopted in the WTS. A block diagram of the vector control of an induction motor in the torque mode is shown in Figure 3.6.
Figure 3.6: Vector torque mode control of the induction motor

where $v_s$ and $i_s$ are the stator voltages and currents with subscripts $dq$, $abc$ and $ref$ representing $d-q$ axes frame, $abc$ frame and reference, respectively. The diagram shows only one loop for torque control, as torque mode control is implemented in the WTS. The flux is assumed to be constant. The reference torque ($T_{ref}$) is compared with the motor torque ($T$), and the error is minimized by a PID controller. This current regulator monitors the current in $d-q$ axes as per the reference value, and the outputs are the $d-q$ axes voltages, which are the reference signals to the gate drive of the converter. The gate drive is used to trigger the converter on/off modes to supply the required power to the motor. The stator currents are fed back to the motor model to estimate the motor torque based on (3.12) and the flux.

The interesting aspect of Figure 3.6 is to identify the angle ($\delta$), which is the prime parameter to transform between $abc$ and $dq$ frames. Usually, the motor speed is measured and fed back into the motor model to identify the angle, but in the stator field coordinates, the flux rotating angle is estimated by using a flux observer. This is achieved by using (3.5) and substituting $\overline{\lambda_s} = L_m \overline{i_{ms}}$, $\overline{i_s} e^{-j\delta} = i_{sd} - j i_{sq}$ and $\overline{v_s} e^{-j\delta} = v_{sd} - j v_{sq}$ respectively.

$$L_m \frac{d\overline{i_{ms}}}{dt} = v_{sdq} e^{j\delta} - R_s i_{sdq} e^{j\delta}$$  

Using (3.10) in (3.13), one obtains,

$$L_m \frac{d(\overline{i_{ms}} e^{j\delta})}{dt} = v_{sdq} e^{j\delta} - R_s i_{sdq} e^{j\delta}$$
\[ L_m \frac{d \tilde{i}_{ms}}{dt} e^{j\delta} + j L_m \frac{d \delta}{dt} e^{j\delta} \tilde{i}_{ms} = v_{sdq} e^{j\delta} - R_s i_{sdq} e^{j\delta} \]

Canceling \( e^{j\delta} \) from both sides and dividing the equation into real and imaginary part as shown below

\[ L_m \frac{d \tilde{i}_{ms}}{dt} = v_{sd} - R_s i_{sd} \tag{3.14} \]

\[ L_m \frac{d \delta}{dt} \tilde{i}_{ms} = v_{sq} - R_s i_{sq} \tag{3.15} \]

where, \( \frac{d \delta}{dt} = \omega \) and \( \tilde{i}_{ms} = i_{ms} \) (magnitude in vector form)

Equations (3.14) and (3.15) can be implemented in the IM model block shown in Figure 3.6 as a flux observer.

![Figure 3.7: Configuration of the flux observer](image)

The structure of the estimation algorithms for the rotating angle is shown in Figure 3.7. The estimated angle is utilized in an induction motor control. Hence, the inner loop of the WTS is closed to control the torque in the vector mode.

### 3.1.4 Integration of WTS in a Microgrid

The prototype microgrid developed in the laboratory consists of the developed WTS, roof top PV, battery energy storage, and converters as shown in Figure 3.8. The WTS drives the PMSG with control to emulate the direct drive variable speed wind turbine. This WTS emulates the static and dynamic behavior of a real PWT on the campus roof. The roof top PV and battery are used as another source and storage. A DC-DC converter is also designed and fabricated to support this experiment by extracting the maximum power using the MPPT scheme, as explained in [143]. The IM, PMSG and microgrid parameters are given in the Appendix A.
The design specification of the microgrid is to operate the DC link voltage between a minimum, \( V_{\text{demin}} = 0.95 \) p.u. and a maximum, \( V_{\text{demax}} = 1.05 \) p.u., irrespective of fluctuating weather conditions and load variations. This range is specified by considering the operating range of the battery, the sinusoidal pulse width modulation (PWM) index of the inverter, and the features of energy sources and loads in the islanded microgrid. The total load \( (P_{\text{load}}) \) is met by the wind \( (P_{\text{wt}}) \), PV \( (P_{\text{pv}}) \) and battery storage \( (P_{\text{bat}}) \) in an islanded microgrid as

\[
P_{\text{load}} = P_{\text{wt}} + P_{\text{pv}} + P_{\text{bat}}
\]  

As shown in (3.16), the battery storage supplies the deficit power, which can be created by a WTS, due to the error in tracking the reference power. As a result, the microgrid operates closer to the minimum DLV even during normal operations (no disturbances). This leads to the following issues in a microgrid:

(i) The battery life cycle is reduced faster than designed expectations and would lead to an increase in the overall cost.

(ii) The chances of operating an inverter in an over modulation region in a PWM technique is high, which degrades the performance of the inverter [144].
As long as the DLV is maintained to 1.0 p.u. during normal operation and above 0.95 p.u. during the discharging operational mode of the battery or any disturbances, the operation of the microgrid in the presence of the WTS is considered satisfactory (according to the design). This validates the viability of the WTS, and the proper coordination of energy sources in a microgrid. The disturbances could be the fluctuation in the wind speed. The low wind speed corresponds to low power generation and vice versa.

3.1.5 Experimental Validation

To evaluate the performance of the developed WTS, a series of experiments have been conducted. The tests are focused on both static and dynamic characteristics of the WTS. The characteristics of the considered PWT are determined using the manufacturer data and wind tunnel test results. The WTS is operated under realistic wind condition, which are measured using the weather station (Davis Vantage Pro, sampled at 1 s interval) installed on the tower of the PWT.

3.1.5.1 Static Characteristics

The characteristics of a PWT and WTS are shown in Figure 3.9.

**Figure 3.9:** Comparison of (a) Power curve and (b) $C_p$-TSR curve between the WTS and a PWT
The power speed characteristics are obtained under three wind speeds. The power coefficient ($C_p$) is also plotted against the tip speed ratio (TSR) at a fixed pitch angle. Tests have confirmed that the WTS produces an excellent match to these characteristics under steady state conditions.

### 3.1.5.2 Dynamic Characteristics

The performance of the WTS can only be validated when a comparison to the dynamic performance of the PWT is made. The WTS is compared with the PWT at instantaneous and average (for 60s) wind speed for a given period. The real time measurement data of WTS includes noise in the laboratory environment, due to mechanical vibration and sensors measurement.
The wind speed is normalized at 9.5 m/s. The WTS output power, rotor speed, and torque are very close to the PWT, as shown in Figure 3.10. The noise in the measurement data of WTS increases with increasing wind speed, especially in the instantaneous wind profile. The average wind profile provides relatively less turbulence, which keeps the smooth operation of the simulator. In addition, the errors between the WTS and PWT outputs under the instantaneous wind profile are within 6%. This error has improved to 4% for the average wind profile.

3.1.5.3 Simulator Protection against High Wind Speed

The WTS is protected against the high real wind profile in order to operate with limited size components and the corresponding objectives. This is, in fact, the emulation of a pitch angle control in the PWT, which is used to curtail the power beyond the rated wind speed. The control objective is to maintain the power at rated value beyond a certain wind speed.
The wind profile in Figure 3.11(a) considers the wind speed beyond the rated value, as indicated by the value above the red line. The rotor speed is regulated to the maximum permissible value by controlling the pitch angle in determining the reference power as shown in Figure 3.11(b). The increasing value of pitch angle decreases the power coefficient of the turbine, as shown in Figure 3.11(c). This decreasing power coefficient curtails the power from the maximum possible value. Thus the power is maintained at the rated value for higher wind speed, as shown in Figure 3.11(b).

3.1.5.4 WTS in Microgrid

The microgrid is designed based on the features of the energy sources (the considered PWT, roof top PV, and commercial battery) and programmable load. The WTS and PV systems are operated under their respective MPPT schemes, and the load is kept constant before the experiment starts. The battery storage regulates the DLV. If the WTS does not follow the PWT closely then the storage compensates the degraded performance of WTS, as discussed in Section 4. The impact of the degraded performance of WTS on the microgrid would be critical in the discharging mode of battery because the DLV can fall below the minimum operating level, 0.95 p.u. The objective is to validate the performance of the WTS in accordance to the PWT in the microgrid environment (the microgrid is designed based on the features of the PWT). Therefore, the microgrid is operated in the discharging mode of battery only. The step change in wind speed is considered in the microgrid to test the performance of the WTS and the coordination of the energy sources as shown in Fig. 12 (a).
Figure 3.12: Performance of the WTS within a microgrid environment

Starting Transients
At the start, as the WTS and PV are not fully activated until 2.13s, the battery provides power to the load. The negative battery power in Figure 3.12 (c) means the battery is discharging. Once the WTS is activated at 2.13s, it creates some degree of transients; however, the battery promptly reduces its power output to the load so that more renewable energy can be used. Furthermore, when the PV increases its power output gradually, starting from 3.23s, the participation of the battery further reduces. This can be seen from Figure 3.12 (c) between 2.13s and 8.9s. During all these processes, the DLV is maintained well within the acceptable range, as shown in Figure 3.12 (b).

Low Wind Speed
When the wind speed is dropped to 6m/s at 13.56s, as illustrated in Figure 3.12 (a), the power output from the WTS also drops accordingly. At this point, the battery picks up the power deficiency to balance the load. The DLV drops only slightly, as can be seen from Figure 3.12(b). To see the interaction between the wind and PV sources, assume that there is a sudden increase and decrease in irradiance at 14.1s and 17s respectively. Hence, the PV output power increases at first, and then decreases in proportion to the amount of irradiance. As a result, the battery cuts back its contribution at 14.1s, and then increases again at 17s to maintain the DLV. The coordination between energy sources is smooth, especially during transient periods. This can be seen from Figure 3.12(c) between 14.1 s and 17 s.
**High Wind Speed**

When the wind speed is increased to 7 m/s at 19s, the majority of the load is supported by the WTS. The power output of the WTS at wind speed 6.6-7 m/s is increased marginally under the MPPT scheme as shown in Figure 3.12 (c) between (19 -20)s. It is interesting to note that even when the PV output drops due to reduced irradiance at 19s, the battery still cuts back on its participation. Under these conditions, the WTS becomes the dominant power source to keep the DLV within the desired range, as shown in Figure 3.12 (c).

Thus, the WTS, together with the PV and the battery storage, can indeed participate in a microgrid system. The DLV is maintained above 0.95 p.u. during the discharging mode of operation of the battery under varying weather conditions. This demonstrates that the WTS follows the PWT in the microgrid environment and can operate as a VSDD wind system for further research work.

**3.1.6 Conclusions**

The thesis has utilized the actual wind tunnel test data in the construction of the WTS. An induction motor and variable speed drive have been found to offer an excellent platform for implementing vector torque mode control to achieve desired flexibility for the WTS under the real measured wind profile. The paper has presented a detailed design process and construction procedures for such a WTS. The static and dynamic characteristics of the WTS correlate well with the considered PWT. It has also shown that the designed WTS can successfully interact with other renewal resources and battery storage devices to maintain stable operation of a microgrid.

**3.2 Commercial PV Simulator and Lead Acid Battery**

This section briefly explains the commercial PV simulator and real physical lead acid battery storage. The purpose of this PV simulator is to perform PV research work without relying on weather conditions outside of the environment.
3.2.1 PV Simulator

The PV is considered as one of the non-dispatchable DGs or renewable energy sources in the microgrid. The objective of the research work on the microgrid is to propose a control strategy for power management with the coordination of different sources. Therefore, the commercial PV simulator which closely resembles the characteristics of a real physical PV is considered in the research work.

The model 62050H-600S is considered as a commercial PV simulator which can easily program the PV parameters such as the open circuit voltage, short circuit current, maximum voltage point, and maximum current point respectively, for different PV characteristics. The simulator has a friendly graphical user interface panel. Normally, the simulator has three ways to realize the feature of a real PV: (i) Built in software simulation; (ii) Table mode; and (iii) Program mode.

The parameters of the PV such as open circuit voltage, short circuit current, maximum voltage point, and maximum current point are the inputs and the software generates the I-V curve (feature of PV). The simulator is, therefore, run based on this I-V curve. The table mode is capable of saving a 128 point array of user programmed voltages and currents through a remote interface. The I-V program mode can save up to 100 I-V curves and dwell time intervals are (1-15000)s in memory. The detail explanation of this commercial PV simulator is given in datasheet [145].

The I-V curve obtained from the experimental results on the real physical PV, which is installed on the roof of CMLP building at the University of Western Ontario (UWO) is the input to this commercial simulator. Therefore, the commercial PV simulator can function similar to the real physical PV.

3.2.2 Lead Acid Battery

The types of batteries used with renewable energy sources such as wind and PV are lead acid, sodium sulfur (NaS), lithium-ion (Li-ion), and so on. The lead acid battery is dominantly used all over the world, and accounts for 75 % of renewable energy market [146]. Lithium ion battery has achieved significant penetration into the portable consumer
electronics markets and is becoming popular on the renewable energy market, as well, due to its unavoidable features such as high power density and high efficiency. However, the production cost is still high.

The improved lead acid battery or valve regulated lead acid battery (VRLA) in the market attracts more renewable energy owners. The VRLA cells require minimal maintenance and much lower electrolyte content. This means the shipping and air freight regulations and the battery rooms are dramatically simplified, which, in turn, reduces the life cycle costs. However, lower electrolyte content is prone to dry out failures more than the conventional one; however, this can be tackled through battery management system by using temperature controlled voltage [147]. The VRLA battery encompasses with absorbed glass mat (AGM) provides some of the following advantages:

- Sealed using special pressure valves and should never be opened
- Completely maintenance free
- Non-spillable

A deep cycle battery is designed to discharge deeply using most of its capacity. Unlike automotive batteries, which are designed to deliver short, and high current for cranking the engine. Therefore, a deep cycle battery is useful for renewable energy storage to counteract its stochastic nature.

Thus, the research work in this thesis considers an advanced deep cycle lead acid battery based on VRLA (AGM) with the following improved features:

- High power handling performance
- Longevity competitive with other batteries
- Proven technology in the industry
- Proven safety standards such as transport, fire codes, and building codes
- 100% recycling process

The datasheet for this commercial lead acid battery is given in [148].
3.3 DC-DC Converter

The buck converter is used as a DC-DC converter, which steps down the input voltage. The buck converter is considered in the experiment for interfacing renewable energy sources to DC link because of the following reasons: (i) is simple and cost effective; (ii) is easily integrated to low voltage DC link; (iii) allows direct connection of battery storage with smaller battery pack to DC link; and (iv) provides better safety by de-energizing the switch at the front end. However, some of the issues in the system due to its presence such as input harmonics and low output voltage are overcome by inserting an LC filter at the output of energy sources or before the converter and step up transformer at the output of AC side LC filter.

3.3.1 Converter Topology

The buck converter topology is shown in Figure 3.13. The output of the buck converter is the average DC value of switching waveform. The LC filter is used to remove high frequency components. The combined action of LC blocks the frequency dependent components and only passes the DC component of the input signal. The wide varying input voltage \( V_i \) is stepped down to the output voltage \( V_o \) by controlling a gate signal or duty cycle \( d_c \) of the power electronic switch, MOSFET.

![Figure 3.13: Buck converter topology](image)

When the switch (MOSFET) in Figure 3.13 is ON (topological mode I), the diode is reverse biased and the voltage across the inductor \( V_L = V_i - V_o \) is positive as shown in Figure 3.14. The inductor current \( i_L \) will rise and energy is stored in inductor \( L \).
When the switch (MOSFET) in Figure 3.13 is OFF (topological mode II), the diode is forward biased and the voltage across the inductor \( (V_L = V_i - V_o = -V_o) \) is negative as shown in Figure 3.15. The inductor current will fall and part or all of the energy stored in the inductor is transferred to the output.

When the MOSFET is turned ON and OFF at a certain rate, a pulsed voltage will be generated across the freewheeling diode \( (V_d) \). This voltage contains a DC component equal to the desired average output voltage plus unwanted harmonics that have to be filtered for smooth operation. The \( LC \) form a second order filter of resonant or cutoff frequency \( (f_c) \) as

\[
f_c = \frac{1}{2\pi\sqrt{LC}}
\]  

(3.27)
The rule of the thumb is to choose cutoff frequency at least one decade below the switching frequency \( f_s \). The bandwidth of the system reduces with the small cutoff frequency; however, it can be increased by increasing the switching frequency, which also reduces the size of the filter inductance and capacitance. However, there are some drawbacks with high switching frequency: (i) high switching losses; (ii) lower efficiency; and (iii) larger size of heat sink. A compromise has to be made when selecting the switching frequency.

Consider the buck converter operation in continuous conduction mode. In this mode, the inductor current is always greater than zero, as shown in Figure 3.16.

![Figure 3.16: Inductor voltage and current waveforms](image)

Therefore, the output and input voltage relationship can be derived from the fact that in the repetitive mode of current, the average voltage across the inductor is zero.

\[
\int_{0}^{T_s} V_L \, dt = \int_{0}^{t_{on}} V_L \, dt + \int_{t_{on}}^{T_s} V_L \, dt = 0
\]

where \( t_{on}, t_{off}, \) and \( T_s \) are the on time, off time and total time period of a switch. The area \( A \) and \( B \) in Figure 3.16 are equal, therefore,

\[
(V_l - V_o) \times t_{on} = V_o \times t_{off} = V_o \times (T_s - t_{on})
\]

(3.29)
The output to input voltage relationship of a buck converter in continuous conduction mode can be derived from (3.29) as
\[
\frac{V_o}{V_i} = \frac{t_{on}}{T_s} = d_c
\]  
(3.30)

Therefore,
\[
V_o = d_c V_i
\]  
(3.31)

where \(d_c\) is the duty cycle with the operating range \((0 < d_c < 1)\) and \((V_o < V_i)\).

### 3.3.2 Design and Development of Buck Converter

The design of a DC-DC converter, such as buck converter, is to design the circuit elements and its driving circuit. The circuit elements include the output \(LC\) filter, and switches. Many factors are involved in designing the converter including efficiency, cost, space, electromagnetic interference (EMI), output voltage ripple, transient response, etc. The design requirements usually compete with each other. For example, the value of the \(LC\) filter must be large enough to substantially reduce the output voltage ripple. Increasing the value of the capacitor increases the cost and overall footprint, whereas increasing the value of inductor can decrease the efficiency and can make the transient response slower. The other option to reduce the output voltage ripple is by increasing the switching frequency. However, higher switching frequency may result in higher switching losses. Thus, the designer has to perform some kind of tradeoff between different design requirements. The switching frequency \((f_s)\) is selected at 20 kHz for the considered converter.

#### 3.3.2.1 LC filter

The inductor current ripple \((i_{\text{ripple}})\) is normally given to the designer, which is typically in the range of \((20-40)\%\) of the maximum load. In this thesis, the inductor ripple current is selected at \(30\%\) of the maximum load current. The inductor value \((L_i)\) can be calculated from the inductor current ripple equation, which is derived from the fall time of the current and current slope during switch-OFF state in Figure 3.22 as [149]:
\[
L_i \geq \frac{(V_i - V_o)}{i_{\text{ripple}}} \times \frac{d_c}{f_s}
\]  
(3.32)
The output capacitor value \( (C_{dc}) \) is determined from the output voltage ripple [150]. The ripple current is shared by the capacitor and the load based on their relative impedances at the harmonic frequencies, assuming all the ripple current is flowing through the capacitor and the load is receiving only the average inductor current. The output voltage ripple across the capacitor is, therefore, the sum of ripple voltages due to the effective series resistance (ESR) and inductance (ESL), and the voltage sag due to the load current that must be supplied by the capacitor while the inductor is discharged. Accordingly the equation becomes:

\[
V_{\text{ripple}} = i_{\text{L,ripple}} \times \left( \text{ESR} + \frac{d_c}{C_{dc} f_s} + \frac{\text{ESL}}{d_c f_s} \right) \tag{3.33}
\]

The ESL is neglected in (3.33), as this is a very small value and the output capacitor value is calculated as:

\[
C_{dc} \geq \frac{i_{\text{L,ripple}} \times d_c}{V_{\text{ripple}} - (i_{\text{L,ripple}} \times \text{ESR})} \tag{3.34}
\]

Now, the given specifications for the design of the buck converter are as follows:

- \( f_s = 20 \text{ kHz} \)
- \( V_i = (45 - 180)V \)
- \( V_o = 36 \text{ V} \)
- \( i_{\text{omax}} = 28 \text{ A} \)
- \( i_{\text{L,ripple}} = 0.3 \times i_{\text{omax}} = 8.4 \text{ A} \)
- \( V_{\text{ripple}} = 0.04 \times V_o = 1.44 \text{ V} \) (4 \% of the output voltage)
- \( \text{ESR} = 120 \text{ m\Omega} \)
- \( \text{ESL} = 20 \text{ nH} \)

The inductor and capacitor values are calculated from (3.32) and (3.34) as

\[
L_i \geq \frac{(45 - 36)}{8.4} \times \frac{0.8}{20000} = 42.85 \mu\text{H} \text{ for } (V_i = 45 \text{ V})
\]

\[
L_i \geq \frac{(180 - 36)}{8.4} \times \frac{0.2}{20000} = 171.42 \mu\text{H} \text{ for } (V_i = 180 \text{ V})
\]
Therefore, the inductor value is selected as almost twice the maximum value 340 μH, because the physical inductor is not ideally inductive, but does include the parasitic resistive value which reduces its inductive properties.

\[ C_{dc} \geq \frac{8.4 \times \frac{0.8}{20000}}{1.44 - (8.4 \times 0.12)} = 778 \, \text{μF for } (V_i = 45 \, \text{V}) \]

\[ C_{dc} \geq \frac{8.4 \times \frac{0.2}{20000}}{1.44 - (8.4 \times 0.12)} = 195 \, \text{μF for } (V_i = 180 \, \text{V}) \]

Therefore, the capacitor value is selected as 1000 μF.

### 3.3.2.2 Switch and Diode

The n-channel enhancement mode based power MOSFET is selected for faster response and smaller size. The rated voltage and continuous current are 600 V and 76 A respectively. The pulsed current, which is significantly higher than the rated continuous current, is 228 A. The maximum power that the device can dissipate is referred as power dissipation (\(P_D\)), which is based on the maximum junction temperature (\(T_{j\text{max}}\)) and thermal resistance (\(R_{thjC}\)) at a case temperature (\(T_C\)) of 25°C, as shown below:

\[ P_D = \frac{T_{j\text{max}} - T_C}{R_{thjC}} \quad (3.35) \]

An attempt to calculate some of the parameters of the chosen MOSFET based on datasheet as given in Appendix [151]. Suppose, the junction is allowed to reach 75°C maximum and can maintain the case at 35°C, then the power dissipation would be

\[ P_D = \frac{75 - 35}{0.23} = 173.9 \, \text{W} \quad (3.36) \]

However, the maximum dissipate power at room temperature is 543 W according to the datasheet.

The turn ON (\(E_{onM}\)) and turn OFF (\(E_{offM}\)) energy losses in MOSFET are calculated as:

\[ E_{onM} = V_{DD} \times I_{Don} \times \left( \frac{t_{rc} + t_{fu}}{2} \right) + (Q_{rr} \times V_{DD}) \quad (3.37) \]

\[ E_{offM} = V_{DD} \times I_{Dooff} \times \left( \frac{t_{rv} + t_{fi}}{2} \right) \quad (3.38) \]
where $V_{DD}, I_{Don}, I_{Doff}, t_{rc}, t_{fv}, t_{rv}, t_{fi},$ and $Q_T$ are the converter supply voltage, drain current during ON, drain current during OFF, current rise time, voltage fall time, voltage rise time, current fall time and reverse recovery charge respectively. The current rise and fall time can be calculated from the datasheet whereas voltage rise and fall time can be calculated as:

$$t_{fv} = \frac{t_{fv1} + t_{fv2}}{2}$$  \hspace{1cm} (3.39)

where $t_{fv1}$ and $t_{fv2}$ are the voltage fall time when the drain source voltage ($V_{DS} \in [0.5V_{in}, V_{in}]$) and $V_{DS} \in [0, V_{in}]$ respectively.

$$t_{fv1} = (V_{DD} - (R_{DSon} \times I_{Don})) \times R_{G} \times \frac{(C_{rss} \times V_{DD})}{(V_{Dr} - V_{pla})}$$  \hspace{1cm} (3.40)

$$t_{fv2} = (V_{DD} - (R_{DSon} \times I_{Don})) \times R_{G} \times \frac{(C_{rss} \times (R_{DSon} \times I_{Don}))}{(V_{Dr} - V_{pla})}$$  \hspace{1cm} (3.41)

where $R_{DSon}, R_{G}, C_{rss}, V_{Dr},$ and $V_{pla}$ are static drain to source ON resistance, gate resistance, reverse transfer capacitance, driver output voltage and gate plateau voltage respectively. Given operating parameters for the maximum loading conditions: $V_{DD} = 180\, \text{V}$, $I_{Don} = 23.8\, \text{A}$, $I_{Doff} = 32.2\, \text{A}$, $i_{Tripple} = 30\%$, $R_{G} = 43\, \Omega$, $V_{Dr} = 15\, \text{V}$, $d_c = 0.8$, and $V_{pla} = 5.2\, \text{V}$ respectively.

$$t_{fv1} = 693.3\, \text{ns}$$

$$t_{fv1} = 3.3\, \text{ns}$$

$$t_{fv} = 348.3\, \text{ns}$$  \hspace{1cm} (3.42)

Similarly voltage rise time can be calculated as:

$$t_{rv} = 718.2\, \text{ns}$$  \hspace{1cm} (3.43)

Now substitute voltage fall and rise time from (3.42) and (3.43) in (3.37) and (3.38) such that turn ON and turn OFF energy losses are:

$$E_{onM} = 3750.29\, \mu\text{J}$$  \hspace{1cm} (3.44)

$$E_{offM} = 2081.3\, \mu\text{J}$$  \hspace{1cm} (3.45)

At $75\, ^\circ\text{C}$, $R_{DSon}$ is almost 1.5 times higher than at room temperature (datasheet); therefore, conduction loss at duty cycle 0.8 is

$$P_{cond.} = 1.3 \times 0.036 \times 28^2 \times 0.8 = 33.86\, \text{W}$$  \hspace{1cm} (3.46)
The switching loss is calculated from (3.44) and (3.45) with switching frequency 20 kHz as:

\[
P_{\text{swit.}} = 20 \times (3750.29 + 2081.3) = 116.6 \text{ W}
\]

(3.47)

The total losses are

\[
P_{\text{cond.}} + P_{\text{swit.}} = 150.5 \text{ W}
\]

(3.48)

Therefore, the losses in MOSFET are within what is allowed to keep the junction below 75°C with the case cooled to 35°C. In addition, the MOSFET has the rated current 2.7 times more than the maximum switched current. The losses are further reduced by placing the snubber circuit. The diode is selected with rated current and reverse voltage 1.6 times the maximum average forward current and the maximum operating supply voltage.

### 3.3.2.3 Snubber Circuits

Snubber circuit is placed across semiconductor devices such as a MOSFET switch for protection and to improve performance. The \( RC \) snubber circuit is primarily implemented to do following activities: (i) reduce voltage and current spike; (ii) limit the rate of change of current and voltage; and (iii) reduce total losses due to switching.

The following information is considered for designing the snubber circuit across the switch (MOSFET) and diode [152].

- \( f_i = 35 \text{ MHz} \); ringing frequency of the voltage transient when the MOSFET opens
- \( C_{ad} = 400 \text{ pF} \); capacitance added in parallel to the MOSFET which reduces the ringing frequency to half (17.5 MHz)
- \( f_s = 20 \text{ kHz} \); switching frequency
- \( t_{on} = \frac{0.2}{20 \times 10^3} = 10 \mu\text{s} \); ON time for the MOSFET with a 20% minimum duty cycle
- \( V_{opn} = 180 \text{ V} \); open MOSFET voltage
- \( i_{sw} = 28 \text{ A} \); maximum switch current
- \( C_i = \frac{400}{3} = 134 \text{ pF} \); intrinsic capacitance which is always \( \frac{1}{3} \) of the added capacitance

Now, the circuit inductance is:
The snubber resistor \( (R_s) \) value is:

\[
R_s = \sqrt{\frac{0.154}{134}} \times 10^3 = 40 \, \Omega
\]

The snubber capacitance \( (C_s) \) is calculated based on two requirements: (i) provides final energy storage greater than the energy in the circuit inductance; and (ii) produces a time constant with the snubber resistor that is small compared to the shortest expected ON-time for the MOSFET.

\[
\frac{L_i t_{sw}^2}{V_{opn}^2} < C_s < \frac{t_{on}}{10R_s}
\]

or

\[
\left( \frac{0.154 \times 10^{-6}}{(28)^2} \right) \times (28)^2 < C_s < \frac{10 \times 10^{-6}}{10 \times 40}
\]

or

\[
3.73 < C_s < 25 \, \text{nF}
\]

The standard capacitance is chosen close to the low end of the above range, which is 4.7 nF. Similarly, the RC snubber circuit is chosen for diode.

### 3.3.2.4 Gate Drive Circuits

The location of MOSFET in a buck converter, as shown in Figure 3.17, introduces a challenge for a drive circuit. The source terminal of the MOSFET is not connected to the circuit ground (not ground referenced) and is floating. Unlike in the boost converter, where the source terminal of the MOSFET is connected to the ground referenced and is not floating, which is referred to as a low side switch (MOSFET). This configuration does not pose any challenge to the drive circuit. If the N-channel MOSFET is considered in a buck converter, then the switch is referred to as a high side switch. The high side non–isolated gate drive circuits can be classified by the MOSFET type: N-channel or P-channel, and the type of drive circuit involved such as direct drive, level shifted drive or bootstrap technique [153].

If P-channel MOSFET is used in the buck converter then the drive circuit is no more challenging. The direct drive with simple level shifter circuit can be used to drive the switch. However, P-channel MOSFET has some drawbacks compared to N-channel MOSFET, which are listed below [154]:

\[
L_i = \frac{1}{\left(134 \times 10^{-12}\right) \times \left(2 \times \pi \times 35 \times 10^6\right)^2} = 0.154 \, \mu\text{H}
\]
(i) The mobility of the carriers in an N-channel is approximately 2 to 3 times higher than that of a P-channel. Therefore, the P-channel chip must be 2 to 3 times bigger than that of an N-channel for the same on state resistance ($R_{DS(on)}$) value.

(ii) The dynamic performance of the P-channel is affected proportionally by the chip size. Larger chip size MOSFET has a lower thermal resistance and a higher current rating.

(iii) The P-channel MOSFET has a similar chip size but a lower current rating than that of an N-channel MOSFET for same total gate charges.

Thus, the P-channel MOSFET has higher conduction and switching losses and deteriorated performance comparing to N-channel MOSFET for the same size, otherwise the size needs to increase to enhance the dynamic performance. These are the reasons for selecting N-channel MOSFET in a buck converter by compromising a tricky gate drive circuit.

![Figure 3.17: Buck converter based on N-channel MOSFET](image)

The Kirchhoff's voltage law (KVL) is applied in the loop within the dashed rectangle.

$$V_l - V_{DS} + V_{GS} - V_G = 0$$  \hspace{1cm} (3.49)

Arrange (3.49), so that,

$$V_G = V_l - V_{DS} + V_{GS}$$  \hspace{1cm} (3.50)

Ideally, drain-source voltage ($V_{DS}$) is almost zero considering a small on-state resistance. Therefore (3.50) becomes:

$$V_G = V_l + V_{GS}$$  \hspace{1cm} (3.51)

The MOSFET is switched ON if the gate-source voltage ($V_{GS}$) is in the order of (10-20) V. This implies that the gate voltage ($V_G$) must be (10 to 20) V higher than the input voltage ($V_l$) of the buck converter. If the source terminal is ground referenced or 0 V,
then applying (10-20) V directly at the gate terminal would turn ON the MOSFET. However in Figure 3.24 the source terminal voltage is varied in between $V_i$ (MOSFET ON) to 0 V (MOSFET OFF). Therefore, the direct drive circuit will never provide the $V_{GS}$ in the order of (10 -20) V. The drive circuit needs an auxiliary circuit, such as bootstrap technique. However, the isolated drive circuit is implemented in the thesis, which is explained in the following paragraphs [154].

The isolated drive circuit performs two major tasks (i) isolates the ground reference of the input signal from the microcontroller as a pulse width modulation (PWM) signal from the ground reference of the drive circuit; and (ii) the source terminal of the MOSFET is considered as a ground reference of the entire drive circuit. By using (ii) and applying (10-20) V at the gate drive circuit, the $V_{GS}$ is always maintained at (10 to 20) V irrespective of varying source terminal voltage. The isolated gate drive circuit is shown in Figure 3.18.

![Figure 3.18: Isolated gate drive circuit](image-url)
The opto-coupler is used to isolate the driving signal from the gate drive circuit. The input and output sides of the opto-coupler are operated at different ground levels. The isolated power supply provides the power to both voltage regulator and gate driver. The output voltage of this power supply is operated at a different ground level than the input. The voltage regulator converts the DC 15 V to 5 V, which is the supply rated voltage of the opto-coupler. The high speed gate driver is used to drive the gate with the ground reference voltage similar to the source terminal voltage of the MOSFET. In short, the output of the devices in the circuit, such as opto-coupler, isolated power supply, voltage regulator and gate driver are determined based on the source terminal voltage of the MOSFET as a ground reference level. As a result, by controlling the pulse or driving signal, the gate terminal voltage is always 15 V more than that of the source terminal voltage, and the MOSFET will turn ON.

3.3.2.5 Heat Sinks
The heat sink is determined based on the following steps [155]:
(i) The maximum ambient temperature that the MOSFET can operate is 150°C from the datasheet.
(ii) The assumption that the room temperature is 25°C.
(iii) The temperature difference between junction and the room is 125°C.
(iv) The junction to case thermal resistance is 0.23°C/W and the resistance between case and heatsink due to silicone compound is estimated as 0.05°C/W (from the datasheet).
(v) The power dissipation at maximum current is 150.5 W
(v) The thermal resistance of the heat sink \( R_{thsa} \) is

\[
R_{thsa} = \frac{150 - 25}{150.5} - (0.23 + 0.05) = 0.55°C/W
\]  

(3.52)

Therefore, a heat sink is selected with a thermal resistance or temperature rise less than 0.55°C/W or 82.77°C.

3.4 DC-AC Converters (Inverters)
The existing 1.2 kW inverter in the laboratory is used for the experiments as explained in [156]. However, the following modifications have been done in the inverter to enhance the performance.
• Replace the MOSFET gate driver
• Keep internal signals farther from noisy components.
• Replace the sensors and remove the narrow band filter
• Operate as two stage converter with different control strategy.

3.5 Real Time Controller Platforms

The research has implemented three real time controller platforms: (i) National Instrument (NI) laboratory virtual instrument engineering workbench (LabVIEW); (ii) Texas Instrument (TI) microcontroller; and (iii) dSPACE, with different objectives to perform the real time experiments. The NI LabVIEW is used to operate the wind turbine simulator (WTS) with a data acquisition chassis NI cDAQ 9172. The TI microcontroller is used to control the DC-DC converter in a closed loop environment. Finally, the dSPACE is used to control the DC-AC converter (inverter) in a closed loop environment and to collect the real time data using a dSPACE control desk.

3.5.1 National Instrument (NI) LabVIEW

The NI LabVIEW is a graphical programming platform which is commonly used for data acquisition, instrument control, and industrial automation. The LabVIEW program is called virtual instrument (VI), because its appearance and operation imitates physical instruments, such as oscilloscopes and multimeters. It contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data. LabVIEW also provides a user interface environment or a front panel with controls and indicators. The code is developed using VIs and structures to control the front panel objects. The block diagram contains the code.

The LabVIEW performs two major tasks for WTS: (i) provides a platform to model the physical real wind turbine as a software part; and (ii) interfaces the software to the real hardware system in a closed loop environment. The modeling is performed using a block diagram, as shown in the sample in Figure 3.19, whereas the user interface is developed in the front panel.
Figure 3.19: Block diagram of WTS

The code for LabVIEW is developed in a block diagram as shown in Figure 3.19. The block diagram consists of the modeling (static and dynamic characteristics) of a real physical wind turbine, which sends the torque or angular rotor speed signal to the commercial vector torque controller through a LabVIEW data acquisition interfacing unit called cDAQ 9172, in order to control the induction motor as a wind turbine.

Figure 3.20: Front panel for WTS

The front panel sample is shown in Figure 3.20, and is used to display the features of the WTS and also to control the wind speed manually.
The cDAQ 9172 is the National Instrument (NI) chassis, and has an eight-slot USB
designed for use with C Series input-output (I/O) modules. The cDAQ-9172 chassis is
capable of measuring a broad range of analog and digital I/O and sensors using a Hi-
Speed USB 2.0 interface. For module specifications, refer to the manuals available in the
lab. For wind turbine simulator, NI 9215 is used as an input module and NI 9264 is used
for an output module. NI 9215 is a 4-Channel, 100 kS/s, 16-bit, ±10 V simultaneous
sampling analog input module and NI 9264 is 16-Channel, 25 kS/s/ch ±10 V
simultaneous sampling analog output module. The NI 9215, cDAQ 9172 and NI 9264 are
shown in Figure 3.21.

![Figure 3.21: I/O Module of NI with Chassis](image)

The detailed information for NI LabVIEW is given in the national instrument website:

### 3.5.2 Texas Instrument (TI) Microcontroller

The Texas instrument (TI) C2000 series of a microcontroller based on digital signal
processing (DSP) is considered in this research, and is referred to as TMS320F28335
DSP [157]. The TMS320F28335 is a real time control device which has 32 bit
microcontrollers based on the industry leading C28x central processing unit (CPU). This single chip controller addresses most control challenges through the powerful integrated peripherals such as analog to digital converter (ADC), comparators, pulse width modulation (PWM) and much more.

The embedded target for TI C2000 DSP provides the application programming interfaces required by real time workshop to generate code. The algorithm (or code) is designed and implemented using blocks in a MATLAB Simulink. The link for code composer studio (CCS) is used to invoke the code building process from within CCS to build and execute. This code is then downloaded to the target from where it runs or DSP. The data on the target is accessible in CCS or in MATLAB through a link for CCS, or through a real time data transfer (RTDX) [158].

This TI C2000 is used in the research to control the DC-DC converter through a PWM technique in a current and voltage mode strategy as shown the sample figure in Figure 3.22. The personnel computer (PC) is required to run the Code Composer Studio in order to compile and download code to DSP.

![Figure 3.22: Real time control of DC-DC converter in a microgrid using TI C2000](image)

The following tasks are performed to control the real physical converter in a closed loop using TI C2000:
• Complete the model, algorithm or code using blocks in Simulink as shown in Figure 3.22.
• Add the embedded target for TI C2000 DSP blocks and let the signal sources and output devices communicate with the target preference.
• Add the target preference block from C2000 target preference library to the Simulink.
• Run the diagnostic utility test to ensure the correctness of the board.
• Build the model on the selected target.

3.5.3 dSPACE

The dSPACE is a proven real-time controller and is tightly integrated with the MATLAB Simulink environment. The models or algorithms developed in MATLAB Simulink can be implemented on dSPACE hardware. The real time interface (RTI) concentrates fully on the actual design process and carries out fast design iterations. The MATLAB Simulink coders (formerly real time workshops) are the seamless, automatic implementation of the Simulink models on the real time hardware.

The input/output (I/O) modules are dragged from the RTI block library in a Simulink and connected to the blocks in a Simulink so that the model will interact with the dSPACE I/O board. The real-time model is compiled, downloaded, and started automatically on the real-time hardware, without any code. RTI provides consistency checks, so potential errors can be avoided.

The control platform is the model DS1103 PPC controller board provided by dSPACE [159]. The control platform is interfaced with the inverter through the digital and analog input and output channels. The sample model (control strategy) for the dSPACE inverter control in the MATLAB Simulink is shown in Figure 3.23. The references and the measured values at the output of the inverter are collected using DC and AC sensors, which are connected to the I/O module of the dSPACE hardware board. These sensing values are used in the real time control strategy to generate the switching pulses for the inverter.
The user interface is also developed using the dSPACE control desk tool as shown in Figure 3.24.

The user interface not only displays the assigned parameters graphically in real time but also allows the users to run the inverter in an open loop or control manually. This is particularly useful to calibrate the sensors and diagnose any problems that have occurred in the system.
3.6 Sensors for Converters

The voltage and current sensors are constructed to measure the input and output voltage and current of the converters in order to interface with the real time controller platform. The sensors are equipped with filters to suppress the noises. The DC and AC sensors are designed and implemented for DC and AC systems. The AC sensors are used to measure the inverter three phase output voltages and currents, which are explained in [160]. However, the schematic and printed circuit board diagrams for DC sensors are shown in Figures 3.25 and 3.26 respectively.

Figure 3.25: Schematic diagram of DC voltage and current sensors

Figure 3.26: Printed circuit board diagram for DC voltage and current sensors
These sensors are the crucial part of the experimental setup as they measure the parameters in real time and send it to the control loop through I/O modules of a controller platform.

3.7 Conclusions

In this chapter, the design and development of the physical hardware system which is built in the laboratory along with their real time control platform is presented. The purpose of this physical hardware system is to support the research by validating the proposed control strategies in a real time physical system. The physical wind turbine is simulated using an induction motor, vector torque controller and hardware-in-the-loop concept, such as a wind turbine simulator. The power electronic converters are also designed and developed for energy sources to interface in the microgrid. Furthermore, the real time controller platform is implemented. The sensors and protection devices for the equipment are also designed and developed. The features of the commercial PV simulator and lead acid battery are also presented.
Chapter 4

4 Validation of the System Models

This chapter provides the validation of the system model against the real physical system in the laboratory. The modeling of a PMSG, PV and lead acid battery is performed in Chapter 2, whereas the design and development of a physical system are performed in Chapter 3. The development of the physical system in Chapter 3 helps to test and collect the real time data in order to validate the model performed in Chapter 2. The static and dynamic characteristics of these real physical systems are measured and collected under different operating conditions. These characteristics are then compared against the simulation results based on the developed models under the same operating conditions. The simulation is performed in the PSCAD.

4.1 Permanent Magnet Synchronous Generators

The wind energy source considered in this thesis is Type IV, which consists of turbine, PMSG and power electronic based interfacing units or converters. The wind turbine simulator is developed in the laboratory to mimic the characteristics of a real physical wind turbine, which is explained in Chapter 3. Similarly, the converters are also designed and developed physically based on the simulation study, which is also explained in Chapter 3. The PMSG modeling is performed in Chapter 2. The experimental setup, which is used to validate the PMSG model, is shown in Figure 4.1.

![Figure 4.1: Experimental set up for PMSG]
The PMSG is driven by an induction motor, which is controlled by a commercial vector control drive. The AC output of PMSG is rectified into DC output to feed into the DC load. The PMSG output voltage varies based on the rotational speed of the induction motor, whereas the output current varies based on the load demand. The user interface software which is installed in the personnel computer (PC), is used to vary the DC load. The experimentally obtained static and dynamic characteristics of a PMSG are compared with the simulation results, which is based on the modeling of the PMSG.

### 4.1.1 Static Characteristics

The voltage and current are measured at different loads, but at the same rotational speed. The root mean square (rms) AC voltage is plotted against the rms AC current as shown in Figure 4.2. Similarly, the rectified DC voltage is plotted against the DC current as shown in Figure 4.3. The five rotational speeds or revolutions per minute (rpm) are selected arbitrarily to verify the model. The simulation results are the outcome of the models.
The following observations have been made on Figure 4.2.

- The output voltage rises with rotational speed of the generator.
- The output current rises with the load demand.
- The simulation results closely follow the experimental results under different rotational speeds and load demands.

The experimental results closely follow the simulation results at different rotational speeds; however, a slight deviation occurs as the load demand or the current output increases, which becomes more vulnerable at higher rpm. The deviation at the large load and high rpm is 4.5%. The reason is the temperature rises with the high load demand and the running time. The permanent magnet is susceptible to the temperature, which affects...
the magnetic flux. This flux is responsible for generating the back induced electromotive force, which ultimately affects the generation of electrical parameters such as voltage and current. At 200 rpm, the PMSG has started the first time with normal room temperature under this experiment, which is why the experiment results follow strictly the simulation results at an even higher load. The graph of DC voltage vs DC current is shown in Figure 4.2, where the experimental results followed the simulation results quite closely, below 1% deviation, especially in the most common operating points (mid section).
The DC voltage vs DC current obtained from experiment and simulation also shows the same behavior as in Figure 4.2. However, the DC outputs are the rectified output, which carries both fundamental and harmonic components even though the passive filter is placed to suppress it. These harmonics, along with the rising temperature, deviate the experimental results 4.5% at most as compared to the simulation results. The only behavioral difference between Figure 4.2 and Figure 4.3 is that the deviation in Figure 4.3 has also occurred at normal or light load under some rotational speed. For example: 350 rpm, x-axis-(2-8) A, both experiment and simulation results matched perfectly in Figure 4.2 whereas in Figure 4.3, a slight deviation is seen within 3%.  

### 4.1.2 Dynamic Characteristics

The PMSG is operated at varying input using the experimental set up, as shown in Figure 4.1. The rpm is varied (step change) at the same resistive load to identify whether the modeled PMSG and the real physical PMSG have the same dynamic features or not. The mechanical rotational speed and electrical power and torque characteristics are collected for a particular period in real time under the step change input. The simulation results are shown in Figure 4.4, whereas the experimental results are shown in Figure 4.5.
Figure 4.4: Simulation results of PMSG under variable rpm
The input rpm is a step up at 7.5 s from 650 rpm to 950 rpm under the same resistive load in both simulation and experiment, as shown in Figures 4.4 and 4.5 respectively. The

Figure 4.5: Experimental results of PMSG under variable rpm
output power and torque increases with increasing rpm at the same load. The simulation results in Figure 4.4 match the experimental results perfectly, however, the experimental results carry some noises, due to the vibration of motor and generator set and also the measurement noises which encompass the signals through the sensors. The last graph in Figure 4.4 and 4.5 show the zoom version of electrical power for a period of 1 s. Both results show the similar response time, which is 87 ms.

Both static and dynamic characteristics of the modeled PMSG and real physical PMSG have matched perfectly with a deviation at most 4.5 %, as shown in Figures 4.3, 4.4 and 4.5 respectively. This analysis validates the model of PMSG with the real system.

4.2 Photovoltaic (PV) Source

The PV array comprising of eight PV modules are installed on the roof of the Claudette Mackey-Lassonde Pavilion (CMLP) engineering building. The modules are Sanyo Heterojunction with Intrinsic Thin Layer (HIT)- 200 W with the following ratings: maximum (max) power, $P_{\text{max}} = 200$ W, voltage at maximum power point (mpp), $V_{\text{mpp}} = 55.8$ V, current at maximum power point (mpp), $I_{\text{mpp}} = 3.59$ A, open circuit (oc) voltage, $V_{\text{oc}} = 68.7$ V and short circuit (sc) current, $I_{\text{sc}} = 3.83$ A at the standard condition (1000 W/m$^2$ and 25°C).

The Sanyo HIT solar cell is composed of a thin mono-crystalline silicon wafer surrounded by an ultra thin amorphous silicon layers. The efficiency of the Sanyo HIT solar cell reaches 23 % under laboratory conditions, which is the world record. An experiment is performed in a single module, which has the efficiency of 17.2 % as indicated in their datasheet [161]. The PV modules are mounted on the south-oriented plane with an appropriate tilt angle of 43° based on the latitude of London, Ontario, i.e. 42° 59’ 0 N.

The positive and negative terminals of each panel are brought to a wall-mounted enclosure to the laboratory through a conduit running from PV panels down to the laboratory at CMLP 2327.
The sensors for solar irradiance and temperature are installed on the roof of the CMLP engineering building near the panels. The SP Lite 2 silicon pyranometer is used to measure the irradiance, whereas the thermistor attached to the back of PV modules is used to measure the temperature. The measured data is transmitted to the laboratory through ethernet and recorded using LabVIEW while performing the experiments. The voltage and current sensors are used to measure the PV module voltage and currents, which are placed in the laboratory. The experimental setup is shown in Figure 4.6.

![Figure 4.6: Experimental configuration for the PV source](image)

The PV two terminals, positive and negative, are brought to the laboratory, and connected to the DC programmable loads, as shown in Fig. 4.6. The resistive loads are varied to measure the voltage and current of PV module at the actual weather conditions. The voltage and current sensors, LA 25- P and LA 55- P, are used to measure the voltage and current in real time, and record the data in LabVIEW. One of the Master students was performing this experiment. The experimental results are compared with the simulation results based on the PV model which is shown in Figure 4.7 and 4.8, respectively. The PV model is explained in Chapter 2.
Figure 4.7: I-V characteristics of PV module from simulation and experiment

The current-voltage (I-V) characteristics of a PV module are shown in Figure 4.7 for different irradiance (I) and temperature (T), which are measured in W/m$^2$ and °C respectively. The experimental results match the simulation results perfectly within 2% deviation.
Figure 4.8: P-V characteristics of PV module from simulation and experiment

**Figure 4.8** P-V characteristics of PV module from simulation and experiment
The power-voltage (P-V) characteristics are shown in Figure 4.8 at different irradiance and temperature. The experimental results match the simulation results perfectly within 2% deviation. In addition, the following observations are made on Figures 4.7 and 4.8 respectively.

- The current increases slightly with increasing temperature, which is normally ignored. However, a more significant effect is on the voltage. The voltage decreases effectively with the rise in temperature.
- The voltage increases slightly with increasing temperature, which is normally ignored. However, the current rises substantially with increasing irradiance.
- The power increases with increasing irradiance; however, the maximum power does not vary significantly. In case of temperature variations, the maximum power varies significantly.

4.3 Lead Acid Battery

The deep cycle valve regulated lead acid battery is used for the experiment in the laboratory, as explained in chapter 3. The most well-known CIEMAT model of a lead acid battery is considered, which is explained in chapter 2. The CIEMAT model, which is simulated and compared with the experimental results, is shown in [125]. Therefore, the following two methods are performed for the validation of lead acid battery model:

(i) The results of CIEMAT model in [125] are compared to the simulation results based on the lead acid battery model in PSCAD.

(ii) The real physical lead acid battery is operated under particular operating conditions, and the data is collected for a particular period in a real time through a dSPACE control desk. These experimental results are then compared with the simulation results which are based on the battery model.
The lead acid battery model based on CIEMAT is performed in PSCAD, as shown in Figure 4.9, which is operated under the same conditions as mentioned in [125]. However, the difference is in the operating period. The simulation is performed for 35 s under the same loading conditions with faster load variation period. The objective is to show the simulation results follow the same pattern as in the reference [125].

Figure 4.9: CIEMAT model results from [125]
The battery current in Figure 4.10 follows the same pattern as in Figure 4.9 (first graph). The discharge mean current, which is defined as the average discharge current without considering the charging current, is the important factor to calculate the battery capacity. The discharge mean current in Figure 4.10 perfectly matches the discharge current shown in Figure 4.9 (first graph). Similarly, the state of charge and battery capacity also matches the CIEMAT model results presented in Figure 4.10 (third and fourth graphs). This validates the CIEMAT model of lead acid battery which is developed in PSCAD. The experimental set up using the available lead acid battery in the laboratory is shown in Figure 4.11.
The lead acid battery is directly connected to the DC programmable load through a manual switch as shown in Figure 4.11. The three 12 V batteries are each connected in series, to step up the nominal voltage to 36 V. The DC programmable load has the user interface software through which the load can be connected from no load to full load. The data is collected for a particular period through a dSPACE control desk.
The simulation is performed based on the CIEMAT model. The battery current is varied according to the load variation, as shown in Figure 4.12. The negative value of battery current represents the discharging current whereas the positive value represents the charging current. The state of charge is identified based on the coulomb counting method. The battery output terminal voltage also varies with the charging and discharging current.
The experiment is performed under similar conditions to the simulation. The results illustrated in Figure 4.13 are closely matched to the simulation results in Figure 4.12. Normally, the battery is very fast to react; however, its response depends on the load variations. The experimental results carry some noises, due to the measurement noise and noisy laboratory environment which encompasses into the signals through the sensors.

The results in Figure 4.10 validate the CIEMAT model against the experimental and simulation work performed for the lead acid battery in the literature, whereas the results in Figure 4.13 validate the simulated CIEMAT model against the experimental set up.
4.4 Conclusions
In this chapter, the modeling of PMSG, PV source and lead acid battery which were done in Chapter 2 are validated against the real physical system in the laboratory. The purpose is to design and validate the control strategies under the same simulated and experimental structures. The development of the physical systems such as sensors, real time controller and converters, which were performed in Chapter 3, helped to perform the real time testing of the energy sources. In addition, the data was also collected in real time. These collected data of the physical systems are compared to the PSCAD simulation results based on the developed models. The results show that the models of the physical system are acceptable against the real physical systems.
Chapter 5

5 Control Strategy for an Islanded Wind/Battery Hybrid System: with a Battery Converter

5.1 Introduction

A power management control strategy for a wind/battery hybrid system in an islanded DC microgrid is proposed in this chapter. Different sources and local loads are connected at the DC link, which can operate in both grid and off-grid mode, are formally called DC microgrid [162]. The hybrid systems are integrated at the DC link to form the DC microgrid, as shown in Figure 5.1.

![Figure 5.1: Hybrid system with a conventional structure in a DC microgrid](image)

The ‘n=1…..’ number of hybrid system can be integrated into the microgrid. In addition, the dedicated bidirectional DC-DC converter for the battery, dump load with a crowbar circuit, and backup AC source such as diesel generators are also considered. This is the common configuration for the hybrid wind system; thus, it is considered to be a conventional structure. The local control is responsible for controlling the hybrid system, whereas the supervisory control takes care of overall power management scheme.
In this study, the wind source is operated as a current source under MPPT scheme. Therefore, the wind source supplies a maximum power in all wind and system operating conditions to maximize the revenue. In this scenario, the power flow between the wind source and loads become imbalanced resulting in instability in the system. Thus, the coordinated control strategy among wind, battery, dump load and backup AC source (can be a diesel generator set) is designed to balance the power flow within the system irrespective of fluctuating weather conditions and load demands. The status of DC link voltage (DLV) and the state of charge (SOC) of the battery are used to activate the sources and sinks autonomously. The battery storage is used to regulate the DC link voltage by consuming excess power and supplying deficit power. In addition, the dump load is used to consume excess power in the microgrid during fully charged battery condition. Furthermore, the backup source is activated only during discharging of the battery below the minimum operated voltage and SOC thresholds.

The previous chapters performed the modeling, physical system design and development, and validation of the modeling against the physical systems. The problem statement is discussed in Section 5.2. In Section 5.3 the conventional structure and control objectives are briefly presented. The modeling of the systems is performed in Chapter 2, which is stated in Section 5.4. The concept of a proposed control strategy and its behavior is explained in Section 5.5. The simulations results performed in PSCAD and discussions are presented in Section 5.6, followed by conclusions in Section 5.7.

5.2 Problem Statement

The renewable energy source such as a wind source can’t operate satisfactorily at the desired voltage and frequency under the fluctuating load demand due to its intermittent nature. Some additional sources and sinks are required in order to counter balance the fluctuating nature of the wind. With the rapid development of renewable energy and power electronics technology, cost reduction in energy storage and wider applications of microgrid system, different control strategies and power management systems have been proposed for wind integration [163].
The battery is one of the most commonly used energy storage to counterbalance the intermittent nature of wind source. However, the optimal size of battery has its own operating limits, which provides the operating constraints for the wind source to operate in all system conditions. Therefore, the dump load is introduced to activate during overcharging battery constraints, while the backup AC source is integrated to activate during over discharging battery constraints. As a result, the power is balanced within the system in all conditions and the stability of the system is also maintained by regulating the DC link voltage within the operating limits in the DC microgrid.

In contrast to the diesel generator based microgrid system in the literature where the generator is contributed constantly throughout the operation in order to counter balance the intermittent nature of renewable sources, the developed control strategy operates the diesel generator occasionally in the presence of the battery. The proposed control strategy utilizes local power sources owned by the community as a microgrid at a maximum by deactivating the local grid. In addition, the diesel generator is activated only during abnormal (extreme) conditions, such as low battery energy storage or maintenance requirements. This strategy provides the following advantages: (i) Maximum use of local power reduces the electricity bill from the grid; and (ii) Reduces frequent operation of the diesel generator, which cuts down operating costs of the microgrid.

5.3 Conventional Structure and Control Objectives

The hybrid permanent magnet synchronous generator (PMSG) based variable speed wind turbine (VSWT) and battery energy storage are considered, as shown in Figure 5.2. The PMSG based VSWT is considered as the main source in this topology, and is connected to the DC link (DCL) through a diode bridge rectifier and DC-DC converter (buck converter). The conventional structure contains the dump loads with a crowbar circuit and a bidirectional DC-DC converter for battery storage. By the coordinated control strategy among wind, battery, dump load and diesel generator operated as an AC source during extreme conditions, the power flow is balanced, which, in turn, maintains the DC link (DCL) voltage within the desired operating limits. The AC loads are connected to DCL through DC-AC converter (inverter).
The control objectives are:

(i) The buck converter is used to control the wind output power under maximum power point tracking (MPPT) scheme using power signal feedback technique. Therefore, the MPPT control is based on the converter input power ($P_{in}$), converter output power ($P_{out}$) and revolution per minute (rpm) to trigger the switch ($S_{mppt}$) under pulse width modulation (PWM) technique. The wind current ($I_w$) can flow to the dump load and loads depending upon the strategy.

(ii) The bidirectional converter for battery is used to regulate the DC link voltage ($V_{dc}$) by charging or discharging the battery as per requirements. The battery current ($I_{bat}$) can flow in and out of the battery by triggering the switches ($S_c$ and $S_d$).

(iii) The dump load switch ($S_{dp}$) is used to activate the dump load under certain operating conditions, so that the DC link current ($I_{dc}$) matches the load demand and the battery is not overcharged.

(iv) The bidirectional inverter or converter performs the power flow at AC side by considering the amplitude and frequency of AC link voltage ($V_{abc}$) and output current ($I_{abc}$). During abnormal conditions, the converter operates as a rectifier to regulate the DCL voltage through an AC source by triggering the AC source switch ($S_{123}$). Therefore, the AC source participates occasionally to support the system during abnormal conditions, such as over discharging the battery.
The amplitude and frequency of AC link voltage can be regulated by maintaining the DCL voltage \( V_{dc} \) at its desired level and controlling the modulation index at its certain value, as shown in (5.1).

\[
V_{LL} = 0.612m_a V_{dc} \tag{5.1}
\]

where \( V_{LL} \) is line to line root mean square voltage at the inverter output, and \( m_a \) is the modulation index of the pulse width modulation technique for controlling the inverter.

The frequency can be controlled by maintaining the sinusoidal reference signal in the inverter control strategy.

In this work, the control objective is to maintain the DCL voltage in order to balance the power flow at the DC side; which, in turn, maintained the stability of the DC microgrid \[164\]. Therefore, the detail analysis for inverter control at the AC link is not considered in this chapter. However, the inverter is operated in a voltage control mode as stated in (5.1) during off-grid and as a rectifier to regulate the DC link voltage in order to charge the battery and supply the deficit power at the DC side during low SOC of the battery.

### 5.4 Modeling of the System Components

The system is modeled in the PSCAD. The detail modeling is performed in Chapter 2, which consists of wind turbine, PMSG, and battery energy storage.

### 5.5 Proposed Control Strategy

The proposed control strategy is to regulate the DC link voltage in order to balance the power flow between the generation and load irrespective of variable wind speed, low battery storage, and variable load demand. Therefore, the proposed control strategy is based on the following features:

(i) The control strategy is based on DCL voltage and state of charge (SOC) of the battery.

(ii) The conventional control structure consists of bidirectional DC-DC converter, dump load, and backup AC source (can be a diesel generator set).

(iii) The diesel generator is activated only during low battery storage to charge the battery and meet the load demand.
(iv) The wind is operated at maximum power point tracking (MPPT) scheme under varying wind speed.

(v) The operating limits of the battery are based on SOC, which is selected in between (50-90) % for a longer life cycle.

(vi) The negative current of battery means charging the battery and vice versa. The negative current from the bidirectional inverter means the current is flowing from grid to the DC microgrid system.

The proposed control strategy is explained in Figure 5.3.

If DCL voltage ($V_{dc}$) is more than the reference level ($V_{rl}$), the load demand is less than the generation. In this case, the state of charge (SOC) is checked in order to identify the sink between the battery and dump load. The excess energy is utilized in charging the battery if SOC is less than 90%, or else used for heating purposes, such as a dump load. If $V_{dc}$ is less than $V_{rl}$, this means load demand is more than the generation, hence the power is supplied by the battery providing SOC is greater than 50% or else the grid is activated to supply the load and charge the battery. The DC link voltage reference ($V_{gdc_{ref}}$) during low SOC of the battery is kept a little higher than the actual DC link reference level. The

![Figure 5.3: DC link voltage control strategy](image-url)
purpose is to eliminate interaction between the battery and the backup source DCL voltage regulation strategy. The control strategies for different elements are shown in the following Table 5.1 and Figures 5.4 and 5.5, respectively.

Table 5.1: Control strategy for different elements in a DC microgrid

<table>
<thead>
<tr>
<th>Source</th>
<th>Converter/ Switch</th>
<th>Operating Mode</th>
<th>Operating Range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Buck</td>
<td>Current mode: Maximum or rated power</td>
<td>Cut in - cut off</td>
<td>3 m/s to 25 m/s</td>
</tr>
<tr>
<td>Battery</td>
<td>DC/DC (bidirectional)</td>
<td>High/low wind and low/high demand</td>
<td>Sink: SOC&lt;0.9 Source: SOC&gt;=0.5</td>
<td>Charge up to 90% and discharge until 50% for longer life</td>
</tr>
<tr>
<td>Dump Load</td>
<td>Control Switch</td>
<td>High wind and low demand</td>
<td>Sink: V_{dc}&gt;V_{rl} and SOC&gt;=0.9</td>
<td>Over-wheeling protection, DCL voltage control.</td>
</tr>
<tr>
<td>Backup Source</td>
<td>AC/DC</td>
<td>Low wind, low storage and high demand</td>
<td>Source: V_{dc}&lt;V_{rl} and SOC&lt;0.5</td>
<td>Minimal use of diesel generator, only for battery charging.</td>
</tr>
</tbody>
</table>

Figure 5.4: (a) Battery converter control strategy, and (b) AC source activation signal

The battery bidirectional converter is controlled using a DCL voltage and SOC information, as shown in Figure 5.4. The outer DCL voltage and inner battery current loop is used to regulate the DCL voltage at its reference level. However, the battery status is also incorporated though SOC to identify the charging and discharging stage. If SOC is greater than 50 %, then the battery is eligible for discharging the current or supplying the deficit power. Similarly, if SOC is less than 90 % then the battery is eligible for charging or consuming the excess power.

The isolator for the AC source is also controlled through a signal based on the DCL voltage and SOC. If SOC is less than 50 % and the DCL voltage is less than the reference
value then the AC source is connected to the microgrid through an isolator \((S_{123})\) for charging the battery and meeting the load demand along with wind.

![Diagram of dump load control and AC source based DC link voltage control](image)

**Figure 5.5**: (a) Dump load control, and (b) AC source based DC link voltage control

If the battery is fully charged then the excess power is deviated to dump load. The voltage error between the reference and measured value is compared with the signal generator or predefined signal value (3% more of reference value). If the voltage error is more than or equal to the signal generator then the dump load is energized, providing SOC is at the maximum limit (90%) as shown in Figure 5.5 (a).

The DC-AC converter or inverter is used to regulate the DCL voltage during extreme condition. The bi-directional inverter is operated as a rectifier, and regulated the DC link voltage. In this process, the AC source is used to charge the battery and meet the deficit load demand. The DCL voltage control through the AC source is shown in Figure 5.5 (b). In addition the inverter can also operate either in power (or current) or voltage control mode depending upon the availability of the grid. If the grid is available then the inverter is operated under power mode otherwise in a voltage mode. In this study, the control strategy for the inverter has not been considered as it is out of the scope for this particular study in this chapter. However, later chapters consider the inverter control strategies in detail.
5.6 Simulation Studies and Discussions

The DC link voltage control strategy for a DC microgrid is verified using numerical simulations. The DC link voltage is maintained at 36 V. Therefore, the current flow determines the flow of power in the system. The results are simplified into two scenarios: (i) variable wind speed, and (ii) variable load demand.

(i) Under varying wind speed (step change), the DC and AC loads are constant, wind is operated at MPPT, and the AC source is also activated at certain operating conditions to regulate the DCL voltage and charge the battery with slightly high reference DCL voltage (4% more than the nominal reference value).

(ii) In varying load demand, the AC load is varied at constant average wind speed. The inverter operates at voltage control mode to regulate the amplitude and frequency of AC link voltage and the AC source is not activated as the wind and battery are enough to meet the load demand within the considered operating period.

5.6.1 Variable Wind Speed

Under this scenario, the wind speed is varying, but the load demand is constant. The wind output power rises and falls in proportion to the variable wind speed. The fluctuating power output affects the power balance between the generation and the load. The power imbalances affect the DCL voltage either rises or falls beyond the operating limits. The battery compensates the power difference by injecting the deficit power or consuming the excess power. However, at certain operating conditions, the battery is discharged below its operating limits. In this case, the AC source is activated and charges the battery, as well as meet the load demand. The wind speed is varied as a step change within a small time period of 14 s, as shown in Figure 5.6(a).
The DCL voltage varies with wind speed in the absence of voltage regulation is referred as voltage without control (Vdc-w/oc), which is unacceptable in a microgrid. However, DCL voltage is regulated at the reference level (RL) by the proposed coordinated control strategy and is referred to as voltage with control (Vdc-wc), as shown in Figure 5.6(b). The zoom version of DCL voltage is shown in Figure 5.7 during transient periods.

**Figure 5.6:** (a) Wind speed and (b) DC link voltage with and without control

**Figure 5.7:** Zoom version of DC link voltage during transient (a) at 2s, (b) at 4s, (c) at 6s, and (d) at 10s
The DCL voltage changes (rise or fall) according to the system operating conditions, however, the proposed control strategy brings the DCL voltage back to the nominal steady state level within the fraction of a second, as shown in Figure 5.7. The transient performance for DC link voltage is shown in Figure 5.7(b)–(d) at different operating conditions.

At $t=(0-2)s$, $V_{dc-w/oc}$ is higher than the RL (shown in Figure 5.6 (b)): therefore, the dump load (DL) is consuming excess energy (DL-C) as the battery is fully charged, SOC=90% shown in Figure 5.8(c) and 5.9 (a). At $t=(2-4)s$, $V_{dc-w/oc}$ is lower than the RL; therefore, the required energy is supplied by the battery(B-S), as shown in Figure 5.8 (d) (positive current), hence SOC is falling down. At $t=(4-6)s$, $V_{dc-w/oc}$ is higher than the RL (shown in Figure 5.6 (b), the battery is consuming the excess energy (B-C) as SOC is lower than 90 % and hence starts charging. At $t= (6-8)s$, $V_{dc-w/oc}$ is lower than the RL, hence the battery is supplying the energy (B-S) as SOC is still higher than 50%. The battery is discharging now and SOC is reaching below 50% at $t = 8 s$ as shown in

**Figure 5.8:** Direct current (DC) under changing wind speed: (a) DC load, (b) wind, (c) dump load, (d) battery, and (e) AC source current
Figure 5.9 (a). At $t=(8-10)$ s, the AC source is energizing to regulate the DC link voltage and charge the battery (BS-C) as $V_{dc-w/oc}$ is lower than the RL (shown in Figure 5.6 (b)) and battery is at low SOC (shown in Figure 5.9 (a)).

The inverter current is reversed (or in rectifying mode), as indicated by the negative current shown in Figure 5.8 (e). The negative current means the current is flowing from the AC side through the converter (bidirectional inverter) to the DC system (DC load and battery), in addition to the wind output power. The AC source is now regulating the DCL voltage through the inverter with 4% higher reference level as shown in Figure 5.6 (b). The DC load current also rises 4%, as shown in Figure 5.8 (a) due to the rise in DCL voltage at constant resistive load. The transient effect on load current, due to the grid energization, can be seen in Figure 5.8 (a).

Therefore, the total power generation (AC source plus wind) matches the DC load demand and is also charging the battery (negative current flow to the battery), as shown in Figure 5.8 (a)-(e). The AC loads are solely met by the grid. The zero current is flowing to the dump load due to the deficit of power at DC side.

At $t=10$s, the battery is charged more than 50% through an AC source and wind as a result, the AC source is deactivated. In addition the wind speed is also a step up, which increases the power output of wind. Once the AC source brings the battery back to the operating limits, the source is disconnected. Therefore, $V_{dc-w/oc}$ is higher than the RL (shown in Figure 5.6 (b)), hence the battery is consuming the excess energy and charging to the maximum limit (90%). Once the wind speed is enough to provide the power, the wind is connected and the AC source is disconnected as seen from the switching status shown in Figure 5.10(b) –(d). At $t=(12 \text{ -} 14)$ s, the wind output power matches the load demand perfectly, hence the $V_{dc-w/oc}$ is close to the RL; therefore, both battery and dump load are inactive.
5.6.2 Variable Load Demand

The AC load is varied with constant wind speed; therefore, the current flowing from wind under MPPT strategy is constant, as shown in Figure 5.10 (b). However, the DCL voltage is kept constant using the proposed control strategy, as shown in Figure 5.10 (a).

The DCL current is increasing until 1.5 sec, as shown in Figure 5.10 (a), which indicates the load demand is increasing. Then, the load is suddenly decreasing for 0.3 sec before remaining in steady state value for 0.95 sec. The load demand is further increased until 3 sec. The uncontrolled DCL voltage is fluctuating during all these scenarios. However, the dump load and battery status are changing in order to maintain the DCL voltage to the
desired level (36 V). At t=(0-1) sec, the load demand is less than the wind power production; as a result, the excess energy is dumped as a thermal load, which is indicated by the current flowing into the dump load, as shown in Figure 5.10 (c).

![Figure 5.11: AC link output during variable load: (a) AC voltage (ACV), and (b) AC current (ACC)](image)

At t=(1-1.5) sec, the load demand is more than the wind power production, therefore the required energy is supplied by the battery as shown in Figure 5.10 (d) (positive current). From 1.5 to 3 sec, the load demand is less than the wind power production, hence the battery is floating with zero output current considering the maximum SOC and excess energy is dumping into the dump load. The DC loads are constant; however, the AC loads are fluctuating during this period. The bidirectional inverter is controlled in a voltage control mode (off-grid) to regulate the amplitude and frequency of AC link voltage (ACV), as shown in Figure 5.11 (a). However, the AC current (ACC) is fluctuating with the AC loads, as shown in Figure 5.11 (b). The DCL current in Figure 5.10 (a) and AC load current in Figure 5.11 (b) have the same pattern, which indicates the AC loads are varying.
5.7 Conclusions

The coordinated control strategy for a wind source along with the battery with its own dedicated DC-DC converter, dump loads with a crowbar circuit, and a backup AC source (can be a diesel generator set) is proposed. The control strategy is designed for a wind source to balance the power flow to the load irrespective of fluctuating weather conditions and load demands. It has been shown that the proposed coordinated control strategy can provide several attractive features for a wind/battery system along with dump loads and a diesel generator. First, the wind is operated at maximum power in all operating conditions without any control transition. Second, the wind/battery hybrid system operation in the microgrid is unaffected by the fully charged or over discharged battery, due to the presence of dump loads and a diesel generator. Third, the presence and activation of a diesel generator only during low SOC of the battery provides the following advantages, in addition to charging the battery and meeting the deficit power: (i) Maximum use of local power (wind/battery) reduces the electricity bill from the grid; and (ii) Reduces the frequent operation of a diesel generator, which cuts down the operating cost of the microgrid.
Chapter 6

6 Control Strategy for an Islanded Wind/Battery Hybrid System: without a Battery Converter

6.1 Introduction

In this chapter, an alternative power management control strategy for a wind/battery hybrid system consisting of PMSG based VSWT and battery energy storage is proposed. The proposed strategy offers simple structure with same control objectives in comparison to the strategy introduced in Chapter 5. More specifically, it eliminates the need of a dedicated battery converter and inefficient dump loads. However, it maintains the same level of performance: balanced power flow and stable DC link voltage irrespective of fluctuating weather conditions and load demands. In Chapter 5, the battery is controlled independently through its own dedicated DC-DC converter. In addition, the dump load is used to consume excess power during fully charged battery condition.

However, the proposed strategy in this chapter allows the battery storage to integrate into the system without a dedicated converter and a dump load. In addition, the overcharging condition of the battery is protected through the proposed power curtailment strategy of a wind source. Therefore, the power management strategy controls both the wind source and a battery against overcharging through the same DC-DC converter, hence it is referred to as an integrated control.

In Chapter 5, the hybrid wind/battery system is controlled in the presence of a back up source. The same support can be provided to the wind/battery hybrid system in this chapter by the backup source along with the proposed control strategy without a modification. However, the wind/hybrid system in this chapter is operated in an islanded condition (off-grid mode). Thus, the inverter (or DC-AC converter) is operated in a voltage control mode to maintain the amplitude and frequency of AC link voltage.
The power management strategies at DC and AC link of the hybrid system in a microgrid application consists of: (i) integrated control at DC link; and (ii) dual vector voltage control (DVVC) at AC link. The integrated control at DC link regulates the DC link voltage (DLV) and maintains the balanced power flow. The DVVC strategy regulates the decoupled positive and negative sequence voltages at their reference level, which is implemented in the $d – q$ reference frame for unbalanced loads. The unbalanced voltage which occurs due to the unbalanced loads is separated into positive and negative sequence components using symmetrical components theory. The system performance is validated using experimental results from a prototype microgrid configuration.

The problem statement is discussed in Section 6.2. The structure of the hybrid system is presented in Section 6.3. The issues and function of a wind system are described in Section 6.4. The control objectives and strategy are presented in Section 6.5. The DC and AC link voltage control strategies are presented in Sections 6.6 and 6.7 followed by the experimental results and conclusions in Sections 6.8 and 6.9, respectively.

### 6.2 Problem Statement

In Chapter 5, the conventional structure maintains the stability and the reliability of the hybrid system by regulating the DC link voltage within the operating limits and balancing the power flow in the system irrespective of fluctuating weather and load conditions. In addition, it gives the flexibility of control, but at high structural cost. The hybrid system which is controlled with lesser power electronic components or devices not only reduces the cost but also reduces the failure rate and maintenance period. The possible structure elements that can be removed without affecting the system performance, as shown in Chapter 5, are the battery converter and a dump load. However, the challenges exist in control which requires an intelligent power management scheme to maintain the same level of power stability, and reliability of the system.

In the literature, the structure that considered the directly interfaced battery storage to the DC link operated the wind source as a voltage source. The issue in such a configuration is the protection of a battery charging against the high current. The wind system which is operated as a voltage source charges the battery at continuous high current. As a result,
the life cycle of the battery is deteriorated or in a worst condition (high inrush current), the battery may be damaged. In the proposed control strategy, the wind source is operated as a current source. Therefore, the battery is charging through a regulated current value. Furthermore, the battery is charging smoothly without a high inrush current.

Therefore, the proposed control strategy in the hybrid system features a power management strategy that does not require a converter for the battery, eliminates the need of a dump load and provides simple integration to the distribution network if required, compared with a set of two standalone systems. Thus, the integration of a PMSG based VSWT in a standalone hybrid system is expected to be cost effective and efficient.

6.3 Structure of the Hybrid System

A schematic diagram of the studied hybrid system consisting of PMSG based VSWT, battery storage and an AC interface system is shown in Figure 6.1.

![Figure 6.1: Schematic diagram of the hybrid-wind and battery system](image)

where $\omega_m$, $\theta$, $V_{dc}$, $i_{mp}$, $C_{in}$, $i_w$, SOC, $i_{bat}$, $s_b$, $i_{dc}$, $i_{pabc}$, $V_{pabc}$ and $s_{1–6}$ are turbine angular speed, wind velocity, DC link voltage, reference wind current at maximum power point, input capacitor across the DC-DC converter, output wind current, state of charge of battery, battery current, DC-DC converter switch gate signal, DC link output current, AC current at primary side of transformer, AC voltage at primary side of transformer and
inverter switch gate signal respectively. The wind and AC interface systems share their DC link with a battery bank which serves as the energy storage and maintains the DLV.

The wind turbine together with the PMSG and DC link interfacing unit are defined as the wind system. The battery bank is directly connected to the DC link so that the battery terminal voltage establishes the DC link voltage (DLV). The integrated control in Figure 6.1 collects information from the battery bank and the DC link to maintain the DLV within the operating range and manages the battery operation. The MPPT scheme provides the reference current ($i_{mpp}$) during nominal operation of the hybrid system.

The AC interface system consists of a pulse width modulation (PWM) based inverter, LC filter and transformer to step up the voltage to the required level of AC link. The DVVC strategy is implemented to regulate the AC link voltage and frequency at their prescribed level in the presence of unbalanced loads. The AC interface system can be considered as a load for a DC unit of the hybrid system. Therefore, the output current from the DC link is referred to as the DC load current, which serves both the DC loads and AC loads through the AC interface system. The DC and AC interface system can be assembled through different topologies which can be designed for different purposes. However, the proposed hybrid structure is considered from a cost effective point of view, footprint and straightforward implementation of the control strategy. These features are attractive for applications such as remote communities, military camps and islands.

6.4 Issues and Functions of the Hybrid System

The hybrid system can be used in different structure with the objectives as shown in Figure 6.2.
Figure 6.2: Hybrid system in a microgrid

The operating mode of the hybrid system in Figure 6.2 is shown in Table 6.1.

Table 6.1: Operating mode of the hybrid system (0: open, 1: close)

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>Hybrid System (Operating mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Operated as a standalone-off-grid</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Operated as a standalone-on grid</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Operated in a microgrid-off-grid</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Operated in a microgrid-on grid</td>
</tr>
</tbody>
</table>

The islanded operation of wind source as a standalone or in a microgrid brings following issues:

(1) The wind source cannot operate in a standalone mode due to its stochastic nature, which results in the following issues:
   (i) Imbalanced power flow
   (ii) DLV operates out of operating range
   (iii) Degrades the amplitude and frequency of AC link voltage if the inverter operation is bounded within the linear range of PWM [165].

(2) The hybrid system should justify the complexity of the structure and control algorithm with its associated cost in a microgrid system as shown in Figure 6.2.

(3) The power management for the battery without the dedicated converter requires a protection against the overcharging.

(4) The over spilling of energy without a dump load requires a proper control.

(5) The unbalanced load in a three phase system affects the overall performance of the system and could damage the wind source in an islanded standalone operation.
Therefore, an integrated control strategy for power management at the DC side and DVVC strategy at the AC side are proposed to tackle the above mentioned issues. Accordingly, the combined proposed strategy performs the following functions:

1. The battery storage regulates the DLV within the operating range by compensating the power differences between the wind source and loads. The surplus power is absorbed whereas the deficit power is delivered; hence, the power flow is balanced between the sources and load.

2. The control strategy is designed to curtail the wind power (out of MPPT scheme), if the available wind power is more than the load demand and the battery is fully charged. Basically, the battery is protected against the overcharging.

3. The control strategy is operated with reduced number of power electronic devices (no dedicated battery converter) as an integrated control structure.

4. The amplitude and frequency of AC link voltage are regulated using DVVC strategy to tackle the effects of unbalanced conditions (loads).

6.5 Control Objectives and Strategy

This section defines the control objectives and strategy for energy sources: the wind system and the battery in the hybrid system.

6.5.1 Wind System

The control objectives for the wind system are (i) to operate the wind source in a MPPT scheme as long as the system permits; and (ii) to activate the pitch angle control for the protection of the wind turbine during over speeding conditions. A buck converter is used as a DC-DC converter in between the source and DC link, which operates the wind source under MPPT scheme.

6.5.1.1 Maximum Power Point Tracking (MPPT) Scheme

The power signal feedback control strategy is implemented for the wind turbine as shown in Figure 6.3, where $P_{opt}$, $P_l$, $P_{mpp}$ and $P_e$ are the optimal (maximum) power at the wind turbine, power losses from turbine to the DC-DC converter, extracted
maximum wind power at the converter and electrical output power at the converter respectively [166].

![MPPT scheme for a wind system](image)

**Figure 6.3:** MPPT scheme for a wind system

### 6.5.1.2 Pitch Angle Control Scheme

The pitch angle of the turbine blades are controlled to protect the wind turbine from excessive rotational speed and to limit the maximum power at high wind speeds [167]. The pitch angle control scheme is shown in Fig. 4, where $\omega_{mref}$, $\beta_{ref}$ and $\beta$ are the turbine angular speed reference, pitch angle reference and measured pitch angle respectively.

![Pitch angle control scheme](image)

**Figure 6.4:** Pitch angle control scheme

The control scheme maintains the turbine angular speed at a defined maximum permissible value ($\omega_{mref}$) by rotating each blade about its axis in the direction out of the wind so that the energy captured at the particular wind speed is reduced and hence the turbine rotor angular speed ($\omega_m$) is also reduced in proportion to the energy captured. The outer loop determines the amount of energy captured by the wind turbine through the reference turbine rotor angular speed, which is normally kept to the maximum permissible value. The PI controller which is used to compensate the turbine rotor angular speed error determines the pitch angle. This pitch angle, which is the reference value in the inner loop, determines the position of the turbine blade to maintain the turbine rotor angular speed.
6.5.1.3 DC-DC Converter

A buck converter regulates the output current of the wind turbine considering the operating conditions of the hybrid system. The average current mode control is employed which provides more robust control and higher noise immunity comparing to peak current mode control [168]. The PWM technique is used to generate the gate signal which controls the duty cycle of the converter.

![Figure 6.5: Block diagram of DC link voltage control](image)

The reference current ($i_{mpp}/i_{wref}$) in Figure 6.5 is determined from either the MPPT scheme or the battery current regulation scheme, which is explained in Section 6.5. The PI controller is used to compensate the error between the reference current and the measured wind converter output current ($i_w$) to generate the gate signal ($s_b$).

6.5.2 Battery System

The battery is connected directly to the DC link without a dedicated DC-DC converter. This structure possesses two challenges: (i) operated either at a low voltage or a high number of batteries in the series; and (ii) no control of battery current against overcharging and discharging. These challenges are solved by using the proposed structure and control: (i) a buck converter is used as a DC-DC converter to step down the DLV and a transformer to step up the AC link voltage. As a result, the system operates with less number of batteries in series without compromising the AC link voltage level; and (ii) an integrated control for power management in the hybrid system is proposed that considers the state of charge (SOC) and power flow to/from the battery. As a result, the charging and discharging current of the battery is maintained within the safe levels at all time. In addition, the system structure is less complex with a reduced number of power electronic devices and control; thus, reduced the overall cost.
6.6 Integrated Control Strategy (DC link)

The power management scheme is focused on controlling the power flow at the DC side irrespective of fluctuating wind speed and varying load demands. The power management scheme is implemented using an integrated control strategy for the wind source and battery energy storage. In this case, the AC interface system is considered as a load to the DC system. The integrated control strategy considers the operating conditions of the hybrid system, battery status, and wind profile. The prime objective of this control strategy is to maintain the DLV within the operating range, regardless of fluctuating wind speed, load demand and battery status. The control strategy is implemented, as shown in Figure 6.6.

![Figure 6.6: Power management scheme using integrated control strategy](image)

6.6.1 Operating Strategy at DC link

The integrated control for hybrid system performs two major tasks: (i) Operates the wind source at MPPT scheme; and (ii) Operates the wind source at battery current regulation.

6.6.1.1 Operates the Wind Source at MPPT Scheme

The hybrid system operates under MPPT scheme at three conditions: (i) DC link voltage \( (V_{dc}) = \text{nominal DC link voltage (} V_{nom} \text{)} \), the wind source meets all of the available load
demand with/without power flow to/from the battery; (ii) $V_{dc} = V_{min}$ (minimum DC voltage), the wind source along with the battery (discharging) meets all of the available load demand while the SOC of the battery is still within the operating range; and (iii) $V_{dc} = V_{max}$ (maximum DC voltage): the wind source meets all the available load demand and also charges the battery while the SOC is below the maximum level.

6.6.1.2 Operates the Wind Source at Battery Current Regulation Scheme

This strategy maintains the DLV within the operating range ($V_{min} \leq V_{dc} \leq V_{max}$) by regulating the battery current to zero. The surplus wind power generation is absorbed by the battery; as a result, the terminal or DLV reaches the maximum limit ($V_{max}$). The battery current regulation scheme regulates the battery current to the reference value which is zero in this case. The compensator output provides the reference current for the wind source, which shifts the operating point to the right of the power curve. The integrated control; thus, reduces the wind output power to match the load demands without charging the battery. At high wind speeds and light load conditions, there is a risk of exceeding the speed limit of the wind turbine which may damage the turbine. The pitch angle control, which is shown in Figure 6.4, is used to regulate the turbine angular speed to the maximum permissible level. In this way, the integrated control meets the load demand irrespective of weather conditions and load demands and to protect the battery against an overcharging.

6.6.2 Control Strategy Selection Signal

The control strategy selection signal is used to activate either the MPPT scheme or the battery current regulation scheme based on the DLV and SOC of the battery. The reference voltage ($V_{ref}$) is the nominal voltage of the battery which is compared to the DLV of the hybrid system ($V_{dc}$), as shown in Figure 6.6. The ratio of the voltage difference to the reference voltage is determined, and then the absolute value is calculated. This absolute value is the input to the relay which consists of a hysteresis block. The hysteresis block is operated based on (6.1).

\[
\begin{cases}
\geq 5\%: \text{ON (1)} \\
< 5\%: \text{OFF (0)}
\end{cases}
\]  

(6.1)
If the ratio is greater than or equal to 5% of the nominal voltage then the switch selection block activates the battery current regulation scheme. Otherwise, the MPPT scheme is activated. The SOC of the battery is also considered by the control selection signal block. If the SOC is greater than the prescribed maximum value (SOC$_{max}$ = 95%), then the output signal is set to 1 otherwise it is set to 0. The DLV signal is sufficient for the control selection, but the SOC provides the additional information about the status of the battery. The battery terminal voltage and the SOC depend on the changes in the operating temperature and internal resistance, due to charging and discharging.

The DLV is also affected by the measurement error, due to non perfect calibration and noises. Therefore, the DLV needs additional information to check the accurate status of the battery. Thus, the control signal considers information from DC link voltage for power flow strategy and SOC for the battery status. The protection of the battery against overcharging is one of the prime objectives of the hybrid system. Therefore, SOC information plays a backup role for the protection. In ideal conditions, both signals provide the same information about the battery status; however, for any non-ideal reason, if they are different at critical point, the battery is still protected considering the signal close to the maximum limit. The relationship between the SOC and DLV signals are created, as shown in Table 6.2.

<table>
<thead>
<tr>
<th>Case</th>
<th>SOC</th>
<th>DLV</th>
<th>Signal output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

If the output signal of SOC block is 0, it means the battery is still within the operating range and the power management scheme is selected based on the DLV. If both control signals provide the same output as in cases 1 and 4 in Table 6.2, then the agreement has been reached. If not, then either case 2 or 3 has occurred. Both cases provide protection for the battery. If case 2 occurs, then the battery current regulation scheme is activated, even though the SOC is within the maximum limit. When the case 3 condition occurs, again the battery current regulation scheme is activated even though the DLV does not
reveal it. The SOC information is considered more reliable than the DC link voltage for the battery status.

6.7 Dual Vector Voltage Control Strategy (AC link)

An unbalanced load causes the flow of current in each phase to be of a different magnitude as a result the voltage drop across the LC filter and the impedance of each phase is not equal. The unbalanced voltage drop in each phase causes an unbalanced voltage at the AC link. The unbalanced voltage can be represented by splitting the voltage waveform into its positive and negative sequence components. The negative sequence voltage increases with the percentage of unbalanced loads in the system. Ideally, the negative sequence voltage should be zero. Therefore, the DVVC strategy is implemented as two separate PI controllers for controlling the positive sequence and negative sequence voltages and currents in positive and negative d – q reference frames. The control signals from each frame are combined, which provides compensation to balance the voltage irrespective of unbalanced loads. The DVVC strategy is implemented, as shown in Figure 6.7.

![Dual vector voltage control strategy for unbalanced AC link voltage](image)
6.7.1 Sequence Decomposition

An unbalanced three phase voltage and current can be decomposed into two sets of components based on the instantaneous symmetrical components theory [169]. The positive and negative sequence components can be implemented using a band pass filter as described in [170].

6.7.2 Sequence Transformation

The AC voltage and current signals are measured and decomposed into symmetrical components to identify the positive and negative sequence components. The voltage and current measurements are projected onto the \(d-q\) synchronous reference frame (SRF) at the fundamental frequency. The positive reference frame rotates in a counter clockwise, therefore the voltage and current are rotated in a positive SRF using positive fundamental frequency. The negative reference frame rotates in a clockwise direction, therefore the voltage and current are rotated in a negative SRF using negative fundamental frequency as shown in Figure 6.7. A phase locked loop (PLL) is used to extract the fundamental frequency (\(\omega\)) and phase angle (\(\delta\)) from the reference sinusoidal voltage signal (\(V_{qp}\)).

6.7.3 Voltage Loop

The dynamics of the AC link voltage is defined in (6.2) as a space phasor expressed at the primary side of the transformer

\[
C_f \frac{d\hat{V}}{dx} = \hat{i} - \hat{i}_o
\]  

(6.2)

where \(\hat{V}, \hat{i}\) and \(\hat{i}_o\) are the AC link voltage at the primary side of the transformer, current before the filter capacitance, and current after the filter capacitance in space phasor form. Using Park’s transformation technique, the space phasor is transformed into the \(d-q\) SRF as shown in (6.3).
\[
\begin{align*}
C_f \frac{dV_{dx}}{dt} &= (C_f \omega)V_{qx} + i_{dx} - i_{odx} \\
C_f \frac{dV_{qx}}{dt} &= -(C_f \omega)V_{dx} + i_{qx} - i_{oqx}
\end{align*}
\]

(6.3)

where subscript ‘x’ defines the positive ‘p’ and negative ‘n’ sequence components. Therefore, (6.3) can be expressed for both positive and negative sequence components. A feed-forward scheme in the voltage loop is employed to eliminate the coupling between the \( d - q \) axis voltages as shown in Figure 6.7. The currents are also measured and feed-forwarded to mitigate the impact of the load dynamics on the AC link voltage. Therefore, (6.3) can be expressed as in (6.4),

\[
\begin{align*}
i_{dx} &= C_f \frac{dV_{dx}}{dt} - (C_f \omega)V_{qx} + i_{odx} \\
i_{qx} &= C_f \frac{dV_{qx}}{dt} + (C_f \omega)V_{dx} + i_{oqx}
\end{align*}
\]

(6.4)

where \( C_f \frac{dV_{zx}}{dt} \) is the result of controller output, \( (C_f \omega)V_{zx} + i_{ozx} \) is the feedforward term and \( z = d, q \). The right hand terms in (6.4) provides the reference current \( (i_{zx}^*) \) for the inner current loop, thus (6.4) can be written as

\[
\begin{align*}
i_{dx}^* &= u_{dx} - (C_f \omega)V_{qx} + i_{odx} \\
i_{qx}^* &= u_{qx} + (C_f \omega)V_{dx} + i_{oqx}
\end{align*}
\]

(6.5)

(6.6)

where \( u_{dx} \) and \( u_{qx} \) are the PI controller outputs of the voltage error. Therefore, the reference current for the inner current loop is determined by the PI controller and feed-forward terms in the outer voltage loop.

### 6.7.4 Current Loop

The inverter AC side terminal voltage \( (V_{d,q,x}) \) in the \( d - q \) frame is defined in (6.7).

\[
\begin{align*}
V_{dx} &= -L \left( \frac{di_{dx}}{dt} \right) - Ri_{dx} + \omega L i_{qp} + V_{ldx} \\
V_{qx} &= -L \left( \frac{di_{qx}}{dt} \right) - Ri_{qx} - \omega L i_{dx} + V_{lqx}
\end{align*}
\]

(6.7)

The inverter terminal voltage \( (V_{ld,q,x}) \) is controlled in the \( d - q \) frame by the pulse width modulating signals of the inverter, as defined in (6.8)

\[
\begin{align*}
V_{ldx} &= \frac{V_{dc}}{2} m_{dx} \\
V_{ldx} &= \frac{V_{dc}}{2} m_{qx}
\end{align*}
\]

(6.8)
Substituting (6.8) in (6.7) allows the current controller to be expressed as (6.9).

\[
\begin{align*}
L \left( \frac{d i_{dx}}{dt} \right) + R i_{dx} &= \omega L i_{qx} + \frac{V_{dc}}{2} m_{dx} - V_{dx} \\
L \left( \frac{d i_{qx}}{dt} \right) + R i_{qx} &= -\omega L i_{dx} + \frac{V_{dc}}{2} m_{dx} - V_{qx}
\end{align*}
\]  
(6.9)

The terms at the right hand side of (6.9) are the feed-forward terms, which are implemented in vector current control to decouple the dynamics of \( d-q \) axes currents, mitigate the dynamic effect of DC voltage variations, and react rapidly to mitigate any changes in AC link voltage. Therefore, (6.9) can be reduced to a first order system using the feed-forward scheme as shown in (6.10).

\[
\begin{align*}
L \left( \frac{d i_{dx}}{dt} \right) + R i_{dx} &= y_{dx} \\
L \left( \frac{d i_{qx}}{dt} \right) + R i_{qx} &= y_{qx}
\end{align*}
\]  
(6.10)

The outputs of the \( PI \) controllers \((y_{dx} \text{ and } y_{qx})\) are used in the current loop allowing the modulating signals \((m_{dx} \text{ and } m_{qx})\) to be determined by substituting (6.10) in (6.9).

\[
\begin{align*}
m_{dx} &= \frac{2}{V_{dc}} (y_{dx} - \omega L i_{qx} + V_{dx}) \\
m_{qx} &= \frac{2}{V_{dc}} (y_{qx} + \omega L i_{dx} + V_{qx})
\end{align*}
\]  
(6.11)

Hence, the vector outer voltage loop and inner current loop can be separately implemented with regards to positive and negative SRF using (6.5), (6.6) and (6.11), as shown in Figure 6.7.

### 6.7.5 Sequence Composition

The modulating signal \((m_{dq})\) of positive and negative sequence components are composed in the \( d-q \) frame as shown in (6.12).

\[
\begin{align*}
m_d &= m_{dp} + m_{dn} \\
m_q &= m_{qp} + m_{qn}
\end{align*}
\]  
(6.12)

The modulating signal is transformed into the ‘abc’ form so that the pulse width modulating (PWM) technique can be employed to regulate the amplitude and frequency of the AC link voltage at their respective reference levels irrespective of balanced or unbalanced loads.
6.7.6 Proportional-Integral (PI) Controller

The positive sequence $d$- $q$ voltages and currents appear as DC quantities in the positive sequence reference frame. Similarly, the negative sequence $d$- $q$ voltages and currents appear as DC quantities in the negative sequence reference frame. Therefore, the PI controller is implemented to regulate the voltage and current as per their reference values in the respective rotating reference frame. The integral part of PI controller takes care of zero steady state error; however, the frequency response analysis technique [171] is used to enhance the stability of the closed loop system. In this application, ideally a high bandwidth is required to have fast dynamics and attenuation of harmonic distortion. However, the bandwidth must be considerably smaller than the switching frequency of 10 kHz [172]. Therefore, the PI controllers are designed with the bandwidth 1/8 times of the switching frequency with a phase margin $53^\circ$ for inner current loop and $66.7^\circ$ for outer voltage loop.

6.8 Experimental Validation

An experimental investigation is performed to validate the effectiveness of the proposed control strategy for a hybrid system consisting of a wind source, battery energy storage and loads. The experimental setup is shown in Figure 6.8. An induction motor drives the PMSG generator with control to emulate the wind turbine as a wind turbine simulator (WTS). This WTS emulates the static and dynamic behavior of a real wind turbine installed at the campus. A lead acid battery is used as the energy storage device. A DC-DC converter and an inverter are also designed and fabricated to support this experiment. The Texas Instrument (TI) controller and National Instrument (NI) LabVIEW controller are used to control the DC-DC converter and the WTS, respectively. The data is collected through the dSPACE control desk using a step size of 58 µsec and down-sampled by a factor of 5. The system parameters are given in Appendix A.
The following facts need to be considered for the experimental results.

1. The experiment is performed over a short duration; therefore, the state of charge (SOC) of the battery does not change drastically;
2. The DLV is the same for all sources and load connected to the DC link; therefore, the flow of current determines the power output and is used as an equivalent term for analysis; and
3. Some of the experimental results were observed to contain measurement and machine noises, particularly when the wind source was activated.

6.8.1 Case Study I: System Start-Up Procedure

Under this study, the experiment is performed to start-up the hybrid system. The battery storage is used as a black-start source followed by the activation of the wind source. The experimental results are shown in Figure 6.9.
The battery energy storage starts the system at $t = 6\) s by discharging the current to meet all the load demand, as shown in Figure 6.9 (c). As a result, the DLV and SOC are dropping, as shown in Figures 6.9 (a) and 6.9 (f), respectively. The wind source is then activated at $t=34s$ with a constant average wind speed of 6 m/s. The wind source is operated under MPPT scheme; thus, it delivers the constant average output current with maximum power coefficient as shown in Figures 6.9 (d) and 6.9 (e) respectively. The starting transient effect of the wind source can be seen with an overshoot for a quick period. However, the wind source reduces the power delivered from the battery, as shown in Figure 6.9 (c). In fact the battery starts charging as the wind power is more than the load demand. The load keeps increasing, as shown in Figure 6.9 (b), which diverts the flow of wind power from the battery and, ultimately, the battery reaches the floating condition with zero power flow. As a result, the DLV which tends to rise beyond nominal value is settled down, as shown in Figure 6.9 (a). In addition, the SOC is also rising before the battery power is regulated to zero as shown in Figure 6.9 (f). In this way, the battery and wind sources are activated in the hybrid system with the proposed control strategy.

### 6.8.2 Case Study II: Charging Mode

In this case study, the load demand is less than the wind generation which is operated under the MPPT scheme. The battery energy storage consumes any generated power that
is in excess of the load. The experiment is performed with a constant wind speed and varying load demand as shown in Figure 6.10.

Figure 6.10: Battery charging mode of operation in hybrid system (a) DC link voltage (b) Load current (c) Battery current (d) Wind current (e) Power coefficient and tip speed ratio and (f) Battery’s state of charge

The normalized tip speed ratio and power coefficient are maintained at optimal/maximum values as shown in Figure 6.10 (e), which indicates the wind source is under the MPPT scheme. Therefore, the wind source delivers the constant output current as shown in Figure 6.10 (d). Until t=9s, the wind source output matches the load demand, which keeps the battery in a floating condition with zero power flow and steady state SOC, as shown in Figures 6.10 (c) and 6.10 (f), respectively. In addition, the DLV is maintained at nominal value as shown in Figure 6.10 (a). The load suddenly starts to decrease at t= 9s, as a result, the wind power is more than the load demand as shown in Figure 6.10 (b). The battery consumes the excess energy to balance the power flow as the DLV and SOC are within the maximum limit (1.05 p.u. and 95%), as shown in Figures 6.10 (c) and 6.10 (f) respectively. In addition, the DLV starts to rise towards the maximum limit, as shown in Fig. 10 (a). Furthermore, the load demand reaches minimum at t=20 s before it rises
and settles down to the initial value at $t = 36$ s, as shown in Figure 6.10 (b). The battery is slowly decreasing its energy consumption because the load is demanding more power from the wind source. Thus, the battery reaches the floating condition with zero output power, as shown in Figure 6.10 (c). In addition, the DLV falls down to the nominal value before it crosses the maximum limit, as shown in Figure 6.10 (a). Finally, the SOC has the increment of 1.5%, as shown in Figure 6.10 (f).

### 6.8.3 Case Study III: Discharging Mode

The discharging mode of the battery occurs when the load demand is more than the wind generation which is operated under the MPPT scheme. Therefore the battery energy storage delivers the deficit power to the load in order to balance the power flow and maintain the stability of the system. The experiment is performed with a constant load demand as shown in Figure 6.11 (b) and step changing wind speed as shown in Figure 6.11 (d).
The wind source matches the load demand until t =12 s under the MPPT scheme as shown in Figures 6.11 (e) and 6.11 (f). In addition, the battery is in the floating condition with zero current flow as shown in Figure 6.11(c). Suddenly, wind speed starts decreasing at t=12s until t=22.5s, as shown in Figure 6.11 (d). The stepping down of the wind speed decreases the wind generation, as shown in Figure 6.11 (e), which creates insufficient power to the load. As a result, the battery discharges the current to meet the deficit power at the load demand as shown in Figure 6.11 (c). Thus, the SOC is also dropping down as shown in Figure 6.11 (g). In addition, the DLV which was at nominal level, reaches close to the minimum operating limit (0.95 p.u.). However, the wind output generation begins to rise at t= 22.5s due to the stepping up of the wind speed, as shown in Figures 6.11(d) and 6.11(e), respectively. Therefore, the battery reduces its discharging current in proportion to the rise in power output of the wind source, as shown in Figure 6.11(c). In addition, the DLV rises to the nominal level, as shown in Figure 6.11 (a). Finally the battery reaches the floating condition with zero output power and steady state SOC, as shown in Figures 6.11 (c) and 6.11 (g), respectively.

6.8.4 Case Study IV: Power Curtailment

This case study examines the power curtailment strategy when the wind generation is more than the load demand in the presence of a fully charged battery. The generated power may exceed the load demand for a period of time, and will need to be curtailed because the hybrid system does not have a dump load. The proposed control system is required to balance the power flow and maintain the DC link voltage at its respective operating level. The experimental results are shown in Figure 6.12.
Figure 6.12: Power curtailment in hybrid system (a) DC link voltage (b) Load current (c) Battery current (d) Wind current (e) Power coefficient (f) Wind turbine rotor speed (g) Pitch angle and (h) Battery’s state of charge

The hybrid system follows the same operating principle as explained in above cases until t=12s. The load demand starts decreasing at t=12 s, as shown in Figure 6.12 (b). As a result, the wind power is more than the load demand as indicated by the battery which consumes the excess power as shown in Figure 6.12 (c). In addition, the DLV starts rising towards the maximum limit at t=18 s. During this operating period, the battery SOC reaches to the maximum defined limit (95 %), as shown in Figure 6.12 (h) due to the continuous consumption of excess power, as shown in Figure 6.12 (c). The control strategy of the hybrid system operates the wind source to curtail its power to match the load demand without charging the battery, as shown in Figure 6.12 (d). Therefore, the
wind source is out of the MPPT scheme, as seen in Figure 6.12 (e) where the power coefficient reduces from the maximum value.

On the other side, the battery also reduces energy consumption and reaches to the floating condition, as shown in Figure 6.12 (c). Thus, the SOC is maintained within the maximum limit without overcharging the battery, as shown in Figure 6.12 (h). Furthermore, the DLV is regulated at the maximum limit before it comes down to the nominal value as shown in Figure 6.12 (a). However, the wind turbine rotor speed is increasing due to the low power at the same wind speed (out of MPPT scheme) as shown in Figure 6.12 (f). The rotor speed reaches to the maximum permissible speed (1.2 p.u.) of the wind turbine at \( t = 20 \) s. Therefore, the pitch angle control is activated to regulate the speed at the maximum permissible value, as shown in Figure 6.12 (g). An overshoot occurs due to the inertial momentum of the wind turbine during the transient.

The load is slowly increasing towards the full demand at \( t = 40s \). Therefore, the wind source again enters into the MPPT scheme to match the load demand, as shown in Figure 6.12 (d). Consequently the power coefficient jumps to the maximum value, as shown in Figure 6.12 (e). In addition, the rotor speed comes down to its nominal value, hence the pitch angle control is also deactivated in order to generate more power by facing the blade towards the wind direction, as shown in Figures 6.12 (f) and 6.12 (g) respectively.

### 6.8.5 Case Study V: Unbalanced Voltage

The control scheme is examined under the conditions of an unbalanced load in the three phase system. The amplitude and frequency of the AC link voltage are affected by the unbalanced load as shown in Figures 6.13 (a) and 6.13 (c) respectively.
Figure 6.13: AC link of hybrid system under unbalanced load (a) AC link voltage (b) AC link current (c) AC link frequency

The AC loads in each phase are different, as shown in the current flow in Figure 6.13 (b). The voltage drop at each phase becomes different which results in an unbalanced voltage in each phase. The unbalanced voltage is not acceptable for any loads or in the distribution network which can cause overheating, losses and power quality issues. The PLL regulates the system frequency at its reference level. However, the unbalanced load also affects the PLL. The frequency oscillates with amplitude of 4% more than the reference level as shown in Figure 6.13 (c). The proposed DVVC technique is implemented to overcome the effect of the unbalanced loads as shown in Figure 6.14.

Figure 6.14: AC link of hybrid system under unbalanced load with proposed technique: (a) AC link voltage (b) AC link current (c) AC link frequency

The AC link voltage becomes symmetrical with the same amplitude in each phase, as shown in Figure 6.14 (a). The PLL regulates the frequency to the reference level without any oscillation, as shown in Figure 6.14 (c). However, the amplitude of AC current remains asymmetrical, due to unbalanced loads in each phase, as shown in Figure 6.14.
(b). The hybrid system operates at the reference amplitude and frequency of the AC link in the presence of unbalanced loads (thanks to DVVC strategy).

6.9 Conclusions

In this chapter, the integrated control and DVVC strategies at the DC and AC link of the hybrid system consisting of a PMSG based direct drive wind turbine and battery energy storage are proposed. In contrast to the common way of controlling wind source as a voltage source in the literature, it is shown that controlling the wind source as a current source in a hybrid system that follows an integrated control strategy, can charge the battery with a regulated current value instead of a high continuous current. As a result, the battery life cycle has been improved and protected against high inrush current during fast transition of system operation, such as load variations. Furthermore, system performance is maintained without the need of a dedicated battery converter and a dump load as required in Chapter 5. On the other side, the DVVC strategy regulates the amplitude and frequency of the AC link voltage without deteriorating the performance in the presence of unbalanced loads. The obtained experimental results show the operation of the hybrid system in a satisfactorily manner under steady state as well as transient conditions by achieving the following results: (i) regulating of DLV within the operating range irrespective of fluctuating weather conditions and load demands; (ii) operating the wind source under MPPT scheme; (iii) protecting the battery from overcharging; and (iv) regulating the AC link voltage and frequency at references irrespective of unbalanced load conditions. Thus, the control strategy provides a stable operation with a cost effective and efficient configuration.
Chapter 7

7 Control Strategy for an Islanded Wind/PV/Battery- DC Microgrid: without a Battery Converter

7.1 Introduction

The DC microgrid is gaining popularity due to its features, such as low cost, easy control with no reactive power concern, higher energy conversion efficiency with fewer components, modular and scalable, and various applications recently [23],[24]. Some of the application areas are rural electrifications, electric ships and aircraft, military zones, telecommunications, data centers, and industrial or commercial power systems. The renewable energy has further increased in popularity, due to its free energy without the need of transporting.

However, the renewable energy cost is high compared to other conventional DG, such as a diesel generator. The overall cost can be reduced by using the optimum control strategy with possibly less equipment in the system. The study is performed in renewable based islanded DC microgrid because it provides the challenges of unpredictable input power and the stability and reliability issues in the absence of a grid support [173].

Thus, this chapter implements the same concept of Chapter 6: no dedicated battery DC-DC converter and crowbar circuit, for a DC microgrid consisting of wind (PMSG based VSWT), PV and battery storage. However, the power management control strategy is different in operation because the system consists of more than one source in a microgrid, unlike in a hybrid system in Chapter 6. The integrated control strategy between the wind source and battery could balance the power flow in the hybrid system.

However, the control strategy does not work satisfactorily if the number of sources is increased in the system. The wind source is used to adjust the generated power in order to maintain the balanced power flow in the hybrid system using the battery information, terminal voltage and SOC. In the presence of additional source in the system as a microgrid, the only battery information is not enough to maintain the power flow. Furthermore, the strategy requires a smooth coordination between energy sources, in
addition to protecting the battery storage together (coordinating wise) against overcharging in the absence of a dedicated DC-DC converter.

A distributed control strategy using DLV based control law is proposed. The DLV provides useful information regarding the behavior of the DC microgrid system [79]. If the load demand is greater than the supplied power, the DLV decreases, and vice versa. This information can be used to schedule sources, to select different operating modes, and to demand side management such as load shedding. Under the proposed control strategy, the renewable energy sources are operated at maximum power point (MPP) scheme whereas the battery storage establishes the DLV. During extreme conditions such as a fully charged battery, the renewable sources are shifted to voltage regulation operating (VRO) mode based on the proposed dynamic control law without any real time communication. The effectiveness of the proposed distributed control strategy is validated through experimental results conducted in a prototype microgrid.

The problem statement is presented in 7.2. The system configuration and proposed control structure are presented in Section 7.3. The proposed control and operating strategy are discussed in Section 7.4. Implementation of the control strategy is explained in Section 7.5. The controller design and stability analysis are performed in Section 7.6. The simulation and experimental results are followed by discussions and conclusions in Sections 7.7, 7.8, 7.9 and 7.10, respectively.

7.2 Problem Statement

The issues of balanced power flow, stable DLV within operating limits, and protection against battery overcharging and under discharging in the microgrid, cannot be solved by the integrated control strategy proposed in Chapter 6 with the same system configuration features: no dedicated battery converter and a dump load. Therefore, a distributed control strategy using DLV based control law is proposed for a DC microgrid.

In the literature, the centralized and decentralized power management strategies for a DC microgrid are commonly considered. The centralized control, such as master-slave, has acquired information by a central control to perform the operation, which relies heavily
on the communication link. The failure in communication links can degrade system reliability. This issue is avoided by a decentralized control such as droop control, which is based on the local information measurements. Nevertheless, this improvement is at the cost of both inaccurate power sharing or poor voltage regulation and circulating currents, due to a mismatch in the parallel converter’s output voltages.

The alternative solution for centralized and decentralized control is a distributed control based power management strategy. Instead of a single secondary control, distributed control is incorporated in each source. A typical distributed control strategy applied to a DC microgrid is the average current sharing. This algorithm requires the average current of each source to set the voltage reference. The complexity rises with the increasing number of sources. Therefore, a distributed control strategy using DLV based control law is proposed. The proposed strategy provides the following features to improve the issues occurred in the literature.

(i) Unlike in a droop control, the renewable sources are operated in a current mode under the MPPT scheme as long as the source is not assigned to participate in regulating the DLV. In droop control, the sources are operated under voltage control mode to regulate the DLV together. The sources are out of MPPT scheme most of the time.

(ii) Under the proposed strategy, the one source at a time is operated in the voltage regulation mode unlike in a droop control; therefore, the issues of inaccurate power sharing or poor voltage regulation and circulating current do not exist.

(iii) The proposed strategy operated in a distributed manner with local information; therefore, it does not require a real time communication link as in the centralized controller.

(iv) The offline communication link is used to update the set values for sources when it requires the integrating of new sources and revising of priority level. As a result, the renewables are at their maximum power output without frequent switching from one operating mode to another which can create a less transient effect in the system.

In addition, the sources are considered close to the DC link in a DC microgrid. As a result, the line resistance is ignored in the literature. However, the stability of the system is affected beyond a certain line length. Some reasons are: (i) the voltage drop increases
in proportion to the line resistance, which weakens the source to the farthest DC link; and 
(ii) the non-ideal power electronic converter has its own constraints such as delay time, 
gate drive circuitry, signal noises, switching and power losses which limit the operating 
conditions. Therefore, the stability analysis with the line resistance is performed in 
designing the control strategy.

7.3 Microgrid Configuration and Proposed Control Structure

7.3.1 DC Microgrid Configuration

The configuration of the DC microgrid studied in this paper is shown in Figure 7.1, 
where \( \omega_m, V_{dc}, i_{out}, i_{bat}, R_{ls=1,2}, s_b, \) and \( s_{1-6} \) are turbine angular speed, DC link 
voltage, output source current, battery current, line resistances, DC-DC converter switch 
gate signal, and inverter switch gate signal respectively. The objective of the proposed 
control strategy is to use renewable energy at its maximum with minimum power 
electronic components and maintenance cost. The reliability can be improved by 
introducing a backup source such as diesel generator or grid network, which can be 
available if requires, but not particularly considered in this study.

![Figure 7.1: Schematic diagram of a studied islanded microgrid](image-url)
The microgrid considered in this paper consists of a permanent magnet synchronous generator based variable speed wind turbine, photovoltaic, battery storage and loads. Each of these sources is an active source, not a backup source and is connected to the DC link through a DC-DC converter, however battery storage is directly connected to the DC link, negligible line resistance. The state of charge and the voltage across the battery indicate the operational status of the battery. The SOC is estimated by integrating the battery current, as in [174].

The microgrid structure can be of different forms with different sources, storage and loads. However, the primary requirement of any DC microgrid operation is to maintain the DLV within the operating level irrespective of operating conditions. Furthermore, the stable DLV within the operating range will ensure the stable and balance power flow. Under this study, the AC side system is not considered, as it appeared as a load to the DC system.

7.3.2 Proposed Control Structure

The block diagram of the proposed control structure for a DC microgrid is shown in Figure 7.2. Each active source is controlled locally as shown in Figure 7.2. However, the system operator is used to update the set values in control law if the system integrates new sources or revises the priority level of each active source through offline communication. The control law is assigned to each active source separately in a distributed manner, so that the source can operate independently of each other.

The objective is to collect the DLV information locally, and decide the activation of either MPP scheme or VRO scheme. Furthermore, each of these blocks determines the reference current to the primary current control. The primary control block regulates the current of the converter as per the reference current which is either the result of MPP scheme or VRO scheme. Both schemes are operated based on the condition of the system such as weather conditions, battery status, and load demand.
The loads are scattered throughout the microgrid system. Some loads are non-sensitive and can be controlled through electronic switches. Therefore, control law, which is close to these non-sensitive loads, is used to send a switching signal to turn on/off the loads.

### 7.4 Control and Operational Strategy

#### 7.4.1 Control Law

Control law is established for the operation of a DC microgrid, which determines the voltage threshold for the operating modes. The operating modes are (i) MPP operating mode, and (ii) voltage regulation operating (VRO) mode. Under MPP operating mode, all active sources are operated in a current control mode while battery regulates the DLV. This mode can exist in both normal and abnormal conditions, such as overloading conditions. The VRO mode exists only when the battery is fully charged. The control law based on DLV information is shown in Figure 7.3.
Figure 7.3: Control law for a DC microgrid

where $I_{Lmax}$, $I_{chg}$, $I_{wmpp}$, $I_{pvmpp}$, $I_{Lmin}$, $I_{min}$ and $I_{dischg}$ are maximum load current, battery charging current, wind MPP current, PV MPP current, minimum load current, minimum source current and battery discharging current respectively.

Two extreme voltage thresholds are identified as $v_1$ (minimum operating limit) and $v_4$ (maximum operating limit). The operating status of renewables in Figure 7.3 is based on average constant weather conditions. The PV and wind are operated at MPP until middle and upper thresholds ($v_2$ and $v_3$). The battery is charging while the load drops. As a result, the DLV (or battery terminal voltage) reaches middle threshold. The PV source which has given the first priority to protect the battery against overcharging, is shifted to VRO scheme (shaded portion), as shown in Figure 7.3. Under the VRO scheme, the PV source regulates the DLV by curtailing excess power delivering to the battery. However, the wind remains in MPP scheme. If the PV source cannot regulate the DLV within the upper threshold ($v_3$), then the PV source controller saturates at minimum output limit.
If the load is further dropped, as shown in Figure 7.3, then the battery will consume the excess energy. In return the DLV crosses the upper threshold. The wind source, which has given the second priority to protect the battery from overcharging, is now shifted to VRO scheme. The power is curtailing in order to maintain zero current flow in the battery. In other words, the wind regulates the DLV at maximum operating limit ($v_4$). The operation between $v_2$ and $v_3$ is considered as a normal operating voltage range. Under normal operating range, renewables are operating in MPP scheme while the battery is either charging or discharging based on the variations of loads and weather.

If the load is increasing beyond the renewable generated power, the deficit power must be supplied by battery. As a result, the DLV falls below the lower limit ($v_1$). In this case DLV is maintained above minimum operating limit either by starting the backup source or shedding some of the non-sensitive loads [174], as shown in Figure 7.3. As a result, the generated power is more than the load. The excess power is then consumed by the battery which, in turn, brings the voltage level back to normal.

7.4.2 Determination of Voltage Threshold

The operating range of DLV is selected based on the SOC of the battery. For example, in this paper, the battery is operated from 45% to 95% SOC for better life cycle. The battery terminal voltage is determined during these two limits: 45% and 95% SOC, which is found to be +/- 5.5% of the nominal voltage ($V_n$) in the considered system i.e. $v_1 = 0.95V_n$ and $v_4 = 1.05V_n$. The voltage thresholds in between minimum and maximum limits are divided based on the number of active sources and the tolerance margin. Therefore, for the considered system two thresholds (middle and upper) are determined with 5% margin. The filters are used to cut the high frequency components in order to reduce the tolerance margin.

7.4.3 Operational Strategy

The operational strategy for the considered microgrid is developed using the control law and two operating modes. The operating modes of the active sources in the microgrid change frequently depending on the weather conditions, load demands, and storage availability. Therefore, three operating levels are defined for the considered microgrid.
7.4.3.1 Level 1

Both normal and abnormal conditions can occur, as shown in Figure 7.3; normal condition- renewables are in the MPP scheme and the DLV is in normal operating range; and abnormal condition- renewables are in the MPP scheme and load shedding is occurring to maintain the DLV above the minimum limit.

7.4.3.2 Level 2

The PV source is shifted to VRO scheme in order to protect the battery from overcharging or power curtailment to maintain the DLV within the upper threshold. However, the wind is at MPP scheme.

7.4.3.3 Level 3

The wind source is shifted to the VRO scheme to protect the battery from overcharging or power curtailment to maintain the DLV within the maximum limit while the PV power is limited to minimum output.

7.4.4 Smooth Operation of the Microgrid

The smooth operation of a microgrid is determined by: (i) easy accommodation of new sources without affecting others; and (ii) fewer number of operating mode transitions. These issues can be explained by using Figure 7.4, where $I_{s=1-5}$ and $I_{\text{min}}$ are the different source currents and minimum source current.

The number of voltage threshold can be increased to incorporate new sources, as shown in Figure 7.4. The one source is added in the considered system. As a result, one more threshold voltage is occurred for VRO scheme at point A. However, two major issues would appeared: (i) the nominal voltage range is reduced in between $0.95V_n$ to $1.04V_n$, and as a result frequent transition between operating modes can exist; and (ii) the possibility of false switching between active sources due to small tolerance margin.
These issues will jeopardize the smooth operation of active sources in the microgrid. Therefore, voltage threshold based operation brings limits in the connection of new sources beyond a certain number. A well-established droop control can be used to operate multiple sources at the same voltage level effectively in a VRO scheme, as shown in Figure 7.4 at point C. The proposed control strategy activates the droop control at certain voltage level only, if the condition exists.

The number of mode transitions can be reduced by assigning first priority to the large energy source for VRO, followed by the small one. For example, in Figure 7.3, the small energy source (PV) operates first under VRO scheme at point A. The power curtailment is not enough to bring the DLV back to normal range. Therefore, the wind is also required to shift into VRO mode. If the control law is based on Figure 7.4, then the first source at point A is enough to curtail the power in order to maintain the DLV within normal range. The other sources kept on operating in the MPP scheme without any mode transitions. However, the generated maximum power from renewable does not depend on size, but on weather conditions (providing not the extreme large size difference). In some location during particular period, wind is better than the sun or vice versa; this information needs to be updated for optimal operation. Hence, the control law varies depending on the situation, and referred as a dynamic control law.
The system operator collects information about the weather and integration of new sources (adjustment in threshold value/priority level) and sends the information to each control law through offline-communication. This information does not change the control strategy or the structure of any source; instead it only updates the threshold value.

7.5 Implementation of the Control Strategy

7.5.1 Maximum Power Point (MPP) Scheme

The renewable energy sources, such as wind and PV, are operated at the maximum power point (MPP) as long as the system permits. The power signal feedback control strategy is implemented for wind turbine, as shown in Figure 7.5(a). The PV is extracting maximum power based on the regulation of PV array output voltage ($V_{pv}$) and current, ($I_{pv}$) respectively, as shown in Figure 7.5(b).

![Figure 7.5: MPP scheme for: (a) Wind (b) PV](image)

where $\theta$, $\eta_{opt}$, $r$, $\omega_m$, $P_{opt}$, $P_l$, $P_{mpp}$, $P_e$, and $I_{opt}$ are wind speed, optimal tip speed ratio, turbine radius, turbine rotor angular speed, power extracted at the optimal point or MPP, total energy conversion losses from turbine to converter, maximum power point including losses, electrical power at the output of the wind source DC-DC converter, and optimal current, respectively. The parameter $k_{opt}$ corresponds to the power speed characteristics of a turbine that extracts maximum power at any given wind speed. The PV output
voltage reference \( (V_{pvref}) \) is obtained from the perturbation and observation method as explained in [175].

The optimal reference current obtained from the wind and PV MPP scheme is compared with the wind converter and PV array output current, so that the error is compensated by the \( PI \) controller in order to track the maximum power. The controller generates the pulse \( (s_b) \) to drive the switch under pulse width modulation (PWM) technique.

### 7.5.2 Voltage Regulation Operating (VRO) Scheme

Under this strategy, the battery voltage is maintained at more than the nominal voltage level. Either one or more sources under droop control are participating to protect the battery from overcharging by regulating the DLV within the operating range.

#### 7.5.2.1 Control Strategy for a Single Active Source

The control strategy is shown in Figure 7.6.

![Control block diagram for voltage threshold based VRO](image)

**Figure 7.6:** Control block diagram for voltage threshold based VRO

The DLV \( (V_{dc}) \) does not regulate accurately if the line resistance \( (R_l) \) is not considered. The voltage drop across the line resistance \( (\Delta V) \) is compensated through a control loop using the concept (1).

\[
V_o = V_{dc} + I_{out}R_l = V_{dc} + \Delta V
\]  

(7.1)

where \( V_o \) and \( I_{out} \) are the source converter output voltage and current, respectively. The error between the reference \( (V_{dcref}) \) and measured \( (V_{dc}) \) DLV is passed through the \( PI \) controller to compensate the voltage drop across the line resistance. As a result, the
converter output voltage \( (V_o) \) is regulated at the reference \( (V_{oref}) \) more than the DLV. The additional amount to the DLV reference \( (V_{dcref}) \) determines the voltage drop \( (\Delta V) \) across the line resistance. Hence, the DLV is maintained at the exact reference level. The \( PI \) controller is used to regulate the converter output voltage to its reference value which provides the reference current \( (I_{ref}) \) to regulate the output current of the source.

### 7.5.2.2 Control Strategy for Multiple Active Sources

The droop control is activated for operating multiple sources in the VRO scheme. The droop control method is based on the virtual output resistance [71] as

\[
V_{oref} = V_{onl} + \delta V_{dc} - I_{out} R_d
\]  

(7.2)

where \( V_{oref}, V_{onl}, \delta V_{dc}, I_{out} \) and \( R_d \) are the reference output voltage of the converter, output voltage of the converter at no load, DLV deviation, output current of the converter, and virtual output resistance. The DLV deviation can be eliminated by using the secondary control loop as shown in (7.3)

\[
\delta V_{dc} = k_p (V_{dcref} - V_{dc}) + k_i \int (V_{dcref} - V_{dc}) dt
\]  

(7.3)

The droop control method is implemented using (7.2). The virtual output resistance based droop control is implemented in Figure 7.7, which regulates the DLV. The droop coefficient which is in fact the virtual output resistance is calculated based on the voltage deviation (2%) and full load output current of the converter.

\[
R_d \leq \frac{\Delta V_{omax}}{I_{outf}}
\]  

(7.4)
where $\Delta V_{omax}$ and $I_{outf}$ are the maximum deviation in the output voltage and full load output current of the converter. The droop control shown in Figure 7.6 is implemented for all active sources operated at same voltage threshold in the VRO scheme.

7.6 Controller Design and Stability Analysis

7.6.1 Controller Design

The eigenvalue analysis technique is used to design the PI controller. The averaging technique is used to derive the transfer function model of the buck converter [176]. The hat (\(^\hat\)) represents the average value. The transfer function, $G_{vd}(s) = \frac{\hat{v}_{dc}(s)}{\hat{d}_{c}(s)}$, between the control input $\hat{d}_{c}(s)$ and the output voltage $\hat{v}_{dc}(s)$, can be written as

$$G_{vd}(s) = \frac{RV_{in}(1 + sR_{c}C_{dc})}{R + s(L_{i} + R_{R}C_{dc}) + s^{2}(R + R_{c})L_{i}C_{dc}} \tag{7.5}$$

where $L_{i}$, $C_{dc}$, $R$ and $R_{c}$ are buck converter inductance, DC link capacitor, loads and effective resistance in DC link capacitor, respectively. The transfer function, $G_{id}(s) = \frac{i_{ind}(s)}{\hat{d}_{c}(s)}$, between the control input $\hat{d}_{c}(s)$ to the inductor current, $i_{ind}(s)$ can be written as

$$G_{id}(s) = \frac{V_{in}(1 + s(R + R_{c})C_{dc})}{R + s(L_{i} + R_{R}C_{dc}) + s^{2}(R + R_{c})L_{i}C_{dc}} \tag{7.6}$$

The block diagram of the voltage control system with the inner current control loop is shown in Figure 7.8.

![Figure 7.8: Control block diagram of buck converter](image-url)
The transfer functions $C_{vi}(s)$ and $C_{id}(s)$ represent the $PI$ controllers in the voltage ($k_p = 0.7095$ and $k_i = 391.88$) and current ($k_p = 0.1012$ and $k_i = 109.96$) loops, respectively. The transfer function of the inner current loop is represented as

$$Gi(s) = \frac{C_{id}(s)}{1 + G_{id}(s)C_{id}(s)} \quad (7.7)$$

The $PI$ controllers are designed to eliminate the steady state error subject to a step change in references; also to enhance the stability of the closed-loop system. The first objective is obtained by using an integrator; the second is by moving the critical modes of the system far from imaginary axis to the left half of the $s$-plane. The integrator gain ($k_i$) is changing by keeping the proportional gain ($k_p$) constant in both inner and outer current and voltage loops. The trajectories of modes are identified to fit the best controller as shown in Figures 7.9 (a) and 7.9 (b) respectively.

**Figure 7.9**: Modes trajectories in an $s$-plane (a) inner current loop (b) outer voltage loop

With increasing ‘$k_i$’ the modes are moving away from imaginary axis, however beyond certain value of ‘$k_i$’, the real negative modes become oscillatory but still stable. Therefore, ‘$k_i$’ is selected in such a way that the modes are only negative real and far from imaginary axis that lies in (III) and (II) in Figures 7.9 (a) and 7.9 (b) respectively.
7.6.2 Effect of Line Resistance and Stability Analysis

The stability analysis for the operation of an active source, due to the line resistance, is analyzed. The stability of the system becomes affected beyond certain line length. Some reasons could be: (i) the voltage drop increases in proportion to the line resistance, which weakens the source to the farthest DC link; and (ii) the non ideal power electronic converter has its own constraints such as delay time, gate drive circuitry, offsets, signal noises, switching and power losses [177] which limit the operating conditions.

The small signal models of the system are derived from Figure 7.8 to show the modes trajectories due to the different size of line resistance in the \( s\)-plane (Figure 7.10). The objective is to move all the modes far away from the imaginary axis to the left half of the \( s\)-plane. The line resistance \( R_{ls} \) varies from (0.01 to 10) ohm for the studied system shown in Figure 7.1. For a small value of resistance, all modes are negative real, some are at region (I) and few of them are at region (II) in Figure 7.10.

![Figure 7.10: Modes trajectories in an s-plane due to line resistance](image)

However, with increasing value, the region (I) modes are moving closer to an imaginary axis whereas region (II) modes are moving away from an imaginary axis. At certain point, the complex conjugate poles have also appeared, and move towards the imaginary axis, as shown in Figure 7.10. Further increasing the line resistance, the modes come closer to the imaginary axis and on the verge of becoming unstable at region (III). Therefore the possible farthest distance of a source from the microgrid is at the point where the modes are closer to an imaginary axis, but are still at the left half of the \( s\)-plane.
7.7 Simulation Studies

The numerical simulations are performed in PSCAD for a renewable energy dominated microgrid using the proposed control strategy. The simulations results are classified into two case studies: (1) *Case Study I* – load shedding scenario is analyzed; and (2) *Case Study II*- droop control in VRO mode is performed. The current flow from sources (wind and PV) is shown in the presence of common DLV. In this study, it is assumed that the average wind speed fluctuation is faster than that of the average irradiance changes (i.e. cloud moves slower than change of the wind). However, the time constant for the source also depends on the PECs, which decouples the source and the load side dynamics.

7.7.1 Case Study I: Load Shedding Scenario

Under this study, the DLV falls below the lower threshold level due to the high load demands. The renewable sources are operated at constant average weather conditions; however, the loads vary for this short operating period. The proposed control strategy sheds some of non-sensitive loads to maintain DLV at lower threshold voltage, as illustrated in Figure 7.11.

![Figure 7.11: Microgrid operation including load shedding (a) DC link voltage (b) Load shedding signal and (c) Current flow (sources, storage and load)](image)

The microgrid operates at DLV nominal to maximum (1.0 -1.055) p.u. at varying load demand until t=30s. After the sources activated and performed steady, at t=14s, the DLV
crosses the middle threshold (1.045 p.u.). The control law assigned the PV source to respond first in VRO mode. Accordingly, PV curtailed its output power/current to maintain the DLV at 1.05 p.u, as shown in Figures 7.11(a) and 7.11(c), respectively.

However, the possible maximum PV power curtailment (close to zero output) does not maintain the DLV within the upper voltage threshold (1.05 p.u). As a result, the wind source, which is in MPP scheme, enters into the VRO scheme and curtails its output power to maintain the DLV at its maximum operating limit 1.055 p.u., as shown in Figures 7.11 (a) and 7.11 (c). The battery current is maintained close to zero throughout the operating period t= (14-30) s.

At t=(30-39)s, the load demand is more than the generation (under MPP scheme); as a result, the battery meets the deficit power, as shown in Figure 7.11 (c). In addition, the DLV reaches the lower threshold (0.945 p.u.) at t=39 s. The control law sends the signal (1-connects and 0-disconnects) to the controllable loads for load shedding as shown in Figure 7.11 (b) to maintain the DLV at 0.945 p.u. Hence the battery current is also regulated to zero.

At t=50 s, the uncontrollable load demand is reduced; as a result, the power mismatch occurs between the sources and the load. The excess power is consumed by the battery, as shown in Figure 7.11(a) so that the DLV increases beyond the lower threshold. In turn, the control law sends the signal again to connect the loads, as shown in Figure 7.11 (b). The process is repeated depending on the load demands. The same procedure will follow for fluctuating weather conditions to operate the microgrid within the prescribed DLV limits irrespective of fluctuating weather conditions and load demands.

### 7.7.2 Case Study II: Droop Control in VRO Mode

This case study is performed for multiple sources operated under VRO mode at the same voltage level using droop control strategy. The microgrid in this study is operated under the same operating condition as in Case Study I. Based on the rated power and voltage fluctuation margin, both sources are assigned with the droop values 0.006 Ω for wind
source and 0.0192 $\Omega$ for PV source to share the current under the same voltage level. The simulation results are shown in Figure 7.12.

![Figure 7.12: Microgrid operation using droop control in the control law (a) DC link voltage and (b) Current flow](image)

The microgrid operation, shown in Figure 7.12, is similar to Figure 7.11 before $t=15s$ and after $t=30s$. In between ($15 \leq t \leq 30$) s, active sources are operated in a droop control. The DLV reaches the upper threshold voltage (1.05 p.u.) at $t=15s$. As a result, both wind and PV are curtailing output power to limit DLV at 1.055 p.u., as shown in Figure 7.12 (b). However, the wind remains at MPP in Figure 7.11 (c). The load is further reduced at $t=20s$, hence the wind and PV have further reduced their output power until $t=30s$ to maintain the DLV. However, there is a transient effect under droop control at $t=14s$, unlike to Figure 7.11 (a).

### 7.8 Experimental Validation

The experimental investigation is also performed to validate the effectiveness of the proposed control strategy in the DC microgrid consisting of wind, PV, battery storage and loads. The experimental setup is shown in Figure 7.13.
Figure 7.13: Experimental setup for DC microgrid

An induction motor (M) drives the PMSG generator (G) with control to emulate the static and dynamic behavior of a real wind turbine on the campus roof as the wind turbine simulator. The PV simulator following roof top PV characteristics and battery are used as other source and storage. A DC-DC converter and inverter are also designed and fabricated to support this experiment. The DC link, which is designed to connect all sources, storage, DC loads and inverter, is maintained at 36 V as nominal voltage. The Texas Instrument (TI) controller and National Instrument (NI) LabVIEW controller are used to control the DC-DC converters and the WTS, respectively. The data is collected through dSPACE control desk at the step size of 58 μs and down-sampled by a factor of 5. The parameters for the system are given in Appendix A.

7.8.1 Case Study I: Normal Operation (MPP Scheme)

This is the case study for normal operation where the sources are operated under the MPP scheme and DLV is within the prescribed range irrespective of fluctuating wind condition and load demands. The experimental results are shown in Figure 7.14.
Figure 7.14: Microgrid normal operation (a) DC link voltage (b) Load current (c) Battery current (d) Wind speed (e) Wind current (f) Rotor speed and (g) PV current

Event 1-sources energized in the microgrid (t=0-90)s: The battery starts the microgrid at t=3s, meeting all the load demands before the wind and PV are energized. The turbine dynamics introduce the initial transient while connecting to the system at t=13.5s (Figure 7.14 (f)). The effect can be seen in DLV (Figure 7.14(a)), battery current (Figure 7.14 (c)) and wind current (Figure 7.14 (e)). The wind is assumed to be under constant average wind speed (Figure 7.14 (d)) for a given period and operated in the MPP scheme to meet all the load demand (Figure 7.14 (b)), while the battery is in floating condition with zero output. At t=60s, the load demand is stepped up. The wind cannot meet the load alone. Hence the battery discharges to meet the rising (deficit) load, as shown in Figure 7.14 (c). In addition the DLV drops towards the lower threshold. The PV is then connected to the microgrid smoothly at t=70s because PV does not have any rotating parts. The PV cuts the power from the battery as the load is solely met by the combined sources.

Event 2-microgrid operation (t=90-170)s: The irradiance is assumed to be constant, whereas wind speed is varied for a given period. As a result, the PV power remains
constant (Figure 7.14 (g)) and the wind power is varied (Figure 7.14 (e)) under the MPP scheme (constant power irrespective of varying load demands). The generation becomes more than the load demand at t=94s because the wind power increases with increasing wind speed. The turbine dynamics perform satisfactorily as the angular rotor speed increases smoothly, as shown in Figure 7.14 (f). The mismatch or excess power is then consumed by the battery, and the DLV starts increasing as shown in Figures 7.14 (c) and 7.14 (a). The load is then stepped up at t=108s (Figure 7.14 (b)), before the DLV crosses the middle threshold voltage (1.045 p.u). In this case, the deficit power in the microgrid is supplied by the battery (Figure 7.14 (c)); as a result, the DLV is falling down to nominal level.

The load and wind speed further step down at t=126 s and t=133s. The power becomes imbalanced as the generation is at a maximum under the MPP scheme and the load has been reduced. Therefore the battery consumes the excess power between t=126s to t=133s. As a result DLV rises towards middle threshold (within nominal range). At t=133s, the power is balanced between the generation and load demand, thanks to the reduced wind power. In addition, the battery is in floating condition with zero current flow and the DLV is regulated at nominal value (1.0 p.u.). The acceptable transient effect of sudden rise and fall of loads are seen in the output current of wind, PV, and battery storage at t= 108 s and t= 126 s respectively.

7.8.2 Case Study II: Power Curtailment (VRO Scheme)

This study is performed for the microgrid when the generation is more than the load demand, and the battery is fully charged. With the proposed control strategy, the microgrid is still operated safely within the limits. In this particular study, the control law has assigned the same voltage threshold (1.05 p.u.) for both the PV and wind to regulate the DLV instead of (1.045 and 1.055) p.u. in previous studies. The purpose is to show the dynamic nature of control law. The experimental results are shown in Figure 7.15.
Figure 7.15: Microgrid operation during extreme condition: (a) DC link voltage (b) Resistive load (c) Battery current (d) Wind speed (e) Wind current (f) Power coefficient (Cp) and normalized tip speed ratio (TSR) and (g) PV current

*Event 1-starting and normal operation* (*t=0-190)s: The nominal disturbances in the microgrid: wind speed and load demands are constant until they increase at *t=249s* (Figure 7.15 (d)) and decrease at *t=295s* (Figure 7.15 (b)) whereas irradiance varies for a given period. The microgrid operates similarly as in previous two case studies: starting procedure and normal operation. The battery balances the deficit and excess power (Figure 7.15 (c)) in the different operating conditions: black start (absence of sources) and irradiance variation (PV power increases as shown in Figure 7.15 (g)).

*Event 2- PV in VRO scheme* (*t=190-295)s: The battery continuously consumes the increasing power of PV, as a result the DLV reaches the limit, 1.05p.u. (Figure 7.15 (a)).
The PV now shifted to VRO scheme by curtailing its power (Figure 7.15 (g)) to maintain the DLV at the limit. The battery is now in floating condition (Figure 7.15 (c)). However, at t=249s, the wind power increases which, again, imbalances the power flow. The PV curtails its power further to the minimum output limit (Figure 7.15(g)) before the DLV crosses the prescribed threshold, 1.05 p.u.. The transient effect of turbine dynamics can be seen in the DLV, battery current, and wind current in Figures 7.15 (a), 7.15 (c) and 7.15 (e), respectively. The wind source is still under MPP scheme as the power coefficient and tip speed ratio are maintained at the optimal values, as shown in Figure 7.15 (f).

Event 2- wind in VRO scheme (t=295-350)s: At t= 295s, the power is further imbalanced in the presence of the reduced load. The battery is already at its maximum limit, and PV is at minimum output (VRO scheme), hence the wind source promptly curtails its power under VRO scheme (Figure 7.15 (e)). The power coefficient and tip speed ratio are decreased and increased, respectively, for out of MPP scheme (Figure 7.15 (f)). As a result, the DLV is regulated at the prescribed limit (1.05 p.u.).

Thus, the experimental study shows that the sources are cordially operated in the microgrid under the proposed control strategy to maintain the DLV within the operating range irrespective of weather conditions and load demand.

7.9 Discussions

When the DC microgrid, under the proposed control strategy, is interfaced to AC link through the inverter in the islanded and grid connected mode, we foresee the following:

(1) Under islanded mode, the control scheme is operated exactly the same as mentioned in the research work. The inverter is controlled to regulate the amplitude and frequency of voltage at the AC link, which acts as a load to the DC microgrid.

(2) Under grid connected mode, the grid can be operated in two ways: (i) the grid will activate only to curtail the load shedding or (ii) the grid will participate actively in microgrid operations as a load and source depending upon the operating conditions. In this case, there is no VRO mode, and DLV is regulated by the inverter and the
battery is in floating condition as a back up during intentional and non-intentional islanding conditions.

7.10 Conclusions

In this chapter, the distributed control strategy using the DC link voltage based control law for power management in a DC microgrid is presented and validated experimentally in a system consisting of a PMSG based variable speed wind turbine, PV, battery energy, storage, and loads. In contrast to the common way of controlling sources under droop control to regulate the DC link voltage in a DC microgrid, it is shown that controlling the sources under distributed control using an established dynamic control law, the power sharing and voltage regulation have been improved, and there is no issue with circulating current. In addition, the strategy does not require a real time communication link. However, the offline communication is proposed to enhance the performance by reducing the frequent operating mode transitions. As a result, the smooth coordination of sources is maintained along with the renewable operation under MPPT scheme. The proposed strategy is operated in the same system configuration features: no battery converter and a dump load, for the advantages explained in Chapter 6. Thus, it is believed to be cost effective, efficient and straightforward to implement, as local information is required without any need of real time information exchanged.
Chapter 8

8 Control Strategy for a Grid Connected Wind System

8.1 Introduction

The power management strategy for a Type IV wind system -PMSG based VSWT, in a distribution grid network is proposed in this chapter. The control strategy for a wind system with battery storage and other source, PV as a hybrid and microgrid system in an islanded condition (off-grid) have been presented in Chapters 5, 6 and 7, respectively. In previous chapters, the focused is mainly on power management strategy with the issues in islanded conditions. However, this chapter is focused on the control strategy for the low voltage distribution grid connected wind system at the point of common coupling (PCC) using the existing converters without any crowbar circuit. The concept mentioned in Chapters 6 and 7 for the configuration with possible least components is also valid in this grid connected configuration while designing the control strategy.

In Chapters 5, 6 and 7, the control strategy is primarily designed for a hybrid system and a DC microgrid to maintain the DC link voltage irrespective of the system operating conditions. The same concept is implemented in this chapter for the DC link control strategy. In addition, a single inverter is used in the hybrid system or a DC microgrid to integrate the DC link to the AC link in both islanded and grid connected mode. Therefore, the studies are performed with a wind source only in this chapter considering the common grid disturbance at the distributed network: voltage sag. Voltage sags are defined as a drop in voltage lasting between a half-cycle and up to a minute [178]. These sags can be either balanced or unbalanced, depending upon their causes such as asymmetrical loads or faults [59],[179].

In recent years, small scale wind turbines (SSWT) are gaining popularity due to their relatively small footprint, lower noise level, quick-payback, and capability to operate in grid connected or islanded modes [16]. The SSWT defined here is not a megawatt (MW) wind turbine or a big wind farm.
These SSWTs can be connected to the low voltage distribution grid network as an active distributed generator (DG). The disconnection of a SSWT does not threaten the stability of the grid; however, the loss of large scale (MW) wind energy source (WES) or a wind farm affects the stability of the grid significantly. These MW wind turbines or farms are normally integrated at the medium voltage (MV) to high voltage (HV) grid network. For this reason, grid codes have been developed mandating that WESs remain connected and provide support to the grid [13]. However, this research work argues, if a large number of SSWTs disconnect from the LV DGN within a short period time, then the grid may also encounter instability issues. This is a foreseen condition considering the increasing penetration of SSWTs at the LV distribution grid network.

Unlike HV grid network, the LV distribution grid network has a resistive dominant line impedance \( R/X > 1 \), which demands more active power than reactive power to impact the voltage sag [188]. Therefore, the SSWTs at LV distribution network is controlled to operate at unity power factor before and during the voltage sag.

The proposed approach produces a balanced positive-sequence sinusoidal current output from the inverter by regulating the flow of negative-sequence current to zero. This is achieved by feeding forward the negative-sequence voltage to the positive-sequence vector current controller. Hence, the scheme is referred to here as vector current control with a feed-forward of negative-sequence voltage, or VCCF. This strategy is further enhanced by maintaining the grid current output within safe levels without any hard switch limit, which prevents both, damage to the power electronic components and saturation of the \( LC \) filter. This concept is referred to here as the power compensation factor (PCF). The proposed control strategy is validated against the real physical system developed in the laboratory.

The problem statement is presented in Section 8.2. Section 8.3 provides a description of the system, as well as the control objectives. The detailed control strategy for both DC and AC sides including the controller design are presented in Section 8.4. The simulation and experimental results are illustrated in Sections 8.5 and 8.6, respectively, and Section 8.7 outlines the conclusions.
8.2 Problem Statement
The issues related to the DC link are studied in Chapters 5, 6, and 7 for a wind source as a hybrid system and a DC microgrid. In previous chapters the developed control strategies are used to coordinate the sources in order to regulate the DC link voltage and maintain the DC link stability. The same concept is implemented in this chapter, as well, but with a grid connected wind source only. The generator side converter or DC-DC converter is used to regulate the DC link voltage and maintain the DC link stability. Therefore, the issues related to the network side converter or inverter at AC link in the presence of voltage sag at the PCC is the primary focus in this chapter. The PMSG-based VSWTs that are integrated with the grid have the following issues during voltage sag:

(iv) Conventionally, the controller output of the DC link voltage determines the flow of the active power, making the active power flow inaccurate to the reference.

(v) The negative-sequence currents flow from the inverter to the grid, causing unacceptable oscillation at twice the system frequency during unbalanced voltage sags at the PCC [80]. This oscillation creates instability in the system.

(vi) The imbalanced power flow occurs between the generator and the grid side inverter, causing the DC link voltage to rise abruptly with ripple during balanced voltage sags at the PCC [80], and

(vii) The inverter output current can rise drastically during voltage sags.

These issues may potentially cause damage to the DC link capacitor, and the power electronic components, which in turn, forces the WPS to disconnect from the grid.

If the voltage sag issue at the PCC is not considered while developing a control strategy for a WPS, then the WPS may be disconnected from the grid or damaged during the voltage sag. In addition, the grid code is mandatory for WPS to support the grid, such as active filters or shunt/series inverters [81]. Unfortunately, this solution may not be suitable for small scale wind turbines, SSWTs (< 300 kW) in the low voltage distribution network.

Based on the issues discussed above, the following control objectives are set for PMSG-based VSWT.
(i) The DC-DC converter regulates the DC link voltage.

(ii) The inverter control performs the following functions, depending on the conditions of the grid:

- Achieving maximum power point tracking (MPPT).
- Regulating the negative-sequence currents to zero.
- Maintaining the inverter output currents symmetrical, and at the pre-disturbance amplitude irrespective of grid disturbances.
- Balancing the active power between the generator and the grid side inverter during grid voltage sags.

This configuration decouples the control objectives, allowing for the separation of control dynamics at both the generator and the grid side converter. This leads not only to the accurate flow of active power due to the direct power control, but also permits independent control of DC link voltage, and active and reactive power under the vector control strategy. An additional advantage of this control strategy is that it allows the system to ride through grid disturbances without the need to add additional components, such as a chopper to the system.

Therefore, the proposed control strategy enables the wind turbine system to be optimally designed without the need for oversized converters, a large DC link capacitor and a crowbar circuit, which reduces the overall cost of the system. In addition, the PMSG based VSWT remains on grid in the presence of unbalanced voltage sag without damaging itself and provides support to the grid to maintain stability by supplying reduced power during the voltage sag, and full power right after the clearance without a significant delay.

8.3 System Description and Proposed Control Objectives

8.3.1 System Description

A PMSG-based WPS is connected to a distribution grid through a series of power electronic-based interfacing units, as illustrated in Figure 8.1. The PMSG based WT system has been designed and developed in a laboratory for prototype experiments, and consists of a diode rectifier, a buck converter as a DC-DC converter, an inverter, an LC
filter, and a transformer. The choice of a buck converter is motivated by its simple and cost-effective topology, and is technically viable for small WT [180]. The modeling of the PMSG based VSWT system is well performed in [181]. The LC filter is used in line with the inverter to provide a smooth and pure sinusoidal waveform, while the step up transformer is used to bring the inverter output voltage up to the distribution voltage level at the PCC, as shown in Figure 8.1. Both the amplitude and frequency of the voltage are maintained in accordance with that of the PCC for grid synchronization.

![Figure 8.1: Schematic diagram of PMSG based WPS connected to grid](image)

### 8.3.2 Control Objectives

The following control objectives are set for PMSG-based VSWT.

(i) The DC-DC converter regulates the DLV, decoupled from the inverter side.

(ii) The inverter control (VCCF+PCF) performs the following functions, depending on the grid disturbances: achieving maximum power point tracking (MPPT); regulating the negative-sequence currents to zero; maintaining the current level within a safe limit to protect the inverter components; and balancing the power flow between the generator and the grid side inverter.

Conventionally, the compensated output of the DLV controller determines the flow of the active power [128], making the active power flow inaccurate to the reference. However,
the proposed configuration decouples the control objectives, allowing for the separation of control dynamics at both the generator and the grid side converter. This leads not only to the accurate flow of active power due to the direct power control, but also permits independent control of the DLV, and active and reactive power under the vector control strategy. An additional advantage of this control strategy is that it allows the system to ride through grid disturbances without additional circuit such as crowbar.

8.4 Control System Design and Implementation

8.4.1 DC-DC Converter

The averaging technique is used to derive the transfer function model of the buck converter [187], as shown in (8.1) and (8.2)

\[ G_{vd}(s) = \frac{RV_{in}(1 + sR_cC_{dc})}{R + s(L_i + RR_cC_{dc}) + s^2(R + R_c)L_iC_{dc}} \]  
\[ G_{id}(s) = \frac{V_{in}(1 + s(R + R_c)C_{dc})}{R + s(L_i + RR_cC_{dc}) + s^2(R + R_c)L_iC_{dc}} \]

where \( d_c, G_{vd}(s) = \frac{\ddot{v}_{dc}(s)}{\dot{d}_c(s)}, G_{id}(s) = \frac{i_{ind}(s)}{\dot{d}_c(s)}, V_{in}, L_i, C_{dc}, R \) and \( R_c \) are the duty cycle, the transfer function of the average output voltage to the duty cycle, the transfer function of the average inductor current to the duty cycle, the input voltage, the buck converter inductance, the DC link capacitor, the loads and the effective resistance in the DC link capacitor, respectively.

Two closed-loop PI controllers are designed for the output voltage (\( V_{dc} \)) and inner inductor current (\( i_{ind} \)) loops, so that (\( V_{dc} \)) approaches the reference voltage (\( V_{dc_ref} \)) by adjusting the duty cycle (\( d_c \)) of the switch as shown in Figure 8.2.

![Control block diagram of DC link voltage control](image)
The eigenvalue analysis technique is used to design the PI controller in Figure 8.2. The transfer functions $C_{vl}(s)$ and $C_{id}(s)$ represent the PI controllers in the voltage ($k_p = 0.7095$ and $k_i = 281.88$) and current ($k_p = 0.1012$ and $k_i = 89.96$) loops, respectively. The transfer function of the inner current loop is represented as:

$$Gi(s) = \frac{C_{id}(s)}{1 + C_{id}(s)C_{id}(s)} \quad (8.3)$$

The objectives of the PI controller are to (i) eliminate the steady state error subject to a step change in references; and (ii) enhance the stability of the closed-loop system. The first objective is obtained by introduction of an integrator, and the second is by the critical modes of the uncompensated system further away to the left half of $s$-plane. The critical modes of uncompensated and compensated systems for the loops are shown in Table 8.1.

<table>
<thead>
<tr>
<th>Inner current loop modes</th>
<th>Outer voltage loop modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncompensated</td>
<td>Compensated</td>
</tr>
<tr>
<td>$-166.7 \pm j986.01$</td>
<td>$-166.7 \pm j986.01$</td>
</tr>
<tr>
<td>$-1107$</td>
<td>$-11087$</td>
</tr>
<tr>
<td>$-293$</td>
<td>$-10154$</td>
</tr>
<tr>
<td>$-293$</td>
<td>$-2019$</td>
</tr>
<tr>
<td></td>
<td>$-188$</td>
</tr>
</tbody>
</table>

8.4.2 Inverter

The PMSG-based VSWT is operated under an MPPT scheme, as long as the conditions on the system and environment permit. Otherwise the WPS comes out from the MPPT scheme, especially during grid disturbances, to balance the power flow with stable and symmetrical three phase current output.

8.4.2.1 Control during Normal Operation (MPPT Scheme)

The power coefficient ($C_p$) is also a function of the pitch angle ($\beta$) and the tip speed ratio ($\eta$). The optimal tip speed ratio ($\eta_{opt}$) is where the power coefficient reaches the maximum ($C_{p\text{max}}$), which corresponds to the maximal power extracted from the WT, as shown in (8.4). The maximum (optimal) wind turbine power ($P_{opt}$) can be calculated as
\[ P_{opt} = 0.5 \rho C_{p\max} A \left( \frac{\omega_m}{\eta_{opt}} \right)^3 = k_{opt} \omega_m^3 \quad \text{and} \quad k_{opt} = 0.5 \rho C_{p\max} A \left( \frac{r}{\eta_{opt}} \right)^3 \]  

(8.4)

where \( \rho \), \( A \), and \( r \) are air density, rotor swept area, and rotor radius. The maximum electrical power \( (P_{el}) \) reference for the inverter is obtained from the optimal wind turbine power, mechanical shaft power, generator and converter power losses, and the DC link capacitor power as

\[ P_{el} = P_{opt} - J \omega_m \frac{d\omega_m}{dt} - P_{g-loss} - P_{c-loss} - C_{dc} \frac{dV_{dc}}{dt} = P_{opt} - P_l \]  

(8.5)

where \( P_l \) is the total losses, including generator losses \( (P_{g-loss}) \), converter losses \( (P_{c-loss}) \) and other losses, such as those of the mechanical shaft and the DC link capacitor.

### 8.4.2.2 Control during Balanced Voltage Sag (Out of MPPT Scheme)

The PCF technique is implemented during balanced voltage sag. The controller has two tasks: (i) balancing the power flow between the wind generation and the inverter output; and (ii) maintaining the amplitude of the inverter output current within the safe level or pre-disturbed level. The active power \( P \) and reactive power \( Q \) in \( d-q \) positive SRF can be represented as

\[ P = \frac{3}{2} \left[ V_{pdp}i_{pdp} + V_{qpq}i_{qpq} \right] \]  

(8.6)

\[ Q = \frac{3}{2} \left[ -V_{pdp}i_{qpq} + V_{qpq}i_{pdp} \right] \]  

(8.7)

The phase locked loop (PLL) is considered to extract the system frequency for synchronization, which regulates the positive sequence \( q \)-axis voltage to zero \( (V_{qpq} = 0) \). As a result, this PLL eliminates the effect of disturbances in the voltage phase angle at the PCC [182]. From (8.6) and (8.7), the current references in \( d-q \) components can be calculated as

\[ i_{pdpref} = \frac{2}{3V_{pdp}} P_{ref} \]  

(8.8)
\[ i_{pq\text{ref}} = -\frac{2}{3V_{pdp}} Q_{ref} \] (8.9)

The reactive power reference \( Q_{ref} \) (i.e. the \( q \)-axis current reference, \( i_{pq\text{ref}} \)) is regulated to zero under the unity power factor. The reference active power, \( P_{ref} \) (i.e. the \( d \)-axis current reference, \( i_{pd\text{pref}} \)) can be obtained from the MPPT scheme. From (8.8), the reference active power is written as

\[ P_{ref} = 1.5V_{pdp}i_{pd\text{pref}} \] (8.10)

When the grid voltage is symmetrical, the voltage is equal to the nominal rated voltage denoted by \( V_{nom} \). The power injected into the grid is equal to the optimal power \( (P_{opt}) \) from the MPPT scheme, such that

\[ P_{opt} - P_i = 1.5V_{nom}i_{pd\text{pref}} \] (8.11)

From (8.10) and (8.11), the reference power becomes

\[ P_{ref} = \frac{V_{pdp}}{V_{nom}} (P_{opt} - P_i) = \text{PCF} \times P_{el} ; \text{PCF} = \frac{V_{pdp}}{V_{nom}} \] (8.12)

By introducing (8.12) in the MPPT scheme shown in Figure 8.3, any disturbance occurring in the grid voltage can be captured as the PCF by the ratio between the positive-sequence voltage and the nominal rated voltage. The voltage sag at the distribution network having low X/R ratio can be dealt with by injecting active power as much as possible up to the rated value. However, unlike dispatchable sources, the WPS cannot maintain the rated output value due to the fluctuating wind conditions. Therefore, at the rated wind condition, the inverter current is maintained at the rated value during the voltage sag. In addition, the current is reduced with decreasing wind speed but still maintained at the MPPT value irrespective of grid voltage conditions. Therefore, the PCF based control strategy is proposed to control the active power injection to remain in a grid.
during the voltage sag so that the MPPT power level can be maintained right after the fault clearance.

When the voltage sag occurs, the PCF will reduce the power output from the wind turbine to the grid. As a result, the angular rotor speed of the wind turbine rises over the maximum limit and at the same wind speed. For the purpose of illustration, let us assume that the PMSG based VSWT is in its normal operating mode to begin, with $\beta = \beta_{\text{min}}$ (minimum value), $P_{\text{ref}} = P_{\text{opt}}$ (optimal/maximum value) and $\omega_m = \omega_{\text{opt}}$ (optimal value), as shown in Figure 8.4.

Assume that the PCF is activated now. The power, which is at the optimal value $P_{\text{opt}}$ at A, drops to $P_{bc}$ at B. The turbine rotor speed increases to the new value $\omega_m = \omega_{mb}$ with reduced generating power $P_{\text{ref}} = P_{bc}$ for the same wind speed. If the rotor speed is within the maximum permissible speed, $\omega_{\text{max}}$, the power remains in the same curve with no activation of the pitch control. Otherwise, the pitch control mechanism is activated with $\beta > \beta_{\text{min}}$ and the power is shifted to the second curve with $P_{\text{ref}} = P_{bc}$ and $\omega_m = \omega_{\text{max}}$ at C. If the disturbance in the grid is cleared, the PCF acts as a unity factor control and the MPPT scheme resumes again, with the operating point power moving back to A.

8.4.2.3 Control during Unbalanced Voltage Sag (Out of MPPT Scheme)

The VCCF in addition to the PCF in the positive synchronous reference frame (SRF), is proposed to eliminate the negative-sequence currents at the output terminal of the inverter
during an unbalanced grid voltage sag. Therefore, this control strategy requires information about the positive- and the negative-sequence of the system voltage as explained in [178]. The system frequency is also extracted through a PLL scheme [182]. The unbalanced grid voltage on the primary side of the transformer and the inverter voltage and current can be represented by positive- and negative-sequence voltages in d-q SRF as

\[ V_{pdq} = e^{j\omega t}V_{pdq} + e^{-j\omega t}V_{pdq} \] (8.13)

\[ V_{idq} = e^{j\omega t}V_{idq} + e^{-j\omega t}V_{idq} \text{ and } i_{pdq} = e^{j\omega t}i_{pdq} + e^{-j\omega t}i_{pdq} \] (8.14)

where \( K_{xpdq} = K_{xpd} + jK_{xq} \) is the positive-sequence component, \( K_{xpdq} = K_{xqdn} + jK_{xqdn} \) is the negative-sequence component, \( K = V, i \) and \( x = p, i \) respectively. The inverter model has been explained in [179], where the inverter’s AC side terminal d-q voltage is

\[ V_{idq} = V_{pdq} + L \frac{di_{pdq}}{dt} + R_i_{pdq} \] (8.15)

The inverter terminal voltage can be controlled in d-q frame by the pulse width modulation (PWM) signals of the inverter as

\[ V_{idq} = \frac{V_{dc}}{2} m_{dq} \] (8.16)

Substituting the positive-sequence component from (8.13) and (8.14) into (8.15), it follows that:

\[ e^{j\omega t}V_{idq} = e^{j\omega t}V_{pdq} + L \frac{d(e^{j\omega t}i_{pdq})}{dt} + Re^{j\omega t}i_{pdq} \] (8.17)

Now expanding

\[ L \frac{d(e^{j\omega t}i_{pdq})}{dt} = j\omega Li_{pdq}e^{j\omega t} + L e^{j\omega t} \left( \frac{di_{pdq}}{dt} \right) \] (8.18)

Substituting (8.18) into (8.17), it follows that:

\[ V_{idq} = V_{pdq} + j\omega Li_{pdq} + L \left( \frac{di_{pdq}}{dt} \right) + R_i_{pdq} \]

or \( L \left( \frac{di_{pdq}}{dt} \right) = -j\omega Li_{pdq} - R_i_{pdq} + V_{idq} - V_{pdq} \) (8.19)

Decomposing (8.19) into d-q components, one can show that:
\[ V_{pdp} = -L \frac{di_{pdp}}{dt} - Ri_{pdp} + \omega Li_{pqp} + V_{idp} \quad (8.20) \]

\[ V_{pqp} = -L \frac{di_{pqp}}{dt} - Ri_{pqp} - \omega Li_{pdp} + V_{iqp} \quad (8.21) \]

Substituting the positive sequence components from (8.14) into (8.16) and then substitute in (8.20) and (8.21) and arrange it so that,

\[ L \left( \frac{di_{pdp}}{dt} \right) + Ri_{pdp} = \omega Li_{pqp} + \frac{V_{dc}}{2} m_d - V_{pdp} \quad (8.22) \]

\[ L \left( \frac{di_{pqp}}{dt} \right) + Ri_{pqp} = -\omega Li_{pdp} + \frac{V_{dc}}{2} m_q - V_{pqp} \quad (8.23) \]

The terms at the right hand side of (8.22) and (8.23) are the feed-forward terms, which can be implemented in vector current control to decouple the dynamics of the \( d \)-\( q \) axes currents, mitigate the dynamic effect of DLV variations, and rapidly mitigate any changes in positive-sequence grid voltage. By representing the right hand sides with \( y_d \) and \( y_q \), (22) and (23) can be reduced to a first order system using the feed-forward scheme as

\[ L \left( \frac{di_{pdp}}{dt} \right) + Ri_{pdp} = y_d \quad (8.24) \]

\[ L \left( \frac{di_{pqp}}{dt} \right) + Ri_{pqp} = y_q \quad (8.25) \]

where \( y_d \) and \( y_q \) are the outputs of the controllers used in the inverter current control system. In addition, \( m_d \) and \( m_q \) are determined by using (8.24) and (8.25) in (8.22) and (8.23) along with the addition of negative-sequence voltages as

\[ m_d = \frac{2}{V_{dc}} (y_d - \omega Li_{pqp} + V_{pdp} + V_{pdc}) \quad (8.26) \]

\[ m_q = \frac{2}{V_{dc}} (y_q + \omega Li_{pdp} + V_{pqp} + V_{pqn}) \quad (8.27) \]

A schematic block diagram of the inverter from (8.26) and (8.27) is shown in Figure 8.5, which represents the VCCF control scheme.
The currents in \( d-q \) axes are regulated in positive SRF, as per the active and reactive power references determined by the MPPT block and the grid requirements. The systems associated with the active and reactive powers are decoupled and controlled independently. Therefore, the current compensator is augmented with a measure of positive and negative-sequence voltages, along with other feed-forward terms to decouple the dynamics of the \( d-q \) axes components. The positive- and negative-sequence voltages at the inverter terminal and the PCC cancel each other out, leaving the current flow from the inverter terminal to be determined solely by the compensator (\( PI \) controller), which operates in positive SRF and carries the positive-sequence currents only.

8.4.2.4 Tuning the \( PI \) Compensator

The frequency response technique is used to design the gain values for the \( PI \) controller. The time constant (\( \tau_I \)) is selected based on the fast current control response, and the bandwidth is at least ten times smaller than that of the switching frequency of the inverter [179], such that \( \tau_I = 0.5 \text{ms} \).
8.5 Simulation Studies

Computer simulations have been carried out in PSCAD to show the adverse effects of voltage sag on a wind turbine system, and experiments are performed to validate the proposed concept (Section 8.5). The parameters of this physical wind turbine simulator and grid are listed in Table 8.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage/frequency</td>
<td>170 [V]/60 [Hz]</td>
</tr>
<tr>
<td>Rated power</td>
<td>1.2 [kW]</td>
</tr>
<tr>
<td>Rated rotational speed</td>
<td>900 [rpm]</td>
</tr>
<tr>
<td>Stator reactance</td>
<td>3.067 [Ω]</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>1.03 [Ω]</td>
</tr>
<tr>
<td>Flux linkage</td>
<td>0.1976 [Wb]</td>
</tr>
<tr>
<td>Number of poles</td>
<td>8</td>
</tr>
<tr>
<td>Blade radius</td>
<td>1.2 [m]</td>
</tr>
<tr>
<td>Optimal power coefficient</td>
<td>0.43</td>
</tr>
<tr>
<td>Optimal tip speed ratio</td>
<td>6.28</td>
</tr>
</tbody>
</table>

8.5.1 Case Study I: Without Proposed Control

In this study, it is assumed that unbalanced voltage sag (13%, 63%, 50%) has occurred due to asymmetrical phase disturbances. The disturbance has lasted for 82 cycles starting from 0.174 s, as shown in Figure 8.6.
Figure 8.6: Performance of the wind system under an unbalanced three phase grid voltage sag without control (Zoomed waveform before and after the fault is shown just below each waveform): (a) Grid AC voltage at PCC (b) Positive-sequence $d-q$ axes voltage (c) Reference and positive-sequence $d-q$ components of current (d) Negative-sequence $d-q$ components of current (e) PLL-Omega (rad/s) and $q$-axis voltage and (f) DLV

Since the VCCF along with the PCF is implemented in $d$-$q$ SRF, the analysis is primarily done in $d$-$q$ axes, currents and voltages. The proposed control scheme is not used in this case study. The outputs of WPS, such as voltages, currents, and the extracted frequency exhibit oscillations at twice the system frequency due to the unbalanced voltage sag as shown in Figure 8.6(b-e). In addition, the voltage drops and the current rises drastically, due to the voltage sag. Due to the imbalanced power flow between the generator and the grid side converter, as well as the presence of negative-sequence components, the DLV has also increased and is oscillating, as shown in Figure 8.6(f).

8.5.2 Case Study II: Analysis of Wind System Output Current

In this study, the three phase output current of the wind system is analyzed with and without the proposed control strategy shown in Figure 8.7 under the same disturbance described in Case Study I. The zoomed waveform of the phase currents is shown for 24 cycles before and after the unbalanced voltage sag.
In the absence of the proposed control strategy, the phase current becomes asymmetrical and rises to almost 2.0 p.u. of the nominal value, until the disturbance is cleared at 1.554s as shown in Figure 8.7(a). With VCCF, the current becomes symmetrical during an unbalanced voltage sag; however, the amplitudes of the currents are still not maintained at their nominal value of 1.0 p.u., as shown in Figure 8.7(b). The effectiveness of the combined VCCF and PCF control strategy in dealing with this issue is shown in Figure 8.7(c). The phase currents remain symmetrical at the same amplitude throughout the operating period, irrespective of symmetrical or asymmetrical disturbances. This is because the negative-sequence currents have been eliminated, while active power generation has been reduced in proportion to the voltage sag, such that the power balance is maintained without disturbing the current.

8.6 Experimental Validation

An experimental investigation has also been performed to validate the effectiveness of the proposed control strategy in a realistic environment. The experimental setup is shown in Figure 8.8.
An induction motor is controlled to drive the PMSG to emulate the WT as the wind turbine simulator. A buck converter and an inverter have also been designed and fabricated to support this experiment. The DLV is maintained at 36 V, while the grid is emulated by a commercial 1.5 kVA AC source. The Texas Instruments controller and National Instruments LabVIEW controller are used to control the buck converter and WTS, respectively. The inverter control is implemented in dSPACE, and the data is collected through dSPACE control desk with a step size of 58 μsec, down-sampled by a factor of 5. The parameters are given in Appendix A.

8.6.1 Case Study I: Unbalanced Voltage Sag (13%, 63%, 50%)

The physical WTS is operated under the same scenario as in Case Study I in the simulation section, but with the proposed control. The zoomed waveform for the three phase grid voltage is shown in Figure 8.9(a), before and after the disturbance for 70 ms.
Figure 8.9: Performance of the wind system under an unbalanced three phase grid voltage sag with the proposed control: (a) Wind system AC voltage (b) Positive-sequence $d-q$ components of the voltage (c) Positive-sequence $d-q$ components of the current (d) Negative-sequence $d-q$ components of the current (e) PLL-Omega and $q$-axis voltage and (f) DLV

The oscillation which occurs at twice the system frequency has been eliminated by canceling out the flow of negative sequence current. In comparison to Figure 8.6(b-f), the experimental results with the proposed control strategy show that the oscillation dies out, positive sequence current is at the pre-disturbed level, negative sequence current is zero, frequency is at the nominal value with 9% fluctuation during the transient period for a short interval of 1.5 ms, and the DLV is also at the nominal value with no oscillations; however a fluctuation of 2.5% occurred during the transient period as shown in Figure 8.9 (b-f).

8.6.2 Case Study II: Balanced Voltage Sag (46%, 46%, 46%)

In the second experimental case study, the balanced grid voltage sag is studied under the proposed control strategy, as shown in Figure 8.10. The balanced grid voltage sag is caused by a symmetrical fault at 20.18 ms for 6.3 cycles, as shown in Figure 8.10 (a). The wind speed is maintained at 9 m/s. It is observed from Figure 8.10 (b-c), that the turbine power and torque have both decreased. Although the rotational speed of the wind turbine increases for lighter load conditions, the rotational speed is still within the rated value, as shown in Figure 8.10 (d).
Figure 8.10: Performance of the wind system under an balanced three phase grid voltage sag with the proposed control: (a) Grid AC voltage (b) Turbine power (c) Turbine torque (d) Rotational speed (e) Power coefficient (f) DLV (g) Positive-sequence $d - q$ components of voltage (h) Positive-and negative- sequence $d - q$ components of the current (i) PLL-Omega and $q$ –axis voltage and (j) Active and reactive power

The power coefficient is also reduced, as shown in Figure 8.10 (e), while the DLV has been regulated with a 1% fluctuation around the reference, irrespective of grid conditions, as seen in Figure 8.10 (f). While the positive-sequence $d$-axis voltage has sagged due to the balanced grid voltage sag, the positive-sequence $q$-axis voltage is maintained at its
reference zero value, as shown in Figure 8.10 (g). Due to the balanced grid voltage sag shown in Figure 8.10 (h), the positive-sequence $d-q$ currents are regulated at their respective reference values with no negative-sequence currents, and the PLL is able to extract the system frequency precisely with zero $q$-axis secondary voltage, as shown in Figure 8.10 (i). The balanced grid voltage sag also means that the power delivered to the grid is reduced to balance the power flow between the generator and the inverter, as shown in Figure 8.10 (j).

### 8.7 Conclusions

This chapter proposes a power control strategy for PMSG-based VSWTs in order to keep the WPS connected to the low voltage distribution grid network during balanced and unbalanced grid voltage sags caused by faults or unbalanced loads. Two control strategies have been developed: One is to use a feed-forward path to regulate the negative-sequence current, while the other one is to curtail the wind power output to balance the power flow. The cost-effective proposed control strategies which do not require oversized converters, large DC link capacitor, and a crowbar circuit, have been implemented on an experimental test facility to validate their effectiveness. The experimental results show that the control strategies are effective in maintaining the negative-sequence current to zero, balancing the power flow during unbalanced and balanced grid voltage sags, and maintaining the inverter peak current within the safe, pre-disturbance value.
Chapter 9

9 Control Strategy for a Grid Connected Wind System based on Sliding Mode Control Approach

9.1 Introduction

The grid connected wind source is normally operated in a current or power controlled mode. Thus the vector current control strategy is used to enhance the performance [183]. However, the performance of the control strategy degrades in the presence of unbalanced voltage sags at PCC. Therefore, the VCCF including the current limiting strategy: PCF is proposed in Chapter 8 using the linear \(PI\) controller. This proposed strategy is further enhanced by using the non-linear sliding mode controller (SMC) in order to suppress the transient effect and bring robustness to the parametric variations, in addition to the features obtained in Chapter 8. Therefore, the same control strategies explained in Chapter 8 are implemented under the SMC approach. In addition, the proposed control strategy is demonstrated under an appropriate grid code (supplying reactive power) in this chapter.

The PMSG based VSWT is connected to the grid at the point of common coupling through a power electronic converter which can often be divided into two stages. The first stage consists of a three phase diode rectifier plus a DC-DC converter (generator side converter (GSC)) to interface to the DC link, and the second stage is DC-AC converter (inverter or network side converter (NSC)) to interface to the AC bus. The VCCF includes the current limiting strategy under the SMC approach at the NSC, and SMC based DC link voltage regulation at the GSC is proposed.

The validity of the proposed control strategy is verified by simulation and experimental results under unbalanced voltage sags at the PCC. The experimental results show that the negative sequence current is regulated to zero, a ripple free DC link voltage is maintained, the extracted frequency is free of oscillation, and the output currents are maintained within the safe levels (pre-disturbed value). In addition, the transient performance of the system has been improved in comparison with the classical \(PI\)
controller. The robustness of SMC has also been examined against parametric variations. Therefore, the proposed control strategy provides safe and reliable operation of the PMSG based VSWT at the distributed grid network using SMC approach.

The problem statement is presented in Section 9.2. The Section 9.3 presents the system description. The proposed SMC based control strategy is discussed in Section 9.4. The numerical simulations and experimental results are followed by conclusions in Sections 9.5, 9.6, and 9.7, respectively.

9.2 Problem Statement

The WES is a non-linear system, which requires a non-linear and robust controller to perform satisfactorily. The classical $PI$ linear controller is used commonly in WES, which performs well under small disturbances but may not be effective in the presence of large disturbances, such as transient disturbances [96]. This is because $PI$ controllers are designed based on linearized small signal models. These models become invalid under large disturbances [97]. In addition, SSWTs at the distribution grid network are highly exposed to inherent transient disturbances, such as frequent weather fluctuations, variations in dynamic loads, and temporary faults. The reason could be the close proximity of such wind turbines to the loads and surroundings such as trees, and buildings. These transient disturbances create stress on the PEC [184], where a large amplitude transient can shorten the life span of the components and lead to premature failures [11],[185].

In the literature, the non-linear controllers have been used in PEC such as adaptive control, hysteresis control, intelligent control, and modern control theory based controllers such as state feedback controllers and self-tuning controllers. However, most of the nonlinear controls are application dependent and difficult to design and implement, whereas sliding mode control (SMC) is an exception, as it is straightforward to design and easy to implement. Furthermore, the conventional control strategy for the GSC is to carry out maximum power point tracking schemes, whereas the power flow in the NSC is determined by the DC link voltage regulation [57]. This conventional control strategy has two issues:
(i) The power flow is not accurate to the reference as the controller output of the DLV regulation determines the power flow;

(ii) The complexity arises for the implementation of SMC [103]. The number of differentiations of the output function required for the input to appear explicitly is called the relative degree of the system [186], which becomes 2 for the NSC.

With the proposed control strategy the DLV, active power, and reactive power control are decoupled, so that a separate sliding surface for each variable with a relative degree 1 is considered. As a result, all variables are regulated independently with smooth transient effects and no complexity. Therefore, the proposed control strategy is performing the following tasks under the SMC approach: (i) GSC- DLV regulation; and (ii) NSC- power injection strategy:

(i) The reactive power is injected based on the grid code during the voltage sag to support the voltage at the grid.

(ii) The active power is the difference between the MPPT power and reactive power, so that the amplitude of converter current is maintained within the safe limits.

(iii) The VCCF in the positive synchronous reference frame (SRF) is proposed to regulate the negative sequence currents to zero during unbalanced voltage sag.

The control strategy achieved the same performance as shown in Chapter 8 in the presence of unbalanced voltage sag at PCC, in addition to the suppressed transient effect and robustness to the parameter variations. In addition, the loops for feed forward terms in the control strategy in Chapter 8 are eliminated with SMC approach. The complexity of the control structure is reduced.
9.3 System Description

The PMSG based VSWT investigated in this paper is shown in Figure 9.1.

![Diagram of PMSG based VSWT in Power Grid Network](image)

**Figure 9.1:** Schematic diagram of PMSG based VSWT in Power Grid Network

At present, the PMSG technology commercially uses a passive rectifier instead of a highly efficient but costly voltage source converter [183]. The buck converter topology is chosen for the DC-DC converter in the laboratory environment for its simplicity and cost effectiveness. The three phase inverter (DC-AC converter) with a low input DLV and step up transformer is considered to perform the study on the proposed control strategy. The GSC is used to regulate the DLV in voltage control mode with inner current closed loop, whereas the NSC performs the power flow control based on maximum power point tracking scheme. The \( LC \) filter is used in line with the inverter to provide a smooth and pure sinusoidal waveform, while the step up transformer is used to bring the inverter output voltage up to the level at the PCC, as shown in Figure 9.1.

9.4 Proposed Sliding Mode Control Based Control Strategy

The objective of SMC is to slide over a pre-defined manifold which is chosen based on the desired behavior of the system as the states converge to this manifold. The general equation to determine the sliding surface is as follows:

\[
s = \left( \frac{d}{dt} + c \right)^{n-1} e
\]

where \( c \) is a positive coefficient which describes the band width of the controller, \( e \) is the output error and \( n \) is the relative degree of the state variable. A Lyapunov approach is used to select the sliding surface based on the control law that will drive the state orbit to the equilibrium manifold. The positive scalar Lyapunov function is:
The necessary condition for the system to remain within the vicinity of the manifold or always converging to the sliding manifold is $s \dot{s} < 0$. The switching function of the sliding mode controller ensures the stability by keeping the state trajectories on the sliding manifold. Therefore, the switching control is calculated based on the system behavior along the sliding mode described as
\[ s = \dot{s} = 0 \]  \hspace{1cm} (9.3)

**9.4.1 GSC: DC Link Voltage Regulation**

The buck converter is used to regulate the DLV ($V_{dc}$), hence the output state of the converter is taken as $V_{dc}$. The converter dynamic model is derived by using the generalized state space averaging (GSSA) method [187], which provides two sets of topological circuit state-space equations as:

\[
\begin{align*}
\frac{di_{ind}}{dt} &= \frac{1}{L_i} (d_c V_{in} - V_{dc}) \\
\frac{dV_{dc}}{dt} &= \frac{1}{C_{dc}} \left( i_{ind} - \frac{V_{dc}}{R_l} \right)
\end{align*}
\]  \hspace{1cm} (9.4)

where $V_{in}$, $d_c$, $i_{ind}$, $L_i$, $C_{dc}$ and $R_l$ are input voltage, duty cycle of the pulse width modulation (PWM) technique, inductor current, line inductor, DC link capacitor, and the resistive load, respectively. The sliding surface for the output is chosen with a relative degree 1 from (9.1). The surface is written as
\[ s = e \]  \hspace{1cm} (9.5)

The linear combination of the state variables, as shown in (9.4) is set as the sliding surface of the converter, therefore,
\[ e = ae_1 + be_2 + ce_3 = 0 \]  \hspace{1cm} (9.6)

where $a$, $b$, and $c$ are the coefficients of the SMC, while $e_1$, $e_2$, and $e_3$ are the current error, voltage error, and error dynamics, which are defined as
\[
\begin{align*}
e_1 &= i_{ref} - i_{ind} \\
e_2 &= V_{dc ref} - V_{dc} \\
e_3 &= \int (e_1 + e_2) dt
\end{align*}
\]  \hspace{1cm} (9.7)
where $i_{ref} = ke_2$ is the reference average inductor current, $k =$ voltage error gain and $V_{dc \text{ref}}$ is the reference DLV. Now substituting (9.7) in (9.6) and applying in (9.5), so that

$$s = a(i_{ref} - i_{\text{ind}}) + b(V_{dc \text{ref}} - V_{dc}) + c \int (e_1 + e_2) \, dt = 0$$

Then, substitute $i_{ref}$ and differentiate with respect to time,

$$\frac{ds}{dt} = ak \frac{dV_{dc \text{ref}}}{dt} - ak \frac{dV_{dc}}{dt} - a \frac{di_{\text{ind}}}{dt} + b \frac{dV_{dc \text{ref}}}{dt} - b \frac{dV_{dc}}{dt}$$

$$+ c(k + 1)(V_{dc \text{ref}} - V_{dc}) - ci_{\text{ind}} = 0 \quad (9.8)$$

Substituting (9.4) in (9.8) and replaced $d_c$ by $u_{eq}$, so that,

$$\frac{ds}{dt} = \frac{-a_u_{eq} V_{\text{in}}}{L_i} + \frac{aV_{dc}}{L_i} - \frac{b i_{\text{ind}}}{C_{dc}} + \frac{bV_{dc}}{R_i C_{dc}} - \frac{ak i_{\text{ind}}}{C_{dc}} + \frac{akV_{dc}}{R_i C_{dc}}$$

$$+ c(k + 1)(V_{dc \text{ref}} - V_{dc}) - ci_{\text{ind}} = 0 \quad (9.9)$$

From (9.9), $u_{eq}$ is derived as

$$u_{eq} = \frac{aR_i C_{dc} V_{dc} - (R_i i_{\text{ind}} - V_{dc})(bL_i + aL_i k)}{aR_i C_{dc} V_{\text{in}}}$$

$$+ \frac{cR_i L_i C_{dc} [(k + 1)(V_{dc \text{ref}} - V_{dc}) - i_{\text{ind}}]}{aR_i C_{dc} V_{\text{in}}} \quad (9.10)$$

where $u_{eq}$ is the equivalent control signal. The equivalent control signal performs satisfactorily if the SMC is ideal or only low frequency components exist. However, in the practical implementation, the signal slides over the manifold with high frequency components as well. Thus, the low pass filter is used to filter out the high frequency component during the experiments. Therefore, the control law is of the form

$$u_{st} = \begin{cases} 1 = \text{ON}, & \text{if } s > 0 \\ 0 = \text{OFF}, & \text{if } s \leq 0 \end{cases} \quad (9.11)$$

The switching control law makes sure the trajectory is directed towards the sliding manifold. However, it does not guarantee that the trajectory is maintained on the selected manifold. Therefore, the Lyapunov function as stated in (9.2) must be obeyed to ensure
the trajectory is maintained on the selected manifold. Hence, the phase trajectory is given by the combined switching function \( sf(t) \) as
\[
sf(t) = u_{eq} + u_{st}
\]
(9.12)
The equation (9.12) is implemented to regulate the DLV under the SMC scheme.

9.4.2 NSC: Power Injection Strategy

The power reference is determined from the MPPT scheme to inject maximum power during normal conditions. However, the active power injection has been reduced during unbalanced voltage sag for two reasons: (i) to support the grid by supplying the reactive power; and (ii) to limit the current output within the safe level. The active power \( P \) and reactive power \( Q \) in \( d-q \) positive synchronous reference frame (SRF) can be represented as
\[
\begin{align*}
P &= \frac{3}{2} [V_{pdp}i_{pdp} + V_{pqp}i_{pqp}] \\
Q &= \frac{3}{2} [-V_{pdp}i_{pqp} + V_{pqp}i_{pdp}]
\end{align*}
\]
(9.13)
where \( V_p \) and \( i_p \) are the primary side voltage and current, with subscripts \( d, q, p \) and \( n \) denoting \( d \) axis, \( q \) axis, positive sequence and negative sequence, respectively. The PLL regulates the positive sequence \( q \)-axis voltage to zero \( (V_{pqp} = 0) \) to extract the system frequency for synchronization. Therefore, the current references in \( d-q \) frame \( (i_{pdpref} \) and \( i_{pqpref} \)) can be calculated from (9.13) as
\[
\begin{align*}
i_{pdpref} &= \frac{2}{3V_{pdp}} P_{ref} \\
i_{pqpref} &= \frac{2}{3V_{pdp}} Q_{ref}
\end{align*}
\]
(9.14)
The reactive power reference \( Q_{ref} \) (i.e. the \( q \)-axis current reference, \( i_{pqpref} \)) is determined from the mandatory grid code. Whereas the active power reference is the difference between the MPPT power and reactive power. From (9.14), the reference active power is written as
\[
P_{ref} = 1.5V_{pdp}i_{pdpref}
\]
(9.15)
When the grid voltage is symmetrical, the voltage is equal to the nominal rated voltage denoted by ‘$V_{nom}$’. The power injected into the grid is equal to the maximum power ($P_{mppt}$) from the MPPT scheme (reactive power is zero), such that

$$P_{mppt} = 1.5V_{nom}i_{pd pref}$$  \hspace{1cm} (9.16)

From (9.15) and (9.16), the reference power becomes

$$\begin{cases} 
    P_{ref} = \frac{V_{pd p}}{V_{nom}} P_{mppt} \\
    \text{PCF} = \frac{V_{pd p}}{V_{nom}} 
\end{cases}$$  \hspace{1cm} (9.17)

The ratio between the positive sequence voltage and the nominal voltage is referred to as the power compensation factor (PCF). As shown in (9.17), the injected power during an unbalanced voltage sag is proportional to the positive sequence voltage. Based on the PCF, the reactive power requirement is determined from the grid code. The active power flow is the difference between the MPPT power and the reactive power. As a result, the WES output current is maintained within the inverter rated current irrespective of grid voltage condition.

The turbine rotor speed increases with decreasing power demand. If the turbine rotor speed spins over the maximum permissible speed then the wind turbine is in danger of mechanical failure. Therefore, pitch angle control must be energized to maintain the turbine rotor speed within the maximum permissible speed, as explained in [189].

**9.4.3 NSC: Negative Sequence Current Regulation**

The VCCF in the positive SRF is proposed to regulate the negative sequence currents to zero during unbalanced grid voltage. Therefore, this control strategy requires information on the positive and the negative sequences of the system voltage, and the extracted system frequency through the PLL, as shown in Figure 9.2.
where $\delta$, $V_s$, $V_p$, and $i_p$ are the phase angle, secondary side voltage, primary side voltage and primary side current, respectively, with subscripts $abc$, $d$, $q$, $p$ and $n$ denoting $abc$ axes, $d$–axis, $q$–axis, positive sequence and negative sequence, respectively. The voltages and currents are decomposed into positive and negative sequence components and then transformed into positive sequence $d - q$ coordinates as shown in Figure 9.2. The angle required to transform $abc$ axes to $d - q$ axes is extracted from the grid using a PLL scheme. The vector current control using SMC is implemented in the positive SRF, while the negative sequence grid voltage is augmented with the current compensator output as a feed-forward scheme shown in Figure 9.2. Therefore, the voltage generated at the inverter has exactly the same negative sequence voltage as the grid voltage. The negative sequence voltage difference between the inverter terminal and the local grid becomes zero. This means the flow of negative sequence current is zero. Consequently, only the positive sequence current flows to the grid. This concept is implemented using SMC in the following manner.

The SMC is designed to generate the inverter output voltage, which is the input to the PWM technique. Hence, the output states are the positive sequence $d - q$ axis primary side currents, $i_{pdp}$ and $i_{pq}$, which are used to control the active and reactive power independently. The sliding surface for the output is chosen with a relative degree 1 from (9.1). The surface that satisfies the chosen output states is written as

$$s_1 = e_1 \text{ and } s_2 = e_2$$

(9.18)

where $e_1 = i_{pdp} - i_{pdpref}$ and $e_2 = i_{pq} - i_{pqpref}$
The reference $q$–axis current $i_{pq\text{ref}}$ is determined from the grid code in order to supply the reactive power, whereas the reference $d$–axis current $i_{pd\text{ref}}$, represents the active power flow, is obtained from the difference between the MPPT and reactive power requirements.

The manifolds $s_1 = e_1 = 0$ and $s_2 = e_2 = 0$ indicate that the sliding mode occurs only at the origin. Therefore, smooth transients and robustness cannot be guaranteed in the transient state for all disturbances. To solve this problem, an integral function is included in the sliding surface mentioned in (9.1). Therefore, the sliding surfaces are

$$s_1 = e_1 + k_1 \int e_1 dt$$  \hspace{1cm} (9.19)

$$s_2 = e_2 + k_2 \int e_2 dt$$  \hspace{1cm} (9.20)

where $k_1$ and $k_2$ are integral constants. From (9.3) and (9.19),

$$s_1 = s_2 = \dot{s}_1 = \dot{s}_2 = 0$$  \hspace{1cm} (9.21)

$$\dot{s}_1 = \frac{de_1}{dt} + k_1 e_1 = 0$$  \hspace{1cm} (9.21)

$$\dot{s}_2 = \frac{de_2}{dt} + k_2 e_2 = 0$$  \hspace{1cm} (9.22)

Substitute $e_1$ in (9.21),

$$\dot{s}_1 = \frac{d(i_{pd} - i_{pd\text{ref}})}{dt} + k_1 (i_{pd} - i_{pd\text{ref}}) = 0$$  \hspace{1cm} (9.23)

or

$$\dot{s}_1 = \frac{di_{pd}}{dt} + k_1 (i_{pd} - i_{pd\text{ref}}) = 0$$  \hspace{1cm} (9.23)

The $d$–$q$ components of the inverter AC side terminal voltage in positive sequence are represented as [179]

$$V_{pdp} = -L \left( \frac{di_{pd}}{dt} \right) - Ri_{pd} + \omega Li_{qp} + V_{idp}$$  \hspace{1cm} (9.24)

$$V_{qpq} = -L \left( \frac{di_{qp}}{dt} \right) - Ri_{qp} - \omega Li_{pd} + V_{iqp}$$  \hspace{1cm} (9.25)

where $V_{idp}$, $V_{iqp}$, $R$, and $L$ are positive sequence inverter output voltages in $d$–$q$ axes, line resistance, and the inductance of the LC filter after the inverter.

Re-arranging (9.24) and substituting into (9.23),

$$\dot{s}_1 = \frac{1}{L} (-V_{pdp} - Ri_{pd} + \omega Li_{qp} + V_{idp}) + k_1 (i_{pd} - i_{pd\text{ref}}) = 0$$
Then,

\[ f_1 = \frac{1}{L}(-V_{pdp} - Ri_{pdp} + \omega L i_{pq}), \quad g_1 = \frac{1}{L}, \quad u_1 = V_{lp} \]

Then,

\[ \dot{s}_1 = f_1 + g_1 u_1 \quad (9.26) \]

Similarly, (9.22) is derived as

\[ \dot{s}_2 = f_2 + g_2 u_2 \quad (9.27) \]

where

\[ f_2 = \frac{1}{L}(-V_{pqp} - Ri_{pqp} - \omega L i_{pq}), \quad g_2 = \frac{1}{L}, \quad u_2 = V_{lq} \]

Then,

\[ F = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix}, \quad G = \begin{bmatrix} g_2 & 0 \\ 0 & g_2 \end{bmatrix}, \quad U = \begin{bmatrix} V_{pdp} \\ V_{pqp} \end{bmatrix} \quad \text{and} \quad s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \]

Taking the derivative of the Lyapunov function in (9.2) with respect to time,

\[ \frac{dW}{dt} = s^T \frac{ds}{dt} \quad (9.28) \]

Substitute (9.26) and (9.27) in (9.28),

\[ \frac{dW}{dt} = s^T (F + GU) \quad (9.29) \]

The switch control law must be chosen such that (9.29) is definitely negative with \( s \neq 0 \). Hence the stability is maintained. Therefore, the control law is selected as

\[ U = -G^{-1} \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} + \begin{bmatrix} -c_1 & 0 \\ 0 & -c_2 \end{bmatrix} \begin{bmatrix} \tanh(s_1) \\ \tanh(s_2) \end{bmatrix} \quad (9.30) \]

where \( c_1 \) and \( c_2 \) are the positive constants. The sliding surface dynamics are selected as the tangent function of the surface such that the switching function is continuous and chatter free as explained in [190]. The SMC based control block diagram is shown in Figure 9.3 using (9.30).
9.4.4 NSC: Overall Control Strategy

The overall control strategy block for the NSC is shown in Figure 9.4.

![Figure 9.3: Block diagram of the simplified SMC for inverter voltage output](image)

![Figure 9.4: Control strategy for NSC in positive sequence SRF](image)

This block is categorized into three sections:

(i) **Power injection strategy:** The reference power is determined based on the grid code during voltage disturbance at the PCC. The power extracted from the MPPT scheme is the apparent power for the NSC. The control strategy shown in Figure 9.4 can inject the reactive power based on the grid code requirements. The active power is the difference between the MPPT power and the injected reactive power. The PCF is used to determine the reactive power. If the grid is normal, then the PCF is 1. In this case, the WES is operated in unity power factor under MPPT scheme. If the PCF < 1 then the active power flow is less than the MPPT output to balance the power flow. According to the proposed control strategy, the WES injects active and reactive power based on the mandatory grid code.
(ii) **SMC based current control:** The negative sequence current is regulated to zero and the positive sequence current is allowed to flow from NSC to DGN. The block diagram shown in Figure 9.3 is implemented in this block.

(iii) **PWM block:** The sliding mode current controller is designed to generate the inverter output voltage. This inverter output voltage, along with feed-forward of the negative sequence voltage, is the input to the PWM block in Figure 9.4. The modulating signals \( m_d \) and \( m_q \) in the PWM technique can be generated as

\[
\begin{align*}
V_{idp} + V_{pdn} &= \frac{V_{dc}}{2} m_d \\
V_{iqp} + V_{pqn} &= \frac{V_{dc}}{2} m_q
\end{align*}
\]

(9.31)

The NSC terminal voltage in positive sequence \( d-q \) axis \( (V_{idp} \text{ and } V_{iqp}) \), along with negative sequence voltages as feed-forward terms and the DC link voltage, determine the modulating (control) signals of the control strategy. Since the flow of negative sequence current is regulated to zero, the control signals are responsible for the flow of positive sequence currents only.

### 9.5 Simulation Studies

The parameters of the wind system and network considered in this study are provided in Appendix. A grid disturbance of an unbalanced voltage sag is considered to examine the proposed SMC based control strategy for SSWT. The inherent transient disturbances such as changes in wind speed and parameter variations are also evaluated to validate the improvement in transient conditions and robustness of the SMC. Furthermore the SMC is compared against that of a classical \( PI \) controller to justify the performance under the disturbances. The \( PI \) controllers for the converters are designed using the frequency response technique and selected such that the system has a phase margin of at least 60° (the values are given in the Appendix).

#### 9.5.1 Case Study I: Fluctuating Wind Speed

The wind speed (normalized at 9.5 m/s) with turbulence effect is shown in Figure 9.5 (a). The average wind speed is increased from 6.5 m/s to 9 m/s at 0.59 s and decreased again to
6.5 m/s at 1.01s, respectively. This rise and fall of the wind speed has introduced transients in the wind system.

Figure 9.5: (a) Wind speed (normalized at 9.5 m/s), (b) Control signal, (c) DC link voltage and (d) Inverter current

The control signal of the PI is not as smooth as that of the SMC during a transient as shown in Figure 9.5(b). The PI controller demands a tradeoff between the overshoot and settling time. As a result, the PI controller could not stabilize the system as quickly as the SMC. Hence, the DLV has also the undershoot and overshoot of 9.2 % during wind speed fluctuations with PI control, as shown in Figure 9.5(c). However, the smooth DLV is observed with SMC. The output power from the WES increases with increasing wind speed, hence the output current also increases with constant grid voltage. Moreover, the current has transient effects such as oscillation before reaching steady state with PI controller, as shown in Figure 9.5(d). This oscillation is removed when SMC is implemented. The smooth transient is observed with SMC during fluctuations in wind speed.

9.5.2 Case Study II: Varying System Frequency

This scenario is considered to show the robustness of the proposed SMC. The grid frequency is deliberately reduced by 10 % (339.3 rad/s) at 0.591s and brought back to the nominal value (377 rad/s) at 0.91s as shown in Figure 9.6(a).
Figure 9.6: (a) System frequency-omega (rad/s), (b) DC link voltage (c) Inverter current

The DLV has an overshoot and undershoot of 5.75% at 0.591s and 0.91s, respectively, with PI control, as shown in Figure 9.6(b). However, the transient effect can hardly be noticed with the SMC as shown in Figure 9.6 (b). This is because SMC is designed to slide over the given surface irrespective of system operating conditions. Similarly, the inverter output current is also maintained at reference level under the SMC, as shown in Figure 9.6(c). However, the current increases to compensate for the decreased frequency through its PI controller. However it saturates at its maximum limit, and does not increase drastically. This demonstrates the robustness of the SMC against parametric variations.

9.5.3 Case study III: Unbalanced Grid Voltage Sag (13%, 63% and 50 %) without Compensation

The unbalanced network voltage sag occurs, due to asymmetrical loads on the three phases. The asymmetrical loads are considered for 82 cycles starting at 0.174 s, as shown in Figure 9.7(a). The negative sequence current appears in the system due to the unbalanced loads, as shown in Figure 9.7(b).
Figure 9.7: Wind system during an unbalanced voltage sag with PI control but without the proposed control strategy (zoomed version on top): (a) AC voltage at PCC, (b) Inverter negative sequence $d-q$ axis currents, (c) Inverter positive sequence $d-q$ axis voltages, (d) Inverter positive sequence $d-q$ axis currents, (e) DC link voltage, and (f) Extracted frequency-omega (rad/s).

As a result, the inverter $d-q$ axis positive sequence voltages and currents oscillate at twice the system frequency as shown in Figures 9.7(c) and 9.7(d). The voltage and current oscillates for a few cycles even after the clearance of the unbalanced condition in the presence of the linear PI controller. The current hits the upper saturation limit for the pre-disturbed power reference and reduced voltages as shown in Figure 9.7(d). The DLV also oscillates at 20% of amplitude with PI control under the conventional control structure, as shown in Figure 9.7(e). The rise in the DLV with oscillation indicates that the power flow is imbalanced between the generator and the NSC in the presence of negative sequence currents. The unbalanced network voltage sag also destabilizes the system frequency, as shown in Figure 9.7(f). The frequency which is represented in rad/s as omega is oscillating at 15% of the nominal value.
9.5.4 Case study IV: Unbalanced Grid Voltage Sag (13%, 63% and 50%) with Compensation

With the proposed control strategy using SMC, the negative sequence currents are regulated to zero, as shown in Figure 9.8(a). As a result, the oscillation in the wind system variables such as positive sequence voltages and currents at the output of the NSC, DLV and extracted frequency are removed, as shown in Figure 9.8(b)-(e).

![Figure 9.8](image)

**Figure 9.8:** Wind system during an unbalanced voltage sag under the proposed SMC based control strategy (zoomed version on top): (a) Inverter negative sequence $d-q$ axis currents, (b) Inverter positive sequence $d-q$ axis voltages, (c) Inverter positive sequence $d-q$ axis currents, (d) DC link voltage, and (e) Extracted frequency-omega (rad/s).

The positive sequence voltage is reduced due to the voltage sag at the PCC; however it is free of oscillation, as shown in Figure 9.8(b). The $q-$axis voltage is regulated to zero to extract the system frequency in the PLL scheme. The positive sequence $d-$axis current is maintained at the pre-disturbed value where as the positive sequence $q-$axis current is increased to supply the reactive power to the system during the voltage sag as shown in Figure 9.8(c). However, the supplied reactive power is limited to the capacity of NSC.
after supplying the active power. The active power is delivered in proportion to the positive sequence voltage. The DLV and extracted frequency are regulated to their pre-disturbed values without oscillations, as shown in Figures 9.8(d) and 9.8(e) respectively. In addition, the transient response has been improved by the use of non linear SMC.

9.6 Experimental Validation

An experimental investigation is also performed to validate the effectiveness of the SMC based control strategy. The experimental set up is shown in Figure 9.9.

The performance of the SMC during an unbalanced network voltage sag is investigated. For the experimental test-bed, the induction motor is coupled with the PMSG with control to emulate the wind turbine as the WTS. A DC-DC converter and an inverter are also designed and constructed for the test bed. The grid is emulated by a 2 kVA AC power supply. The data is collected through dSPACE control desk with a step size of 58 µsec and downsampled by a factor of 5. The parameters are given in Appendix A.

9.6.1 Unbalanced Grid Voltage Sag (13%, 63% and 50 %) with Compensation (SMC based control strategy)

The unbalanced network voltage sag occurs due to asymmetrical loads on different phases. The asymmetrical loads are considered for 82 cycles starting at 0.174 s, as shown
in Figure 9.10(a). Therefore, the SMC based control strategy for an unbalanced network voltage sag is implemented and performed similar to Case Study IV in Section 9.4. However, the experimental results appear with some measurement noise and offsets, due to scaling factors in the sensor devices.

The negative sequence currents are regulated to zero as shown in Figure 9.10(b). Thus, the oscillation in the positive sequence voltages are eliminated; however the sag is still persisting as shown in Figure 9.10(c). The $q$-axis voltage is regulated to zero to extract the system frequency in the PLL scheme. In comparison to the simulation result, the $q$-axis voltage is regulated with some offset value. The positive sequence $d-q$ axis currents are regulated according to the grid code to support the voltage at PCC during voltage sag, as shown in Fig. 9.10 (d). The positive sequence $d$-axis current is reduced whereas the positive sequence $q$-axis current is increased to provide reactive power.
The DLV is maintained at its reference level without any oscillation throughout the experiment as shown in Figure 9.10(e). However some noise and offset is present. The frequency is also maintained at its nominal value (377 rad/s), as shown in Figure 9.10 (f), similar to the simulation result shown in Figure 9.8(e).

The unbalanced network voltage sag experiments show that the SMC based control strategy removes wind system oscillations (appearance of negative sequence currents), the rise in the DLV with oscillations (imbalanced power flow), and the increase in inverter current (beyond the safe limit). In addition, the SMC smoothed out the transient effects quite effectively. As a result, the PMSG based VSWT can stay connected in the distributed grid network during an unbalanced voltage sag at the PCC.

9.7 Conclusions

In this chapter the same control strategy proposed in Chapter 8 is implemented using sliding mode control approach. However, the strategy is performed under a grid code (supplying reactive power). The experimental results show that the control strategy maintains the performance of VCCF and PCF in the presence of voltage sag at PCC, as explained in Chapter 8: regulating negative sequence current to zero, balancing the power flow, and maintaining the peak current within the safe limit. In addition, the SMC brings following advantages to the control strategy: suppressing the transient effects, bringing the robustness to the parameter variations, and reducing the complexities in the control structure by eliminating the loops for feed-forward terms.
Chapter 10

10 Conclusions and Future Work

10.1 General Conclusion

The power management control strategies for a direct drive PMSG based VSWT (wind Type IV) in different structures such as hybrid, microgrid and distribution grid network are presented in this thesis. The power management control strategies are varied according to the structure; however, the objectives of regulating DC link voltage, amplitude and the frequency of AC link voltage, and balanced power flow are the same and are maintained irrespective of inherent disturbances (weather fluctuation for renewable sources), varying load demands, and grid side issues, such as balanced and unbalanced voltage sag. The hybrid system and microgrid in Chapters 6 and 7 are operated without a dedicated battery converter and a dump load/crowbar circuit under the proposed power management control strategies. Similarly, the grid connected wind system in Chapters 8 and 9 are operated without crowbar circuits under the proposed control strategy. Thus, the designed control strategies for power management in a hybrid, microgrid, and distributed grid network are assumed to be simple implementation, cost effective and efficient.

The conclusions for the work done in each chapter are presented in the following:

CHAPTER 1

In this chapter, the motivation and benefits of the research presented in this thesis has been discussed. In addition, the problem statements and objectives of the thesis have also been presented. The possible wind power system operating structure and the control strategies for power management define the scope of the thesis, which are classified as hybrid, microgrid and low voltage distribution grid network. Accordingly, the contributions of the thesis have been listed out. The literature surveys pertinent to the research have been also presented.
CHAPTER 2
In this chapter, the modeling of energy sources is carried out. The modeling is performed to test the proposed control strategy before validating in a physical hardware system. The wind system types are briefly explained in order to highlight the advantages of type IV wind system, which is considered in the research. The static and dynamic characteristics of Type IV wind system are presented. Furthermore, the permanent magnet synchronous generator is modeled in the $d-q$ synchronous reference frame. In addition, the PV source and lead acid battery are also modeled. The widely used approach for PV source is considered, which is to mathematically formulate the relationship between model parameters and solar irradiance and temperature. The CIEMAT (Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas) model for lead acid battery which is the detailed and accurate model is considered in this study. The most common structures and controls of renewable energy based power system are also reviewed in order to highlight the contributions of the work.

CHAPTER 3
In this chapter, the design and development of the physical hardware system, which is built in the laboratory along with their real time control platform, is presented. The purpose of this physical hardware system is to support the research by validating the proposed control strategies in a real time physical system. The physical wind turbine is simulated using an induction motor, vector torque controller, and hardware-in-the-loop concept such as a wind turbine simulator (WTS). The power electronic converters are also designed and developed for energy sources to interface in the microgrid. Furthermore, the real time controller platform is implemented. The sensors and protection devices for the equipment are also designed and developed. The features of the commercial PV simulator and lead acid battery are also presented.

CHAPTER 4
In this chapter, the modeling of PMSG, PV source and lead acid battery which were done in Chapter 2 are validated against the real physical system in the laboratory. The purpose is to design and validate the control strategies under the same simulated and experimental structures. The development of the physical systems such as sensors, real time controller
and converters, which were performed in Chapter 3, helped perform real time testing of
the energy sources. In addition, the data were also collected in a real time. These
collected data of the physical systems are compared with the PSCAD simulation results
based on the developed models. The results show that the models of the physical system
are acceptable against the real physical systems.

CHAPTER 5

In this chapter, the coordinated control strategy for a wind source along with the battery
with its own dedicated DC-DC converter, dump loads with a crowbar circuit, and a
backup AC source (can be a diesel generator) is proposed. The control strategy is
designed for a wind source to balance the power flow to the load irrespective of
fluctuating weather conditions and load demands. It has been shown that the proposed
coordinated control strategy can provide several attractive features for a wind/battery
system along with dump loads and a diesel generator. First, the wind is operated at
maximum power in all operating conditions without any control transition. Second, the
wind/battery hybrid system operation in the microgrid is unaffected by the fully charged
or over discharged battery due to the presence of dump loads and a diesel generator.
Otherwise, the instability issues would occur in the microgrid. Third, the presence and
activation of a diesel generator only during low SOC of the battery provides the
following advantages in addition to charge the battery and meet the deficit power: (i)
Maximum use of local power (wind/battery) reduces the electricity bill from the grid; and
(ii) Reduces the frequent operation of diesel generator, which cust down the operating
cost of the microgrid.

CHAPTER 6

In this chapter, the integrated control and DVVC strategies at DC and AC link of the
hybrid system consisting of a PMSG based direct drive wind turbine and battery energy
storage are proposed. In contrast to the common way of controlling wind source as a
voltage source in the literature, it is shown that controlling the wind source as a current
source in a hybrid system that follows an integrated control strategy, can charge the
battery with regulated current value instead of high continuous current. As a result, the
battery life cycle has been improved and protected against high inrush current during fast transition of system operation, such as load variations. Furthermore, the system performance is maintained without the need of a dedicated battery converter and a dump load as illustrated in Chapter 5. On the other side, the DVVC strategy regulates the amplitude and frequency of the AC link voltage without deteriorating the performance in the presence of unbalanced loads. The obtained experimental results show that the operation of the hybrid system in a satisfactorily manner under steady state as well as transient conditions by achieving the following results: (i) regulating the DLV within the operating range irrespective of fluctuating weather conditions and load demands; (ii) operating the wind source under MPPT scheme; (iii) protecting the battery from overcharging; and (iv) regulating the AC link voltage and frequency at references irrespective of unbalanced load conditions. Thus, the control strategy provides a stable operation with a cost effective and efficient configuration.

CHAPTER 7

In this chapter, the distributed control strategy using DC link voltage based control law for power management in a DC microgrid is presented and validated experimentally in a system consisting of PMSG based variable speed wind turbine, PV, battery energy storage and loads. In contrast to the common way of controlling sources under droop control to regulate the DC link voltage in a DC microgrid, it is shown that controlling the sources under distributed control using an established dynamic control law, the power sharing and voltage regulation have been improved, and there is no issue with the circulating current. In addition, the strategy does not require a real time communication link. However, the offline communication is proposed to enhance the performance by reducing the frequent operating mode transitions. As a result, the smooth coordination of sources is maintained along with the renewable operation under MPPT scheme. The proposed strategy is operated in the same system configuration features: no battery converter and a dump load, for the advantages explained in Chapter 6. Thus, it is believed to be cost effective, efficient, and straightforward to implement as local information is required without any need of exchanging real time information.
CHAPTER 8

In this chapter, a power control strategy for PMSG-based VSWTs is proposed in order to keep the WPS connected to the grid during balanced and unbalanced grid voltage sags caused by faults or unbalanced loads in the distribution system. Two control strategies have been developed: One is to use a feed-forward path to regulate the negative-sequence current, while the other one is to curtail the wind power output to balance the power flow. The cost effective proposed control strategies which do not require oversized converters, large DC link capacitor, and a crowbar circuit, have been implemented on an experimental test facility to validate their effectiveness. The experimental results show that the control strategies are effective in maintaining the negative-sequence current to zero, balancing the power flow during unbalanced and balanced grid voltage sags, and maintaining the inverter peak current within the safe, pre-disturbance value.

CHAPTER 9

In this chapter, the same control strategy proposed in Chapter 8 is implemented using the sliding mode control (SMC) approach. However, the strategy is performed under a grid code (supplying reactive power). The experimental results show that the control strategy maintains the performance of VCCF and PCF in the presence of voltage sag at PCC, as explained in Chapter 8: regulating negative sequence current to zero, balancing the power flow, and maintaining the peak current within the safe limit. In addition, the SMC brings the following advantages to the control strategy: suppressing the transient effects, bringing the robustness to the parameter variations, and reducing the complexities in the control structure by eliminating the loops for feed-forward terms.

10.2 Future Work

The proposed control strategies in this thesis are validated against certain type of hybrid systems (wind/battery), DC microgrid (wind/PV/battery) and grid networks (voltage sag disturbance). The control strategies can be evaluated with different combinations (hybrid/microgrid) and characteristics (slow/fast dynamics) of sources and grid disturbance (voltage swell) in order to identify limitations and potential issues of the
proposed control strategies. Based on this, the potential future work is suggested as follows:

- The thesis presents the integrated control strategy without a bidirectional converter and a crowbar circuit for a hybrid wind/battery system. This concept can be analyzed with multiple hybrid wind/battery systems. The interesting aspects could be the balanced power flow and their dynamic interactions in the system.

- The distributed control strategy based on the established dynamic control law for a DC microgrid is proposed in the thesis. The concept is validated in the microgrid consisting of a Type IV wind system and a PV source. The presence of full scale frequency converter in both sources, provides the same dynamics to the system. However, the proposed concept can be implemented in a microgrid consisting of both fast and slow dynamic sources such as wind/PV and fuel cell. The control law needs to be modified to balance the power flow with smooth coordination and without frequent mode of transitions.

- The proposed concept of power management strategy with optimum number of power electronic devices or components can be employed in small and medium sized renewable sources based AC microgrid. The motivation is to increase the revenue of the renewable energy sources by reducing the components failure rate and the maintenance time and the costs.

- The VCCF and PCF techniques are proposed for a small wind system integrated at distribution network in order to remain on grid without damaging itself, and provide support to the grid in order to maintain stability by supplying reduced power during an unbalanced voltage sag, and full power right after the clearance without a significant delay. With the slight modification on PCF concept, the same techniques can be implemented for voltage swell conditions as well.

- The WTS is designed and developed using an induction motor, vector torque mode controller, and hardware-in-the-loop-concept. In the proposed technique, the feedback torque is estimated using a detailed induction motor model and flux observer. Instead of estimating torque, a dynamometer can be used to identify the exact torque value.
This will bring the WTS further close to the PWT. In addition, the inclusion of detailed aerodynamic model consisting of gravity and gyroscopic force of wind turbine would add up one more dimension in the simulator. Therefore, the research work such as fault tolerant control against mechanical failure of the wind turbine can be validated through the simulator.
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http://www.iitmicrogrid.net/windconsortium-pdf.aspx#prettyPhoto/2/


www.truenorthpower.com/images/stories/FilesDNLD/wind_arrow_manual_wav1.6e.pdf,


http://www.chromausa.com/dc-power-supply.php


Appendix A

A.1 Induction Motor Parameters (WTS)

Table A.1: Induction motor parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>3</td>
<td>hp</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Stator resistance</td>
<td>2.63</td>
<td>Ω</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>1.73</td>
<td>Ω</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>0.0155</td>
<td>H</td>
</tr>
<tr>
<td>Rotor inductance</td>
<td>0.021</td>
<td>H</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>0.4224</td>
<td>H</td>
</tr>
<tr>
<td>Inertia of rotor</td>
<td>0.284</td>
<td>lb-ft²</td>
</tr>
<tr>
<td>Inertia of maximum load</td>
<td>40</td>
<td>lb-ft²</td>
</tr>
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</table>

A.2 Permanent Magnet Synchronous Generator Parameters

Table A.2: PMSG parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>8</td>
<td>N/A</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>94.23</td>
<td>rad/s</td>
</tr>
<tr>
<td>Armature resistance</td>
<td>1.03</td>
<td>Ω</td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>0.395</td>
<td>Wb</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>9.2</td>
<td>mH</td>
</tr>
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</table>

A.3 Hybrid Wind/Battery System Parameters

Table A.3: Hybrid system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of wind</td>
<td>1.0</td>
<td>kW</td>
</tr>
<tr>
<td>Rated battery capacity</td>
<td>32</td>
<td>Ah</td>
</tr>
<tr>
<td>Nominal DC link voltage</td>
<td>36</td>
<td>V</td>
</tr>
<tr>
<td>Capacitor across buck converter input</td>
<td>2000</td>
<td>uF</td>
</tr>
<tr>
<td>Capacitor across the DC link</td>
<td>4700</td>
<td>uF</td>
</tr>
<tr>
<td>Inductor for the buck converter</td>
<td>1.02</td>
<td>mH</td>
</tr>
<tr>
<td>Switching frequency of buck converter</td>
<td>20</td>
<td>kHz</td>
</tr>
<tr>
<td>LC filter</td>
<td>140/405</td>
<td>uH/uF</td>
</tr>
<tr>
<td>Transformer turns ratio</td>
<td>12/208</td>
<td>V</td>
</tr>
<tr>
<td>Leakage inductance</td>
<td>0.1</td>
<td>p.u.</td>
</tr>
<tr>
<td>Switching frequency of inverter</td>
<td>9.7</td>
<td>kHz</td>
</tr>
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</table>
## A.4 DC Microgrid System Parameters

**Table A.4:** DC microgrid system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of wind</td>
<td>1.0</td>
<td>kW</td>
</tr>
<tr>
<td>Rated power of PV</td>
<td>0.6</td>
<td>kW</td>
</tr>
<tr>
<td>Rated battery capacity</td>
<td>32</td>
<td>Ah</td>
</tr>
<tr>
<td>Nominal DC link voltage</td>
<td>36</td>
<td>V</td>
</tr>
<tr>
<td>Capacitor across buck converter input</td>
<td>2000</td>
<td>uF</td>
</tr>
<tr>
<td>Capacitor across the DC link</td>
<td>4700</td>
<td>uF</td>
</tr>
<tr>
<td>Inductor for the buck converter</td>
<td>1.02</td>
<td>mH</td>
</tr>
<tr>
<td>Switching frequency of the converters</td>
<td>20</td>
<td>kHz</td>
</tr>
</tbody>
</table>
Appendix B

B.1 Major Components for Converter and Roof Wind Turbine Development

The detailed design and analysis reports for the major physical systems: (i) WTS; (ii) Roof wind turbine connection; and (iii) Buck converter, are available in the DG Laboratory (CMLP 2327).

Table B.1: Major Components for the Buck Converter

<table>
<thead>
<tr>
<th>S. N</th>
<th>Components</th>
<th>Part No.</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input capacitor</td>
<td>E36D401HLN182MCA5M-ND</td>
<td>Input filter (Main board)</td>
</tr>
<tr>
<td>2</td>
<td>MOSFET</td>
<td>FCH76N60N-ND</td>
<td>Switch (Main Board)</td>
</tr>
<tr>
<td>3</td>
<td>Diode</td>
<td>APT30S20BG-ND</td>
<td>Main Board</td>
</tr>
<tr>
<td>4</td>
<td>Inductor</td>
<td>ES55246-171M-40AH</td>
<td>Filter (Main board)</td>
</tr>
<tr>
<td>5</td>
<td>Output capacitor</td>
<td>495-3499-ND</td>
<td>Output filter (Main board)</td>
</tr>
<tr>
<td>6</td>
<td>Current sensor</td>
<td>398-1010-ND</td>
<td>Sensor board</td>
</tr>
<tr>
<td>7</td>
<td>Voltage sensor</td>
<td>398-1019-ND</td>
<td>Sensor board</td>
</tr>
<tr>
<td>8</td>
<td>MOSFET driver</td>
<td>CLA357-ND</td>
<td>Drive circuit</td>
</tr>
<tr>
<td>9</td>
<td>Optocoupler</td>
<td>516-1104-5-ND</td>
<td>Drive circuit</td>
</tr>
<tr>
<td>10</td>
<td>Isolated power supply</td>
<td>835-1118-ND</td>
<td>Drive circuit</td>
</tr>
<tr>
<td>11</td>
<td>Voltage regulator</td>
<td>LM7805CT-ND</td>
<td>Drive circuit</td>
</tr>
<tr>
<td>12</td>
<td>Heat sink</td>
<td>RA-T2X-64E-ND</td>
<td>Main board</td>
</tr>
<tr>
<td>13</td>
<td>Fan</td>
<td>Q622-ND</td>
<td>Enclosure</td>
</tr>
<tr>
<td>14</td>
<td>Power supply</td>
<td>102-1332-ND</td>
<td>Sensor (Main board)</td>
</tr>
<tr>
<td>15</td>
<td>Power supply</td>
<td>102-2039-ND</td>
<td>Fan (Main board)</td>
</tr>
<tr>
<td>16</td>
<td>Power supply</td>
<td>102-2414-ND</td>
<td>Drive circuit (Main board)</td>
</tr>
<tr>
<td>17</td>
<td>Board</td>
<td>V1048-ND</td>
<td>Main circuit board</td>
</tr>
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<td>Facilities Provided</td>
<td>Components</td>
<td>Parts No.</td>
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<td>--------------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>Turbine Room</td>
<td>Transfer switch</td>
<td>EAT1DT321NF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conduit, wires</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>Wind Turbine AC Box</td>
<td>Transfer switch</td>
<td>EAT1DT321NF</td>
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<tr>
<td>Wind Turbine DC Box</td>
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<td>PAXLVD00</td>
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<td>Current meter DC</td>
<td>PAXLID00</td>
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<tr>
<td></td>
<td>Power supply 24 DC</td>
<td>102-2414-ND</td>
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<tr>
<td></td>
<td>Enclosure</td>
<td>EJ16148 HAMEJ16148</td>
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<tr>
<td></td>
<td>Lightning Arrestor</td>
<td>LA302-DC Delta</td>
<td></td>
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<td>DC switch</td>
<td>SXDC1003 Mersen</td>
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<td></td>
<td>Handle</td>
<td>HSPR</td>
<td></td>
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<tr>
<td></td>
<td>Conductor, 40 ft</td>
<td>4BD-100310-3C SEOOW</td>
<td></td>
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<tr>
<td></td>
<td>IEC connector</td>
<td>Q302-ND</td>
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<td></td>
<td>Cable grips (10-12) AWG</td>
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<td></td>
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<td></td>
<td>Cable grips (18-24) AWG</td>
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<td></td>
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<tr>
<td></td>
<td>MOSFET</td>
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<tr>
<td>Weather Station</td>
<td>Weather Link</td>
<td>DAV6510USB</td>
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<td></td>
<td>Vantage Vu Console</td>
<td>DAV6351</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Fuses, wires etc</td>
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</table>
Appendix C

C.1 Algorithm for Optimal Location and Size for a Wind Source

The algorithm for optimal location and size of both dispatchable and non-dispatchable DG for enhancing loading margin (LM) and reducing system loss in a grid network is presented in this section.

C.1 Problem and proposed methodology

The power flow problem can be formulated by the following four variables associated with each bus, say bus $K$ – voltage magnitude ($V_K$), voltage angle ($\theta_K$), net active power ($P_K$) and reactive power ($Q_K$). At each bus, two of these variables are specified as input data and the other two are unknowns to be solved by the power flow equations. Consider a power system with $N$ buses, we can obtain the following non-linear power flow equations at bus $K$ in the rectangular coordinate form as:

$$P_K = V_K \sum_{i=1}^{N} V_i \left[ G_{Ki} \cos \theta_{Ki} + B_{Ki} \sin \theta_{Ki} \right], \quad K = 1, 2, \ldots, N$$  \hspace{2cm} (C.1)

$$Q_K = V_K \sum_{i=1}^{N} V_i \left[ G_{Ki} \sin \theta_{Ki} - B_{Ki} \cos \theta_{Ki} \right]$$  \hspace{2cm} (C.2)

where $P_K = P_{GK} - P_{LK}$ and $Q_K = Q_{GK} - Q_{LK}$ are the net injected active and reactive power. $P_{GK}$ and $Q_{GK}$ are the generated active and reactive power at bus $K$, whereas $P_{LK}$ and $Q_{LK}$ are the active and reactive load power at bus $K$ respectively. $Y_{Ki} = G_{Ki} + jB_{Ki}$ and $\theta_{Ki} = \theta_K - \theta_i$ are the admittance matrix and voltage angle between buses $K$ and $i$. $V_i$ is the voltage magnitude at bus $i$. The solution of (C.1) and (C.2) is obtained and linearized to form the Jacobian matrix as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$  \hspace{2cm} (C.3)

where $A_{11} = \frac{\partial P}{\partial \theta}$, $A_{12} = \frac{\partial P}{\partial V}$, $A_{21} = \frac{\partial Q}{\partial \theta}$ and $A_{22} = \frac{\partial Q}{\partial V}$ are the Jacobian submatrices representing the sensitivities of active and reactive power with respect to the bus angle and the voltage magnitude. The modal participation factor involves the computation of eigenvalues and the associated eigenvectors of a reduced Jacobian matrix which retains
the bus/voltage angle ($\theta$) – active power ($P$) relationships in the network. The sensitivity analysis of the bus angle with respect to active power is performed to identify the optimal location in the network for reducing system loss and enhancing loading margin (LM). The loading margin of the system is measured through the nose curve as the reduced Jacobian becomes singular at this point.

Only an active power producing DG, such as a PMSG based direct drive WTG operating at unity power factor, is considered. Thus, it is assumed $\Delta Q = 0$. Now rearrange (C.3) such that

$$0 = A_{21}\Delta \theta + A_{22}\Delta V$$

(C.4)

$$\Delta V = (-)(A_{22})^{-1}A_{21}\Delta \theta$$

(C.5)

$$\Delta P = A_{11}\Delta \theta + A_{12}\Delta V$$

(C.6)

Substituting (C.5) in (C.6),

$$\Delta P = [A_{11} - A_{12}(A_{22})^{-1}A_{21}]\Delta \theta$$

(C.7)

where, $A_{11} - A_{12}(A_{22})^{-1}A_{21} = J_p$ is the reduced Jacobian matrix containing $\theta$ and $P$ components only.

$$\Delta \theta = J_p^{-1}\Delta P$$

(C.8)

Equation (C.3) can also be written as

$$[\Delta \theta] = \begin{bmatrix} J_p^{-1} & J_p^{-1}A_{12}A_{22}^{-1} \\ -J_v^{-1}A_{21}A_{11}^{-1} & J_v^{-1} \end{bmatrix} [\Delta P] = J_f^{-1} [\Delta Q]$$

(C.9)

From (C.9), with $\Delta Q=0$,

$$\Delta V = -J_v^{-1}A_{21}A_{11}^{-1}\Delta P$$

(C.10)

The following relations can also be derived [C.1].

$$\det(J_f) = \det(A_{11})\det(J_v)$$

$$\det(J_f) = \det(A_{22})\det(J_v)$$

(C.11)

where $J_f$=full matrix

$J_v$=Reduced matrix with zero active power
\( J_p \) = Reduced matrix with zero reactive power

Since \( A_{11} \) and \( A_{22} \) are not singular for a practical power system [C.2], one can conclude that the singularity of the full matrix is determined solely by the singularity of the two submatrices, \( J_v \) and \( J_p \). From (C.11), it can also be shown that reduced matrices \( J_p \) and \( J_v \) are singular at the same point. Thus, (C.10) suggests that a small increase in active power will collapse the voltage magnitude at the singular point of the reduced Jacobian \( J_p \). Therefore, modal participation factor analysis of \( J_p \) will provide the impact of active power on voltage stability or LM. The \( \theta - P \) sensitivity analysis with respect to the participation factor can be derived in the following ways.

Let, \( J_p = \zeta \Lambda \eta \) \hspace{1cm} (C.12)

where \( \zeta \) = right eigenvector matrix of \( J_p \), \( \eta \) = left eigenvector matrix of \( J_p \) and \( \Lambda \) = matrix with eigenvalues of \( J_p \).

On the diagonals, and \( J_p^{-1} = \zeta \Lambda^{-1} \eta \) \hspace{1cm} (C.13)

From (C.8) and (C.13), it can be obtained that

\[ \Delta \theta = \zeta \Lambda^{-1} \eta \Delta P \text{ or } \Delta \theta = \sum_i \frac{\zeta_i \eta_i}{\lambda_i} \Delta P \] \hspace{1cm} (C.14)

where \( \zeta_i \) is the \( i \)th column right eigenvector of \( J_p \), \( \eta_i \) is the \( i \)th column left eigenvector of \( J_p \) and \( \lambda_i \) is the eigenvalue of \( \Lambda \) of the \( i \)th mode. Now, \( \theta - P \) sensitivity analysis at bus \( k \) becomes

\[ \frac{\partial \theta_k}{\partial P_k} = \sum_i \frac{\zeta_k \eta_i}{\lambda_i} \text{ or } \frac{\partial \theta_k}{\partial P_k} = \sum_i \frac{p_{ki}}{\lambda_i} \] \hspace{1cm} (C.15)

where \( p_{ki} \) is the participation factor of bus \( k \) to mode \( i \). It measures the contribution of the \( i \)th eigenvalue to the \( \theta - P \) sensitivity at bus \( k \). The bigger the value of \( p_{ki} \), the more contributions the mode \( \lambda_i \) makes to \( \theta - P \) sensitivity at bus \( k \).

**C.2 Demonstration example and discussions**

The proposed methodology has been tested on the IEEE 14 bus test system with a total load of 259 MW and 73.5 MVar [C.3]. A single line diagram of the system is shown in Figure C.1.
Table C.1: Participation factors of the dominant buses in IEEE 14 bus test system

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Participation Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.6707</td>
</tr>
<tr>
<td>9</td>
<td>0.6514</td>
</tr>
<tr>
<td>10</td>
<td>0.3876</td>
</tr>
<tr>
<td>13</td>
<td>0.3411</td>
</tr>
<tr>
<td>12</td>
<td>0.3316</td>
</tr>
<tr>
<td>8</td>
<td>0.1325</td>
</tr>
</tbody>
</table>

Table C.1 shows the participation factors of the dominant buses in this system. The dominant buses are defined as those buses which have comparatively larger participation factors such that the more \( \lambda_i \) contributes in determining \( \theta - P \) sensitivity at that bus. If a DG is placed at this location, it will have stronger influence on the system voltage stability and losses. It can be seen from Table C.1, the bus 14 is the most dominant bus in the test system.

C.2.1 Optimum Location of DG for Enhancing LM

When the DG is placed at bus 14, the improvement of the LM is shown in Figure C.2. The DG penetration is 0.38\% of the total system load, which improves the LM by 4.4 \%. The small penetration of DG, only 0.038\% of the total system load, is placed at each dominant bus to compare the improvement in the LM. The bus 14 has the maximal LM compared to other dominant buses in the system as shown in Figure C.3. Therefore, 0.038\% of DG penetration increases 1.528\% of LM with respect to the base case. Other dominant buses with DG can also improve the LM but not as much as for bus 14.
C.2.2 Optimal Size of DG

As shown in Figures C.4 and C.5, the LM and the system loss can be improved further, if the size of DG is increased between (16 - 20) % of the total system load. However, the situation worsens if the size goes beyond 20%. The optimal size of DG is 18% for this test system. The system loading margin is increased by 20.73% and the system loss is reduced by 18.93% with the optimal size DG at the optimal location.
Figure C.4: Loading factor with increasing penetration of DG at bus 14

Figure C.5: System loss with increasing penetration of DG at bus 14

C.3 Impact of Wind Source on LM and System Loss

An intermittent DG, such as wind or PV, is non-dispatchable source with fluctuating output. A wind turbine generator is used as an example. The sensitivity analysis of WTG at the closest dominant buses with respect to wind speed is investigated to improve LM and to reduce system loss. The optimal location for a WTG is at the location with high average wind speed, however, that does not necessarily lead to improved LM, nor reduced system loss.
The average wind speed and power at the Midwestern USA are shown in Figures C.6 and C.7 respectively. The raw wind speed is recorded at every minute. The average is taken for this raw wind speed over the period of one year. In this analysis, capacity factor (CF) is considered to determine the strength of the wind speed and hence its energy output. Since the CF depends dominantly on the location of installation and the turbine design, the same WTG is considered for three different locations. Based on the annual CF values, the locations have been determined as low (L: CF =0.2512), medium (M: CF=0.3587) and high (H: CF=0.4532) wind site. From the proposed methodology, buses 14 and 9 are found to be the dominant buses.
The LM of the system with WTG at two dominant buses 14 and 9 under three different wind profiles are shown in Figure C.8. The LM at the particular bus location changes with the wind speed profile. Tables C.2 and C.3 provide the suitable location of the WTG in a considered wind profile for enhanced LM and reduced system loss.

**Table C.2**: Best location of WTG based on loading margin

<table>
<thead>
<tr>
<th>Annual Average Wind Speed</th>
<th>Best Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (1.035)</td>
<td>L (1.062)</td>
</tr>
<tr>
<td>L (1.035)</td>
<td>M (1.09)</td>
</tr>
<tr>
<td>L (1.035)</td>
<td>H (1.108)</td>
</tr>
<tr>
<td>M (1.065)</td>
<td>L (1.062)</td>
</tr>
<tr>
<td>M (1.065)</td>
<td>M (1.09)</td>
</tr>
<tr>
<td>M (1.065)</td>
<td>H (1.108)</td>
</tr>
<tr>
<td>H (1.096)</td>
<td>L (1.062)</td>
</tr>
<tr>
<td>H (1.096)</td>
<td>M (1.09)</td>
</tr>
<tr>
<td>H (1.096)</td>
<td>H (1.108)</td>
</tr>
</tbody>
</table>

**Table C.3**: Best location of WTG based on system loss

<table>
<thead>
<tr>
<th>Annual Average Wind Speed</th>
<th>Best Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 9 (Loss %)</td>
<td>Bus 14 (Loss %)</td>
</tr>
<tr>
<td>L (4.544)</td>
<td>L (4.495)</td>
</tr>
<tr>
<td>L (4.544)</td>
<td>M (4.210)</td>
</tr>
<tr>
<td>L (4.544)</td>
<td>H (3.948)</td>
</tr>
<tr>
<td>M (4.314)</td>
<td>L (4.495)</td>
</tr>
<tr>
<td>M (4.314)</td>
<td>M (4.210)</td>
</tr>
<tr>
<td>M (4.314)</td>
<td>H (3.948)</td>
</tr>
<tr>
<td>H (4.244)</td>
<td>L (4.495)</td>
</tr>
<tr>
<td>H (4.244)</td>
<td>M (4.210)</td>
</tr>
<tr>
<td>H (4.244)</td>
<td>H (3.948)</td>
</tr>
</tbody>
</table>
From the above analysis, it is clear that the wind profile can cause changes to the optimal location from one dominant bus to its next closest one to improve LM and reduce system loss. For example, row 6 of Table C.3 with M wind speed at bus 9 and L wind speed at bus 14, the best location would be at bus 9. However, with dispatchable DG, bus 14 is still the optimal location.

C.3. Conclusions

This paper presents a method based on modal participation factor analysis to determine the optimal location and size of a DG operating at unity power factor. The location of the DG that maximizes the loading margin and minimizes the system loss would be considered as the dominant bus. However, the location of non-dispatchable DG can be influenced by the weather conditions. Therefore, the sensitivity analysis is performed with non-dispatchable DG at the closest dominant buses to identify the optimal location. This approach would be of interest to distribution companies who can improve their profit margins by enhancing the loading margin and reducing the system losses.

C.4. References


Curriculum Vitae

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