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Novel Control of PV Solar and Wind Farm Inverters as STATCOM for Increasing Connectivity of Distributed Generators

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

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NOVEL CONTROL OF PV SOLAR AND WIND FARM INVERTERS AS STATCOM FOR INCREASING CONNECTIVITY OF DISTRIBUTED GENERATORS

(Thesis format: Monograph Article)

by

Mahendra AC

Graduate Program in Engineering Science
Department of Electrical and Computer Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering Science

The School of Graduate and Postdoctoral Studies
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London, Ontario, Canada

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ABSTRACT

The integration of distributed generators (DGs) such as wind farms and PV solar farms in distribution networks is getting severely constrained due to problems of steady state voltage rise and temporary overvoltages (TOV). This thesis presents a first time application of a patent-pending PV solar farm control as a dynamic reactive power compensator (STATCOM), termed PV-STATCOM, for mitigating the voltage rise and TOV issues, and significantly enhancing the connectivity of a neighbouring wind farm both during night and day in a realistic distribution feeder in Ontario. The effectiveness of PV-STATCOM is demonstrated even if the solar farm is located 30 km away from wind farm on a common distribution line. The PV-STATCOM utilizes the entire inverter capacity in the nighttime and the inverter capacity remaining after solar power generation during daytime. A novel control of full converter based wind farm as Wind-STATCOM for substantially increasing the connectivity of a neighbouring PV solar farm is also described. The Wind-STATCOM employs the inverter capacity left after that needed for wind power production, both during night and day. Subsequently, a new combined application of PV-STATCOM and Wind-STATCOM to improve the connectivities of both solar farm and wind farm to significantly high levels in a common distribution feeder is presented. These studies have been conducted for the first time in known literature. Commercial grade software PSS/E and PSCAD/EMTDC are used to evaluate the steady state voltage profile and TOVs, respectively, in distribution feeder having different Reactance (X)/Resistance (R) ratios.

Keywords:
Distributed Generator (DG), Static Synchronous Compensator (STATCOM), Photovoltaic (PV) solar farm, wind farm, steady-state voltage, temporary overvoltage (TOV)
Dedicated to

Samman and Sraddha
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<tr>
<td>ALFC</td>
<td>Automatic Load Frequency Controller</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator</td>
</tr>
<tr>
<td>CBEMA</td>
<td>Computer and Business Equipment Manufacturer’s Association</td>
</tr>
<tr>
<td>CSC</td>
<td>Current Sourced Converter</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>DFIG</td>
<td>Doubly Fed Induction Generator</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation/Distributed Generator</td>
</tr>
<tr>
<td>DR</td>
<td>Distributed Resources</td>
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<td>EMTDC</td>
<td>Electromagnetic Transients including DC</td>
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<td>EPS</td>
<td>Electric Power System</td>
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<td>FACTS</td>
<td>Flexible AC Transmission Systems</td>
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<td>FIT</td>
<td>Feed-In Tariff</td>
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<td>GTO</td>
<td>Gate Turn-off Thyristor</td>
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<td>HONI</td>
<td>Hydro One Networks Inc.</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
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<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
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<tr>
<td>ITIC</td>
<td>Information Technology Industry Council</td>
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<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
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<tr>
<td>OLTC</td>
<td>On Load Tap Changer</td>
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<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
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<tr>
<td>PF</td>
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<td>Acronym</td>
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<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
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<td>PMSG</td>
<td>Permanent Magnet Synchronous Generator</td>
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<td>PSCAD</td>
<td>Power Systems Computer Aided Design</td>
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<td>Power System Simulator for Engineers</td>
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<td>TOV</td>
<td>Temporary Overvoltage</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Sourced Converter</td>
</tr>
<tr>
<td>Wind-STATCOM</td>
<td>Wind turbine (Inverter) Static Synchronous Compensator</td>
</tr>
<tr>
<td>WRSG</td>
<td>Wound Rotor Synchronous Generator</td>
</tr>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

$P_{LD}$ : Active power consumed by load

$Q_{LD}$ : Reactive power consumed by load

$P_{SF}$ : Active power supplied by solar farm

$Q_{SF}$ : Reactive power compensation by solar farm
  Positive - Inductive mode (consumed by solar farm),
  Negative - Capacitive mode (Supplied by solar farm)

$P_{WF}$ : Active power supplied by wind farm

$Q_{WF}$ : Reactive power compensation by wind farm
  Positive - Inductive mode (consumed by wind farm),
  Negative - Capacitive mode (Supplied by wind farm)

$V_{bus1}$ : Voltage magnitude at Bus 1 (in pu)

$V_{bus2}$ : Voltage magnitude at Bus 2 (in pu)

$V_{bus3}$ : Voltage magnitude at Bus 3 (in pu)

$V_{bus4}$ : Voltage magnitude at Bus 4 (in pu)

$V_{bus5}$ : Voltage magnitude at Bus 5 (in pu)

$I_{src}$ : Current magnitude flowing through supply end of feeder line (in Amps)
Chapter 1

INTRODUCTION

1.1 Growth of Wind Power and PV Solar Power Based Distributed Generators

Solar farms and wind farms are the most common distributed generators (DGs) that are primarily being connected in power distribution networks worldwide [1], [2]. By the end of 2012 global wind energy installed capacity increased to 276,055 MW, which was a significant growth from 4,800 MW in 1995 with average cumulative annual growth rate of about 28.5% [3]. The total installed capacity of the world’s major wind power producing countries is shown in Figure 1.1 whereas, the growth of wind power in Canada is given in Figure 1.2.

Due to incentives provided by several governments, small and medium scale PV solar installations are being increasingly installed worldwide [4]. Feed-in Tariff (FIT) program implemented by Ontario Government has helped to boost the growth of PV solar farm and wind farm in Ontario. The worldwide installations of PV solar capacity is shown in Figure 1.3 whereas the same for Canada is illustrated in Figure 1.4.
Figure 1.1 Total installed capacity (end of 2011) and new capacity added in 2011 for top 10 wind power producing countries

Figure 1.2 Growth of wind generation installed capacity in Canada
Figure 1.3 Total installed capacity (end of 2011) and new capacity added in 2011 for top 10 solar power producing countries

Figure 1.4 Growth of PV solar installed capacity in Canada
1.2 Issues with Grid Integration of DGs

Traditionally, power grids are fed from large centralized generating stations mainly based on hydro, thermal or nuclear generation technologies. The integrated power grids are characterized by large generation, bulk transmission and end use through distribution network. However, the distributed nature of renewable energy resources like solar and wind have transformed this traditional integrated power network with presence of a large number of small scale distributed generators (DGs) \[5\]. These distributed generators are normally connected to the medium voltage (MV) and low voltage (LV) distribution networks.

The interconnection of DGs in distribution network provides additional benefits in the network. With the development of solar farm and wind farm in medium voltage distribution network, the increase in the demand can be locally fulfilled reducing the cost of transmission network expansion. It also helps to reduce the transmission congestion in existing network. The transmission and distribution losses are reduced increasing the system efficiency. However, these benefits come along with new challenges to the system operator. The major issues encountered by the medium voltage distribution with the integration of distributed generation include, but not limited to, steady state voltage rise, increased temporary overvoltage (TOV), increase in voltage flicker and harmonic components, and restrictions on operation of existing grid protection \[5\] – \[7\] .

1.2.1 Steady state voltages

Connecting the DGs towards the receiving end of radial distribution system may create reverse power flow during the light load condition (off-peak load during nighttime). In this situation, the distribution line, traditionally operated to carry designed amount of power from the source end towards the load end, is likely to face increased voltage at the receiving end due to reverse power flow \[6\]. A typical scenario of reverse power flow can occur when DG output is greater than the load for the distribution network, shown in Figure 1.5.
For this network, the receiving end voltage is given by:

\[ V_{RE} = V_{SE} - I \cdot (R_L + j \cdot X_L) \]  \hspace{1cm} (1.1)

where, \( I = (P_{LD} - j \cdot Q_{LD})/V_{RE} \)

and, \( V_{SE} \) – Sending end voltage \\
\( V_{RE} \) – Receiving end voltage \\
\( P_{LD} \) – Load active power \\
\( Q_{LD} \) – Load reactive power \\
\( R_L \) – Line resistance \\
\( X_L \) – Line reactance

Here \( V_{RE} = V_{SE} - [(P_{LD} - j \cdot Q_{LD})/V_{RE}] \cdot [R_L + j \cdot X_L] \)

or, \( V_{RE} = V_{SE} - (P_{LD} \cdot R_L + Q_{LD} \cdot X_L)/V_{RE} + j \cdot (Q_{LD} \cdot R_L - P_{LD} \cdot X_L)/V_{RE} \) \hspace{1cm} (1.2)

The approximate expression for receiving end voltage is:

\[ V_{RE} \approx V_{SE} - (P_{LD} \cdot R_L + Q_{LD} \cdot X_L)/V_{RE} \] \hspace{1cm} (1.3)

For the DG in the receiving end with active power injection of \( P_{DG} \) at unity power factor, the receiving end voltage is given by:

\[ V_{RE} \approx V_{SE} - [(P_{LD} - P_{DG}) \cdot R_L + Q_{LD} \cdot X_L]/V_{RE} \] \hspace{1cm} (1.4)

From this expression we can identify that the receiving end voltage will increase depending on the reverse power flow created by the difference between load and...
generation at receiving end \((P_{LD} - P_{DG})\) and the line resistance \(R_L\). For a distribution system with low \(X/R\) ratio (i.e. high line resistance \(R\)), the rise in voltage can be substantial.

The guidelines provided by IEEE Standards (IEEE Std 1547-2003: IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems) [8] – [10] and CSA Standards (CSA C22.3 No. 9-08: Interconnection of distributed resources and electricity supply systems) [11] are widely implemented to specify the permissible steady-state voltage variation in distribution network. The steady state voltage limit of \(\pm 6\%\) of nominal value at the end user terminal is permitted in Hydro One’s Technical Interconnection Requirements [7]. Appropriate reactive power compensation is required to maintain steady state voltage within permissible limits. The conventional mitigation measures for voltage issues are discussed in Section 1.3 whereas measures based on Flexible AC Transmission Systems (FACTS) are discussed in Section 1.4.

### 1.2.2 Temporary overvoltage

In medium voltage networks, unbalanced faults, such as single line to ground fault (SLGF) in the network causes temporary overvoltages (TOV) on the healthy phases of the network feeder [12], [13]. Overvoltages between one phase and ground or between two phases are classified based on the shape of the voltage, percentage increase from nominal value and duration of application. Temporary overvoltages (TOV) originating from switching or system faults (e.g. load rejection, unbalanced faults) or from nonlinearities (ferroresonance effects, harmonics) are normally undamped or weakly damped [10].

Integration of distributed generators causes changes in fault level, fault current distribution and voltage profile in the distribution line. TOV in the distribution line mainly depends on pre-fault voltage, type of fault, fault resistance, etc. Single line to ground bolted fault is considered to observe the impact of temporary overvoltage in this thesis. The types of distributed generator and configuration of its interconnection transformer play important role in the temporary overvoltage.
The range of higher and lower level of system voltages, that end user equipment can safely handle, are specified by CBEMA voltage curves [14]. These characteristic shows that the voltage level as well as the time interval for which such voltages appear are both important in identifying the level of acceptable temporary overvoltage. The temporary rises in voltage are specified by IEEE standards [8] and CSA standards [11]. Based on these requirements, Hydro One Networks Inc. has specified that the TOV anywhere in the distribution network under no circumstances shall exceed 130% [7].

1.3 Conventional Mitigation Measures for Voltage Issues

In any power network, voltages at various system buses change continuously according to the variation in demand, switching of lines and transformers, and system contingencies. Power system operators are responsible for maintaining system voltages within permissible limits in all operating conditions. Typically, on load tap changing (OLTC) transformers are used to maintain voltages in medium voltage distribution network.

1.3.1 Voltage Regulation

Voltage control is achieved by implementing voltage regulators [15] at various locations in power network. Most of the existing voltage regulators in the distribution network are implemented for unidirectional power flow from the source to the load ends. Increased DG output during off-peak load hours, may result in reverse power flows. The upstream voltage regulators are affected by such reverse power flow [15]. Modifications of the controller have been proposed for the upstream line voltage regulators if DGs are connected to the system. Multiple line drop compensation based voltage regulators are effective to regulate the system voltage even with high penetration of distributed generators [16]. In the traditional distribution system, the system voltage is maintained by implementing upstream voltage regulators and the load end reactive power compensators. The DGs themselves are not allowed to regulate the bus voltages [7].
1.3.2 Reactive Power Compensation

It is a well-known fact that shunt compensation can be used to provide reactive power compensation locally at load buses. Conventional shunt capacitors or shunt inductors are used for this purpose. Capacitive reactive power compensation is used to increase the system voltage to desired level whereas inductive compensation is used to reduce the voltage during light load (off-peak) conditions. The terminal characteristic (I-V characteristic) for fixed capacitor and inductor is shown in Figure 1.6.

Shunt capacitors and inductors provide fixed compensation. Variable compensation is implemented by switching appropriate combination of capacitors or inductors. The variability of distributed generation resources and requirement of dynamic reactive power support make these conventional devices less effective in resolving voltage issues created by DGs. Synchronous condensers can provide continuously controlled reactive power output from inductive to capacitive region [17]. However, such devices have slow response and are less commonly employed in distribution systems due to their high cost.

![Figure 1.6 Terminal characteristic of fixed Capacitor/Inductor](image-url)
1.4 FACTS Controller based Mitigation Measures for Voltage Issues

Flexible AC Transmission System (FACTS) is defined as the AC transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability [18]. The FACTS Controllers impart the following benefits to the electric power network:

- Provides reactive power compensation
- Provides voltage regulation
- Improves steady-state stability and transient stability
- Damps power system oscillations
- Improves voltage stability
- Increases power transfer capability

In medium voltage distribution networks, shunt FACTS devices are used to provide very fast and continuous reactive power support. It helps to improve system power factor and regulate the system voltage. Due to their fast response and dynamic reactive power support capability, FACTS Controllers are most suitable to mitigate voltage fluctuation created by the solar and wind power integration to the grid [19]. Mostly, Static Var Compensator (SVC) – a thyristor based FACTS Controller [17], [20] and Static Synchronous Compensator (STATCOM) – a voltage source converter based FACTS Controller are used in medium voltage distribution network.

1.4.1 Static Synchronous Compensators (STATCOM)

The Static Synchronous Compensator (STATCOM) is a FACTS Controller utilized at the transmission and distribution level [18], and as a custom power device at end users’ electrical installations [21]. The major applications of STATCOM in these contexts include voltage regulation, power factor correction, damping power oscillations, and load balancing.
1.4.1.1 Principle of Operation

Static synchronous compensator (STATCOM) is a voltage sourced converter (VSC) based on controllable switches. A STATCOM is a shunt connected device that provides rapid reactive power compensation in the network.

STATCOM, which injects sinusoidal current at the point of common coupling, can emulate itself as inductive or capacitive reactive power source by aligning the injected current almost in quadrature with line voltage [22], [23]. A STATCOM with proper control strategy can be effectively used to suppress voltage fluctuation in the network [24], [25], [26].

A functional representation of the STATCOM showing various components is shown in Figure 1.7. The STATCOM is connected to the AC system terminal bus through a coupling transformer. The terminal characteristic for such STATCOM is shown in Figure 1.8. It is seen that the STATCOM can provide rated capacitive current at very low voltages. This feature is very helpful in voltage regulation. Pulse Width Modulation (PWM) controller is used to provide the firing pulses to the converter switches to achieve the control on active and reactive power flow from the STATCOM. A 2-level, 6-pulse, three phase converter is modeled as Static Synchronous Compensator (STATCOM) in this thesis.

![Figure 1.7 STATCOM connected to AC system through coupling transformer](image-url)
The single line diagram representing the grid and the STATCOM is shown in Figure 1.9. A STATCOM basically produces a set of balanced 3-phase sinusoidal voltages at fundamental frequency with fast voltage magnitude and phase angle control capability. The active and reactive power exchange between the STATCOM and the grid (flow from STATCOM terminal to grid side terminal) can be represented by the following expressions [17]:

\[ P = \frac{V_{BUS} \cdot V_{VSC}}{X_L} \cdot \sin(\delta) \] \hspace{1cm} (1.5)

\[ Q = \frac{V_{VSC}^2 - V_{BUS} \cdot V_{VSC} \cdot \cos(\delta)}{X_L} \] \hspace{1cm} (1.6)
From (1.5), it is noted that the real power transfer is dependent on the power angle ($\delta$) between STATCOM terminal and grid side terminal for nominal values of voltage magnitudes. Similarly from (1.6) it is seen that for small power angle $\delta$, the reactive power exchange is dependent on STATCOM terminal voltage magnitude compared to grid terminal voltage magnitude. Accordingly, various combinations of active and reactive power transfer to and from STATCOM may arise. The four combinations of active and reactive power transfer are illustrated with the help of phasor diagrams. The exchange of reactive power to and from the STATCOM is shown in Figure 1.10. The STATCOM will consume reactive power in inductive mode of operation if $V_{\text{VSC}} < V_{\text{BUS}}$ and will supply reactive power in capacitive mode of operation if $V_{\text{VSC}} > V_{\text{BUS}}$. Similarly, the exchange of active power is given in Figure 1.11. Active power will flow from AC side (Grid) to DC side (STATCOM) when power angle $\delta$ is negative. This will increase the DC link voltage. When power angle $\delta$ is positive, active power will flow from DC side to the AC side and the DC link voltage will decrease.

![Phasor diagram showing reactive power control by STATCOM](image1)

**Figure 1.10** Phasor diagram showing reactive power control by STATCOM,
(a) Reactive power consumed by STATCOM – Inductive mode, and
(b) Reactive power supplied by STATCOM – Capacitive mode

![Phasor diagram showing active power control by STATCOM](image2)

**Figure 1.11** Phasor diagram showing active power control by STATCOM -
(a) Active power consumed by STATCOM – Power flow from AC side to DC side
(b) Active power supplied by STATCOM – Power flow from DC side to AC side
1.4.1.2 STATCOM Controller

Based on the analysis presented above, a phase angle regulator and a voltage magnitude regulator are used to control the transfer of active power and reactive power respectively between the grid and the STATCOM. Accordingly, STATCOM can provide control on voltage magnitude and phase angle at its terminal.

Voltage Sourced Converters employ either fundamental frequency switching or pulse width modulation switching strategies. Due to low switching frequency in fundamental frequency switching technique, there is less loss in converter switching mechanism. However, this switching technique injects more harmonic components in the system. Normally, Gate Turnoff Thyristors (GTO’s) are used as controllable switches at fundamental frequency and multi-level voltage switching is used to reduce harmonic component. Alternatively, pulse width modulation (PWM) technique can be used to eliminate lower order harmonics and reduce the total harmonic distortion due to converters. Insulated Gate Bipolar Transistors (IGBT’s) are used as controlled switches to reduce switching losses in PWM converters. In sinusoidal pulse width modulation (SPWM), which is the most common PWM technique, the magnitude and frequency of the sinusoidal fundamental component are controlled by pulse width modulation. In such converters, the higher the switching frequency, the better will be the quality of the resulting waveform and smaller the filter capacitor and inductors requirements [27].

In PWM technique, the information about the fundamental component of the output voltage is embedded (modulated) in the widths of the output voltage pulses. The demodulation takes place in the output low-pass filter (LC filters), where the switching harmonics are separated from the fundamental component, or in the inductive load, where the pulsed voltage waveform is transformed to a sinusoidal current at the fundamental frequency. The Sinusoidal Pulse Width Modulation (SPWM) is based on generation of sinusoidal modulating signal and the triangular carrier signal [28], [29]. The sinusoidal modulating signal is compared with a triangular carrier signal of constant amplitude and frequency to generate the gate pulses for the switches. For three phase PWM converter, the AC voltage magnitude is given by:
\[ V_{LL} = \frac{\sqrt{3} \cdot m_a \cdot V_{DC}}{2\sqrt{2}} = 0.6124 \cdot m_a \cdot V_{DC} \] .......................... (1.7)

where,

- \( V_{LL} \) – AC side terminal voltage of 3 – phase converter
- \( V_{DC} \) – DC link voltage of the converter
- \( m_a \) – Amplitude modulation ratio (Modulation Index)
- \( m_f \) – Frequency modulation ratio

Here, \( m_a = \frac{V_{contorl}}{V_{tri}} \); i.e. \( \frac{\text{Peak value of sinusoidal modulating signal}}{\text{Peak value of triangular carrier signal}} \)

\( m_f = \frac{f_0}{f_1} \); i.e. \( \frac{\text{frequency of triangular carrier signal}}{\text{frequency of sinusoidal modulation signal}} \)

1.5 Mitigation Measures using DG based STATCOM

1.5.1 PV Solar Farm based STATCOM (PV-STATCOM)

Solar farms are equipped with grid tied inverters to facilitate the transfer of DC power generated from photovoltaic modules to the power grid. These inverters consist of voltage sourced converters with pulse width modulated (PWM) switching and necessary filter and/or interconnection transformer between the converter and the grid. PV solar farms are absolutely idle in the nighttime and only partially utilized during early morning and late evening hours. A novel control of PV solar farm inverter as STATCOM (termed PV-STATCOM) was proposed by Varma [30]. The PV-STATCOM can provide dynamic reactive power compensation utilizing the entire inverter capacity during nighttime and the inverter capacity remaining after real power generation during daytime [1], [31].
Figure 1.12 Active/reactive power capability curve for PV-STATCOM

Assuming the inverter capacity $S$ to be the same as the peak output power capacity of the photovoltaic modules, the active power $P$ and reactive power capability $\left( Q = \sqrt{S^2 - P^2} \right)$ of the PV-STATCOM is shown in Figure 1.12. It is noted that the PV-STATCOM can deliver up to 66% of reactive power when it is producing 75% of rated real power. Significant availability of reactive power even with large production of active power makes such PV-STATCOM control very effective in reactive power compensation. The detailed modeling and control of solar farm converter as STATCOM is presented in Chapter 2.
1.5.2 Wind Farm based STATCOM (Wind-STATCOM)

The flexibility of voltage sourced converters (VSC) and their fast response make it possible to control wind farm converters to provide FACTS-like performance characteristics for low voltage ride through applications [32]. For wind farms with variable speed permanent magnet synchronous generator and back to back full converter based interface connection, the VSC based grid side converter can be controlled as STATCOM [30]. Such STATCOM, referred as Wind-STATCOM, is incorporated in this thesis to achieve the required reactive power injection along with available active power. This reactive power injection is achieved by controlling the converter AC terminal voltage. The available active injection is controlled by controlling shift angle between PCC and converter AC terminal voltage. The active power and reactive power capability curve for Wind-STATCOM is similar to that of PV-STATCOM as shown in Figure 1.12. The detailed modeling and control of Wind-STATCOM is presented in Chapter 2.

1.6 Motivation of Thesis

The widespread growth of wind farms and PV solar farms is increasing their likelihood of being connected on same distribution networks. It is known that the reverse power flow due to increased DG output during light load condition causes steady-state voltage rise. Also, increased output from the DGs causes high temporary overvoltage for unbalanced faults. All these issues limit the amount of power that can be injected into the grid from wind farms and PV solar farms.

In this thesis, a novel control of existing inverters of solar farm as well as wind farm as STATCOM are presented to address the challenges created by grid integration of distributed generation. These challenges relate to steady state voltage rise due to reverse power flow with the increased generation in distribution network and the temporary overvoltage created by unbalanced faults with higher distributed generation integration. The application of novel PV-STATCOM and Wind-STATCOM controllers to address
these problems is the major focus of this thesis. It is expected that the implementation of such controller will be useful in significantly enhancing the DG connectivity in distribution networks.

### 1.7 Scope of Research

The dynamic reactive power compensation provided by the novel control applied to the existing solar farm inverters can be used in the transmission and distribution network for various applications [33] – [36]. Varma et al in [33] used a novel control concept by which the existing PV solar farm inverter is operated as STATCOM to improve the transient stability of the transmission network and consequently increase the power transfer capability of an existing transmission line.

In [34], authors have demonstrated voltage regulation and power factor correction using PV-STATCOM both during nighttime and daytime. The optimal utilization of solar farm for 24-hours is demonstrated on a 10kW photovoltaic system in Bluewater Power Corporation’s network. The voltage regulation and power factor correction features of PV-STATCOM are demonstrated with Real Time Digital Simulator (RTDS) in [35]. The application of PV-STATCOM to prevent instability of a neighbouring induction motor load is presented in [36].

In this thesis, the novel control of existing PV solar farm and wind farm inverter resulting in PV-STATCOM and Wind-STATCOM is used to regulate steady state voltage and suppress temporary overvoltage so that the amount of power that can be injected from the neighbouring solar farm and wind farm can be increased. The partial converter based wind farms that employ Doubly Fed Induction Generator (DFIG) are not covered in this research.

A realistic medium voltage distribution network with radial feeder is considered as the study system. Research is carried out to study to the effectiveness of PV-STATCOM with
varying distances from the IG based wind farm. Also, the effectiveness of PV-STATCOM and Wind-STATCOM for the same radial distribution feeder with different conductors having different X/R ratios is studied.

The modeling and analyses in this thesis are performed using commercial grade softwares, PSS/E and PSCAD/EMTDC. Power System Simulator for Engineers (PSS/E) and Power Systems Computer Aided Design using Electromagnetic Transients including DC (PSCAD/EMTDC) are two industry standard software tools used in simulation studies of power system networks. PSS/E is used for steady-state load flow analysis as well as transient stability analysis [37]. PSCAD/EMTDC is used to perform electromagnetic transient simulations during system faults [38], [39]. The switching operation in power electronics based converters is considered in PSCAD/EMTDC.

1.8 Objective of the Thesis

The objectives of this thesis are as follows:

1. To develop a system model of a realistic distribution feeder line with PV solar farm modeled as PV-STATCOM and a full converter based wind farm modeled as Wind-STATCOM.

2. To study the enhancement of wind farm connectivity in medium voltage (MV) distribution network by addressing steady-state voltage rise and temporary overvoltage issues with the help of PV-STATCOM.

3. To examine the improvement of PV solar farm connectivity in distribution network by utilizing the wind farm converter as STATCOM to address steady-state voltage rise and temporary overvoltage issues.

4. To evaluate the additional PV solar farm and wind farm connectivity achievable by using combined PV-STATCOM and Wind-STATCOM control.
1.9 Outline of Thesis

An introduction of the various issues faced by medium voltage distribution network due to DG connectivity and the mitigating measures to address the issues of high bus voltage and TOVs are presented in Chapter 1. The principle of STATCOM, and the novel concepts of utilizing PV solar farm as PV-STATCOM and full converter based wind farm as Wind-STATCOM are also presented. The rest of this thesis is organized as below.

Chapter 2 deals with the modeling of the medium voltage distribution network as well as development of PV-STATCOM and Wind-STATCOM models. Models are developed for both load flow studies and electromagnetic transient simulation studies.

Chapter 3 deals with the application of PV solar converter as STATCOM (PV-STATCOM) to enhance the connectivity of wind farm. A base case scenario of the study system is presented and the issues of steady-state voltage and temporary overvoltage are evaluated. The steady-state analysis is based on PSS/E model of the study system and transient analysis is based on PSCAD/EMTDC model of the complete system. This chapter focuses on the evaluation of increased wind farm connectivity with the help of PV-STATCOM both during nighttime and daytime.

Chapter 4 deals with the application of full converter based wind farm as STATCOM (Wind-STATCOM) to enhance the connectivity of PV solar farm during daytime. Here, PSS/E model is used for steady-state analysis and PSCAD/EMTDC model is used for fault study.

Chapter 5 presents the combined operation of PV-STATCOM and Wind-STATCOM to maximize the system’s capability in integrating DGs in the distribution network.

The conclusions from this thesis work and recommendations for further research are presented in Chapter 6.
Chapter 2

SYSTEM MODELING

2.1 Introduction

This chapter deals with the modeling of a realistic medium voltage radial distribution line connected with a PV solar farm, a wind farm along with loads. The system model implemented in PSS/E software is used for steady state analyses. The system model implemented in PSCAD/EMTDC is used for electromagnetic transient analyses. This chapter further presents the system modeling from the perspectives of both load flow studies with PSS/E and fault studies with PSCAD/EMTDC software.

2.2 Study System

A realistic medium-voltage distribution system shown in Figure 2.1 is considered as the study system in this thesis. The system data corresponds to an actual Hydro One feeder in Ontario (name withheld due to confidentiality). The study system consists of 45 km of 27.6 kV radial distribution network connected to a supply substation through 118kV/27.6kV transformer. The load is approximated as lumped a load at bus no. 5 at the end of the radial network. Here, peak load (daytime load) is considered as 4.82 MW active and 2.197 Mvar reactive (5.3 MVA at 0.91 lagging power factor). The off-peak load (nighttime load) is considered as 1.6 MW active and 0.73 Mvar reactive (1.76 MVA
at 0.91 lagging power factor). A wind farm of 9.9 \textit{MW} capacity is located at bus no. 4 at a distance of 5.0 km from the load bus. Also, a PV solar farm of 8.5 \textit{MW} capacity is located at bus no. 3 at a distance of 5.0 km from the wind farm terminal. A brief description of the five buses considered in the network is given in Table 2.1. The parameters for the study system and various components are provided in Appendix – A.

![Figure 2.1 Study system](image)

**Table 2.1 Study system bus identification**

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supply end bus (primary side of transformer)</td>
</tr>
<tr>
<td>2</td>
<td>Secondary side of transformer</td>
</tr>
<tr>
<td>3</td>
<td>PV solar farm connection bus (Point of Common Coupling – PCC bus for solar farm)</td>
</tr>
<tr>
<td>4</td>
<td>Wind farm connection bus (Point of Common Coupling – PCC bus for wind farm)</td>
</tr>
<tr>
<td>5</td>
<td>Load bus (Lumped load)</td>
</tr>
</tbody>
</table>
2.3 Network and Load Model

2.3.1 Grid Model

For steady-state analysis in PSS/E, the grid is represented by a slack bus/infinite bus capable of supplying the required power at specified bus voltage. The generator considered at slack bus can supply the active power (including total system loss and load) required by the distribution network or it can absorb the excess active power in case of reverse power flow due to distributed generators. Also, such generators can supply or consume reactive power at specified voltage as required by the feeder.

For electromagnetic transient simulation in PSCAD/EMTDC, the grid feeding the distribution line is represented by a voltage source behind equivalent source impedance as shown in Figure 2.2. The equivalent series impedance of the grid consists of series resistance, $R_{SRC}$ and the series reactance, $X_{SRC}$. The voltage behind the reactance, $E$, is fixed whereas the terminal voltage $V_{Bus-i}$ depends on the loading condition of the distribution feeder.

![Figure 2.2 Grid modeled as voltage source with equivalent impedance](image)

2.3.2 Transformer Modeling

Electric power grid basically consists of generation, transmission and distribution systems which normally exist at different voltage levels. In such power grids, transformers are widely used to connect the systems at different voltage levels. The transformer is typically represented by series and shunt parameters. The series
parameters, which consist of series resistance and reactance, are used to represent the copper loss and the leakage flux of the windings, respectively. The copper loss and the leakage flux for both the primary and secondary windings depend on transformer loading.

The net flux that links the transformer windings and the iron loss (hysteresis loss and eddy current loss) are fixed for a transformer with rated voltage and independent of the transformer loading condition. Shunt parameters, namely shunt resistance and reactance are used to represent such fixed loss and flux in the transformer. The shunt resistance and reactance are very high and their effect in the system is neglected for complete system analysis. Also, copper loss in the transformer windings is significantly low compared to the network losses and hence a loss less transformer is used for the study system. In this scenario, the transformer can be modeled as a reactance $X_{TR}$ in series with an ideal transformer between two system buses $i$ and $j$ as shown in Figure 2.3. $V_{Bus-i}$ and $V_{Bus-j}$ denote the voltage at buses $i$ and $j$, respectively.

Figure 2.3 Transformer model - ideal transformer with series reactance

2.3.3 Line Modeling

Electrical parameters of a transmission line are based on size of conductors and their geometrical configuration. An overhead transmission line is represented by series parameters (series resistance, $r$, and reactance, $x$) and shunt parameters (shunt conductance, $g$, and susceptance, $b$) as below.

$$z = r + jx \quad \Omega/km \quad \text{.................................................................(2.1)}$$

$$y = g + jb \quad \Omega/km \quad \text{.................................................................(2.2)}$$

where $z =$ Series impedance, and $y =$ Shunt admittance
For the medium voltage overhead feeder, these distributed line parameters are represented by lumped model both for steady-state and transient analyses. The series parameters are represented by equivalent resistance, $R$ and equivalent reactance, $X$. The shunt conductance, $G$ is negligible for the overhead lines and half of capacitive susceptance ($Y/2$) is used to represent shunt parameters on each terminal of the line. The resulting equivalent \( \pi \)-model, as shown in Figure 2.4, is used to represent the line sections of the study system between Bus-\textit{i} and Bus-\textit{j}.

\begin{align*}
R &= r \cdot l \quad \text{(2.3)} \\
X &= x \cdot l \quad \text{(2.4)} \\
Y &= y \cdot l \quad \text{(2.5)}
\end{align*}

where, $l = \text{Line length}$

\[ \text{Figure 2.4 Equivalent } \pi \text{-model of overhead line (lumped parameters)} \]

### 2.3.4 Load Model

The load in a distribution network consists of various types of heating, lighting and motor loads. Individual loads vary widely in their performance characteristic. The equivalent characteristic of the load viewed from the medium voltage side (secondary of the feeder transformer) will be obtained by the net effect of the individual loads. The net active power and reactive power of a given load are affected by the terminal voltage and the system frequency from the network side [41].
Based on the study requirements, load models are broadly classified into two types: static load models and dynamic load models. Static load models used in load flow studies are expressed as steady state active and reactive powers as function of bus voltage and system frequency. Dynamic load models, on the other hand, are used for stability studies that involve load dynamics (as in voltage stability studies). Static load models are traditionally classified into following three types [41].

- **Constant power load model (Constant \( P \)):** A static load model in which the power does not vary with voltage magnitude. It is also referred to as constant MVA load model.
- **Constant current load model (Constant \( I \)):** A static load model in which the power varies directly with voltage magnitude.
- **Constant impedance load model (Constant \( Z \)):** A static load model in which the power varies with the square of the voltage magnitude.

Though the individual characteristics vary widely, the aggregated load characteristic of typical commercial and domestic loads are given as:

\[
P = P_0 \left( \frac{V}{V_0} \right)^{N_{VP}} (1 + N_{FP} \cdot dF) \tag{2.6}
\]

\[
Q = Q_0 \left( \frac{V}{V_0} \right)^{N_{VQ}} (1 + N_{FQ} \cdot dF) \tag{2.7}
\]

where,

\( N_{VP} \) – Voltage index for active power
\( N_{VQ} \) – Voltage index for reactive power
\( N_{FP} \) – Frequency index for real power
\( N_{FQ} \) – Frequency index for reactive power
\( P_0 \) – Real power at nominal voltage and frequency
\( Q_0 \) – Reactive power at nominal voltage and frequency
\( V_0 \) – Nominal voltage
\( V \) – Actual voltage
In this thesis constant power static load models are used for load flow studies as well as transient (fault) studies. The load is considered to be lumped at the receiving end (Bus 5) of the network. The constant power load with power factor of 0.91 lagging is considered both for steady state and transient studies.

2.4 PV System Model

PV solar system basically consists of photovoltaic cells that produce DC electricity, an inverter that converts DC to AC, an LC line filter that removes the harmonic components produced by inverter, and coupling transformer that connects AC side of the PV system to the point of common coupling (PCC) at grid. The DC side voltage, $V_{DC}$, DC current, $I_{DC}$, AC side three phase voltages $V_{ABC}$ and three phase line currents $I_{ABC}$ are used as input to the inverter controller which generates gate drive pulse signal to operate inverter switches. A schematic diagram of PV system is shown in Figure 2.5.

2.4.1 Photovoltaic Array

Photovoltaic cell, which consists of semiconductor material, is the basic unit of a PV solar system. Based on the nature of material used in the semiconductor doping, such
semiconductor PV cells are classified in three categories: Monocrystalline, Polycrystalline, and Amorphous. Monocrystalline PV cells require pure silicon and complicated crystal growth technology making them most expensive among various PV cell technologies. However, these monocrystalline cells have highest efficiency and are used in critical applications where generating more power utilizing less space is of importance. Polycrystalline cells, on the other hand, contain many crystals and have a less perfect surface than monocrystalline cells. Polycrystalline PV cells are widely used due to their low cost and moderate efficiency. Amorphous cells, with the thinner silicon wafers compared to crystallized PV cells, are more flexible than the other types. Though the efficiency is least of the three, amorphous silicon cells have gained wider application in recent days with the development of thin film photovoltaic (TFPV) technology. With this technology, low cost PV modules can be made in variety of sizes and shapes.

The basic units of photovoltaic technology referred as PV cells are connected in a combination of series and parallel connection to increase the voltage and current available from the photovoltaic cells. Such combination of cells is referred as PV solar module. Typical solar module consists of 36 to 72 cells and ranges from 75 W to 350 W in peak output power ($W_p$). A PV array is the combination of PV modules connected in series and parallel to match the requirement of inverter for grid integration. A PV solar farm may consist of a number of solar arrays based on its capacity.

![Figure 2.6 Equivalent circuit of PV solar cell](image)
A solar module can be represented by simplified equivalent circuit as shown in Figure 2.6. Based on this equivalent circuit, the relationship between the terminal voltage of solar module and the current delivered to the load is:

\[
I = I_{ph} - I_O \left( e^{\frac{V + I \cdot R_{SR}}{N_S V_t}} - 1 \right) - \left( \frac{V + I \cdot R_{SR}}{R_{SH}} \right) \quad \text{......................... (2.8)}
\]

where,

- \(I_{ph}\) – Photo generated current (function of solar radiation and cell temperature)
- \(I_O\) – Reverse saturation current (function of cell temperature)
- \(V\) – Terminal voltage of PV module
- \(I\) – Output current of PV module
- \(I_D\) – Diode current
- \(I_{SH}\) – Current through shunt branch of the module
- \(R_{SE}\) – PV module series resistance
- \(R_{SH}\) – PV module shunt resistance
- \(V_t\) – Junction thermal voltage \((A k T_c / q)\)
- \(k\) – Boltzmann's constant \((1.381 \times 10^{-23} \text{ J/K})\)
- \(T_c\) – Cell temperature in kelvin \((^\circ \text{K})\)
- \(q\) – Electrical charge of an electron
- \(A\) – Diode ideality factor (quality)
- \(N_S\) – No of PV cells in series

Based on the equivalent circuit shown in Figure 2.6 and relationship given in (2.8), a typical I-V characteristic curve for given insolation and cell temperatures at standard test condition is depicted in Figure 2.7. The voltage at open terminals of the module is referred as open circuit voltage \((V_{OC})\). For this open circuit case, the voltage across the terminals is maximum for given operating conditions and the current through the PV terminals is zero. The terminal voltage decreases slightly as the current drawn from the PV terminals increases. This drop in voltage is affected by the series resistance value \(R_{SE}\) of the PV module \((\Delta V = I \cdot R_{SE})\). However, there is sharp fall in the voltage as the
current increases beyond certain value. This sharp fall in current depends on the value of shunt resistance $R_{SH}$ of the module ($\Delta I = V/R_{SH}$). The maximum current from the PV module, when its terminals are shorted, is referred as short circuit current, $I_{SH}$.

This unique I-V characteristic of PV modules provides self-regulation for battery charging applications. However, an additional control is provided to operate PV modules for maximum power output when connected to the power grid. The nominal voltage and current magnitude are identified by the voltage and current at maximum power point at the nominal insolation and nominal ambient temperature (standard test conditions). The short-circuit current and open-circuit voltage are slightly higher than respective nominal voltage and current. The ratio of the maximum power ($V_{MP} \cdot I_{MP}$) to the product of open-circuit voltage and short-circuit current ($V_{oc} \cdot I_{sc}$) as given in (2.9) is defined as the fill factor of PV module

$$\text{Fill Factor} = \frac{V_{MP} \cdot I_{MP}}{V_{oc} \cdot I_{sc}}$$

Figure 2.7 A typical current-voltage characteristic of PV module

where,

$V_{MP} - \text{Maximum power point voltage}$

$I_{MP} - \text{Maximum power point current}$
Fill factor generally varies between 0.8 and 0.9. It depends on series and shunt resistance values shown in the equivalent circuit of Figure 2.6. Fill factor represents the measure of efficiency of the PV module. For nominal operating condition, the variation in terminal voltage with the variation of power output is minimal. Accordingly, the DC side voltage of the solar inverter can be approximated by the nominal DC voltage to study the impact of PV solar farm integration to the grid. Such equivalent DC voltage source along with series resistance to represent the DC side loss, are used to model the PV solar array. The MPPT is not modeled in the PV solar farm model in this thesis, as only the inverter capacity remaining after real power generation is being utilized for voltage control.

2.4.2 Line Filter

Voltage Source Converter (VSC) based PV inverters produce various harmonic components based on the control strategy and switching frequency [48]. The pulse width modulation (PWM) technique can be used to eliminate lower order harmonics and reduce the total harmonic distortion due to converters. In sinusoidal pulse width modulation (SPWM), which is the most common PWM technique, the magnitude and frequency of the sinusoidal fundamental component are controlled by pulse width modulation. In such converters, the higher the switching frequency, the better is the quality of the resulting waveform and smaller the filter capacitor and inductors requirements.

A low-pass LC filter, as shown in Figure 2.8, is used to remove the harmonic components and provide smooth sinusoidal waveform at the point of common coupling (PCC). In PWM technique, the information about the fundamental component of the output voltage is embedded (modulated) in the widths of the output voltage pulses. The demodulation takes place in the output low-pass filter (LC filters), where the switching harmonics are separated from the fundamental component, or in the inductive load, where the pulsed voltage waveform is transformed to a sinusoidal current at the fundamental frequency.
The odd value of frequency modulation index is chosen as it provides a half-wave symmetry in resulting output waveform. Half-wave symmetry is useful in converter output as it eliminates even harmonic components. The harmonic components in output waveform will appear as sidebands around the switching frequency and its multiples. The frequencies of harmonic components are given by the following expression.

\[ f_h = j \cdot f_s \pm k \cdot f_1 \]  \hspace{1cm} (2.10)

Here value of \( k \) is even when \( j \) is odd, and \( k \) is odd when \( j \) is even. The frequency modulation is selected in such a way that significantly higher order harmonics will appear in the output (which are relatively easier to filter out) and switching loss is maintained within acceptable value.

The series inductor (\( L_f \)) used in the LC filter provides sufficient impedance between the AC side of the inverter and the point of common coupling of the grid. The shunt capacitor (\( C_f \)) provides attenuation to the harmonic components of the inverter AC side voltage.

![Figure 2.8 Schematic diagram of LC filter and coupling transformer](Image)
The line filter is designed in such a way that minimum voltage distortion occurs at PCC. The line inductance is chosen typically between 0.1 pu and 0.25 pu [57] so that it provides sufficient impedance between the AC side of the inverter and the PCC and causes only limited voltage drop. Higher values of the series inductance will be more effective to suppress ripples in the AC side current. However, it may cause higher voltage drop resulting in a higher DC voltage requirement. The selection of the shunt capacitor determines the resonant frequency of LC filter. It is designed to achieve resonant frequency sufficiently larger than the fundamental frequency and considerably smaller than the switching frequency. From the filter design point of view, higher switching frequency will provide smaller filter capacitor requirement. Damping resistors (not shown in figure) are used in LC filter to suppress oscillations. The damping resistance is kept minimum to limit the overall loss of the inverter within acceptable value.

2.4.3 Coupling Transformer

Medium to large scale three-phase grid-tied PV inverters use coupling transformer to match the voltage on AC side of the inverter and the grid side voltage. It also helps to maintain electrical isolation between the PV system and the grid.

Various configurations of 3-phase transformer windings are used to connect PV solar output to the grid. The transformer selection is based on the guidelines provided in Hydro One’s DG technical interconnection requirements [7]. Star-Delta configuration as shown in Figure 2.8 is used for PV solar farm integration at Bus-3 of the study system. Similar Star-Delta configuration coupling transformer is also used for wind farm integration at Bus-4. For simulation studies, the transformer is represented by ideal transformer in series with leakage reactance as shown in Figure 2.3.

2.4.4 PV Solar Inverter

PV solar inverter is used to convert the DC power generated by PV modules to the AC power of the electric grid. These inverters are tied to the grid voltage and designed to transfer maximum power available from the PV modules based on the solar irradiance
and the cell temperature. Typically, a three phase, 2-level, 6-pulse voltage sourced converter (VSC) is used to convert DC to AC in the PV inverters. Such PV inverters that convert DC to AC are made possible with the development of high power switches like Gate Turn-off Thyristors (GTO). A GTO can be turned ON or turned OFF with gate pulses (turned ON by positive polarity pulse and turned OFF by negative polarity pulse on gate terminal). However, these devices produce high loss for high switching frequency applications. The switching losses are significantly minimized in Insulated Gate Bipolar Transistor (IGBT) with fully controlled capability. Sinusoidal pulse width modulation (SPWM) gate pulses are generated based on the DC terminal voltage and current as well as the grid side voltage and output current of the inverter.

2.4.5 Model of PV Solar Inverter as STATCOM (PV-STATCOM)

The principle of PV-STATCOM is already described in Chapter 1, Section 1.5.1. The Sinusoidal Pulse Width Modulation (SPWM) is based on generation of sinusoidal modulating signal and the triangular carrier signal [28], [29]. The sinusoidal modulating signal is compared with a triangular carrier signal of constant amplitude and frequency to generate the gate pulses for the switches. The AC terminal voltage of the converter depends on the modulation index and the DC link voltage as given in Section 1.4.2.

The generation of sinusoidal modulating signal in PSCAD/EMTDC model is given in Figure 2.9. Phase locked loop (PLL) block generates reference phase angle as a ramp signal (0 to 360°) synchronized with PCC voltage (Va, Vb, Vc). This reference angle is shifted to match the required angle ‘shift’ and phase shift created by coupling transformer (30°). Six sinusoidal reference signals (RefSgnON) are generated that correspond to the turn ON sequence of 6 switches (1, 2, 3, 4, 5, 6). The sinusoidal reference signals for turn OFF (RefSgnOFF) are generated in the sequence of switches (4, 5, 6, 1, 2, 3) to make sure that only one of the upper and lower limb switches of 3-phase, 6 pulse converter is ON at a time. The magnitude of these modulating signals is set by multiplying the base sinusoidal signal to the modulation index (mi).
The generation of triangular carrier waveforms is given in Figure 2.10. The triangular carrier signals, TriSgnON and TriSgnOFF, corresponding to the turn ON and turn OFF sequence of 3-phase converter switches, are generated by multiplying synchronized phase angle output of PLL and the frequency modulation index ($m_f = 33$). The ‘Angle Resolver’ generates ramp signal of phase angle between 0 to 360º. This ramp signal is finally converted to triangular waveforms of magnitude unity (peak) and frequency 1.98 kHz ($33 \times 60$ Hz) for the turn ON and turn OFF sequence of the switches.

PSCAD/EMTDC built-in firing pulse generator is used to generate firing pulses for 3-phase, 6-pulse converter based on these sinusoidal and triangular signals for turn ON and OFF sequence (RefSgnON, TriSgnON, RefSgnOFF, TriSgnOFF) [38].

Figure 2.9 Generation of sinusoidal reference signal (for firing pulse generation for SPWM control)
Figure 2.10 Generation of triangular reference signal (for PWM control)

The AC voltage magnitude is controlled by controlling the modulation index, \( m_a \) or DC side voltage, \( V_{DC} \). The DC side voltage control is based on charging and discharging of DC side capacitor which involves the transfer of active power by controlling the shift angle.

The modulation index control to regulate the AC side voltage and corresponding reactive power flow is shown in Figure 2.11. Here 3.0% droop characteristic is used to increase the range of voltage control available and improve the dynamic performance of the converter [18], [17]. A Proportional-Integral (PI) controller is used to reduce the steady state error as well to obtain a good transient response characteristic i.e. faster response with minimal overshoot and small settling time. The shift angle control is also used to get the desired active power transfer between the STATCOM and the grid.

The reactive power transfer (\( Q_{svc} \)) is divided by base value (20.0 Mvar) and then by the terminal voltage (\( V_{bus\_pu} \)) or 0.1 pu (when terminal voltage is less than 0.1 pu due to faults) to obtain the STATCOM reactive current. This is multiplied by 0.03 to provide the 3.0% voltage droop component. The addition of this voltage droop component to the terminal voltage (\( V_{bus\_pu} \)) contribute feedback signal in the voltage control loop. The error signal is obtained from the difference of reference voltage (\( V_{ref\_pu} \)) and the feedback voltage. Then the PI controller, with proportional gain \( K_p1 \) and integral time constant \( Ti1 \), is applied to get the required modulation index (\( m_i \)).
Figure 2.11 STATCOM voltage control with 3% droop characteristics

The control of active power using PI controller is shown in Figure 2.12. In this case, the measured value of active power transfer \( P_{vsc} \) and the reference value \( P_{ref\_MW} \) are normalized by dividing with base value (20.0 MW). The PI controller with proportional gain \( Kp3 \) and integral time constant \( Ti3 \) is applied to the error signal to get the required angle shift \( \text{Shift} \). This control option is implemented when solar farm converter operates as conventional inverter to transfer available solar power.

Figure 2.12 Phase shift angle control to maintain real power transfer

Alternatively, the shift angle control is applied get the desired DC side voltage as shown in Figure 2.13. In this case, the error signal is obtained by comparing the DC link voltage \( V_{dc} \) with reference value \( V_{dc\_\text{ref}} = 24.5 \text{ kV} \). The DC gain \( DcGain \) and logical control signal \( Blk \) are applied to the error signal. The control signal \( Blk \) depends on the status of converter operation mode (high or low depending on DC voltage control mode). The DC gain of unity is used in this case. The PI controller with proportional gain \( Kp2 \) and integral time constant \( Ti2 \) is applied to the error signal to get the required angle shift.
(Shift). This control option is implemented when solar farm converter is operating as PV-STATCOM. DC side voltage control can be used to control the AC terminal voltage.

![Figure 2.13 DC side voltage control with real power transfer](image)

Temporary overvoltages (TOVs) are typically observed in healthy phases in case of unbalanced faults. The PV-STATCOM is used to suppress such temporary overvoltage due to single line to ground fault in the distribution network. In such unbalanced system condition, the control strategy to provide the compensation and accordingly suppress the overvoltage is given in Figure 2.14. The balanced three phase voltage ($V_{pu3ph}$) is used to control the reactive power injection in steady state condition. Whereas phase voltages ($V_{a1}$, $V_{b1}$ and $V_{c1}$) are used to calculate the average of healthy phases which experience overvoltage in case of single line to ground fault.

By comparing each voltage pair ($V_{a1}$, $V_{b1}$), ($V_{b1}$, $V_{c1}$) and ($V_{c1}$, $V_{a1}$), two higher magnitude voltages are selected. The average of these two voltages is used for the voltage control loop of PV-STATCOM when there is a fault. The 3-phase voltage $V_{pu3ph}$ is used during normal operating condition. The selection of these two conditions is based on the voltage difference ($|V_{a1} - V_{b1}|$) and ($|V_{b1} - V_{c1}|$). The comparator block is used to identify the faulted condition when the maximum of the absolute values of voltage difference is greater than 0.4 pu.

The overall representation of the study system in PSCAD/EMTDC software is shown in Figure 2.15.
Figure 2.14 Voltage control strategy for unbalanced fault conditions
Figure 2.15 Study system model with PV-STATCOM (PSCAD/EMTDC model)
2.5 Design of PV-STATCOM Controller

2.5.1 Voltage Controller Parameters

PV-STATCOM as described in Section 2.4.5 provides dynamic reactive power compensation for voltage control. A Proportional-Integral (PI) controller is used for voltage control with droop characteristic [18], [17]. The parameters of PI-controller are selected based on the performance for step response. For a step change in reference voltage, $V_{ref}$, the corresponding voltage at point of common coupling, $V_{pcc}$ is observed. The controller performance is evaluated for two cases of PV-STATCOM operation: Case 1 with no active power output ($P_{SF} = 0.0 \ MW$), and Case 2 with 5.0 $MW$ active power output of solar farm ($P_{SF} = 5.0 \ MW$).

For Case 1, the step response with variation of proportional gain, $K_p$, with constant $T_i = 0.01$ sec., is shown in Figure 2.16. At higher gain $K_p = 5.0$, the system response is faster (low rise time). However, the output oscillates for longer time. At very low gain $K_p = 0.05$, the peak overshoot is high. From these set of step responses, the proportional gain of 0.5 is selected as the best value. This results in small rise time, peak overshoot less than 10% and a small settling time.

For Case 1, $P_{SF} = 0.0 \ MW$. 

![Figure 2.16 Step response with variation of proportional gain, $K_p$. Case 1, $P_{SF} = 0.0 \ MW$.](image)
The step response with variation of integral time constant $T_i$ for a constant $K_p = 0.5$ is shown in Figure 2.17. For high time constant $T_i = 1.0$ sec., the system response is overdamped and slow (large rise time and settling time). The step response becomes faster as the time constant is decreased. However, peak overshoot and oscillations grow as time constant is decreased. The best response is observed for time constant $T_i = 0.01s$ based on overshoot, rise time and settling time consideration as in previous case.

Similarly, the step responses for Case 2 with 5.0 MW of solar farm output are shown in Figure 2.18 and Figure 2.19. In this case as well, the best proportional gain and integral time constant are found to be 0.5 and 0.01 sec., respectively. The best values of $K_p$ and $T_i$ are observed to be same for both 0.0 MW and 5.0 MW of solar farm output conditions.
Figure 2.18 Step response with variation of proportional gain, $K_p$

Case 2, $P_{SF} = 5.0$ MW

Figure 2.19 Step response with variation of integral time constant, $T_i$

Case 2, $P_{SF} = 5.0$ MW
2.5.2 Steady-state and Transient Performance

The performance of PV-STATCOM controller implemented in PSCAD/EMTDC is evaluated for steady-state as well as transient conditions. The studies are carried out for two cases: Case 1 for nighttime loading and no solar farm output \( (P_{SF} = 0.0 \text{ MW}) \) so that full solar farm capacity \( (8.5 \text{ Mvar}) \) can be used for voltage control, and Case 2 for daytime loading with \( 5.0 \text{ MW} \) solar farm output so that remaining capacity \( (8.67 \text{ Mvar}) \) can be used for reactive power compensation to achieve necessary voltage control. The simulation results are depicted in Figure 2.20 for Case 1 and Figure 2.21 for Case 2 studies, respectively. The first time interval \( (T_0 \text{ to } T_1) \) represents the steady state condition without any wind farm power output. Wind farm output of \( 10.0 \text{ MW} \) is injected at time instant \( T_1 \). From time interval \( T_0 \) to \( T_2 \), solar farm is operated as conventional inverter without any reactive power output. At time instant \( T_2 \), the solar farm converter is controlled as PV-STATCOM with voltage control to regulate the PCC voltage. Region within red ellipse in these figures demonstrates the step response of PV-STATCOM.

For Case 1 (Nighttime loading with no solar farm output), the steady state voltages of \( 1.028 \text{ pu} \) at solar farm PCC and \( 1.024 \text{ pu} \) at wind farm PCC are observed for no wind farm output between time interval \( T_0 \) and \( T_1 \). These voltages rise up to \( 1.088 \text{ pu} \) at solar farm PCC and \( 1.094 \text{ pu} \) at wind farm PCC for wind farm output for \( 10.0 \text{ MW} \) for time interval between \( T_1 \) and \( T_2 \) when no reactive power compensation is provided. The solar farm converter controlled as PV-STATCOM provides the reactive power compensation of about \( 3.7 \text{ Mvar} \) to bring the solar farm PCC voltage to \( 1.0 \text{ pu} \) and the wind farm PCC voltage to \( 1.007 \text{ pu} \).

Similarly for Case 2 (Daytime loading with \( 5.0 \text{ MW} \) solar farm output), the steady state voltages of \( 1.003 \text{ pu} \) at solar farm PCC and \( 0.992 \text{ pu} \) at wind farm PCC are observed for no wind farm output between time interval \( T_0 \) and \( T_1 \). These voltages rise up to \( 1.064 \text{ pu} \) at solar farm PCC and \( 1.063 \text{ pu} \) at wind farm PCC for wind farm output for \( 10.0 \text{ MW} \) for time interval between \( T_1 \) and \( T_2 \) when no reactive power compensation is provided. The
solar farm converter controlled as PV-STATCOM provides the reactive power compensation of about 2.4 \( Mvar \) to bring the solar farm PCC voltage to 1.0 \( pu \) and the wind farm PCC voltage to 0.998 \( pu \).

Figure 2.20 PCC voltage control with PV-STATCOM:
Case 1, Nighttime loading with \( P_{SF} = 0.0 \, MW \) and \( P_{WF} = 10.0 \, MW \)
The PV-STATCOM model developed in this thesis using PSCAD/EMTDC was validated by performing same studies as reported in [1] using MATLAB-Simulink model of solar farm as STATCOM and noting that the two sets of results were in very correlation.
2.5.3 Temporary Overvoltage (TOV) Control

The temporary overvoltage in healthy lines may increase beyond permissible limits due to single line to ground fault in the system. The PV-STATCOM can be controlled to suppress temporary overvoltage in the system within the permissible limits [7]. The performance of PV-STATCOM to reduce the temporary overvoltage is shown in Figure 2.22 below. The phase voltages are observed for single line to ground fault for 100 ms without and with PV-STATCOM. For the study system with nighttime loading and 10.0 MW wind farm output condition, the TOV of 31.3 kV peak (1.389 pu) is observed without PV-STATCOM. The PV-STATCOM reduces the TOV to 26.8 kV peak (1.189 pu) which is within permissible limits [7].

2.6 Wind Turbine Generator Model

Different types of electric generators along with auxiliary equipment are utilized for power generation from wind turbines. The most common of them are Self Excited Induction Generator (SEIG), Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generators (PMSG) [50].

A basic schematic representation of the Wind Turbine Generator (WTG) system is shown in Figure 2.23. The WTG system consists of rotor blades attached to a shaft which rotates at lower speed. A gear box connects the low speed shaft to a high speed shaft suitable for generator. The generator along with use of partial or full converters provides a range of wind turbine operation from constant speed to variable speed. Fixed-speed wind turbine normally uses Squirrel Cage Induction Generator and is connected to the electrical grid through coupling transformer. Permanent Magnet Synchronous Generator is used to achieve variable speed operation with wide wind speed range and is connected to the grid through back to back full converter. The detailed modeling of Induction Generator based fixed speed wind turbines and Permanent Magnet Synchronous Generator based variable speed wind turbines are discussed in next subsections.
Figure 2.22 Phase voltages without and with PV-STATCOM for single line to ground fault (SLGF) for 0.1 sec.

Figure 2.23 Schematic representation of typical wind turbine system
2.6.1 Induction Generator Based WTG

Squirrel Cage Induction Generator (SCIG), also referred as Self Excited Induction Generator (SEIG) is used as fixed speed wind generator [50]. These fixed speed wind turbines, also referred as Danish Model, are widely used from the very beginning of wind energy deployment for electric power generation. The induction generator has low cost and maintenance free rugged construction making them first choice in most of the small scale wind turbines [58]. A typical representation of such fixed speed wind turbine is shown in Figure 2.16.

![Figure 2.24 Induction Generator based wind turbine generator (fixed speed operation)](image)

The output terminals of such induction generator are connected to the grid through coupling transformer. Induction generator consumes substantial reactive power to maintain its excitation flux. Normally, a static capacitor bank connected to the armature terminal of the three phase machine provides the reactive power requirement for induction generators. The wind turbine is connected to the generator shaft through gearbox to match the low speed of wind turbine shaft and high speed of generator shaft. Pitch control is applied in the rotor blades to operate the rotor at fixed speed over wide range of wind speed. Accordingly, active power output of the generator can be controlled irrespective of the wind speed. However, there is no reactive power control mechanism in fixed speed wind turbine generators.
2.6.1.1 Induction Generator Model

The equivalent circuit of an induction machine is similar to that of transformer with its stator windings as primary and rotor windings (or rotor conductors in squirrel cage induction machine) as secondary windings. Unlike the transformer, the secondary winding terminals or rotor winding terminals are shorted together with/without external resistance [58]. The schematic representation of such machine is shown in Figure 2.25.

![Stator and rotor representation of induction machine](image)

**Figure 2.25 Stator and rotor representation of induction machine**

The per-phase equivalent circuit for such machines referred to primary side (stator side) is given in Figure 2.26 [58]. Here the stator side resistance and leakage reactance are represented by \( R_1 \) and \( X_1 \), respectively. The rotor side resistance and leakage reactance referred to primary side (stator side) are represented by \( R'_2 \) and \( X'_2 \), respectively. The iron loss in the core is represented by shunt resistance \( R_C \) and the air gap flux that links stator winding and the rotor windings or rotor conductors is represented by shunt reactance \( X_M \). The stator side (primary side) current per phase is given by \( I_1 \) and the equivalent rotor side current referred to stator side is given by \( I'_2 \). For wind turbine generators, the mechanical torque \( (T_{mech}) \) is produced by the wind turbine blades. An opposing electrical torque \( (T_{elec}) \) is produced in the air gap.
For an asynchronous machine the slip is defined as

\[
 s = \left( \frac{\omega_{\text{sync}} - \omega_{\text{actual}}}{\omega_{\text{sync}}} \right) \quad \text{........................................................................................................................................................................(2.12)}
\]

where,

\[
 \omega_{\text{sync}} \quad \text{Synchronous speed of the induction machine (rad/sec)}
\]

\[
 \omega_{\text{actual}} \quad \text{Actual speed of rotation of the rotor shaft (rad/sec)}
\]

The net electromagnetic power transfer from the rotor shaft via air gap is given by

\[
 P_{\text{elec}} = 3. (I_2')^2. R_2' \left( \frac{1 - s}{s} \right) \quad \text{........................................................................................................................................................................(2.13)}
\]

The induction machine will operate as generator when it rotates above synchronous speed. In this condition slip will be negative. Expression (2.13) shows that the electrical power transfer via air gap, \( P_{\text{elec}} \) will be negative in this operating condition. This negative power represents that the induction machine is operating in generating mode and the power is transferred from the rotor shaft to the stator windings via the air gap. For the study system, the net mechanical power available from wind turbine blades is represented by equivalent negative torque input to the induction machine.
2.6.2 Full Converter Based WTG

Permanent Magnet Synchronous Generator (PMSG) is used as variable speed wind generators. These variable speed wind turbines are being widely used for wind energy deployment for electric power generation [50]. A typical representation of such variable speed wind turbine is shown in Figure 2.27.

![Diagram of Permanent Magnet Synchronous Generator (PMSG) based wind turbine (variable speed operation)](image)

Full converter based wind turbine generators are variable speed wind turbines with a wide range of speed variation. The direct drive Permanent Magnet Synchronous Generator (PMSG) or the Wound Rotor Synchronous Generator (WRSG) is used in such wind turbines.

A schematic diagram of the variable speed wind turbine generator is shown in Figure 2.16. The wind turbine rotor shaft is directly connected to the low speed permanent magnet generator shaft. The full converter connected back to back completely decouples the frequency of grid and the wind generator. Following the variation in wind speed, the pitch angle control provided in the rotor blades will vary the shaft speed as per the turbine characteristic to produce maximum output power with optimal turbine performance. The grid side converter can be controlled appropriately to deliver required reactive power for the system whereas the DG side converter can be controlled to achieve the maximum
power output from the wind generator. These fast acting VSC based converter can significantly improve the dynamic performance of the system. The grid side converter can provide reactive power to the grid even when there is no power output from the wind turbine generator.

### 2.6.2.1 Permanent Magnet Synchronous Generator and Rectifier

A permanent Magnet Synchronous Generator (PMSG) consists of 3-phase armature winding in its stator core with magnetic field established by the permanent magnet typically consisting of rare-earth material (Samarium-Cobalt, Sm-Co and neodymium-iron-boron, Nd-Fe-B magnets). The use of rare-earth magnets provides several benefits in wind turbine generator. It eliminates the requirement of excitation system which reduces the overall cost and increases the reliability of the generator. The use of permanent magnet reduces the core loss component caused by rotor excitation in conventional synchronous generator. The machine can be operated over wide range of rotor speed providing the flexibility or direct shaft connection between the turbine blades and the generator. The elimination of gear box reduces the cost, reduces the maintenance, increases the system reliability and reduces the total weight in nacelle.

With permanent magnet in synchronous generator, a higher efficiency can be achieved along with light weight, small size and less maintenance. However, such permanent magnet generator lacks the ability for excitation variation to control the output voltage. The wide range of speed variation on the rotor shaft is achieved by allowing variation in the output frequency. This speed variation control increases the generator output allowing to harness the maximum power from the wind turbines. However, this operation eliminates the possibility of direct connection of generator output to the grid. The grid integration is achieved by using back-to-back full scale converter in which the generator output is rectified to get the DC voltage which is then converted back to AC voltage that matches the grid frequency and voltage level.
The wind turbine controller determines the available power from wind turbine and adjusts the blade pitch angle based on turbine-generator shaft speed. It provides the reference power ($P_{ref}$) to the generator side converter controller. The converter controller provides necessary switching pulses based on reference power ($P_{ref}$) as well as generator voltage and current ($V_{ABC}$ and $I_{ABC}$) and DC side voltage and current ($V_{DC}$ and $I_{DC}$). The DC side voltage is maintained at nominal value by controlling rectifier output (controlled rectifier). The maximum power point tracking is used in controlled rectifier to match the available power from the wind turbine and power delivered to the grid. The control schemes for rectifier and wind turbine are shown in Figure 2.28.

![Figure 2.28 Wind turbine and rectifier control schemes](image)

2.6.2.2 Inverter Model

The control of PMSG is simplified by the absence of exciter. Accordingly, there is no voltage control mechanism in the generator side. However, the converter at the grid side can be controlled to achieve voltage and reactive power control on the grid side. Also, the frequency of output voltage depends on the speed of the rotor shaft obtained through pitch control to achieve the maximum power output for the given wind speed. The grid side converter is used to match the voltage and frequency for grid integration.
The variable speed synchronous generator along with the generator side converter (rectifier) is represented by the DC source. The DC link capacitor is used to maintain DC side voltage during transients. The schematic representation of the grid side converter and associated control is shown in Figure 2.29. The grid side converter provides necessary switching pulses to the grid-tied inverter based on reference power \( P_{\text{ref}} \) obtained from wind turbine controller as well as grid voltage \( V_{ABC} \), AC side current \( I_{ABC} \), DC link voltage \( V_{DC} \), and DC side current \( I_{DC} \) [56].

![Figure 2.29 Schematic diagram of Wind-STATCOM control](image)

### 2.6.2.3 Grid Side Converter as STATCOM (Wind-STATCOM)

A novel control scheme applied to the grid side converter of wind turbine can achieve the reactive power exchange which helps to control the voltage at the point of common coupling (PCC) has been proposed [30], [32]. Such novel control, applied in this thesis, is referred as Wind-STATCOM. The control scheme of the Wind-STATCOM is similar to the control scheme of PV-STATCOM presented in Section 2.4 and hence not repeated here. The voltage control with droop characteristic [17] is achieved by controlling modulation index of the PWM output waveform. The transfer of real power is maintained by controlling the shift angle for reference signal of PWM. A similar procedure is
followed as in Section 2.5 for the selection of the best proportional gain and integral time constant of Wind-STATCOM to obtain the best voltage control performance and TOV control. (although not repeated here). The best $K_p$ and $T_i$ are found to be 0.5 and 0.01 sec., respectively. The grid side inverter is controlled as STATCOM with the inverter capacity remaining after real power generation during partial wind or no-wind conditions [30].

The representation of the study system with Wind-STATCOM in PSCAD/EMTDC is shown in Figure 2.30. This model is used to study the application of Wind-STATCOM to suppress TOV and increase solar farm connectivity.

### 2.7 System Model for Steady-state Studies using PSS/E

The steady-state analysis of the study is carried out PSS/E software. PSS/E uses electromechanical dynamics of the system components with averaged model for power electronics based converters. Besides steady-state and dynamic analyses, PSS/E provides users with a wide range of auxiliary features like optimal power flow studies, balanced and unbalanced fault analysis, available transfer capability evaluation, etc.

A collection of predefined library functions are used to represent power system components for the study system. In this thesis, the medium voltage distribution network with generic shunt FACTS device as STATCOM and generic power source as Wind Farm are modeled in PSS/E. Figure 2.31 shows the PSS/E model of the complete system with solar farm and wind farm connected at Bus 3 and Bus 4, respectively. Load flow is used to analyze the steady-state performance of the study system for various wind farm and solar farm output conditions.
Figure 2.30 PSCAD/EMTDC model of the study system with Wind-STATCOM
2.8 Conclusion

This chapter presents the modeling of a realistic distribution feeder in Ontario having both the wind farm and solar farm connected. The modeling of various components of the power system namely, grid, feeder transformer, overhead line, load, solar farm and wind farm are described. The modeling of the system components is based on the system studies requirement of steady-state analysis in PSS/E and electromagnetic transient analysis in PSCAD/EMTDC software. The modeling of a novel control of the PV solar farm converter as PV-STATCOM is presented. This control technique is extended to use wind farm converter as Wind-STATCOM. The modeling of the grid side converter of PMSG based variable speed wind turbine as Wind-STATCOM is also described. These component models are used as basis for various studies presented in subsequent chapters.
Chapter 3

PV-STATCOM CONTROL FOR INCREASING WIND FARM CONNECTIVITY

3.1 Introduction

This chapter deals with the impact of wind farm integration in a medium voltage (MV) distribution network and use of a neighbouring solar farm as PV-STATCOM to mitigate the resulting problems thereby increasing wind connectivity. The issues of steady state voltage rise due to reverse power flow and the temporary overvoltage (TOV) due to unbalanced faults are, considered in this study.

The industry grade power system simulation software PSS/E, that utilizes Newton-Raphson’s algorithm to perform power flow studies, is used for the steady state analysis. The fault analysis is carried out using commercial grade electromagnetic transient program PSCAD/EMTDC. The line to ground fault is the most common of all fault types in a distribution system. Such unbalanced faults create temporary overvoltages in the healthy lines in the system. In this chapter, the temporary overvoltages in the study system due to a single line to ground fault (SLGF) are studied and the dynamic compensation provided by PV-STATCOM is used to suppress such overvoltage so that an increased amount of wind power can be integrated with the grid. The studies are performed both for nighttime and daytime. The application of an 8.5 MW solar farm as PV-STATCOM to increase the wind farm connectivity from 9.9 MW up to 30.0 MW is presented.
3.2 Base Case Studies

A 5-bus medium-voltage radial distribution feeder consisting of an equivalent grid source, solar farm, wind farm and a lumped load is considered as the study system. The detailed modeling of individual components of the study system is presented in Chapter 2. The single line diagram of the study system with the PV solar farm operated PV-STATCOM is shown in Figure 3.1. The complete system model in PSS/E, given in Chapter 2 (Section 2.7, Figure 2.31), is used for steady state analysis. In PSS/E, the solar farm is considered as PQ bus with active power $P$ being the solar farm power output. $Q$ represents the reactive power output of the PV-STATCOM, which is required to maintain the bus voltage within permissible limits. The maximum value of $Q$ can be up to the inverter capacity remaining after real power generation $Q = \sqrt{S^2 - P^2}$. The self-excited induction generator based wind farm is considered as a real power source with zero reactive power output (unity power factor). The complete system model in PSCAD/EMTDC, given in Chapter 2 (Section 2.4.5, Figure 2.15), is used for electromagnetic transient studies.

![Figure 3.1 Study system with PV-STATCOM](image)

The base case is considered without any PV solar farm and wind farm integrated in the system. The base case analysis provides the operating scenario of the distribution network intended to deliver the estimated load for daytime (peak-load condition) and nighttime (off-peak load condition). Steady state analyses are carried out to identify the deviation of steady state voltages and electromagnetic transient analyses are carried out to determine the temporary overvoltages for single line to ground fault at the receiving end.
3.2.1 Steady State Analysis

The steady state network status namely bus voltage magnitude, voltage angle, active and reactive power flows, and losses are evaluated using load flow studies in PSS/E. The detailed load flow results for base case scenario with peak load (daytime) and off-peak load (nighttime) are listed in Appendix – B. With the sending end voltage set to 1.055 pu, the steady state results are obtained without voltage regulation for both the peak-load and off-peak load conditions. Peak loads of active power, $P_{LD} = 4.82 \text{ MW}$ and reactive power, $Q_{LD} = 2.19 \text{ Mvar}$ are used for daytime. Off-peak loads of active power, $P_{LD} = 1.6 \text{ MW}$ and reactive power, $Q_{LD} = 0.73 \text{ Mvar}$ are used for nighttime. Bus voltage magnitudes for daytime and nighttime loading conditions are given in Table 3.1.

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Voltage (pu)</th>
<th>Bus No.</th>
<th>Voltage (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0550</td>
<td>1</td>
<td>1.0550</td>
</tr>
<tr>
<td>2</td>
<td>1.0536</td>
<td>2</td>
<td>1.0547</td>
</tr>
<tr>
<td>3</td>
<td>0.9657</td>
<td>3</td>
<td>1.0299</td>
</tr>
<tr>
<td>4</td>
<td>0.9534</td>
<td>4</td>
<td>1.0263</td>
</tr>
<tr>
<td>5</td>
<td>0.9413</td>
<td>5</td>
<td>1.0226</td>
</tr>
</tbody>
</table>

In this scenario, the receiving end voltage is observed to be 0.9413 pu at peak-load condition (daytime) and 1.0226 pu during off-peak load condition (nighttime). The voltages at all the buses in the network are within the permissible limits of ±6% of rated values for Hydro One’s network [7]. The base case voltage magnitude at all fives buses of the network for peak load (Daytime loading) and off-peak load (Nighttime loading) are graphically illustrated in Figure 3.2.
3.2.2 Temporary Overvoltage (TOV) Analysis

Single line to ground fault (SLGF) at receiving end (load end) for 6 cycles (100 ms) is considered in this study. The phase voltage observed for such unbalanced faults at the load end are shown in Figure 3.3 and Figure 3.4 for daytime and nighttime loadings, respectively. The temporary overvoltage on healthy phases is observed to be 1.092 pu for daytime and 1.189 pu for nighttime loading conditions. Both these values are within the permissible limit of 130% of the nominal voltage for Hydro One’s network [7].
From the steady-state analysis as well as transient analysis for SLGF, it is observed for the study system with both peak and off-peak loading conditions that both the steady state voltages and temporary overvoltages are within the permissible limits for base case.

### 3.3 Effect of Wind Farm Integration on Steady State Voltage

The base case study system is now modified with the addition of solar farm and the wind farm. A solar farm of 8.5 MW is considered at Bus 3 whereas Self Excited Induction Generator (SEIG) based wind farm is considered at Bus 4. The integration of wind farm in the distribution network will reduce the amount of power flow from the supply end to the receiving end or cause reverse power flow depending on the amount of loading in the network and the output of wind farm. The steady state effects of wind farm integration are shown below for daytime and nighttime scenarios.

The steady state voltage at 5 buses in the network: $V_{bus1}$, $V_{bus2}$, $V_{bus3}$, $V_{bus4}$ and $V_{bus5}$ are evaluated with increasing wind farm output ($P_{WF}$). The flow through the line is measured in terms of line current from the source terminal ($I_{src}$). Both the voltage limits as per the Hydro One’s specifications and line flow limits based on the conductor ampacity are considered to evaluate the impact of wind farm integration during steady state operation.
of the distribution system. To observe the effect of wind farm integration in the grid, no reactive power compensation is considered. In this condition, purely active power injection is considered for both the wind farm and solar farm.

### 3.3.1 Daytime Analysis

A peak load of 4.82 MW active power and 2.19 Mvar of reactive power are considered. Three conditions of solar farm output: Case 1 with 0% (0.0 MW), Case 2 with 50% (4.25 MW), and Case 3 with 100% (8.5 MW) are considered for daytime studies. The load flow analyses are carried out for all three cases with increasing wind farm output. The steady state bus voltages at all buses of the system for Case 1, Case 2 and Case 3 solar farm output conditions are given in Table 3.2, Table 3.3 and Table 3.4, respectively. These steady state voltages are computed for increasing wind farm output. For Case 1 with 0% solar farm output, the wind farm output can go up to 13.1 MW without violating any voltage limits in the system for daytime. The maximum wind power that can be incorporated into the grid without violating limits in the grid is 8.8 MW for Case 2 with 50% (4.25 MW) solar farm output. For Case 3 with 100% (8.5 MW) solar farm output, only 4.36 MW of wind farm output can be integrated into the grid, without violating the steady state voltage limit of 1.06 pu.

#### Table 3.2 Steady state results for daytime loading

**Case 1: 0% Solar farm output, P_{SF} = 0.0 MW, Q_{SF} = 0.0 Mvar**

<table>
<thead>
<tr>
<th>P_{WF} (MW)</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>13.1</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>36.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{bus1} (pu)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>V_{bus2} (pu)</td>
<td>1.054</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.044</td>
</tr>
<tr>
<td>V_{bus3} (pu)</td>
<td>0.966</td>
<td>1.013</td>
<td>1.044</td>
<td>1.058</td>
<td><strong>1.063</strong></td>
<td><strong>1.071</strong></td>
<td><strong>1.067</strong></td>
<td><strong>1.047</strong></td>
<td>0.974</td>
</tr>
<tr>
<td>V_{bus4} (pu)</td>
<td>0.954</td>
<td>1.007</td>
<td>1.044</td>
<td><strong>1.060</strong></td>
<td><strong>1.068</strong></td>
<td><strong>1.080</strong></td>
<td><strong>1.081</strong></td>
<td><strong>1.065</strong></td>
<td>0.999</td>
</tr>
<tr>
<td>V_{bus5} (pu)</td>
<td>0.941</td>
<td>0.996</td>
<td>1.033</td>
<td>1.049</td>
<td>1.057</td>
<td><strong>1.070</strong></td>
<td><strong>1.070</strong></td>
<td><strong>1.054</strong></td>
<td>0.987</td>
</tr>
<tr>
<td>I_{src} (Amp)</td>
<td>116.5</td>
<td>44.6</td>
<td>111.6</td>
<td>171.6</td>
<td>202.9</td>
<td>295.9</td>
<td>391.7</td>
<td>495.2</td>
<td>663.1</td>
</tr>
</tbody>
</table>
Table 3.3 Steady state results for daytime loading
Case 2: 50% Solar farm output, $P_{SF} = 4.25 \text{ MW}, Q_{SF} = 0.0 \text{ Mvar}$

<table>
<thead>
<tr>
<th>$P_{WF} (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>8.8</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>32.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.051</td>
<td>1.049</td>
<td>1.046</td>
<td>1.044</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.006</td>
<td>1.042</td>
<td><strong>1.060</strong></td>
<td><strong>1.065</strong></td>
<td><strong>1.076</strong></td>
<td><strong>1.076</strong></td>
<td><strong>1.063</strong></td>
<td>1.026</td>
<td>0.987</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>0.994</td>
<td>1.036</td>
<td>1.058</td>
<td><strong>1.064</strong></td>
<td><strong>1.081</strong></td>
<td><strong>1.086</strong></td>
<td><strong>1.076</strong></td>
<td>1.044</td>
<td>1.009</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>0.982</td>
<td>1.025</td>
<td>1.047</td>
<td>1.053</td>
<td><strong>1.070</strong></td>
<td><strong>1.075</strong></td>
<td><strong>1.066</strong></td>
<td>1.033</td>
<td>0.997</td>
</tr>
<tr>
<td>$I_{src} (Amp)$</td>
<td>48.1</td>
<td>98.1</td>
<td>166.9</td>
<td>189.0</td>
<td>281.5</td>
<td>376.0</td>
<td>476.1</td>
<td>590.9</td>
<td>663.4</td>
</tr>
</tbody>
</table>

Table 3.4 Steady state results for daytime loading
Case 3: 100% Solar farm output, $P_{SF} = 8.5 \text{ MW}, Q_{SF} = 0.0 \text{ Mvar}$

<table>
<thead>
<tr>
<th>$P_{WF} (MW)$</th>
<th>0.0</th>
<th>4.36</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>28.5</th>
<th>30.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.053</td>
<td>1.052</td>
<td>1.051</td>
<td>1.049</td>
<td>1.047</td>
<td>1.044</td>
<td>1.047</td>
<td>0.973</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.036</td>
<td><strong>1.060</strong></td>
<td><strong>1.063</strong></td>
<td><strong>1.078</strong></td>
<td><strong>1.083</strong></td>
<td><strong>1.074</strong></td>
<td><strong>1.047</strong></td>
<td>1.005</td>
<td>0.973</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.024</td>
<td>1.054</td>
<td>1.057</td>
<td><strong>1.078</strong></td>
<td><strong>1.087</strong></td>
<td><strong>1.083</strong></td>
<td><strong>1.061</strong></td>
<td>1.023</td>
<td>0.992</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.013</td>
<td>1.043</td>
<td>1.046</td>
<td><strong>1.067</strong></td>
<td><strong>1.076</strong></td>
<td><strong>1.073</strong></td>
<td><strong>1.050</strong></td>
<td>1.012</td>
<td>0.980</td>
</tr>
<tr>
<td>$I_{src} (Amp)$</td>
<td>85.6</td>
<td>163.4</td>
<td>175.1</td>
<td>267.4</td>
<td>361.0</td>
<td>458.9</td>
<td>567.4</td>
<td>660.2</td>
<td>712.5</td>
</tr>
</tbody>
</table>

In this study, the maximum wind farm output that can be integrated to the grid is limited by the rise in voltage due to reverse power flow. The output of the solar farm adds up to the reverse power flow and hence further reduces the availability for wind farm integration during daytime. The variation in the PCC bus voltage for various cases of solar farm output with increasing wind farm integration is shown in Figure 3.5. Increasing wind power output leads to higher reverse power flow. The voltage at the point of common coupling (Bus 4) increases with wind farm output up to certain stage after which it again decreases. The rise in receiving end voltage is due to increased reverse power flow and is particularly dominant in a system with low $X/R$ ratio [6].
The decrease in voltage is due to increased reactive power loss in the line with higher wind power output. This effect of the distributed generation on the steady state voltage is already discussed in Section 1.2.1 in Chapter 1.

3.3.2 Nighttime Analysis

An off-peak load of 2.1 MW active power and 0.73 Mvar reactive power (1.76 MVA at 0.91 lagging power factor) is considered for nighttime analysis. During nighttime the load is lower as compared to daytime. The voltage magnitudes at various buses in the system for nighttime loading condition are presented in Table 3.5. It is observed that a maximum wind power of 4.04 MW can be integrated into the network during nighttime without violating the voltage limit of 106% of nominal voltage, for all buses.

The node voltages at the solar farm terminal (Bus 3), wind farm terminal (Bus 4) and receiving end (Bus 5) are higher during nighttime as compared to peak loading condition during daytime. The variation in voltage for nighttime with increasing wind farm integration is shown in Figure 3.5. This demonstrates that during nighttime, even though the wind availability is high, the corresponding wind power cannot be integrated into the grid as it results in unacceptably high steady state voltages.

| Table 3.5 Steady state results for nighttime loading, $P_{SF} = 0.0$ MW, $Q_{SF} = 0.0$ Mvar |
|---------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $P_{WF}$ (MW) | 0.0 | 4.04 | 5.0 | 10.0 | 15.0 | 20.0 | 25.0 | 30.0 | 34.5 |
| $V_{bus1}$ (pu) | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 |
| $V_{bus2}$ (pu) | 1.055 | 1.055 | 1.055 | 1.054 | 1.053 | 1.052 | 1.050 | 1.048 | 1.044 |
| $V_{bus3}$ (pu) | 1.030 | 1.059 | **1.065** | **1.088** | **1.101** | **1.104** | **1.095** | **1.068** | 1.013 |
| $V_{bus4}$ (pu) | 1.026 | **1.060** | **1.067** | **1.095** | **1.112** | **1.119** | **1.115** | **1.093** | 1.043 |
| $V_{bus5}$ (pu) | 1.023 | 1.056 | **1.063** | **1.091** | **1.109** | **1.116** | **1.111** | **1.090** | 1.039 |
| $I_{src}$ (Amp) | 34.9 | 49.4 | 67.5 | 160.6 | 251.9 | 343.5 | 438.7 | 543.0 | 659.2 |
3.4 Effect of Wind Farm Integration on Temporary Overvoltage

As in base case scenario presented in Section 3.2.2, a single line to ground fault (SLGF) of 6 cycles at the receiving end (load end) is applied to examine the effect of increased wind farm output on the temporary overvoltages in the study system. The effect of increased wind farm connectivity on the temporary overvoltage is analyzed for both daytime and nighttime in the following sub-sections.

3.4.1 Daytime Analysis

A typical condition of 20.0 MW wind farm output with no photovoltaic solar farm output ($P_{SF} = 0.0 MW$) is considered for the daytime. A high temporary overvoltage (1.371 pu) is observed. The phase voltages for this operating condition are shown in Figure 3.6.
Temporary overvoltage are evaluated for three solar farm output cases (0%, 50% and 98% solar farm output) as in the case of steady state analysis presented in Section 3.3. This is done to determine the maximum wind connectivity from TOV considerations. For Case 1 with 0% solar farm output ($P_{SF} = 0.0 \text{ MW}$), maximum 11.5 MW of wind farm output can be integrated into the grid with temporary voltage within the permissible limits of 130%. The phase voltages for this loading condition are shown in Figure 3.7 with TOV of 1.287 pu.

**Figure 3.6 Phase voltages for daytime loading with SLGF**

*Case 1: $P_{SF} = 0.0 \text{ MW}, P_{WF} = 20.0 \text{ MW}*$

**Figure 3.7 Phase voltages for daytime loading with SLGF**

*Case 1: $P_{SF} = 0.0 \text{ MW}, P_{WF} = 11.5 \text{ MW}$*
For 50% solar farm output ($P_{SF} = 4.25 \, MW$), the maximum wind power that can be integrated into the network is limited to 5.4 MW which causes a TOV of 1.296 pu. The wind power output is limited to 2.1 MW for 98% of solar farm output ($P_{SF} = 8.33 \, MW$) which causes TOV of 1.291 pu. The phase voltages with single line to ground fault for these two conditions are shown in Figure 3.8 and Figure 3.9, respectively.

**Figure 3.8 Phase voltages for daytime loading with SLGF**

Case 2: $P_{SF} = 4.25 \, MW$, $P_{WF} = 5.4 \, MW$

**Figure 3.9 Phase voltages for daytime loading with SLGF**

Case 3: $P_{SF} = 8.33 \, MW$, $P_{WF} = 2.1 \, MW$
3.4.2 Nighttime Analysis

To evaluate the temporary overvoltage with SLGF with increased wind power output for nighttime, a typical condition of 20 MW wind farm output is considered with nighttime loading condition. The phase voltages for this condition are shown in Figure 3.10. This scenario leads to a temporary overvoltage of 1.45 pu which is much higher than the corresponding wind farm output condition during daytime.

For nighttime loading, a maximum 3.9 MW of wind farm output can be integrated into the grid with a temporary overvoltage of 1.296 pu which is within the permissible limits.
of 130%. The phase voltages for this loading condition are shown in Figure 3.11. It is then observed that in the nighttime, the wind power that can be integrated into the network is less than that can be integrated during daytime, from TOV considerations.

3.5 Steady-state Voltage Control by PV-STATCOM

The steady-state voltages for different cases of daytime and nighttime are analyzed in Section 3.3. It is seen that wind farm integration is limited by the steady-state voltage rise due to reverse power flow. Such a rise in voltage can be reduced by reactive power compensation in the network. In this thesis, the application of PV solar farm converter operating as STATCOM, referred as PV-STATCOM, is proposed. The effectiveness of such PV-STATCOM to regulate the steady-state voltage thereby increasing the connectivity of the wind farm into the distribution network is investigated. The steady state analysis is carried out to evaluate the requirement of reactive power compensation at the PV solar farm terminal to maintain voltages between 0.94 pu and 1.06 pu for all the buses in the network.

3.5.1 Daytime Analysis

For Case 1 (0% solar farm output, $P_{SF} = 0.0 \, MW$) during daytime loading, the voltages for all the buses are within limits up to 13.1 MW wind farm injection without reactive power compensation. With the appropriate reactive power compensation, the wind power injection can be increased up to 36.0 MW while maintaining the conductor ampacity of 665 Amp and voltages at all buses within limits. The compensation requirements for this condition are shown in Table 3.6.

For Case 2 (50% solar farm output, $P_{SF} = 4.25 \, MW$) during daytime, up to 8.8 MW of wind farm output can be injected into the network with all the voltages staying within limits without compensation. With appropriate reactive power compensation, the wind farm injection can be increased up to 32.5 MW while maintaining the conductor ampacity and voltages at all buses within limits. The reactive power compensation requirements for this condition are shown in Table 3.7.
Table 3.6 Steady state voltages with reactive power compensation during daytime

Case 1: 0% solar farm output, $P_{SF} = 0.0$ MW

<table>
<thead>
<tr>
<th>$P_{WF}$ (MW)</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>13.1</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>36.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}$ (pu)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}$ (pu)</td>
<td>1.054</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.051</td>
<td>1.050</td>
<td>1.048</td>
<td>1.044</td>
</tr>
<tr>
<td>$V_{bus3}$ (pu)</td>
<td>0.966</td>
<td>1.013</td>
<td>1.044</td>
<td>1.058</td>
<td>1.056</td>
<td>1.051</td>
<td>1.046</td>
<td>1.041</td>
<td>0.974</td>
</tr>
<tr>
<td>$V_{bus4}$ (pu)</td>
<td>0.954</td>
<td>1.007</td>
<td>1.044</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>0.999</td>
</tr>
<tr>
<td>$V_{bus5}$ (pu)</td>
<td>0.941</td>
<td>0.996</td>
<td>1.033</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>0.987</td>
</tr>
<tr>
<td>$I_{src}$ (Amp)</td>
<td>116.5</td>
<td>44.6</td>
<td>111.6</td>
<td>171.6</td>
<td>206.3</td>
<td>305.4</td>
<td>402.4</td>
<td>498.1</td>
<td>653.1</td>
</tr>
<tr>
<td>$Q_{SF}$ (Mvar)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.38 0.93 0.85 0.18 0.0</td>
</tr>
</tbody>
</table>

Table 3.7 Steady state voltages with reactive power compensation during daytime

Case 2: 50% solar farm output, $P_{SF} = 4.25$ MW

<table>
<thead>
<tr>
<th>$P_{WF}$ (MW)</th>
<th>0.0</th>
<th>5.0</th>
<th>8.8</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>32.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}$ (pu)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}$ (pu)</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.046</td>
<td>1.044</td>
</tr>
<tr>
<td>$V_{bus3}$ (pu)</td>
<td>1.006</td>
<td>1.042</td>
<td>1.060</td>
<td>1.059</td>
<td>1.056</td>
<td>1.051</td>
<td>1.046</td>
<td>1.026</td>
<td>0.987</td>
</tr>
<tr>
<td>$V_{bus4}$ (pu)</td>
<td>0.994</td>
<td>1.036</td>
<td>1.058</td>
<td>1.059</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.044</td>
<td>1.009</td>
</tr>
<tr>
<td>$V_{bus5}$ (pu)</td>
<td>0.982</td>
<td>1.025</td>
<td>1.047</td>
<td>1.048</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>1.033</td>
<td>0.997</td>
</tr>
<tr>
<td>$I_{src}$ (Amp)</td>
<td>48.1</td>
<td>98.1</td>
<td>166.9</td>
<td>191.1</td>
<td>290.7</td>
<td>388.7</td>
<td>485.3</td>
<td>590.9</td>
<td>663.4</td>
</tr>
<tr>
<td>$Q_{SF}$ (Mvar)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25 0.96 1.1 0.62 0.0 0.0</td>
</tr>
</tbody>
</table>

Similarly for Case 3 (98% solar farm output, $P_{SF} = 8.33$ MW) during daytime loading, only up to 4.58 MW of wind farm output can be injected into the network with all the voltages remaining within limits without compensation. With appropriate reactive power compensation, the wind power injection can be increased up to 28.7 MW while maintaining the conductor ampacity and voltages at all buses within limits. The reactive power compensation requirements for this condition are shown in Table 3.8.
Table 3.8 Steady state voltages with reactive power compensation during daytime

Case 3: 98% solar farm output, $P_{SF} = 8.33 \ MW$

<table>
<thead>
<tr>
<th>$P_{WF} (MW)$</th>
<th>0.0</th>
<th>4.58</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>28.7</th>
<th>30.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.049</td>
<td>1.047</td>
<td>1.044</td>
<td>1.042</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.036</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.055</td>
<td>1.051</td>
<td>1.046</td>
<td>1.005</td>
<td>0.973</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.024</td>
<td>1.054</td>
<td>1.054</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.023</td>
<td>0.992</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.013</td>
<td>1.043</td>
<td>1.043</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>1.049</td>
<td>0.980</td>
</tr>
<tr>
<td>$I_{src} (Amp)$</td>
<td>85.6</td>
<td>163.4</td>
<td>176.3</td>
<td>275.1</td>
<td>374.0</td>
<td>471.4</td>
<td>567.8</td>
<td>660.2</td>
<td>712.5</td>
</tr>
<tr>
<td>$Q_{SF} (Mvar)$</td>
<td>0.14</td>
<td>0.85</td>
<td>1.2</td>
<td>0.92</td>
<td>0.02</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.5.2 Nighttime Analysis

For nighttime loading, wind farm integration without compensation is limited to 4.04 $MW$. The reactive power compensation at solar farm terminal can increase wind farm connectivity up to 34.5 $MW$ while maintaining the steady-state voltages and conductor ampacity. The required reactive power compensation from the PV-STATCOM for nighttime loading scenario is shown in Table 3.9.

Table 3.9 Steady state voltages with reactive power compensation

Nighttime loading: $P_{SF} = 0.0 \ MW$

<table>
<thead>
<tr>
<th>$P_{WF} (MW)$</th>
<th>0.0</th>
<th>4.04</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>34.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.054</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.047</td>
<td>1.044</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.030</td>
<td>1.059</td>
<td>1.058</td>
<td>1.053</td>
<td>1.048</td>
<td>1.044</td>
<td>1.039</td>
<td>1.035</td>
<td>1.013</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.026</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.043</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.023</td>
<td>1.056</td>
<td>1.056</td>
<td>1.056</td>
<td>1.056</td>
<td>1.056</td>
<td>1.056</td>
<td>1.056</td>
<td>1.039</td>
</tr>
<tr>
<td>$I_{src} (Amp)$</td>
<td>34.9</td>
<td>49.4</td>
<td>69.6</td>
<td>172.8</td>
<td>272.9</td>
<td>370.8</td>
<td>467.1</td>
<td>562.3</td>
<td>659.2</td>
</tr>
<tr>
<td>$Q_{SF} (Mvar)$</td>
<td>0.36</td>
<td>1.78</td>
<td>2.53</td>
<td>2.66</td>
<td>2.18</td>
<td>1.09</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thus, maximum reactive power, $Q_{SF} = 2.66 \ Mvar$ is needed for regulating the steady state voltage within acceptable limits.
3.6 Temporary Overvoltage Control by PV-STATCOM

3.6.1 Daytime Analysis

For daytime loading condition with 0% solar farm output, the full PV inverter capacity is available for reactive power compensation. The phase voltages at the point of common coupling (PCC) of wind farm for single line to ground fault are shown in Figure 3.12. In such a condition, the PV-STATCOM can increase wind farm connectivity from 11.5 MW to 19.5 MW. A temporary overvoltage of 1.297 pu is observed which is within the permissible limit of 130%.

![Figure 3.12 Phase voltages for daytime loading with SLGF, $P_{SF} = 0.0$ MW, $P_{WF} = 19.5$ MW](image)

3.6.2 Nighttime Analysis

For nighttime loading condition, the phase voltages at the point of common coupling (PCC) of wind farm for single line to ground fault are shown in Figure 3.13. With PV-STATCOM controlled to suppress the temporary overvoltage caused by single line to ground fault, the wind farm connectivity increases from 3.9 MW to 16.6 MW maintaining the temporary overvoltage at 1.30 pu. As noted in sections 3.3 and 3.4, nighttime loading presents the worst case scenario from steady state voltage and temporary overvoltage.
considerations. Hence, the significant improvement in wind farm connectivity for nighttime demonstrates the effectiveness of using PV solar farm inverter as STATCOM.

![Figure 3.13 Phase voltages for nighttime loading with SLGF, $P_{SF} = 0.0\ MW, P_{WF} = 16.6\ MW$](image)

3.7 Reactive Power Compensation Requirement

In this section, the availability and the requirement of the reactive power compensation for controlling steady state voltage for various conditions of wind farm output are examined. The availability of reactive power from the PV-STATCOM is based on the net remaining inverter capacity for the daytime and the full rating of the PV inverter during nighttime.

For the analysis of nighttime and daytime active power generation and availability of reactive power compensation, May 01, 2012 as a typical day has been considered in this study. From the annual sunshine graph shown in Figure 3.14, the daytime is considered from 6:00 am to 8:30 pm for May 01, 2012 in London, Ontario. The remaining hours of the day i.e. from 8:30 pm to 6:00 am is considered as nighttime for the purpose of analysis here.

The peak solar irradiance is considered from 11:00am to 3:30pm. The typical available active power based on the daily variation in solar irradiance and the corresponding
availability of reactive power based on remaining capacity of PV inverter (both in terms of percentage of PV solar farm capacity) are shown in Figure 3.15.

Figure 3.14 Annual sunshine graph for London, Ontario (Source: www.gaisma.com)

The amount of reactive power compensation required to maintain voltages within the permissible limits of 0.94 $pu$ – 1.06 $pu$ at all the buses in the network for various operating conditions with increasing wind farm connectivity are evaluated and presented in Figure 3.16. The voltages at various buses increase due to reverse power flow. However, after certain wind farm output and corresponding reverse power flow, the voltage decreases due to increased reactive power consumption in the line with increased current. For the given study system, the maximum reactive compensation requirement is 1.2 Mvar for 98% solar farm output ($P_{SF} = 8.33 MW$) with 15.0 MW of wind farm output. For nighttime, the reactive power requirement increases up to 2.66 Mvar with 20.0 MW of wind farm output.
Figure 3.15 Available active and reactive power capacity for solar farm converter based on typical insolation (approximate sunshine data) and PV module output

Figure 3.16 Reactive power compensation provided by solar farm (PV-STATCOM) to maintain PCC voltages within permissible limits (±6%)
3.8 Effect of Solar Farm Location

The above analysis shows that the maximum reactive power compensation required to maintain steady state voltage for all buses within limits is $2.6 \, \text{Mvar}$ for the specific location of PV solar farm and wind farm considered in this study. The entire $8.5 \, \text{Mvar}$ capacity of PV converter is available for reactive power compensation during nighttime. This reactive power availability is, however, dependent on time of the day and solar irradiance for the daytime.

Due to the distributed nature of the PV solar installations, the location of PV solar farm relative to the wind farm installation may vary. The reactive power requirement to maintain the voltages within permissible limits for nighttime as well as all the cases of daytime with increasing distance of PV-STATCOM from the wind farm is shown in Figure 3.17.

![Figure 3.17 Maximum reactive power compensation provided by PV-STATCOM to maintain steady-state voltage within permissible limits](image-url)
The PV-STATCOM reactive power, required to maintain voltages within limits at all the buses, increases as the PV solar farm location moves away from wind farm location. With this compensation from PV-STATCOM, the wind farm connectivity is enhanced up to ampacity limit of feeder conductor considering steady-state voltage criteria. This analysis shows that the PV-STATCOM of rating 8.5 Mvar is effective in maintaining voltages even if the solar farm is located 30 km away from the wind farm.

3.9 Effect of $X/R$ Ratio in Base Case Scenario

The distribution systems are characterized by low $X/R$ ratio compared to transmission network. Both steady-state voltage profile and the temporary overvoltage due to unbalanced faults in the system are affected by $X/R$ ratio for the system. The preceding analyses of the study system were carried out with $X/R$ ratio of 2.472 for 336AL427 conductor used in the distribution line. The impact on both the steady state voltages and temporary overvoltage for half and double of the $X/R$ ratio, i.e. $X/R$ ratio of 1.236 and 4.944 respectively, is considered here, keeping the impedance of the line constant.

The base case scenario of $X/R$ ratio variation analysis is carried out for the system without solar farm and wind farm. The steady state voltages for the daytime loading and nighttime loading with $X/R$ ratio variation are presented in Table 3.10.

<table>
<thead>
<tr>
<th>Table 3.10 Base case steady state voltages with $X/R$ ratio variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Daytime</strong></td>
</tr>
<tr>
<td>$V_{bus1} (pu)$</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
</tr>
</tbody>
</table>
Compared to the base case results for original $X/R$ ratio listed in Table 3.1 (Section 3.2), the steady state voltages at the PCC terminals for solar farm (Bus 3) and wind farm (Bus 4) as well as the receiving end (Bus 5) get decreased for half $X/R$ ratio but are slightly improved for double $X/R$ ratio. The comparative results in voltage profile for wind farm PCC (Bus 4) are shown in Figure 3.18.

### 3.9.1 Daytime Analysis

The steady-state wind farm PCC voltage (Bus 4) is less than the permissible limit of 0.96 $pu$ for daytime loading with half $X/R$ ratio even for the base case operation of the system. The temporary overvoltages for SLGF for base case scenario with half and double of the original $X/R$ ratio are determined. The phase voltage at wind farm terminal for SLGF at the receiving end for study system configuration with half (1.236) and double (4.944) $X/R$ ratios are depicted in Figure 3.19 and Figure 3.20, respectively, for daytime loading condition. Temporary overvoltages of 1.063 $pu$ and 1.098 $pu$ are observed for half and double $X/R$ ratio conditions, respectively. In this case the TOV is within permissible limit of 130% for daytime base case scenario.
3.9.2 Nighttime Analysis

The temporary overvoltages for nighttime loading condition for half (1.236) and double (4.944) \(X/R\) ratios are presented in Figure 3.21 and Figure 3.22, respectively. Temporary overvoltages of 1.18 pu and 1.217 pu are observed for half and double \(X/R\) ratio conditions, respectively for nighttime base case scenario. As in the analysis of steady
state voltages, the temporary overvoltages are decreased for less $X/R$ ratio and increased for higher $X/R$ ratio. However, for all the cases for $X/R$ ratio, the TOV in the study system are within permissible limits (130%) with base case loading for nighttime.

![Figure 3.21 Phase voltages for SLGF](image1)

**Nighttime base case loading: Half $X/R$ (1.236)**

![Figure 3.22 Phase voltages for SLGF](image2)

**Nighttime base case - Double $X/R$ (4.994)**

The base case (No solar farm and wind farm outputs) results for the steady state as well as temporary overvoltage for various $X/R$ ratios considered in this study are summarized in Table 3.11.
Table 3.11 Base case results for $X/R$ ratio variation, $P_{SF} = 0.0\, MW$, $P_{WF} = 0.0\, MW$

<table>
<thead>
<tr>
<th></th>
<th>Steady state voltage</th>
<th>Temporary overvoltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daytime</td>
<td>Nighttime</td>
</tr>
<tr>
<td>Half $X/R$ ratio (1.236)</td>
<td>0.930 pu</td>
<td>1.019 pu</td>
</tr>
<tr>
<td>Original $X/R$ ratio (2.472)</td>
<td>0.953 pu</td>
<td>1.026 pu</td>
</tr>
<tr>
<td>Double $X/R$ ratio (4.944)</td>
<td>0.972 pu</td>
<td>1.032 pu</td>
</tr>
</tbody>
</table>

3.10 Effect of $X/R$ ratio on Wind Farm Connectivity with PV-STATCOM Control

3.10.1 Daytime Analysis

For the study system with half $X/R$ ratio and daytime loading with 0% solar farm output, the wind power output that can be injected without violating the voltage limits is 8.26 MW as shown in Table 3.12. For normal $X/R$ ratio keeping all the operating condition unchanged (daytime loading with 0% solar farm output), the maximum wind farm connectivity was found to be 13.1 MW. When the $X/R$ ratio is doubled, the receiving end voltage decreases even with high wind farm connectivity and increased reverse power flow. This scenario provides better condition for wind farm injection into the grid. For the study system, up to 26.6 MW of wind farm output can be injected into the grid without violating the voltage limits with no reactive power compensation in the system.

Studies are now conducted with reactive power compensation provided by PV-STATCOM. It is observed that the wind farm injection can be increased up to 35.0 MW for 0% solar farm output in both the cases of half $X/R$ ratio and double $X/R$ ratio with appropriate reactive power compensation from the PV-STATCOM. The reactive power
compensation required for half X/R ratio condition is 8.29 Mvar absorption by the PV-STATCOM to reduce the voltage. However a reactive power injection of 4.57 Mvar is needed to increase the voltage to permissible limits for double X/R ratio condition. The steady-state voltages at various buses of the network are presented in Table 3.12.

The steady state voltage and the wind farm output without PV-STATCOM and with appropriated reactive power compensation from PV-STATCOM for both the half and double X/R ratios are presented in Table 3.13 and Table 3.14 with 50% solar farm output and 95% solar farm output, respectively, for daytime loading condition.

For 50% solar farm output, the wind farm connectivity can be increased upto 19.5 MW for half X/R ratio with reactive power absorption of 7.36 Mvar and upto 31.0 MW for double X/R ratio with reactive power injection of 4.08 Mvar. The permissible wind farm connectivity reduces to 4.65 MW for half X/R ratio and 25.68 MW for double X/R ratio for 95% solar farm output condition.

<table>
<thead>
<tr>
<th></th>
<th>Without PV-STATCOM</th>
<th>With PV-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{WF}$</td>
<td>8.26 MW</td>
<td>13.1 MW</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 pu</td>
<td>1.0550 pu</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0539 pu</td>
<td>1.0533 pu</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0589 pu</td>
<td>1.0575 pu</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0600 pu</td>
<td>1.0600 pu</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0466 pu</td>
<td>1.0492 pu</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>78.7 Amp</td>
<td>167.9 Amp</td>
</tr>
<tr>
<td>$Q_{SF}$</td>
<td>8.29 Mvar</td>
<td>0.0 Mvar</td>
</tr>
</tbody>
</table>
Table 3.13 Steady state voltages with X/R ratio variation for daytime
Case 2: 50% solar farm output, $P_{SF} = 4.25 MW$

<table>
<thead>
<tr>
<th></th>
<th>Without PV-STATCOM</th>
<th>With PV-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{WF}$ ⇒</td>
<td>4.06 $MW$</td>
<td>8.8 $MW$</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 $pu$</td>
<td>1.0550 $pu$</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0539 $pu$</td>
<td>1.0534 $pu$</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0600 $pu$</td>
<td>1.0600 $pu$</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0537 $pu$</td>
<td>1.0583 $pu$</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0402 $pu$</td>
<td>1.0474 $pu$</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>79.6 Amp</td>
<td>166.88 Amp</td>
</tr>
<tr>
<td>$Q_{SF}$</td>
<td>7.36 $Mvar$</td>
<td>0.0 $Mvar$</td>
</tr>
</tbody>
</table>

Table 3.14 Steady state voltages with X/R ratio variation for daytime
Case 3: 95% solar farm output, $P_{SF} = 8.07 MW$

<table>
<thead>
<tr>
<th></th>
<th>Without PV-STATCOM</th>
<th>With PV-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{WF}$ ⇒</td>
<td>0.34 $MW$</td>
<td>4.8 $MW$</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 $pu$</td>
<td>1.0550 $pu$</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0539 $pu$</td>
<td>1.0534 $pu$</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0600 $pu$</td>
<td>1.0600 $pu$</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0470 $pu$</td>
<td>1.0542 $pu$</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0335 $pu$</td>
<td>1.0432 $pu$</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>81.1 Amp</td>
<td>163.5 Amp</td>
</tr>
<tr>
<td>$Q_{SF}$</td>
<td>2.36 $Mvar$</td>
<td>0.0 $Mvar$</td>
</tr>
</tbody>
</table>
3.10.2 Nighttime Analysis

For nighttime loading condition, the steady state voltages and the wind farm output as well as the reactive power compensation from the PV-STATCOM are presented in Table 3.15. It is observed that the wind farm injection can be increased up to 18.56 MW in the cases of half $X/R$ ratio and up to 32 MW in case of double $X/R$ ratio with appropriate reactive power compensation from the PV-STATCOM.

The reactive power compensation required is 8.5 Mvar absorption by the PV-STATCOM to reduce the voltage within limits for half $X/R$ ratio condition. However, reactive power injection of 3.06 Mvar by PV-STATCOM is needed to increase the voltage to permissible limits for double $X/R$ ratio condition.

Table 3.15 Steady state voltages with $X/R$ ratio variation for nighttime, $P_{SF} = 0.0 \, MW$

<table>
<thead>
<tr>
<th>Without STATCOM</th>
<th>With PV-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{WF}$</td>
<td>2.82 MW</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 pu</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0547 pu</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0594 pu</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0600 pu</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0556 pu</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>26.6 Amp</td>
</tr>
<tr>
<td>$Q_{SF}$</td>
<td>8.5 Mvar</td>
</tr>
</tbody>
</table>

3.11 Increase in Wind Farm Connectivity with PV-STATCOM

With the application of novel PV-STATCOM controller, both the steady state voltage rise and temporary overvoltage can be controlled for enhancing wind power connectivity.
in the distribution grid. The available wind farm connectivity based on the conductor ampacity, steady state voltage limits and the temporary overvoltage limits for the study system, with and without PV-STATCOM, are summarized in Table 3.16. The net reverse power flow in this study system due to wind power integration into the grid is determined for given loading condition and solar farm output condition. The net reverse flow is used to evaluate conductor ampacity limit at the supply end of the distribution line. This is the maximum limit beyond which the wind farm connectivity cannot be improved. The nominal $X/R$ ratio of 2.476 is considered for this study.

Table 3.16 Summarized results for wind farm connectivity

<table>
<thead>
<tr>
<th>Solar Farm Output $P_{SF}$ (% of its capacity)</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 $MW$ (0%)</td>
<td>4.25 $MW$ (50%)</td>
<td>8.33 $MW$ (98%)</td>
</tr>
</tbody>
</table>

| Conductor Ampacity Limits (665 Amp)           |
|-----------------------------------------------|---------|-----------|---------|---------|
| 36.0 $MW$                                   | 32.5 $MW$ | 28.7 $MW$ | 34.5 $MW$ |

| Steady-State Voltage Limits (0.94 pu – 1.06 pu) |
|-----------------------------------------------|---------|-----------|---------|---------|
| Without PV-STATCOM                            | 13.1 $MW$ | 8.8 $MW$  | 4.58 $MW$ | 4.04 $MW$ |
| With PV-STATCOM                               | 36.0 $MW$ | 32.5 $MW$ | 28.5 $MW$ | 34.5 $MW$ |

| Temporary Overvoltage Limit (130%)           |
|-----------------------------------------------|---------|-----------|---------|---------|
| Without PV-STATCOM                            | 11.5 $MW$ | 5.4 $MW$  | 2.1 $MW$ | 3.9 $MW$ |
| With PV-STATCOM                               | 19.5 $MW$ | 9.0 $MW$  | 4.5 $MW$ | 16.6 $MW$ |

The reverse power flow causes the steady state voltage to increase beyond permissible limits in the study system. The PV-STATCOM is very effective in maintaining steady state voltages. With proper reactive power compensation with PV-STATCOM the wind farm connectivity can be increased up to conductor ampacity limit.
The wind power connectivity is, however, limited by temporary overvoltage in the system. The PV-STATCOM controller can increase the wind farm connectivity up to $16.6 \, MW$ during nighttime. Whereas for the daytime, these values get limited by the solar farm active power output. For daytime loading with 0% solar farm output, the maximum wind farm connectivity can increase up to $19.5 \, MW$. These maximum wind connectivity values are reduced to $9.0 \, MW$ and $4.5 \, MW$ for 50% solar farm output and 98% solar farm output, respectively. The overall wind farm connectivity results are presented in Figure 3.23 for various operating conditions that may be encountered on a typical day considered for this study. It may be noted that the TOV considerations override the steady state voltage consideration in this analysis.

For 100% solar farm output ($8.5 \, MW$) during peak irradiance (11:00 am – 3:30 pm), all the inverter capacity is used for active power transfer and no reactive power capacity for PV-STATCOM operation is available. In this condition, the wind farm connectivity is limited to $2.1 \, MW$. The available wind farm connectivity considering no reactive power availability for peak irradiance is shown in Figure 3.24.
3.12 Conclusion

This chapter demonstrates the effectiveness of a novel control of PV solar farm as PV-STATCOM in significantly enhancing the connectivity (power output) of a neighbouring IG based wind farm in a radial distribution feeder.

The steady state analysis is carried using PSS/E software and electromagnetic transient simulation is carried using PSCAD/EMTDC software. For steady-state analysis the rise in voltages, due to reverse power flow caused by wind farm integration, is observed. The increase in temporary overvoltage for single line to ground fault is determined from electromagnetic transient simulation. The effectiveness of PV-STATCOM to mitigate both the steady-state voltage rise and temporary overvoltage is evaluated so that wind power injection into the grid can be increased. For the study system, the TOV considerations override the steady state voltage rise considerations. Without PV-STATCOM, the wind farm connectivity is limited to 2.1 MW for daytime and 3.9 MW for nighttime. With the 8.5 MW PV solar farm converter operated as PV-STATCOM, the wind farm connectivity can be increased from 11.5 MW to 19.5 MW for 0% solar farm...
output, from $5.4 \, MW$ to $9.0 \, MW$ for 50% solar farm output and from $2.1 \, MW$ to $4.5 \, MW$ for 98% solar farm output for daytime, and from $3.9 \, MW$ to $16.6 \, MW$ for nighttime.

These above results are evaluated based on the $8.5 \, MW$ PV solar farm located $5 \, km$ from the wind farm towards the supply end. The effectiveness of PV-STATCOM with respect to its distance from the wind farm is also evaluated. The PV-STATCOM requires more reactive power compensation to maintain permissible steady-state voltage as it moves away from the wind farm. It is demonstrated that the solar farm can effectively regulate bus voltages and help increase wind connectivity even if it is located $30 \, km$ away from the wind farm.

The feeder $X/R$ ratio is an important factor in determining voltage rise due to reverse power flow. Decrease in $X/R$ ratio to half further increases steady-state voltages due to reverse power flow and reduces wind farm connectivity as compared to the system with original $X/R$ ratio. Therefore, more reactive power compensation from PV-STATCOM is required to regulate the voltage within permissible limits. For the study system with daytime loading and 0% solar farm output, reactive power compensation of $8.29 \, Mvar$ from PV-STATCOM increases wind connectivity from $8.26 \, MW$ to $35.0 \, MW$. For the system with original $X/R$ ratio and same loading condition (daytime with 0% solar farm output), only $0.93 \, Mvar$ of reactive compensation is required to increase wind connectivity from $13.1 \, MW$ to $36.0 \, MW$.

For double $X/R$ ratio, there is an acceptable rise in voltage for small wind power outputs, but an unacceptable decrease in voltage for large wind power outputs. For the daytime loading with 0% solar farm output, wind farm connectivity is increased from $26.6 \, MW$ to $35.0 \, MW$ with PV-STATCOM. In this case, PV-STATCOM supplies reactive power of $4.57 \, Mvar$ to the system to boost PCC voltage up to minimum permissible limit.

The PV-STATCOM is thus shown to effectively increase the amount of wind power generation that can be supplied to the grid both during night and day. The PV-STATCOM is able to accomplish this objective with the full PV solar inverter capacity during nighttime, and with the inverter capacity remaining after real power generation during daytime.
Chapter 4

WIND-STATCOM CONTROL FOR INCREASING SOLAR FARM CONNECTIVITY

4.1 Introduction

Due to increased proliferation of renewable energy systems in distribution systems, the likelihood of PV solar generators and wind turbine generators being on the same distribution feeder is becoming quite high. In recent days, full-converter based permanent magnet synchronous generators (PMSG) are being used in such medium voltage distribution networks. The issue of steady-state voltage rise due to reverse power flow caused by increased DG connections was investigated in Chapter 3. This chapter deals with application of a novel control of the wind farm converter as STATCOM, referred as Wind-STATCOM. The Wind-STATCOM is utilized to maintain steady-state voltage and temporary overvoltage within acceptable limits in order to increase the connectivity of a neighbouring PV solar system. The application of a 9.9 MW wind farm as Wind-STATCOM to increase the PV solar farm connectivity up to 30.0 MW is investigated in this chapter.

The steady-state analysis of the study system is carried out using PSS/E. A complete assessment of voltage profile with increasing solar farm output for various scenarios of wind farm generation is used to identify the challenges for PV solar farm integration to the grid. The maximum solar farm connectivity is evaluated with reactive power compensation from the Wind-STATCOM. The electromagnetic transient model of Wind-
STATCOM is implemented in PSCAD/EMTDC and its effectiveness in reducing temporary overvoltage caused by single line to ground fault is studied.

Feeder $X/R$ ratio is an important factor in determining voltage rise and thereby increasing DG connectivity. The solar farm connectivity is also evaluated for the system with high and low $X/R$ ratios.

### 4.2 Daytime Base Case Studies

A 5-bus medium voltage radial distribution feeder consisting of grid supply, solar farm, full converter based wind farm and lumped load is considered as the study system. The detailed modeling of individual components of the study system is presented in Chapter 2. The single line diagram of study system with Wind-STATCOM is shown in Figure 4.1. For steady state analysis, the complete system model in PSS/E given in Chapter 2 (Section 2.7, Figure 2.31) is used. The wind farm is considered as PQ bus with active power output based on wind availability and reactive power output based on the capacity of converter remaining after real power generation. The supply voltage is kept constant at 1.055 $pu$ in this study. Daytime load (peak load) of active power, $P_{LD} = 4.82$ $MW$ and reactive power, $Q_{LD} = 2.19$ $Mvar$ (5.3 $MVA$ at 0.91 lagging power factor) is used at the receiving end. The complete system model in PSCAD/EMTDC, given in Chapter 2 (Section 2.6.2, Figure 2.30), is used for electromagnetic transient studies.

![Figure 4.1 Study system with Wind-STATCOM](image)

In the Wind-STATCOM mode of operation, the active power output of the wind farm depends on wind speed whereas the reactive power output depends on the reactive power
availability after active power generation and reactive power requirement for maintaining voltages within permissible limits. As the solar farms produce active power only during daytime, the role of Wind-STATCOM controller for increasing the solar farm connectivity has been evaluated only for daytime in the subsequent sections. For the study system, the daytime base case studies to evaluate the steady state voltage as well as transient overvoltage, carried out without both the solar farm and wind farm, are presented in this section.

4.2.1 Steady State Analysis

In steady state analysis, system quantities like bus voltage magnitude, voltage angle, active and reactive power flows are evaluated using the load flow studies in PSS/E. The bus voltages for various buses in the system with daytime loading condition are given in Figure 4.2.

![Figure 4.2 Base case steady state voltage profile for $P_{LD} = 4.82\ MW$, $Q_{LD} = 2.19\ Mvar$](image_url)

Figure 4.2 Base case steady state voltage profile for $P_{LD} = 4.82\ MW$, $Q_{LD} = 2.19\ Mvar$
The load flow results show a decreasing voltage profile from supply end towards the receiving end. For the supply end bus voltage (voltage at Bus 1) maintained at 1.055 pu, the voltages at all the buses are seen to be within permissible limits (0.94 pu – 1.06 pu). The detailed results of PSS/E simulation for daytime analysis for base case are given in Appendix – B2.

4.2.2 Temporary Overvoltage (TOV) Analysis

The transient behavior of the system for daytime base case studies are carried out with single line to ground fault for 100 ms (6 cycles) applied at the receiving end terminal. The phase voltages for such fault are shown in Figure 4.3. The temporary overvoltage for the given fault at the point of common coupling is found to be 1.092 pu which is within the permissible limits of 130% [7].

Figure 4.3 Phase voltages for daytime loading with SLGF
4.3 Effect of Solar Farm Integration on Steady-state Voltages

In the previous section, the base case scenario without solar farm and wind farm was considered. In this section, a wind farm of capacity 9.9 MW installed at Bus 4 is considered. Three cases of wind farm generation, namely, Case 1 for 0% wind farm output \( (P_{WF} = 0.0 \, MW) \), Case 2 for 50% wind farm output \( (P_{WF} = 4.95 \, MW) \) and Case 3 for 100% wind farm output \( (P_{WF} = 9.9 \, MW) \) are considered to evaluate the impact of solar farm integration on steady state voltages. The daytime loading with different wind farm output conditions is considered without any reactive power compensation.

For 0% wind farm output \( (P_{WF} = 0.0 \, MW) \), the voltage at various buses with increasing solar farm output are shown in Table 4.1. It is observed that the steady state voltages are within permissible limits \((1.06 \, pu)\) up to 13.1 MW active power injection from the solar farm. Similarly, the steady state voltages for 50% wind farm output \( (P_{WF} = 4.95 \, MW) \) and 100% wind farm output \( (P_{WF} = 9.9 \, MW) \) are given in Table 4.2 and Table 4.3, respectively. Here, the maximum solar farm output that can be injected into the grid without any reactive power compensation for daytime loading are 7.84 MW and 3.16 MW for 50% and 100% wind farm outputs conditions, respectively.

As observed in Section 3.2, the voltage at PCC goes on increasing with increased reverse power flow. However, after a certain line flow, the voltage starts decreasing due to increased reactive power consumption in the distribution line. In this scenario, it is observed that the steady state voltage reduces to within acceptable limits for 37.5 MW of solar farm injection in Case 1 with 0% wind farm output. The ampacity limit \((665 \, Amp)\) of conductor is not violated. For Case 2 and Case 3 with 50% and 100% wind farm outputs, the steady state voltage reduces to within acceptable limits for 32.8 MW and 27.8 MW of solar farm injections, respectively. For each of these cases, the ampacity limit of the conductor is not exceeded. The steady state voltage profile for three cases of wind farm output with increasing solar farm output for daytime loading conditions are shown in Figure 4.4.
Table 4.1 Steady state voltage for daytime loading
Case 1: 0% wind farm output, $P_{WF} = 0.0 \ MW$, $Q_{WF} = 0.0 \ Mvar$

<table>
<thead>
<tr>
<th>$P_{SF}\ (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>13.1</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
<th>37.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}\ (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}\ (pu)$</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.051</td>
<td>1.049</td>
<td>1.047</td>
<td>1.045</td>
<td></td>
</tr>
<tr>
<td>$V_{bus3}\ (pu)$</td>
<td>0.966</td>
<td>1.011</td>
<td>1.044</td>
<td>1.060</td>
<td>1.068</td>
<td>1.082</td>
<td>1.087</td>
<td>1.082</td>
<td>1.063</td>
<td>1.045</td>
</tr>
<tr>
<td>$V_{bus4}\ (pu)$</td>
<td>0.954</td>
<td>1.000</td>
<td>1.033</td>
<td>1.049</td>
<td>1.057</td>
<td>1.071</td>
<td>1.076</td>
<td>1.072</td>
<td>1.052</td>
<td>1.033</td>
</tr>
<tr>
<td>$V_{bus5}\ (pu)$</td>
<td>0.941</td>
<td>0.988</td>
<td>1.022</td>
<td>1.038</td>
<td>1.046</td>
<td>1.060</td>
<td>1.066</td>
<td>1.061</td>
<td>1.041</td>
<td>1.022</td>
</tr>
<tr>
<td>$I_{src}\ (Amps)$</td>
<td>116.5</td>
<td>46.0</td>
<td>111.5</td>
<td>167.8</td>
<td>202.8</td>
<td>295.2</td>
<td>389.1</td>
<td>487.0</td>
<td>593.7</td>
<td>654.1</td>
</tr>
</tbody>
</table>

Table 4.2 Steady state voltage for daytime loading
Case 2: 50% wind farm output, $P_{WF} = 4.95 \ MW$, $Q_{WF} = 0.0 \ Mvar$

<table>
<thead>
<tr>
<th>$P_{SF}\ (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>7.84</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>32.8</th>
<th>35.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}\ (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}\ (pu)$</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.051</td>
<td>1.049</td>
<td>1.047</td>
<td>1.045</td>
<td>1.043</td>
</tr>
<tr>
<td>$V_{bus3}\ (pu)$</td>
<td>1.013</td>
<td>1.046</td>
<td>1.060</td>
<td>1.069</td>
<td>1.083</td>
<td>1.088</td>
<td>1.084</td>
<td>1.065</td>
<td>1.044</td>
<td>1.017</td>
</tr>
<tr>
<td>$V_{bus4}\ (pu)$</td>
<td>1.007</td>
<td>1.040</td>
<td>1.054</td>
<td>1.063</td>
<td>1.077</td>
<td>1.083</td>
<td>1.078</td>
<td>1.059</td>
<td>1.038</td>
<td>1.011</td>
</tr>
<tr>
<td>$V_{bus5}\ (pu)$</td>
<td>0.996</td>
<td>1.029</td>
<td>1.043</td>
<td>1.052</td>
<td>1.067</td>
<td>1.072</td>
<td>1.067</td>
<td>1.048</td>
<td>1.027</td>
<td>1.000</td>
</tr>
<tr>
<td>$I_{src}\ (Amps)$</td>
<td>44.6</td>
<td>111.4</td>
<td>163.0</td>
<td>202.8</td>
<td>295.2</td>
<td>389.0</td>
<td>486.7</td>
<td>593.3</td>
<td>661.1</td>
<td>723.6</td>
</tr>
</tbody>
</table>

Table 4.3 Steady state voltage for daytime loading
Case 3: 100% wind farm output, $P_{WF} = 9.9 \ MW$, $Q_{WF} = 0.0 \ Mvar$

<table>
<thead>
<tr>
<th>$P_{SF}\ (MW)$</th>
<th>0.0</th>
<th>3.16</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>27.8</th>
<th>30.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}\ (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}\ (pu)$</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.051</td>
<td>1.049</td>
<td>1.047</td>
<td>1.045</td>
<td>1.043</td>
</tr>
<tr>
<td>$V_{bus3}\ (pu)$</td>
<td>1.044</td>
<td>1.060</td>
<td>1.067</td>
<td>1.082</td>
<td>1.087</td>
<td>1.082</td>
<td>1.063</td>
<td>1.042</td>
<td>1.014</td>
</tr>
<tr>
<td>$V_{bus4}\ (pu)$</td>
<td>1.044</td>
<td>1.059</td>
<td>1.067</td>
<td>1.081</td>
<td>1.087</td>
<td>1.082</td>
<td>1.062</td>
<td>1.041</td>
<td>1.014</td>
</tr>
<tr>
<td>$V_{bus5}\ (pu)$</td>
<td>1.033</td>
<td>1.049</td>
<td>1.056</td>
<td>1.071</td>
<td>1.076</td>
<td>1.071</td>
<td>1.052</td>
<td>1.030</td>
<td>1.002</td>
</tr>
<tr>
<td>$I_{src}\ (Amps)$</td>
<td>111.6</td>
<td>168.9</td>
<td>202.8</td>
<td>295.2</td>
<td>389.2</td>
<td>487.0</td>
<td>593.8</td>
<td>661.9</td>
<td>725.0</td>
</tr>
</tbody>
</table>
4.4 Effect of Solar Farm Integration on Temporary Overvoltage

To evaluate the effect of PV solar farm integration on the temporary overvoltage (TOV), a single line to ground fault (SLGF) for 6 cycles (100 ms) is applied at receiving end terminal. The daytime load (peak load) of active power, $P_{LD} = 4.82 \text{ MW}$, and reactive power, $Q_{LD} = 2.19 \text{ Mvar}$ is considered. Here, the temporary overvoltage is evaluated for increasing solar farm output scenario without any Wind-STATCOM operation in the system.

Three wind farm output cases, namely Case 1 with 0% wind farm output ($P_{WF} = 0.0\text{ MW}$), Case 2 with 50% wind farm output ($P_{WF} = 4.95 \text{ MW}$), and Case 3 with 100% wind farm output ($P_{WF} = 9.9 \text{ MW}$) are considered. The phase voltages for these three cases of study and the temporary overvoltage (TOV) in these conditions are shown in Figure 4.5, Figure 4.4 PCC bus voltages for various wind farm output cases with increasing solar farm output (Daytime loading without compensation)
4.6, and Figure 4.7, respectively. These results show that the temporary overvoltages are 1.24 pu, 1.26 pu, and 1.274 pu for maximum solar farm output of 20.0 MW considered for the transient simulation of the given study system. These TOV values are within the permissible limit of 130% [7]. Hence, TOV is not a consideration in determining the connectivity of PV solar farm in this study system.

Figure 4.5 Phase voltages for daytime loading with SLGF,
Case 1: $P_{WF} = 0.0 \text{ MW}, P_{SF} = 20.0 \text{ MW}$

Figure 4.6 Phase voltages for daytime loading with SLGF,
Case 2: $P_{WF} = 4.95 \text{ MW}, P_{SF} = 20.0 \text{ MW}$
4.5 Control of Steady-state Voltages by Wind-STATCOM

In Section 4.2, it is seen that the output of the solar farm is limited by the rise in voltage. Reactive power compensation from the Wind-STATCOM is now utilized to limit the voltage rise and hence increase the solar power injection into the grid. The voltages at various buses in the network and the line current on the secondary side of the supply end transformer are shown in Table 4.4 for Case 1 with 0% wind farm output. In this case, the solar farm connectivity can be increased from 13.1 MW to 35.0 MW with the reactive power compensation from Wind-STATCOM in order to maintain voltage at buses within acceptable limits. The maximum reactive power compensation needed in this case is 1.18 Mvar for 25.0 MW solar farm output. Similarly, the voltages at various buses in the network and the line current on the secondary side of the supply end transformer with 50% wind farm output are shown in Table 4.5 for Case 2. In this case, the solar farm connectivity can be increased from 7.84 MW to 30.0 MW without violating line ampacity limit. The maximum reactive power compensation from the Wind-STATCOM is 1.24 Mvar for 20.0 MW solar farm output. The voltages at various buses and the line current on the secondary side of the supply end transformer are shown in Table 4.6 for Case 3. With 99% wind farm output, the solar farm connectivity can be increased from 3.16 MW to 28.0 MW without exceeding line ampacity limit. The maximum reactive power compensation needed in this study is 1.18 Mvar for 15.0 MW solar farm output.
Table 4.4 Steady state voltages with reactive power compensation from Wind-STATCOM, Case 1: 0% wind farm output $P_{WF} = 0.0 \text{ MW}$

<table>
<thead>
<tr>
<th>$P_{SF} (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>13.1</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.046</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>0.966</td>
<td>1.011</td>
<td>1.044</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>0.954</td>
<td>1.000</td>
<td>1.033</td>
<td>1.049</td>
<td>1.048</td>
<td>1.046</td>
<td>1.046</td>
<td>1.047</td>
<td>1.049</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>0.941</td>
<td>0.988</td>
<td>1.022</td>
<td>1.038</td>
<td>1.037</td>
<td>1.035</td>
<td>1.035</td>
<td>1.036</td>
<td>1.038</td>
</tr>
<tr>
<td>$I_{src} (Amps)$</td>
<td>116.5</td>
<td>46.0</td>
<td>111.5</td>
<td>167.8</td>
<td>205.8</td>
<td>304.9</td>
<td>402.2</td>
<td>499.0</td>
<td>595.7</td>
</tr>
<tr>
<td>$Q_{WF} (Mvar)$</td>
<td>0.36</td>
<td>1.02</td>
<td>1.18</td>
<td>0.88</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 Steady state voltages with reactive power compensation from Wind-STATCOM, Case 2: 50% wind farm output $P_{WF} = 4.95 \text{ MW}$

<table>
<thead>
<tr>
<th>$P_{SF} (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>7.84</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.046</td>
<td>1.043</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.013</td>
<td>1.046</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.017</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.007</td>
<td>1.040</td>
<td>1.054</td>
<td>1.053</td>
<td>1.051</td>
<td>1.051</td>
<td>1.052</td>
<td>1.054</td>
<td>1.011</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>0.996</td>
<td>1.029</td>
<td>1.043</td>
<td>1.042</td>
<td>1.040</td>
<td>1.040</td>
<td>1.041</td>
<td>1.043</td>
<td>1.000</td>
</tr>
<tr>
<td>$I_{src} (Amps)$</td>
<td>44.6</td>
<td>111.4</td>
<td>163.0</td>
<td>206.3</td>
<td>305.2</td>
<td>402.7</td>
<td>499.5</td>
<td>596.1</td>
<td>723.6</td>
</tr>
<tr>
<td>$Q_{WF} (Mvar)$</td>
<td>0.43</td>
<td>1.07</td>
<td>1.24</td>
<td>0.94</td>
<td>0.16</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 Steady state voltages with reactive power compensation from Wind-STATCOM, Case 3: 99% wind farm output $P_{WF} = 9.8 \text{ MW}$

<table>
<thead>
<tr>
<th>$P_{SF} (MW)$</th>
<th>0.0</th>
<th>3.16</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>28.0</th>
<th>30.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.054</td>
<td>1.053</td>
<td>1.053</td>
<td>1.052</td>
<td>1.050</td>
<td>1.048</td>
<td>1.046</td>
<td>1.045</td>
<td>1.042</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.044</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>1.060</td>
<td>0.973</td>
<td></td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.044</td>
<td>1.059</td>
<td>1.059</td>
<td>1.057</td>
<td>1.056</td>
<td>1.057</td>
<td>1.059</td>
<td>1.041</td>
<td>0.992</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.033</td>
<td>1.049</td>
<td>1.048</td>
<td>1.046</td>
<td>1.045</td>
<td>1.046</td>
<td>1.048</td>
<td>1.030</td>
<td>0.980</td>
</tr>
<tr>
<td>$I_{src} (Amps)$</td>
<td>111.6</td>
<td>168.9</td>
<td>205.8</td>
<td>304.7</td>
<td>402.3</td>
<td>499.0</td>
<td>595.6</td>
<td>661.9</td>
<td>712.5</td>
</tr>
<tr>
<td>$Q_{WF} (Mvar)$</td>
<td>0.33</td>
<td>1.0</td>
<td>1.18</td>
<td>0.88</td>
<td>0.10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

The requirement of reactive power from Wind-STATCOM to maintain voltage within permissible limits in steady state conditions for various solar farm connectivity scenarios is shown in Figure 4.8. The requirement of reactive power to maintain steady-state voltage is much less than the capacity of Wind-STATCOM. Thus, Wind-STATCOM is quite effective in maintaining the voltages within limits even with significant solar power generation and with substantial reverse power flow.

![Figure 4.8 Reactive power compensation provided by Wind-STATCOM to maintain PCC voltages within permissible limits (0.94 \textit{pu} – 1.06 \textit{pu})](image)

**4.6 Effect of Feeder X/R Ratio in Solar Farm Connectivity**

In this section, the effects of different X/R ratio of the distribution feeder on the steady-state voltage are investigated. The X/R ratios considered are half (1.236) and double (4.944) of the original (2.472) X/R ratio for the study system.

The effect of X/R ratios is studied for three cases, namely, Case 1 with 0% wind farm output, Case 2 with 50% wind farm output, and Case 3 with 95% wind farm output. The maximum amount of solar farm connectivity ($P_{SF}$) is evaluated with and without reactive
power compensation from Wind-STATCOM such that all the bus voltages and line flows are within permissible limits.

Table 4.7 shows the steady state voltages for different feeder $X/R$ ratios for Case 1 with 0% wind farm output ($P_{WF} = 0.0 \, MW$). From Table 4.7, it is seen that without Wind-STATCOM the solar farm output is $8.26 \, MW$ for half $X/R$ ratio whereas it increases to $26.6 \, MW$ for double $X/R$ ratio while maintaining all system voltages and line flows within limits. It is noted here that the solar farm connectivity is limited by increase in PCC voltage due to reverse power flow for low $X/R$ ratio whereas it is limited by decrease in receiving end voltage for high $X/R$ ratio. In Case 1, the solar farm output can be increased up to $35.0 \, MW$ with reactive power compensation from Wind-STATCOM both for half $X/R$ ratio and double $X/R$ ratio conditions. The reactive power requirements in these two cases are $8.6 \, Mvar$ inductive (consumption of reactive power) and $6.45 \, Mvar$ capacitive (injection of reactive power), respectively.

Table 4.7 Steady state voltages with $X/R$ ratio variation – without and with Wind-STATCOM, Case 1: 0% wind farm output $P_{WF} = 0.0 \, MW$

<table>
<thead>
<tr>
<th></th>
<th>Without Wind-STATCOM</th>
<th>With Wind-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{SF} \Rightarrow$</td>
<td>8.26 $MW$</td>
<td>13.15 $MW$</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 $pu$</td>
<td>1.0550 $pu$</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0539 $pu$</td>
<td>1.0534 $pu$</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0599 $pu$</td>
<td>1.0600 $pu$</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0464 $pu$</td>
<td>1.0489 $pu$</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0328 $pu$</td>
<td>1.0380 $pu$</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>81.3 $Amp$</td>
<td>168.7 $Amp$</td>
</tr>
<tr>
<td>$Q_{WF}$</td>
<td></td>
<td>8.6 $Mvar$</td>
</tr>
</tbody>
</table>

Table 4.8 and Table 4.9 show the steady state voltages with $X/R$ ratio variation for Case 2 with 50% wind farm output ($P_{WF} = 4.95 \, MW$) and Case 3 with 95% wind farm output ($P_{WF} = 9.4 \, MW$), respectively. In case 2, the solar farm output is limited to $3.3 MW$ for
half $X/R$ ratio condition, whereas, up to 24.88 $MW$ of solar farm connectivity is possible for double $X/R$ ratio without reactive power compensation. With Wind-STATCOM the solar farm connectivity for half $X/R$ ratio case can be increased up to 31.0 $MW$ with reactive power compensation of 8.66 $Mvar$ inductive; and up to 32.0 $MW$ with reactive power injection of 5.5 $Mvar$ capacitive for double $X/R$ ratio conditions.

Table 4.8 Steady state voltages with $X/R$ ratio variation – with and without Wind-STATCOM, Case 2: 50% wind farm output $P_{WF} = 4.95$ $MW$

<table>
<thead>
<tr>
<th></th>
<th>Without Wind-STATCOM</th>
<th>With Wind-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{SF} \Rightarrow$</td>
<td>3.3 $MW$</td>
<td>7.9 $MW$</td>
</tr>
<tr>
<td>$V_{bus1}$</td>
<td>1.0550 pu</td>
<td>1.0550 pu</td>
</tr>
<tr>
<td>$V_{bus2}$</td>
<td>1.0539 pu</td>
<td>1.0534 pu</td>
</tr>
<tr>
<td>$V_{bus3}$</td>
<td>1.0599 pu</td>
<td>1.0600 pu</td>
</tr>
<tr>
<td>$V_{bus4}$</td>
<td>1.0553 pu</td>
<td>1.0542 pu</td>
</tr>
<tr>
<td>$V_{bus5}$</td>
<td>1.0418 pu</td>
<td>1.0433 pu</td>
</tr>
<tr>
<td>$I_{src}$</td>
<td>79.4 Amp</td>
<td>163.18 Amp</td>
</tr>
<tr>
<td>$Q_{WF}$</td>
<td>8.66 Mvar</td>
<td>0.0 Mvar</td>
</tr>
</tbody>
</table>

In Case 3 with 95% wind farm output, no solar farm connectivity is available without reactive power compensation for half $X/R$ ratio condition. In this case, the solar farm connectivity can be increased up to 4.38 $MW$ with reactive compensation of 3.12 $Mvar$ inductive provided by Wind-STATCOM for half $X/R$ ratio condition. Similarly, for double $X/R$ ratio condition, up to 26.0 $MW$ of solar farm connectivity is made possible with reactive power compensation of 3.0 $Mvar$ capacitive. The availability of reactive power from Wind-STATCOM is limited due to increased wind farm output (9.4 $MW$) in this particular case.
Table 4.9 Steady state voltages with \( X/R \) ratio variation – with and without Wind-STATCOM, Case 3: 95% wind farm output \( P_{WF} = 9.4 \, MW \)

<table>
<thead>
<tr>
<th></th>
<th>Without Wind-STATCOM</th>
<th>With Wind-STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Half ( X/R )</td>
<td>Normal ( X/R )</td>
</tr>
<tr>
<td></td>
<td>(1.236)</td>
<td>(2.472)</td>
</tr>
<tr>
<td>( P_{SF} \Rightarrow )</td>
<td>0.0 WM</td>
<td>3.7 WM</td>
</tr>
<tr>
<td>( V_{bus1} )</td>
<td>1.0550 pu</td>
<td>1.0550 pu</td>
</tr>
<tr>
<td>( V_{bus2} )</td>
<td>1.0538 pu</td>
<td>1.0534 pu</td>
</tr>
<tr>
<td>( V_{bus3} )</td>
<td>1.0719 pu</td>
<td>1.0600 pu</td>
</tr>
<tr>
<td>( V_{bus4} )</td>
<td>1.0751 pu</td>
<td>1.0589 pu</td>
</tr>
<tr>
<td>( V_{bus5} )</td>
<td>1.0619 pu</td>
<td>1.0480 pu</td>
</tr>
<tr>
<td>( I_{src} )</td>
<td>98.9 Amp</td>
<td>167.80 Amp</td>
</tr>
<tr>
<td>( Q_{WF} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In all the three cases, the solar farm connectivity is limited by steady state voltage criteria for half \( X/R \) ratio whereas it is limited by line flow limit based on conductor ampacity for double \( X/R \) ratio of the distribution feeder. The full converter based wind farm operating as Wind-STATCOM can successfully increase the solar farm connectivity with its reactive power support.

### 4.7 Discussions

In this chapter, the solar farm connectivity is analyzed based on the steady state voltages at all the buses of the network and temporary overvoltage at the point of common coupling of wind farm and solar farm, for single line to ground fault (SLGF) condition. The application of full converter based wind farm as Wind-STATCOM to increase the connectivity of solar farm for daytime loading condition is evaluated. The summarized results are presented in Table 4.10.

The conductor ampacity limit of 665.0 \( Amp \) determines the maximum solar farm connectivity based on conductor size. In no condition, the solar farm connectivity can go
beyond this limit. However, the solar farm connectivity is affected by steady-state voltage rise due to reverse power flow and temporary overvoltage due to unbalanced faults. In all three cases of wind farm output, Case 1 with 0% wind farm output, Case 2 with 50% wind farm output and Case 3 with 99% wind farm output, the solar farm output connectivity based on steady state voltage criteria is much lower than the solar farm output limited by temporary overvoltage. The temporary overvoltages are within limits up to 20.0 \( MW \) of solar farm output. It is seen that the limits on solar farm connectivity imposed by steady state voltage rise can be increased with the use of wind farm converter as Wind-STATCOM.

### Table 4.10 Summarized results for solar farm connectivity

<table>
<thead>
<tr>
<th>Solar Farm Connectivity</th>
<th>Daytime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Farm Output ( P_{WF} ) (% of its capacity)</td>
<td>0.0 ( MW ) (0%)</td>
</tr>
<tr>
<td>Conductor Ampacity Limits ( (665 \text{ Amp}) )</td>
<td>37.5 ( MW )</td>
</tr>
<tr>
<td>Steady-State Voltage Limits (±6%)</td>
<td>Without Wind-STATCOM</td>
</tr>
<tr>
<td></td>
<td>With Wind-STATCOM</td>
</tr>
<tr>
<td>Temporary Overvoltage Limits (130%)</td>
<td>Without Wind-STATCOM</td>
</tr>
</tbody>
</table>

#### 4.8 Conclusion

This chapter presents a novel control of full converter based wind turbine generators as Wind-STATCOM for increasing the connectivity of a neighbouring PV solar farm in a medium voltage distribution feeder. The steady-state analyses are carried out using PSS/E and electromagnetic transient simulations for TOV evaluation are performed using PSCAD/EMTDC.
The steady-state voltages at all the buses for daytime loading without solar farm and wind farm (base case) are within acceptable limits \((0.94 \pu{} - 1.06 \pu{})\). However, the steady-state voltages increase beyond acceptable limits due to reverse power flow caused by integration of PV solar farm and wind farm. The Wind-STATCOM is used to provide reactive power compensation and maintain voltage within acceptable limits. With maximum reactive power injection of \(1.24 \text{ Mvar}\), Wind-STATCOM is able to maintain voltages within acceptable limits for all operating conditions considered for the study system. The PV solar farm connectivity considering conductor ampacity limit as well as steady-state bus voltage limits with reactive power compensation from Wind-STATCOM increases from 13.1 \text{ MW} to 37.5 \text{ MW}, 7.84 \text{ MW} to 32.8 \text{ MW} and 3.16 \text{ MW} to 27.8 \text{ MW} for Case 1 with 0% wind farm output, Case 2 with 50% wind farm output and Case 3 with 99% wind farm output, respectively.

The temporary overvoltage for the study system for single line to ground fault at receiving end is within acceptable limit (130%) for the maximum 20.0 \text{ MW} solar farm output. Hence, for the study system, TOV at solar farm PCC terminal is not a the limiting factor for solar farm connectivity.

The impact of feeder \(X/R\) ratio on solar farm connectivity is also examined. It is observed that the steady state voltage increases further with half \(X/R\) ratio without compensation. Therefore, the amount of reactive power compensation required to increase solar farm connectivity is much higher compared to the system with original \(X/R\) ratio. However, for double \(X/R\) ratio the receiving end voltages decrease with increased solar power output. The solar farm connectivity is limited by decrease in voltage. In this condition, a high solar farm connectivity is possible without any reactive power compensation. For example, 24.88 \text{ MW} of solar farm connectivity is possible without compensation for system with double \(X/R\) ratio compared to only 3.3 \text{ MW} for system with half \(X/R\) for 50% wind farm output condition. However, 5.5 \text{ Mvar} capacitive reactive power compensation from Wind-STATCOM increases PV solar connectivity from 24.88 \text{ MW} to 32.0 \text{ MW}. 
Chapter 5

COMBINATION OF PV-STATCOM AND WIND-STATCOM

5.1 Introduction

The application of PV solar inverter as STATCOM (PV-STATCOM) and its effectiveness in increasing the connectivity of a neighbouring wind farm both during night and day were studied in Chapter 3. Similarly, the application of wind farm converter as STATCOM (Wind-STATCOM) and its effectiveness in enhancing the connectivity of a neighbouring solar farm was presented in Chapter 4. In this chapter, the combined application of PV solar farm as PV-STATCOM and wind farm converter as Wind-STATCOM is investigated. This combined application increases the flexibility of the available reactive power compensation in the system so that maximum active power injection from both distributed generators (PV solar farm and wind farm) can be achieved. The application of PV-STATCOM and Wind-STATCOM to increase the connectivity of both the solar farm and wind farm up to 20.0 MW is investigated.

For steady-state analysis, the reactive power compensation from both the PV-STATCOM and Wind-STATCOM are used to suppress the voltage rise due to reverse power flow so that voltages at all the buses in the system can be maintained within permissible limits. The steady-state analysis is based on load flow solution using commercial load flow software PSS/E as described in Chapter 2. The electromagnetic transients model of PV-STATCOM and Wind-STATCOM developed in industry standard software PSCAD/EMTDC, used in Chapter 3 and Chapter 4 respectively, are used for the dynamic reactive power compensation required to suppress the temporary overvoltages during unbalanced fault in the system.
5.2 Base Case System Analysis with PV Solar and Wind Farms

5.2.1 Steady State Analysis

The base case scenario with PV solar farm and wind farm is considered with installed capacity of 8.5 MW for solar farm and 9.9 MW for wind farm along with peak loads of active power, $P_{LD} = 4.82$ MW and reactive power, $Q_{LD} = 2.19$ Mvar for daytime, and off-peak loads of active power, $P_{LD} = 1.6$ MW and reactive power, $Q_{LD} = 0.73$ Mvar for nighttime. The voltage profile and line flow from the source end for various combinations of PV solar farm and wind farm outputs for daytime and wind farm output for nighttime are evaluated. The bus voltages at all the buses and the current flowing through the source end of the distribution line for various combinations of solar farm output, $P_{SF}$ and wind farm output, $P_{WF}$ during daytime, are shown in Table 5.1. From the steady-state results, it is observed that, without any reactive power compensation, the system voltages violate the permissible limits for 50% (4.25 MW) of solar farm output with 100% (9.9 MW) of wind farm output. Also the bus voltages exceed permissible limits for 100% (8.5 MW) of solar farm output with 50% (4.95 MW) of wind farm output.

<table>
<thead>
<tr>
<th>$P_{WF}$ (MW)</th>
<th>$P_{SF} = 0.0$ MW (0%)</th>
<th>$P_{SF} = 4.25$ MW (50%)</th>
<th>$P_{SF} = 8.5$ MW (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>4.95</td>
<td>9.9</td>
</tr>
<tr>
<td>$V_{bus1}$ (pu)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}$ (pu)</td>
<td>1.054</td>
<td>1.054</td>
<td>1.054</td>
</tr>
<tr>
<td>$V_{bus3}$ (pu)</td>
<td>0.966</td>
<td>1.013</td>
<td>1.044</td>
</tr>
<tr>
<td>$V_{bus4}$ (pu)</td>
<td>0.953</td>
<td>1.007</td>
<td>1.043</td>
</tr>
<tr>
<td>$V_{bus5}$ (pu)</td>
<td>0.941</td>
<td>0.995</td>
<td>1.032</td>
</tr>
<tr>
<td>$I_{src}$ (Amps)</td>
<td>116.5</td>
<td>44.5</td>
<td>109.8</td>
</tr>
</tbody>
</table>
Similarly, the bus voltages at all the buses and the current flowing though source end of the distribution line for the combination of wind farm output $P_{WF}$ for nighttime loading condition with zero solar farm output are shown in Table 5.2. In this condition, the system voltage goes beyond permissible limits beyond 4.04 $MW$ of wind farm output.

<table>
<thead>
<tr>
<th>$P_{WF} (MW)$</th>
<th>$P_{SF} = 0.0$ $MW$</th>
<th>4.04</th>
<th>4.95</th>
<th>9.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1}$ ($pu$)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
</tr>
<tr>
<td>$V_{bus2}$ ($pu$)</td>
<td>1.055</td>
<td>1.055</td>
<td>1.055</td>
<td>1.054</td>
</tr>
<tr>
<td>$V_{bus3}$ ($pu$)</td>
<td>1.030</td>
<td>1.059</td>
<td><strong>1.065</strong></td>
<td><strong>1.088</strong></td>
</tr>
<tr>
<td>$V_{bus4}$ ($pu$)</td>
<td>1.026</td>
<td>1.060</td>
<td><strong>1.066</strong></td>
<td><strong>1.094</strong></td>
</tr>
<tr>
<td>$V_{bus5}$ ($pu$)</td>
<td>1.023</td>
<td>1.056</td>
<td><strong>1.063</strong></td>
<td><strong>1.091</strong></td>
</tr>
<tr>
<td>$I_{src}$ (Amps)</td>
<td>34.9</td>
<td>49.4</td>
<td>66.6</td>
<td>158.8</td>
</tr>
</tbody>
</table>

### 5.2.2 Temporary Overvoltage (TOV) Analysis

For the daytime scenario described in Section 5.2.1, a single line to ground fault (SLGF) is applied at the load end and the phase voltages are observed at the wind farm PCC.

The phase voltage for daytime loading with base PV solar farm output of 8.5 $MW$ and wind farm output of 9.9 $MW$ without reactive power compensation is shown in Figure 5.1. Temporary overvoltage of 1.209 $pu$ is observed for single line to ground fault for 100 msec. (6 cycles). Similarly, for nighttime loading with wind farm output of 9.9 $MW$ without reactive power compensation is shown in Figure 5.2. In this case the temporary overvoltage is observed to be 1.18 $pu$. Both these values are within the permissible limits of 130% [7].
5.3 Impact of Increasing PV Solar and Wind Farms Output

5.3.1 Steady State Analysis

The base case analysis presented in Section 5.2.1 is extended considering up to 20.0 $MW$ of outputs both for solar farm and wind farm to observe the impact of combined PV solar farm and wind farm integration into the medium voltage distribution network, during
daytime. The impact of increasing wind farm connectivity on the steady-state voltage at the wind farm PCC for various cases of solar farm outputs (0.0 MW, 5.0 MW, 10.0 MW, 15 MW and 20 MW) is shown in Figure 5.2. It is observed that for 0.0 MW solar farm output condition, the PCC voltage goes on increasing with increasing wind farm connectivity and crosses the permissible limit at 13.1 MW of wind farm generation. However, for 20.0 MW solar farm output, the PCC voltage is significantly above the permissible limits for low wind farm connectivity and starts decreasing as the wind farm output power is increased and attains permissible voltage after 15.37 MW of wind farm output.

![Figure 5.3 Steady-state voltage profile at wind farm PCC (Daytime loading)](image)

For nighttime loading with 0.0 MW solar farm output, the increase in voltage due to the increased DG connectivity up to 20.0 MW is shown in Figure 5.3. The DG connectivity in order to maintain the steady-state voltage within permissible limits without reactive power compensation is 4.04 MW. The need for PV-STATCOM for dynamic reactive power compensation is clearly seen during nighttime when more wind power is available to be connected, knowing that the PV solar inverter is fully available for compensation.
5.3.2 Temporary Overvoltage (TOV) Analysis

The base case transient analysis with 8.5 MW of solar farm and 9.9 MW of wind farm presented in Sub-section 5.2.2 is extended to 20.0 MW of outputs both for solar farm and wind farm to observe the temporary overvoltage with combined PV solar farm and wind farm integration into the MV distribution network. The phase voltage for SLGF at the load end with solar farm and wind farm outputs of 20.0 MW each, is shown in Figure 5.5.

Here, the temporary overvoltage is observed to be 1.123 pu which is less than the TOV for base case with 8.5 MW of solar farm output and 9.9 MW of wind farm output. This decrease in PCC voltage with increased DG connectivity for daytime loading is observed for the steady-state voltage as well (presented in Section 5.3.1). However during nighttime, an enhanced wind farm output of 20.0 MW causes increase in TOV to 1.212 pu. In this case as well, the temporary overvoltage is within the permissible limit of 130%. From this analysis it is observed that for converter based wind farm and solar farm, the temporary overvoltage is within permissible limits for all scenarios.
5.4 Steady State Voltage Control using PV-STATCOM

As observed in Section 5.3.1, the violation of steady state voltage limit occurs with increasing wind farm output for all levels of solar farm output. Here, the steady state voltage regulation using reactive power compensation with PV-STATCOM for increasing wind farm for 0.0 MW and 20.0 MW of solar farm output is considered. The daytime loading is considered for 0.0 MW and 20.0 MW of solar farm output conditions.
The voltage at all the buses along with the reactive power compensation from the PV-STATCOM for 20.0 MW solar farm output case is shown in Table 5.3. For 0.0 MW solar farm output, the wind farm output up to 13.1 MW can be incorporated without reactive power compensation as shown in Table 3.6 in Chapter 3. This can be increased up to 36.0 MW with reactive power compensation from the PV-STATCOM. For 20.0 MW solar farm output, not wind farm connectivity is available without compensation. However, with maximum of 1.25 Mvar reactive power compensation from PV-STATCOM, wind farm connectivity upto 17.74 MW can be achieved.

Table 5.3 Steady-state voltages with reactive power compensation using PV-STATCOM (Daytime loading, Solar farm output, $P_{SF} = 20.0 \text{ MW}$)

<table>
<thead>
<tr>
<th>$P_{WF} (\text{MW})$</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>15.37</th>
<th>17.74</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.0515</td>
<td>1.0500</td>
<td>1.0483</td>
<td>1.0463</td>
<td>1.0461</td>
<td>1.0444</td>
<td>1.0421</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.0600</td>
<td>1.0600</td>
<td>1.0599</td>
<td>1.0554</td>
<td>1.0552</td>
<td>1.0313</td>
<td>0.9925</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.0489</td>
<td>1.0543</td>
<td>1.0594</td>
<td>1.0598</td>
<td>1.0600</td>
<td>1.0385</td>
<td>1.0022</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.0379</td>
<td>1.0434</td>
<td>1.0485</td>
<td>1.0489</td>
<td>1.0491</td>
<td>1.0274</td>
<td>0.9907</td>
</tr>
<tr>
<td>$I_{src} (\text{Amp})$</td>
<td>304.81</td>
<td>402.75</td>
<td>499.04</td>
<td>596.97</td>
<td>604.11</td>
<td>664.96</td>
<td>736.95</td>
</tr>
<tr>
<td>$Q_{SF} (\text{Mvar})$</td>
<td>1.02</td>
<td>1.25</td>
<td>0.89</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For nighttime loading the with 0.0 MW solar farm output the reactive compensation provided by PV-STATCOM, required to maintain the voltage within permissible limits (0.94 $pu$ – 1.06 $pu$), is shown in Table 3.9 (Chapter 3). In this case, wind farm connectivity is increased from 4.04 MW to 34.5 MW with the maximum reactive power compensation of 2.66 Mvar from PV-STATCOM.

5.5 Steady State Voltage Control using Wind-STATCOM

For increased PV solar farm output during daytime, the Wind-STATCOM can be used to maintain the steady-state voltages in the distribution network. Two cases of wind farm output namely 0.0 MW and 20.0 MW outputs are considered to evaluate the requirement
of reactive power compensation by the Wind-STATCOM. For 0.0 MW wind farm output, the solar farm output up to 13.16 MW can be incorporated without reactive power compensation as shown in Table 4.4 in Chapter 4. This can be increased up to 35.0 MW with reactive power compensation from the Wind-STATCOM. For 20.0 MW wind farm output condition, the reactive power compensation from the Wind-STATCOM is required to maintain the voltages even for low solar farm connectivity. However, the voltage decreases and no compensation is required above 14.82 MW of solar farm output. The steady-state voltage for all the system bus for this scenario is presented in Table 5.4.

<table>
<thead>
<tr>
<th>$P_{SF} (MW)$</th>
<th>0.0</th>
<th>5.0</th>
<th>10.0</th>
<th>14.82</th>
<th>15.0</th>
<th>17.65</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{bus1} (pu)$</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
<td>1.0550</td>
</tr>
<tr>
<td>$V_{bus2} (pu)$</td>
<td>1.0514</td>
<td>1.0498</td>
<td>1.0481</td>
<td>1.0462</td>
<td>1.0461</td>
<td>1.0443</td>
<td>1.0421</td>
</tr>
<tr>
<td>$V_{bus3} (pu)$</td>
<td>1.0528</td>
<td>1.0532</td>
<td>1.0526</td>
<td>1.0508</td>
<td>1.0496</td>
<td>1.0271</td>
<td>0.9925</td>
</tr>
<tr>
<td>$V_{bus4} (pu)$</td>
<td>1.0599</td>
<td>1.0599</td>
<td>1.0600</td>
<td>1.0600</td>
<td>1.0589</td>
<td>1.0365</td>
<td>1.0022</td>
</tr>
<tr>
<td>$V_{bus5} (pu)$</td>
<td>1.0490</td>
<td>1.0490</td>
<td>1.0492</td>
<td>1.0492</td>
<td>1.0480</td>
<td>1.0254</td>
<td>0.9907</td>
</tr>
<tr>
<td>$I_{src} (Amp)$</td>
<td>304.23</td>
<td>401.84</td>
<td>499.26</td>
<td>593.90</td>
<td>598.12</td>
<td>664.79</td>
<td>736.95</td>
</tr>
<tr>
<td>$Q_{WF} (Mvar)$</td>
<td><strong>0.82</strong></td>
<td><strong>0.97</strong></td>
<td><strong>0.69</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 5.6 Conclusion

In this chapter, the combined impact of increased PV solar farm and wind farm integration into the grid is assessed by observing the steady-state voltage as well as temporary overvoltage. The reverse power flow due to increased solar farm and wind farm output causes increase in steady-state voltages. The voltage profile at the wind farm PCC for various combinations of PV solar farm and wind farm outputs shows that the variation in steady-state voltage with increased wind farm output depends on the solar farm output. At zero solar farm output, the steady-state voltage is within permissible
limits for low wind farm output but exceeds the permissible limit of 1.06 pu as the wind farm output is increased. However, for 20.0 MW solar farm output, the steady-state voltage exceeds the permissible limits for low wind farm output but decreases to a level within permissible limits at increased wind farm output. The temporary overvoltage is observed to be within permissible limits of 130% for all considered combinations of solar DG and wind DG outputs.

The reactive power compensation of PV-STATCOM increases the wind farm connectivity up to 17.74 MW both for daytime loading conditions maintaining 20.0 MW of solar farm output. Similarly, the Wind-STATCOM increases the PV solar farm connectivity up to 17.65 MW for daytime maintaining 20.0 MW of wind power output. The combined application of PV-STATCOM and Wind-STATCOM is found to be effective to increase the solar farm and wind farm integration up to 20.0 MW each, while maintaining the steady-state voltage within permissible limits.
Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 General

The integration of distributed generators (DGs) such as wind farms and PV solar farms in distribution networks is getting limited due to problems of steady state voltage rise and temporary overvoltages (TOV). This thesis deals with the assessment of these problems in a realistic distribution system and presents novel controls of both PV solar farm inverter and wind farm inverter to mitigate these issues and increase DG connectivity. These novel controls transform PV solar farm and full inverter based wind farms into dynamic reactive power compensators known as STATCOM, without impacting their real power production.

The PV solar farm controlled as STATCOM is termed PV-STATCOM. It utilizes the entire inverter capacity in the nighttime and the inverter capacity remaining after solar power generation during daytime. The full converter based wind farm controlled as STATOM is called Wind-STATCOM, which utilizes the inverter capacity left after that needed for wind power production, both during night and day.

The reactive power compensation provided by both PV-STATCOM and Wind-STATCOM are employed to effectively regulate steady state voltages and TOVs, thereby enhancing the connectivity of both the wind farm and solar farm installed on a common distribution feeder. Commercial grade software PSS/E and PSCAD/EMTDC are used to evaluate the steady state voltage profile and TOVs, respectively.

The conclusions drawn from different studies incorporated in Chapters 2, 3, 4 and 5 in this thesis, are presented below.
6.2 System Modeling

An actual radial distribution feeder of Hydro One Networks (name withheld due to confidentiality) is modeled in PSS/E software for steady-state studies and PSCAD/EMTDC software for fault studies. This system model includes the supply substation, overhead radial distribution line, PV solar farm, wind farm and the lumped load at the feeder end. The load is modeled with fixed magnitude ($MW$ and $Mvar$); the line is represented by $\pi$-model and the lossless transformer is modeled with a series reactance.

The novel PV-STATCOM control is applied to the voltage sourced inverter used in the PV solar farm. The 2-level, 6-pulse inverter is controlled with sinusoidal pulse width modulation technique. The desired reactive power flow and the corresponding terminal voltage are achieved through modulation index control. Similarly, the active power flow and the DC voltage regulation are accomplished through shift angle control. Proportional-Integral controllers are used in both the modulation index and shift angle controllers. The active power control is based on the available solar irradiance. The reactive power control is based on the inverter capacity available after solar power generation. The control technique used in PV-STATCOM is extended for the grid side inverter of the variable speed full converter based wind turbine generator. The active power control is based on wind speed and the reactive power control is based on the inverter capacity remaining after wind power production.

6.3 PV-STATCOM Control for Increasing Wind Power Connectivity

The analysis of study system shows an increase in steady-state voltage as well as temporary overvoltage due to increased wind farm integration into the grid. The permissible limits of steady-state voltage and temporary overvoltage adopted by the utilities restrict the system’s capability to accommodate increased wind farm connectivity. The novel PV-STATCOM control is demonstrated to be an effective means
to mitigate the issues of steady-state voltage rise and temporary overvoltage and to significantly increase wind farm connectivity in the distribution system. With PV-STATCOM, the wind farm connectivity can be increased during nighttime from 3.9 MW to 16.65 MW; and during daytime from 11.5 MW to 19.5 MW for 0% solar farm output and from 2.1 MW to 4.5 MW for 98% solar farm output.

The above stated significant enhancement of wind farm connectivity is achieved with the PV-STATCOM located at 5.0 km away from the wind farm. The reactive power required to maintain steady-state voltages within permissible limits increases as the PV-STATCOM is located away from the wind farm. For the study system, even if the 8.5 MW solar farm is located 30.0 km away from the wind farm, it can successfully regulate the wind farm PCC voltage and increase wind farm connectivity substantially.

### 6.3.1 Impact of X/R ratio Variation

The rise in receiving end voltage due to reverse power flow depends on the X/R ratio of the grid. In Chapter 3, the effectiveness of PV-STATCOM is evaluated by varying the X/R ratio to half and double of the original X/R ratio. For the study system, the impact of X/R ratio variation is also observed. A decrease in X/R ratio to half of original X/R ratio of the study system further increases voltage rise due to reverse power flow. This limits the wind farm connectivity without reactive power compensation. The wind farm connectivity can be increased with reactive power compensation from PV-STATCOM. However, the amount of reactive power required to maintain the voltage within limits is higher compared to system with original X/R ratio.

With increase in X/R ratio to double of the original X/R ratio of the study system, there is no significant voltage rise. However, a decrease in voltage is observed with increased wind farm output. In this scenario, the PV-STATCOM is utilized to provide the reactive power compensation to boost the voltage above minimum permissible limit of 0.94 pu.
6.4 Wind-STATCOM Control for Increasing PV Solar Power Connectivity

In Chapter 4, the application of a novel control on the grid side inverter of a full converter based wind farm as Wind-STATCOM to provide dynamic reactive power compensation, is presented. The detailed assessment of the study system is carried out to evaluate steady-state voltage and TOV for daytime loading conditions.

Both steady state voltage and temporary overvoltage in the study system are within permissible limits for base case scenario with daytime loading. However, the steady state voltage increases due to reverse power flow caused by increased PV solar farm output. Wind-STATCOM is found to be effective in regulating such steady state voltages at all the buses and increase PV solar farm connectivity. For daytime loading, a maximum reactive power compensation of $1.24 \text{ Mvar}$ is needed from Wind-STATCOM to regulate voltages within permissible limits for all operating conditions (0%, 50% and 99% wind farm outputs) considered in the study. With this compensation, PV solar farm connectivity is increased from $3.16 \text{ MW}$ to $27.8 \text{ MW}$. For the study system with PV solar farm integration, temporary overvoltages remain within permissible limits for the PV solar farm output up to $20.0 \text{ MW}$. Thus, TOV is not limiting factor in PV solar farm integration.

The variation of feeder $X/R$ ratio is also investigated. If $X/R$ ratio is halved, the steady-state voltage increases further and more inductive reactive power compensation from Wind-STATCOM is required to maintain voltages. When feeder $X/R$ ratio is doubled, the receiving end voltages decrease with increased solar power output. It is noted that the PV solar farm connectivity without reactive power compensation is higher for double $X/R$ ratio compared to the system with original $X/R$ ratio. However, this solar connectivity can be increased even further with capacitive reactive power compensation from Wind-STATCOM.
6.5 Combined Application of PV-STATCOM and Wind-STATCOM

The combined impact of PV-STATCOM and Wind-STATCOM on the steady state voltages and temporary overvoltages in the distribution system is presented in chapter 5. The voltage profile in the system for various combinations of PV solar farm output and wind farm output up to 20.0 MW each, are observed. For 0.0 MW solar farm output, the steady state voltages remain within permissible limits for low wind farm output and increase as wind farm output is increased. However, for 20.0 MW solar farm output, steady state voltages exceed permissible limits for small wind power output but decrease to acceptable values for large wind farm outputs. Hence, reactive power compensation is required both for low and high wind farm output depending on the power output of solar farm. The temporary overvoltages remain within permissible limits of 130% for all combinations of solar farm and wind farm outputs up to 20.0 MW each.

Reactive power compensation of 1.25 Mvar provided by PV-STATCOM increases the wind farm connectivity up to 17.74 MW while maintaining 20.0 MW output of the solar farm. However, only 0.97 Mvar reactive power compensation from Wind-STATCOM is required to regulate steady state voltages within permissible limits to achieve solar farm connectivity of 17.65 MW while maintaining wind farm connectivity of 20.0 MW. The application of PV-STATCOM and Wind-STATCOM in the same distribution network provides a wide range of reactive power availability both for daytime and nighttime without compromising active power output from either the solar farm or wind farm.

6.6 Thesis Contributions

The following are the major contributions of this thesis:

1) An innovative PV solar farm control as a dynamic reactive power compensator, PV-STATCOM, is presented for significantly enhancing the connectivity of a neighbouring wind farm both during night and day, in a realistic distribution feeder in Ontario. The effectiveness of PV-STATCOM is demonstrated even if the solar farm is located 30 km away from wind farm. This is the first application of an international patent filed [30].
2) A novel control of full converter based wind farm as Wind-STATCOM for substantially increasing the connectivity of a neighbouring PV solar farm is also demonstrated. *Such a study has been conducted for the first time in known literature.*

3) A new combined application of PV-STATCOM and Wind-STATCOM to enhance the connectivities of both solar farm and wind farm to significantly high levels in a distribution feeder is presented. *This study has been performed for the first time in available literature.*

**Paper published from this thesis:**


### 6.7 Future Work

Some of the studies that can be undertaken in future research are outlined as follows.

- This thesis covers the detailed assessment of DG connectivity in a radial feeder. This assessment can be extended to different feeder configurations involving more number of PV solar farms and wind farms at different location in the distribution network.

- The application of PV-STATCOM and Wind-STATCOM to mitigate other issues such as fault current, harmonic distortion, and system stability may be studied.

- The coordinated control between PV-STATCOM and Wind-STATCOM needs to be investigated.
References


synchronous generator and full-size power converter for large-scale power system

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generation on directional overcurrent relay coordination: a case study,” IET

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generation on power systems: Part 1 - Radial distribution systems," Power

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Appendix– A: Study System Parameters

1) Three Phase Distribution Feeder Parameters (π-section)

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<tr>
<td>$R_1$</td>
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<td>$X_1$</td>
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<td>$B_1$</td>
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<tr>
<td>$B_0$</td>
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2) Grid Source Parameters

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3) Supply Station Transformer (Y-Y Connected)

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<td>$V_1 / V_2$</td>
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<td>$R$</td>
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Appendix– B1: Base Case Load Flow Results for Daytime Loading

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<th>TO GENERATION</th>
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<th>VAR</th>
<th>VA</th>
<th>PU</th>
<th>LOSSES</th>
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Appendix– B2: Base Case Load Flow Results for Nighttime Loading

PTI INTERACTIVE POWER SYSTEM SIMULATOR - PSS®E

DAYTIME/ NIGHTTIME APPLICATIONS OF SOLAR FARM AND WIND FARM CONVERTERS

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<tr>
<th>BUS</th>
<th>FROM GENERATION</th>
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</table>
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Publication