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Control and Operation of a Microgrid Involving a PEM Fuel Cell Through Analysis and Experimentation

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Control and Operation of a Microgrid Involving a PEM Fuel Cell Through Analysis and Experimentation

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ABSTRACT

The work presented in this thesis addresses the dynamic characteristics of a microgrid consisting of an inverter interfaced proton exchange membrane fuel cell (PEMFC) power module and two synchronous generators operating in an islanded mode. The work includes the experimental investigation of the dynamic characteristics of the distributed generators in this prototype microgrid.

A control and operation system is developed for the prototype microgrid using LabVIEW program, data acquisition devices, and hardware sensing circuitries. This structure with hierarchical architecture, consisting of a control center at a supervisory level, and real-time controllers coupled with individual distributed generators, is used to facilitate the integration of multiple distributed resources into a microgrid. The detailed implementation of this system is presented in this thesis.

The AC voltage and the frequency characteristics of the inverter interfaced PEMFC power module and the two synchronous generators in stand-alone application are investigated experimentally. Using the LabVIEW based microgrid control and operation instrumentation, the DC to AC conversion efficiency of the power electronic inverter is investigated under different load conditions.

The load sharing issue of the prototype microgrid employs a novel scheme using load-voltage droops. A PC based feedback voltage regulator is designed for the inverter interfaced PEMFC. It is intended to achieve the dynamic load regulation of the inverter, and to verify the dynamic load sharing scheme with load-voltage droops. With the aid of the computer based microgrid control and operation system, two economic dispatch strategies are proposed with underlining roles that an alternative energy source may play in a microgrid. The advantages and disadvantages of both strategies are evaluated based on the utilization of the PEMFC power module.

Keywords:

Distributed Generation, Microgrid, Hierarchical Control Architecture, Data Acquisition, Graphical User Interface, Proportional-Integral Control, Tuning, Load Sharing, Frequency Droop, Voltage Droop, Dispatch Strategy, Proton Exchange Membrane Fuel Cell, Synchronous Generator

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ABBREVIATIONS AND NOMENCLATURE

AC	Alternative Current
CERTS	Consortium for Electric Reliability Technology Solutions
CETC	CANMET Energy Technology Center
CHP	Combined Heat and Power
CT	Current Transformer
DAQ	Data Acquisition
DC	Direct Current
DER-CAM	Distributed Energy Resources Customer Adoption Model
DG	Distributed Generation
EU	European Union
GUI	Graphical User Interface
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IPP	Independent Power Producer
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LV	Low Voltage
MCFC	Molten Carbonate Fuel Cell
MV	Medium Voltage
NEDO	New Energy & Industrial Technology Development Organization (Japan)
NI	National Instruments
NRCan	Natural Resource Canada
NTUA	National Technical University of Athens
PAFC	Phosphoric Acid Fuel Cell
PCC	Point of Common Coupling
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Proportional-Integral
PV	Photovoltaic
PWM	Pulse Width Modulation

RMS	Root Mean Square
RSE	Referenced Single-End
SCADA	Supervisory Control and Data Acquisition
SOFC	Solid Oxide Fuel Cell
subVI	sub Virtual Instrumentation
VI	Virtual Instrumentation
VT	Voltage Transformer

P	Active Power
Q	Reactive Power
ΔP	Change of Active Load Demand
ΔQ	Change of Reactive Load Demand
ΔV	Change of Bus Voltage
Δf	Change of Output Frequency
pf	Power Factor
θ	Power Factor angle
K_p	Proportional Gain
T_i	Integral Time Constant
K_{cr}	Critical Gain
P_{cr}	Corresponding Oscillation Period at the Critical Gain
K_f	Slope of the Frequency Droop
K_v	Slope of the Voltage Droop
f_N	Nominal Frequency
V_N	Nominal Voltage

I. Introduction

1.1 Research Background

In modern society, electrical energy has long been recognized as one of the most important elements of a higher quality of life. Indicated in Fig. 1.1, the world electricity consumption is expected to exceed 30,000 Billion kWh within the next two decades [1]. According to the statistical results from International Energy Agency, the demand for electricity in North America is anticipated to grow more than 40% by 2025 [2]. Furthermore, with the thriving economies of developing countries, such as China and India, the overall electricity demands in these regions will escalate even faster [3].

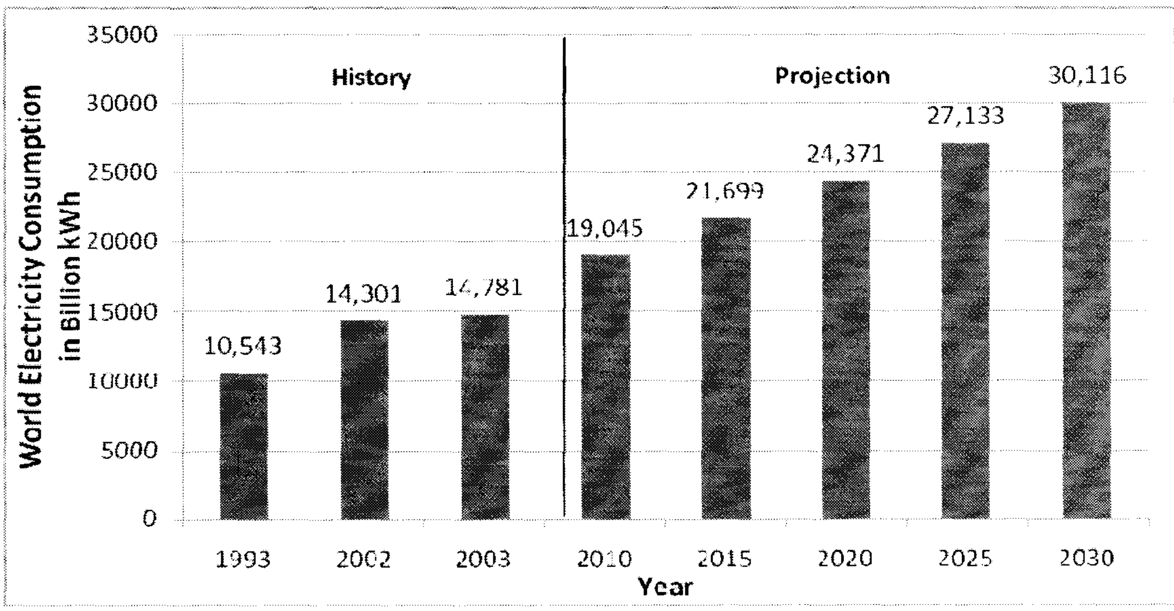

Fig.1.1. Statistic and projected world electricity consumption from 1993 to 2030 [1]

To meet the demands of the ever increasing electricity consumption, the worldwide electricity markets are undergoing an expansion by installing extensive generation capacity. Worldwide installed generating capacity is projected to exceed 5,500 GW in 2025, with an average annual increase of 2.2% [1]. In the meantime, electricity demands in Canada will continue to grow at an average annual rate of 1.5 to 2%. This means that an extra 800 Billion kWh of electricity supply must be installed by 2020 in order to meet this increase in consumption. Based on statistics, with the anticipation of retirement facilities, the generation capacity of Canada is expected to grow about 54% in the first two decades of the new millennium [4]. By comparing consumption and generation capacity data, it is obvious that the predicted increase in electricity demands is much higher than the rate at which new power plants are being built. In other words, to balance the inequality between the demands and the generation, more forms of electricity generation will be required.

Currently, the main energy sources used in conventional power plants include coal, nature gas, uranium, and hydro power, etc [5]. The 2004 statistical analysis of the contribution of conventional energy sources to world electricity generation capacity confirmed that the global electricity generation relies greatly on these resources [5]. However, the use of conventional energy sources has led to numerous issues as demand increases [6-7].

Besides the green house gas emissions caused by the use of fossil fuel, the political concerns with nuclear power, and the ecological damage associated with the construction of water dams for hydroelectric power, conventional power systems, with large centralized plants, also faces many additional challenges. For example, North American utility systems are currently being pressured to pursue a more economically and environmentally acceptable operating mode. The aging and capacity-limiting capital, intensive transmission networks, and distribution infrastructures have delayed investments in the construction of the large centralized power plants. On the other hand, to meet the electricity consumption demands, market forces and regulatory environments are forcing the industry to increase the utilization of the existing system, rather than building or upgrading the transmission and distribution systems. To alleviate the pressure on conventional utility systems, several practical, yet effective, solutions have been employed [1]. As the most promising technologies, distributed generation (DG) and microgrid become very attractive to the power system engineers. This thesis will focus on several issues surrounding distributed generation and microgrid.

1.2 Distributed Generation and Microgrid

In recent years, many electricity markets have undergone restructure and deregulation, such as the Ontario market in 2002 [8]. The once vertically integrated electric utilities providing generation, transmission, and distribution services by a monopoly are now separated into distinct entities. This free market is created with the intention of protecting average consumers by providing open competition to the independent power producers.

1.2.1 Distributed Generation

As the restructure of electricity markets continues, a number of new generation technologies begin to influence the outlook of the power industry. Contrary to the conventional utility with large power plants connected to high-voltage transmission lines, some small generators are directly connected to low-voltage distribution networks, and are producing electricity and/or heat on a customer site [9]. The exact definition of distributed generation varies from one organization or institution to another. However, it is generally accepted that a distributed generator usually has the capacity ranging from a few kW up to 10 MW, and it is connected to a distribution network (≤50 kV in Ontario legislation) [8-9]. The main objectives of using distributed generation are to seek cost reduction for consumers and utilities, to improve the reliability of existing utility, to reduce the environmental impact caused by the growth of consumption, and to utilize the renewable resources [10]. The main advantages of the DG technology are listed below [10].

- DG diminishes the investment needed for the construction of new centralized power plants using conventional fuels; this is accomplished by providing additional generation capacity to end customers locally, or in proximity.

- DG reduces the energy loss during power transmission and distribution; this improves the operation efficiency of utility systems.

- DG, with Combined Heat and Power (CHP) technologies, produces electricity and usable heat as a by-product, which can be used for heating purpose.

- DG promotes the utilization of non-conventional fuels, such as landfill gas and biogas. At the same time, DG encourages the development of renewable energy sources.

In the meantime, the application of distributed generation is facing numerous challenges in practice. Presently, the unit capital cost per kilowatt of a distributed generator is much higher than that of a large centralized power plant [8]. Additionally, the conventional utility system is not designed to accommodate power generation at the distribution level. To integrate distributed resources to an existing distribution system, many interconnection regulations must be met [8]. As one of the regulatory standards, IEEE-P1547™ is focusing on establishing the uniform nation technical specifications for the interconnection and testing of DGs [11].

Besides economic and regulation issues, DG application also introduces concerns about voltage and frequency instability when the distributed generators are connected to a feeder in a distribution network [12-13]. One example of this is when a distributed generator is installed at a low-voltage feeder; the power injected by the generator may cause the rising of the voltage profile of that feeder [12]. This will result in a negative impact on the power flow. It will further worsen the voltage stability, if system operators are not aware of the penetration level of the DG. Moreover, when a distributed generator is interfaced with the AC system, by means of rotating machines, it may also lead to stability issues on the distribution network [13]. It has been recognized that when a significant amount of small generators are installed across the low-voltage network indiscriminately, they tend to worsen the power system stability rather than to improve it [14].Therefore, there is a need to aggregate the distributed resources in a subsystem (a microgrid) in order to facilitate their operation and to alleviate their impact on the mainstream utility grid.

1.2.2 Microgrid Concept

The concept of microgrid, intended as a small subsystem of the utility grid, is to mitigate the problems originated by DGs. Generally speaking, a microgrid is a small and integrated power system consisting of distributed resources and interconnected loads, and it is connected to distribution networks. These small power systems, which have their own local customers, present themselves as independent bodies to the mainstream grid [15]. The capacity and voltage level of a microgrid are associated with specific applications. As an integrated system, a microgrid can either operate in parallel with the grid, or in an islanded mode. The capacity of a microgrid should be sufficient to provide a continuous electricity supply to a significant portion of local load demands. In addition, the microgrid possesses independent controls, which can transfer the microgrid between islanded and grid-connected modes of operations with minimal service disruptions [15]. An example of a microgrid is shown in Fig. 1.2. The Consortium for Electric Reliability Technology Solutions (CERTS) initiated the research regarding the impact of microgrid applications on existing power systems [15]. One key feature of a microgrid is the high penetration of power electronic devices, which act as the interface between the power sources and distribution networks. The application of power electronics provides extra controllability for a microgrid in both grid-connected mode and islanded operation mode. Another key feature of a microgrid is the single-point connection (point of common coupling, PCC) to the rest of the utility grid. This approach allows the microgrid to operate as a single dispatchable unit from the grid side. The interconnection standards, such as IEEE-P1547™, are only enforced at the point of connection [11].

1.2.3 Alternative Resources in Distributed Generation and Microgrid

The restructure of electricity markets, and the development of DG technologies, both promote the utilization of small generation units with the capacity less than a few megawatts. Currently, the internal combustion engine (ICE) technology is still considered the most established technology, and it accounts for a large number of installed distributed generations. However, as public awareness about environmental protection issues increases, fossil-fuel costs continue to climb, and the political and social concerns about nuclear power escalate, these factors force the industry to pay more attention to alternative/renewable energy sources.

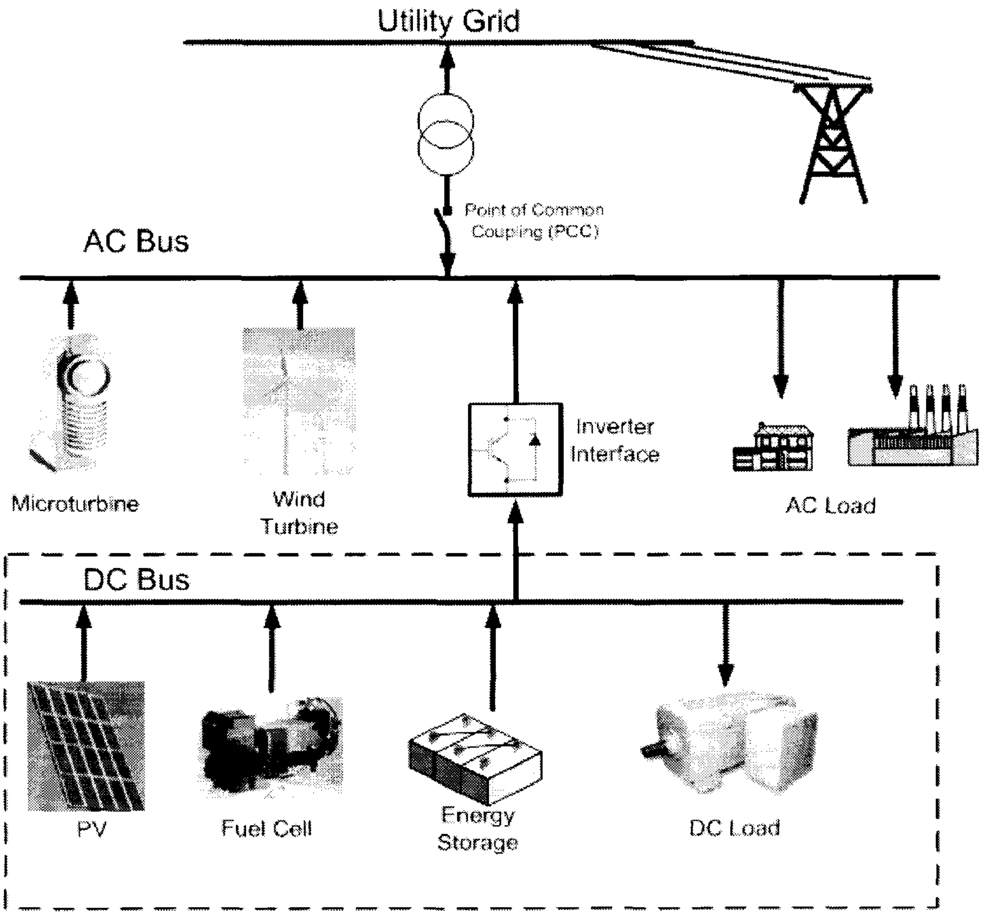

Fig.1.2. An example of an alternative energy sources based microgrid

In this thesis, the term "alternative energy" refers to energy produced by a number of environmentally friendly energy sources as an alternative to the conventional fuels, such as fossil fuels. In order to qualify as a renewable energy source, the alternative energy source cannot deplete, nor can it cause a great deal of harm to the environment; these guidelines are intended so that there will be no need to set restriction for its use. There are many different alternative energy sources which are currently being utilized in various DG and microgrid applications. In the following section, three main alternative energy technologies will be introduced. These three technologies include solar, wind, and fuel cell.

Solar

Photovoltaic (PV) technology is a solar power technology that uses a range of photovoltaic solar cells to convert the solar energy from the sun directly into electricity. It is the world fastest growing energy technology, which contributed over 12,000 megawatts of energy by the end of 2007 [2]. Nowadays, even though the PV conversion system has a high initial cost, however, in long term, it is still considered a cost effective option, especially in remote areas outside a major distribution network.

Wind

Wind energy is converted into electricity through the use of wind turbines. This type of energy accounts for a large percentage of electricity generation in many European countries, such as Netherland, Denmark and Spain. Wind energy is plentiful, renewable, clean, and widely distributed, which make the wind technology suitable to DG applications. On the other hand, wind turbine does not normally generate stable power output, because of the discontinuity of the wind. Moreover, wind turbines can only be installed where the wind is plentiful. These issues become the major drawbacks associated with the wind technologies [16].

Fuel Cell

Fuel cells are electrochemical energy conversion devices that use hydrogen and oxygen to produce electricity. Currently, fuel cells have attracted major attention in transportation applications, while stationary power generation is seen as a potential market where fuel cells could be commercialized [9].

Fuel cells have a very high electricity conversion efficiency rate (35-60%) in comparison to conventional technologies, such as gas turbines [17]. Because of the high efficiency, the low emission, and the flexible modular structure, fuel cells have a wide variety of potential applications including auxiliary power, transportation, residential power, and other DG applications. Currently, only phosphoric acid fuel cells (PAFC) are commercialized for power plants. However, three other types of fuel cells, molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and proton exchange membrane fuel cell (PEMFC), are undergoing intensive research and development in DG applications. Since fuel cells can produce reliable backup power with less emission in the event of utility power failure, many hospitals and telecommunication centers may find fuel cell power plants attractive [17]. PEMFCs with higher operation temperatures are also under development for CHP application [14].

Other Alternative Energy Sources

In addition to the above mentioned alternative energy sources, there are many other alternative energy technologies, such as biomass, geothermal power, microturbines, etc, that are currently being investigated for DG and microgrid applications [16].

Interconnection Techniques

Because the electrical output of these energy sources are usually unregulated, power conditioning units, such as power electronic DC/DC converters and DC/AC inverters are used to interface the output from the energy sources to the loads (DC or AC) [16]. Several configuration schemes are suggested to integrate different alternative/renewable energy sources to form a hybrid power generation system. The methods can generally be classified into two categories: DC coupling and AC coupling [16]. The more detailed discussion on different configurations of integrating alternative energy sources will be given in Chapter 2.

1.3 Challenges and Motivation

Although a microgrid can provide a possible solution to alleviate the problem associated with DG applications, utilities are cautious in connecting a microgrid to their networks. The current distribution protections and control practices are incompatible with the microgrid concept. In addition to the need for a clear and consistent standard in order to help both independent power producers (IPP) and utilities in the domain of DG and microgrid, there are still many technical and non-technical challenges in integrating microgrids to existing networks. Several of these challenges are listed below:

- Technical challenges: issues such as safety, intentional and unintentional islanding, reconnection from scheduled and unscheduled shut downs, capacity and reserve management, and protection coordination, etc.

- Non-technical challenges: issues such as pricing, incentives, risk responsibility and insurance for new technologies adaptation, interconnection standards and regulatory control, etc.

In addition, allowing smaller generators to contribute to power generation implies that hundreds of thousands of distributed resources will be added to the grid. The need for successful integration of the DGs and operation of microgrid demands an appropriate architecture. This architecture should be easily implemented when constructing a microgrid. The key issues in determining a microgrid structure include: interface, interconnection, control, and protection requirements for the distributed generators. The microgrid voltage control, power flow control, load sharing, protection, and stability issues also determine the microgrid structure [18]. The ability of the microgrid to operate connected to the grid, as well as smooth transition to and from the islanding mode, is another challenge for constructing a microgrid.

Moreover, a variety of energy sources may co-exist in a microgrid. Different from conventional energy sources, which are mainly in AC form, the power output from a distributed source may be either in AC form or DC form. They require power electronic devices (inverters or converters) in order to interface to the AC power system [16]. When energy sources are interfaced with power electronic devices, the control of the power electronic interface becomes the main concern in a microgrid. From one aspect, the involvement of power electronic devices provides the required flexibility needed to ensure the reliable operation of a microgrid. On the other hand, the control methodologies in a conventional system may not be adequate for microgrid applications. The non-conventional generation requires new control strategies, which becomes a major challenge to successfully operate a microgrid.

Furthermore, to utilize the alternative energy in a microgrid, an appropriate load sharing scheme must be established, especially when the energy from the utility grid is not available, or the microgrid is operating in an islanded mode. This scheme must be made based on the type of energy sources used, and their operational constraints. For example, the energy from wind turbines and solar panels are preferred mainly due to their renewable nature. However, the fluctuant availability of both the solar energy and wind make them unreliable from a scheduling point of view. They require backup support from other energy sources, such as fuel cells or diesel generators. Therefore, a proper load sharing scheme is essential for the economical operation of a microgrid. There is an optimization problem associated with selecting the proper type of resources with the right capacities at the right locations. With this stated, research on possible control schemes for the inverter interfaced generators, and an investigation of power distribution strategies in an alternative resources based microgrid, become the main focus of this thesis.

In order to utilize energy sources in an economical way, while maintaining a reliable system, two main components are unique to the architecture of a microgrid that differentiates it from the traditional utility. The first element is the power and voltage controllers, which when coupled with the DG units locally, provide a fast response to voltage disturbances and load changes. The second element is the supervisory energy management of a microgrid. The control center provides energy management by dispatching power and voltage setpoint to individual DG controllers. Development of such structure becomes one of the challenges in this thesis.

1.4 Scope and Objectives of the Thesis

Scope

From the marketing viewpoint, the construction of a microgrid involves extensive investment in building infrastructures, such as transmission and distribution lines, protection devices, transformers, in addition to the cost of energy conversion devices. The cost of construction restricts the competitiveness of a microgrid as an independent power producer. Therefore, finding the proper applications becomes difficult for the microgrid owners. They may aim to provide the services that mainstream utility may not be able to provide, such as the uninterrupted power supply (UPS) for sensitive loads or a continuous power supply for remote communities.

To create a microgrid system in a laboratory environment, and investigate the possible control solutions for power electronic interfaced resources, the Distributed Generation Group at the University of Western Ontario installed a prototype microgrid that consists of an alternative energy source (fuel cell) and traditional DG technology (synchronous generators), as shown in Fig. 1.3. The target application of this microgrid is to provide a continuous power supply to the loads in proximity with the capability of exporting extra power to the utility grid. At the current stage, this system is operating in an islanded mode. The commissioning results of developed software based microgrid control and operation system are examined in this microgrid. Thus far, in regards to the load condition concern, only resistive load is considered. Furthermore, this research mainly emphasizes the dynamic load sharing and dispatching strategies of the prototype microgrid in a three-phase balanced load condition. The system protection, harmonics, and the automatic synchronization mechanism of the generators are beyond the scope of current study.

Objectives

The main objectives of the research are summarized as follow:

1. To design and implement a computerized microgrid control and operation instrumentation. This system is used to: (a) monitor real-time operational information of the microgrid; (b) analyze the dynamic characteristics of the distributed generators in the microgrid; and (c) investigate the dynamic response of the microgrid in different load sharing schemes.

2. To verify the effectiveness of the dynamic load sharing scheme with the load-voltage droop of a microgrid involving power electronic interface devices.

3. To develop suitable dispatching strategies for the economic and efficient operation of the microgrid in an islanded mode.

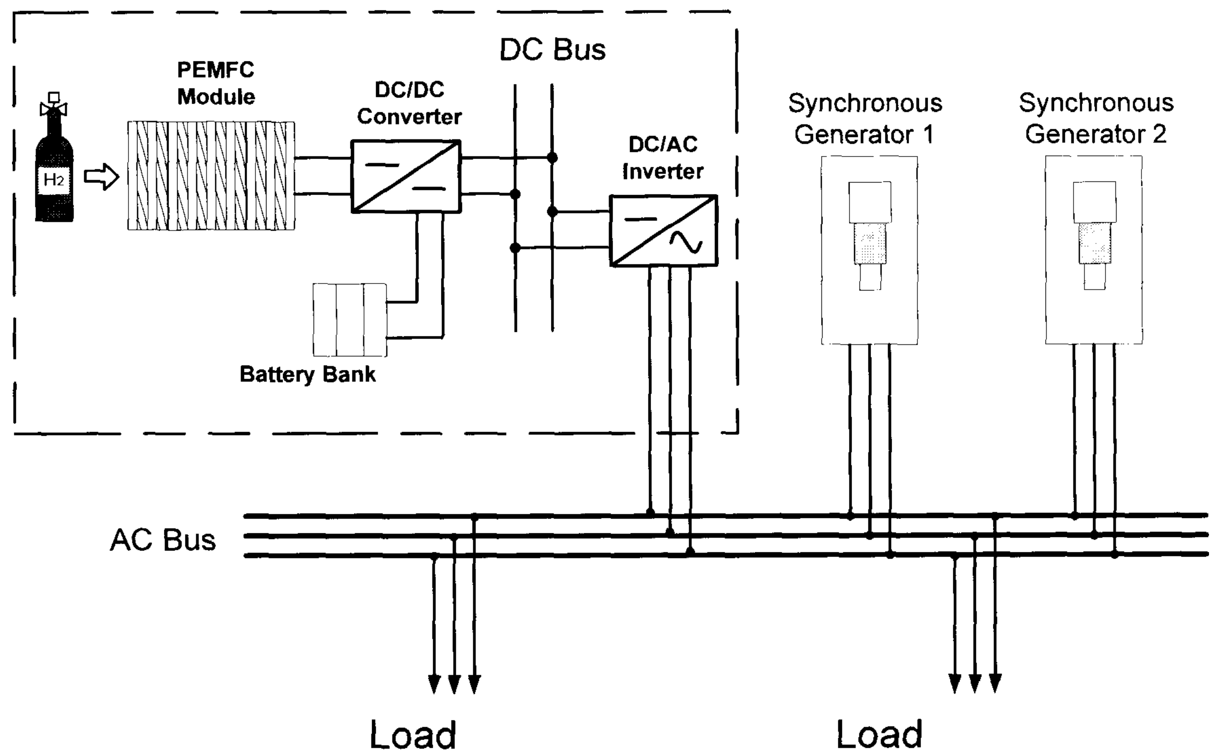

Fig.1.3. The configuration of the prototype microgrid

1.5 Organization of the Thesis

The thesis is organized as follows: Chapter II presents a literature survey of the previous work done in the area of the interconnection of multiple resources in distributed generation, and in the area of microgrid applications; the application of fuel cells in DG and microgrid is also examined. Furthermore, the challenges associated with microgrid energy management systems are identified. Several state-of-the-art microgrid demonstration projects are introduced as well. In Chapter III, the design architecture and technical requirements of the proposed microgrid is discussed. The configuration of the prototype microgrid with the PEM fuel cell power module is also presented. Chapter IV addresses the design and technical challenges associated with the implementation of the microgrid control and operation instrumentation. The development of the graphical user interface for real-time monitoring and control is also presented in this chapter. The voltage and frequency characteristics of the inverter interfaced PEMFC, and the two synchronous generators are examined in Chapter V. The conversion efficiency of the inverter is also investigated. Chapter VI discusses the effectiveness of the novel load sharing scheme with the load-voltage droop. A feedback voltage regulator is designed for the dynamic voltage regulation of the inverter. Several issues associated with the dynamic load sharing schemes are explored as well. Chapter VII discusses two dispatching strategies for the economic operation of the microgrid in an islanded mode. Finally, Chapter VIII concludes the thesis and provides potential direction into future research.

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II. Literature Survey

This chapter provides a review of previous work reported in literature concerning the interconnection configurations of multiple distributed resources in DG and microgrid applications. The fuel cell related DG technologies, and their applications in microgrids, are also introduced in this chapter. It is followed by a survey of the microgrid energy management systems. At the end of this chapter, the state-of-the-art microgrid demonstration projects, in different regions around the world, are also summarized.

2.1 DG and Microgrid with Power Electronic Interface

2.1.1 Interface and Interconnection Topologies of Multiple DGs

Interface Topologies

One of the distinguishing features of the microgrid concept employed in this thesis is the amount of the alternative energy used as primary sources. Contrary to the conventional power system, which is dominated by rotating machines, distributed resources may produce power in different forms. For example, fuel cells and PVs produce DC power directly, which can be interfaced with the AC bus through DC/AC inverters. Others, such as microturbines or wind turbines, usually generate high-frequency AC power or variable frequency power. The output power is normally rectified to an intermediate stage in DC, through the use of AC/DC rectifiers, and it is subsequently converted to the standard 60 Hz AC power by DC/AC inverter. Two different interface topologies used to integrate the distributed energy sources with the AC power system are illustrated in Fig. 2.1, [1-2]. An enabling technology for energy sources has been the breakthrough in the integrated system for power electronics. These devices, based on silicon technology, are able to withstand higher voltages, larger currents, and they are able to switch at higher frequencies. Many works have elaborated on the advanced power electronics designs for DG applications, such as power converters, PWM techniques, and electronic control units [3-5].

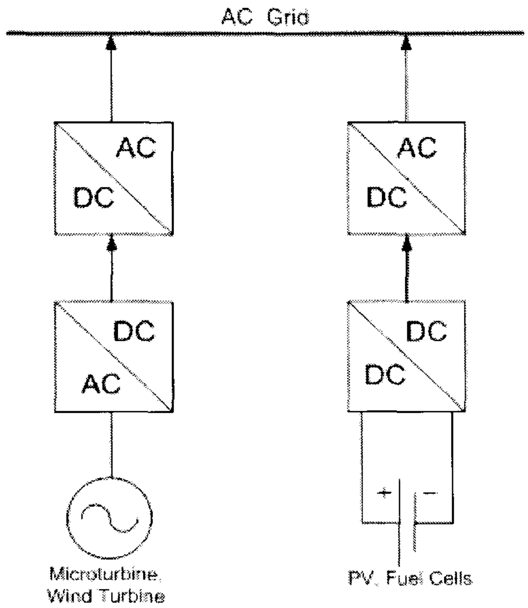

Fig.2.1. Two power electronic interface topologies

DC-Link and AC-Link

Forming a microgrid requires proper configuration to interconnect multiple distributed resources. Suggested in [6-9], the DC power is fed to a common DC voltage bus. The AC output from the rotatory generators, such as wind turbines and microturbines, is first rectified into DC form, and connected to the same DC voltage bus. To interface the DC power to the AC loads, a single DC/AC inverter is used for interconnection. One of the advantages of using the DC-link configuration is that it eliminates the generation of the reactive power. As a result, it reduces energy loss during power transmission and distribution [7]. However, this type of configuration relies substantially on the availability of the DC/AC inverter interface. Once the inverter is out of service, the whole system fails to supply AC power.

Meanwhile, a lot of research has focused on the AC coupling configuration [10-12]. In this configuration, different energy sources are coupled with the AC load individually using the interface topologies shown in Fig. 2.1. The power from rotatory generators is directly connected to the AC bus. With an AC-link configuration, there is no need to construct new DC distribution networks, and the multiple energy sources are ready for grid connection; therefore, it utilizes the existing distribution infrastructures. Unlike the DC-link configuration, which depends highly on the inverter interface, if any of the inverter in the AC-link fails, the problem can be isolated, and the rest of the generators can still support the AC loads. Synchronization of multiple generators is a challenge facing the AC-link configuration. It is suggested that the fundamental phasor components between the inverter output voltage and the AC bus voltage can be used for synchronization purposes [13].

A comparison of advantages and disadvantages between AC-link and DC-link configuration is given in [10]. This comparison can be used to evaluate the possible interconnection techniques when additional energy sources are introduced to the existing microgrid.

2.1.2 Examples of Multi-Sources Distributed Generation System

Different energy sources can complement each other, and can also provide higher quality and more reliable power to customers, when they are integrated. Many combinations of alternative energy sources and storage devices are reported in literatures, including: (1) PV/FC/Energy storage devices [14-15]; (2) Wind/FC [5]; (3) Microturbine/FC [16], etc. However, these projects only address applications of renewable energy. They neglect the fact that current distributed generation is dominated by electrical generators driven by prime movers. There is clearly lacking of guidelines associated with microgrids when PEMFC and synchronous generators are involved.

2.2 Fuel Cell Applications in Distributed Generation and Microgrid

2.2.1 Fuel Cell Applications in Distributed Generation

Among the alternative energy technologies, the fuel cell technology is one of the most promising options for future DG and microgrid applications [17]. A fuel cell is an electrochemical energy conversion device that converts the chemical energy into direct current electricity. Categorized based on the electrolytes used, there are four major types of fuel cells that operate on a similar principle; these fuel cells include Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC) [17-18]. The reactant fuel is separated into electrons and protons, and the electrolyte permits the proton to pass between the anode and the cathode, which causes the electrons to travel in an external circuit and form a direct current path [17]. Table 2.1 outlines the differences of these four types of fuel cells, as well as their applications in power generation.

Table 2.1. The comparison of different fuel cell technologies

FC Type	Electrolyte	Charge Carrier	Fuel	Operating Temperature	Applications
PEMFC	Solid polymer (Nafion)	H^+	Pure H_2	50-100°C	Portable, automotive, CHP
PAFC	Phosphoric acid	H^+	Pure H_2	~220°C	CHP
MCFC	Lithium and potassium carbonate	CO_3^{2-}	H_2, CO, CH_4, other hydrocarbons	~650°C	CHP, stand-alone
SOFC	Solid oxide electrolyte (zirconia)	O^{2-}	H_2, CO, CH_4, other hydrocarbons	~1000°C	CHP, stand-alone

Since there is no combustion, and with less mechanical moving parts involved during the power generation process of fuel cells, the greenhouse gas emission problem, as well as the energy conversion efficiency, are dramatically improved. Compared to the conventional power sources, such as engine driven generators, fuel cells have various advantages, such as low (or zero) emission, flexible fuel, higher efficiency than gas engines, low noise, and modular design for flexible installation [19]. These advantages make the fuel cell technology a good candidate for distributed generation, especially in remote locations, where the main utility grid is difficult to reach [20].

In many cases, fuel cells are integrated with other alternative energy sources in order to form a hybrid system. For example, when fuel cells are integrated with wind power, they can be used as backup generators in situations where wind is not available [21]. Similar applications of fuel cells, as standby power supplies, have shown its effectiveness to compensate the inherent disadvantages of solar energy by provide premium power, as discussed in [22]. Moreover, if the fuel cell units are equipped with electrolysers, they can be used as long term energy storage in a hybrid system [2].

2.2.2 Fuel Cell Applications in Microgrid

Many fuel cell technologies are not yet ready for widespread deployment; this is mainly because of their high initial cost. However, they have great potential for microgrid applications, when they are integrated with other resources. Lasseter *et al* [23] discussed the integration of alternative energy sources, including fuel cell, in the microgrid from a conceptual perspective. Hoff *et al* [24] compared the existing utility services of residential customers with a hybrid microgrid consisting of PV and FC. From an economic point of view, it proved the potential advantage of a microgrid to reduce the cost for consumers; this is because the microgrid does not burden the cost of transmission systems. Similar issues were also addressed in [25]. Senju *et al* [26] analyzed the possibility of installing a hybrid microgrid system in remote locations with wind turbines and fuel cells, and where fuel cells are used as energy storage devices. D. Audring and G. Balzer [27] analyzed the protection issues related to a fuel cells based microgrid. However, in this case, fuel cells are the sole energy provider. In his dissertation, Z.

Zhang developed a microgrid model with PEMFC and synchronous generators [28], and a novel control scheme for this microgrid; however, the dynamic response of such control scheme requires further investigation. Hernandez-Aramburo *el al* [29] described the dispatch strategies of a microgrid with fuel cells, microturbines, and gas engines. The fuel consumption in different scenarios is compared for the optimal operation of the microgrid. In the work of Lopes *et al* [30], the basic control strategy for fuel cells based microgrids, in an islanded mode, is discussed and simulated.

2.3 Microgrid Energy Management System

To alleviate the issues caused by the large penetration of the distributed generators to the existing utility system, the microgrid technology is considered as a potential solution. To maintain safe and efficient operation of a microgrid, a supervisory system is required in order to perform control and energy management functions.

Since first introduced in the 1960's, Supervisory Control and Data Acquisition (SCADA) Systems have been improved significantly. A modern SCADA, with an open distributed system, is founded on the network-based distributed computing technology [31]. The utility energy management system relies heavily upon the SCADA system to gather system data and to issue control and energy management commands. As the expansion of the utility grid continues, traditional SCADA systems become highly reliant on communication network to exchange large quantities of system data with the generators, and other devices in the grid, for example protection system [32]. Geographical dispersion of the distributed resources has led to the great challenge of incorporating the DGs into the existing centralized SCADA systems. As a result, a new control and management system is required for the operation of a microgrid.

Similar to the SCADA systems in the conventional utility, the microgrid energy management system does not only limit to the generation control; it will further manage information in order to improve the overall profitability of the microgrid owners [33]. Suggested by the CERTS, the energy management system of a microgrid aims to deliver cost effective control without compromising the interoperability of distributed resources

[34]. The challenges of the energy management system are to minimize energy consumption, as well as to analyze energy and cost saving opportunities. The current development of microgrid energy management systems is more on a conceptual level. There are only limited discussions presented in literature. Although there is no fully developed energy management system for microgrid, manufactories have already introduced innovative products that can serve as building blocks for versatile systems [34]. The basic task of the energy management system is to optimally dispatch DG equipment and loads in response to the energy demands, pricing and operational constraints [35]. The design criteria of an energy management system, and the basic control strategies, are given in [30, 34].

2.4 Microgrid Demonstration Projects

The design and operation of a microgrid demand new skills and technologies. Many ongoing research, development, and demonstration efforts are currently underway in the United States, Canada, Japan, and Europe.

The United States

In the U.S., the CERTS is currently pursuing R&D effort to use a microgrid as an alternative to integrate small-scale distributed resources. The concept of the CERTS microgrid was fully specified in 2002 [33], and several demonstration projects took place as a result. These physical examples include the laboratory-scale test system at the University of Wisconsin, Madison and the full-scale test bed at Dolan Technology Center in Columbus, Ohio, which mainly consists of small synchronous generators [36]. General Electric Global Research also participates in the R&D of microgrid with specific focus on the development of an energy management framework. In addition, a number of microgrid projects emphasize on the necessary tools needed for microgrid deployment. Two major institutes utilizing this approach are Georgia Institute of Technology, which introduced "μgrid Analysis Tool", and another being the Berkeley Lab, which developed "Distributed Energy Resources Customer Adoption Model (DER-CAM)" [36].

Canada

In Canada, the microgrid research and development is mainly focused on the medium voltage level. Most of the projects are initiated by universities, or managed by CANMET Energy Technology Center (CETC) in Varennes, Quebec, funded by Natural Resources Canada (NRCan). Their research interests primarily focus on the control and protection of autonomous control of a microgrid, power balancing and energy management strategies, and parallel operation and interactions of power electronic devices [37-38]. For remote microgrid applications, Ramea islands demonstration project was built with the integration of wind and diesel generation [39]. This project also explores the communication, and the SCADA systems, in the operation and control of a microgrid. In Alberta, the Fortis-Alberta distributed system was built for the grid-connected microgrid application [39]. In order to investigate the intentional islanding issues associated with a microgrid, British Columbia Hydro constructed the Boston Bar system that consists of a substation supplying three radial feeders [39]. This project focuses on the load management and load-following capability of an islanded microgrid. The synchronization issue is also described in this work.

Japan

Currently, Japan is the world leader in microgrid demonstration projects, as the government ambitiously aims to increase the utilization of renewable energy sources. The research at the New Energy and Industrial Technology Development Organization (NEDO) mainly addresses the integration of new energy sources into a local distribution network. The Aomori project in Hachinohe uses only renewable energy sources, including PV, wind, and biomass to supply electricity and heat [40]. The fuel cell technology is applied in the Aichi project and Central Japan Airport [40]. Two 300 kW MCFCs, four 200 kW PAFCs, and one 50 kW SOFC are integrated into this microgrid configuration. This system also includes PV and battery for load balancing.

European Union (EU)

In Europe, microgrids are considered a basic form of future active distribution networks, with fully utilization of alternative energy sources. Led by the National Technical University of Athens (NTUA), the microgrid investigation in EU aims at the alternative control strategies, the alternative network designs, the development of new tools for multi-microgrids management operation, the standardization of technical, and commercial microgrid protocols. One of several pilot demonstration sites is the LABEIN's commercial feeder in Spain. At this site, a microgrid consists of PV, wind, backup generators, and energy storage devices connected to the MV network [41]. This network is used to test both centralized and decentralized control strategies in grid interconnected mode. In contrast, the Kythos Island Microgrid in Greece is used to study similar issues for an islanded microgrid. Another DG test facility installed in Milan is used for characterizing, testing, and evaluating the performance of interconnected DG sources [41]. A high-speed data acquisition (DAQ) system is employed to collect and analyze the experimental data derived from the field test; this data is used to monitor power quality, harmonic distortion and electric transient.

2.5 Summary

The advance of power electronics technologies in distributed generation applications brings the possibility of integrating alternative energy sources with the output in different forms (DC or AC) into the existing AC system. This chapter first reviews two interface topologies used to connect DC power sources and rotatory generators to the AC loads. For the interconnection of multiple distributed resources with power electronic interfaces, DC-link and AC-link configurations are compared. The pros-and-cons of the two schemes can be used to determine the most suitable configuration when more energy sources are integrated into the prototype microgrid.

For its excellent performance in high fuel efficiency and low emission, fuel cell technology has attracted a great deal of attention to DG and microgrid applications. This section discussed the four types of fuel cell technologies, and their applications in distributed generation and microgrid. This part of the survey conveys the information needed to understand the different roles that fuel cells may play in an electricity market.

In order to maintain reliable and economic operation of a microgrid, the functions of a microgrid energy management system are emphasized. Similar to the SCADA system in a conventional utility system, the microgrid energy management system aims to provide the cost effective control, without compromising the interoperability of distributed generators. Even though there are only limited discussions presented in literature for this subject, the microgrid concept of CERTS provides a general guideline for the design and development of such a system.

At the end of this survey, several microgrid demonstration projects, from different regions around the world, are briefly introduced, with specific focus on their main contributions to the development of microgrids.

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III. Architecture of Microgrid Control and Operation Systems

A microgrid requires proper control and operation systems in order to ensure voltage and frequency stability, while maximizing the profit of the microgrid owners. Such a system has to be flexible in order to accommodate the constantly expanding nature of a microgrid. The system should aim to facilitate the integration of a variety of different distributed resources. This chapter introduces a hierarchical control architecture used to study the dynamic characteristics of the distributed generators in a microgrid environment and investigate the possible solutions to utilize the resources in an economic way. A laboratory-scale microgrid consisting of a PEMFC and two synchronous generators is designed for experimentation and testing purposes. This chapter emphasizes how this hierarchical configuration is adopted for the study of the characteristics of the distributed resources, the load sharing schemes for a microgrid with the involvement of power electronic interfacing devices, and the microgrid dispatch strategies will be discussed in Chapter 5, Chapter 6 and Chapter 7, respectively.

3.1 Architecture of Microgrid Control and Operation Systems

The microgrid structure adopted in this research involves an operational architecture, which is suggested for CERTS microgrid research projects [1-3]. It is assumed that the microgrid consists of a large amount of power electronics based distributed resources. This microgrid is connected to a low voltage distribution network, and it is interfaced to the mainstream utility; it is interfaced through a point of common coupling (PCC). In addition to the power electronics based control for the distributed resources, this microgrid also requires executive level management to ensure the economic operation of the overall generation satisfies the environmental and financial constraints. Supported by the existing communication infrastructures, such as telecommunication or internet, a hierarchical control and operation system is used to monitor the operation of the system and control the distributed generators, loads, and energy storage devices in the microgrid. This control system consists of several decision-making components. The levels of the hierarchy exchange information vertically, as shown in Fig. 3.1. More details are given in Fig. 3.2.

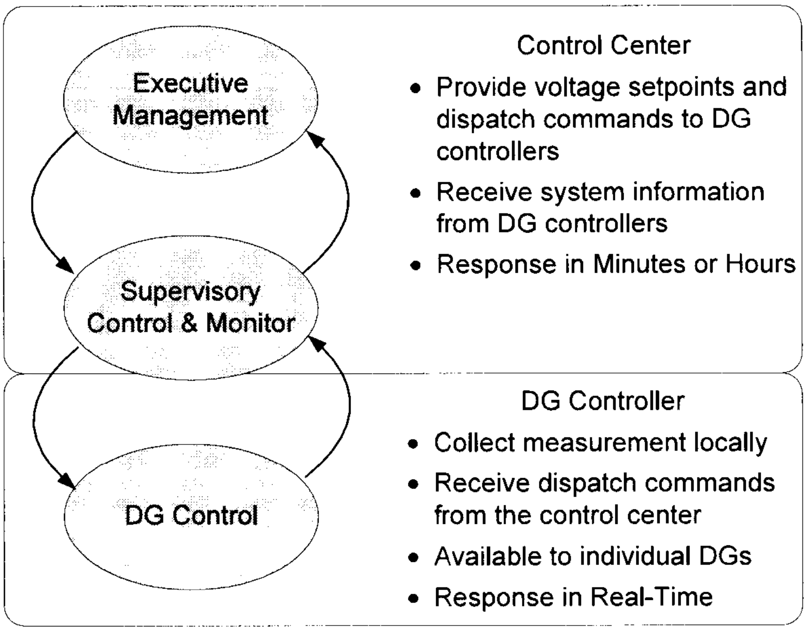


Fig.3.1. Hierarchical microgrid control architectures

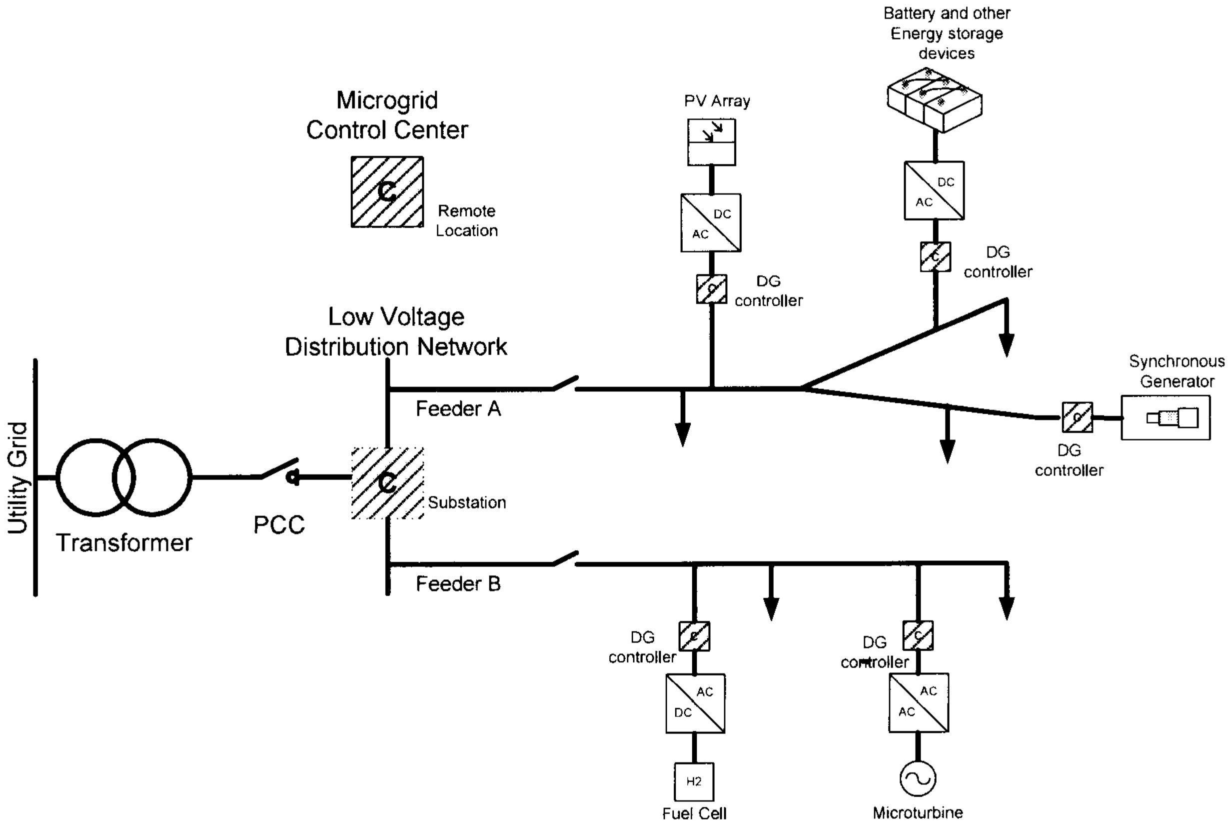


Fig.3.2. Microgrid architecture comprising DGs, loads, and control units

As shown in Fig. 3.1 and Fig. 3.2, this architecture suggests the microgrid to be centrally controlled, and operated by a main controller. This main control center is located either at the substation of the distribution network, or at a remote location, depending on the local geography. At the top level, the main control station performs the functions, such as providing voltage setpoints, power dispatching and other energy management commands to the lower level DG controllers. The actual values for the dispatched power and voltage depend on the operational needs of the loads, as well as efforts to minimize emissions and enhancing the efficiency of DG sources. Such information can be obtained from a microgrid energy management system, which can be found at a higher level or is embedded with the control center. The control at this level is also responsible for the implementation of the control schemes to produce as much energy from the system as possible, in order to recover the installation expenses. Typically, the sampling times on the order of minutes or hours are required to implement this functionality.

The DG sources in the microgrid are locally equipped with individual DG controllers. At the DG control level, these DG controllers collect the measurement data locally. The DG controllers provide basic functions, such as regulating the voltage at the interface of each DG source with the load changes in the system and ensuring that each source quickly picks up its load share during an islanding operation.

The hierarchical structure provides a flexible platform for the microgrid system operators to collect system information from local DG controllers and to make dispatch plans based on the economic decisions. Since the information transferred within this hierarchical system only contains monitoring signals, dispatch commands and setpoints, the amount of data exchanged is relatively small.

The control center does not need to update itself when the size of the microgrid changes. It only monitors the system and performs decision-making functions, which lend well to a dynamically configured system. Due to the wide variety of the power electronic devices involved in the system, different types of control techniques can be adopted at the DG control level. The DG controllers can promptly respond to disturbances according to predetermined manner using voltage and current measured locally without the information from the remote energy sources. It enhances the flexibility and the plug-and-play feature of the microgrid, without the need of extensive reconfiguration of the overall system. This architecture is selected for the microgrid control system design as well as the study of the load sharing strategy of a microgrid in this thesis.

3.2 Configuration of the Prototype Microgrid with PEMFC

3.2.1 Prototype Microgrid Configuration

In a microgrid, with multiple distributed energy sources driven by different types of prime movers, the energy generated from the renewable sources, such as wind and solar, is preferred due to the replenishing nature, cost efficiency, and its clean form. However, the electricity production of PV and wind is highly dependent on the availability of solar energy and wind, which can be unreliable from a scheduling point of view. Therefore, wind and PV are categorized as non-dispatchable distributed generators in power management. They usually require other sources to provide a backup power supply. In the meantime, distributed resources, such as the fuel cells or the reciprocating engine driven generators, are able to provide the backup power for wind and PV, as long as there is constant fuel supply. These dispatchable distributed generators are especially important for the uninterrupted power supply (UPS) applications when the utility grid is unavailable or the microgrid is operating in an islanded mode. However, the generation cost and fuel efficiency of these generators must be taken into consideration for economic operation. Consequently, the economic aspects of load distribution strategies are mainly focusing on how to utilize the energy from the resources with dispatchable characteristics.

In order to study the appropriate load sharing schemes and evaluate the feasibility of the selected power distribution solutions in a microgrid, a laboratory-scale microgrid, with multiple small-capacity energy sources of dispatchable nature, was installed in the Distributed Generation Laboratory at the University of Western Ontario, as shown in Fig. 1.3. The prototype microgrid consists of a 1.2 kW PEM fuel cell power module (Nexa™)

from Ballard and a 24 V DC battery bank, with the power electronics interface of a DC/DC converter, and a 3-phase DC/AC inverter. Connecting to an AC voltage bus, two small synchronous generators (rated at 0.25 kW) driven by DC motors, are used to simulate the reciprocating engine driven synchronous generators in a real DG environment. They are integrated together in order to provide electricity to a nearby load center. The physical connection of the prototype microgrid with the measuring units is presented in Fig. 3.3. The analog sensors located at the output terminals of the inverter, and the synchronous generators, are used to measure the local AC voltage and current. A three-phase-four-wire configuration is used to construct the AC bus. The neutral line is not shown in the figure. The detailed justifications of the devices are as follows:

1. PEMFC power module: the PEMFC used in this thesis is rated at 1.2kW. Its dynamic characteristics and the modeling details have been elaborated in [4-5]. The voltage and frequency characteristics of the inverter interfaced PEMFC power module are investigated in Chapter 5. Due to its dominant capacity, when compared to the synchronous generators, the PEMFC power module greatly influences the dynamic characteristics of the overall microgrid. The detailed explanations and the roles that the PEMFC power module may play in the load sharing of the microgrid are discussed in Chapter 6 and Chapter 7, respectively.

2. Battery: due to the electrochemical and thermodynamic process of a PEMFC, it cannot quickly respond to the load change in transients. Therefore, a 24V lead-acid battery bank is employed to moderate the impact on the fuel cell caused by the load disturbances. The battery also supplies the auxiliary energy to the fuel cell module during the start up and shut down processes. As an energy storage device, the battery stores the excess energy from the fuel cell module in light load condition. However, the battery bank is not considered to be an active generation source in the development of load sharing schemes.

3. DC/DC converter: the function of the half-bridge buck converter is threefold: (a) it regulates the unstable voltage output from the fuel cell power module, before it is converted into AC form; (b) it manages the power flow between the DC sources (i.e. fuel cell and battery) and the inverter; and (c) it prevents current flow back from the battery to the fuel cell.

4. DC/AC inverter: to interface the regulated DC power from the PEMFC and the battery to the AC load, a 3-phase DC/AC inverter is employed. This inverter has a terminal voltage control function, which is used for voltage regulation and load sharing purposes. It will be further discussed in Chapter 6 and Chapter 7.

5. Synchronous generators: although the reciprocating engine driven generators are widely used in present DG applications, they are not preferred as a primary source in a microgrid; this is due to the pollution issues it causes, especially when power from utility grid is available. Therefore, two small size synchronous generators (0.25 kW each), with identical internal electrical parameters, are used in this prototype microgrid. The capacity of the synchronous generators is selected specifically so that they do not have significant influence over the overall microgrid. In addition to actively participating in the power contribution, the synchronous generators may also be considered as a backup power supply in the development of various dispatch strategies.

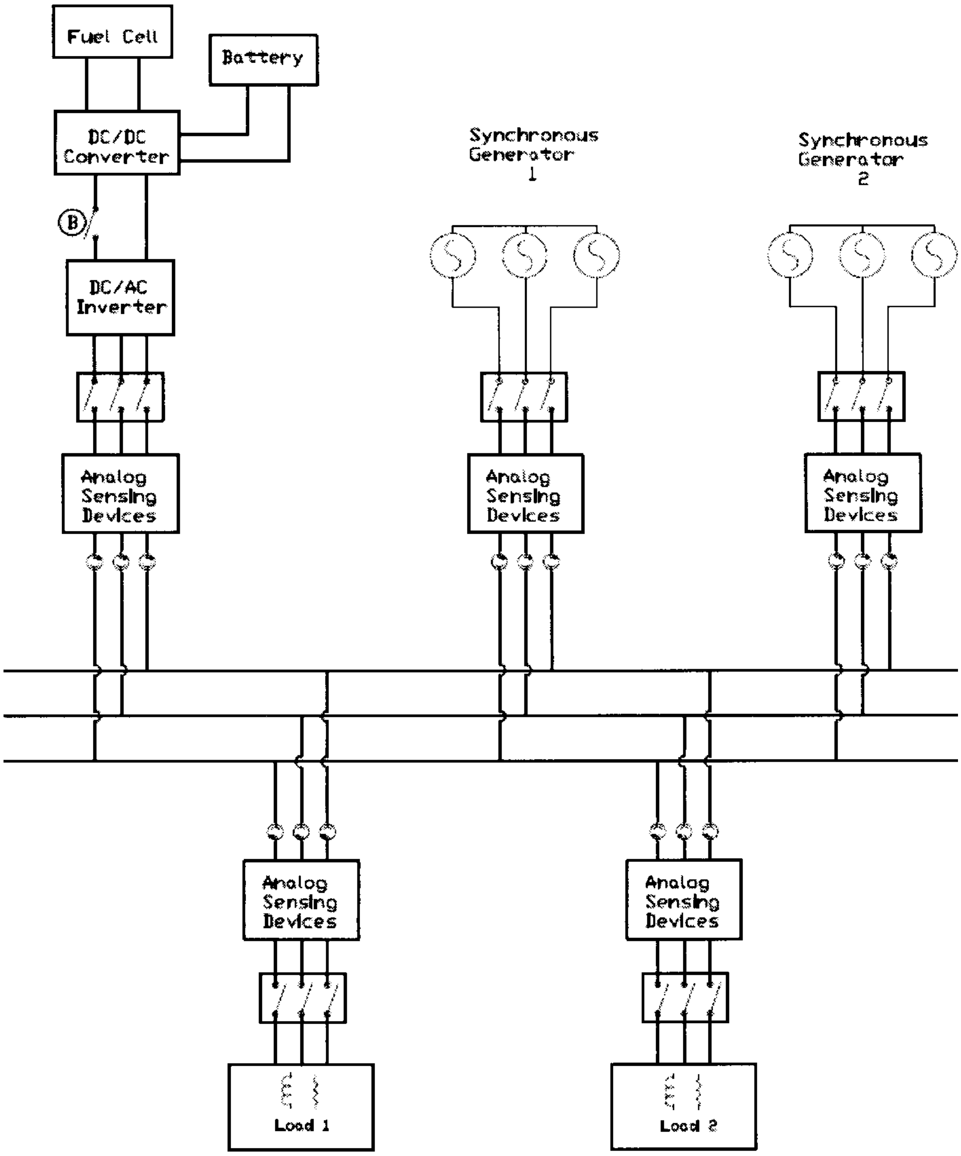


Fig.3.3. Interconnection of the prototype microgrid with measuring units

3.2.2 Requirements on the Microgrid Control and Operation System for the Study of Load Distribution Strategies

The information required for the microgrid control and operation system depends on the types of control strategies used for the distributed resources, as well as the data requested by the microgrid operator. This thesis emphasizes on the investigation of the appropriate load sharing control and the power distribution strategies of the microgrid. Several basic variables are required by the top level control center for monitoring and data logging purposes. The information includes, but is not limited to, the active and reactive power outputs from distributed generators and the load demand, and the frequency and voltage profile of the AC bus. So far, as the implementation of the proposed load sharing scheme is concerned, the control center should provide the voltage and frequency references to the individually distributed resources. Moreover, the load distribution strategies should be based on the utilization of the resources in the microgrid, especially the alternative energy sources with the prime movers in DC form. Therefore, the operational efficiency and fuel consumption of the DC sources are also considered in the energy management. In the meantime, the terminal voltages of individual generators are also used to implement the proposed DG control scheme to the individually distributed resources on the DG control level.

To receive the variables required by the control center, the measurement of the following data are required for the monitoring purposes and the control of the distributed resources:

- Terminal voltages: phase voltage is measured at the terminal of each DG source and is fed back to individual DG controllers for voltage regulation when the inverter of a voltage source is in operation. The AC voltage information is also used for power calculations.

- Output currents: AC current output from each DG source is measured locally. It is used together with the AC terminal voltage for the calculation of real-time active and reactive power.

- DC voltage and current: to observe the operation status of the DC energy sources, the DC voltage and current are measured at the output terminal of the fuel cell module. The DC information is also used to monitor the operation efficiency of the inverter.

Design Specifications

In order to meet the technical requirements for the investigation of the load sharing control and power dispatch strategies, the developed control and operation system for the prototype microgrid must satisfy the system specification listed in Table 3.1.

Table 3.1. Design specifications of the microgrid control and operation system

Items	Specifications
Voltage Sensor	• AC Input: 100~140 V AC Output: ±10 V AC • DC Input: 0~26 V DC Output: 0~10 V DC
Current Sensor	• AC Input: 0~5 A AC Output: ±10 V AC • DC Input: 0~50 A DC Output: 0~10 V DC
Data Acquisition Board	• Input Simultaneous sampling, Sampling rate ≥ 1k sample/sec Channel-to-channel isolation • Output ±10 V analog voltage output
Power Calculation	• AC Receive measurement data (V and I) in AC form Calculate instantaneous P, Q, θ, *pf* • DC Receive measurement data (V and I) in DC form Calculate DC power input of the inverter Calculate instantaneous efficiency of the inverter
Graphical User Interface	• Display Synchronous generator: P, Q, θ, *pf*, I_{rms} PEMFC based inverter: P, Q, θ, *pf*, I_{rms} Bus voltage System frequency PEMFC output current and voltage Inverter operation efficiency Battery current (direction) • Input Synchronous generators: excitation voltage, prime mover speed Inverter: voltage setpoint, PI control parameters

3.3 Prototype Microgrid with Control and Operation System

As discussed earlier, the prototype microgrid used in this thesis adopts the hierarchical control and operation system in order to conduct the study on load sharing strategies. The employment of such architecture is also used for the purpose of accommodating further expansion of the existing microgrid, without extensive reconfigurations of the software based control and monitoring center. The basic operation of the microgrid is assigned to the controllers, coupled with individual distributed resource. The proposed microgrid control system is integrated with the prototype microgrid, as shown in Fig. 3.4. The distributed generators in this microgrid are equipped with their own controllers, so that the inverter and the synchronous generators can respond to load changes in a predetermined manner without the data from each others. For example, the inverter is equipped with a terminal voltage control regulator, which will be discussed in Chapter 5, while the synchronous generators have simple open-loop controllers for the primary movers and the exciters adjustment. Both the AC current and voltage are measured at the output terminal, and then fed back to the corresponding controllers. The DG controller then executes the measuring data and performs the pre-defined functions, such as the voltage control and the power information calculation. Without relying on the external communication infrastructures, the controllers, which are coupled with the generators, will provide control in real-time to overcome the voltage disturbances and supply the load demands.

In the meantime, the DG controllers also calculate the power information based on the measured voltage and current. The value of active power, reactive power, frequency, and voltage profile of the AC bus (with additional information such as power factor (*pf*) and power factor angle (θ)) are sent to the control center. According to the requirements on the monitoring system, the information sent to the control center could be in real-time or it may experience some delays. On the reverse direction, the data sent from the control center includes voltage setpoints and scheduling decisions. The response time for this function can be measured in minutes. So far as the analysis of the operating characteristics of individual DG and the power distribution strategies of this test bench microgrid is concerned, the control center and the individual DG controllers are integrated in a single PC which eliminates the need of communication network for information exchange. The dynamics of the distributed resources (PEMFC and synchronous generators) as well as the load condition are monitored and recorded in real-time where the control center with the graphical user interface (GUI) can be used as a real-time monitoring instrumentation. Analog input data acquisition (DAQ) devices from National Instruments (NI) are used to convert the measuring data into digital form for the PC based DG controllers. The control signals are sent from the PC to the control actuators via analog output DAQ devices.

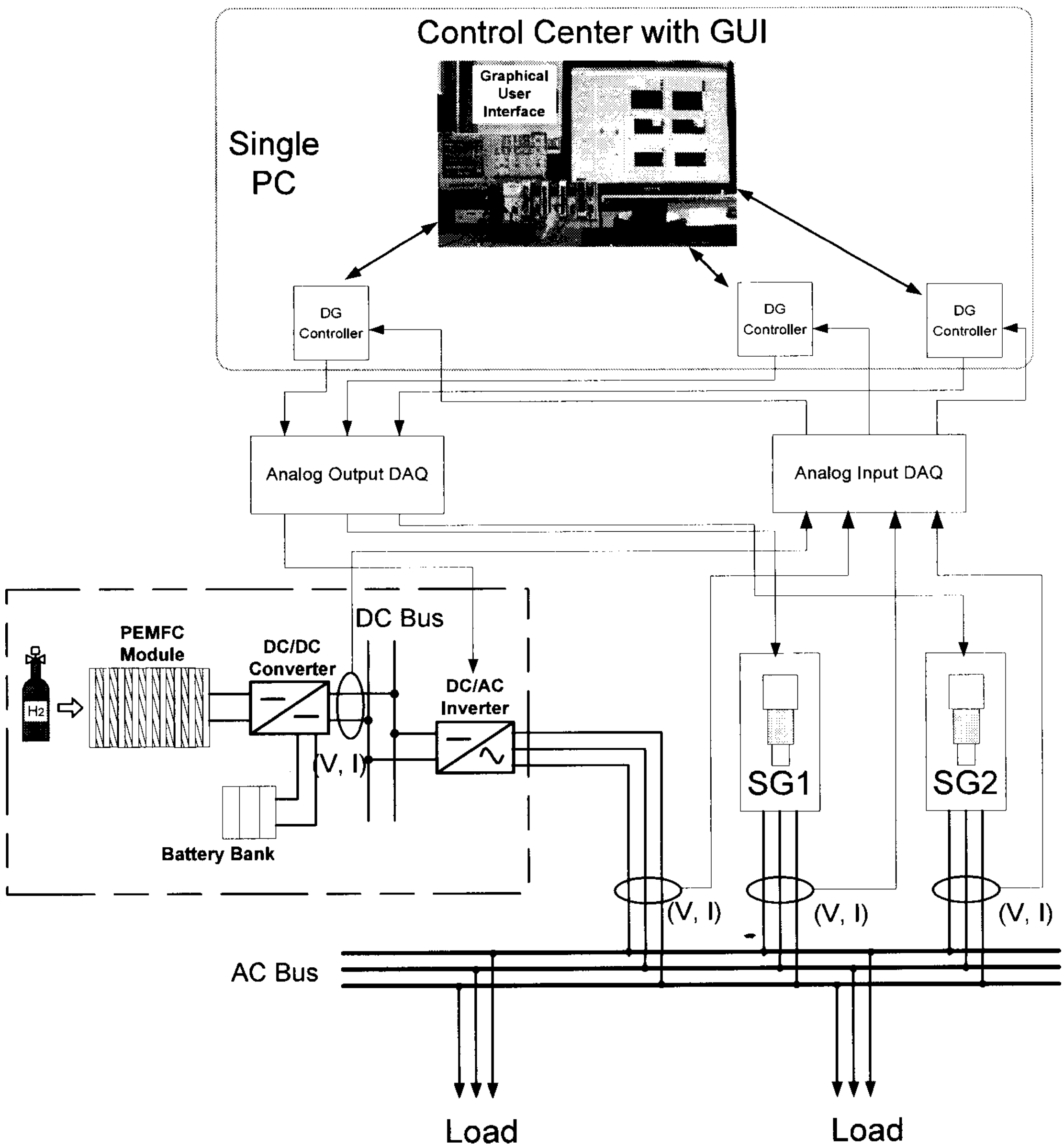


Fig.3.4. The prototype microgrid with the hierarchical control and operation system

3.4 Summary

In this chapter, a detailed discussion about the hierarchical architecture of the design of microgrid control and operation system is presented. This architecture proposes a control center that manages the microgrid energy resources distribution by providing dispatch commands to corresponding controllers. The control center is also responsible for providing the distributed resources with nominal voltage and frequency setpoints. At the lower level of this hierarchy, it is suggested that the distributed generators should have their own locally coupled controllers to communicate with the control center. The individual DG controllers collect measurement data locally and provide necessary control actions as needed in order to maintain the voltage level and the frequency according to the preset command received from the control center.

The proposed microgrid control and operation system is implemented to the prototype microgrid, which consists of an inverter interfaced PEMFC power module and two synchronous generators. This system is used to investigate the load sharing control and power dispatch strategies of the prototype microgrid. The technical requirements and design specifications of the proposed system are also illustrated in this chapter.

3.5 References

[1] G. Gibson, "Intelligent Software Agents for Control and Scheduling of Distributed Generation," California Energy Commission, http://www.energy.ca.gov/reports/2002-01-11_600-01-010.pdf, 2001

[2] R. Lasseter *et al.,* "White Paper on Integration of Distributed Energy Resources- The CERTS Microgrid Concept," http://certs.lbl.gov/pdf/LBNL_50 829.pdf, 2008

[3] R. Firestone and C. Marnay, "Energy Manager Design for Microgrid," Consortium for Electric reliability Technology Solutions, http://repositories.cdlib.org/lbnl/LBNL-54447, 2005

[4] Z. Zhang, Modeling, Analysis, and Control of a PEM Fuel Cell Based Micro-Grid Power System, Ph. D. Dissertation, Dept. ECE. Univ. Western Ontario, 2007

[5] Nexa^{TM} (310-0027) Power Module User's Manual, Ballard Power Systems Inc., 2003

IV. Design and Implementation of the Microgrid Control and Operation System

The physical implementation of the microgrid control and operation system is divided into two main sections: the software unit and the hardware unit. The block diagram shown in Fig. 4.1, demonstrates the signal flow within the subdivisions of these two main sections. The AC current and voltage transformers (CT & VT) convert the high level current and voltage to the electrical digital signal level (±10V DC), which can be safely measured by data acquisition (DAQ) devices. The input DAQs sample the analog input signals from CTs and VTs and convert them into the digital form. The sampled V and I, in digital form, are used by the DG controllers to execute the desired control. They are also sent to the power calculation unit for monitoring and data logging purposes. In this thesis, NI 9215 analog input DAQ, with simultaneous sampling capability, is selected in order [1] to meet the design specification in Table 3.1. In the meantime, output DAQs (NI 9201) are used to convert the control output to analog signal and send to the corresponding DG control actuators. This chapter focuses on the physical implementation of the control system of the prototype microgrid. The operation interface of the system, as well as detailed programming and calculation methodologies, are both presented in this section.

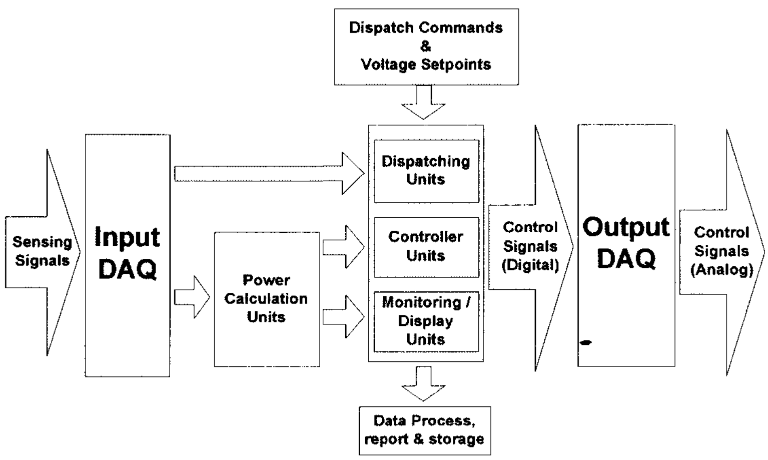


Fig.4.1. Block diagram of hardware and software composition of the control and operation system

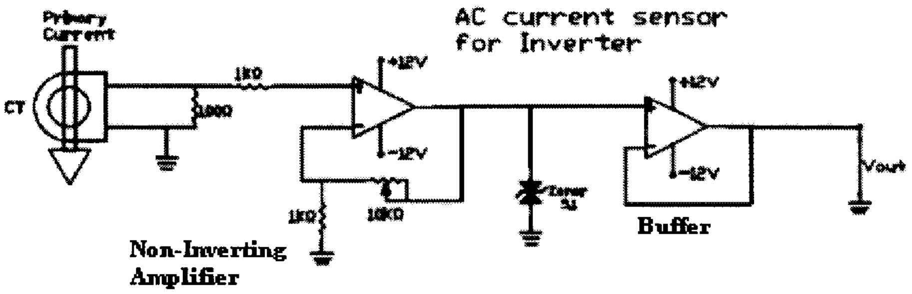
4.1 Hardware Sensing Circuits Design and Implementation

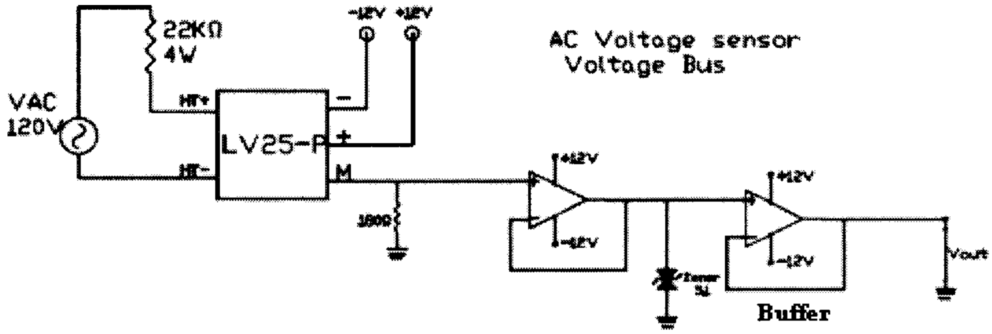
Table 4.1 lists the specifications of the selected CTs and VTs for the sensing circuits. These transformers are designed specifically for metering, as well as analog-to-digital circuits with galvanic isolation between the primary circuits and the secondary circuits. The designs of the sensing circuits are illustrated in Table 4.2. The selection of the current and voltage sensors and the design of the sensing circuitries are both meant to satisfy the design specification indicated in Table 3.1.

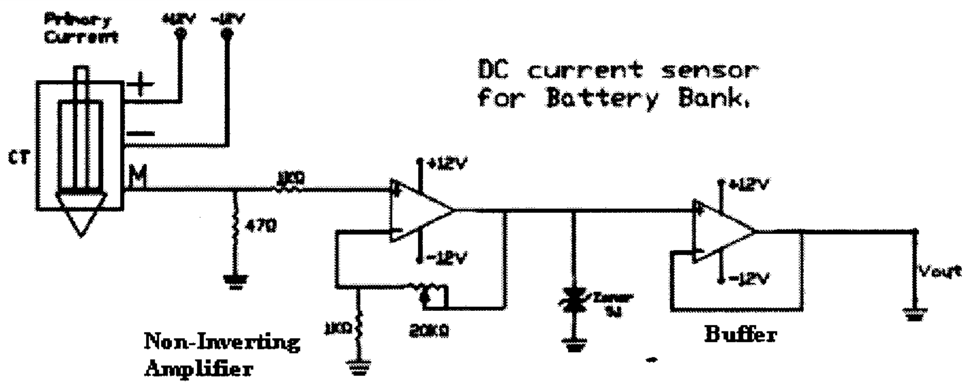
Table 4.1. Summary of current transformers and voltage transformers in use

Description	Input	Nominal Input	Conversion Ratio	Measuring Location	Item / Manufacture
Current Transformer	AC current	5A AC	1000:1	DGs AC output terminals	AC1005 / Talema
Current Transformer	DC current	50A DC	2000:1	Battery, fuel cell output	LA 100-P / LEM
Voltage Transformer	AC voltage	120V AC	2500:1000	DGs AC output terminals	LV 25-P / LEM
Voltage Transformer	DC voltage	26V DC	2500:1000	Battery, fuel cell output	LV 25-P / LEM

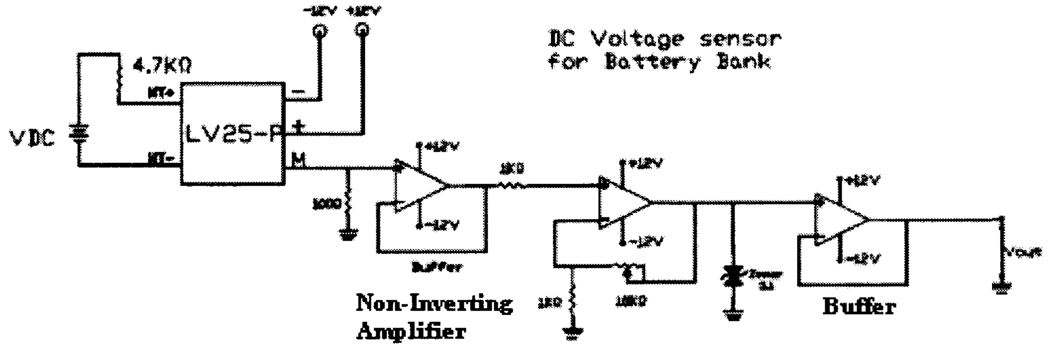
Table 4.2. The diagrams of the sensing circuits

<table>
<tr><th>Name</th><th>Hardware Design of the Sensing Circuits</th></tr>
<tr><td>AC Current Sensor</td><td>


- Primary AC current (5 A nominal) is converted into AC voltage (low level) by the current transformer
- Low level AC voltage is amplified by the non-inverting amplifier
- Buffer is used to increase the input impedance
</td></tr>
<tr><td>AC Voltage Sensor</td><td>


- Primary AC voltage (120 V nominal) is converted into AC voltage (low level) by the voltage sensor
- Buffer is used to increase the input impedance
</td></tr>
<tr><td>DC Current Sensor</td><td>


- Primary DC current (50 A nominal) is converted into DC voltage (low level) by the current transformer
- Low level AC voltage is amplified by the non-inverting amplifier
- Buffer is used to increase the input impedance
</td></tr>
</table>

Name	Hardware Design of the Sensing Circuits
DC Voltage Sensor	 • Primary DC voltage (26 V nominal) is converted into DC voltage (low level) by the voltage sensor. • Low level DC voltage is amplified by the non-inverting amplifier • Buffer is used to increase the input impedance

The output signals generated by CTs and VTs are all floating (non-referenced), and the referenced single-end (RSE) mode is used, as shown in Fig. 4.2 [2]. The RSE configuration also doubles the available measuring channels by sharing the common reference source, which provides the possibility of expanding the system with lower investment.

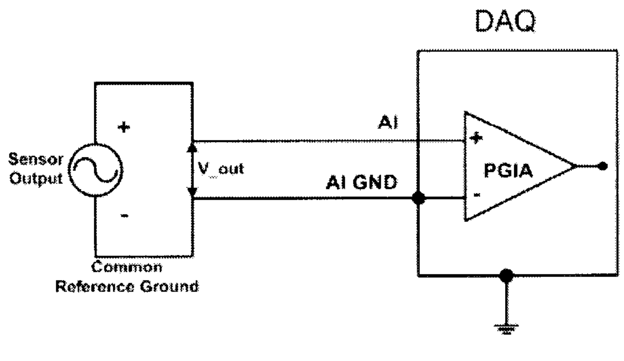


Fig.4.2. Referenced single-end (RSE) input configuration

4.2 Software Design and Implementation

4.2.1 Power Calculation Unit

Since the current and voltage measured by the DAQ boards are both in AC form, they are executed by the software and converted into system monitoring information by the power calculation unit. The real-time information includes the active and reactive power generated from each DG unit, the system frequency, the bus voltage level, and the system power factor. The instantaneous DC power output from the fuel cell module is also monitored. The equations used in power calculation and in the sub Virtual Instrument (subVI) block diagram (of the power calculation unit in LabVIEW) are given in Appendix A. As shown in Fig. 4.3, this subVI is commonly applied for the measurement of all the DGs and the load in the main program. In the future, any additional generator may use the same program for the power measurement. The results of active power (P), reactive power (Q), phase angle (θ), and power factor (*pf*) are connected to the front panel, and the corresponding information is sent to the monitoring graphical user interface (GUI) with appropriate scaling factors.

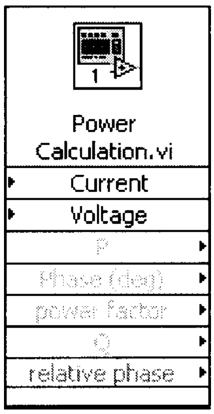


Fig.4.3. subVI of the power calculation unit in LabVIEW

4.2.2 Graphical User Interface

The developed GUI consists of display windows used to demonstrate the waveforms of data sent from the power calculation unit, as shown in Fig. 4.4. For example, in order to obtain the dynamic responses of the microgrid, the instantaneous power (P&Q) output from the fuel cell power module and two synchronous generators are constantly monitored, as are the load condition of the load sharing analysis. The AC bus voltage and the frequency displays are set in bold. On the DC side, the operating status of the inverter is also displayed. The efficiency of the inverter is obtained by comparing the AC power output of the device with the DC power input. Even though this thesis does not carry out the analysis on the characteristics of the battery, the option is available on the GUI, which observes and records the value and the direction of the DC current from the battery during transients. One of the advantages of the LabVIEW based GUI is the option of recording the necessary data for further analysis. The collected data is further used in the investigation in Chapter 5, Chapter 6, and Chapter 7 with either Excel or Matlab tools.

Two individual control units are developed in LabVIEW for the control of the synchronous generators and the inverter interfaced PEMFC unit, as shown in Fig. 4.5 (a) and (b), respectively. The excitation voltage of the synchronous generators and the input power of the DC motors (prime movers) are controlled by open-loop controllers. An emergency stop button is also designed for the synchronous generators, which is able to shut down remotely during an emergency. A detailed discussion of the inverter control unit will be presented in Chapter 5. So far, in the current experiment setup, the whole system is integrated in a single computer, but the control and operation scheme still represents the hierarchical management structure discussed in Chapter 3.

The overall configuration of the control and operation system is illustrated in Appendix B, including a list of sensors used for the system implementation. The final laboratory setup of the prototype microgrid with the proposed control and operation center is shown in Fig. 4.6. The fuel cell and synchronous generators are scattered around the load center, and they are connected at a 120V AC bus. The control and operation center is positioned in a remote location, where it monitors the operation of the overall microgrid.

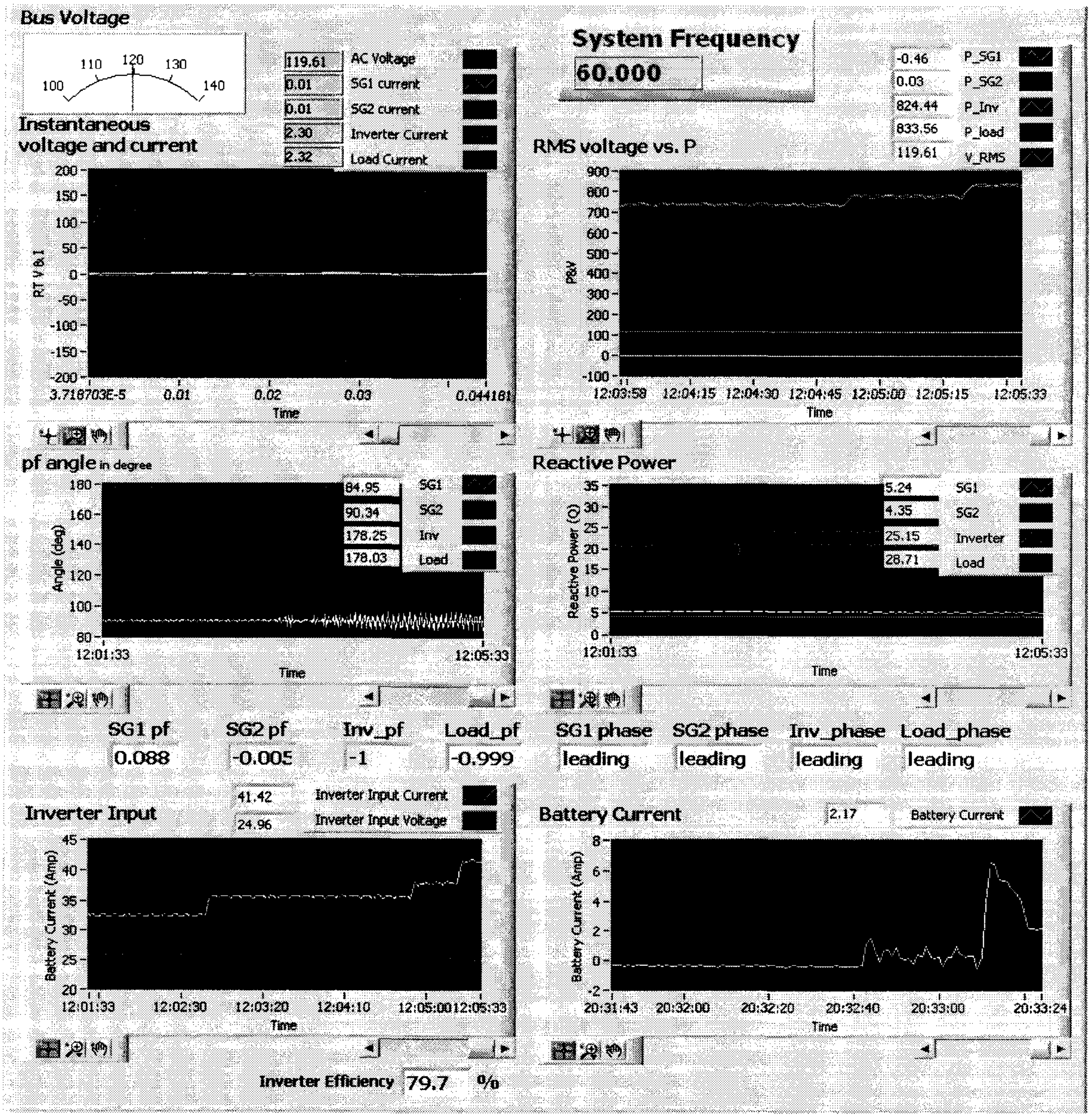
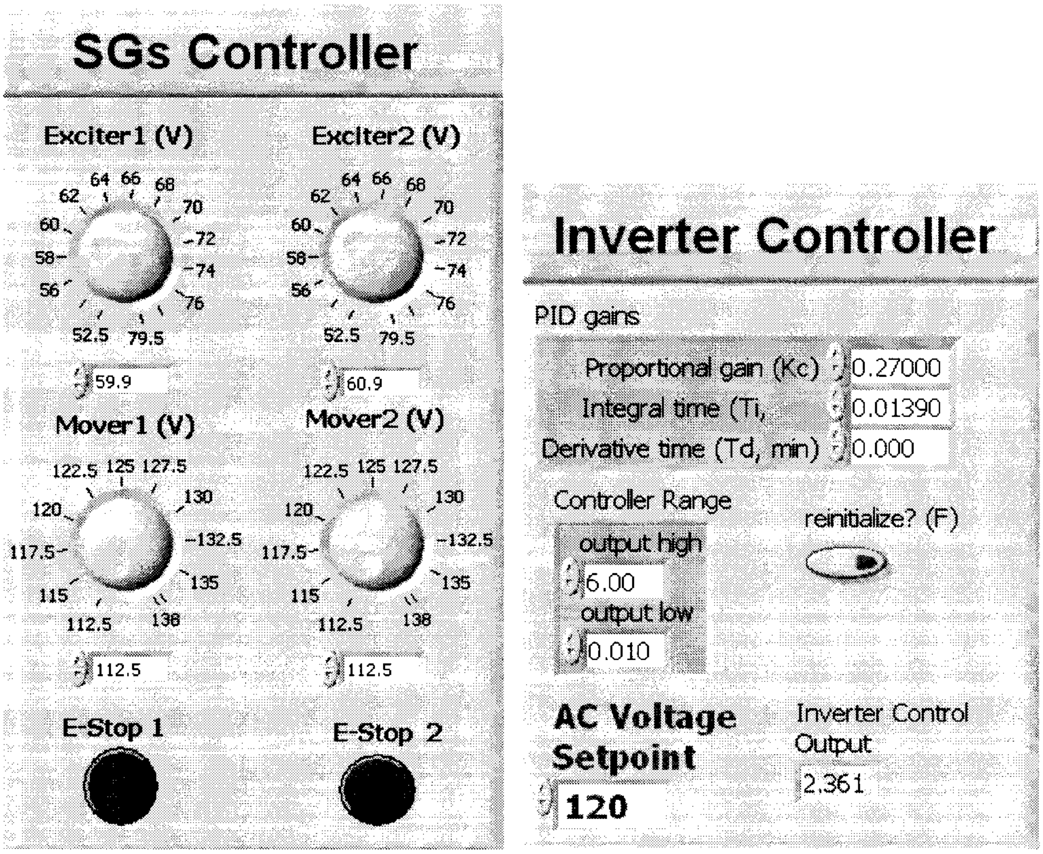


Fig.4.4. The front panel of the monitoring interface of the microgrid control system



(a) (b)

Fig.4.5. The control interface of (a) SG1 and SG2; (b) fuel cell powered inverter

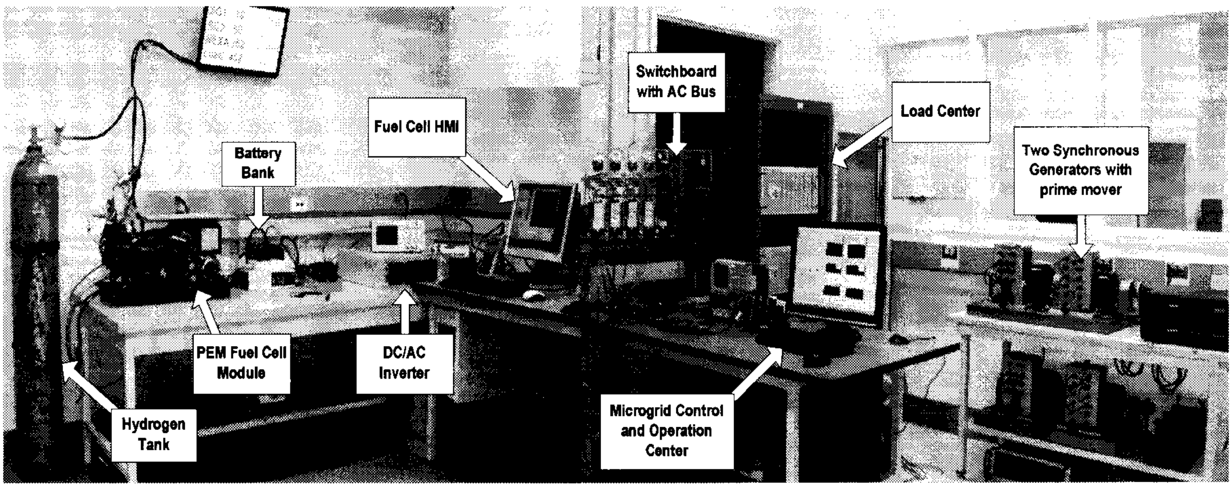


Fig.4.6. Prototype microgrid with the control center

4.3 Summary

In this chapter, the design and development of the microgrid control and operation systems are presented in detail. The design of the hardware circuits for the voltage and current sensors is clearly illustrated, and the specifications of the sensors in used are summarized. The selected DAQ board features simultaneous sampling capability, which enhances the performance of the computer program by eliminating the time delay between sampling channels.

The design of the software units using LabVIEW emphasizes the power calculation unit and the graphical user interface. The variables such as active and reactive power, power factor/angle, system frequency and bus voltage, as well as the operating status of the inverter are all collected and monitored in real-time by the developed graphical user interface. These data can be recorded in a computer and future processed in Excel or Matlab. The laboratory setup of the prototype microgrid with the control center is demonstrated in this chapter.

4.4 References

[1] NI CompacDAQ 9215 Operating Instruction and Specifications, http://digital.ni.com/manuals.nsf/websearch/5F2E9640C1CFE645862573AF007ABAD9, 2008

[2] J. R. Barnes, Electronic System Design: Interference and Noise Control Techniques, New Jersey: Prentice-Hall, Inc., 1987

V. Experimental Investigation of the Inverter Interfaced PEMFC and the Synchronous Generators

In order to make proper operational decisions for a microgrid, the dynamic characteristics of distributed resources must be known. The theoretical analysis and the mathematical modeling of the PEMFC power module and the synchronous generators used in this thesis have been carried out in [1]. However, previous work only considered the steady-state characteristics of the inverter interfaced PEMFC. The dynamic voltage and frequency characteristics associated with the inverter and the two synchronous generators are investigated in this chapter. Furthermore, the DC to AC conversion efficiency of the inverter is also analyzed in order to assist in the development of dispatch strategies in Chapter 7. The microgrid control and operation system in LabVIEW is used as an instrumentation in monitoring the voltage and the frequency response, as well as the efficiency of the inverter in real-time.

5.1 Voltage and Frequency Characteristics of the Inverter Interfaced PEMFC

The majority of the power electronic inverters employ a similar two-stage inverting concept [2]. First, a low voltage DC power from an energy source is converted into an intermediate stage, where the voltage level is boosted-up to be equal or higher than that of the desired AC voltage. During the second stage, this intermediate DC voltage is inverted into an AC form via an inverter. The AC power has to pass through an extensive filtering process in order to become to a clean sinusoidal waveform. The AC voltage is controlled by a pulse width-modulation (PWM) scheme, while the frequency is maintained by an internal crystal stabilizer. In this prototype microgrid, the three-phase power inverter, CTP1500, boosts-up the 26 V DC input voltage from the PEMFC power module to 170 V DC. This high DC voltage is then inverted into a three-phase sinusoidal voltage with the frequency of 60 Hz. At the no load condition, the nominal AC output voltage of the inverter is 120 Vrms. A voltage control actuator is available in order to adjust the output voltage level externally.

The capacity of the PEMFC module is rated at 1.2 kW, with a nominal output voltage of 26 V DC. Due to power de-rating factor [3], the actual capacity of the fuel cell unit is around 1100 W (net). The storage loss and aging effect further reduce the overall capacity of the fuel cell unit. It is reasonable to consider the capacity of the PEMFC module to be around 1 kW at 26 V DC. In addition, the electronic power conversion devices in the inverter consume energy in order to maintain operating condition. The actual maximum power output of the inverter with the energy supplied by the PEMFC module is approximately 900 W.

Moreover, the DC/AC inverter is an energy conversion device but not an energy source. Its characteristics depend on the internal power electronics, as well as its energy supply. This means that the characteristics of the inverter used in this study are influenced by the output from the PEMFC power module. To investigate the characteristics of the inverter, experiments are conducted for the PEMFC powered inverter in stand-alone operating mode.

5.1.1 Inverter without External Voltage Controller

Fig. 5.1 shows the dynamic response of the phase voltage of the inverter to the load changes. When the inverter interfaced PEMFC power module operates in a stand-alone mode, the output voltage of the inverter does not remain constant as the load varies. As the load demand increases from 0 W to 800 W, the voltage drops from its nominal 120 Vrms to 112.5 Vrms; if the enforced voltage variation of the system is between 114 Vrms and 126 Vrms (120 Vrms ± 5%), the output voltage of the inverter can drift outside the acceptable limit as the load continues to increases. It can be better observed in Fig. 5.2, which depicts the "load vs. voltage" characteristics of the PEMFC powered inverter in steady-state. When the load demand is less than 500 W, the output voltage level of the inverter is above 114 Vrms. However, as the load increases beyond 500 W, the terminal voltage starts to drop below 114 Vrms. As the load exceeds 800 W, the output voltage of the inverter collapses. In contrast, the frequency of the inverter always remains constant at 60 Hz, regardless of any change in the load, as shown in Fig. 5.3.

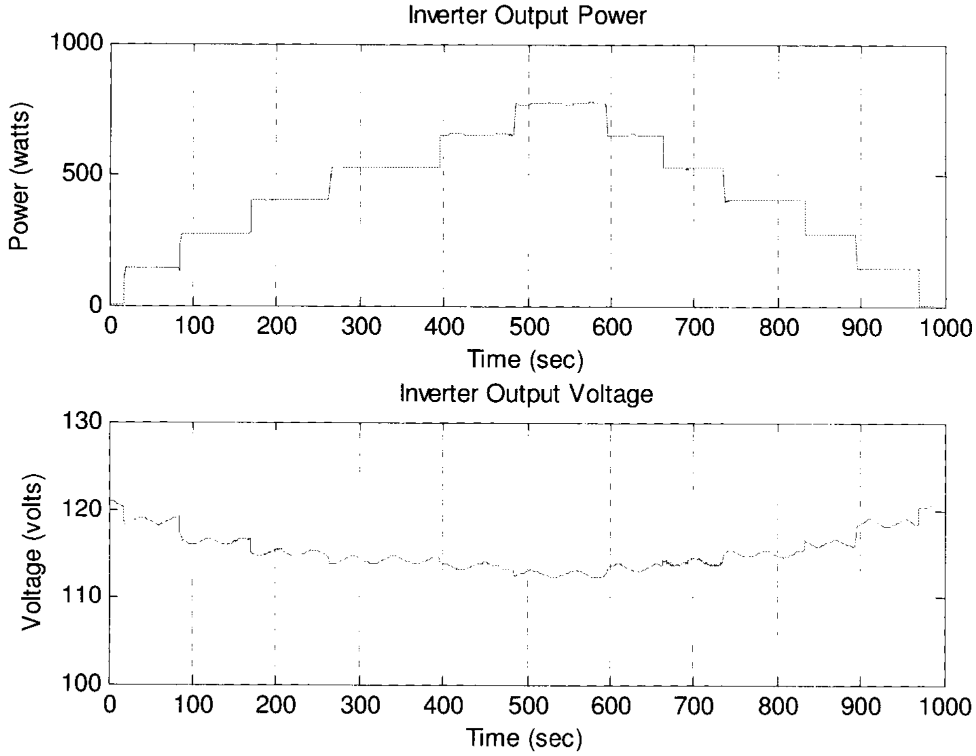


Fig.5.1. Output power vs. output voltage of the inverter

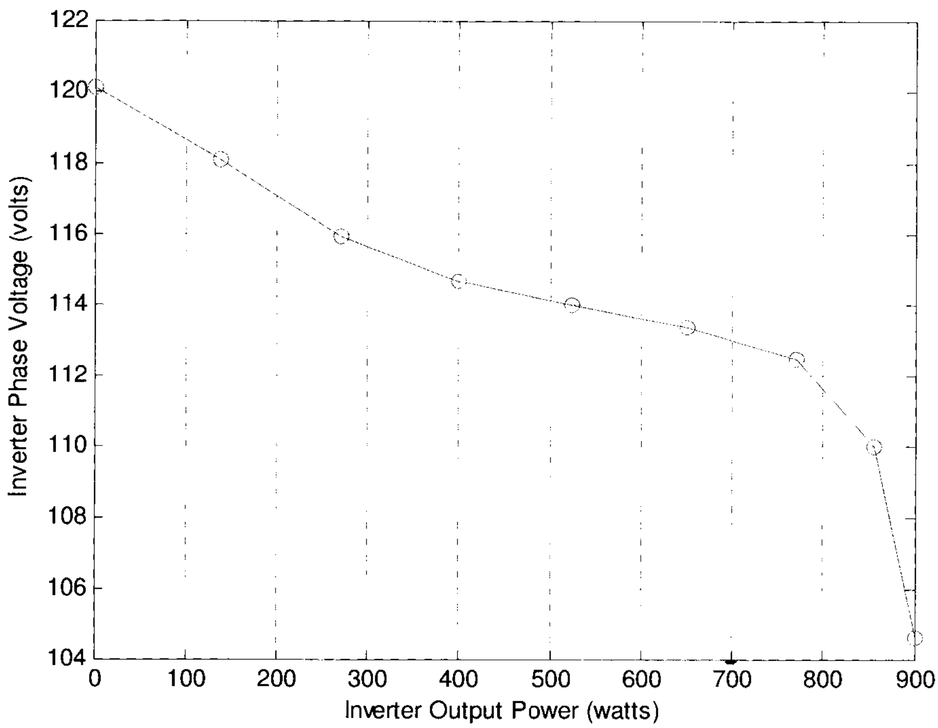


Fig.5.2. The load-voltage characteristics of the inverter at steady-state

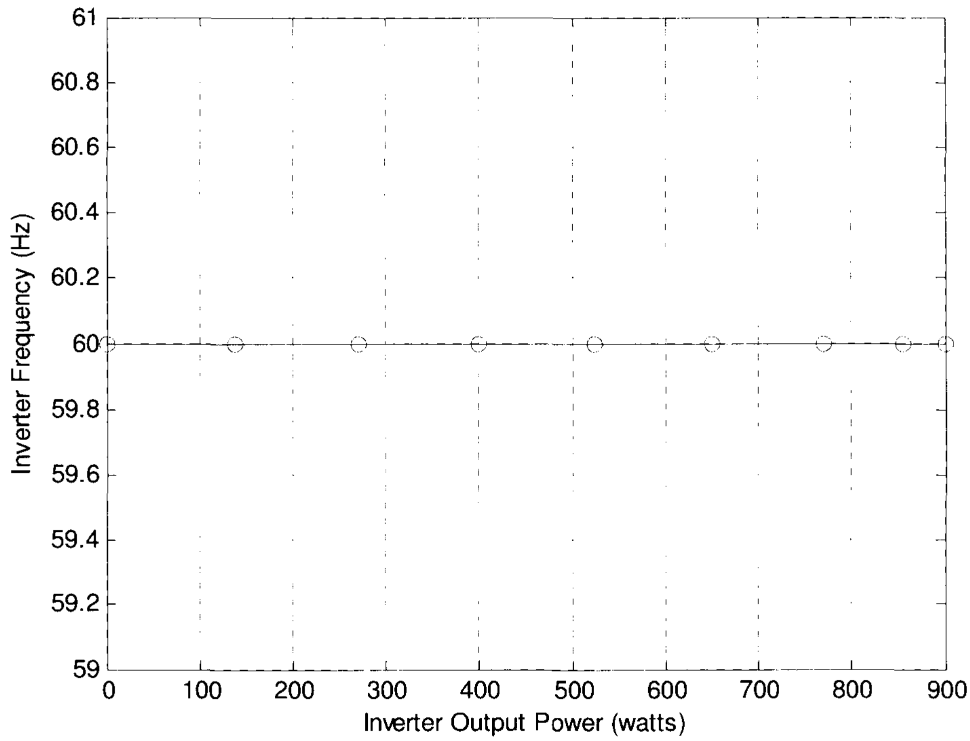


Fig.5.3. Frequency of the inverter output voltage at different power output

5.1.2 Inverter with Open-Loop Voltage Regulation

The phase voltage of the inverter can be adjusted by providing constant compensation to the voltage control actuator of the inverter. For this experiment, an external 0-10 V DC voltage supply is used to regulate the inverter output voltage, as shown in Fig. 5.4. This is essentially an open-loop voltage regulation of the inverter under different load conditions.

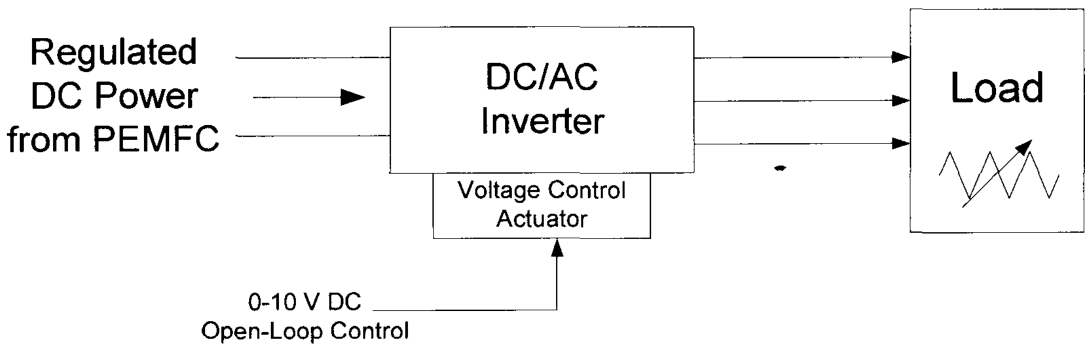


Fig.5.4. The experimental setup for inverter open-loop voltage regulation

The voltage vs. power output of the inverter interfaced PEMFC unit under different no-load voltage setpoints at steady-state is demonstrated in Fig. 5.5. When the DC regulation voltage is set at 0 V, 2 V, 4 V, and 6 V, the RMS voltage of 120.5 V, 124.5 V, 128.5 V, and 132.5 V (in no-load condition) can be obtained. It is observed that the terminal voltage of the inverter decreases with the increase of the active power output. The output power and the phase voltage exhibit clear drooping characteristics. The slopes of the droops are practically constant for the inverter with different no-load setpoints. When the power output increases from no-load to full-load, the voltage of the inverter will decline from its initial level to 110 Vrms.

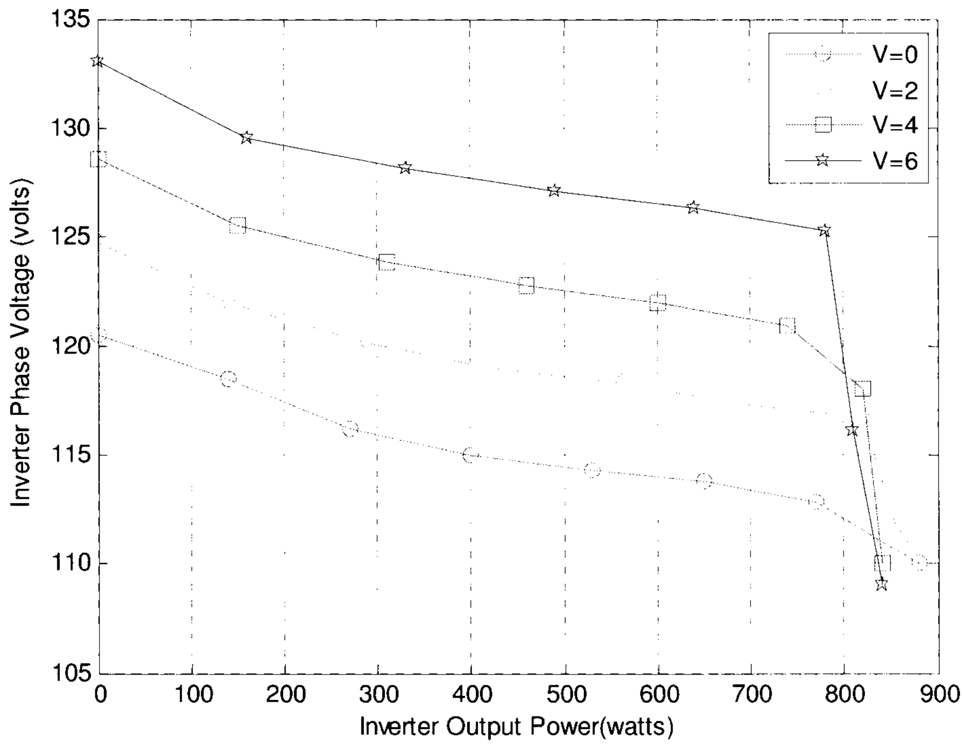


Fig.5.5. Load-voltage characteristics of the inverter at different voltage setpoints (open-loop control)

As indicated in Fig. 5.5, the slopes of the four voltage droops at different voltage setpoints are nearly constant. This means that the terminal voltage with different setpoints will drop at the same ratio as the load increases. When the output of the inverter is slightly beyond 800 W, the terminal voltage will drop below 116 V, regardless of the compensation. Consequently, any further increase of the voltage setpoint will not bring the output voltage of the inverter back to the nominal 120 Vrms. When the inverter power output is beyond 850 W, the terminal voltage will drop to 110 Vrms. Therefore, it can be concluded that as the load demand increases beyond what the fuel cell can provide, the phase voltage will not sustain the same linear drooping relationship with the load.

5.2 DC to AC Conversion Efficiency of the Inverter

The internal power consumption of the inverter can be calculated in Eq. (5.1):

$$\begin{aligned} \text{Inverter Power Consumption} = {} & \text{Inverter Power Input}_{(DC)} \\ & - \text{Inverter Power Output}_{(AC)} \end{aligned} \tag{5.1}$$

The DC to AC conversion efficiency of the inverter can be expressed in Eq. (5.2):

$$\text{Inverter Conversion Efficiency} = \frac{\text{Inverter Power Output}_{(AC)}}{\text{Inverter Power Input}_{(DC)}} \times 100\% \tag{5.2}$$

The conversion efficiency of the inverter with respect to the power output is demonstrated in Fig. 5.6. It is observed that the efficiency level is relatively low at the light load compared to the condition during heavy load demand. During low power output, the inverter effectively transfers about 60 percent of its DC power input into AC form. This efficiency improves as the load increases. As the load demand approaches to the rated capacity of the PEMFC module, the efficiency of the inverter reaches about 80 percent; this is shown in Fig. 5.6. This is because the electricity consumption of the internal electronic devices of the inverter is not a constant value with respect to the change in the instantaneous power output. Therefore, at a lower output level, the internal energy loss is considerably higher than it is at a higher output level.

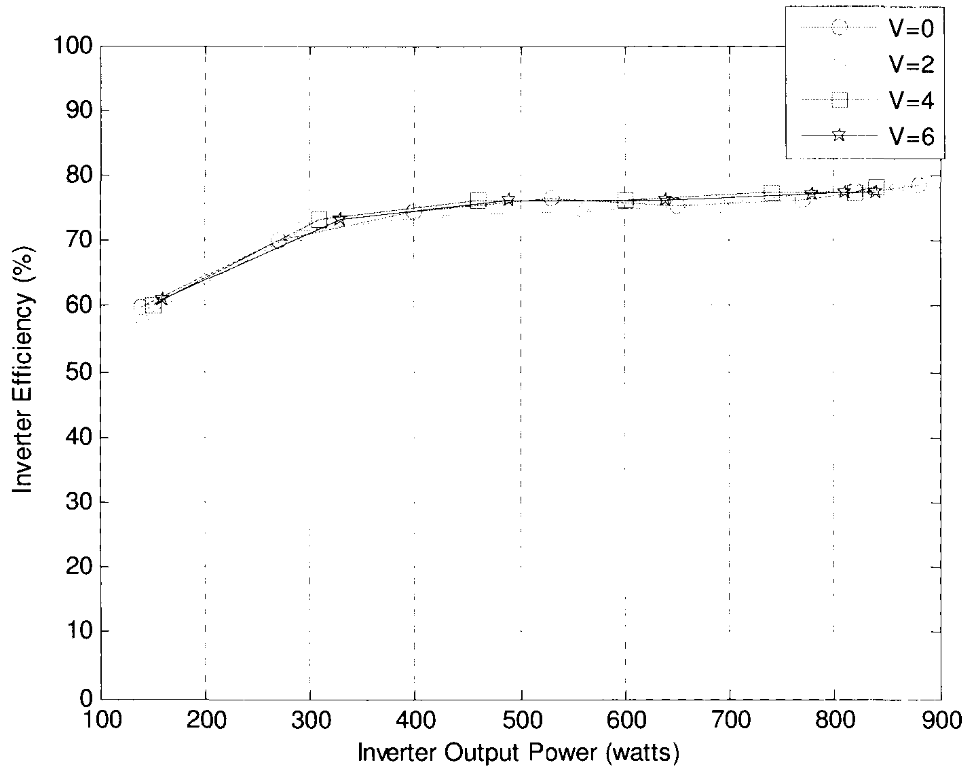


Fig.5.6. The conversion efficiency of the inverter at different voltage setpoints

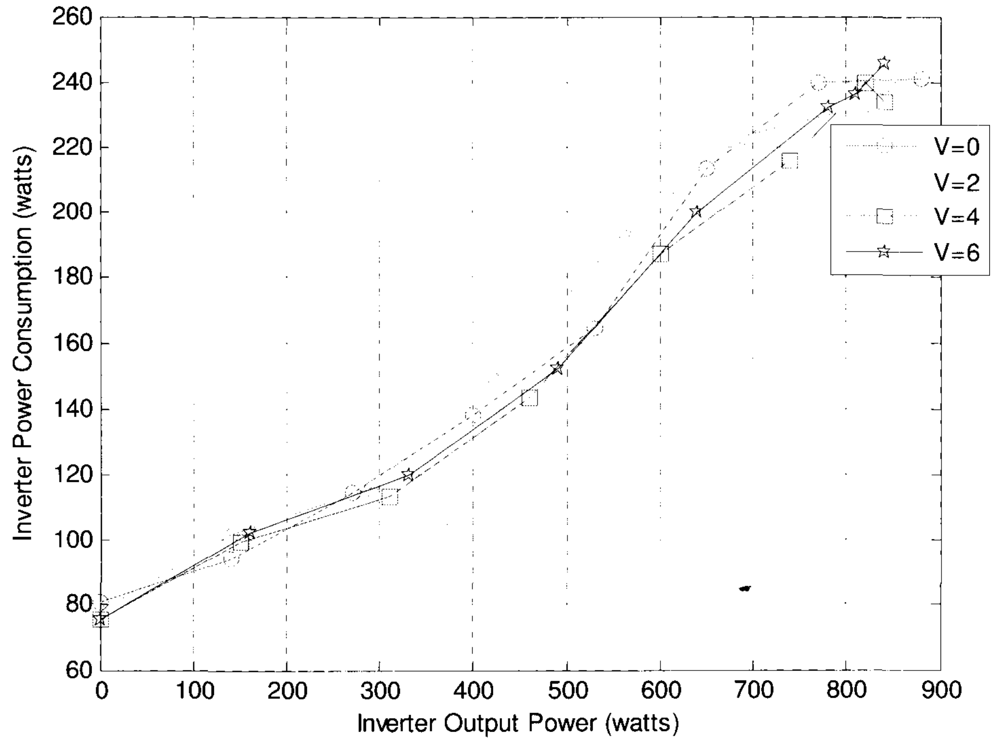


Fig.5.7. Internal power consumption vs. power output

The power consumption of the inverter, at different AC outputs, is shown in Fig. 5.7. When thc fuel cell is used to supply the inverter, the overall generation capacity is reduced to 900 W, neglecting the power consumption of the DC/DC converter. Under this condition, the inverter consumes a total of 250 W. Therefore, it is reasonable to claim that the output capacity of the overall inverter interfaced PEMFC module is close to 850W. The terminal voltage controller will not be effective when the power demand on the inverter is beyond this value. Fig. 5.6 and Fig 5.7 also indicate that the energy conversion of the inverter is independent of its actual voltage setpoint, and it can only be affected by the power output. Table 5.1 summarizes the DC to AC conversion efficiency of the inverter at specific load conditions. For the output power below 100 W, the efficiency of the inverter is expected to be lower than 60 percent.

Table 5.1. DC to AC conversion efficiency of the inverter

DC Input (W)	AC Output (W)	Power Consumption (W)	Efficiency (%)
75	0	75	0
250	150	100	60.0
450	330	120	73.3
600	460	140	76.7
750	560	190	74.7
900	676	224	75.1
1050	820	230	78.1
1100	860	240	78.2

5.3 Voltage and Frequency Characteristics of the Synchronous Generators

In addition to the investigation of the inverter interfaced PEMFC, experiments are carried out in order to examine the load-voltage and load-frequency characteristics of the synchronous generators. It has been concluded that for a single synchronous generator in stand-alone mode, both the frequency and the output voltage are functions of the active power output of the generator [1]. As the output power increases, the frequency and the voltage will decline and establish a linear drooping characteristic. In this thesis, the dynamic response of the bus voltage and the frequency are investigated for two synchronous generators (SG1 and SG2) in parallel. The power output characteristics of these synchronous generators, with respect to load variations, are demonstrated in Fig. 5.8. The AC bus voltage and the frequency response are shown in Fig. 5.9. In this experiment, the initial bus voltage is set at 120 Vrms. When multiple generators with similar internal electric parameters are operating in parallel, each generator shares approximately an equal proportion of the load change. For this reason, the load sharing characteristics of both generators are very similar. Moreover, it is observed that the load change affects not only the bus voltage, but also the frequency. In other words, if the voltage tolerance of this system is confined within ±5% of the nominal voltage (120 V), the synchronous generators would not be able to sustain the voltage within the acceptable range without using a governor mechanism.

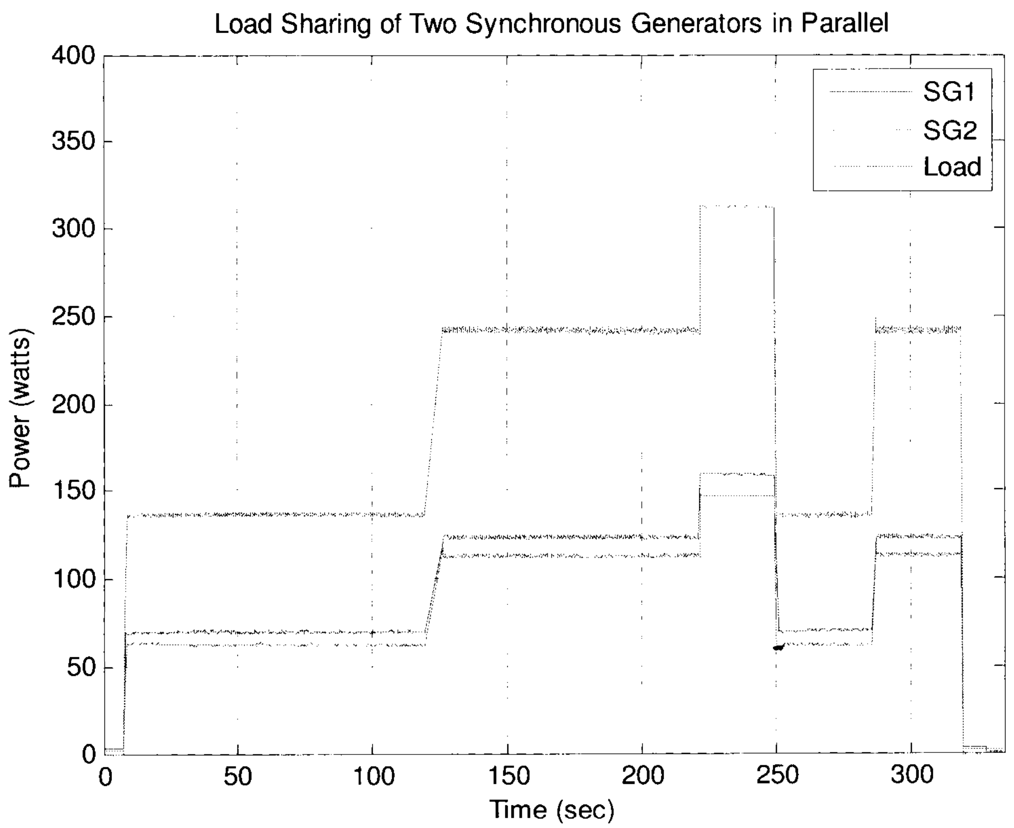


Fig.5.8. Power output of the two synchronous generators with respect to load variations

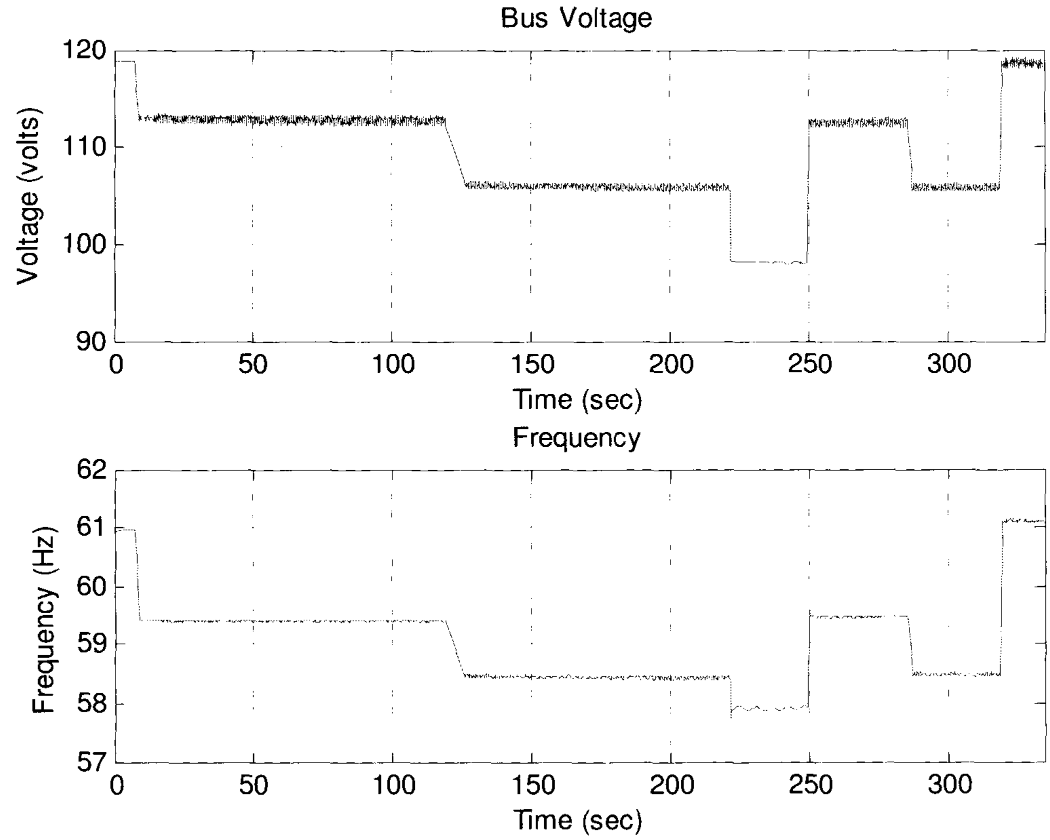


Fig.5.9. Bus voltage and frequency response of the two synchronous generators in parallel

5.4 Summary

Using the LabVIEW based microgrid control and operation interface, both the dynamic characteristics of the AC output voltage and frequency of the inverter interfaced PEMFC power module are examined. The results show that the output frequency of the inverter is fixed at a constant level of 60 Hz by its internal control loop. It is also observed that the output voltage of the inverter decreases with the increase in load demands. By applying open-loop voltage regulation, it is observed that the inverter output voltage has similar drooping characteristics at different voltage setpoints; the slopes of the droops are equal. This fact is applied to the development of the load sharing scheme in Chapter 6.

In addition, tests are conducted to analyze the DC to AC conversion efficiency of the inverter under different power outputs. The results are then used to determine the optimal operating point for the inverter. It is demonstrated that the efficiency of the inverter increases as the power output increases. The efficiency can reach about 80 percent at the highest level when the output power approaches to the generation capacity of the PEMFC. Therefore, the inverter is preferred to operate at a higher power output level in order to fully utilize the PEMFC power module. This conclusion is applied in Chapter 7 in the study of economic dispatch strategies.

Furthermore, the experiments are conducted in order to examine the dynamic characteristic of the synchronous generators. The research addresses the bus voltage and the frequency response, as well as the load sharing characterises of the two synchronous generators in parallel. The results are applied to the development of the load sharing schemes in Chapter 6.

5.5 References

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VI. Dynamic Load Sharing of the Microgrid

Uninterrupted power supply in an islanded microgrid has become increasingly important, especially for the sensitive loads. To provide a continuous power supply, while enhancing the microgrid reliability, one possible approach is to couple multiple DG units in parallel to support the load demand. One of the technical challenges of this approach is how to distribute the load demand among distributed generators in a predetermined manner. Several load sharing methods have been developed in the conventional utility system. However, for a microgrid with power electronics interfaced distributed resources, the load sharing schemes used in the conventional system may not be applicable. In this chapter, load sharing schemes in conventional power systems are introduced first. For the inverter interfaced DGs, the dynamic load sharing scheme using load-voltage droops is discussed [1]. Furthermore, this scheme is established experimentally for the prototype microgrid. A feedback voltage regulator is used for the inverter interfaced PEMFC to achieve dynamic load sharing.

6.1 Load Sharing in Conventional Power Systems

The conventional approach used for the load sharing control of multiple generators in parallel involves the definitions of the frequency droop and the voltage droop [2]. This approach does not require a dedicated communication link to coordinate the load sharing. To illustrate two load sharing schemes in the conventional approach, a simple example of two distributed generators (generator1 and generator2) operating in parallel is considered, as shown in Fig.6.1. The linear drooping relationship between the frequency and the active power output of the individual generator can be expressed in Eq. (6.1). The relationship between the output voltage and the reactive power output is expressed in Eq. (6.2). Two equations are schematically depicted in Fig. 6.2 (a) and Fig. 6.2 (b), respectively. In these equations, Δf and ΔP represent the changes in frequency and active power output; ΔV and ΔQ represent the changes in the output voltage and the reactive power output; K_f, K_V are the slopes of the frequency and voltage droop, respectively. For simplicity, the discussion of the load sharing schemes is emphasized on the active power distribution.

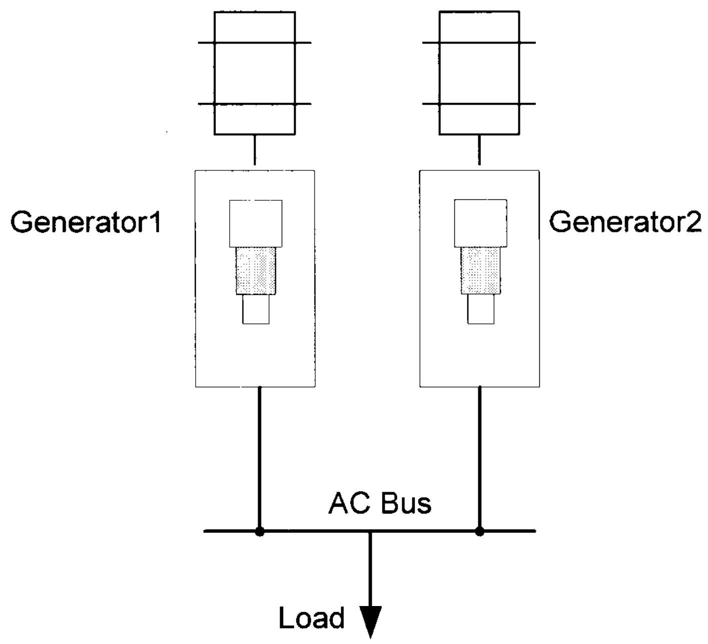

Fig.6.1. Two distributed generators operating in parallel

$$\Delta f = K_f \Delta P \tag{6.1}$$

$$\Delta V = K_V \Delta Q \tag{6.2}$$

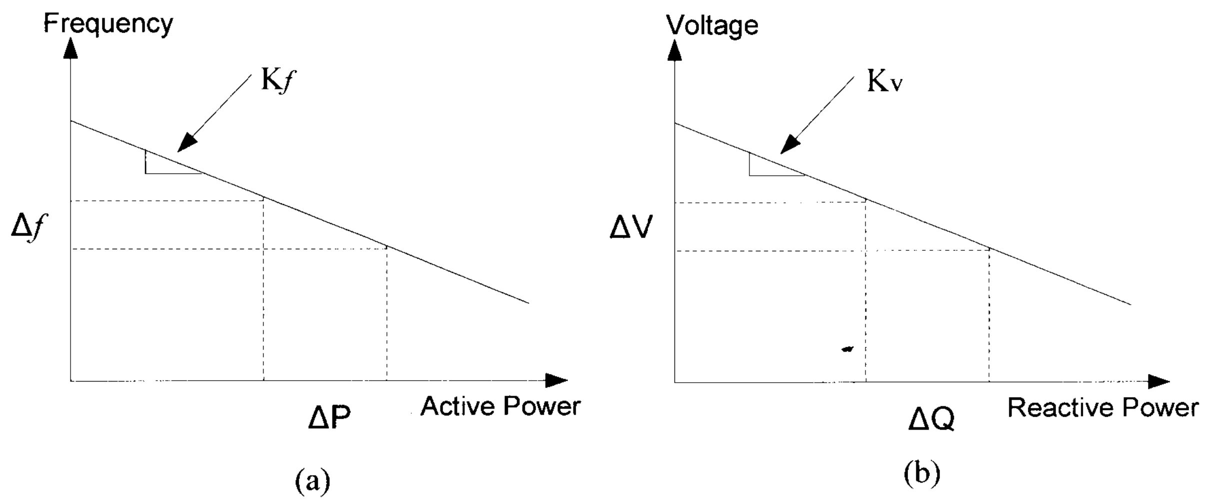

Fig.6.2. (a) Frequency droop and (b) Voltage droop

6.1.1 Static Load Sharing Scheme

The static load sharing scheme uses the frequency droop and the voltage droop of the generators to establish a linear load sharing strategy. This is done without dependence on any external communication links. This scheme relies on a change in the frequency of the load bus to determine the amount of active power that each generator should contribute. As shown in Fig. 6.3, when multiple generators are operating in parallel, the bus frequency f_N is projected to the frequency droops of both generators. The active power output (P1 and P2) is defined by the slopes of the droops (K_{f1} and K_{f2}), as well as the frequency-interception (f_0), as expressed in Eq. (6.3) and Eq. (6.4). There is always a unique frequency (f_N) when multiple generators with frequency droops are operating in parallel. In another words, K_f determines the change of the output power of a generator for a given change in frequency. The increase of the load is compensated by each generator with the output proportional to the slopes of individual droops.

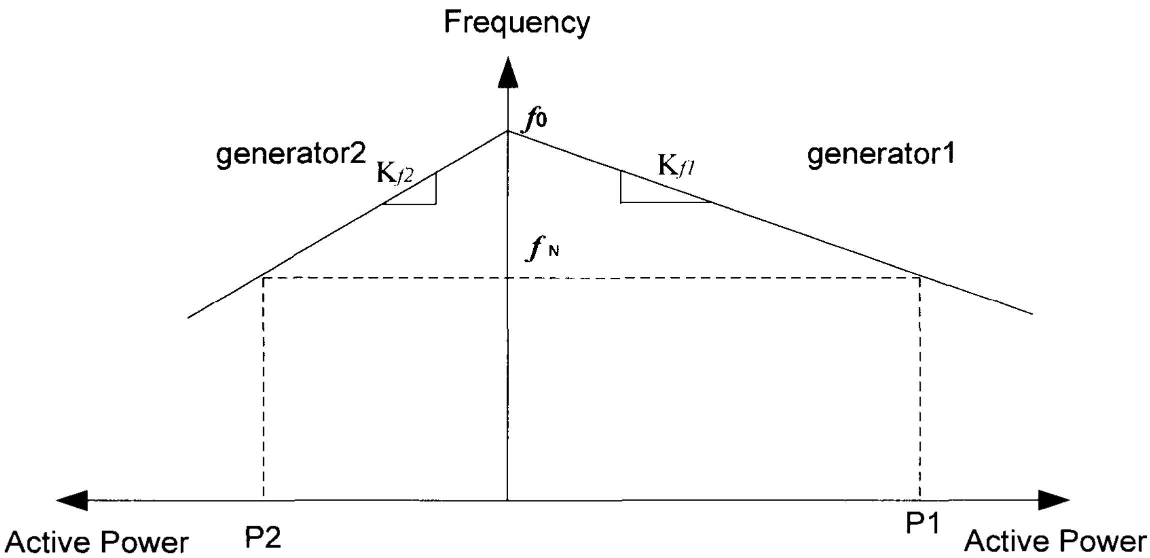

Fig.6.3. Static load sharing scheme for multiple generators operating in parallel

$$P1 = \frac{1}{K_{f1}}(f_0 - f_N) \tag{6.3}$$

$$P2 = \frac{1}{K_{f2}}(f_0 - f_N) \tag{6.4}$$

6.1.2 Dynamic Load Sharing Scheme

By employing the frequency droop into the static load sharing scheme, this scheme allows the dynamic adjustment of no-load setpoint (the vertical intersection) of the frequency droops, independently. This scheme is schematically demonstrated in Fig. 6.4. Assuming generator1 and generator2 are operating at the nominal frequency, f_N, when the load increases from P_{load} to P_{load}', the frequency on the AC bus will drop as it did in the static load sharing scheme. However, in this dynamic scheme, the frequency setpoint of a generator can be altered to bring the frequency back to f_N. In this case, generator1 will increase the setpoint from $f1$ to $f1$', and generator2 will change the setpoint from $f2$ to $f2$'.By adjusting their frequency setpoints, generator1 increases the power output from P1 to P1', and generator 2 increases the power output from P2 to P2', respectively. At this moment, the total power output from generator1 and generator2, (P1'+P2'), equal to P_{load}', and the bus frequency is restored to the nominal level, f_N. This equilibrium is maintained until the load demand changes again. This dynamic change of frequency droop offers the possibility of maintaining the system frequency at a steady level for any load condition. At the same time, the ratio of the load distribution of different generators can be altered or remained constant by adjusting their frequency setpoints accordingly.

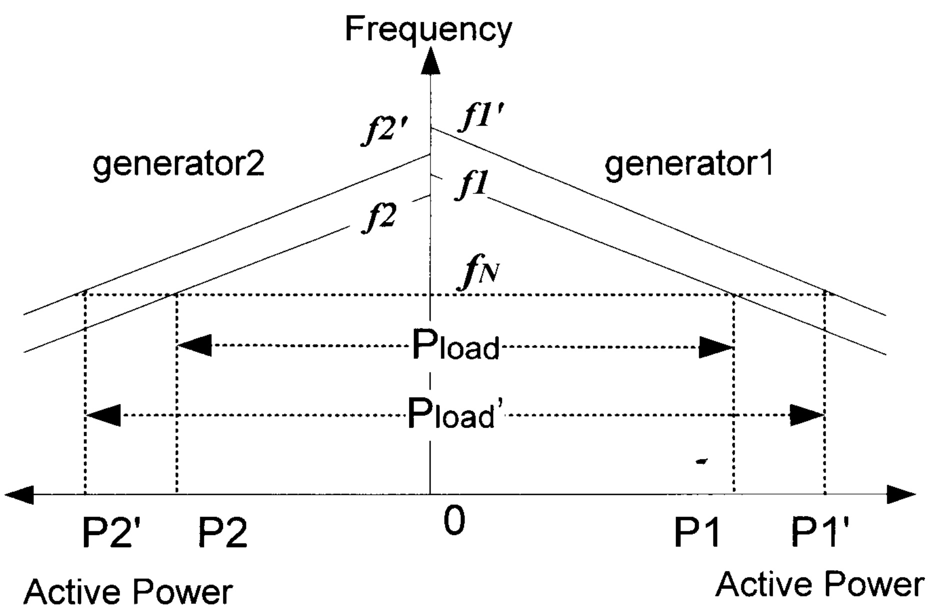

Fig.6.4. Dynamic load sharing scheme

One of the common features of the static and dynamic load sharing schemes is that they are fault tolerant, with respect to the failure of a generator. If any one of the generators fails, the scheme will allow automatic redistribution of the load to the remaining DGs, as long as the rest of the generators can handle the total load demand. However, these two schemes in conventional approaches may not be suitable for a microgrid with power electronics interfaced distributed resources. For example, unlike conventional generators, which frequency is directly related to the mechanical energy from the prime mover, the frequency of inverter interfaced DGs is PWM controlled. The frequency may not have the same drooping relationship with the output power, such as the inverter used in the prototype microgrid. This fact is explained in the following experiment.

6.2 Static Load Sharing of the Prototype Microgrid

The following experiment is conducted to demonstrate the static load sharing characteristics of the prototype microgrid. The inverter interfaced PEMFC unit and the two synchronous generators are connected in parallel. Depicted in Fig. 6.5, the PEMFC, with the dominant capacity, closely follows the change in load, and it supplies the majority of the power demand. Meanwhile, the output power of two synchronous generators also changes as the load changes. However, it is observed that the power contribution from these two generators is relatively small in comparison to that of the PEMFC power module. The proportion of the load sharing of different DGs is independent of their rated generation capacity.

In addition, the dynamic response of the AC bus voltage and the frequency with respect to load variations are illustrated in Fig. 6.6. By comparing this with the load profile, it is evident that when the microgrid adopts the static load sharing scheme, the bus voltage drops considerably as the load increases. When the load reaches 900 W, the bus voltage drops below 112 Vrms, which is not acceptable for the operation of the microgrid (120 Vrms ± 5%). In contrast, the frequency of the microgrid does not change, and it maintains at 60 Hz. This is because the dominant capacity of the inverter interfaced PEMFC pins the frequency when all the generators are synchronized together.

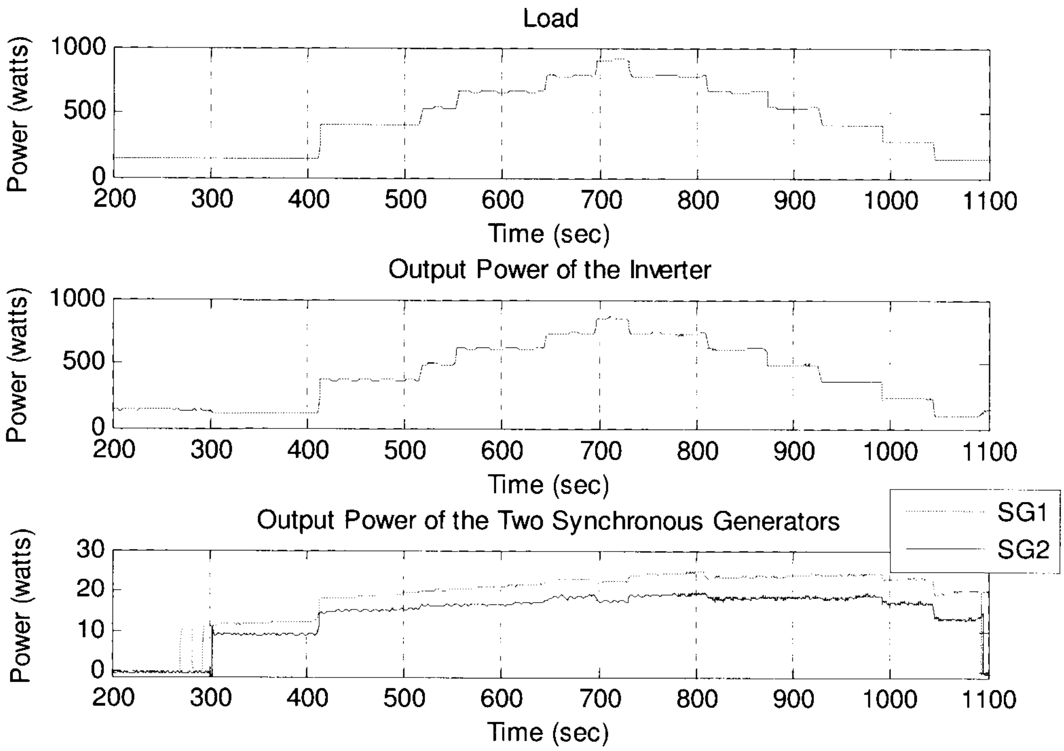

Fig.6.5. The load distribution among DGs of the prototype microgrid without voltage regulation

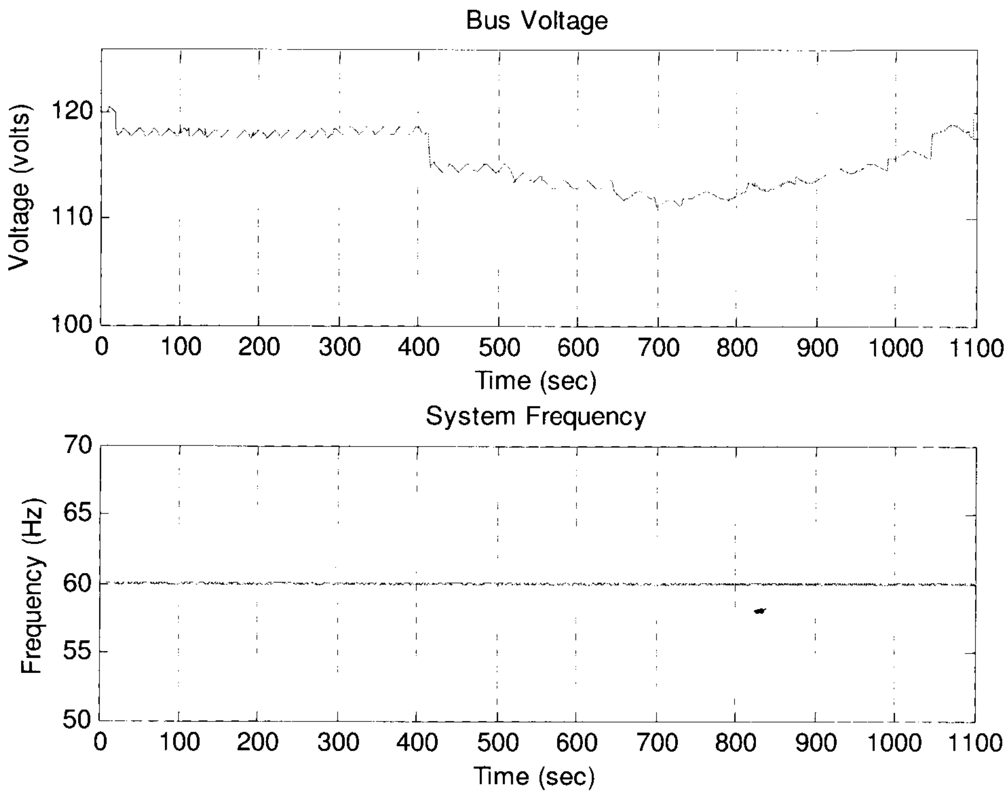

Fig.6.6. The bus voltage and the frequency response of the microgrid without voltage regulation

In this case, because the power output and the frequency of the generators in the microgrid do not establish a linear drooping characteristic as it does in the conventional system. One can no longer use the frequency droop for the active load sharing in such microgrids. Therefore, to alleviate the challenge of the active load sharing in a microgrid with fixed frequency, a novel load sharing scheme is proposed with the employment of the load-voltage droop [1].

6.3 Dynamic Load Sharing with Load-Voltage Droop

As proposed in [1], in order to achieve a proper load sharing in a microgrid with fixed frequency, one can adopt the voltage characteristics of the inverter with the similar drooping characteristics as the frequency droop. In the voltage droop scheme, the distributed generators communicate with the AC bus voltage instead of the frequency for the active load sharing. This scheme can be expressed in Eq. 6.5:

$$V' = V + K_V \Delta P \tag{6.5}$$

where V represents the initial voltage setpoint and V' is the adjusted voltage setpoint; ΔP and K_V are changes in the output active power, and load-voltage droop, respectively.

As depicted in Fig. 6.7, two distributed generators (DG1 and DG2) establish load-voltage drooping characteristics. In this case, only DG1 is equipped with the voltage regulator that can adjust the voltage setpoint dynamically. The bus voltage of this microgrid is initially maintained at V_N. V_1 and V_2 are the initial voltage setpoints of DG1 and DG2. As the active load changes from initial value, P_{load}, to P_{load}' ($\Delta P = P_{load}' - P_{load}$), the terminal voltage of both DG1 and DG2 will decrease until it reaches another balanced level. If the voltage level is beyond the enforced range of tolerance, one or both generators will adjust their voltage setpoints to bring the bus voltage back. In this case, DG1 will increase its voltage setpoint from V_1 to V_1', so that the bus voltage is stored to the nominal level, V_N. At this moment, the increase in the load, ΔP, is entirely compensated by the output of DG1. The balanced bus voltage V_N is maintained between DG1 and DG2. The load sharing is achieved by using different droops of DG1 and DG2.

If DG2 is equipped with a dynamic voltage setpoint controller, the balanced bus voltage can also be achieved by adjusting the voltage setpoints of both generators. Using this method, a predefined percentage of the contribution of each generator can be preserved without compromising the level of the bus voltage.

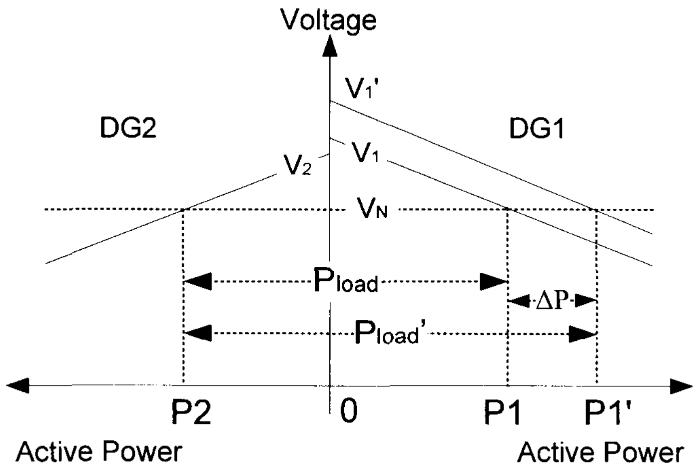

Fig.6.7. Dynamic load sharing scheme with load-voltage droop

6.4 Feedback Voltage Regulation of the Inverter Interfaced PEMFC

In order to achieve the dynamic adjustment of the voltage setpoint of a DG and maintain the bus voltage at a constant level, a feedback voltage regulator is required. In a conventional utility system, the dynamic control of the frequency droop employs the proportional-integral (PI) control method [2-3]. In this thesis, a closed-loop controller using PI control method is employed to achieve the dynamic voltage regulation of the inverter interfaced PEMFC power module, as shown in Fig. 6.8. The software module of the controller (available in LabVIEW (PID.vi)) is used. The output from the AC voltage sensor is fed back to the digital controller via DAQ. The measured voltage (V) is compared with a reference voltage V_{ref} (120 Vrms), in order to produce an error signal, ΔV. The error signal is multiplied by the proportional gain (K_p) and integrated over time with the integral time constant (T_i) to produce the digital control signal. The digital signal is then converted into analog using analog DAQs. Since the voltage control actuator does not allow negative voltage input, the control signal is limited between 0 to 6 V DC.

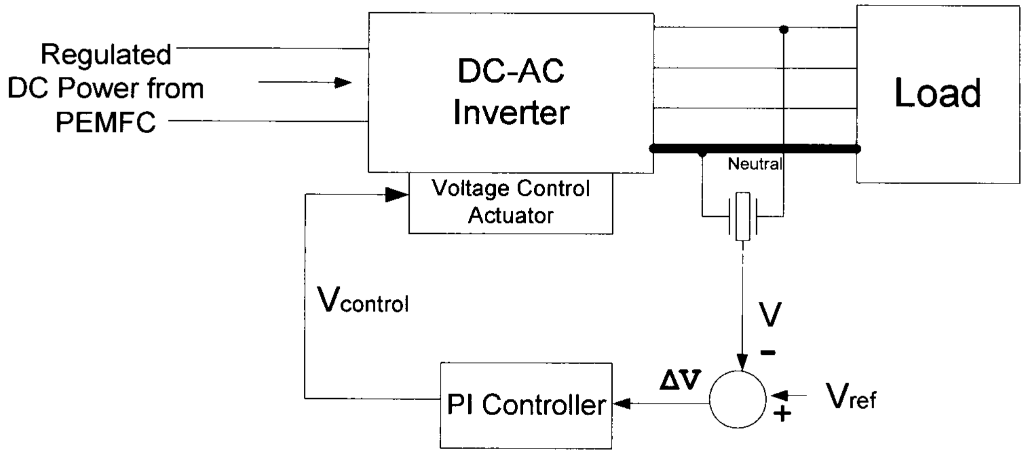

Fig.6.8. Closed-loop voltage regulator of the inverter interfaced PEMFC

Tuning of the Feedback Voltage Regulator

The reasons that a proportional-integral control method is sufficient for this research are: (a) The proportional control gives a control signal that is proportional to the error between the measured voltage and the reference voltage; (b) Integral control can eliminate the error in steady-state by integrating the error signal over time [4]. However, one of the challenges in the design of the feedback voltage regulator is selecting the proper control parameters (Kp and Ti) without introducing instability to the inverter output. This is especially difficult when the mathematical model of the inverter is not available. In this thesis, the "Ziegler-Nichols frequency response tuning rule" is employed to determine the control parameters, experimentally [4-5].

As suggested in [4-5], the integral time constant (Ti) of the voltage regulator is set as "∞". Only the proportional gain (Kp) is increased until the output voltage of the inverter starts to exhibit sustained oscillation. At this moment, the proportional gain of the regulator is considered as the critical gain (Kcr). The frequency of the oscillation is the stability limit, and the corresponding period (Pcr) is recorded. Based on the experiment, the values of Kcr and Pcr are determined (Kcr = 0.6 and Pcr ≈ 1sec). Then, these values are applied to the "Ziegler-Nichols tuning table" to determine the control parameters. Table 6.1 illustrates the values of Kp and Ti selected for the voltage regulator of the inverter.

Table 6.1. Control parameters of the feedback voltage regulator of the inverter

Type of Controller	K_p	T_i in Minutes
P	0.3	∞
PI	0.27	0.0139

Fig.6.9 depicts the outcome voltage response of the inverter with the feedback voltage regulator as the load changes. It can be seen that when the load of the inverter interfaced PEMFC suddenly increases from 150 W to 450 W, the output voltage of the inverter is first dropped to 117 Vrms. The feedback voltage regulator responds to the change in the voltage and increases the output voltage of the inverter to compensate the load changes. It takes about 2.4 seconds for the voltage to reach the steady-state after the load disturbance.

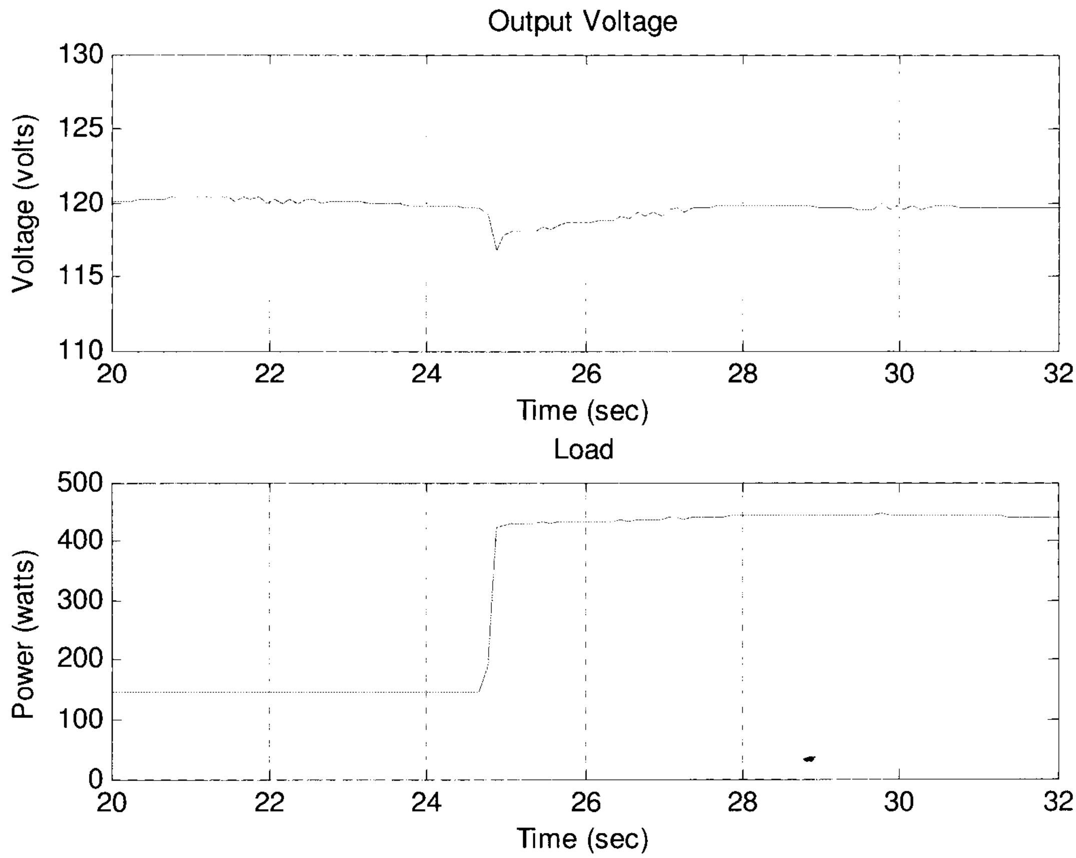

Fig.6.9. Dynamic response of the output voltage of the inverter with the feedback voltage regulator

The voltage profile and control signals at different load conditions are indicated in Fig. 6.10. The results verify that the feedback regulator can effectively maintain the output voltage of the inverter at the desired level. In other words, the regulated inverter is now able to sustain the terminal voltage at 120 Vrms as long as the load is within the capacity of the PEM fuel cell power module. The spikes on the voltage profile can be reduced by improving the voltage regulator in future studies. Meanwhile, the system frequency stays at 60 Hz, which ensures a good overall power quality.

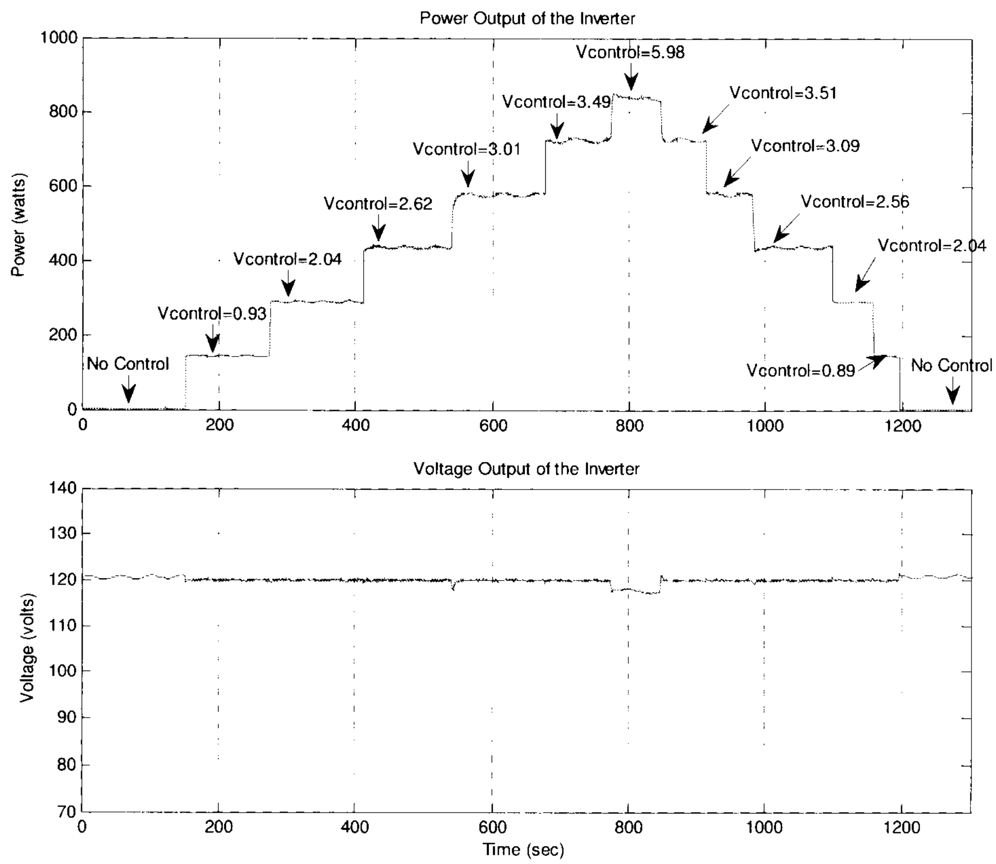

Fig.6.10. Inverter load-voltage characteristics with feedback voltage regulator

6.5 Verification of the Dynamic Load Sharing Scheme with Load-Voltage Droop

The effectiveness of the inverter voltage regulation in the microgrid is experimentally verified. As shown in Fig. 6.11, with the feedback voltage regulator, the bus voltage is sustained at 120 Vrms, as long as the load is within the total generation capacity of the microgrid. The spikes on the voltage profile are caused by large load disturbance, which occurs during the experiment (when toggle switches are used to change the load). This large disturbance is quickly recovered by the control action of the inverter, which thereby proves the effectiveness of the voltage regulator. Meanwhile, the system frequency is still retained at 60 Hz. The power output characteristics of the inverter and the synchronous generators are depicted in Fig. 6.12. This figure reveals a fact that because the bus voltage sustains at a constant level by the inverter voltage regulator, the two synchronous generators do not experience big change in the terminal voltage.

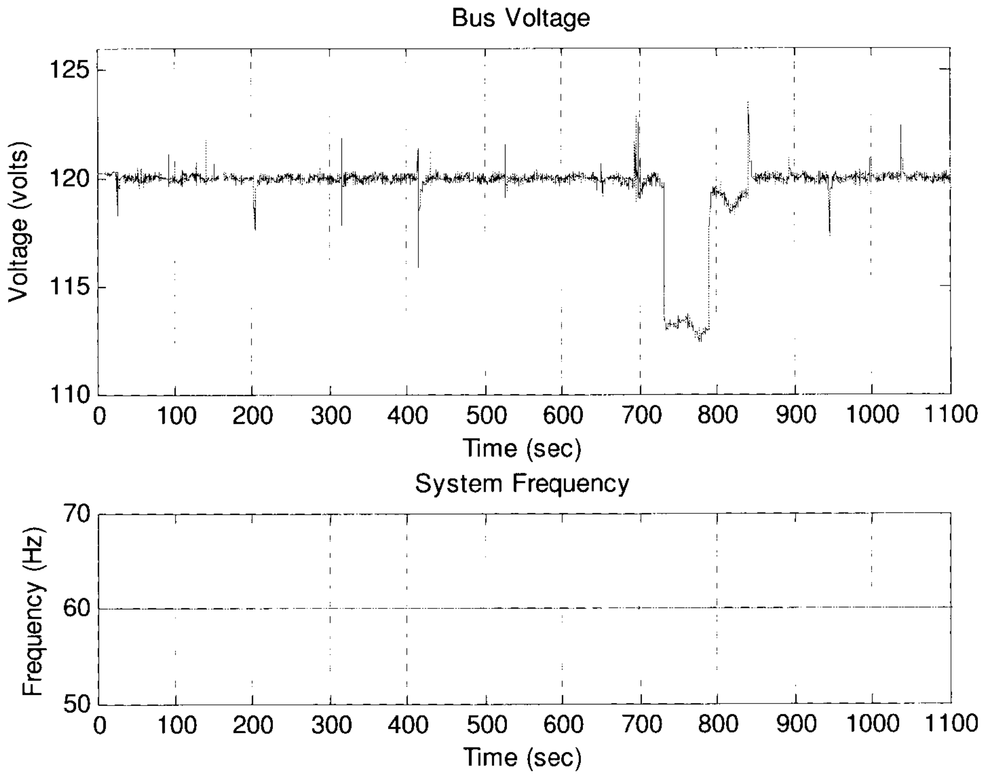

Fig.6.11. The bus voltage and frequency response of the microgrid with the inverter voltage regulator

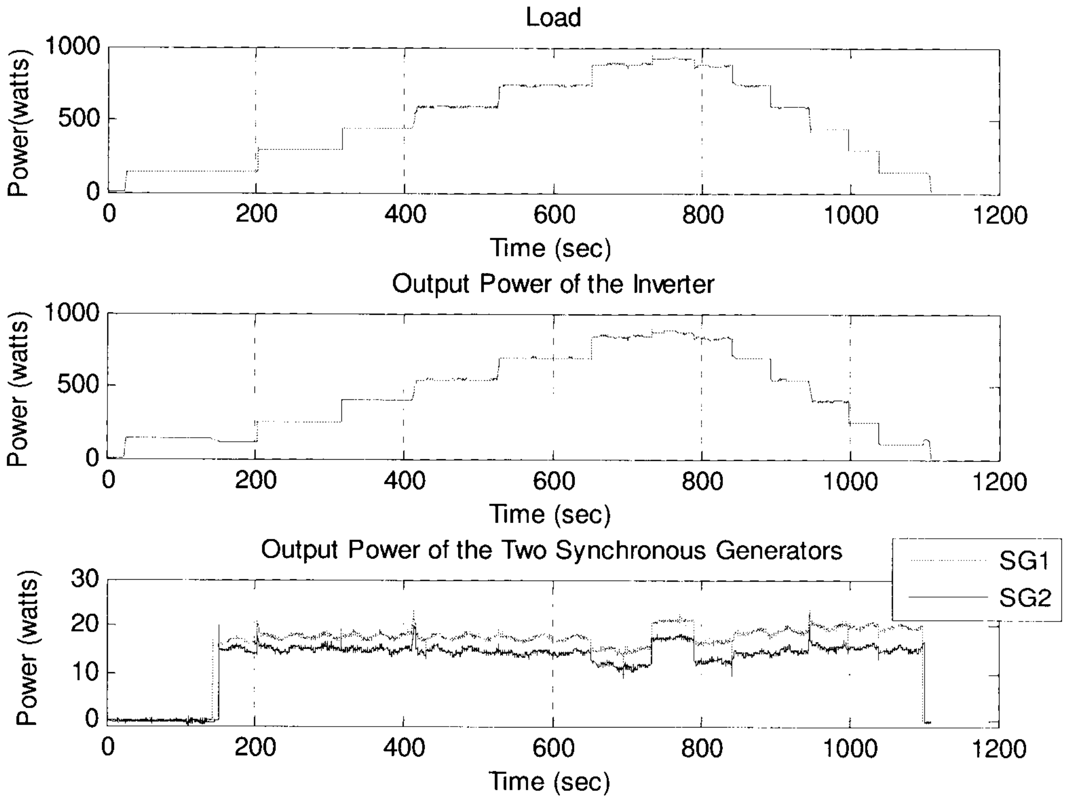

Fig.6.12. Load sharing of the microgrid with the inverter voltage regulator

6.6 Load Sharing by Adjusting Setpoints of the Synchronous Generator

In the previous experiments, the two synchronous generators are preset to have similar initial settings. In this section, the no-load setpoint of SG1 is adjusted so that it produces more active power than SG2 does during normal operations. The voltage regulator is used to maintain a constant voltage.

Fig. 6.13 and Fig. 6.14 demonstrate the load deployment of the microgrid, and voltage and frequency response, respectively. From the results, it can be determined that SG1 provides more power in comparison with the previous experiment, while SG2 stays the same power output level. The output of the generators upholds an almost constant value, while the inverter actively responds to the change in the load.

The load sharing profile in Fig. 6.13 can be explained with the help of Fig. 6.7. In this figure, DG1 represents the inverter interfaced PEMFC system and DG2 symbolizes the combination of the two synchronous generators. Before the load changes, the inverter interfaced PEMFC and the two synchronous generators are generating a combined output power of P_{load} at a bus voltage level of V_N, (120 Vrms). When the load suddenly increases to P_{load}', where P_{load}'= P_{load}+ ΔP, this change causes the bus voltage to drop. The voltage controller of the inverter responds to the change in the bus voltage, and as a result, it increases the terminal voltage setpoint of the inverter to V_1'. Therefore the inverter generates more power to compensate for the load increase, ΔP. Because it balances the load demand and power generation, the bus voltage returns to the initial value of 120 Vrms. The experimental results indicate that it is feasible to adopt the load-voltage drooping characteristics of the inverter based DG resources to achieve a proper load distribution in a microgrid system with a fixed system frequency, while maintaining a stable bus voltage. The feedback voltage regulator of the inverter is very useful in this application.

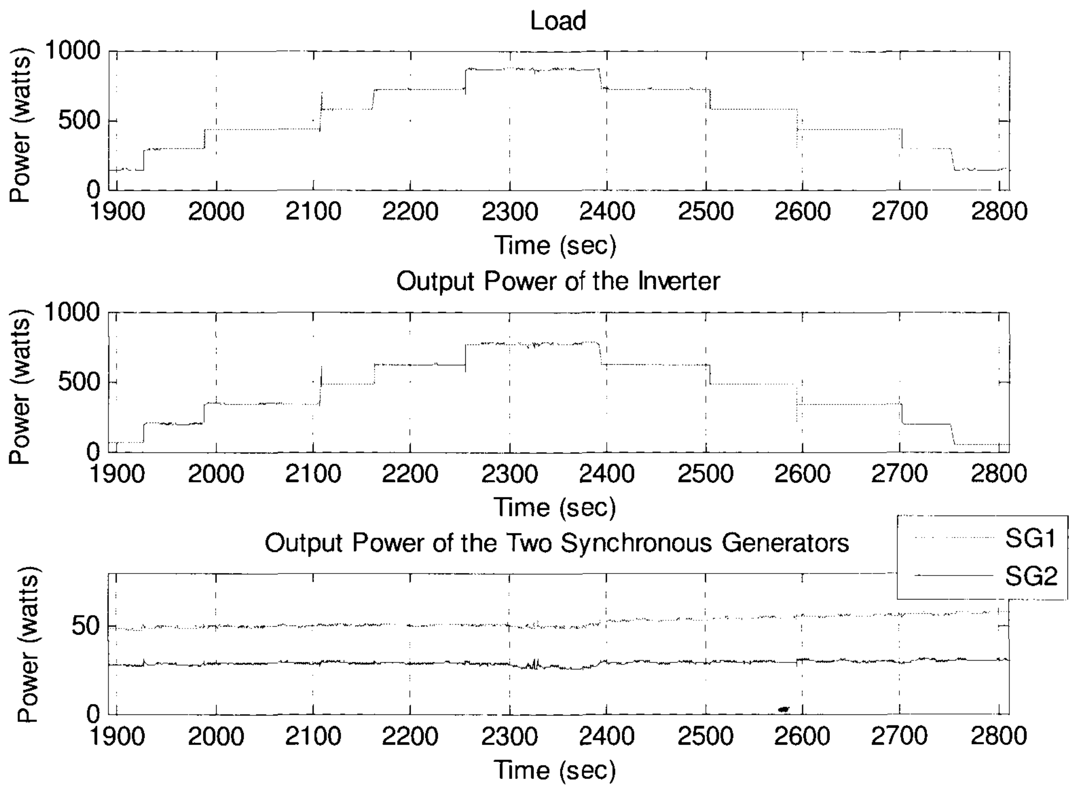

Fig.6.13. Load sharing characteristics of the microgrid (when SG1 at a different setpoint)

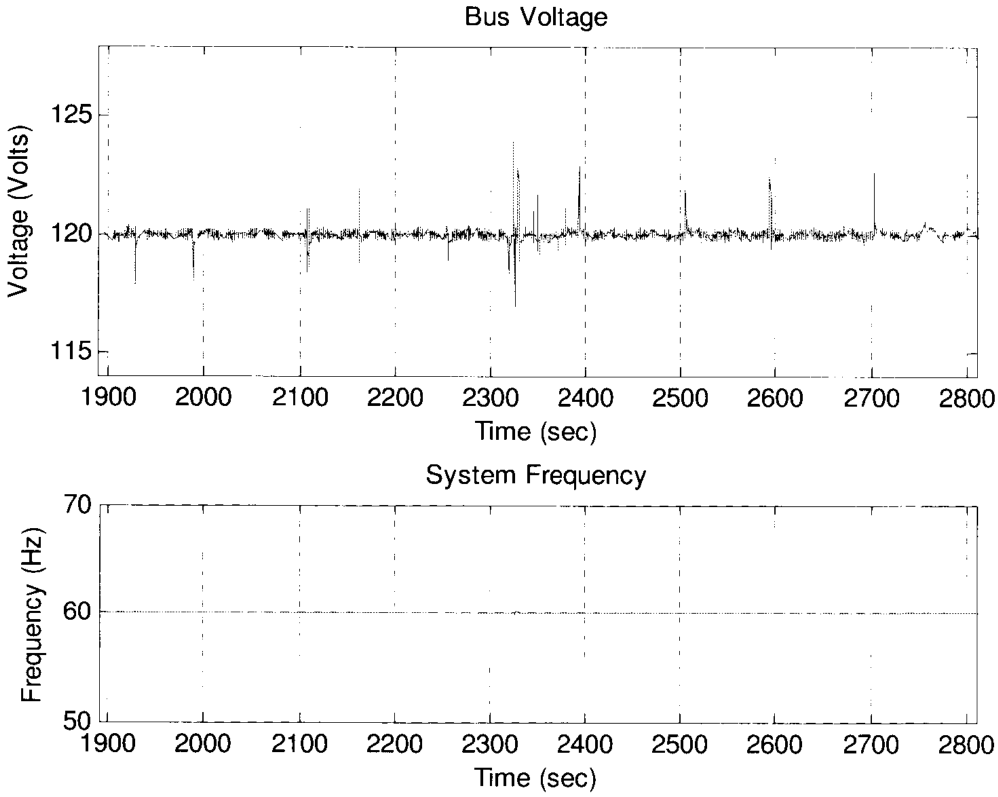

Fig.6.14. Bus voltage and system frequency response of the microgrid

6.7 Load sharing of the microgrid when two synchronous generators are not matching

For multiple DGs in an islanded mode, the slope of the load-voltage droop determines the actual amount of power output from the corresponding DG units when the load changes. However, two synchronous generators used in this prototype microgrid have identical parameters and they establish similar load-voltage drooping characteristics, as shown in Fig.5.8. In order to create a condition where two synchronous generators with different internal parameters are used in this prototype microgrid, an external inductor (Z_E) is connected at each phase of SG2, as shown in Fig. 6.15. This is done to artificially change the equivalent internal impedance of SG2, so that the slope of the load-voltage droop of SG2 is different from SG1 [1].

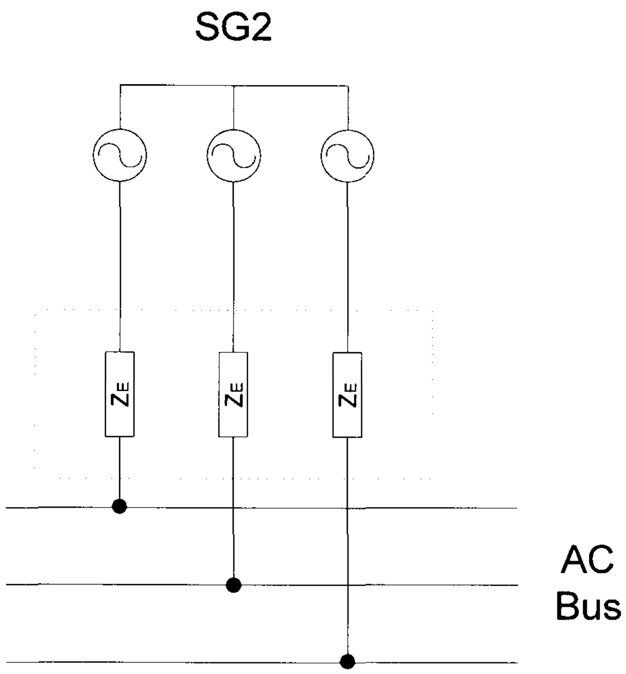

Fig.6.15. Artificial modification of the SG2's equivalent internal impedance

Three experiments are conducted to investigate the load sharing of the microgrid when two synchronous generators with different load-voltage droops are involved in the microgrid. The following are the results and comparison of the tests.

1. Fig. 6.16 and Fig. 6.17 show the load sharing dynamics of the microgrid and the bus voltage response when a 7.5 mH inductor is attached externally to the phases of SG2 to change its equivalent internal impedance.

2. Fig. 6.18 and Fig. 6.19 show the load sharing dynamics of the microgrid and bus voltage response when a 15 mH inductor is added to SG2.

3. Fig. 6.20 and Fig. 6.21 are at the same condition as in (2), but with the initial power output of SG2 adjusted by increasing the power from its prime mover.

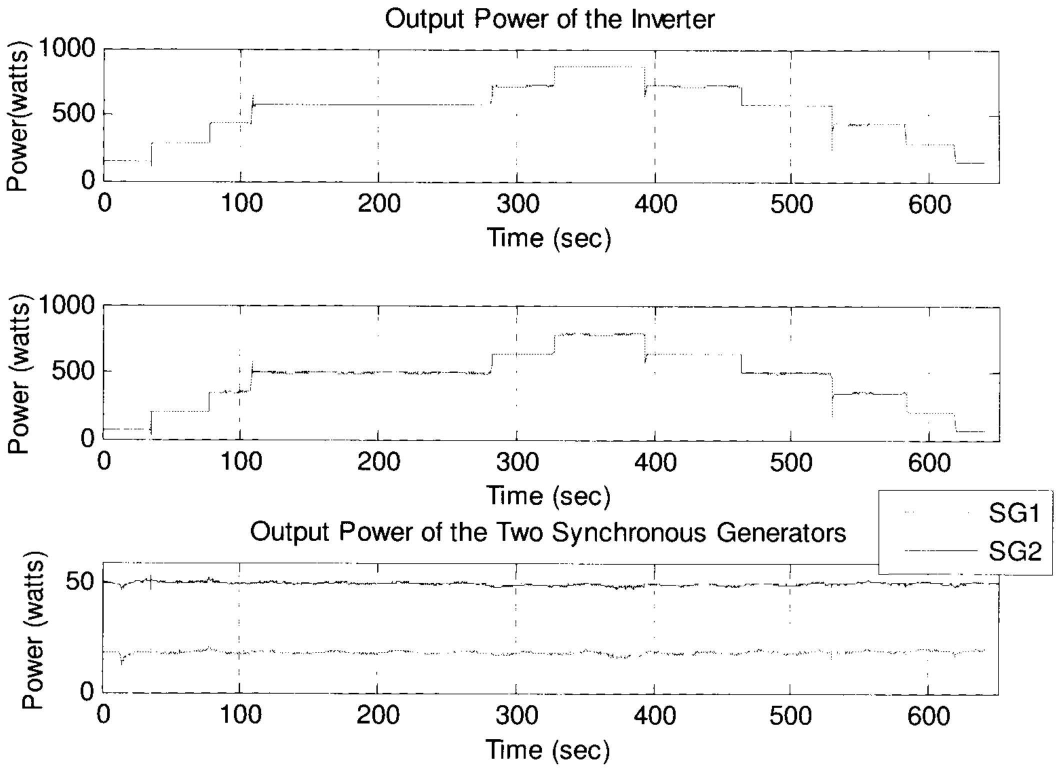

Fig.6.16. Load distribution in the microgrid when a 7.5 mH inductance is added to SG2

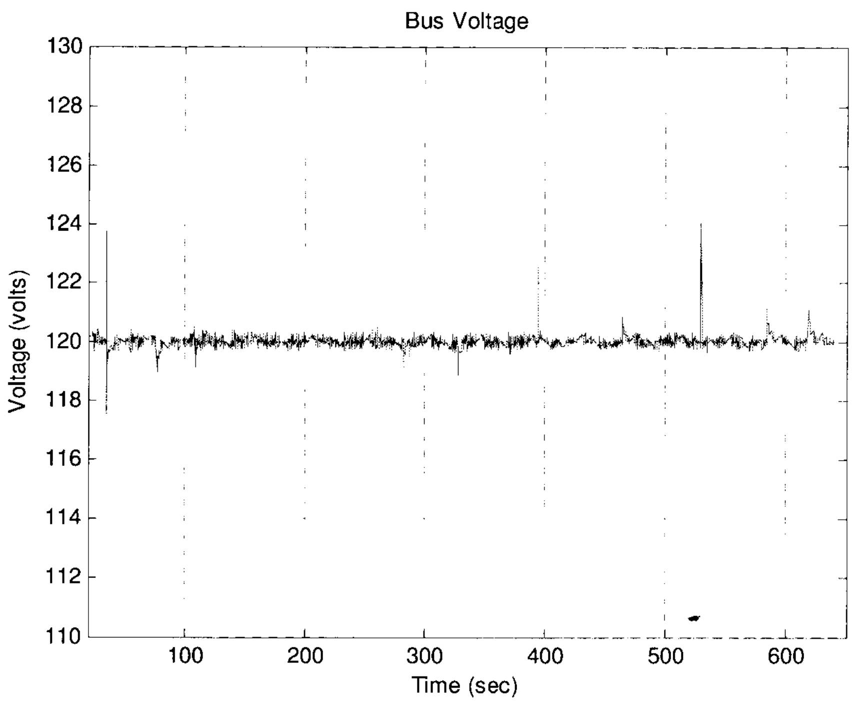

Fig.6.17. AC bus voltage of the microgrid when a 7.5 mH inductance is added to SG2

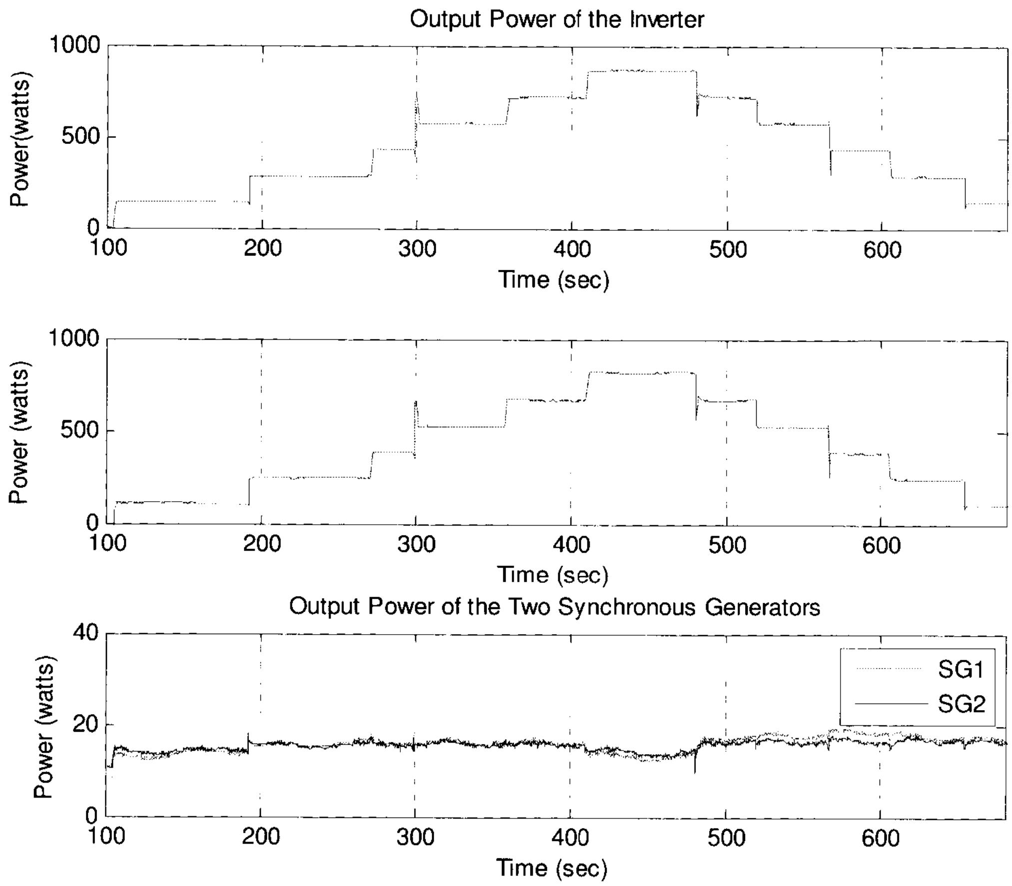

Fig.6.18. Load distribution of the microgrid when a 15 mH inductance is added to SG2

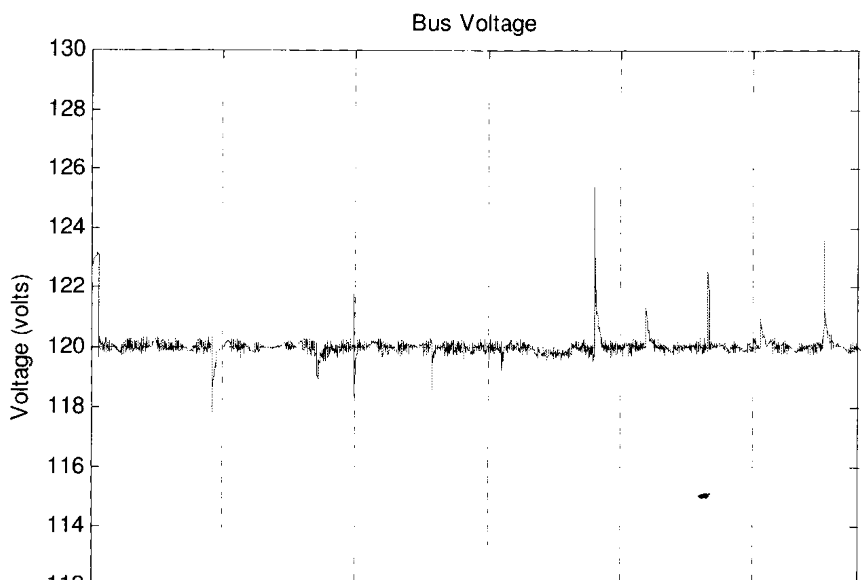

Fig.6.19. AC bus voltage of the microgrid when a 15 mH inductance is added to SG2

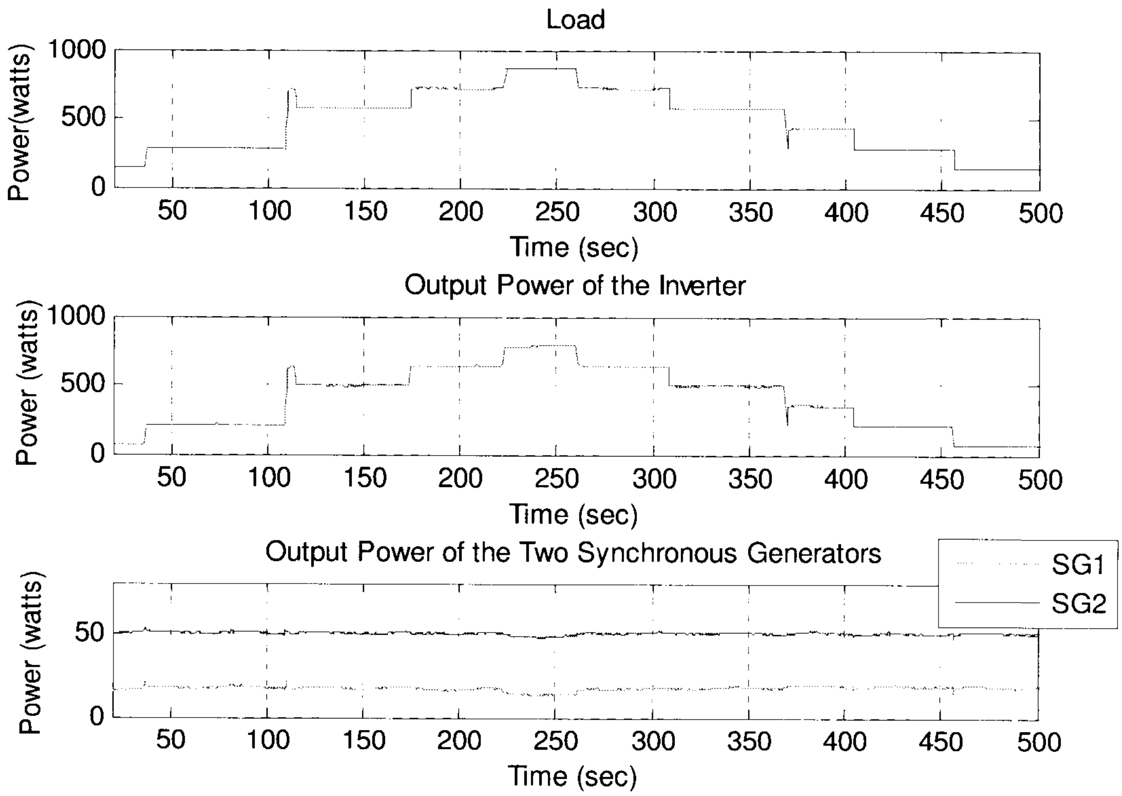

Fig.6.20. Load distribution of the microgrid when a 15 mH inductance is added to SG2 (setpoint adjusted)

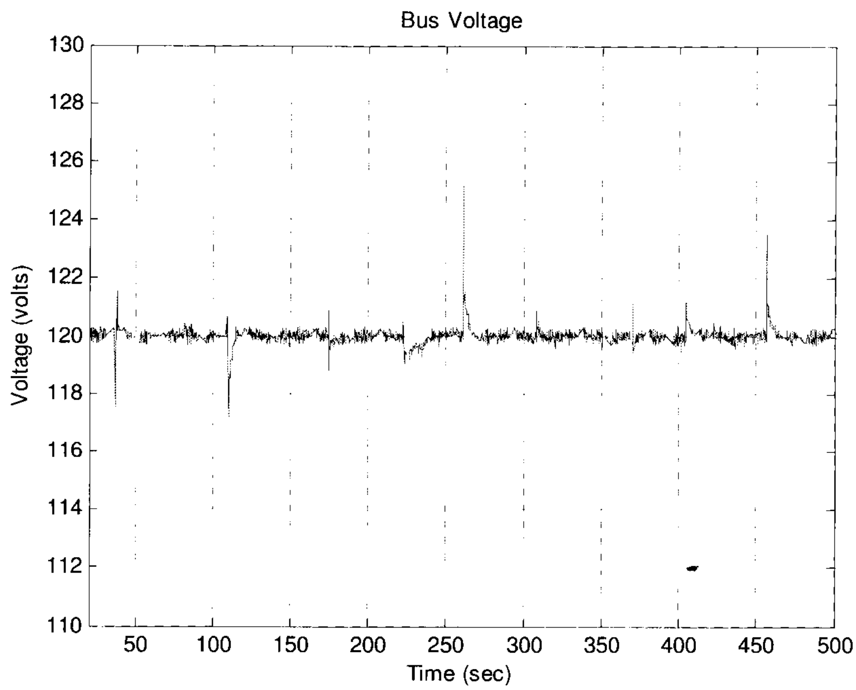

Fig.6.21. AC bus voltage of the microgrid when a 15 mH inductance is added to SG2 (setpoint adjusted)

It is observed that when the inductors with different values are added to change the equivalent internal impedance of SG2, the change in load is still always picked up by the inverter interfaced PEMFC. The power output from neither of the synchronous generators will respond to the load variation. This is because the response of the inverter voltage regulator is prompt. It picks up the voltage change and compensates the load changes rapidly. This means that synchronous generators will not inherently respond to the change in load when the bus voltage is regulated by the inverter.

Comparing the experimental results above, it can be seen that changing the equivalent internal impedance of a synchronous generator will change the corresponding load-voltage droop. However, this does not effectively change the dynamic load sharing behaviour of the synchronous generators when the feedback voltage regulator is used only for the inverter interfaced PEMFC module. The amount of the power generated by the synchronous generators is only determined by the predetermine setpoints, rather than the internal impedance. As long as the AC bus voltage is regulated by the voltage regulator of the inverter, they do not have significant contribution to the load change. These experiments also show that through the change in the input power of the prime mover, the output power of the synchronous generators can be changed accordingly.

6.8 Summary

This chapter introduces the static load sharing and the dynamic load sharing scheme in a conventional power system. Due to the involvement of the power electronic interface, one may no longer use the frequency droop for active load sharing in a microgrid with fixed frequency. The novel load sharing scheme using the linear drooping relationship between the active power output and the voltage of a generator is discussed.

The previously developed microgrid control and operation interface makes it possible to conduct many experiments on the dynamic characteristics of the existing prototype microgrid. To dynamically regulate the output voltage of the inverter interfaced PEMFC, a feedback regulator with PI control method is used in this research. Adopting the "Ziegler-Nichols frequency response tuning rule", the control parameters are obtained.

The experimental results show that the voltage regulator can maintain the inverter output at a constant level under various load conditions.

Moreover, dynamic load sharing scheme using voltage droops is experimental verified on the prototype microgrid when the inverter voltage regulation is involved. It is shown that by dynamically adjusting the voltage setpoints of the inverter, the inverter can pick up the change in load demand, and it can maintain an almost constant bus voltage. In the meantime, the other two synchronous generators will keep a constant power output.

In order to create a condition where two synchronous generators with different parameters are used in this microgrid, a small inductor is added to artificially change the internal impedance of a synchronous generator. However, the experimental results indicate that it is not a reasonable solution to change the load sharing profile of the microgrid. This is because the voltage regulator of the inverter compensates the voltage variation quickly, and the two synchronous generators do not experience any voltage droop; therefore, they will maintain constant.

6.9 References

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VII. Dispatch Strategies of the Microgrid

For certain applications, the load sharing schemes discussed in Chapter 6 are sufficient. When the synchronous generators are equipped with automatic voltage regulator, an economic dispatch strategy may be created by assigned a fixed percentage of the power contribution to the synchronous generators and the inverter interfaced PEMFC. Several methods for the economic dispatch problem in a conventional power system are discussed in [1], such as gradient methods, and the Newton's method, etc. These methods assume that there are N generating units connected to a single voltage bus serving a load center. The economic dispatch problem is converted into minimizing the total cost for supplying the indicated load, while having the enough generation to meet the load demand. This problem can be expressed mathematically as in (6.1):

$$\begin{aligned} F_T &= F_1 + F_2 \cdots + F_N \\ &= \sum_{i=1}^{N} C_i(P_i) \end{aligned} \tag{6.1}$$

where F_T is the total cost of generation, C_i is the cost rate of each unit, P_i is the power generated by the corresponding unit, and F_N is the generation cost of the N^{th} unit.

It is concluded that the necessary condition for the existence of a minimum cost-operating condition is that the incremental cost rate of all the generating units must be equal to a certain value [1]. Such condition can be met in a conventional system where the cost of the electricity generation is directly associated with the cost of the fuel, such as coals or diesel. However, for non-conventional sources with power electronic interface used in a microgrid, the generation cost of these sources is not only related to the fuel cost but also to the consumption of the power electronic devices, as shown in Fig. 5.7. Therefore, the conventional methods are facing difficulties in solving the economic dispatch problem in a microgrid.

Furthermore, the economic dispatch problem assumes that there are N units already connected to the system. It does not consider the operational cost associated with running a generator. However, it is concluded that the least expensive way to supply the generation is not with all generators running. Rather, the optimum commitment is to only run enough generators to cover the maximum system load and leave them running. It leads to the problem of the unit commitment, which demands a generator to be on or off at a certain load condition [1]. Different from the generation constraints in a conventional system [2], the concept of economic dispatch and unit commitment in a microgrid has to consider following factors. First, the generation capacity of a distributed resource is much less than that of a large power plant in the conventional system. Second, the inherent simplicity in switching on and off smaller distributed generators, especially with power electronic devices, opens up the possibility of easily requesting a generator plant for operation. Third, due to the involvement of renewable energy sources in a microgrid, one may schedule the participation of the renewable resources as much as possible.

In order to investigate the possible solutions to commit the distributed generators in this microgrid and operate the microgrid in an economic way, two scheduling strategies are discussed in this chapter. They emphasize on the different roles that a certain type of distributed resources may play in a microgrid. The rule of these two unit dispatch strategies is only committing enough DGs into generation at a certain load condition. The restriction associated with the dispatch strategies of an islanded microgrid is that the power generation within the microgrid has to match the load demand while minimizing the total expenses associated with the power production.

7.1 Minimal Unit Participation Strategy

Taking into consideration of the generation cost of both 250 W synchronous generators and the efficiency of the inverter with the 1.2 kW PEM fuel cell module, the Minimal Unit Participation Strategy of the prototype microgrid is presented in Fig.7.1. This scheme proposes the minimal participation of a distributed generator during operation. The issue associated with the security reserve is not included in this figure.

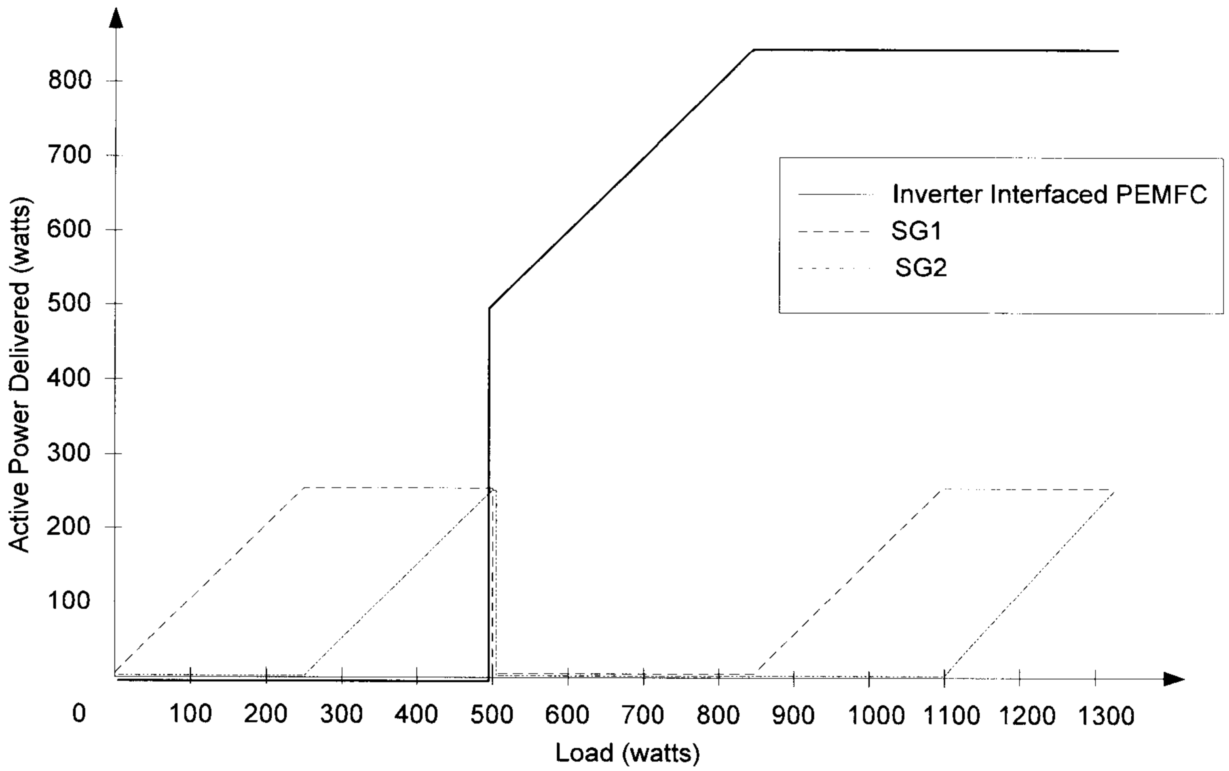

Fig.7.1. Minimal Unit Participation Strategy for the microgrid

Different from the dynamic load sharing scheme in Chapter 6, where two synchronous generators and the inverter interfaced PEMFC are operating all the time, this scheme calls for only one generator online at a time. When the load is relatively small and can be entirely supported by SG1, both the PEMFC power unit and SG2 are offline. When the load demand exceeds the capacity of SG1, SG2 will be requested to contribute while SG1 maintains its maximum power output.

As the power demand keeps increasing and eventually exceeds the combined capacity of both SG1 and SG2, the entire power generation will be switched over to the larger generator, which is the inverter interfaced PEMFC in this prototype microgrid. The switchover procedure should ensure that the inverter is brought online and committed before disconnecting the synchronous generators. Once the inverter cannot meet the additional load increase, SG1 and SG2 will be brought back online to supply the exceeded power consumption in a sequential order. At the same time, the fuel cell system will be operating at its maximal capacity.

The previously discussed dynamic load sharing scheme with voltage droop can be used to implement this power dispatch scheme, including the switchover procedure. If the load can be entirely covered by SG1, the voltage droop of SG2 will be adjusted so that it will not contribute to the load. Under this condition, SG2 can be disconnected from the AC bus, or even completely shut down, depending on the system requirement during the start up period. When SG2 is called back online, it will simply increase its voltage setpoint so that the active power can be once again injected into the system. The synchronization procedures have to be performed in this application; however, this is beyond the scope of this research.

When the switchover between the inverter and the synchronous generators occurs, the inverter will dynamically increase its voltage setpoint and surpass the operating voltage of SG1 and SG2. At the same time, SG1 and SG2 will lower their voltage setpoints, so that they cease to provide power to the load. They may be further disconnected from the AC voltage bus.

Finally, when the power demand exceeds the capacity of the inverter, the voltage setpoint of the inverter will be set to a higher value so that it produces the maximum power to supply the load. Meanwhile, SG1 and SG2 will increase their voltage setpoints as much as it is needed in order to ensure that the bus voltage does not decline and the load demand is met successfully.

Although in Fig. 7.1, it indicates that the distributed generators are supplying their rated power, a security reserve should be taken into consideration in reality. This is necessary in order to allow the microgrid to respond to unexpected and sudden rise of the local power demand when there are no other energy sources available. The selection of the security margin depends on the type of loads that the microgrid is supporting. When the microgrid is in a grid connected mode, the power from the utility grid can also be used for the security reserve. In this thesis, 20 percent of power from individual DG is reserved at discretion specifically for this purpose.

It is obvious that above procedures requires coordination between different generators. This is especially important for a microgrid with many renewable energy sources and where operating conditions highly depend on environmental conditions, e.g. wind turbines, and PV.

Experimental Results

The experimental results for the load distribution profile, as well as the frequency and the bus voltage responses of the microgrid under Minimal Unit Participation Strategy are illustrated in Fig. 7.2 and Fig.7.3, respectively. In this experiment, the load is increased from almost zero to the rated capacity of the prototype microgrid (1.2 kW). The maximum power output from the two synchronous generators is rated at 200 W, with an extra 50 W as operational reserves. The capacity of the inverter interfaced PEMFC is considered to be 850 W.

As shown in Fig.7.2, when the load demand is less than 200 W, only SG1 is connected online. The exciter and prime mover of the synchronous generator are adjusted with open-loop control so that the bus voltage is maintained within ±5% of the nominal 120 Vrms, and the system frequency is within the range of 60.5-59.3 Hz. When the load demand exceeds the capacity of SG1, SG2 is called into operation. Manual synchronization is applied in this thesis. As the active power demand rises, SG2 increases its output to supply the excess load, while maintaining the bus voltage and the system frequency within the enforced range. Due to the lack of dynamic feedback controllers for the power generation of the synchronous generators, bus voltage and system frequency experience some fluctuations, as shown in Fig. 7.3 before the 900th second. This can be eliminated by employing the governor mechanism for the synchronous generators. During this period, SG1 is producing a virtually constant power.

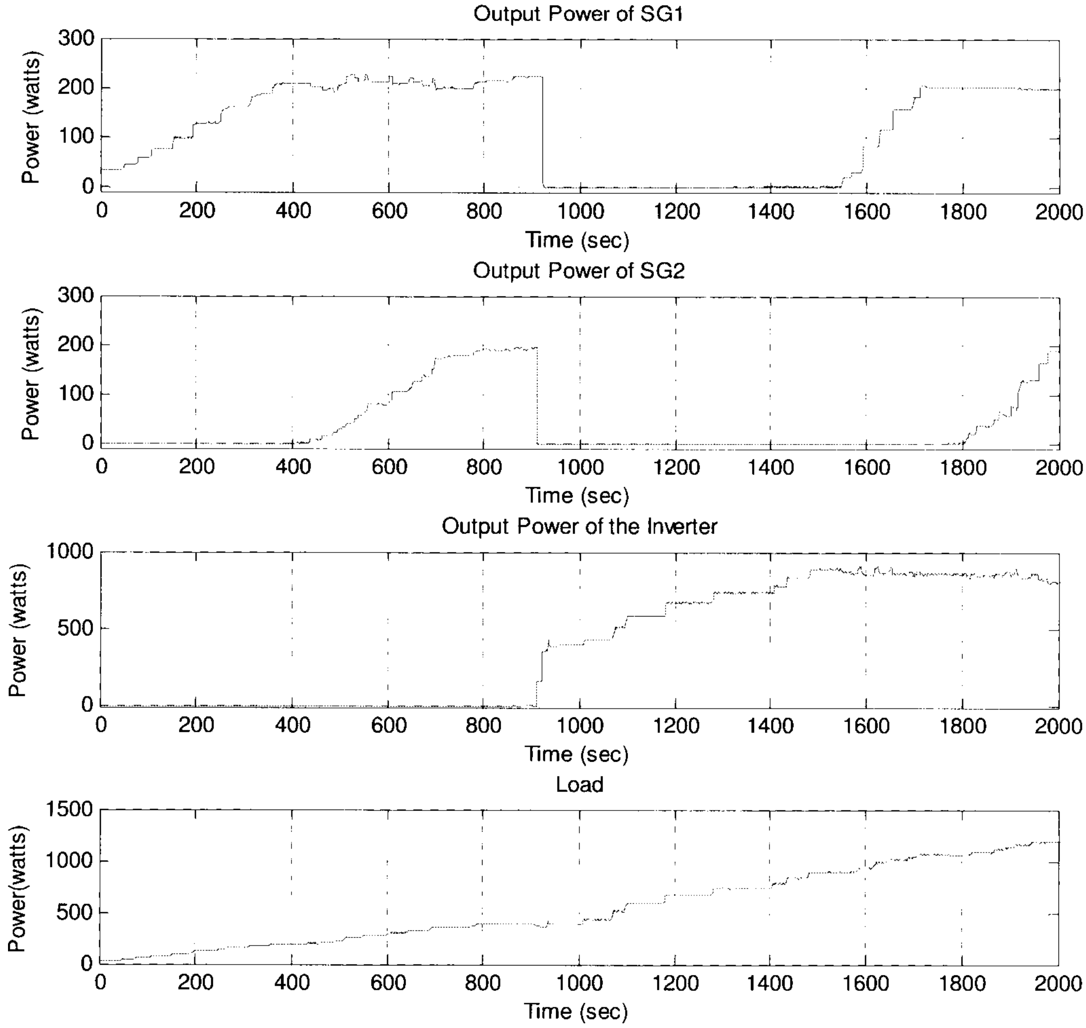

Fig.7.2. Load distribution profile of the Minimal Unit Participation Strategy

When the load approaches the combined capacity of SG1 and SG2 (around the 900th second), the PEMFC power module is requested to participate. In the meantime, the two synchronous generators will lower their voltage setpoints and disconnect themselves from the AC bus. As soon as the PEMFC powered inverter is connected to AC bus, the system frequency is fixed at 60 Hz. The voltage profile is shown in Fig. 7.3. The contribution of the feedback voltage regulator of the inverter effectively maintains the bus voltage at 120 Vrms.

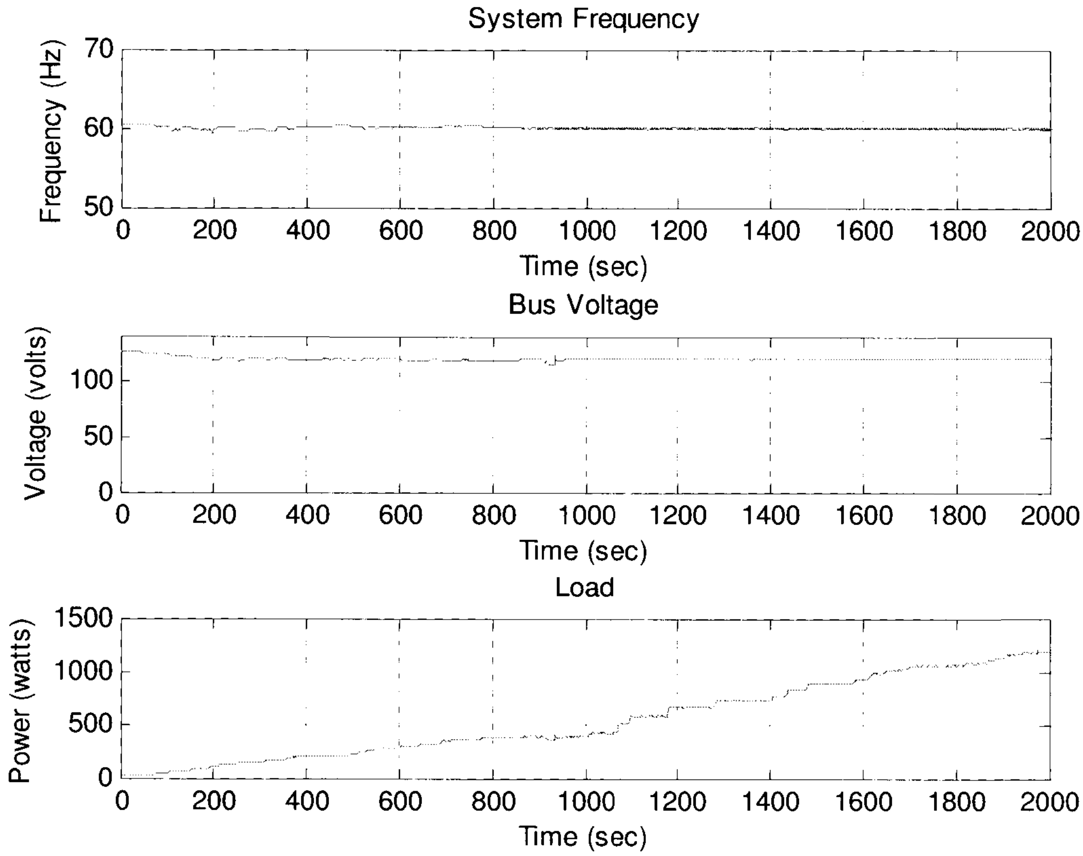

Fig.7.3. Frequency and AC bus voltage profile of the Minimal Unit Participation Strategy

The above analysis and experiments describe a dispatch scheme for the microgrid operation. It aims to minimize the participation of individual DGs. It also aspires to minimize the potential costs associated with the hydrogen consumption of the microgrid, while maintaining a high operational efficiency of the fuel cell unit. Because of the switchover steps, this strategy is only feasible when all the DGs are equipped with autonomous synchronization devices. One of the disadvantages of this strategy is that when the load is comparable low, the microgrid system does not fully utilize the benefits of the fuel cell or the power electronic devices. Therefore, the emission problem associated with using generators still exists when the load is light. This scheme also highly relies on the communication infrastructure to coordinate the operation of multiple generators. Also, a significant amount of switchover and synchronization actions will further introduce transients that affect the power quality in the microgrid.

7.2 Base Load Priority Strategy

A different dispatch strategy is created to elaborately promote the utilization of the alternative energy sources by scheduling alternative resources as the base load provider. In this case, the engine driven generators are considered as backup when the load exceeds the generation capacity of the alternative resources. So far as the prototype microgrid is concerned, the PEMFC is used to support the base load of the microgrid. In situations where the load demand is below generation capacity, the fuel cell acts as the sole power supply of the microgrid. As the load increases and exceeds the capacity of the fuel cell, SG1 will be called online by simply increasing its voltage setpoint and synchronizing with the rest of the microgrid. In a situation where both fuel cell and SG1 cannot meet the load demand, SG2 will be brought online. This dispatch strategy is demonstrated in Fig.7.4.

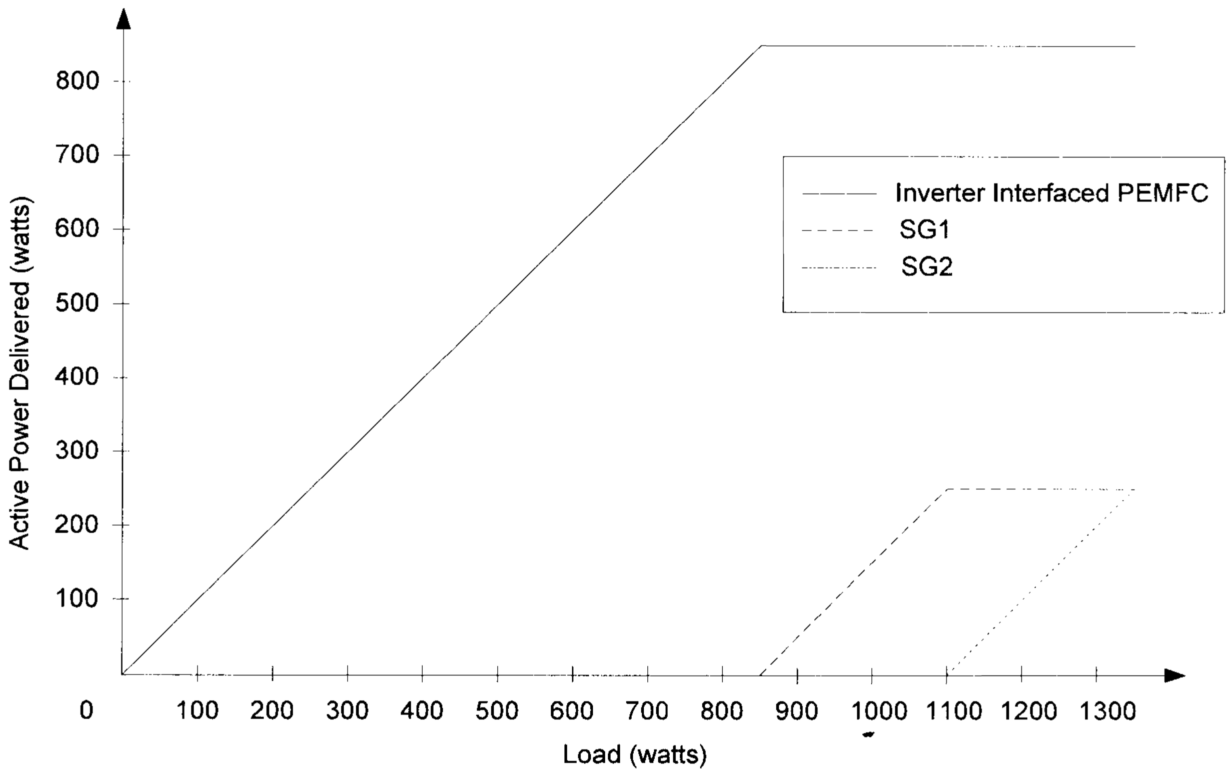

Fig.7.4. Base Load Provider Strategy

This scheme uses the PEMFC as the base load supply of the microgrid operating during the entire load span. Any load demand above the generation capacity of the fuel cell module will be topped up by the synchronous generators. This dispatch scheme fully utilizes the advantages of using PEMFC as a clean energy source in distributed generation. It also eliminates the necessity of switchovers between the generators and the fuel cell throughout the operation; therefore reducing the complexity of the microgrid operation. However, at low load levels, the operation of the microgrid has to suffer the low conversion efficiency of the inverter.

Experimental Results

The experimental verification is conducted for the microgrid under the Base Load Priority strategy. The results of load distribution profile, bus voltage, and system frequency responses of the microgrid under this strategy are demonstrated in Fig. 7.5 and Fig. 7.6. In this case, the rated capacity of the fuel cell powered inverter and the two synchronous generators are set identically to the previous scheme. As shown in Fig. 7.5, the inverter is operating online over the entire load span. SG1 is brought to production when the load exceeds the capacity of the inverter interfaced PEMFC (850 W). Considered as a backup power supply, SG2 participates only when the load demand is higher than the combined capacity of the inverter and SG1 (1050 W). In this scheme, there is no switchover needed between the inverter and the synchronous generators set. The synchronization action of one generator is only required when the load is surpassing a certain level. For the rest of the load conditions, fuel cell is the sole power supply of this microgrid. Therefore, the instability and harmonics introduced by the synchronization action is dramatically reduced in comparison with the Minimal Unit Participation Strategy.

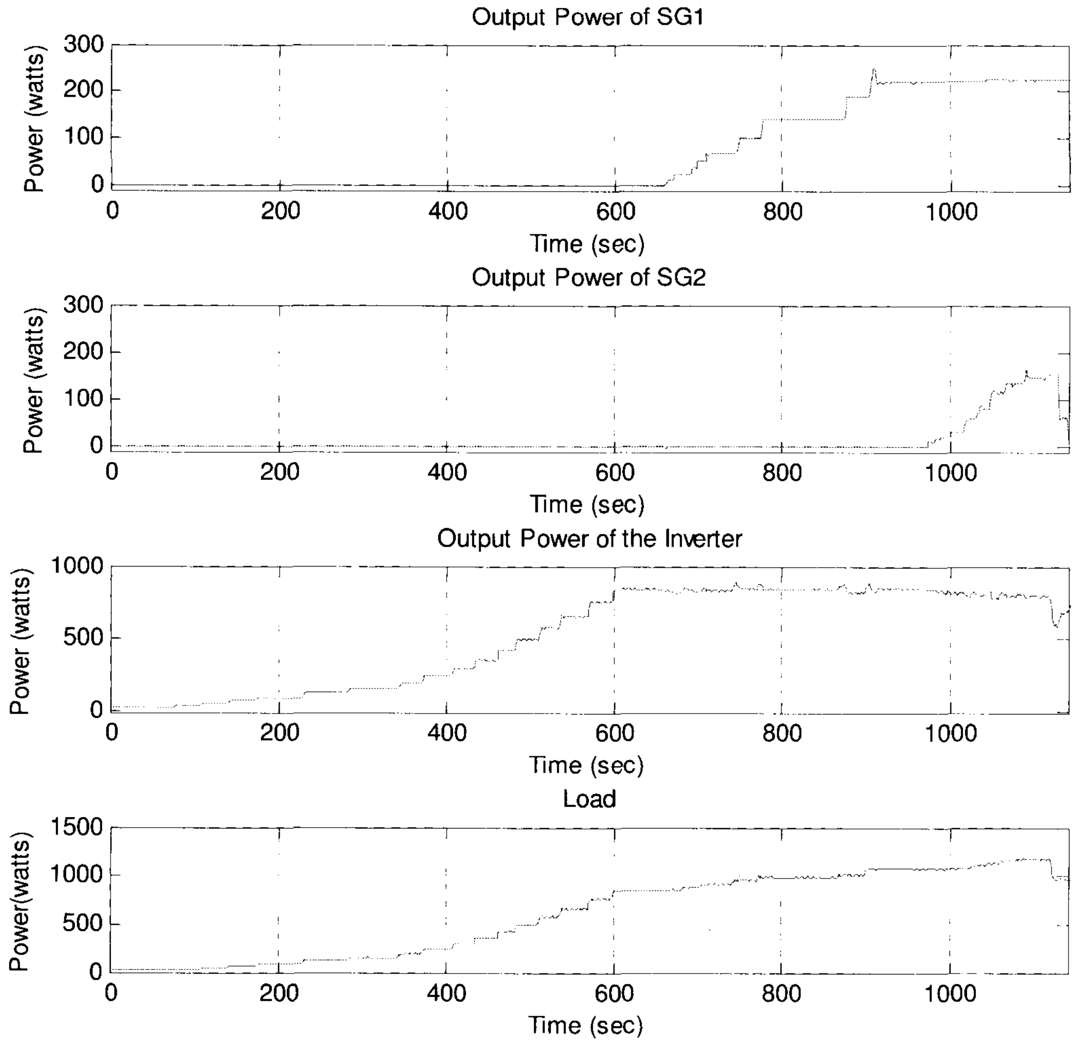

Fig.7.5. Load distribution profile of the Base Load Priority Strategy

Unlike the bus voltage response in the Minimal Unit Participation Strategy, the bus voltage stays close enough to the nominal voltage (120 Vrms) with less distortion. This is because the voltage regulator of the inverter is present the whole time. For the same reason, the system frequency is also constant over the entire load span. This can be observed from Fig. 7.6.

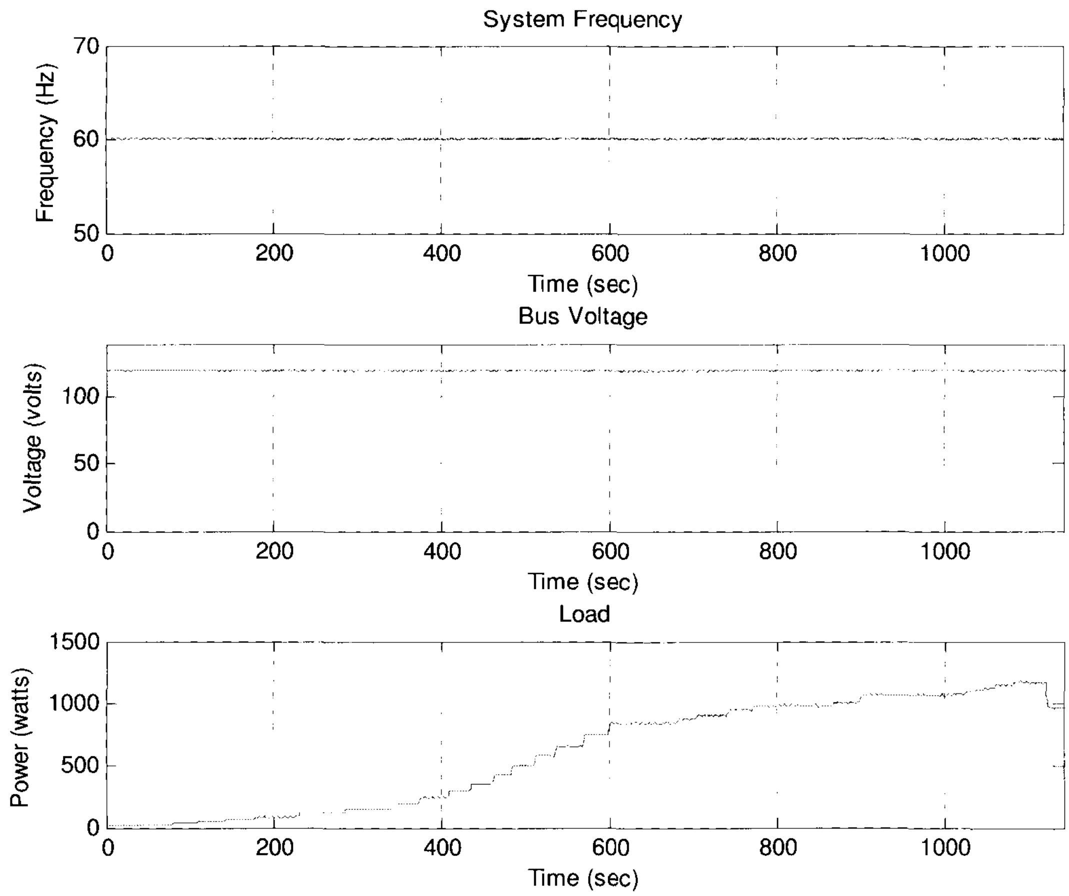

Fig.7.6. Frequency and AC bus voltage profile of the Base Load Priority Strategy

7.3 Comparison of the Utilization of the PEMFC

One of the distinguishing features of previously discussed dispatch schemes is the degree of the utilization of alternative energy sources – the PEMFC in this microgrid. Using the developed microgrid control and operation interface, the efficiency status of the inverter is recorded in real-time. The efficiency curves of the inverter under the above two schemes are illustrated in Fig. 7.7 and Fig.7.8, where the horizontal axis is the instantaneous load value, and the vertical axis is the inverter's conversion efficiency at the corresponding load condition.

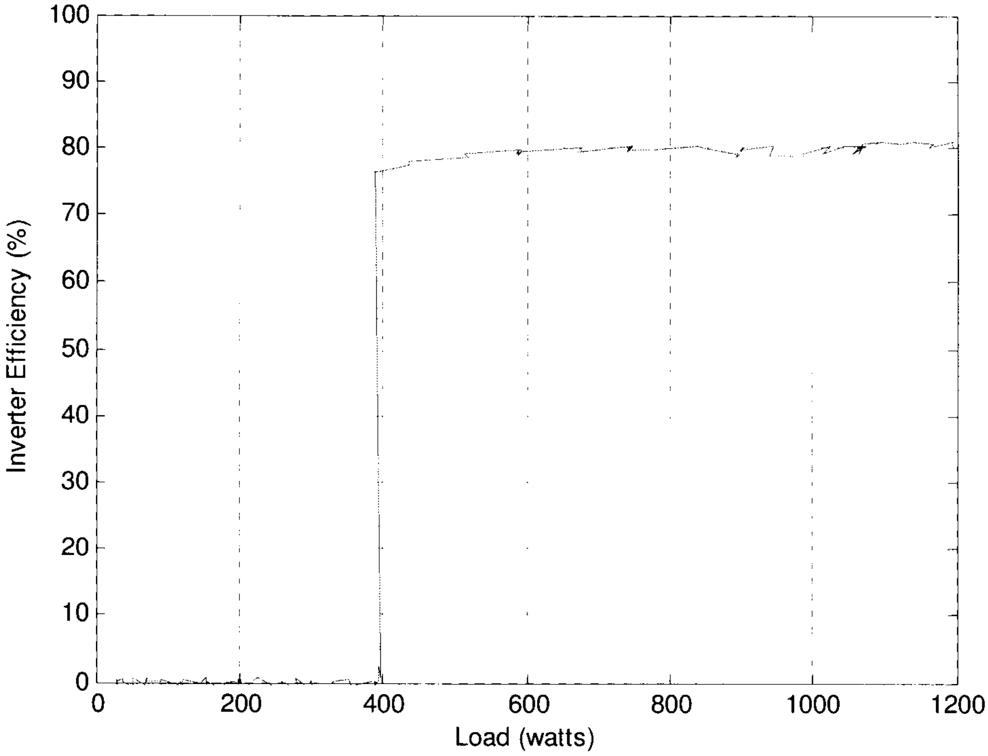

Fig.7.7. Operating efficiency curve of the inverter under the Minimal Unit Participation Strategy

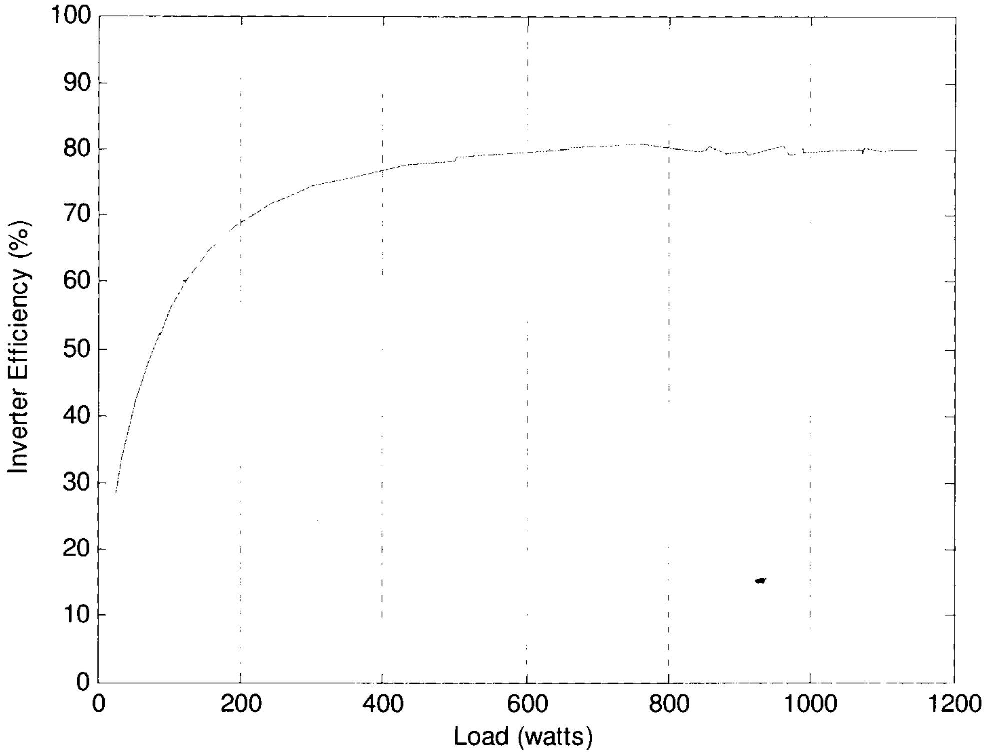

Fig.7.8. Operating efficiency curve of the inverter under the Base Load Priority Strategy

It is concluded that the DC to AC conversion efficiency of the inverter improves as its power output increases. This efficiency reaches its maximum when the power output is higher than the half of the total capacity of the inverter (400 W). This maximum level of efficiency is maintained for any power output beyond this point. In the Minimal Unit Participation Strategy, the inverter is scheduled to operate when the load is beyond the combined capacity of the two synchronous generators. This means that when the inverter is brought online, its output has to match the load demand (400 W). At this output level, the inverter is already operating at its highest efficiency level, as shown in Fig.7.7. Therefore, the power produced by the PEMFC power module is converted into AC form maximally. When the fuel cell is not requested to participate, it will stay idle with minimal loss. At this moment, the PEMFC is disconnected from the inverter to prevent the inverter from consuming energy. The zero percent efficiency from the efficiency curve means that the inverter is not providing any power at this time.

As shown in Fig. 7.8, for the conversion efficiency in the Base Load Priority Strategy, since the inverter interfaced PEMFC is scheduled to operate continuously, in the light load condition (less than half of the rated capacity of the PEMFC), the inverter is operating in the low efficiency region. A large proportion of the DC electricity is wasted in the DC to AC conversion process. The efficiency of the inverter improves as the actual load demand increases. It once again reaches its maximum point when the output approaches 400 W.

7.4 Discussions

From previous discussion regarding the load distribution strategies, as well as the degree of the utilization of fuel cell unit, it can be concluded that the Minimal Unit Participation Strategy optimally utilizes the fuel cell by scheduling it only at its most efficient operating state. However, this strategy ignores the fuel costs of running the synchronize generators. At light load conditions, this dispatch scheme cannot eliminate the problem of emission and noise, which is usually associated with the application of engine driven generators. Furthermore, a large amount of synchronization and switchover actions are required in this strategy, which introduces instability and harmonics to the system.

The Base Load Priority Strategy considers alternative energy sources as the base load supplies and the synchronous generators are considered as the backup power. This scheme certainly improves the problem brought by the switchover and synchronization actions by eliminating the necessity of such actions. However, this benefit comes through sacrificing the operational efficiency of the inverter at lower power output level. This strategy can be used when environmental constraints are strict to a point where only clean energy sources, such as fuel cells, can be used. This situation can be further improved by employing renewable energy sources, such as PV and wind, into the microgrid. In this situation, the fuel cell power module can only be used at a time when other energy sources are not sufficient.

In conclusion, there is no strategy that optimally satisfies every condition. The most suitable dispatching decision should be made based on a comprehensively analysis of system constraints, electricity market situations, the availability of the energy sources, as well as environmental requirements at the time.

7.5 Summary

In this chapter, the Minimal Unit Participation Strategy and the Base Load Priority Strategy, which were developed for the prototype microgrid, are compared theoretically and experimentally. These two dispatch schemes assign different roles to the inverter interfaced PEMFC and the synchronous generators. The Minimal Unit Participation Strategy operates the PEMFC power module when the inverter is at its highest conversion efficiency point. It then uses the synchronous generators for the rest of the load condition. On the other hand, the Base Load Priority Strategy commits the PEMFC over the entire load span as a base load provider, and considers the synchronous generators as backup power supplies. It has been argued that both strategies have their distinctive advantages and disadvantages. The DC to AC conversion efficiency of the inverter in these two strategies has also been compared. It has been concluded that an appropriate decision should be made based on many economic and environmental conditions.

7.6 References

[1] A.J. Wood and B.F. Wollenberg, Power Generation, Operation and Control, 2nd ed., John Wiley & Sons Inc, New York, 1996

[2] A. Fahmideh-Vojdani and F. Galiana, "Economic Dispatch with Generation Constraints," *IEEE Trans. Autom. Control*, vol. AC-25, no. 2, pp. 213–216, Apr. 1980

VIII. Conclusions

The research work presented in this thesis focuses on the design and development of a microgrid control instrumentation, which is dedicated to the investigation of possible load sharing schemes and dispatch strategies of a microgrid in islanded mode. The first part of the thesis focuses on the architecture of the proposed control and operation system, as well as the challenges during the physical implementation of the system. The dynamic characteristics of the inverter interfaced PEMFC power module and the synchronous generators are examined. A feedback voltage regulator is used to dynamically change the voltage setpoint of the inverter. The effectiveness of the dynamic load sharing scheme with voltage droop is investigated experimentally using the developed operation and control interface. Finally, two economic dispatch strategies for the prototype microgrid are proposed and experimentally validated.

8.1 Summary of Contributions

The major contributions of the work presented in this thesis include the following:

- In this thesis, a microgrid control and operation with hierarchical architecture is realized using the LabVIEW programming language and interfaced with the physical microgrid through hardware circuitries. The AC current and voltage, and DC current and voltage sensing circuitries are designed to satisfy the system requirements of the prototype microgrid in the Distributed Generation Laboratory at the University of Western Ontario. This microgrid control and operation interface is capable of monitoring and recording the real-time information on active and reactive power, system frequency and voltage profiles, power factor/angle, and the conversion efficiency of the inverter interfaced PEMFC power module.

- Utilizing the real-time monitoring capability of the developed microgrid control system, the dynamic characteristics of the inverter interfaced PEMFC power module are analyzed to complement the previous work done on the steady-state study. It is observed that the output voltage and the frequency of the synchronous generators have a drooping characteristic, with an increase of active power output. In the meantime, the output voltage of the inverter shows a similar drooping behaviour, but the output frequency exhibits inflexibility, and it is fixed at a constant level. These results are used to validate the proposed load sharing scheme with load-voltage droops for a microgrid with fixed frequency.

- The DC to AC conversion efficiency of the DC/AC inverter is obtained by experimentations. It is shown that the conversion efficiency of the inverter improves as the actual power output increases. A maximal efficiency of 80 percent is reached when the inverter is operating at about half of its rated capacity. For this reason, it is preferable to operate the inverter interfaced PEMFC at a higher output level to maximize the conversion efficiency.

- To dynamically regulate the output voltage of the inverter interfaced PEMFC, a feedback voltage regulator is developed. The control parameters are given by online tuning. The performance of the feedback voltage regulator is verified.

- The load sharing scheme with load-voltage droop is validated using the developed microgrid control system. The results show that by dynamically shifting the voltage setpoints of the inverter, the PEMFC power module is able to pick up the change in the load, while maintaining a constant system voltage. The results experimentally prove the effectiveness of this novel load sharing scheme.

- For the purpose of minimizing the generation costs of a microgrid in an islanded mode, two power dispatch strategies are proposed for the prototype microgrid and compared theoretically and experimentally. One is based on progressive unit participation, and the other relies on the alternative energy as base load providers. The comparison shows that each strategy has its own advantages and disadvantages. For this reason, a proper scheduling decision must be made based on the real-time market information and environmental constraints.

8.2 Suggestions for Future Work

Following subjects are suggested for the continuation of work on the microgrid systems:

1. The microgrid, considered in this research, is operating in an islanded mode. It would be useful to investigate the grid-connected capability of the existing microgrid.
2. At present, fuel cell technology for stationary power generation is still at its infancy. It is suggested to integrate other renewable energy sources, such as PV and wind into this microgrid.
3. As more alternative energy sources being integrated into the microgrid, it is worthwhile to investigate different operational strategies and dispatch schemes for this microgrid.
4. So far the load sharing scheme has focused on the active load only. It is worthwhile to investigate the role that the reactive power plays in this microgrid.

APPENDIX A: Power Calculation Unit

A. 1. Power Calculation Unit in LabVIEW

Following equations are used for the power information calculation:

The instantaneous power delivered can be expressed as

$$p_{(t)} = v_{(t)} \times i_{(t)} \quad \text{(A.1)}$$

where:

$$v_{(t)} = \sqrt{2} V_{rms} \cos(\omega t)$$

$$i_{(t)} = \sqrt{2} I_{rms} \cos(\omega t + \theta)$$

$$p_{(t)} = V_{rms} I_{rms} \cos(\theta) + V_{rms} I_{rms} \cos(2\omega t + \theta) \quad \text{(A.2)}$$

The magnitude of the complex power is:

$$\mathbf{S} = V_{rms}\, I_{rms} \quad \text{(A.3)}$$

The magnitude of the active power is:

$$\mathbf{P} = V_{average}\, I_{average} \quad \text{(A.4)}$$

The reactive power is:

$$\mathbf{Q} = \sqrt{\mathbf{S}^2 - \mathbf{P}^2} \quad \text{(A.5)}$$

The power factor is:

$$pf = \mathbf{P} / \mathbf{S} \tag{A.6}$$

The phase angle is:

$$\theta = \cos^{-1} pf \tag{A.7}$$

The sub virtual instrumentation (subVI) for the power calculation unit is shown in Fig. A.1. The inputs to this subVI are the filtered voltage and current in AC form. The active power is obtained by taking the average of the multiplication of the instantaneous AC voltage and current. The magnitude of the complex power is obtained by multiplying the RMS value of the instantaneous AC voltage and current. The active power is calculated by averaging the multiplication of the instantaneous value of the AC voltage and current. The leading or lagging power factor is calculated using the embedded "Lag-Lead.vi" subVI program module available in LabVIEW.

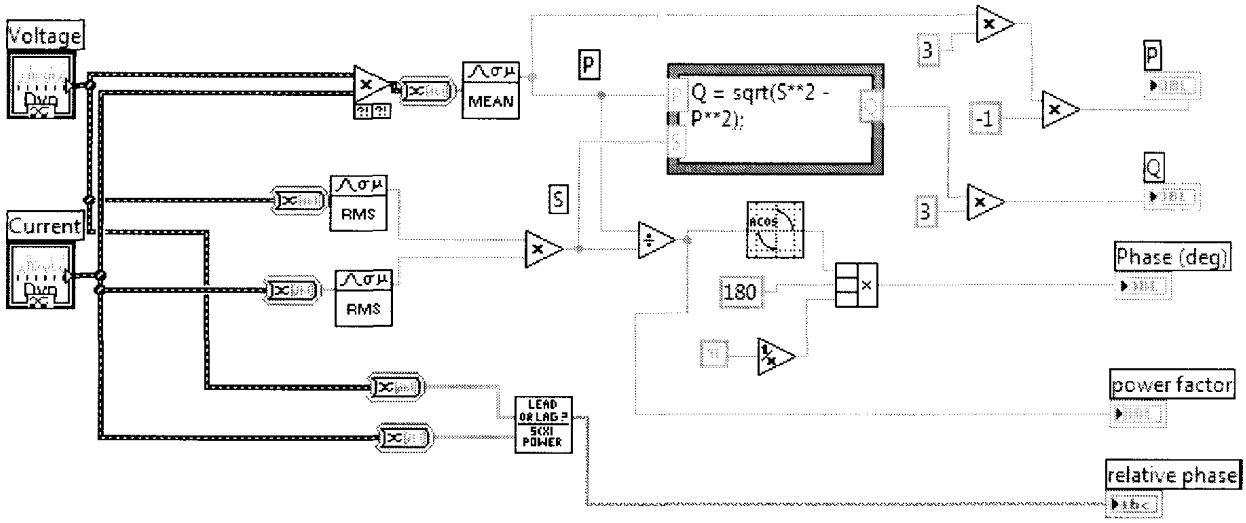

Fig. A.1. The block diagram of the power calculation unit in LabVIEW

APPENDIX B: System Configuration with Measurement Devices

The list of voltage and current sensors used for the system implementation is illustrated in Table B.1. Fig.B.1 depicts the overall configuration of the microgrid control and operation system. The locations of the corresponding sensors are also indicated in Fig.B.1.

Table B.1. Current sensors and votlage sensors corresponding to the locations shown in Fig. B.1

Name	Location	Purpose
AC Voltage Sensor	1	Measure the output AC voltage of the power inverter
AC Voltage Sensor	2	Measure the output AC voltage of synchronous generator 1
AC Voltage Sensor	3	Measure the output AC voltage of synchronous generator 2
AC Current Sensor	4	Measure the output AC current of the power inverter
AC Current Sensor	5	Measure the output AC current of synchronous generator 1
AC Current Sensor	6	Measure the output AC current of synchronous generator 2
DC Voltage Sensor	7	Measure the output DC voltage of the DC/DC converter
DC Current Sensor	8	Measure the output DC current of the DC/DC converter
DC Voltage Sensor	9	Measure the output DC voltage directly from the PEM fuel cell module
DC Current Sensor	10	Measure the output DC current directly from the PEM fuel cell module
DC Current Sensor	11	Measure the output current and its direction of the battery bank

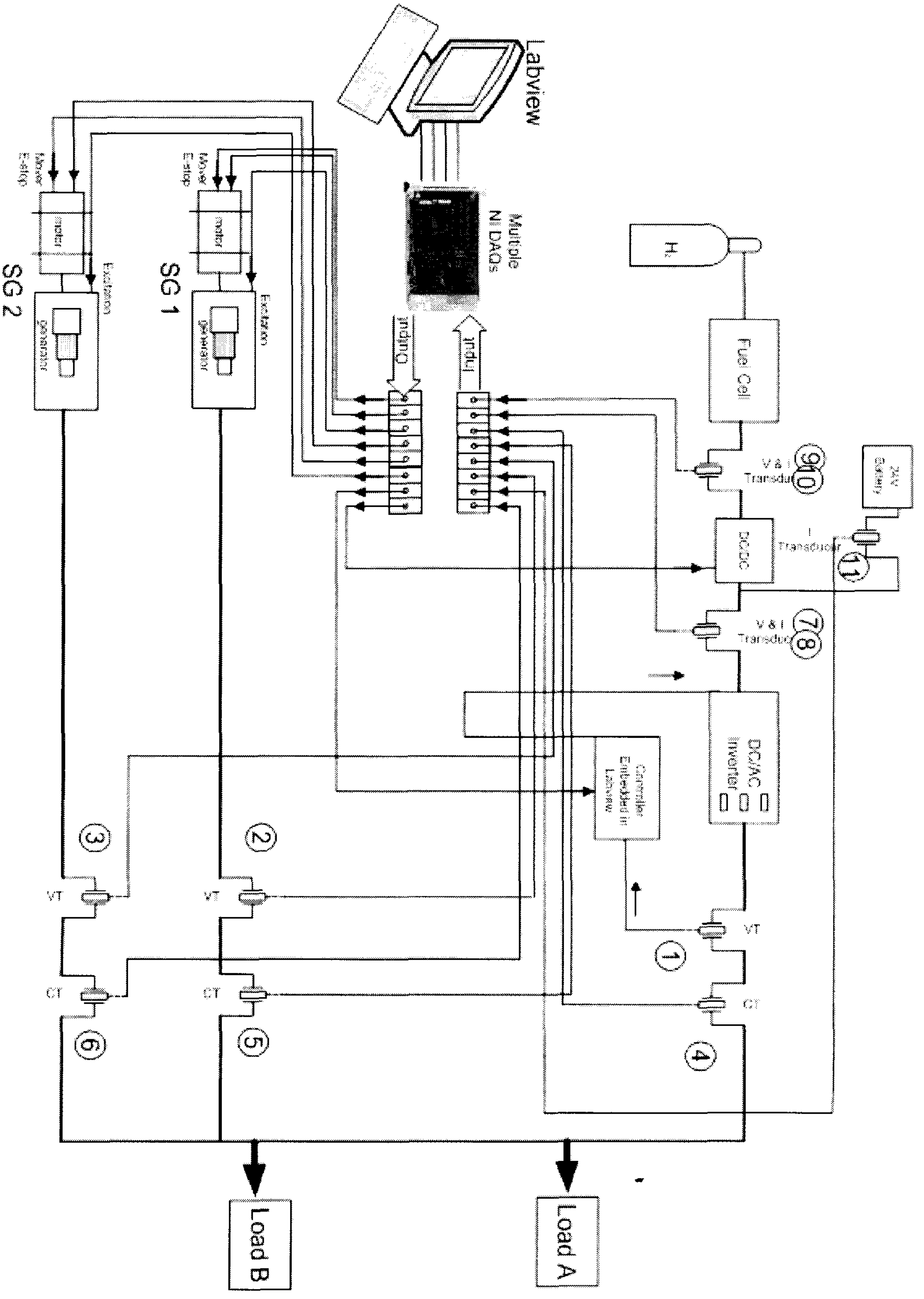

Fig. B.1. System configuration with current and voltage sensors