Role of solid oxide fuel cell distributed generator for stationary power application

Li, Yonghui

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The Role of Solid Oxide Fuel Cell Distributed Generator for Stationary Power Application

Li Yonghui

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

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List of Symbols

The following symbols are used throughout the thesis:

$p_{H_2}, p_{O_2}, p_{H_2O}$:	Cell stack output partial pressure of hydrogen, oxygen and water respectively.
$N_f, N_{H_2}, N_{O_2}, N_{H_2O}$:	Gas molar flow rate of natural gas input, hydrogen, oxygen and water respectively.
$N_{H_2}^{in}, N_{O_2}^{in}$:	Cell stack input gas molar flow rate of hydrogen and oxygen respectively.
$N_{H_2}^r, N_{O_2}^r, N_{H_2O}^r$:	Reacted gas molar flow rate of hydrogen, oxygen and water respectively.
$N_{H_2}^{out}, N_{O_2}^{out}, N_{H_2O}^{out}$:	Cell stack output gas molar flow rate of hydrogen, oxygen and water respectively.
E :	FC open-circuit EMF.
E_0 :	FC ideal standard potential.
R :	Gas constant.
T :	FC operation temperature.
N_0 :	Number of series cells in the stack.
K_r :	FC modeling constant.
$K_{H_2}, K_{O_2}, K_{H_2O}$:	Valve molar constant of hydrogen, oxygen and water respectively.
$\tau_{H_2}, \tau_{H_2O}, \tau_{O_2}$:	Flow response time of hydrogen, oxygen and water respectively.
τ_f :	FC power plant fuel processor response time.
r_{H_2O} :	Ratio of hydrogen and oxygen.
u :	FC fuel utilization factor.
u_s :	Fuel utilization factor setting.
V_{dc} :	FC terminal voltage.
I_{FC} :	FC stack current.

r :	FC Ohmic loss.
$\Delta V_{act}, \Delta V_{ohm}, \Delta V_{con}$	FC activation, Ohmic and concentration voltage drop respectively.
a_{act} :	FC Tafel constant.
b_{act} :	FC Tafel slope.
a_{con}, b_{con} :	FC concentration loss constant.
m :	PCU control variables modulation index.
δ_f :	PCU control variable phase shift angle.
R_F, L_F, C_F :	Filter resistor, inductor and capacitor respectively.
Q_f :	Quality factor of filter.
ω_f :	Cut-off frequency of filter.
ε_v :	THD of the load voltage.
ε_I :	THD of the PCU output current.
ε_p :	Power loss caused by filter.
$\dot{V}_f, \dot{V}_s, \dot{V}_p$:	Phasor vector of PCU output, upstream source and PCC voltage respectively.
V_f, V_s, V_p :	Magnitude of PCU output, upstream source and PCC voltage respectively.
$\dot{I}_f, \dot{I}_{df}, \dot{I}_{qf}$:	Phasor vector of PCU output current and its corresponding d and q axis components.
I_f, I_{df}, I_{qf} :	Magnitude of PCU output current and its corresponding d and q axis components.
ε_u :	Fuel utilization factor deviation percentage from u_s .
$P_{dg}, P_{DC}, P_{SP}, P_{HQ}, P_{OQ}$:	Output power of DG, real power of DC, SP, HQ and OQ load respectively.
Q_{SP}, Q_{HQ}, Q_{OQ} :	Reactive power of SP, HQ and OQ load respectively.
P_r, Q_r :	Real and reactive power that FC send to the PCC.
P_{max}, P_{min} :	Maximum and minimum FC real power output respectively.
X_f :	Linking impedance between FC power plant and the PCC bus.

List of Abbreviations

The following abbreviations are used throughout the thesis:

AC:	Alternating Current.
BOP:	Balance of Plant.
CB:	Circuit Breaker.
CHP:	Combined Heat and Power.
DC:	Direct Current.
DG:	Distributed Generation.
DSTATCOM:	Distribution STATCOM.
DVR:	Dynamic Voltage Restorer.
FC:	Fuel Cell.
FOA:	Feasible Operating Area.
HQ:	High Quality.
ICE:	Internal Combustion Engine.
IGBT:	Insulated Gate Bipolar Transistor.
IM:	Induction Motor.
MCFC:	Molten carbonate fuel cell.
MPPT:	Maximum Power Point Tracking.
MT:	Microturbine.
OQ:	Ordinary Quality.
PAFC:	Phosphoric Acid Fuel Cell.
PCC:	Point of Common Coupling.
PCU:	Power-Conditioning Unit.
PI:	Proportional Integration.
PLL:	Phase Lock Loop.
PQCC:	Power Quality Control Center.
PV:	Photovoltaic.
PWM:	Pulse Width Modulation.
RRPC:	Real and Reactive Power Controller.
SC:	Series Compensator.

List of Abbreviations

SOFC:	Solid Oxide Fuel Cell.
SP:	Super Premium.
SPWM:	Sinusoidal PWM.
SSCB:	Solid State Circuit Breaker.
SSCL:	Solid State Current Limiter.
T&D:	Transmission and Distribution.
THD:	Total Harmonic Distortion.
UPS:	Uninterruptible Power Supply.
VSI:	Voltage Source Inverter.
WT:	Wind Turbine.

Summary

Distributed power (DG) generation technology is envisaged to play an increasingly important role in electrical power systems. Among all the DG types that can be used for stationary power supply, the natural gas-fed fuel cell (FC) attracts much attention due to its advantages of high efficiency, environmental friendliness and the ease to site. Developed electrical networks such as that of Singapore, in an attempt to diversify the mode generation of electricity in order to enhance system reliability, efforts have been made to explore the use of the FC-based DG technology. The technology, if properly used, may help the grid to also enhance power quality.

The FC-based DG technology is still far from mature. Continuous improvements on the FC performance, durability and making it economically competitive are needed in order to encourage its wide application. This project is concerned with the operation and control of the Solid Oxide Fuel Cell (SOFC) power plant for stationary power supply. In particular, how the FC power plant would alleviate power quality problems such as that during load-tracking and short-term voltage disturbance are studied.

Starting from an available SOFC dynamic model, the relationship between the FC terminal voltage, stack current and fuel utilization factor is established through analysis. Based on the derived analytical results, the concept of Feasible Operating Area (FOA) is introduced as the theoretical framework for the FC operation and control. FC is studied under an isolated condition and a grid-connected condition.

In an isolated condition, FC could be used to solve the slow power quality issue such as load tracking. Based on the derived small-signal dynamic model and the concept of FOA, FC could be controlled with either constant fuel utilization factor scheme or constant voltage scheme.

Harmonic is the possible power quality issue caused by the FC-based DG. To mitigate the harmonic issue in an isolated system, an analytic method used to design the reliable, low-cost second-order low-pass filter is given.

The fastest and yet prudent ways of changing the output power level of an SOFC power plant to solve the load-tracking problem under grid-connected condition is also explored. Four strategies are provided to achieve the different power demand. Namely, step strategy, ramp strategy, step plus ramp strategy and on-line strategy. On-line strategy can achieve the large power demand with minimum time and is independent of the models of the fuel processor and the cell stack.

The role of the SOFC in a distribution system of the future is examined. It consists of a Power Quality Control Center (PQCC). Under normal network condition, the SOFC could be used to supply the local loads. When short-duration voltage disturbance occurs, a new PQCC operating scheme is then proposed to alleviate the impacts of the disturbance. Different loads can therefore enjoy the unbundled power quality supply offered by the PQCC.

Chapter 1

Introduction

1.1 Motivation

Due to the deregulation of the power supply industry and the growing emphasis on environment, utilities have shown greater interest to develop distributed generation (DG) technologies [1-4]. Compared to the traditional centralized fossil fuel power plant, DG is the concept that provides electricity at or near load [2, 3]. DG schemes can be divided into two types. One type is the fossil fuel-based sources such as fuel cell (FC) and high-speed microturbines. The other type is the renewable sources such as those depend on solar and wind energy. The capacity of DG can range from 5 kW to 10 MW. It is envisaged to play a leading role as a new means of power generation, to meet the demand for new generation capacities [4]. By the end of year 2004, the total DG installation capacity worldwide is estimated to reach approximately 31 GW. Studies predicted that DG might account for up to 20% of all new generation going online by the year 2010 [5]. DG is a challenge to the conventional power systems. It has been claimed that DG can provide reliable, cost-effective, high-quality power to the utility customers [6-9]. Furthermore, many DG systems produce so little noise and emissions that they can be located near buildings [2, 4]. This greatly simplifies the problems of conventional distribution network infrastructure development. The local DG power supply could decrease transmission and distribution power losses.

At the other end of the electricity supply system is the customer loads. In a typical modern power system, there may be a large proportion of the so-called sensitive loads such as that in hospitals, process plants, air traffic control, financial institutions and numerous other data processing and service providers. All these loads require “clean” and uninterrupted high quality power. Power quality problems such as supply frequency deviation, harmonics, voltage sag etc can cause loss of production, damage to equipment or even be detrimental to human health.

Thus, with the introduction of more and more DG into the system, the possible impacts on network due to the DG must be carefully investigated [16-21]. One obvious effect is that the contribution from the DG may change the power flow direction in the distribution network. This will bring some new but related problems such as voltage regulation, harmonics and voltage stability which may not have been factored into doing the design of the existing conventional power systems [10-15]. Hence, DG may have some positive as well as negative effects on power quality.

Among all DG technologies, the modular, high-efficiency, environmentally-friendly Solid Oxide Fuel Cell (SOFC) DG is an attractive option for stationary power supply. SOFC DG is still on its early stage of commercial development [22-25]. Some demonstrative SOFC power plants have been reported in [24-27]. The current main challenge to develop this DG technology to wide-spread use is to explore the high performance and durable promises of SOFC (for over 40,000 hours for stationary applications and more than 50,000 hours for transportation applications) while reducing its cost. Although great efforts have been made by researchers, much works remain to be done on the FC-based DG for power generation.

In the stationary power supply application, modeling the SOFC DG and its effects on power quality are not well reported in the literature yet. Therefore, the research work described in this thesis was carried out under the following two aspects:-

A. Modeling of SOFC Power Plant

When FC generates electricity, it involves complex thermodynamic, electrochemical and electrical processes. In order to gain some insights into these processes, it is necessary to build a suitable SOFC power plant model. Depending on different research interest, there have been several approaches to modeling the FC [28-34]. This thesis is focused on the electrical aspect of the FC. Therefore, the SOFC plant model to be derived and used in the investigation must be suitable for power system analysis. Earlier works directed toward this area are described in [34, 35]. Although these works are based on certain approximations, the dynamic model provided by them is to some extents, being accepted by power engineers and applied in their studies [36, 37]. During the energy

conversion process, a number of variables may affect the steady and dynamic state performance of the FC. Due to the complex relationships of these variables, the general methods of examining the relationships between these variables are through analysis, supported through experimental measurements and simulations. Based on these results, an interesting analytical method relating to the FC electrical variables (FC terminal voltage and stack current) and performance variable (fuel utilization factor) can be derived. This will be discussed in Chapter 3. This result depicts some operating constraints of the cell and it affects the operation and control schemes of the FC.

The dynamic model described in [34] is a nonlinear model in the frequency domain. This model is not amenable for the analytical study of the control of the FC through classical method. A simplified SOFC dynamic model can be derived by linearizing the model. From the frequency domain analysis, the essential dynamic characteristics of the FC can be obtained. The analytical results are also useful for the design of possible power quality improvement schemes which are based on the SOFC DG.

B. Power Quality Improvement

DG is an electricity generation plant in which through manipulation of its controls, it can regulate its reactive power output to fully utilize its capacity. The operating and control scheme of the DG may affect supply reliability and quality. Three power quality issues related to DG will be discussed in this thesis. They are:

- Harmonics

As will be discussed in Chapter 2, the output of the SOFC DG is in the form of DC power. To convert the DC power into the AC form, a Power-Conditioning Unit (PCU) is a necessary component of the SOFC power plant. The fast-acting power electronic switches in the PCU alternatively connect the FC terminal to the external AC system. Unless special design steps are taken, the output voltage of the PCU is usually not in a perfect sinusoidal form and will contain harmonics. The harmonics generated during the switching process may provoke malfunction of load equipment and reduce the life of sensitive loads. To improve power quality, low-pass filter is a widely-used harmonic mitigation solution. It can be connected between the PCU and the external circuit. In the present context, the filter design is related to the SOFC control scheme, the PCU

switching method and the external circuit. The output filter for the FC in an isolated system will be discussed in Chapter 5.

- Load tracking

From the derived simplified SOFC model, it is seen that SOFC is relatively slow compared to a conventional AC generator. However, normal load variations which appear in normal network operations can be monitored and tracked by this kind of stationary power supply. The SOFC DG can operate either in an isolated system or in a grid-connected system. In the load-tracking application, the natural gas input to the FC and the PCU can be controlled to cater for different power demand. Although some researchers have investigated this problem, they have not given a clear and convincing analysis on how to control the FC in order to support the varying load. Regardless of the control scheme, fuel utilization factor, the most important FC performance variable must be taken into consideration. A fast yet prudent way for load-tracking need to be explored. The load-tracking problem will be addressed in Chapters 4 and 6.

- Voltage sag mitigation

Voltage sag is the most devastating occurrence that could affect power quality. Its impacts to industries have been costly [38-41]. In order to help loads ride through this kind of short duration disturbance, it has been suggested that SOFC power plant may be used. Although the FC is slow in nature, the fast-acting PCU can quickly regulate the real and reactive power in the distribution network. A flexible control scheme suitable for the SOFC power plant can provide different levels of power quality to the various loads. This form of a future distribution network is investigated in Chapter 7.

From the above introduction, the objective of this research work is therefore to find a proper operation and control scheme for the SOFC power plant to supply the load and improve load power quality. The proposed method will then be applied to SOFC for application into power systems. Successful application of the FC-based power plant can help the development of this type of DG.

1.2 Major Contributions of the Thesis

As a result of the research work, the following original contributions have been made.

a. The concept of the feasible operating area (FOA) for the SOFC is introduced and a small-signal SOFC dynamic model is derived. Based on an available SOFC dynamic model and the FC operating constraints, the FOA is derived. FOA provides a theoretical framework under which a safe operating regime of the FC can be readily determined. It is the only known concept describing the FC operation by relating the fuel utilization factor, fuel cell current and terminal voltage in a graphical manner. Starting from the FOA, feasible operation and control schemes for the FC have been derived, in which the steady state and transient state operations remain within the FOA are guaranteed. This would ensure the SOFC to operate safely. In particular, based on the derived SOFC dynamic model, operation of SOFC under constant fuel input and constant fuel utilization conditions are analyzed in the frequency domain. It shows that the FC is a slow-acting power source. Under a load current step change, it is found from the numerical analysis that the FC under constant fuel utilization can effectively smooth out terminal voltage variations. The use of shunt capacitor as an energy balancer appears to be ineffective.

b. Analysis and design the SOFC controller for load tracking in an isolated system condition is considered. In order to maintain the FC operating point to within the FOA during the load-tracking process, FC can be controlled under either constant fuel utilization scheme or constant terminal voltage scheme. The former control scheme can be easily implemented by introducing a simple current feedback. On the other hand, the latter control scheme is more complex and the controller in this scheme should be designed based on the most onerous condition. When the external load supplied by the FC varied with different step and ramp speed, simulation results validate the feasibility of the proposed control scheme.

c. To show how the output harmonics can be mitigated, an output filter design for the SOFC power plant in an isolated system is studied. In order to eliminate the harmonics caused by the PCU, a second order low-pass filter can be connected between the PCU and load. In accordance with the FC operation scheme, an analytical design scheme has been proposed. The filter will ensure that the load voltage total harmonic distortion (THD), current THD and power loss in the filter will be within acceptable range simultaneously.

d. Analysis and design the control scheme of the SOFC power plant for load tracking in a grid-connected condition is also investigated. By tuning the PCU two control variables, modulation index and the phase shift angle, the SOFC power plant can be made to supply the required real and reactive power to the external grid by adopting the constant fuel utilization control scheme. A mathematical description of the relationship between the fuel processor, stack current and fuel utilization factor is established. By the proper manipulation of the stack current, the analysis shows that power demand changes of up to a limited value can be safely achieved in a single step change of the stack current. The limit is dependent on the allowable range of utilization factor and the initial operating stack current. Such limit can also be used to support the step load change. For a larger change of power, however, the maximum step change should be superimposed with a ramp change in current so that the utilization factor is maintained at the boundary of the FOA until the desired power level is reached. For large power changes, the ramp rate needs to be varied by on-line control such that the utilization factor remains at the boundary of the FOA. Based on the on-line information, the proposed current control strategy is not only independent of the cell model, but also independent of the fuel processor model. The real power change can be achieved in minimum time by maintaining all the FC transient operating points within the FOA.

e. Voltage sag ride-through scheme through the use of Power Quality Control Center (PQCC) is studied. This is a new scheme in that the embedded FC-based DG in the PQCC is designed to play an important role in the distribution network of the future. Through regulating the back-to-back converters, PQCC has the ability of manipulating the power flow flexibly. Under normal state, the SOFC works as a DG and provides power to the local loads at high efficiency. When the upstream system experiences a voltage-sag, the Center could operate as a shunt compensator and it provides unbundled power quality to different loads while maintaining the operating points of the FC within the FOA. Under less severe voltage sags, a decoupled control method is used by the PQCC to supply a certain level of real and reactive power to the other two lower quality-level loads (HQ and OQ) and maintain interconnected operation. The SOFC would still be free from the disturbance. If the voltage sag exceeds a certain level, the PQCC will be disconnected from the upstream source and it will operate in an isolated mode. By fully

utilizing the capability of the SOFC and inverters, different loads in the PQCC can enjoy different levels of power quality.

1.3 Organization of the Thesis

The motivation and major contributions of the research are outlined in this chapter. A review of the power quality problems and mitigation solutions, DG technologies and its effects on power quality will be discussed in Chapter 2. Specifically, a brief introduction of the SOFC power plant structure, fundamental electrode reaction within the FC, power plant efficiency and the Nernst equation used to calculate the cell EMF will also be given.

Based on the available SOFC dynamic model, the concept of the FOA will be derived and shown in Chapter 3. Using small-signal analysis, a linearized SOFC dynamic model is derived and used to analyze the constant fuel input and constant fuel utilization operating conditions of the FC. From the derived transfer function of the FC EMF with respect to the stack current, it is shown that the FC EMF is slow to respond the current change. Numerical method shows that shunt capacitor energy storage is not required when the FC is operated under constant fuel utilization manner.

Based on the concept of FOA, the SOFC power plant used to track load in an isolated system is discussed in Chapter 4. When the external load varies slowly, FC can be operated under the constant fuel utilization condition. This is achieved by regulating the fuel intake according to the stack current. Any FC steady-state operation point will be forced to settle on the pre-set constant fuel utilization line. Combined with this inner current feedback, a voltage control loop can also be used to maintain the FC terminal voltage. The classical control method based on the small-signal FC dynamic model derived in Chapter 3 is used to design the controller.

In accordance with the FC possible operation scheme, an output filter design method for the SOFC power plant in an isolated system is proposed in Chapter 5. The second order

low-pass filter can improve the load power quality by alleviating the harmonic levels in the AC network.

SOFC power plant load-tracking application in the grid-connected system is introduced in Chapter 6. The phase shift and modulation index control variables of the PCU are utilized to regulate the stack current and to keep the power factor of the plant constant for all power levels. Different strategies in which the stack current can be changed are studied to achieve the objective of minimizing the transient time while maintaining the utilization factor in the allowable region. Power demand of different magnitude can be met through by the strategies described in the chapter.

Operation and control the PQCC is then discussed in Chapter 7. The SOFC based DG is used to help load ride-through during short-duration voltage disturbances. The PQCC can deliver unbundled power quality to different loads by taking advantage of the flexibility offered by the SOFC and the inverters.

The main findings of the research and recommendations for future work are given in Chapter 8.

Chapter 2

Power Quality and Distributed Generation

2.1 Introduction

Long-term growth in electrical demand and ever increasing concern on environment encourage the search for clean and abundant sources of energy. Traditional method to satisfy the power demand is by establishing bulk power plant. Typically, the power plant is sited near the source of fuel but could be far from the load center. The plant will need a long lead-time to construct. The burning of the fuel (e.g. coal) may cause environmental problems such as acid rain and photochemical smog. In addition, the transmission and distribution (T&D) networks need to be reconstructed if there are transmission constraints [2]. This approach to power network development may cause the new installations to lag the increasing load demand, often leading to degradation in supply reliability. Therefore, some new approaches to meet the load demands have to be found. On the load side, ever-increasing amount of sensitive loads in the network requires high quality power supply. Excessive deviations of the supply frequency and voltage, even for a short duration, could cause unscheduled shutdown of industrial processes or equipment failure, resulting in substantial financial losses for customers. During the disturbances, governors and exciters of the generators are often too slow to carry out corrective actions. To mitigate the disturbances, it is necessary for the power system to possess some additional schemes to improve load-side power quality. Distributed generation (DG) is one possible solution [2-4].

DG technology is a challenge to the conventional power systems. On the plus side, most of the distributed generators are modular, environmental friendly and easy to site. DG becomes a viable option to increase the generating capacity on the load side and makes it possible to avoid the cost of reconstructing the T&D networks. As DG has the capability to provide real and reactive power, DG is expected to provide improved quality of power to the nearby loads. The extent of the improvement will clearly depend on the reliability and maturity of the operation and control schemes of the DG. Among all types of DG,

the Solid Oxide Fuel Cell (SOFC) power plant is one of the best candidates for stationary power supply. This thesis will focus on the electrical aspects of the SOFC power plant, particularly its impacts on power quality.

This chapter is organized as follows. Section 2.2 will provide a brief introduction on power quality issues. Some widely used power quality improvement methods will then be shown in Section 2.3. Various DG technologies and their possible effects on power quality will be reviewed in Sections 2.4 and 2.5 respectively. Finally, some basic knowledge on the fuel cell power plant will be described in Section 2.6.

2.2 Power Quality Problems

In a power system operating under steady state, the generated power and load demand are balanced. The network operates with constant voltage and frequency. Uncontrollable disturbances, such as the continuously varying load and randomly occurred faults, will cause a power unbalance between generation and demand. The real power unbalance will cause the frequency to deviate from the steady-state value while unbalanced reactive power mainly affects the voltage magnitude. To evaluate supply quality, the concept of power quality has to be understood.

Power quality refers to the provision of the voltages and system design so that the user of electric power can utilize electric energy from the system without interference or interruption [38-40]. Power quality of an AC system can be quantified technically on the basis of the following criteria:-

- Constant sinusoidal waveshape with no harmonic component.
- Constancy in frequency.
- Symmetrical or balanced three-phase.
- Constancy in rms voltage value.
- Reliable electricity supply.

Technical terms to clarify power quality issues are well documented in the literature. The following power quality problems are defined and briefly discussed [38-41]:-

- Voltage sags: A decrease in rms voltage at power frequency for a duration of 0.5 cycles to 1 minute with voltage magnitude decrease ranges from 0.1 to 0.9 p.u. Causes of the voltage sags are local and remote faults in the power system, switching of large induction motor loads etc. Voltage sags have the potential to disrupt sensitive load operation and cause loss of production. Studies have shown that voltage sags as the cause of 70% to 90% of power quality problems.
- Short interruptions: The complete loss of voltage (below 0.1 p.u.) on one or more phase conductors for a time period between 0.5 cycles to 3 seconds. The causes of short interruptions include fault clearing by the protection system and incorrect protection intervention.
- Voltage swells: A temporary increase in rms voltage of more than 10% of the nominal value at power system frequency which lasts from 0.5 cycles to 1 minutes. Typical range is 1.1 to 1.8 p.u. When a single-line-to-ground fault occurs in the power system, for example, voltage of the healthy phases rise (swell) above the nominal voltage.
- Transients: These are related to the phenomena of supply voltage varying between two consecutive steady states during an interval which is short compared with the time scale of interest. A transient can be a unidirectional impulse of either polarity, or damped oscillatory wave with the first peaking occurring in either polarity. Although most transients are usually generated near the user by other equipment, switching operations on the utility network pose a more serious problem. Capacitor switching can lead to transients with magnitudes of 2~3 p.u. and energy levels which can considerably shorten the life of surge protection devices.
- Voltage flickers: The impression of unsteadiness of visual sensation included by a light stimulus whose luminance or spectral distribution fluctuates with time. Arc furnace is one of most common causes of flicker.
- Supply frequency variations: Continuous load variation will cause real power unbalance. The supply frequency will deviate from the nominal frequency 50Hz. The

maximum tolerable variation in supply frequency is often limited within $\pm 0.5\text{Hz}$. Compared with the above fast variation power quality problems, the load variation duration is relative slow and associated with daily, weekly and seasonal patterns, typically of several minutes to hours. If this load variation is not properly tracked, the sustained real power unbalance will cause the supply frequency to deviate outside the tolerable range and reduce the life span of generators and loads.

- **Harmonics:** Sinusoidal voltage or currents having frequencies that are multiples of the fundamental power frequency. Distorted waveforms can be decomposed into a sum of the fundamental frequency wave and the harmonics caused by nonlinear characteristics of power system devices and loads. With the growth of non-linear loads such as personal computers and energy efficient fluorescent light sources, the combined effect of several thousand of such devices on a feeder can lead to the situations where the harmonic distortion can be greater than the 5~10% levels normally set by regulation standards. These loads are often unpredictable and harmonic content can vary greatly according to load. Harmonic effects on power system include increased losses, equipment heating and loss of plant life, and interference with protection system, control as well as customer loads.

There are other power quality problems such as voltage unbalance, over-voltage, under-voltage and voltage notch. Interested readers may refer to [38-44].

2.3 Methods to Enhance Power Quality

Power quality problems have already existed since the inception of power systems. Due to the proliferation of microcomputer-based systems which are sensitive to power disturbances, power quality problems have attracted the attention of the utility industry in recent years. Two kinds of power devices have been proposed in the literature to enhance power quality. One is Custom Power device. The other is DG [3, 6, 7].

The Custom Power devices can again be sub-divided into two types: network reconfiguring type and compensating type [42, 43]. The network reconfiguring

equipment can be GTO-based or thyristor-based. They are usually used in the distribution feeders for fast current limiting and current breaking during faults. They can also prompt a fast load transfer to an alternative feeder and protect sensitive loads from voltage sag/swell or fault in the supplying feeder. Family members of network reconfiguring devices are:-

- Solid State Current Limiter (SSCL): This is a GTO-based device that inserts a fault current limiting inductor in series with the faulted circuit as soon as the fault is detected. The inductor is removed from the circuit once the fault is cleared.
- Solid State Circuit Breaker (SSCB): This is a device that can rapidly interrupt a fault current and also performs auto-reclosing function. Based on a combination of GTO and thyristor switches, this device is much faster than the mechanical circuit breaker and is an ideal device for Custom Power applications.
- Solid State Transfer Switch (SSTS): This thyristor-based device is used to protect sensitive loads from sag/swell. It can transfer the load undergoing a voltage sag/swell to an alternative feeder within sub-cycle. A SSTS can also be used as a bus coupler between two incoming feeders.

The compensating type of devices are used for active filtering, load balancing, power factor correction and voltage regulation. Some of these devices are used in load compensation while others are operated to provide balanced, harmonic-free voltage to the customers. Family members of compensating type devices are:-

- Distribution STATCOM (DSTATCOM): This is a shunt-connected device that can perform load compensation, i.e., power factor correction, harmonic filtering, load balancing etc. when connected to the load terminals. It can also perform voltage regulation, when connected to a distribution bus, by injecting an unbalanced and harmonically distorted current to the poor power quality feeder. The protected load will receive a distortion-free voltage [44].

- **Uninterruptible Power Supply (UPS):** This is the most widely used shunt compensation device that can help sensitive loads ride through disturbances. UPS can be operated on-line or on stand by mode [38].
- **Dynamic Voltage Restorer (DVR):** This is one of the most promising series-connected devices to mitigate voltage sag/swell. DVR can rapidly inject series voltage to compensate for balanced or unbalanced sag/swell in the upstream supply voltage [45]. DVR can also be used as a series active filter [46].
- **Unified Power Quality Conditioner:** This is a versatile device that can inject current in shunt and voltage in series simultaneously in a dual control mode. Therefore, it can perform both the functions of load compensation and voltage control at the same time by injecting unbalanced and distorted voltage and current to the feeder [47].

DG as a power quality enhancement device can increase the generating capacity. With significant DG sources installed, the nearby load variation can be readily tracked, thus the supply frequency variations can be reduced. Detailed DG technology and its effects on power quality will be discussed in the following two sections.

Figure 2-1 A Custom Power park

In order to illustrate the role the power quality enhancement devices can play in a network, Figure 2-1 shows an example of a Custom Power park. The SSTS is normally opened. The sensitive load and the other regular loads are supplied by feeders A and B independently. Any fault upstream or downstream in feeder B does not affect the sensitive load. For a fault upstream in feeder A, the SSCB opens and the sensitive load is

transferred to feeder B in less than a cycle by the rapid closure of the switches in the SSTS. At the same time, the DVR will inject a series voltage to maintain the sensitive load terminal voltage to within an acceptable range. In addition to the Custom Power devices, a DG can be installed close to the sensitive load. It can share the load demand with the upstream power source and track the load variation. In case of emergency, say when the SSCB and SSTS in Figure 2-1 are both open, DG can then supply the sensitive load independently.

2.4 Distributed Generation

Unlike conventional sources such as hydro, coal, oil and nuclear, DG technologies include mostly electrical energy provided by alternate sources of energy. DG can be broadly divided into two kinds: renewable sources and fossil fuel based sources. The renewable sources include photovoltaics and wind turbines. The fossil fuel based DG include internal combustion engines, microturbines and fuel cells. Each of the DG technology will be introduced briefly.

2.4.1 Photovoltaics

Photovoltaic (PV) is a proven and widely used form of renewable energy system. The current available PV capacity has a range of 1 kW to 1 MW with 6%~19% efficiency. Today, there is a PV market worldwide of the order of 100 MW per year and is expected to be more widely used when the cost is reduced even further [4].

PV cells directly convert sufficiently energetic photons in sunlight to electricity. As the sunlight is a diffuse resource, maximum power point tracking (MPPT) devices are used to make the best use of the PV cells. Various MPPT methods are now available to improve the performance of PV [48]. The output DC power needs to be converted to an AC form through a DC/AC converter. It can then be interconnected to a grid system. Figure 2-2 shows the typical configuration of a PV power plant.

Figure 2-2 Photovoltaic electrical system

Attractive features of PV systems include emission-free operation, no fossil fuel consumption, possible low temperature thermal cogeneration (using integrated modules) for space heating, excellent modularity, negligible maintenance except where batteries are involved, and excellent part load efficiency. The key barriers to PV usage include: (1) The price of the delivered power exceeds other DG. The capital cost is some \$6600/kW. Subsidies exist in some countries that make PV produced power competitive; (2) PV is strongly dependent of the weather condition and it cannot provide power at night, batteries or energy storage systems are often needed [2, 49].

2.4.2 Wind turbines

Wind turbine (WT) is the most widely used renewable energy DG. The current available WT capacity has a range of 10 kW to 1 MW with 25% efficiency. They are expected to provide up to 10% of the residential power in the world by 2020 [2].

Figure 2-3 Wind turbine electrical system

Wind power generation harness the kinetic energy in wind to drive the WT. The WT has a same rotor with an induction motor (IM), which is operated in the generation mode and converts the mechanical power to electrical power. As the output AC power of the IM

depends on the wind speed, AC/DC and DC/AC converters would be need to interconnect to the grid. Figure 2-3 shows the typical configuration of a WT power plant.

The advantages of wind generation are: there is no fuel charge; it is non-polluting; units are modular with a linear power vs. cost relationship for large-scale installation, and unlike solar conversion, it is potentially a 24-hour per day source of energy. Disadvantages are high initial cost (\$1000/kW), unpredictability of energy production, no viable storage system that can store the produced power, and environmental impacts considered to be greater than that with solar power [2].

Wind power generation is strongly dependent of the weather condition. Wind fluctuation may cause power quality issue such as voltage flicker. In order to overcome this problem, WT are always operating in parallel with other DG or with energy storage systems. For example, reference [50] presents a control strategy for voltage flicker in wind energy applications. A flywheel is used to smooth out the WT output power fluctuations.

2.4.3 Internal Combustion Engines

Reciprocating internal combustion engine (ICE) such as diesel is a proven, mature and commercialized DG technology. The current available ICE capacity has a range of 500 kW to 5 MW. Indeed, it has been predicted that this technology would hold 93% of the DG market until the middle of 21st century [2].

ICE converts the energy contained in the fuel such as natural gas into mechanical power based on the principle of the four-step Otto cycle. This mechanical power is used to turn a shaft in the engine. A generator is attached to the ICE to convert the rotational motion into electrical power. According to the size and rotation speed of ICE, three types of generator can be used. They are the synchronous AC generators, inductive AC generators, DC generators with DC/AC conversion.

Attractive ICE features include: (1) Capital cost is lowest of the DG (\$200~350/kW); (2) Efficiency is good (32 to 36%); (3) Thermal or electrical cogeneration is possible in buildings; (4) Modularity is excellent. Nearly any building-related load can be matched

well (kW to MW range); (5) Part load efficiency is good. The key barriers to ICE usage include the following: (1) Maintenance cost is the highest among the DG technologies due to the large number of moving parts; (2) NO_x emissions are the highest among the DG technologies: 15-20 PPM even for lean burn designs; (3) Noise is low frequency and more difficult to control than for other technologies, adequate attenuation is possible [2].

Working in conjunctions with the other forms of DG, ICE can operate in parallel with the utility to solve the power quality issues. For example, reference [18] proposed a distribution network that consists of two types of DG: WT and ICE. When WT output power fluctuates or load varies, ICE can regulate its governor and exciter to keep the supply frequency and voltage within an acceptable range.

2.4.4 Microturbines

Microturbine (MT) is still under active development. The current capacity of MT ranges from 30 kW to 500 kW. Over time, a larger market for MT is expected as the technology improves and the cost is reduced significantly [2].

Figure 2-4 Microturbine electrical system

A MT is a small combustion turbine using atmospheric air and natural gas fuel to produce mechanical power. Driven by the mechanical power produced by the turbine, a single or a dual shaft permanent magnet generator rotates at a speed of up to 120,000 RPM. It provides a high frequency AC power which must be rectified to a DC form firstly before it is converted to an AC form for connection to the external AC system. Figure 2-4 shows the typical configuration of a MT power plant.

Attractive MT features include [2, 4]: (1) Its power generators have a very low weight-horsepower ratio. The weight advantage, coupled with smaller dimensions, results in

lighter generator sets than any other source of rotating power; (2) The simplicity of the design. The pure rotary motion, and the minimal contamination of the lubrication system by fuel by-products, as compared to reciprocating engines, provides very high reliability; (3) Turbines have superior response to load variations and excellent steady-state frequency regulation, compared to other types of generators; (4) It can use either natural gas, diesel fuel, propane, jet fuel, kerosene, methane, or waste gas as fuel. Hence it is versatile; (5) There are no liquid cooling systems to maintain and little contamination of the lubrication system with exhaust by-products, as can happen continuously in reciprocating engines; (6) The exhaust gases have plenty of heat for industrial processes, water heating, space heating purpose; (7) The combustion process inside a turbine takes place in an excess of air and the products of combustion are therefore inherently cleaner than the exhaust gases of ICE. Major disadvantages of MT include: (1) The high capital cost of the MT (\$450~870/kW) is due to the expensive, high temperature materials required for its manufacture, the precision of machining needed in some stages, and its lower production volume; (2) A generally higher level of expertise is required, and replacement parts cannot be machined or “field repaired” as easily as they can with piston-engine system; (3) Thermal management system needs to be improved. Compared with the other fossil fuel DG, the MT has the lowest efficiency in the range of 20%~30%; (4) Sensitive to ambient air temperature, many must have their capacity “de-rated”. Operation of a standard MT at any altitude above sea level slightly degrades efficiency and maximum output. This problem can be solved by using over pressurized air; (5) MT produce a very loud “turbine-like” hissing which is not easy to muffle without seriously degrading fuel efficiency and peak output. They produce far less rumbling and vibration than reciprocating engines of comparable output, but are much noisier than fuel cells.

MT tend to be feasible for peak load shaving and providing high quality power to the utilities. MT can be operated together with the fuel cell power plant to build a co-generation system, which can have a very high efficiency through thermal management [51].

2.4.5 Fuel cells

The first laboratory fuel cell (FC) was found by William Grove in 1839. More than one century later, U.S and Europe developed the operational FC in the 1950s independently [24]. From then on, continuous efforts have been made and much investment directed toward improving the technology. The current capacity of the FC ranges from 50 kW to 2 MW.

A FC is an electrochemical device that converts chemical energy directly into electrical energy. Like a battery, a FC consists of a pair of electrodes and an electrolyte. Unlike a battery, however, the chemical materials consumed during the electrochemical reactions are continuously replenished so that there is no need to recharge the cell. FC are generally characterized by the type of electrolyte. Presently, the most promising FC types are: proton exchange membrane FC, phosphoric acid FC, molten carbonate FC and solid oxide FC. These four major FC types have similar structure and chemical reactions. Generally, a fuel, usually hydrogen, is supplied to the FC anode. At the anode, the fuel is oxidized, yielding electrons which travel through the external circuit. At the cathode, the oxidant reacts with the electrons from the external circuit. Ions travel through the electrolyte to balance the flow of electrons through the external circuit. The anode and cathode reactions and the composition and direction of flow of the mobile ion vary with the type of FC. Table 2-1 gives a summary of the electrode reaction of FC [26]. Despite the similarities, however, these four types of FC are very different with respect to operating characteristics, materials of construction, and potential application. The following sections will briefly discuss each FC type.

Table 2-1 Summary of the electrode reaction of the different FC

FC type	Anode reaction	Mobile ion	Cathode reaction
PEMFC	$\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$	H^+	$1/2\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$
PAFC	$\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$	H^+	$1/2\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$
MCFC	$\text{H}_2\text{O} + \text{CO}_3^{2-} \rightarrow$ $\text{H}_2\text{O} + \text{CO}_2 + 2\text{e}^-$	CO_3^{2-}	$1/2\text{O}_2 + \text{CO}_2 + 2\text{e}^- \rightarrow \text{CO}_3^{2-}$
SOFC	$\text{H}_2 + \text{O}^{2-} \rightarrow \text{H}_2\text{O} + 2\text{e}^-$	O^{2-}	$1/2\text{O}_2 + 2\text{e}^- \rightarrow \text{O}^{2-}$

2.4.5.1 Proton exchange membrane fuel cell (PEMFC)

PEMFC is characterized by a solid polymer electrolyte and pure hydrogen is the fuel used. The cell operates at a relatively low temperature of 60°C~80°C with efficiency no better than 40%. The low operating temperature permits the FC to reach operating temperature quickly. This characteristic makes PEMFC the most widely used FC. PEMFC has been commercialized for the portable, vehicular and residential applications [52, 53]. Significant research achievements have also been made in the modeling, control and performance analysis of PEMFC in the recent past [54-56]. However, the low operating temperature of the PEMFC leads to very slow chemical kinetics. Precious metal catalysts, typically platinum, must be used at the electrodes to facilitate the reactions. Due to the lower efficiency, the dependency on pure hydrogen as the fuel input and the expensive catalysts, PEMFC has not been seriously considered for stationary power applications.

2.4.5.2 Phosphoric acid fuel cell (PAFC)

PAFC was the first FC to be commercially available. It uses phosphoric acid as its electrolyte and has corrosive problems. The cell operating temperature is around 200°C with efficiency in the range of 35%~45%. This operating temperature is high enough to facilitate the recovery of heat produced with the stack for water and space heating in building application. However, the operating temperature is not high enough to overcome the need for precious metal catalysts. There have been several demonstrative applications of PAFC systems for stationary power supply [23]. The widespread economic feasibility of PAFC will depend on reducing the overall costs.

2.4.5.3 Molten carbonate fuel cell (MCFC)

MCFC is typically designed for mid-size to large stationary power applications. It uses carbonates such as LiKCO_3 and LiNaCO_3 as electrolytes. The power generating efficiency of such cells is in the range of 45%~55%. The operating temperature is about 650°C. At this temperature, precious metal catalysts are not required for the FC reactions. The heat available from the stack can be used to produce steam and hot water in

buildings for cogeneration applications. Furthermore, at this temperature, MCFC systems can be built with internal reforming, in which fuels such as natural gas are converted to hydrogen directly within the FC while it is operating. Development efforts for MCFC are focused on reducing costs and increasing the life of the cell components in the high temperature environment [23, 26, 27].

2.4.5.4 Solid oxide fuel cell (SOFC)

SOFC operates at the highest temperatures 800°C~1000°C, of all FC systems. These high temperatures not only simplify the system configuration by permitting internal reforming but also facilitate the development of Combined Heat and Power (CHP) applications to improve the system efficiency. Since the electrolyte uses ceramic such as ZrO, SOFC can be constructed in a variety of configurations without dealing with liquid electrolytes-related corrosive problems. Development efforts for SOFC are focused on reducing manufacturing cost, improving system integration, and lowering the operating temperature to the range of 550°C~750°C. The lower operating temperature would still provide the advantages of internal reforming while reducing the material problems associated with very high temperature operation. Systems based on SOFC are attractive to stationary power supply. As the main topics of this thesis are related to the SOFC, further elaboration on the SOFC power plant will be described in Section 2.6.

2.4.5.5 Advantages and disadvantages of FC

A FC power plant combines two essential advantageous features, which are increasingly gaining significance for stationary power supply application. These are the use of natural gas as the lowest carbon contents of all conventional FC and the FC is used as part of a CHP system. A considerably reduction of the energy cost per energy unit produced is achieved in this way. The advantages on the environmental impact due to a FC can be seen in the direct chemical conversion of the electrical source. This will also be described later. Furthermore, FC have no moving parts (except for the auxiliary systems); they are silent and have no vibration. They have potential fuel efficiencies far beyond even the most advanced reciprocating piston or gas turbine generators. Against these good points, FC have one significant disadvantage. They are expensive. The capital cost

is above \$3500/kW [2]. In addition, there are several “nuisance level” factors that are also of concern: they produce high-current/low-voltage DC power, which requires a DC/AC converter and filter system to transform it into AC form. The cells are not easily repaired by anyone except specialists in the technology. These disadvantages could be overcome by sound technical solutions, if it were possible to solve the cost issue. During the last decade of the 20th century, FC emerged as a viable power source for DG applications in situations where cost was less important than environmental concerns. However, widespread usage would have to wait until such time when the FC becomes cost-competitive.

2.5 Impacts of DG on Power Quality

Up to now, every type of DG described in Section 2.4 has been successfully implemented in power systems. With significant amount of DG installed in the power systems, in particular the distribution networks, power systems have to face the challenges brought on by the DG that have not existed in the conventional networks. The simple example in Figure 2-5 shows a distribution network installed with a DG. The upstream power source supplies power to the downstream load through a step-down transformer and a feeder. A DG is sited close to the load. DG could affect the power quality in the following aspects.

Figure 2-5 Distribution network with a DG

2.5.1 Voltage rise

In a conventional power system, the power flow in the distribution network is unidirectional. As shown in Figure 2-5, the power flow is from A to B. When a DG is

embedded in the distribution network, the load would have two supply options. The power flow through the feeder could change due to the contributions from the DG. When DG has surplus power after satisfying the local load, the surplus will cause power flow from B to A. Such reversed power flow would cause the rise of steady-state voltage magnitude, as analyzed in [13]. In a distribution network with a WT, a load control scheme is proposed in this reference to overcome the voltage rise problem. In order to make the full use of WT, additional load will be switched in to maintain the load voltage within the acceptable level. It is not at all certain how the additional load can be arranged, as described. It is one aspect to show that active research works are on-going to find the best solution to the voltage rise problem.

2.5.2 Harmonics

Most types of DG introduced in Section 2.4 need to use inverters to convert the energy from DC to AC form. As high-speed power switches are used in the inverters, voltage and current harmonics would be injected into the distribution network and cause waveform distortions during the switching process. In order to reduce the harmonics to acceptable level in a grid, reference [57] provided a current control scheme in coordination with a low-pass filter and an isolation transformer. The proposed control topology can effectively reject the current harmonic distortion presented in the grid. DG caused harmonics is one of the main technical barriers for the wide application of DG. Harmonic mitigation solutions are under active research.

2.5.3 Load tracking

In the distribution network, typical loads could vary minutes-by-minutes. DG as a power source can readily monitor and track this load variation. In some conditions, it would be more economical to use DG rather than the upstream power plant in this load tracking application to mitigate the power variation problem. In addition, DG can also regulate the reactive power by using the capacity of the DG. Through load tracking, power flow in the distribution network can be regulated flexibly and the possible voltage rise

problem could be solved. In this thesis, the load-tracking problems will be considered in Chapters 4 and 6.

2.5.4 Voltage sag

DG is shunt-connected in the power grid. From the analysis in [58], shunt compensator needs a much larger capacity than the series compensator to maintain the connecting point voltage. Similarly, when a voltage sag occurs due to an upstream fault for example, the small capacity DG cannot significantly maintain load voltage. In addition, DG would increase the short circuit current and cause severe voltage dip. DG effects on voltage sag and its capability to help the sensitive loads ride through the disturbances needs further study.

From the above discussion, DG may have both positive and negative impacts on power quality. This will depend on the type and the capacity of DG, as well as the power interface and control schemes used to connect these units to the grid. Most important of all, the benefits brought on by DG are based on the supply reliability of DG. Among all types of DG, SOFC is a modular, high efficiency, environmentally friendly energy conversion device and has become a promising option for stationary power generation. The current main challenges to develop this DG technology are to reduce the installation cost, to improve overall efficiency and to explore the avenues of increasing the durability to more than 40,000 hours for stationary power applications. In order to have a clear insight of the power generation process of the SOFC power plant, some basic knowledge will be discussed in the following section. Except where stated, hence all the following discussions will use SOFC as an example for DG.

2.6 Fuel Cell Power Plant Basics

From the introduction in Section 2.3, a brief overview of FC DG technology will now be given. As the focus of this thesis is on the electrical aspect of the FC, the thermal and electrochemistry aspects of the FC power plant will be briefly introduced in this section. Interested readers may refer to [22, 23].

2.6.1 A brief description of an SOFC power plant

The process flow diagram for a prototype 200 kW SOFC power plant is shown in Figure 2-6 [59]. It shows the major subsystems and the variety of heat recovery options that are available.

Figure 2-6 Basic flow sheet of an SOFC system

In Figure 2-6, the hydrogen rich natural gas will be fed into the SOFC through the fuel valve. As the natural gas contains sulfur and the FC performance is affected adversely by sulfur, a desulphurization operation is performed before the fuel enters the reformer. The removal of sulfur in the natural gas is readily accomplished in the desulfurizer in which the sulfur reacts with zinc oxide to form zinc sulfide. After a period of operation, the spent zinc oxide bed can be disposed of commercially or recycled.

While the zinc oxide desulfurizer can perform over a range of temperature, optimum performance, which is related to minimum bed volume, occurs at 300°C~400°C. For this reason, the incoming fuel is preheated before it reaches the desulfurizer. This is accomplished by using the SOFC generator exhaust heat. Based on preliminary analysis

[29], it is anticipated that the pre-heaters in the SOFC power plant could be realized using a simple heat exchanger surface that is designed to be in effective contact with the high-temperature exhaust duct in the generator. This approach will provide a double-wall barrier between the fuel and exhaust streams, and should mitigate any concerns associated with fuel leakage and the high-temperature environment. Fuel temperature control at the desulfurizer inlet will be achieved by bypassing fuel around the heat exchanger and controlling the bypass flow based on the mixed-fuel temperature.

The SOFC generator shown in Figure 2-6 uses the fuel reformer to convert the natural gas to the hydrogen. This is accomplished by re-circulating a fraction of the spent fuel stream and mixing it with the un-used hydrogen and water for start-up. The hydrogen is sent to the anode of the cell stack where the electrode reaction (described later) occurs and DC energy will be produced. When combined with the necessary amount of water vapor, the hydrogen will be oxidized rapidly and the thermodynamic equilibrium will also be quickly reached.

The exhaust gases exiting the SOFC, in addition to being clean, are very hot: typically having temperatures above 600°C. The thermal energy contained in the exhaust can therefore be applied to a wide variety of the uses at site. As shown in Figure 2-6, the exhaust gas at the anode can help to reform the hydrogen. Similarly, the exhaust gas at the cathode can pre-heat the incoming air. After the heat exchanger, the temperature of the recirculation flow is about 300°C~400°C. Such medium temperature gases can be used to pre-heat the desulfurizer or support other DG, such as microturbine, to improve its efficiency further. In catalytic burner zone, the unused hydrogen will be oxidized by the unused oxygen and the rest of exhausted gas will be used to preheat the water for start-up and the incoming natural gas. The final exhaust temperature is typically less than 100°C and it can always be utilized in the production of low-pressure steam, hot water and warm air. In the literature, the whole equipment which deal with the fuel and oxidant processing and feeding of the fuel to the stack, as well as the processing of the stack exhausts, is called the Balance of Plant (BOP) [22, 34, 59].

The most important part of the SOFC is the cell stack. It is formed by combining single cell in series-parallel. In the cell stack, DC energy is produced and it can be used either

by the local DC load or converted to the AC form through the Power-Conditioning Unit (PCU). Details of the PCU, one of the most important parts of the FC power plant, will be introduced in a later section.

2.6.2 Electrode reaction

Figure 2-7 SOFC electrode reaction illustration

The FC converts chemical energy directly to electrical energy in the stack. From the inner structure of the cell stack shown in Figure 2-7, the cell stack consists of two porous ceramic electrodes separated by a dense ceramic electrolyte. Typical SOFC materials are stabilized zirconia for the electrolyte, nickel/zirconia cermet for the anode, and doped lanthanum manganite for the cathode [23]. The life of these cell materials are dependent on the operating temperature. Stable operating temperature can retard the degradation speed of the cell materials [59]. The electrodes are continuously replenished by the incoming hydrogen and oxygen, which are transported along the channels close to the electrodes. The fundamental electrode reaction is shown by the following equations

At the cathode of the FC, oxygen gas ionizes and releases electrons and creates O^{2-} ions. This chemical reaction is shown in the cathode reaction in (2-1). At the anode, hydrogen reacts with the O^{2-} ions from the electrolyte, to form gaseous state water. Energy is released in this reaction. This chemical reaction is shown in the anode reaction in (2-1). As both of these reactions will proceed continuously, electrons produced at the anode must pass through an electrical circuit to the cathode. Continuous moving electrons form the stack current I_{FC} . In addition, O^{2-} ions must pass through the electrolyte. Comparing the anode and cathode reactions, it can be found that two hydrogen molecules will be needed for each oxygen molecule if the system is to be kept in balance. This is shown in Figure 2-7. It should be noted that the electrolyte must only allow O^{2-} ions to pass through it, and not electrons. Otherwise, the electrons would go through the electrolyte, not round the external circuit, and no DC power would be generated.

After the electrode reaction, the unused hydrogen and water will form the anode exhaust. The unused oxygen will form the cathode exhaust. Vented through the respective orifice, the electrode exhaust with the reaction heat will be used in the thermal cycle introduced in Section 2.6.1.

2.6.3 Nernst equation and the operational FC voltage

Seeing from the external circuit shown in Figure 2-7, the FC is a power source supplying the load with an internal EMF. This EMF can be derived from the thermodynamic principles and named after the German physical chemist Walther Nernst who first formulated it. Interested readers may refer to [22]. The Nernst equation is given as

$$E = E_0 + \frac{RT}{2F} \ln\left(\frac{p_{H_2} \cdot p_{O_2}^{0.5}}{p_{H_2O}}\right) \quad (2-2)$$

where E_0 is the FC internal EMF at standard pressure (0.1 MPa), R is the gas constant (8.31J/mol °K), F is the Faraday constant (96487 C/mol), T is the FC operating temperature and p_i is the i th exhaust gas partial pressure. As shown in Figure 2-7, all the gases in (2-1) share a same volume. If it is assumed that the cell has a single pressure, all the gases will contribute part of the pressure which is related to their corresponding mole

numbers (gas concentration). When the external load in Figure 2-7 varies, the stack current I_{FC} , the mole numbers in (2-1) and the partial pressure in (2-2) will change. Therefore, the FC terminal voltage V_{dc} will also change.

With typical SOFC data shown in Appendix A, Figure 2-8 shows the relationship between the FC terminal voltage and stack current where the hydrogen input flow rate is 0.75 mol/s and oxygen input flow rate is 0.86 mol/s. The V-I curve can be roughly divided into 3 regions: the rapid initial fall in voltage at light I_{FC} , the voltage falls more slowly and in a nearly linear fashion in the mid-range of I_{FC} , and rapid voltage fall at higher current.

Figure 2-8 Typical SOFC V-I character

The initial voltage fall of the FC is due to the activation loss. This is caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to or from the electrode. This voltage drop ΔV_{ac} is highly non-linear. From experimental observation, rather than theoretical derivation, the loss can be evaluated through empirical Tafel equation [23, 36], i.e.,

$$\Delta V_{act} = a_{act} + b_{act} \log I_{FC} \quad (2-3)$$

where a_{act} and b_{act} are called Tafel constant and Tafel slope respectively. For low-temperature FC, its activation loss is higher than that of high-temperature FC when FC current is low. That is the main reason why the open-circuit voltage of the low temperature FC is less than the theoretical EMF. High-temperature FC only has a small initial drop.

The linear part of the voltage is due to the ohmic loss of the FC. This voltage drop is the straightforward resistance to the flow of the electrons through the material of the electrodes and the various interconnections, as well as the resistance to the flow of ions through the electrolyte. This voltage drop ΔV_{ohm} is essentially proportional to current density, and so is called “ohmic” loss. It can be determined as,

$$\Delta V_{ohm} = R_{FC} I_{FC} \quad (2-4)$$

R_{FC} can be obtained from experimental measurements. FC always works over this linear area. High-temperature FC ohmic voltage drops tend to be less than that in the lower temperature FC. This is purely an observation from experiments rather than from theoretical considerations [23]. It is also the reason why it is desirable to operate the cells on high temperature. The ohmic loss is important in all types of cell, especially in the case of the SOFC.

When stack current is high, the rapid voltage drop is due to the concentration loss. These result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. From (2-2), E is shown to be dependent of the reactants pressures or concentration. This concentration-caused loss is the result of failure to transport sufficient reactant to the electrode surface. Long-time operation in this high current region will degrade the cell materials and reduce the cell life. It is generally agreed among FC researchers that there is no analytical solution to model these loss. One possible approach to evaluate this loss is by the empirical equation [23],

$$\Delta V_{con} = a_{con} \exp(b_{con} I_{FC}) \quad (2-5)$$

where a_{con} and b_{con} are constants to approximate the concentration loss. For SOFC, typical value of a_{con} is 1×10^{-4} V, b_{con} is 8×10^{-3} . In practical application, this operating region must be avoided.

Combining (2-3)~(2-5), the FC terminal voltage V_{dc} can be represented by (2-6) after considering all the voltage losses,

$$V_{dc} = E - \Delta V_{ohm} - \Delta V_{ac} - \Delta V_{con} = E - rI_{FC} \quad (2-6)$$

where r is an equivalent non-linear resistance represented all the voltage losses. For high-temperature SOFC, R_{FC} dominates and this point will be considered further in Chapter 3.

From (2-6), one can calculate the FC thermal efficiency. The thermal efficiency of the FC is defined as the amount of useful energy produced relative to the change in the stored chemical energy that is released when a fuel is reacted with an oxidant. Reference [21] proved that the FC thermal efficiency could be written in terms of the V_{dc} as,

$$\eta = 0.83 \frac{V_{dc}}{E_0} \quad (2-7)$$

If I_{FC} is high and the FC operates in the concentration loss area, it is seen from (2-6) and (2-7) that the FC thermal efficiency will be very low due to the small V_{dc} value. As V_{dc} increases with the decreasing I_{FC} , the thermal efficiency of the cell will also increase. Other components within the FC power plant such as reformer, however, will operate at lower component efficiencies as the system's load is reduced. Consequently, the overall efficiency of a FC power plant unit incorporating a fuel processor may start to fall at loads of less than 25%-40% of full load [22, 60].

When the FC supplies a load, one could also use (2-6) to obtain the relationship between the FC output power and stack current. It is shown in Figure 2-9. It is seen that there is a maximum power point when the stack current is high. However, the FC rated power is typically designed lower than this maximum value to prevent the poor thermal efficiency. Furthermore, as stable SOFC operating temperature, electrochemical and thermodynamic stability are all strongly dependent of the exhaust gas temperature, it is necessary for the SOFC to take on minimum load to produce the required heat. Hence the FC real power output is always between a certain minimum value and its rated value [60]. It therefore results in the FC steady-state operating voltages to be maintained within the linear region shown in Figure 2-8.

Figure 2-9 Typical SOFC P-I character

2.6.4 Power-Conditioning Unit

The output power of the cell stack is in the form of direct current (DC). In many cases, especially for small systems, FC can be directly used to support DC load such as DC motor without any need for other energy conversion device. On the other hand, in larger systems which are connected to an external grid system, the DC must be converted to alternating current (AC) form. Various power electronics devices can be used to transfer the DC power to the AC system. As the capacity of present distributed generators can be from several kW to 10 MW, at the distribution network voltage level from 400V to 22kV, self-commutated Pulse Width Modulation (PWM) Insulated Gate Bipolar Transistor (IGBT) DC/AC system is probably the best trade-off and widely used scheme in the industry. There are many excellent references on the application of PWM scheme for drive systems and on the associated control methods. See for example [61] and [62]. Among all the PWM control schemes, Sinusoidal PWM (SPWM) switching method is the most widely used in practice. As some of the following chapters will use SPWM switching method to achieve the energy conversion process, the basic IGBT operating theory with SPWM switching method will be briefly introduced in this section.

Figure 2-10 shows the three-leg voltage source PWM self-commutated inverter supplies a balanced load $\mathbf{Z}_{LD}$. This is the main part of the FC Power-Conditioning Unit (PCU). The voltage source type converter fed from a DC bus, uses IGBT devices each with an

anti-parallel diode (usually the built-in freewheel diode). Stable input DC voltage and accurate voltage switching signals are the two basic required operating conditions for the PCU. The DC voltage may come from the FC terminal voltage V_{dc} . For the scheme to function, the IGBT T1-T6 would have to be switched on/off in a certain manner through the control of their respective gating signals. The signals sent to the IGBT come from an independent SPWM switching circuit.

Figure 2-10 PWM self-commutated inverter power circuit

For illustration, Figure 2-11 shows the operation scheme of the SPWM switching method. In Figure 2-11a, there are two forms of waveforms used to generate the gate signals, the carrier signal $v_{tri}(t)$ and the control signals $v_{control}(t)$. The carrier signal is typically a triangular voltage signal. The triangular amplitude is V_{tri} and it is fixed. The frequency of the carrier signal is f_s , which is the same as the switching frequency of the IGBT. f_s is a multiple (m_f) times of the control signal frequency. The control signals are three sinusoidal voltage signals with amplitude $V_{control}$ displaced by 120 degree with respect to each other. The frequency of the control signals is same as the fundamental frequency f_n of the AC-side. In Figure 2-11a, f_s is shown to be 15 times of f_n , i.e., $m_f = 15$. $V_{control}$ may vary according to the control demand but $V_{tri} \geq V_{control}$. The ratio of $V_{control}/V_{tri}$ is one control variable of the PWM and is called the modulation index m . Depending on the relative magnitudes of $v_{tri}(t)$ and $v_{control}(t)$, the IGBT in the PCU will be switched on or switched off. Take leg A in Figure 2-10 as an example, when

$v_{control,A}(t) \geq v_{tri}(t)$, T1 is switched on. When $v_{tri}(t) < v(t)$, T4 is switched on. At any time, only one of the two switches in a leg is allowed to be in the “on” state while the other one is in the “off” state. Otherwise this leg will be short circuited.

Figure 2-11 SPWM switching scheme

Figure 2-12 Equivalent inverter circuit at different time

Figure 2-13 Voltage waveform of v_{AO}

Figure 2-11b shows the gate signals generated by the SPWM circuit in one cycle. The output voltage of the inverter is varied according to the gate signals. Take $t = 0$ and $t = t_1$ in Figure 2-11 as an example. When $t = 0$, it can be seen from Figure 2-11a that $v_{control,A} > v_{tri}$, $v_{control,B} < v_{tri}$ and $v_{control,C} > v_{tri}$. From the gate signals given by Figure 2-11b, IGBT T1, T5 and T6 in Figure 2-10 are switched on while T2, T3 and T4 are switched off. Hence, point A and C in Figure 2-10 are connected to the positive DC bus with voltage V_{dc} , while point B is connected to the negative DC bus with voltage 0. The equivalent circuit is shown in Figure 2-12a. The load current flows through T1, T5 and returns through T6. The phase voltage V_{AO} at this time is $V_{dc}/2$. Similarly, when $t = t_1$, the equivalent circuit is shown in Figure 2-12b. The load current flows through T5 and returns through T4, T6. The phase voltage V_{AO} at this time is $-V_{dc}/2$. Every cycle, V_{AO} changes between two voltage levels $V_{dc}/2$ and $-V_{dc}/2$. Therefore, the inverter topology

shown in Figure 2-10 is also called a two-level inverter. The percentage that $V_{AO} = V_{dc}/2$ depends on the control variable m . By varying m , it is seen from Figure 2-11a that cross-over points of the carrier and control signals will change and v_{AO} also varies. When $V_{dc} = 330\text{V}$, the solid line of Figure 2-13 shows that the voltage waveform of v_{AO} clearly contains harmonics. If one were to examine the fundamental component of v_{AO} , the waveform is as shown by the dashed line and it is proportional to m [63].

The harmonics in the inverter output voltage waveform appear as sidebands, centered around f_s and its multiples, i.e., m_f , $2m_f$, $3m_f$ and so on. This general conclusion is true when m_f is in the range 0~1. Increasing m_f can shift the harmonics to the higher orders and a low-pass filter can be used to eliminate the harmonics. However, the switching losses of the inverter are proportional with f_s . Typically, $1\text{ kHz} < f_s < 6\text{ kHz}$. Filter design method will be discussed in Chapter 5.

As the IGBT switching frequency is at least twenty or more times of the fundamental frequency, the switches can be switched on/off so fast that the output voltage can quickly follow the reference control signals. For long-duration power quality problem such as that during load-tracking, the transient process during the switching period can be neglected. The slowly varied external load can be modeled as a quasi-steady state load. The FC power plant used to solve the load-tracking problem in an isolated or grid-connected system will be discussed in Chapters 4 and 6 respectively.

Figure 2-14 SPWM switching method with two control variables

When the FC is operated in a grid-connected condition, the connecting point voltage is measurable. This voltage v_{ref} can be used to provide the phase reference to the PWM control signals through a phase lock loop (PLL) circuit. Figure 2-14 shows the SPWM switching method with two control variables. From this figure, $v_{control,A}$ has a phase shift δ_f with respect to the reference signal v_{ref} . By varying δ_f , the cross-over points of the carrier and control signals will change. Therefore, the gate signals and the inverter output voltages can also change. In the grid-connected system, therefore, the inverter has two control variables: m and δ_f . Inverter control schemes in the grid-connected condition will be discussed in Chapters 6 and 7.

2.7 Conclusions

Power quality issues and mitigation methods are introduced. Custom Power devices are described in their role to improve power quality. A brief introduction on the various DG technologies have also been presented and their advantages/disadvantages compared. DG will bring positive as well as negative effects on power quality.

SOFC power plant is then described for stationary power supply. Three main parts of the SOFC power plant, viz, the BOP, cell stack and the PCU, are described. The well-known Nernst equation, used to calculate the cell EMF, is shown. When a FC supports load, there are three voltage loss components that will cause the FC terminal voltage to vary, namely, ohmic loss, activation loss and concentration loss. Ohmic loss can be determined analytically and it dominates to the voltage losses of the SOFC. However, the other two voltage losses can only be evaluated from the empirical expressions. DC power of the FC can be converted to AC form through the PCU. Through the SPWM switching method, the PCU output voltage can be quickly regulated according to the reference voltage signals.

Chapter 3

Modeling SOFC for Steady-State and Small-Signal Analysis

3.1 Introduction

In the previous chapter, a general form of SOFC for stationary power application has been described. It is shown that in converting the chemical energy from the hydrogen fuel to electrical energy, complex thermodynamic and electrochemical processes are involved. Although this project is focused on the electrical aspects of the FC, these processes would surely affect the dynamic performance of the FC. Hence, operation and control of the FC should take into consideration these processes in order to ensure the reliability of the FC power generation system. An SOFC dynamic model which takes these into account and at the same time, in a form suitable for power system analysis is therefore essential for the present investigation.

In the literature, several FC dynamic models have been proposed for the purpose of studying the various types of application scenario pertaining to stationary power generation. Kim *et al.* [30] described a FC power generation process in terms of an equivalent circuit model. When supplying a DC load, the dynamic processes of the fuel processor and the cell stack were represented by two first order systems through a combination of resistors and capacitors. However, the steady-state FC EMF in the model would be equal to the natural gas fuel input. From (2-2), clearly this is incorrect. Their proposed model is not suitable for the understanding of the detailed dynamic processes in the FC. Kyoungsoo and Rahman [28] proposed a two-loop controller for load-tracking by a grid-connected PV-FC hybrid power plant. The FC model suggested by the authors includes the fuel processor dynamics represented by a first-order system. Although the authors considered the chemical process, the FC terminal voltage during the dynamic period was the value obtained from the steady-state Nernst equation and the thermodynamic process had not been included in the model. Hatziaioniu *et al.* [33] derived a linearized MCFC dynamic model used for transient stability analysis. In their study, the hydrogen fuel input is assumed constant. The relationship between the stack

current and the cell EMF is simplified to a first order system. As the disturbance magnitude is not given in [33], it is uncertain whether the given small-signal model is valid for use in transient stability study. Hall and Colclaser provided an analysis concerning the modeling and simulation of an SOFC under a step load change [31]. The FC model includes both the electrochemical and thermal aspects of the cell performance. However, the fuel processor dynamic was not considered and the fuel input to the cell was assumed constant in the model. The model is also not readily amenable for power system analysis. In a later article, Padullés *et al.* [34] created a simulation model of an SOFC power plant. The main purpose of their work is to develop a model specifically for a well-known power system analysis package. The model is intended for use in steady-state load-flow study, as well as for power system dynamic and transient stability analysis. In this model, the FC stack model is based on the following main assumptions:

- The hydrogen, oxygen and water gases are ideal.
- With reference to SOFC cell stack structure shown in Figure 2-7, the channels that transport the gases along the electrodes have a fixed volume, but their lengths are small. Hence it is only necessary to define one single pressure value in the cell stack interior. The exhaust of each channel is via a single orifice. The ratio of pressures between the interior and exterior of the channel is large enough for the authors to assume that the orifice is choked.
- The temperature is stable at all times.
- Of the losses described in Section 2.6.3, only ohmic loss is considered, as the working conditions of interest of the FC are not close to the upper and lower extremes of current.
- Nernst equation applies.

Based on the above assumptions, the paper shows that the electrochemical and thermodynamic process could be approximated by first order transfer functions. The main contribution of [34] is therefore to facilitate the analysis of the SOFC for power system studies. Based on the results of [34], Zhu and Tomsovic then included the fuel processor in their investigation and used the model to study load-tracking ability of the power plant [35]. Unfortunately, the authors have not provided any analysis on how the SOFC is to be controlled. Also based on [34], Sedghisigarchi and Feliachi modified the dynamic model by including activation and concentration losses in their study [36, 37]. The cell temperature in their simulation model is varied during the load disturbance and

calculated through the energy balance equation. However, one of the most important cell performance variables, fuel utilization, has not been examined.

The intent of this chapter is to collate the findings of the above references and produce an SOFC dynamic model suitable for subsequent investigation.

3.2 An SOFC Dynamic Model

Figure 3-1 An SOFC dynamic model

The SOFC dynamic model used in this project is based on the work of [34] and [35] in which the thermodynamic and electrochemical processes of the FC power plant introduced in Chapter 2 have been considered. Furthermore, the dynamic of the fuel processor is also included in the model. The resulting SOFC power plant dynamic model based on [34, 35] is shown in Figure 3-1. Two main parts can be readily identified in this model. Starting from the fuel input end, one encounters the part of the model representing the so-called Balance of Plant (BOP) described in Section 2.6 while downstream of which is the FC stack. In the BOP, the fuel storage can provide the pre-heated and high-pressure fuel N_r to the fuel processor through the fuel valve. The fuel valve is regulated through a controller, the manner of regulation will be described in the following sections. The fuel processor reforms the natural gas input N_f to form hydrogen-rich fuel. Similar to the approach in [35], the fuel processor is represented herewith simply by a first order model of time constant τ_f . The output of the fuel

processor is directly fed to the FC stack, which forms the second part of the energy conversion process of the power plant. In the model, r_{H_O} defines the ratio of hydrogen to oxygen molar flows. The hydrogen and oxygen reactants are fed into the FC stack where the reaction described by (2-1) occurs. From (2-1), it is seen that full reaction ratio between hydrogen and oxygen is 2 to 1. In order to allow for oxygen to completely react with hydrogen and maintain the pressure difference between the anode and the cathode below a certain threshold value, excess oxygen ($N_{O_2}^{in}$) is provided. Hence, this means that $r_{H_O} < 2$. Typically $1 < r_{H_O} < 1.25$ [22, 35].

To calculate the electrode reaction partial pressures in the Nernst equation (2-2), one can use the idealized gas equation [23]

$$p_i V = n_i R T \quad (3-1)$$

where p_i is the partial pressure of i th gas at the output, V is the compartment volume, n_i is the i th gas mole number in the cell stack, R is the gas constant (8.31J/mol °K) and T is the cell temperature. The i th gas would be either hydrogen, oxygen or water. Taking the time derivative of both sides of (3-1), one can obtain

$$\frac{d}{dt} p_i = \frac{RT}{V} N_i \quad (3-2)$$

where $N_i = \frac{dn_i}{dt}$ is the time derivative of n_i , and represents the i th gas molar flow rate in the cell stack. Take hydrogen as an example, there are three contributions to the hydrogen flow: the input flow rate ($N_{H_2}^{in}$), the flow rate that takes part in the reaction ($N_{H_2}^r$) and the output flow rate at the exit ($N_{H_2}^{out}$). Thus for the i th gas, (3-2) can be rewritten as

$$\frac{d}{dt} p_i = \frac{RT}{V} (N_i^{in} - N_i^{out} - N_i^r) \quad (3-3)$$

According to the basic electrochemical relationships, Padullés *et al.* proved that the mole flow of each gas in reaction (2-1) could be calculated as:

$$N_{H_2}^r = -N_{H_2O}^r = 2N_{O_2}^r = \frac{N_0 I_{FC}}{2F} = 2K_r I_{FC} \quad (3-4)$$

where I_{FC} is the cell current, F is the Faraday constant (96487 C/mole), K_r is a modeling constant which has the value of $N_0/(4F)$ (mole/s.A), N_0 is the number of cells in series in the stack.

Furthermore, the authors had shown that the ratio of the i th gas output molar flow rates to (N_i^{out}) its corresponding partial pressure (p_i) could be considered as a constant, i.e.,

$$K_{H_2} = \frac{N_{H_2}^{out}}{p_{H_2}}, K_{O_2} = \frac{N_{O_2}^{out}}{p_{O_2}}, K_{H_2O} = \frac{N_{H_2O}^{out}}{p_{H_2O}} \quad (3-5)$$

where the K_{H_2} , K_{O_2} and K_{H_2O} are the valve molar constant for hydrogen, oxygen and water respectively and they can be obtained from experimental measurements.

Substituting (3-4) and (3-5) into (3-3) and taking the Laplace transformation on both sides, the partial pressure of every exit gas can be written as

$$\left. \begin{aligned} p_{H_2} &= \frac{1/K_{H_2}}{1 + \tau_{H_2}s} (N_{H_2}^{in} - 2K_r I_{FC}) \\ p_{O_2} &= \frac{1/K_{O_2}}{1 + \tau_{O_2}s} (N_{O_2}^{in} - K_r I_{FC}) \\ p_{H_2O} &= \frac{1/K_{H_2O}}{1 + \tau_{H_2O}s} (-2K_r I_{FC}) \end{aligned} \right\} \quad (3-6)$$

where τ_{H_2} , τ_{O_2} and τ_{H_2O} , expressed in seconds, are the time constants associated with the hydrogen, oxygen and water flow. These time constants can be calculated as [34]:

$$\tau_{H_2} = \frac{V}{K_{H_2}RT}, \tau_{O_2} = \frac{V}{K_{O_2}RT}, \tau_{H_2O} = \frac{V}{K_{H_2O}RT} \quad (3-7)$$

As V , K_{H_2} , K_{O_2} , K_{H_2O} and R in (3-7) are constants, all the above time constants are function of the cell operating temperature. The values of τ_{H_2} , τ_{O_2} and τ_{H_2O} can be obtained from measurements and they are typically between 2~80 seconds [34].

As the temperature of the cell stack is always assumed constant in [34], the thermodynamic process described by (2-1) is an isothermal process. From the First Law of Thermodynamic,

$$\Delta Q = \Delta E_{in} + \Delta W \quad (3-8)$$

where Q is the heat generated in the electrochemical reaction, E_{in} is the gas internal energy and W is the work done by the gases. E_{in} is related to the temperature and it will not change in the isothermal process. Therefore, Q in (2-1) will be equal to the work down by the exhaust gases. Based on this assumption, the time constants in (3-7) are time-invariant. The thermodynamic and electrochemical processes in the FC can be described by the ordinary differential equations (3-6) rather than a set of partial differential equations. In fact, in order to maintain the plant efficiency and to avoid breakage of cell material, it is necessary to maintain the operating temperature T of the FC stack within a limited range around its rated value. This can be achieved by the thermal management system of the plant [22, 60]. Therefore, this project also assumes T is constant. This operation with relatively constant temperature also places a lower limit on the FC output power [60]. With this approximation, the partial pressures in (3-6) can be substituted into (2-2) to calculate the open-circuit EMF of a stack of N_0 number of cells in series. The nonlinear Nernst equation (2-2) can be rewritten as

$$E = N_0 E_0 + E_f \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \quad (3-9)$$

where

$$E_f = \frac{N_0 RT}{2F} \quad (3-10)$$

The above description accompanies the SOFC dynamic model provided in [34, 35], as shown in Figure 3-1. As discussed in Chapter 2, there are the three losses in the FC, namely: the activation loss, the ohmic loss and the concentration loss. As stated there, activation loss is dominant at very low stack currents whereas concentration loss is dominant at very high stack currents. The ohmic loss occurs at all levels of currents. In the model shown in Figure 3-1, these losses are represented simply by the resistance r . In order to limit mathematical complexity, a constant resistance is assumed in this

project. If increased accuracy is desired, all three losses can be accounted for by a nonlinear resistance r which would be a function of the operating current level as in [37, 55].

The stack terminal voltage V_{dc} is the actual voltage available at the terminals after considering the losses. The current drawn from the stack I_{FC} acts as a feedback to adjust the partial pressures of the reactants according to the reaction rate.

It is interesting to note that in the study of the PEMFC, similar model has been used in [55].

3.3 Feasible Operating Area

While the derivation shown above has produced a useful model for power system studies, there is still one most important operating variable which has yet to be considered. This is called the utilization factor, u , of the FC. The utilization factor, not shown explicitly in Figure 3-1, is defined as the ratio between the hydrogen flow rate in the reaction to the hydrogen input flow rate [34], i.e.,

$$u \equiv \frac{N_{H_2}^r}{N_{H_2}^{in}} = \frac{N_{H_2}^{in} - N_{H_2}^{out}}{N_{H_2}^{in}} \quad (3-11)$$

Substituting (3-4) into (3-11), it can be shown that u can be expressed in terms of I_{FC} as

$$u = \frac{2K_r I_{FC}}{N_{H_2}^{in}} \quad (3-12)$$

The desired range of u is from 0.7 to 0.9. Overused-fuel condition ($u > 0.9$) could lead to permanent damage to the cells due to fuel starvation and underused-fuel situation ($u < 0.7$) results in unexpectedly high cell voltages [34]. In practice, the value of u can be determined on-line as $N_{H_2}^{in}$ and I_{FC} are readily measurable. Hence it is possible to continuously track the value of u . The FC must operate within its rated power range and u has to be kept within the allowable range.

In view of the above, it is possible to examine in greater details the steady-state feasible operating regime of a given SOFC. The electrical parameters defining the operating status are I_{FC} and V_{dc} , as shown in Figure 3-1. Specifically, the FC must operate within its rated power and u has to be kept within the range described earlier. Furthermore, in considering the SOFC connected to an external AC system through the arrangement as shown in Figure 2-10, V_{dc} could be constrained to a certain range to meet the voltage specifications of the AC load. These variables are related in a rather complex way, through the Nernst equation. Under steady state, the reaction output partial pressures from (3-6) is:

$$\left. \begin{aligned} p_{H_2,0} &= \frac{N_{H_2}^{in} - 2K_r I_{FC}}{K_{H_2}} \\ p_{H_2O,0} &= \frac{2K_r I_{FC}}{K_{H_2O}} \\ p_{O_2,0} &= \frac{N_{H_2}^{in} / r_{H-O} - K_r I_{FC}}{K_{O_2}} \end{aligned} \right\} \quad (3-13)$$

Substituting the above into (3-9) and considering the definition of u , the FC internal EMF can be written as,

$$E = N_0 E_0 + E_f \{ \ln[(K_{H_2O} / K_{H_2})(K_r / (r_{H-O} K_{O_2}))^{1/2}] + 0.5 \ln[I_{FC} (1/u - 1)^2 (2/u - r_{H-O})] \} \quad (3-14)$$

From Figure 3-1,

$$E = V_{dc} + r I_{FC} \quad (3-15)$$

Therefore, combining (3-14) and (3-15), it can be readily shown that the following equation can be obtained:

$$\left. \begin{aligned} \left(\frac{1}{u} - 1\right)^2 \left(\frac{2}{u} - r_{H-O}\right) &= \frac{\exp(\gamma + 2r I_{FC} / E_f)}{I_{FC}} \\ \gamma &= 2 \frac{V_{dc} - N_0 E_0}{E_f} - 2 \ln \left[\frac{K_{H_2O}}{K_{H_2}} \left(\frac{K_r}{r_{H-O} K_{O_2}} \right)^{0.5} \right] \end{aligned} \right\} \quad (3-16)$$

Equation (3-16) governs the steady-state operating condition of the SOFC. The proof below shows that for a given V_{dc} , u is at maximum value when $I_{FC} = I_{FC,m} = E_f / (2r)$ and from (3-10)

$$I_{FC,m} = \frac{N_0 RT}{4rF} \quad (3-17)$$

Proof:

For a given V_{dc} , the relationship between u and I_{FC} can be examined from (3-16).

Let

$$f(u) = \left(\frac{1}{u} - 1\right)^2 \left(\frac{2}{u} - r_{H-O}\right) = \left(\frac{1}{I_{FC}}\right) \exp\left(\gamma + \frac{2rI_{FC}}{E_f}\right)$$

Then,

$$\frac{du}{dI_{FC}} = \frac{du}{df(u)} \cdot \frac{df(u)}{dI_{FC}} = \frac{df(u)}{dI_{FC}} / \left(\frac{df(u)}{d(1/u)} \cdot \frac{d(1/u)}{du}\right)$$

Consider the term

$$\frac{df(u)}{dI_{FC}} = \frac{\left(\frac{2rI_{FC}}{E_f} - 1\right) \exp\left(\gamma + \frac{2rI_{FC}}{E_f}\right)}{I_{FC}^2}.$$

Clearly, $du/dI_{FC} = 0$ when $(2rI_{FC}/E_f - 1) = 0$. Thus, u has a maximum or minimum value at the stack current $I_{FC,m} = E_f / (2r)$.

Next,

$$\frac{df(u)}{d\left(\frac{1}{u}\right)} = 2\left(\frac{1}{u} - 1\right)\left(\frac{3}{u} - 1 - r_{H-O}\right)$$

As $0 < u < 1$ and $r_{H-O} < 2$, it can be observed that $\frac{df(u)}{d\left(\frac{1}{u}\right)} > 0$ for all stack currents.

However, $\frac{d\left(\frac{1}{u}\right)}{d(u)} = -\frac{1}{u^2} < 0$

Therefore, $\frac{df(u)}{du} < 0$ for all I_{FC} .

It means that if

$$I_{FC} > I_{FC,m} \Rightarrow \frac{df(u)}{dI_{FC}} > 0 \Rightarrow \frac{du}{dI_{FC}} < 0.$$

Conversely if

$$I_{FC} < I_{FC,m} \Rightarrow \frac{df(u)}{dI_{FC}} < 0 \Rightarrow \frac{du}{dI_{FC}} > 0.$$

Hence, at the critical stack current $I_{FC,m} = E_f / (2r)$, u has a maximum value. Q.E.D.

From the above, it is clear that u will be decreasing with an increasing I_{FC} if the FC output power is greater than $V_{dc}I_{FC,m}$. For example, with the typical parameter values given in [34, 35] for a 100 kW SOFC (data also shown in Appendix A), the critical stack current is 83.5A and the corresponding output real power is 27.6 kW when V_{dc} is at the rated value. Note that $I_{FC,m}$ is independent of u or V_{dc} and is a constant for a given FC plant operating under a constant temperature. If the operating temperature T increases, from (3-17), $I_{FC,m}$ is seen to increase proportionally. Furthermore, from (3-16), it is also seen that u is also a function of V_{dc} through the parameter γ .

Figure 3-2 Feasible operating area of fuel cell

Another useful way to explain the concept of SOFC steady-state feasible operating area (FOA) is through Figure 3-2. Based on the typical SOFC data given in [34, 35], Figure 3-2 shows a family of curves describing the relationship between u and I_{FC} obtained through the application of (3-16) for a range of V_{dc} . The figure is based on using the rated power and the rated V_{dc} voltage as the base values. For example, for a constant V_{dc} of 1 p.u., the relationship between u and I_{FC} is given by the curve XZ in the figure. The constraints placed on u are represented by the straight boundary lines AD and BC corresponding to an allowable range of 0.7-0.9. The FC output power P , which is simply the product $V_{dc}I_{FC}$, has been assumed to be confined to the range of 0.1-1.0 p.u. The boundaries of P are shown by the curves AB and CD. Taking all these into consideration, the Feasible Operating Area (FOA) of the SOFC is the area ABCDA of Figure 3-2. Any SOFC operating state outside of the FOA will reduce the cell life and is deemed unacceptable.

From (3-16) or Figure 3-2, it is clear that it is impossible for the SOFC to maintain a simultaneous constant u and constant V_{dc} operating regime for a range of I_{FC} . Furthermore, the existence of the maximum utilization factor u for a given V_{dc} is also apparent from the diagram. For this particular plant, $I_{FC,m}$ occurs at about 0.28 p.u. Indeed, according to the analysis, maximum utilization condition always occurs at a relatively lightly loaded condition. For I_{FC} increasing from this value, u will always be decreasing. Thus, overused fuel situation can certainly be avoided if it can be ensured that overused fuel condition does not occur at $I_{FC,m}$ with the minimum V_{dc} . Furthermore, one could use the FOA to advantage when assessing the steady-state capability of an SOFC power plant. For example, the operating point D corresponds to the condition of maximum I_{FC} of 1.067 p.u. while V_{dc} is at the lowest level of 0.937 p.u., with a 0.9 utilization factor. Conversely, point B yields the minimum I_{FC} of close to 0.093 p.u. when $V_{dc} = 1.072$ p.u. and $u = 0.7$. The maximum V_{dc} value is 1.086 p.u. when $P = 0.299$ p.u. and $u = 0.7$. Therefore, the V_{dc} variation within the u constraints is small and it can be easily handled by the voltage controllability of the PCU to produce a constant output AC voltage, if desired.

In Figure 3-2, only ohmic loss is considered. Beside the ohmic loss, the effects of activation and concentration losses can also be considered. From Chapter 2, it is known

that activation and concentration losses can be approximated by the two empirical equations (2-3) and (2-5) respectively. With the experimental data given in [23], one can use an equivalent non-linear resistance described in (2-6) to redraw the curve represented by (3-16). Figure 3-3 compares the results obtained based on the linear and non-linear resistances respectively. It is seen that the two sets of curves are quite similar. For the same I_{FC} , V_{dc} has a slightly lower value when the two extra losses are included. However, the power losses caused by the activation and concentration losses over the range of the interest are negligible compared to the ohmic loss. It shows that ohmic loss is dominant in the FOA. Therefore, FOA derived using the linear resistance is expected to produce the required accuracy.

Figure 3-3 Comparison results of (3-16) by using linear and non-linear resistance

FOA is a new concept in describing the SOFC operational regime. It is reported in the author's publication [68] and will be used throughout this thesis.

3.4 Small-Signal SOFC Model

Even with the approximation introduced by Padullés *et al.* in [34], the resulting SOFC model shown in Figure 3-1 is still rather complex and is not readily amenable for power system analysis. If it is assumed that the problem in hand is pertaining to the study of small perturbations, such as that due to random load switching of relatively small

capacity, it is then possible to simplify further the model through the small-signal analysis of the nonlinear system. Although this method is valid only for a limited range of the SOFC operation, the result can still be very helpful in providing an understanding of the essence of the dynamic process.

From Figure 3-1 and (3-6), one notes that a variation in either the hydrogen, oxygen, water or stack current will cause a change in the corresponding partial pressure change such that

$$\left. \begin{aligned} \Delta p_{H_2} &= \frac{1/K_{H_2}}{1+\tau_{H_2}s} (\Delta N_{H_2}^{in} - 2K_r \Delta I_{FC}) \\ \Delta p_{O_2} &= \frac{1/K_{O_2}}{1+\tau_{O_2}s} (\Delta N_{O_2}^{in} - K_r \Delta I_{FC}) \\ \Delta p_{H_2O} &= \frac{1/K_{H_2O}}{1+\tau_{H_2O}s} (-2K_r \Delta I_{FC}) \end{aligned} \right\} \quad (3-18)$$

Similarly the Nernst equation can be linearized using the following Taylor series,

$$\ln(1 + \Delta p_i / p_i) = \Delta p_i / p_i - (\Delta p_i / p_i)^2 / 2 + (\Delta p_i / p_i)^3 / 3 - \dots$$

for $-1 < \frac{\Delta p_i}{p_i} \leq 1$. By neglecting the high order terms in the above equation, the SOFC

EMF following the small variations in the reactants will undergo the respective change ΔE around the initial operating point, where

$$\begin{aligned} \Delta E = E_f \left[\frac{1}{p_{H_2,0}} \cdot \frac{1/K_{H_2}}{1+\tau_{H_2}s} (\Delta N_{H_2}^{in} - 2K_r \Delta I_{FC}) + \frac{1}{2p_{O_2,0}} \cdot \frac{1/K_{O_2}}{1+\tau_{O_2}s} \left(\frac{\Delta N_{H_2}^{in}}{r_{H-O}} - K_r \Delta I_{FC} \right) + \right. \\ \left. \frac{1}{p_{H_2O,0}} \cdot \frac{1/K_{H_2O}}{1+\tau_{H_2O}s} \cdot 2K_r \Delta I_{FC} \right] \end{aligned} \quad (3-19)$$

The initial steady-state reactant output partial pressures, shown with the subscript “0”, are as given in (3-13). Based on the above, the behavior of the SOFC power plant can be studied under two possible methods. They are described as follows.

3.4.1 Constant fuel operation

It is interesting to note that in [31, 33, 36, 37], the hydrogen input is assumed constant during a small disturbance, that is $\Delta N_{H_2}^{in} = 0$. This corresponds to the FC operating under a constant fuel condition. In which case, substituting (3-13) into (3-19), (3-19) can be rewritten as (3-20) where the transfer function $F(s)$ is used to relate $\Delta E(s)$ with the change in the stack current $\Delta I_{FC}(s)$:

$$F(s) = \frac{\Delta E(s)}{\Delta I_{FC}(s)} = -k_0 \left[\frac{u_0}{1-u_0} \frac{1}{1+\tau_{H_2}s} + \frac{u_0 r_{H-O}}{2(2-u_0 r_{H-O})} \frac{1}{1+\tau_{O_2}s} - \frac{1}{1+\tau_{H_2O}s} \right] \quad (3-20)$$

where

$$k_0 = \frac{E_f}{I_{FC,0}} \quad (3-21)$$

Notice that as the initial utilization factor $u_0 \leq 0.9$ and $r_{H-O} < 2$, the coefficients associated with the hydrogen and oxygen terms have negative values (as $k_0 > 0$) whereas that of water is positive. If one were to consider a step change in I_{FC} , one therefore concludes that the response in E is made up of three exponential terms, with the responses associated with the hydrogen and oxygen terms deviating in the opposite direction to that of water. Furthermore, it can be seen from (3-20) that under steady state

$$F(0) = -k_0 \left[\frac{u_0}{1-u_0} + \frac{u_0 r_{H-O}}{2(2-u_0 r_{H-O})} - 1 \right] \quad (3-22)$$

Equation (3-22) shows the steady-state change in E is equal to $F(0)$ for a 1 p.u. change in I_{FC} . As typically $0.7 \leq u_0 \leq 0.9$ [34, 35] and $u_0 r_{H-O} \approx 1$, it can be seen that the hydrogen contribution to the steady-state change in E will be about 8 times that of oxygen and 4 times that of water. Therefore, $F(0)$ will assume a negative value. The stack current change will always be in a direction opposite to that of E . In addition, as all the time constants in (3-20) are typically of at least several seconds, the FC will only reach its final steady-state value several time constants later. Therefore, in response to a stack current change, the FC is a power source in which its internal EMF changes relatively slow compared to that of, for example, a conventional AC generator.

3.4.2 Constant fuel utilization factor operation

Constant fuel utilization factor (u) is another possible fuel control method considered in the literature [29]. From Figure 3-1, it is seen that the natural gas input N_f is equal to $N_{H_2}^{in}$ under steady state. From (3-12), the FC steady-state operating point will be guaranteed to settle on a pre-set value, denoted as u_s , if the fuel valve is adjusted in proportion to the FC current I_{FC} , through the relationship

$$N_f = \frac{2K_r}{u_s} I_{FC} \quad (3-23)$$

As $N_{H_2}^{in} = N_f / (1 + \tau_f s)$, substituting (3-23) into the last equation, hydrogen fuel input change ($\Delta N_{H_2}^{in}$) is now related to the stack current change (ΔI_{FC}) via the small-signal form

$$\Delta N_{H_2}^{in} = \frac{2K_r}{u_s(1 + \tau_f s)} \Delta I_{FC} \quad (3-24)$$

Substituting (3-24) and the initial values into (3-19), the relationship between ΔE and ΔI_{FC} can be represented by the following transfer function

$$H(s) = \frac{\Delta E(s)}{\Delta I_{FC}(s)} = k_0 \left[\frac{u_s}{1 - u_s} \frac{1}{1 + \tau_{H_2} s} \left(\frac{1}{1 + \tau_f s} \frac{1}{u_s} - 1 \right) + \frac{u_s r_{H-O}}{2(2 - u_s r_{H-O})} \frac{1}{1 + \tau_{O_2} s} \left(\frac{1}{1 + \tau_f s} \frac{2}{u_s r_{H-O}} - 1 \right) + \frac{1}{1 + \tau_{H_2 O} s} \right] \quad (3-25)$$

$H(s)$ therefore describes the small-signal dynamics of E under the constant u operating strategy when I_{FC} changes. Furthermore, it is seen from (3-25) that under steady state

$$H(0) = 2.5k_0 \quad (3-26)$$

Unlike the case of the constant fuel operation described by (3-22), $H(0) > 0$. This means that E can be adjusted to counter the change in I_{FC} . From (3-21), k_0 is seen to be inversely proportional to $I_{FC,0}$. Hence, $H(0)$ will decrease when $I_{FC,0}$ increases. Therefore,

the extent of the change in E to counter the I_{FC} change will decrease with increasing $I_{FC,0}$.

One can also gain a better insight of the FC dynamics using the frequency response method. With typical SOFC data as that given in Appendix A, Figure 3-4 shows the Bode diagram of $H(s)$ when $u_s = 0.8$, $I_{FC,0}$ is under either one of the two operating conditions of 0.1 p.u. and 1.0 p.u.

Figure 3-4 Bode diagram of $H(s)$ under different $I_{FC,0}$

It is seen from Figure 3-4 that the cross-over frequency of $H(s)$ is typically below 1 rad/sec. The narrow bandwidth of $H(s)$ again shows that the FC is a power source which is relatively slow in nature compared to the other conventional power generators such as a synchronous machine. If a fast disturbance such as that due to a network fault causes I_{FC} to change rapidly, it is impossible for the FC to react to this I_{FC} change by adjusting its EMF E . On the other hand, the response of the FC to load changes which would be well-within the bandwidth of the FC, E can be adjusted to track the I_{FC} change readily. This includes the commonly encountered problem known as the load-tracking ability of the FC. Notice that as $I_{FC,0}$ increases, the bandwidth decreases. The response of the FC to the stack current change will be slower as the SOFC operates into heavier load change.

One potential application of the above dynamic models is for analyzing the performances of the SOFC under the condition of sudden load changes.

3.5 SOFC Step Response to Load Change

When the SOFC supplies power to a load, any load variation will cause a change in the FC current and V_{dc} will then undergo an excursion. Excessive variation in V_{dc} will degrade the supply quality. As the internal EMF of the FC is inherently slow to react, a way of mitigating the V_{dc} variation must be provided. In the literature, energy storage such as a shunt-connected capacitor bank has been proposed to mitigate the problem and smooth the V_{dc} variation [6]. To examine the FC dynamic response after the disturbance, the load variation could be modeled as a step current change as shown in the circuit model of Figure 3-5. The FC is represented by a variable EMF in series with a resistor. The capacitor bank C is connected across the terminals of the FC.

Figure 3-5 Equivalent circuit of the FC power plant under load current disturbance

From Figure 3-5 and in the frequency domain, one obtains the following equation after a sudden change in load current, ΔI_l :

$$\Delta I_{FC}(s) + \Delta I_c(s) = \Delta I_l(s) \quad (3-27)$$

where ΔI_c is the capacitor current and $\Delta I_c = -Cs\Delta V_{dc}$. Suppose the load current change $\Delta I_l(s)$ is a step change of magnitude $\epsilon I_{FC,0}$. Substituting (3-15) into (3-27), the relationship between ΔV_{dc} and ΔI_l can be written in the form

$$\Delta V_{dc}(s) = \frac{R(s)}{T(s)} \Delta I_l(s) \quad (3-28)$$

If the fuel input is kept constant,

$$R(s) = F(s) - r$$

$$T(s) = rCs + 1 - F(s)Cs.$$

where $F(s)$ is given by (3-20).

On the other hand, if the fuel is regulated under the constant fuel utilization manner, from (3-25), therefore,

$$R(s) = H(s) - r$$

$$T(s) = rCs + 1 - H(s)Cs.$$

where $H(s)$ is described by (3-25).

The dynamic SOFC models derived in Section 3.4 can then be used here to evaluate the FC dynamic response. To simplify notation, the value of rC is defined by the equivalent time constant τ , i.e., $\tau = rC$.

3.5.1 Under constant fuel intake

With the fuel input kept constant, one can substitute (3-20) into (3-28) to obtain

$$\Delta V_{dc}(s) = -\frac{e(s)}{a(s)} \Delta I_l(s) \quad (3-29)$$

where

$$e(s) = e_3 s^3 + e_2 s^2 + e_1 s + e_0$$

$$e_0 = r + (k_1 + k_2 - 1)k_0$$

$$e_1 = (\tau_{O_2} + \tau_{H_2} + \tau_{H_2O})r + [(k_2 - 1)\tau_{O_2} + (k_1 - 1)\tau_{H_2} + (k_1 + k_2)\tau_{H_2O}]k_0$$

$$e_2 = (\tau_{O_2}\tau_{H_2} + \tau_{O_2}\tau_{H_2O} + \tau_{H_2}\tau_{H_2O})r + (-\tau_{O_2}\tau_{H_2} + k_2\tau_{O_2}\tau_{H_2O} + k_1\tau_{H_2}\tau_{H_2O})k_0$$

$$e_3 = \tau_{O_2}\tau_{H_2}\tau_{H_2O}r$$

$$k_0 = E_f / I_{FC,0}$$

$$k_1 = \frac{u_0 r_{H-O}}{2(2 - u_0 r_{H-O})}$$

$$k_2 = \frac{u_0}{1 - u_0}$$

$$a(s) = (\tau s + 1)(\tau_{O_2} s + 1)(\tau_{H_2} s + 1)(\tau_{H_2O} s + 1) - k_0 Cs[(k_2 \tau_{O_2} \tau_{H_2O} + k_1 \tau_{H_2} \tau_{H_2O} - \tau_{O_2} \tau_{H_2})s^2 + ((k_2 - 1)\tau_{O_2} + (k_1 - 1)\tau_{H_2} + (k_1 + k_2)\tau_{H_2O})s + k_1 + k_2 - 1].$$

As the fuel intake is kept constant, the time constant of the fuel processor τ_f does not appear in the above expressions. In addition, as typically $0.7 \leq u_0 \leq 0.9$ and $u_0 r_{H_2O} \approx 1$, it is clear that $k_1 > 0$, $k_2 > 2$ and all the coefficients in the numerator of (3-29) are positive. As the load current change is a step with magnitude $\varepsilon I_{FC,0}$, substituting $\varepsilon I_{FC,0} / s$ into (3-29) and using the final value theory, one obtains the final steady-state change in V_{dc} as $\Delta V_{dc}(\infty)$ where

$$\Delta V_{dc}(\infty) = -\varepsilon e_0 I_{FC,0} = -\varepsilon [r I_{FC,0} + (k_1 + k_2 - 1) E_f] \quad (3-30)$$

It is seen from (3-30) that $\Delta V_{dc}(\infty)$ is directly proportional to the FC current variation magnitude $\varepsilon I_{FC,0}$. The capacitor value C will not affect $\Delta V_{dc}(\infty)$. For a positive step increase in the stack current, $V_{dc}(\infty)$ is negative. Hence V_{dc} will settle at a level lower than its initial value $V_{dc,0}$ after the disturbance.

Figure 3-6 V_{dc} based on Figure 3-1 and (3-29) for constant $N_{H_2}^{in}$: $I_{FC,0} = 0.9$ p.u., $\varepsilon = 0.1$

It is difficult to obtain the general analytic expression of ΔV_{dc} in the time domain. In order to assess how the selection of C affects the transient process, one may rely on numerical method. For example, Figure 3-6 shows a comparison of $V_{dc}(t)$ resulting from the simulation of the full model given in Figure 3-1 and that of the expression (3-29) based on the simplified model. In this study, $V_{dc,0} = 330V$ and a step change of $0.1 I_{FC,0}$ is assumed. V_{dc} profiles for values of $C = 0.1F$ and $10F$ are shown in the figure. Curves 1 and 2 correspond to the model in Figure 3-1 where C are $0.1F$ and $10F$ respectively. The

corresponding results based on the model described by (3-29) are shown as curves 3 and 4. It shows that V_{dc} is a monotonic function and only reaches the final steady-state value in about 100 seconds.

It is seen from Figure 3-6 that increasing C can only reduce the transient voltage drop slightly. This can be explained as follows. Suppose over a time period $[t_0, t_1]$, V_{dc} in Figure 3-6 varies from $V_{dc,0}$ to $V_{dc,1}$. The energy change (ΔE_c) released by C is

$$\begin{aligned}\Delta E_c &= - \int_{V_{dc,0}}^{V_{dc,1}} C V_{dc} dV_{dc} \\ &= -\frac{1}{2} C (V_{dc,0}^2 - V_{dc,1}^2)\end{aligned}\quad (3-31)$$

Thus, ΔE_c is only dependent of the V_{dc} values at the start and end time. Letting

$$\lambda = \frac{V_{dc,0} - V_{dc,1}}{V_{dc,0}} \quad (3-32)$$

(3-31) can be approximately written as

$$\Delta E_c \approx \lambda C V_{dc,0}^2 \quad (3-33)$$

During the disturbance, the load power change ΔP_{LD} can be written as

$$\Delta P_{LD} = V_{dc,0} \Delta I_l + I_{l,0} \Delta V_{dc} \quad (3-34)$$

In the last equation, $\Delta I_l = \varepsilon I_{FC,0}$, the initial load current $I_{l,0} = I_{FC,0}$ and the initial load power is $P_{LD,0} = V_{dc,0} I_{FC,0}$. Therefore, (3-34) can be rewritten as

$$\begin{aligned}\Delta P_{LD} &= \varepsilon V_{dc,0} I_{FC,0} + I_{FC,0} \Delta V_{dc} \\ &= \varepsilon P_{LD,0} + I_{FC,0} \Delta V_{dc}\end{aligned}\quad (3-35)$$

From (3-35), the energy change in the load ΔE_{LD} during the time period $[t_0, t_1]$ is

$$\begin{aligned}
\Delta E_{LD} &= \int_{t_0}^{t_1} \Delta P_{LD} dt \\
&= \int_{t_0}^{t_1} (\varepsilon P_{LD,0} + I_{FC,0} \Delta V_{dc}) dt \\
&= \varepsilon P_{LD,0} (t_1 - t_0) + I_{FC,0} \int_{t_0}^{t_1} \Delta V_{dc} dt
\end{aligned} \tag{3-36}$$

From Figure 3-6, as V_{dc} is a monotonic function and from (3-32), therefore

$$\int_{t_0}^{t_1} \Delta V_{dc} dt \leq (V_{dc,0} - V_{dc,1})(t_1 - t_0) = \lambda V_{dc,0} (t_1 - t_0)$$

Letting $t_c = t_1 - t_0$ and substituting the last equation into (3-36), ΔE_{LD} would satisfy the following:

$$\Delta E_{LD} \leq \varepsilon P_{LD,0} t_c + I_{FC,0} \lambda V_{dc,0} t_c = (\varepsilon + \lambda) P_{LD,0} t_c \tag{3-37}$$

To guarantee of C has sufficient capacity to smooth out the V_{dc} variation and provide the required energy ΔE_{LD} , C can be sized thus:

$$\Delta E_c = (\varepsilon + \lambda) P_{LD,0} t_c \tag{3-38}$$

Substituting (3-38) into (3-33), C is

$$C = \frac{(\varepsilon + \lambda)}{\lambda V_{dc,0}^2} P_{LD,0} t_c \tag{3-39}$$

With the given λ , (3-39) shows how C would be determined from known or specified $V_{dc,0}$, $P_{LD,0}$ and t_c . C is proportional to t_c . This means that a longer time period voltage support needs a larger energy storage. As illustration, Figure 3-7 shows the numerical relationship between C and t_c when $V_{dc,0} = 330\text{V}$, $\varepsilon = 0.1$ and $P_{LD,0} = 0.9$ p.u. (90 kW). A 10F capacitor can maintain λ within 3% for about 2.8s. If the duration exceeds 2.8s, ΔV_{dc} will be larger than 3%. To support $\lambda < 3\%$ for hundreds of seconds operation must require the capacitor of hundreds of farad capacity. The cost of installing such a shunt capacitor could be high. Therefore, alternative operating scheme suitable for the SOFC must be found. Note that increasing $V_{dc,0}$ can reduce the size of C . However, higher V_{dc}

level corresponds to a larger number of cells connected in series in the stack. The capacity of the FC power plant will also increase.

Figure 3-7 Relationship between C and t_c

Figure 3-6 also demonstrates the close agreement between the results obtained from the two models Figure 3-1 and (3-29), and the difference in $V_{dc}(\infty)$ as obtained is negligible. Thus, the simplified model provides a convenient yet sufficiently accurate model for most of the purpose of present power system analysis.

3.5.2 Under constant fuel utilization

When the input fuel is regulated to result in the constant fuel utilization manner, one can substitute (3-25) into (3-28) and (3-28) can be rewritten as

$$\Delta V_{dc}(s) = -\frac{d(s)}{b(s)} \Delta I_l(s) \quad (3-40)$$

where

$$d(s) = d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s + d_0$$

$$d_i = m_i - l_i \quad (i = 0, 1, \dots, 4)$$

$$m_0 = r$$

$$m_1 = r(\tau_{O_2} + \tau_f + \tau_{H_2} + \tau_{H_2O})$$

$$m_2 = r(\tau_{O_2}\tau_f + \tau_{O_2}\tau_{H_2} + \tau_{O_2}\tau_{H_2O} + \tau_f\tau_{H_2} + \tau_f\tau_{H_2O} + \tau_{H_2}\tau_{H_2O})$$

$$m_3 = r(\tau_{O_2}\tau_f\tau_{H_2} + \tau_{O_2}\tau_f\tau_{H_2O} + \tau_{O_2}\tau_{H_2}\tau_{H_2O} + \tau_f\tau_{H_2}\tau_{H_2O})$$

$$m_4 = r\tau_{O_2}\tau_f\tau_{H_2}\tau_{H_2O}$$

$$\alpha_1 = u_s / (1 - u_s)$$

$$\alpha_2 = 0.5u_s r_{H-O} / (2 - u_s r_{H-O})$$

$$l_0 = 0.5k_0$$

$$l_1 = [-(\alpha_1 + \alpha_2 + 1)\tau_f - 0.5\tau_{H_2} + 1.5\tau_{H_2O}]k_0$$

$$l_2 = [-(\alpha_1 + 1)\tau_{O_2}\tau_f - \tau_{O_2}\tau_{H_2O} + \tau_{O_2}\tau_{H_2O} - (\alpha_2 + 1)\tau_f\tau_{H_2} - (\alpha_1 + \alpha_2)\tau_f\tau_{H_2O} + 0.5\tau_{H_2}\tau_{H_2O}]k_0$$

$$l_3 = -(\alpha_1\tau_{O_2}\tau_f\tau_{H_2O} + \alpha_2\tau_f\tau_{H_2}\tau_{H_2O} + \tau_{O_2}\tau_f\tau_{H_2})k_0$$

$$l_4 = 0$$

$$b(s) = (1 + \tau s)(1 + \tau_{O_2}s)(1 + \tau_f s)(1 + \tau_{H_2}s)(1 + \tau_{H_2O}s) - k_0 Cs[(1 - \alpha_1\tau_f s)(1 + \tau_{O_2}s)(1 + \tau_{H_2O}s) + (1 - \alpha_2\tau_f s)(1 + \tau_{H_2}s)(1 + \tau_{H_2O}s) + (1 + \tau_{O_2}s)(1 + \tau_f s)(1 + \tau_{H_2}s)]$$

It is seen that $m_3 > 0$, $l_3 < 0$, therefore $d_3 = m_3 - l_3 > 0$. The sign of d_0 ($d_0 = m_0 - l_0 = r - 0.5k_0$) depends on the value of $k_0 = E_f / I_{FC,0}$, i.e., the initial value of stack current. The time constant τ is defined earlier as $\tau = rC$.

Again substituting $\varepsilon I_{FC,0} / s$ into (3-40) and using the final value theory, one can find the final steady-state $\Delta V_{dc}(\infty)$ as

$$\Delta V_{dc}(\infty) = -\varepsilon d_0 I_{FC,0} = -\varepsilon(r I_{FC,0} - 0.5E_f) \quad (3-41)$$

Compared to $\Delta V_{dc}(\infty)$ of (3-30) and as $k_I + k_2 - 1 > 1 > -0.5$, $\Delta V_{dc}(\infty)$ in (3-41) is of a smaller value. This is because when the FC is operated under constant fuel utilization condition, the fuel valve will adjust the fuel input to meet the new load demand during the transient period. Note that $\Delta V_{dc}(\infty)$ is directly proportional to the initial stack current $I_{FC,0}$. When $I_{FC,0} = E_f / (2r) = I_{FC,m}$ and substituting it into (3-41), one notes that $\Delta V_{dc}(\infty) = 0$. Therefore, at $I_{FC,0} = I_{FC,m}$, $V_{dc}(\infty)$ remains at the same level as that before the step disturbance. Similarly, it can be shown that when $I_{FC,0} < I_{FC,m}$, $\Delta V_{dc}(\infty)$ will be negative. This means that ΔV_{dc} will settle in a direction opposite to the load current change. A closer examination of the numerator of (3-40) shows that as $d_3 > 0$ and $d_0 < 0$ when $I_{FC,0} < I_{FC,m}$: there will be one positive zero in the transfer function of (3-40). Therefore,

(3-40) represents a non-minimum phase system. However, in the case when $I_{FC,0} > I_{FC,m}$, ΔV_{dc} will move in the same direction as the load current change. All the above analysis can also be seen from the FOA curve shown in Figure 3-2. When the FC operates on the constant fuel utilization condition, any step load current disturbance which is initiated at a level less than $I_{FC,m}$ will cause $V_{dc}(\infty)$ to assume a level less than that of its initial value. Conversely, the disturbance initially $I_{FC,0}$ larger than $I_{FC,m}$ will cause $V_{dc}(\infty)$ to settle at a level higher than $V_{dc,0}$.

Again it is rather difficult to obtain the analytic expression of ΔV_{dc} in the time domain. One can resort to numerical method to examine the effect of C on the transient process. For example, Figure 3-8 shows a comparison of V_{dc} resulting from the full model given in Figure 3-1 and the expression (3-40) based on the simplified model. In this study, a step change of $0.1I_{FC,0}$ is assumed when $I_{FC,0} = 0.9$ p.u.

Figure 3-8 V_{dc} based on Figure 3-1 and (3-40) with stack-current feedback: $I_{FC,0} = 0.9$ p.u. $> I_{FC,m}$, $\varepsilon = 0.1$

For comparison with Figure 3-6, the same capacitor values have been used to obtain Figure 3-8. Curves 1 and 2 correspond to the results based on the model in Figure 3-1 where C are 0.1F and 10F respectively, curves 3 and 4 those calculated using (3-40). It shows that V_{dc} will decrease to a minimum value before it recovers to a steady-state value. All the transient voltage values are smaller than the initial value and the transient process will end only after about 150~200 seconds. As evident from the figure, the final

value of the voltage is less than its initial level. The initial direction of voltage change is the same as that of the final voltage level. Hence, as predicted in (3-41), the response does not show any non-minimum phase behavior for this initial stack current. Compared to Figure 3-6 in this instance, V_{dc} has undergone a smaller excursion. Further simulation studies show that V_{dc} variation range will be always within 5% of its initial value even without the capacitor. Finally, Figure 3-8 also demonstrates the close agreement between the results obtained by the two models.

If a 0.1 p.u. load current step is applied when $I_{FC,0} = 0.2$ p.u. i.e., $I_{FC,0} < I_{FC,m}$, the terminal voltage is seen to vary in the manner depicted in Figure 3-9. Curve 1 corresponds to the result based on the model shown on Figure 3-1. Curve 2 is calculated using (3-40). As predicted by (3-41), Figure 3-9 shows that over certain transient intervals, the voltage is higher than its initial value before it recovers to a value above $V_{dc,0}$. Such transient behavior is also called undershoot [64-66]. This is the characteristic of a non-minimum phase system. A comparison of the results obtained using the model of Figure 3-1 and (3-40) again shows the simplified model is accurate in predicting the SOFC step response.

Figure 3-9 Example of non-minimum phase behavior for $I_{FC,0} = 0.2$ p.u. $< I_{FC,m}$, $\varepsilon = 0.1$ and $C = 0.1F$

3.6 Conclusions

In this chapter, the concept of the Feasible Operating Area (FOA) is introduced based on an existing non-linear SOFC model. FOA is a useful tool to assess the performance of the FC and allows the steady-state operating status of the FC to be determined readily. Using small-signal analysis, SOFC dynamic model under the constant fuel input and constant fuel utilization operating schemes has been derived. From the derived relationship between the FC EMF and stack current, it is shown that the FC is relatively slow in responding to stack current change. The derived model is then used to evaluate the effectiveness of shunt capacitor to mitigate the effects of a load disturbance. By examining the SOFC step response, simulation results show that the derived SOFC dynamic models agree well with the non-linear model. Compared with the constant fuel intake condition, if the constant fuel utilization strategy is used, the FC terminal voltage V_{dc} is seen to undergo a smaller excursion. This is because by allowing the fuel input to adjust in accordance with the stack current in a proportional manner, the terminal voltage can be regulated to within a narrower range. Furthermore, it is shown that if the initial stack current ($I_{FC,0}$) is above the threshold value $I_{FC,m}$, the steady-state change in the voltage, $\Delta V_{dc}(\infty)$, is in the same direction as the change in current. Conversely, if $I_{FC,0} < I_{FC,m}$, the $\Delta V_{dc}(\infty)$ will be in the opposite direction as the I_{FC} change. Finally, with the typical SOFC obtained from the literature, simulation results verify that $\Delta V_{dc}(t)$ can be maintained within 5% even without the shunt capacitor. The shunt capacitor appears to be ineffective in mitigating the V_{dc} change. Constant fuel utilization control scheme is therefore seen to be a more suitable scheme for controlling the FC.

Chapter 4

Control of the SOFC Power Plant in an Isolated System

4.1 Introduction

Having analyzed FC dynamic performances under load variation, it is shown that FC is relatively slow in responding to external disturbance. From the discussions in Chapter 3, it is concluded that the FC is suitable in tackling problems associated with that during load tracking. There are two possibilities for the FC to meet the load demand [2]. One is the stand-alone operating mode shown in Figure 4-1a. It is also called the isolated mode. The other is the parallel operation, shown in Figure 4-1b, and is also known as interconnected mode. This chapter will discuss the SOFC DG load-tracking problem in an isolated system. The detailed grid-connected operation of the FC DG will be discussed further in Chapters 6 and 7.

Figure 4-1 Grid interconnection options for DG

Based on power level, FC in an isolated system is studied in two areas. One is for low power portable application and the other is for medium power stationary power supply. In the portable applications, researchers have developed commercialized FC systems used in UPS, medical instruments and electrical vehicles [52-54]. As introduced in Chapter 2, PEMFC can use pure hydrogen to generate DC power without the need of fuel processor. This makes PEMFC a good candidate in the portable applications. Compared to a FC having fuel processor, the control scheme for the pure-hydrogen type PEMFC is different. In [54], for example, a linear adaptive control scheme was proposed

to control the PEMFC-driven electrical car. The authors provided a linearized PEMFC dynamic model in their study where the hydrogen fuel was always assumed available. Through a Proportional Integration (PI) type controller, the air flow to the FC stack was controlled to maintain the stack terminal voltage constant. To protect the FC stack from oxygen starvation during step changes of load current demand, an observer was designed. Based on the on-line measured cell oxygen utilization and the state variables such as stack current and electrode reaction output partial pressures, the observer could adaptively regulate the parameters of the PI controller. The proposed control scheme was shown to have the required stability margin. The load current demand could be followed while the oxygen utilization factor could be always maintained within an acceptable range. Taking the cell performance parameter into consideration, as given by [54], is a valuable suggestion for FC load-tracking control.

Until recently, FC has been studied to supply stationary power for an isolated system. One earlier work appeared in the concept of micro-grid proposed by Lasseter [67]. The micro-grid concept assumed a cluster of loads and microsources operating as a single controllable system that could provide both power and heat to its local loads. The microsources of special interest for micro-grid were small units (less than several hundreds kW) with power electronic interface. These sources, typically microturbines, photovoltaics and FC, were expected to track the load power demand and maintain the local voltage constant. Unfortunately, the detailed control scheme for the microsources was not given in [67]. In a later paper, EI-Sharkh *et al.* presented a real and reactive power control scheme for a 5 kW PEMFC power plant in an isolated system [55]. The PEMFC contained a fuel processor which converted natural gas to hydrogen. In the proposed FC system, the fuel processor was modeled in a form of a second order transfer function. The cell stack model was similar to that described in [34]. The PCU was modeled as idealized switches by neglecting the possible harmonics. Two PI controllers obtained from the simulation results were used to control the natural gas and PCU to follow the load power demand. The simulation result showed that the PEMFC could support 0.4 p.u. step load real power change. However, the most important variable, the cell fuel utilization, was not considered in their study. It is doubtful whether the FC could afford such real power change safely. Further studies need to explore the load-tracking ability of the FC.

As the FC is a slow-response power source, any load variation under the normal operating condition has to be slow and is within the FC power plant capacity. In an isolated system, one of the main power quality issues is maintaining the load voltage magnitude within allowable range. This chapter will focus on such a load-tracking problem for the SOFC power plant based on the dynamic model derived in Chapter 3. Clearly, the Power-Conditioning Unit (PCU) of the FC power plant can be relied on to quickly mitigate short duration voltage disturbance by tuning its only control variable which is the modulation index m ($0 \leq m \leq 1$) in such an isolated system. However, if the fuel intake is kept constant while the load varies, the SOFC may be forced to operate beyond the control capability of the PCU and the load voltage may be degraded. Therefore, the fuel intake must also be regulated to satisfy the load demand. The work described also appears in one of the author's publications [68].

4.2 Steady-State Analysis

Figure 4-2 Schematic diagram of an FC power plant in an isolated system

Figure 4-2 shows the schematic diagram of an FC power plant in an isolated system where the FC supplies power to a load Z_{LD} through a transformer. The transformer is likely to be needed to match the voltage levels between the terminals of the power plant and the load. As there is no reference voltage in this isolated system, as described in Section 2.6, the only available control variable for the PCU is the modulation index m . The switching frequency of the PCU is at least tens times of the power frequency. Hence for slow variation in load, the PCU can respond quickly to maintain the load voltage constant through the regulation of m . The fast transients caused by the switching actions

of the PCU can be neglected. Only the fundamental component of the voltage/current on the AC-side would be considered.

In Figure 4-2, the input current of the PCU is the DC stack current I_{FC} . The PCU DC-side voltage is the FC terminal voltage V_{dc} and AC-side voltage is V_f . The equivalent impedance of the load-transformer combination is represented as $R + jX$. If SPWM switching method is used, the fundamental component of V_f can be calculated with the average method and is proportional to m [63]. The rated value of rms phase voltage at the output of the PCU can be derived as

$$V_{f,rated} = 0.5m_{rated}V_{dc,rated} / \sqrt{2} \quad (4-1)$$

where $V_{dc,rated}$ is the rated stack terminal voltage in volts and m_{rated} is the modulation index of the PCU under rated operating condition. Typically m_{rated} has a value of about 0.8. By taking $V_{f,rated}$ given in the above equation as the base value, the inverter output phase voltage can be expressed in per-unit form as

$$V_f = mV_{dc} \quad (4-2)$$

where m is the per-unit value of the variable modulation index with respect to the base value of m_{rated} and V_{dc} is the per unit value of variable stack terminal voltage with respect to the base value of $V_{dc,rated}$.

Under steady state condition and from (4-2), real power P_{LD} on the AC-side of the PCU can be calculated:

$$P_{LD} = \frac{(mV_{dc})^2 R}{R^2 + X^2} \quad (4-3)$$

The DC-side real power P is given by

$$P = V_{dc} I_{FC} \quad (4-4)$$

Neglecting the switching losses, $P = P_{LD}$, thus

$$V_{dc} I_{FC} = \frac{(mV_{dc})^2 R}{R^2 + X^2} \quad (4-5)$$

Hence, the steady-state stack current can be expressed as

$$I_{FC} = \frac{m^2 R V_{dc}}{R^2 + X^2} \quad (4-6)$$

Hence, the stack current is the function of the load-side impedance $R + jX$, the PCU control variable (m) and the FC terminal voltage (V_{dc}). Seen from the PCU DC-side input port, the FC external circuit can be represented by an equivalent shunt resistor R_l . From (4-6), R_l can be expressed as

$$R_l = \frac{R^2 + X^2}{m^2 R} \quad (4-7)$$

Any variation of the load impedance can be treated as a change of R_l when the role of the FC power plant in such an isolated system is to track slow load variations. Formulated in this way, some control methods must be introduced to guarantee that the FC will always operate within the FOA described in Chapter 3. In this chapter, two control methods will be examined using the dynamic model derived earlier. The methods are based on the strategy to maintain a constant fuel utilization or a constant terminal voltage. In studying the load-tracking schemes, the equivalent external resistor R_l simulating the slow load-varying is shown as a variable resistor operating under quasi-steady-state condition.

4.3 Load-Tracking Control Schemes

4.3.1 Constant fuel utilization control

Just as was described in Section 3.3, if the allowable range of the FC output power is known, one can select a suitable pre-set utilization value u_s such that any load variation will result in the final steady-state operating condition to be within the FOA. For example, this means the selection of a constant u_s corresponding to that of the line YZ shown in Figure 4-3. As introduced in Section 3.4.2, this can be achieved by feeding back the stack current with a proportional gain $2K_r / u_s$ to adjust the fuel input N_f such that $N_f = 2K_r I_{FC} / u_s$. It can be calculated from (3-16) that the steady-state voltage

variation along YZ is small. With the constant fuel utilization manner, it is also shown in (3-40) that the transient V_{dc} excursion would be small (less than $\pm 5\%$) if the step load disturbance is up to $\pm 10\%$ of the initial load current. Therefore, a PWM inverter in the PCU can easily handle the resulting small change in V_{dc} in order to keep a constant voltage across the AC load.

Figure 4-3 Constant fuel utilization and constant voltage control schemes in the FOA

4.3.2 Constant voltage control

In some practical cases such as when the PCU inverter is a six-step type having no voltage controllability, or when the load is primarily DC type, it is necessary to maintain a constant V_{dc} at the FC terminals. With the help of FOA such as Figure 4-3, one could select a V_{dc} level to guarantee that u would always be within the range $0.7 \leq u \leq 0.9$ when the FC output power varies. The stack current feedback used in constant utilization factor control scheme can still be included in this instance to form a current loop. This current loop, as discussed in Chapter 3, will smooth out the V_{dc} variation caused by load disturbance, without the need of a shunt capacitor. Furthermore, if there are disturbances originated within the cell stack, the current loop can quickly respond before these disturbances can affect the load voltage. In addition, V_{dc} can also be used as another control signal to regulate the fuel input. This is illustrated by the control block diagram

shown in Figure 4-4 where there are an inner current control loop and an outer voltage control loop. Such multi-loop control scheme has been widely used in the control of UPS, motors and processes [69-71]. In this figure, the fuel processor, the Nernst and thermodynamic equations introduced in Chapter 3 are included. Under this control mode, the steady-state operating state will be for example, along the constant voltage curve XZ of Figure 4-3, for the reference voltage (V_{ref}) of (say) 1 p.u. The controller in this scheme is yet to be determined. It is represented by the transfer function $G_c(s)$. The natural gas fuel input N_f is regulated according to the stack current feedback and the regulated voltage error signal N_r . After the fuel processor, the natural gas input will be reformed to the hydrogen input $N_{H_2}^{in}$ to the stack. Both I_{FC} and $N_{H_2}^{in}$ change will affect the FC EMF E , thus V_{dc} will also change. Including the current loop, the open-loop transfer function between V_{dc} and N_r is represented as $G_p(s)$.

Figure 4-4 Proposed SOFC load-tracking control scheme for constant V_{dc}

The outer voltage loop must be designed to coordinate its operation with that of the inner current loop, for the purpose to achieve acceptable dynamic performance. From Figure 4-4, one can substitute the hydrogen fuel input signal $\Delta N_{H_2}^{in}$ and the initial steady-state reactants values into (3-19). The relationship between ΔE , $\Delta N_{H_2}^{in}$ and ΔI_{FC} is therefore

$$\Delta E(s) = P(s)\Delta N_r(s) + Q(s)\Delta I_{FC}(s) \quad (4-8)$$

It can be shown (as in Appendix B) that

$$P(s) = K \{ [(2 - u_0 r_{H-O}) \tau_{O_2} + (1 - u_0) \tau_{H_2}] s + 3 - u_0 - u_0 r_{H-O} \} / [(1 + \tau_f s)(1 + \tau_{O_2} s)(1 + \tau_{H_2} s)]$$

$$Q(s) = k_0 (b_3 s^3 + b_2 s^2 + b_1 s + b_0) / (a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0)$$

where k_0 , K , a_i and b_j are given in Appendix B. These constants are functions of the time constants associated with the hydrogen, oxygen and water flow, initial fuel utilization factor u_0 and the initial stack current $I_{FC,0}$.

Next, the open-loop transfer function $G_p(s)$ of V_{dc} with respect to the fuel regulation signal N_r can be obtained by substituting $\Delta E = \Delta V_{dc} + r \Delta I_{FC}$ and $\Delta V_{dc} = R_l \Delta I_{FC}$ into (4-8), i.e.,

$$\left. \begin{aligned} G_p(s) &= \frac{\Delta V_{dc}(s)}{\Delta N_r(s)} = K \frac{M(s)}{N(s)} = \frac{P(s)}{1 + r/R_l - Q(s)(1/R_l)} \\ K &= RTu_0 / [I_{FC,0}(1 - u_0)(2 - u_0 r_{H-O})] \end{aligned} \right\} \quad (4-9)$$

where $M(s)$ and $N(s)$ are as given in Appendix B.

G_p describes the open-loop SOFC power plant in an isolated system. As the FC inner power losses caused by r is negligible compared to the load power ($r \ll R_l$) and $E_f \ll V_{dc,0}$ with typical SOFC data, (4-9) can be rewritten as

$$G_p(s) \approx K \frac{[(2 - u_0 r_{H-O}) \tau_{O_2} + (1 - u_0) \tau_{H_2}] s + 3 - u_0 - u_0 r_{H-O}}{(1 + \tau_{H_2} s)(1 + \tau_f s)(1 + \tau_{O_2} s)} \quad (4-10)$$

It is now useful to illustrate the above using the plant parameters given in Appendix A. Figure 4-5 compares the Bode plots resulting from (4-9) and (4-10), when $I_{FC,0}$ is 0.7 p.u. and $V_{dc,0}$ is 1 p.u. It shows the close agreement of the Bode plots of (4-9) and (4-10). Hence the simplified transfer function (4-10) would be satisfactory for use in the design of the controller $G_c(s)$.

Figure 4-5 Bode diagram of SOFC transfer function $\Delta V_{dc}/\Delta N_r$ when $I_{FC,0} = 0.7$ p.u. and $V_{dc,0} = 1$ p.u.

It can be observed from the expression of K in (4-9) that K is a function of initial stack current $I_{FC,0}$ and u_0 , where u_0 can be determined from (3-16) for given $I_{FC,0}$ and $V_{dc,0}$. Numerical results show that K will be maximum when $I_{FC,0}$ is at its lowest level. Hence as $I_{FC,0}$ decreases, the gain of $G_p(s)$ at the crossover frequency will increase and the open-loop system will have a smaller phase margin. This point is illustrated in Figure 4-6 where the Bode plots corresponding to different $I_{FC,0}$ are shown under rated V_{dc} . Note that over this rather wide I_{FC} range, the cross-over frequency ω_c varies in a limited range of between 1.4rad/sec to 4.8rad/sec. This clearly demonstrates the slow response characteristic of the FC power plant.

Controller $G_c(s)$ Design

Having obtained the open-loop transfer function $G_p(s)$ (equation (4-9)) of the SOFC power plant, its controller $G_c(s)$ for constant V_{dc} operation can be designed using the frequency response method. In order to guarantee stability of the closed-loop control scheme shown in Figure 4-4, the controller G_c should be designed under the most onerous system condition. From the analysis of (4-9), it is seen from Figure 4-6 that the point ω_2 ($I_{FC,0} = 0.1$ p.u.) will correspond a smaller phase margin than that of point ω_1 ($I_{FC,0} = 1$ p.u.). The power system will have the smallest stability margin when the initial

stack current is at its minimum, such as point X in the FOA of Figure 4-3 at rated V_{dc} . Note that $G_c(s)$ would also affect the stability of the inner current loop. Large gain of $G_c(s)$ would cause the inner current loop to operate with a cross-over frequency larger than ω_2 . The inner current loop may then be unstable. In order to avoid any undesirable interaction between the two loops and achieve stability for the whole system, $G_c(s)$ should be designed to produce a new cross-over frequency ω'_c which is typically five to ten times lower than the cross-over frequency ω_2 corresponding to the minimum stack current [66].

Figure 4-6 Bode plots of G_p under different FC operating conditions

Suppose G_c is a PI type and has the structure $G_c(s) = k_p + k_i / s$. At ω'_c , denote the plant transfer function $G_p(\omega'_c) = M_p e^{j\theta_p}$. Both M_p and θ_p are known. Therefore the open-loop transfer function $G_c G_p(\omega'_c)$ with a desired phase margin ψ becomes

$$(k_p - jk_i / \omega'_c) M_p e^{j\theta_p} = e^{j(-180^\circ + \psi)} \quad (4-11)$$

Equate the real and imagine parts on both sides of (4-11), one obtains

$$\begin{aligned} -k_p \dot{\omega}_c M_p \sin \theta_p + k_i M_p \cos \theta_p &= \dot{\omega}_c \sin \psi \\ k_p \dot{\omega}_c M_p \cos \theta_p + k_i M_p \sin \theta_p &= -\dot{\omega}_c \cos \psi \end{aligned} \quad (4-12)$$

In solving the above equations, k_p and k_i can be evaluated as

$$\left. \begin{aligned} k_p &= -\frac{\cos(\psi - \theta_p)}{M_p} \\ k_i &= \frac{\dot{\omega}_c \sin(\psi - \theta_p)}{M_p} \end{aligned} \right\} \quad (4-13)$$

As M_p and θ_p are known, also $\dot{\omega}_c$ and ψ are pre-selected to satisfy stability consideration, the RHS of (4-13) are known and therefore k_p and k_i can be evaluated. Typically ψ should be at least 45° .

4.4 Illustrative Examples

The examples in this section will be used to illustrate how the control system of an SOFC power plant in an isolated system can be designed to track slow variations of load. The examples are based on the experimental data given in [34, 35], which are shown in Appendix A. The base values used in the examples are 100 kW, 330V at the FC stack terminals. The controller design is based on the linearized SOFC model described in (3-19). However, the effectiveness of the design is verified through simulation using the non-linear SOFC model shown in Figure 3-1. The simulation tool is MATLAB/SIMULINK.

In the following two illustration conditions, it is assumed that the load resistor has the following variation. The FC is operating at its rated operating condition initially. At 40s, a load disturbance causes the stack current to decrease instantly by 0.1 p.u. (30A). At 160s, the load resistor value is ramped up such that the stack current drops from 0.9 p.u. to 0.4 p.u. in (i) 120s, (ii) 240s or (iii) 480s, at which point the ramp change will cease. At 640s, another step load disturbance results in the stack current to decrease further to 0.3 p.u. At this point, the FC stack current is close to $I_{FC,m}$. After a further 2 minutes, the load resistance excursion is reversed. It finally returns to the initial rated condition.

4.4.1 Constant fuel utilization control

From Figure 4-3, suppose u is set at the value of 0.8 with the help of FOA. Figure 4-7 shows the profiles of I_{FC} , u and V_{dc} following the load disturbance. From the simulation results, it can be seen that the load is properly tracked along the line YZ shown in Figure 4-3 over the complete interval of load variations. When subjected to the step disturbances, the SOFC will assume a larger u excursion when the load is lighter. Under the ramp disturbances, both u and V_{dc} will experience larger excursions when the load resistor ramp rate increases. Compared to the rated FC terminal voltage, both the steady and transient state V_{dc} variation are less than 5% in this instance. Thus, the AC load voltage can be kept constant readily by controlling the modulation index of the PWM inverter.

Figure 4-7 Load tracking under constant u control scheme: load resistance variations in steps and in different ramp rates

According to Figure 4-7, the maximum step change in the load should be less than 0.1 p.u. to avoid overused fuel condition. For a ramp change, the limit is estimated to be about 0.25 p.u. per minute for the same consideration.

4.4.2 Constant voltage control

From the Bode plot of $G_p(s)$ when the initial current is 0.1 p.u., it can be seen from Figure 4-6 that the cut-off frequency ω_c is about 4.8 rad/sec and the phase margin is only 4.8° . With the controller, the new crossover frequency ω'_c is chosen to be 0.48 rad/sec and with a phase margin $\psi = 45^\circ$. The controller is designed using (4-13) and is given as $G_c = 0.008 + 0.0002/s$.

Figure 4-8 shows the profiles of I_{FC} , u and V_{dc} following the same load disturbances as before. The simulation results verify the proposed controller can indeed maintain V_{dc} satisfactorily under different stack current conditions. The load is properly tracked along the curve XZ shown in Figure 4-3. However, compared with the constant fuel utilization control method, this control method is more complex. Furthermore, u will have a larger excursion when the 0.1 p.u. step load change occurs, especially when I_{FC} is close to $I_{FC,m}$.

Figure 4-8 Load tracking under constant V_{dc} control scheme: load resistance variations in steps and in different ramp rates

4.5 Conclusions

Based on the simplified SOFC dynamic model derived in (3-19), the FC load-tracking capability in an isolated power system is examined. The purpose is to ensure that the SOFC would operate within the FOA as load demand varies. In the situation when the external load is a slow varying one, FC can be operated under the constant fuel utilization condition by regulating the fuel intake in proportion to the stack current. The SOFC steady-state operating point will be on the pre-set constant fuel utilization line. Combined this as the inner current feedback, an outer voltage control loop can also be used to maintain the FC terminal voltage. However, this control scheme is more complex than the constant fuel utilization control method. Simulation results show that the use of an SOFC DG is possible as a slow-acting energy source. As the FC terminal voltage variation during the load-tracking process is small, the control scheme can be incorporated with the PCU control to maintain the load voltage within acceptable range such as that defined by the power quality standard.

Chapter 5

Filter Design for SOFC Power Plant in an Isolated System

5.1 Introduction

As described in Chapters 2 and 4, a FC power plant can be interconnected to an AC system through an inverter-based PCU. The voltage source inverter (VSI) converts the FC output DC voltage V_{dc} to produce at its output terminals an AC voltage. However, apart from the fundamental component in the AC output voltage, it invariably contains a certain level of harmonic components, regardless of the method of modulation adopted in the PCU. Indeed, increasing use of the inverter-based DG could result in higher level of harmonics being introduced into the external system. DG-related power quality problem is an important topic being studied in developing the IEEE standard P1549 [1]. It is stated in [41] that the power quality is determined by the voltage quality when the voltage is controllable. If there is connection to an existing stiff grid, then the voltage cannot be controlled. The power quality is then defined by the current quality. In an effort to address this specific issue, reference [1] provides a guide on the maximum harmonic current distortion when the DG is supplying a balanced linear load.

In the literature, the harmonic problems caused by the grid-connected VSI DG are under active study. The harmonic mitigation solutions are categorized as preventive solutions and corrective solutions. The preventive solutions are those methods aiming to avoid harmonics and their consequences. These include: (1) Using complex topology VSI such as multi-level inverter to generate low harmonic output voltage; (2) Developing control methods to reduce or eliminate harmonics. Multi-level inverter can produce several voltage levels on the AC-side. By increasing the number of levels, the output voltage becomes closer to the perfect sinusoidal form and harmonics are reduced. Reference [72] proposed a specially designed PCU for a grid-connected PV generator. The PCU was a 3-phase GTO-based inverters. Each phase had m_p independent 3-level inverters. By comparing the measured output line current to the sinusoidal current reference, the current error was used to adjust the firing angle of each GTO. A $(2m_p + 1)$ levels output

voltage was generated to force the line current to follow the reference. Simulation results showed that the THD of the inverter output line current could be controlled to less than 1%. However, the proposed PCU is highly complex and the cost is high. It is doubtful if such a scheme would be suitable for an SOFC power plant in an isolated network.

Current harmonics can also be reduced through some novel control schemes. Reference [73] proposed a grid-current regulation control scheme for the VSI DG. A shunt-connected low-pass filter, denoted as LCL filter, was placed between the VSI and grid. By feeding back the filter capacitor voltage, filter capacitor current and the injected current to grid (I_2), a complex multi-loop control topology was formed. The measured I_2 was compared to the reference current signal I_2^* . The current error was used to generate the switching signals sent to the VSI through a P plus Resonant type controller. Through the analysis of the closed-loop transfer function $G_{I_2}(s) = I_2(s)/I_2^*(s)$, it was shown that $G_{I_2}(s)$ had a low pass character. Analysis found that increasing the gain of P controller could decrease the current THD but it would reduce the closed-loop system damping. The proposed multi-loop control scheme for harmonic mitigation is very complex for implementation.

Corrective solutions are those techniques aim at overcoming existing harmonic problems. They include active filters and passive filters. The active filter concept uses a power electronic converter to inject harmonic currents with the same amplitude and opposite phase to the load harmonic currents flowing into the line, thus eliminating harmonic currents flowing into the line. However, active filter requires a large rating if there is high peak harmonic and this will result in higher cost investment. Reference [74] proposed a current control scheme for the renewable DG. A LCL filter similar to that in [73] was used. The inverter output current and the current injected to the grid (I_3) were fed back to form a cascade control system. The controller current reference I_3^* contained two components. One was the real component which corresponded to the real power generated by DG. The other was the reactive component which had the same magnitude but opposite phase to the measured grid harmonic current components. The error between the reference current and the injected current was used to regulate the PCU through a PI controller. The open-loop transfer function $G_{I_3} = I_3(s)/I_3^*(s)$ appeared to

have a low pass character. However, the control system in [74] is again rather complex: it requires so many sensors to obtain the required signals. Therefore, using the proposed active filter method to mitigate harmonics would be costly in the SOFC scheme considered in this thesis.

Passive filters have traditionally been used to absorb harmonics generated by large industrial loads, primarily due to their simplicity, low cost and high efficiency. The principle of the passive filters is to provide a low-impedance shunt branch to the load harmonic currents, thus reducing the amount of harmonic currents flowing into the source. However, the source impedance strongly influences the mitigation effects of the passive filters. Passive filters cannot adapt to any variation in the system operating condition as the filter parameters cannot be changed easily. Passive filter were also used in [73,74]. However, the design method for the low-pass LCL filter was not given. A second order low-pass filter designed for the VSI DG was proposed in [57]. The filter consisted of an inductor and a capacitor while the possible resistance in the filter was not considered. The filter inductor was chosen to limit the inductor current ripple while the filter capacitor was chosen to provide the necessary low impedance path for high frequency distortion. With the given design expressions, both parameters were shown to be susceptible to the connecting point system impedance. In order to overcome the variable system parameters' effects on the harmonics mitigation, a cascade controller similar to that in [74] was included. Due to the variable system parameters impacts, passive filters in a grid-connected condition may have to be designed in conjunction with some novel controllers.

From the literature survey, it would appear that research works on harmonic mitigation solutions for the VSI DG in isolated system are active. As isolated loads supplied by DG typically vary in a narrow range because of the limited size of the network, the more economical cheap and reliable passive filter would be a viable option to alleviate the harmonic problem. Notice that as the control schemes for DG may differ, the inverter DC-side voltage may change under different load conditions. Hence, the fixed DC voltage assumption that was used in [57, 72-74] may not be valid. Furthermore, the variable DC-side voltage may also affect the load voltage. This must be taken into

consideration when the harmonic mitigation solution is explored. With these in mind, a passive filter design method is discussed in this chapter.

The work described in this chapter also appears in one of the author's publications [75].

5.2 Low-Pass Filter Design

With the method of SPWM switching, harmonic voltages appear as the side bands of the multiples of the inverter switching frequency. For most practical purposes, consideration of the side bands of up to a few times of the switching frequency is sufficient due to the fact that the magnitude of the harmonics decreases rapidly with the increasing order of the band. Therefore, for analytical purposes, the significant components of the harmonic spectrum can be considered as appearing from a certain lowest order l to a highest order n . If the switching frequency is m_f times the fundamental frequency f_c , the frequencies at which the voltage harmonics occur can be related by [63]

$$f_i = (jm_f \pm q)f_c \quad (5-1)$$

where the i th harmonic equals the q th sideband of j th times the frequency-modulation m_f [63]. For odd values of j , the harmonics exist only for even values of q . Conversely, for even values of j , the harmonics exist only for odd values of q . By choosing m_f as an odd integer, there will only be odd-order harmonics in the PCU output phase voltage and even-order harmonics do not exist. For example, when $j = 1$, q will be $\pm 2, \pm 4, \dots$; when $j = 4$, q will be $\pm 1, \pm 3, \pm 5$ and $\pm 7 \dots$. Typically, $m_f > 9$ for high power application.

The inverter output rms phase voltage of any i th order harmonic component V_{fi} , including the fundamental component at $i = 1$, can be related to the FC terminal voltage V_{dc} as [63]

$$V_{fi} = A_{(i)}V_{dc} \quad (5-2)$$

where $A_{(i)}$ is a voltage coefficient determined by the operating value of modulation index m of the inverter and is almost independent of m_f [63]. The coefficient of the fundamental component is directly proportional to the modulation index as

$A_{(1)} = m/2\sqrt{2}$. However, the coefficients of the harmonic components are not proportional to the m . Instead, reference [76] provides a method to calculate the harmonics coefficients through the Fourier analysis. As an illustration, Figure 5-1 shows $A_{(i)}$ of the fundamental component and $(2m_f-1)$ th order harmonic when m varies between 0.2 and 1. Unlike the fundamental component, $A_{(i)}$ of the harmonic is not linear with m , rather it is a convex function of m .

Figure 5-1 Voltage coefficient comparison of the SPWM switching method

When the FC power plant operates in an isolated system, it is necessary to keep the PCU output voltage constant. From the discussion in Section 4.3, it is known that the FC terminal DC voltage has to be operated within a certain allowable range $V_{dc,min} \leq V_{dc} \leq V_{dc,max}$, regardless of which control scheme is used to regulate the FC fuel valve. The allowable steady-state voltage variation range is limited by the FOA such as that shown in Figure 4-3. The voltage range can also be calculated from (3-16). As V_{dc} is allowed to vary within a given range, the modulation index m will also need to vary within a certain acceptable range $m_{min} \leq m \leq m_{max}$, to maintain a constant PCU output voltage. Typically $0.7 \leq m \leq 0.9$.

In order to suppress the harmonic voltages due to the inverter switching action, a low-pass filter can be introduced between the inverter and the load. Among all types of the low-pass filter, the second order type is most widely used in the industry. Although some higher order filter could be chosen to achieve more desirable waveform, the high order

filters will need additional capacitors and inductors thus the cost is higher [77]. Figure 5-2 shows the per-phase equivalent circuit of the system, as seen on the AC-side of the inverter with the low-pass filter included. As introduced in Section 2.6, the output voltage of the PCU only depends on the switching method and varies in two voltage levels: $V_{dc}/2$ and $-V_{dc}/2$. Seen from the external circuit, the SOFC power plant is a voltage source consisting of the fundamental and harmonic components. In Figure 5-2, the PCU is represented as an equivalent voltage source phasor $\dot{V}_f$. The variable represented as $\dot{X}$ means phasor variable. Variable power demand of the load is represented by a variable impedance Z_{LD} , with its magnitude over the range $Z_{LDmin} \leq Z_{LD} \leq Z_{LDmax}$ and angle with the range $\phi_{LDmin} \leq \phi_{LD} \leq \phi_{LDmax}$. A second order low-pass filter is connected between the voltage source and the load.

Figure 5-2 Per-phase equivalent circuit of the AC system

The filter inductor has an inductance L_F and an internal resistance. The filter capacitor has a capacitance of C_F and is assumed to have a negligible resistance. In order to control the extent of resonance caused by the L_F and C_F , a resistance in series with L_F can be used to provide the required damping [77, 78]. The total resistance (including that of the filter inductor) is R_F . The design problem therefore is to determine suitable values of L_F , R_F and C_F so that the output voltage meets the voltage distortion design specifications while minimizing the cost of the filter. In considering this filter design, the relationship between the filter parameters can be expressed in terms of the cut off frequency ω_f and the quality factor Q_f . They are defined as [77]

$$\omega_f = \frac{1}{\sqrt{L_F C_F}} \quad (5-3)$$

$$Q_f = \frac{1}{R_F} \sqrt{\frac{L_F}{C_F}} = \frac{1}{\omega_f R_F C_F} \quad (5-4)$$

For an ideal low-pass filter, input quantities with frequencies below ω_f can be transmitted through the filter but not those above ω_f . Quantities at frequencies close to ω_f would have their magnitude amplified. The degree of the amplification vs. frequency is named as the damping factor of the filter and it can be measured by Q_f . Large Q_f signifies a sharper peak and may even cause oscillation and it is undesirable. For illustration, one could examine the transfer function $G_F(s) = V_{LD}(s)/V_f(s)$ under no load condition. Figure 5-3 shows the Bode diagram of $G_F(s)$. It is seen from this figure that large Q_f corresponds a sharper peak around the frequency ω_f . Typically, for the low-pass filter, $30 < Q_f < 100$ [78]. In terms of cost, some 60% of the capital cost of the filter is that of the capacitor C_F . Hence, substantial savings are possible by the judicious choice of C_F [77].

Figure 5-3 Bode diagram of filter with different quality factor

5.3 Design Specifications

In considering the arrangement shown in Figure 5-2, there are the following considerations. Firstly, in order to provide the load with a voltage waveform of acceptable quality, the Total Harmonic Distortion (THD) of the load voltage must be kept below a set value ε_v expressed as

$$\sqrt{\sum_{i=1}^n V_{LD(i)}^2} / V_{LD(1)} \leq \varepsilon_v \quad (5-5)$$

where $V_{LD(i)}$ is the i th harmonic component of the load voltage [79], $V_{LD(1)}$ is therefore the fundamental component of the load voltage. In most industrial and international standards, there are clear guidelines on the values of ε_v for power system at different power and voltage levels. See e.g. [78-80].

However, the capacitor acts as a high-pass filter for harmonics of the inverter output current $\dot{I}_f$. In having it connected across $\mathbf{Z}_{LD}$, it may result in unacceptably large inverter currents being drawn into it. As shown in Figure 2-12, the load current would flow through the inverter. Thus, in order to keep the current rating of the switching devices of the inverter to acceptable values, the THD of the inverter output current $\dot{I}_f$ has also to be limited to below a certain set value ε_I as

$$\sqrt{\sum_{i=1}^n I_{f(i)}^2} / I_{f(1)} \leq \varepsilon_I \quad (5-6)$$

At the fundamental frequency $\omega_{(1)}$, the capacitor impedance $Z_{CF(1)} \gg Z_{LD(1)} \gg |R_F + j\omega_{(1)}L_F|$. Hence, the fundamental harmonic component of the voltage drop across $R_F + j\omega_{(1)}L_F$ can be neglected in comparison with $V_{LD(1)}$. Therefore, $I_{f(1)} \approx I_{LD(1)}$ and (5-6) can be rewritten as

$$\sqrt{\sum_{i=1}^n I_{f(i)}^2} / I_{LD(1)} \leq \varepsilon_I \quad (5-7)$$

Finally, as the inductor has a finite resistance R_F , power is dissipated in it. In order to keep the overall efficiency above a reasonable value, the power loss is set below a certain acceptable value ε_p :

$$(I_{f(1)}^2 + \sum_{i=1}^n I_{f(i)}^2) R_F / P_{LD(1)} \leq \varepsilon_p \quad (5-8)$$

where $P_{LD(1)}$ is the real power consumed by the load at the fundamental frequency.

The next step is to examine in detail each of the design specifications.

5.3.1 Voltage THD

Since $\mathbf{Z}_{LD}$ in Figure 5-2 is normally inductive, it is reasonable to assume that all the harmonic currents pass through the low impedance capacitor C_F . Therefore, by neglecting $\mathbf{Z}_{LD}$, the i th order harmonic voltage across the load can be approximately determined as

$$\dot{V}_{LD(i)} = \frac{1/j\omega_i C_F}{R_F + j\omega_i L_F + 1/j\omega_i C_F} \dot{V}_{f(i)} \quad (5-9)$$

and from which,

$$\sum_{i=l}^n V_{LD(i)}^2 = \sum_{i=l}^n \frac{|V_{f(i)}|^2}{(\omega_i R_F C_F)^2 + (\omega_i^2 L_F C_F - 1)^2} \quad (5-10)$$

Substituting (5-2), (5-3) and (5-4) into (5-10), it yields

$$\sum_{i=l}^n V_{LD(i)}^2 = \sum_{i=l}^n \frac{A_{(i)}^2 V_{dc}^2}{\left(\frac{\omega_i}{Q_f \omega_f}\right)^2 + \left(\left(\frac{\omega_i}{\omega_f}\right)^2 - 1\right)^2} \quad (5-11)$$

Since the denominator of the above equation is minimum when $i = l$, an upper bound (5-11) can be identified as

$$\sum_{i=l}^n V_{LD(i)}^2 < \frac{\sum_{i=l}^n A_{(i)}^2 V_{dc}^2}{\left(\frac{\omega_l}{Q_f \omega_f}\right)^2 + \left(\left(\frac{\omega_l}{\omega_f}\right)^2 - 1\right)^2} \quad (5-12)$$

Considering the LHS of (5-12) is typically greater than 1, one can combine (5-12) with the specification for load voltage THD given by (5-5) to yield

$$\sqrt{\sum_{i=1}^n V_{LD(i)}^2} < V_{dc} \sqrt{\frac{\sum_{i=1}^n A_{(i)}^2}{\left(\frac{\omega_l}{Q_f \omega_f}\right)^2 + \left(\left(\frac{\omega_l}{\omega_f}\right)^2 - 1\right)^2}} \leq \varepsilon_v V_{LD(1)} \quad (5-13)$$

By ensuring that the middle term of (5-13) to be less than $\varepsilon_v V_{LD(1)}$ as shown, (5-5) can be automatically satisfied. Since the fundamental frequency component of the voltage drop across the filter inductor is negligible, therefore $V_{LD(1)} \approx V_{f(1)} = A_{(1)} V_{dc}$. Substituting this into (5-13) and simplifying, one can conclude that

$$\frac{1}{\sqrt{\left(\frac{\omega_l}{Q_f \omega_f}\right)^2 + \left(\left(\frac{\omega_l}{\omega_f}\right)^2 - 1\right)^2}} \leq \frac{\varepsilon_v A_{(1)}}{\sqrt{\sum_{i=1}^n A_{(i)}^2}} \quad (5-14)$$

Note that from (5-2), the ratio $\sqrt{\sum_{i=1}^n A_{(i)}^2} / A_{(1)}$ is also equal to the THD of the inverter output voltage before the insertion of the filter. Denote the THD as $h = \sqrt{\sum_{i=1}^n A_{(i)}^2} / A_{(1)}$.

The above inequality can be rewritten as

$$\frac{1}{\sqrt{\left(\frac{\omega_l}{Q_f \omega_f}\right)^2 + \left(\left(\frac{\omega_l}{\omega_f}\right)^2 - 1\right)^2}} \leq \frac{\varepsilon_v}{h} \quad (5-15)$$

Re-arranging terms, an upper bound for the filter cut-off frequency ω_f can then be obtained in terms of h , ε_v , ω_l and ω_f :

$$\omega_f \leq \frac{\omega_l}{\sqrt{\frac{(2 - \frac{1}{Q_f^2}) + \sqrt{(2 - \frac{1}{Q_f^2})^2 + 4((h/\varepsilon_v)^2 - 1)}}{2}}} \quad (5-16)$$

The minimum value of the RHS of the above inequality occurs when h is at its maximum value. Therefore, in order to satisfy the load voltage THD specification under all conceivable operating conditions and to maximize the cut-off frequency ω_f , ω_f can be selected as

$$\omega_f = \frac{\omega_l}{\sqrt{\frac{(2 - \frac{1}{Q_f^2}) + \sqrt{(2 - \frac{1}{Q_f^2})^2 + 4((h_{\max} / \varepsilon_v)^2 - 1)}}{2}}} \quad (5-17)$$

Since the THD of inverter output voltage increases with the decreasing modulation index [63], the value of ω_f should be determined based on the minimum operating modulation index $m_{\min}$, i.e., when the FC has the maximum terminal voltage $V_{dc,\max}$. If the FC fuel valve is controlled under constant fuel utilization manner, it is shown in Chapter 3 that the $V_{dc,\max}$ appears when the stack current is $I_{FC,m}$. Under this most strenuous condition and assume the rated load voltage is $V_{LD,\text{rated}}$, from the relation ship $V_{f(1)} = mV_{dc} / (2\sqrt{2})$ and $V_{LD(1)} \approx V_{f(1)}$, the corresponding $m_{\min}$ can be calculated as $m_{\min} = 2\sqrt{2}V_{f(1)} / V_{dc,\max} \approx 2\sqrt{2}V_{LD,\text{rated}} / V_{dc,\max}$.

5.3.2 Current THD

By neglecting $\mathbf{Z}_{LD}$ in Figure 5-2 in the above analysis, the i th order harmonic current from the PCU can be written as

$$\dot{I}_{f(i)} = \frac{1}{R_F + j\omega_i L_F + 1 / j\omega_i C_F} \dot{V}_{f(i)} \quad (5-18)$$

and from which

$$\sum_{i=1}^n I_{f(i)}^2 = \sum_{i=1}^n \frac{(\omega_i C_F V_{f(i)})^2}{(\omega_i^2 L_F C_F)^2 + (\omega_i R_F C_F)^2} \quad (5-19)$$

Therefore, substituting (5-2), (5-3) and (5-4) into (5-19) and rearranging, one can show that

$$\sqrt{\sum_{i=1}^n I_{f(i)}^2} = \sqrt{\sum_{i=1}^n \frac{(\omega_i C_F A_{(i)} V_{dc})^2}{(\frac{\omega_i}{\omega_f})^4 - (2 - \frac{1}{Q_f^2})(\frac{\omega_i}{\omega_f})^2 + 1}} \quad (5-20)$$

By considering the minimum possible value of the denominator of the RHS of (5-20),

which is typically greater than 1, an upper bound of $\sqrt{\sum_{i=1}^n I_{f(i)}^2}$ can be identified as:

$$\sqrt{\sum_{i=1}^n I_{f(i)}^2} < \frac{C_F V_{dc} \sqrt{\sum_{i=1}^n A_{(i)}^2}}{\frac{1}{\omega_f} \sqrt{\frac{\omega_l^2}{\omega_f^2} - 2 + \frac{1}{Q_f^2}}} \quad (5-21)$$

Combine with the specification on inverter current given by (5-7), the above inequality can be written as,

$$\sqrt{\sum_{i=1}^n I_{f(i)}^2} < \frac{C_F V_{dc} \sqrt{\sum_{i=1}^n A_{(i)}^2}}{\frac{1}{\omega_f} \sqrt{\frac{\omega_l^2}{\omega_f^2} - 2 + \frac{1}{Q_f^2}}} \leq \epsilon_I I_{LD(1)} \quad (5-22)$$

Since $V_{LD(1)} \approx V_{f(1)}$, the load fundamental current can be calculated as,

$$I_{LD(1)} \approx \frac{A_{(1)} V_{dc}}{Z_{LD(1)}} \quad (5-23)$$

Substituting (5-23) into (5-22), and defining

$$k_f = \frac{1}{\omega_f} \sqrt{\frac{\omega_l^2}{\omega_f^2} - 2 + \frac{1}{Q_f^2}} \quad (5-24)$$

(5-22) can be rewritten as,

$$C_F \leq \frac{\epsilon_I A_{(1)} k_f}{Z_{LD(1)} \sqrt{\sum_{i=1}^n A_{(i)}^2}} \quad (5-25)$$

Recognizing that the THD of the inverter output voltage $h = \sqrt{\sum_{i=1}^n A_{(i)}^2} / A_{(1)}$, an upper bound for the filter capacitance can be written as

$$C_F \leq \frac{\epsilon_I k_f}{h Z_{LD(1)}} \quad (5-26)$$

The minimum value of C_f in (5-26) will occur at the maximum value of h and at maximum $Z_{LD(1)}$. Although h and $Z_{LD(1)}$ may not assume the maximum values simultaneously as the FC operating condition changes, in order to satisfy the current THD specification under all conceivable operating conditions and to reduce the capacitor cost, the capacitance should be selected as

$$C_F \leq \frac{\epsilon_I k_f}{h_{\max} Z_{LD\max(1)}} \quad (5-27)$$

C_F is so chosen to ensure that (5-27) will be satisfied under all conceivable conditions. Its value adjusted in the manner to be described in Section 5.3.4.

5.3.3 Power loss

The last parameter that needs to be determined is the filter resistance R_F . Considering the approximation $I_{f(1)} \approx I_{LD(1)}$, the power loss caused by the filter resistance is

$$(I_{f(1)}^2 + \sum_{i=1}^n I_{f(i)}^2) R_F \approx (I_{LD(1)}^2 + \sum_{i=1}^n I_{f(i)}^2) R_F \quad (5-28)$$

From (5-7), as $\sqrt{\sum_{i=1}^n I_{f(i)}^2} \leq \epsilon_I I_{LD(1)}$, one finds that

$$(I_{LD(1)}^2 + \sum_{i=1}^n I_{f(i)}^2) R_F \leq (I_{LD(1)}^2 + \epsilon_I^2 I_{LD(1)}^2) R_F \quad (5-29)$$

If the RHS of (5-29) satisfies

$$(I_{LD(1)}^2 + \epsilon_I^2 I_{LD(1)}^2) R_F \leq \epsilon_p P_{LD(1)} \quad (5-30)$$

then the power loss specification (5-8) will be also satisfied. Therefore, an upper bound on the filter resistance is given by

$$R_F \leq \frac{\epsilon_p P_{LD(1)}}{I_{LD(1)}^2 (1 + \epsilon_I^2)} \quad (5-31)$$

As

$$P_{LD(1)} = V_{LD(1)} I_{LD(1)} \cos \varphi_{LD} \quad (5-32)$$

Substituting (5-32) into (5-31), the minimum value of R_F can be derived as

$$R_F \leq \frac{\epsilon_p Z_{LD \min(1)} (\cos \varphi_{LD})_{\min}}{1 + \epsilon_I^2} \quad (5-33)$$

Thus, the minimum value for R_F has to be calculated by considering the minimum possible values of $Z_{LD(1)}$ and at the lowest load power factor.

5.3.4 Filter design procedure

With the above analysis, the design procedure of the output filter for the SOFC-based DG in the isolated system can be summarized as follows.

Step 1: Based on the FC fuel valve control scheme, specify the possible range of the FC terminal voltage V_{dc} . Based on (5-2) and the given $V_{LD, rated}$, obtain the possible range of m . Determine the maximum THD of inverter output voltage h_{max} for the known range of m . Specify the switching frequency of the inverter and determine the lowest frequency ω_l of dominant harmonics for the known range of m .

Step 2: Specify the range of load impedance $Z_{LD \min} \leq Z_{LD} \leq Z_{LD \max}$ and the minimum value of load power factor $(\cos \varphi_{LD})_{\min}$. Based on the IEEE standard 1159 [79], specify the desired values of load voltage THD ϵ_v , inverter output current THD ϵ_I and the filter power loss factor ϵ_p .

Step 3: Select a reasonable value of quality factor Q_f and use equations (5-17) to obtain ω_f . Substituting ω_f into (5-24) to calculate k_f , then use (5-27) to obtain C_F . From (5-3), L_F can be calculated. Final parameter R_F can then be obtained from (5-4).

Step 4: Check whether the inequality in (5-33) is satisfied. If R_F is much less than the value of the RHS of (5-33), the selected Q_f is too high. Conversely, if R_F is higher than the RHS of (5-33), the selected Q_f has been too low. In these cases, make the necessary adjustment to the Q_f and repeat the process, starting from step 3 until a R_F value slightly below the RHS of (5-33) is achieved.

5.4 A Illustrative Example

The examples in this section will be used to illustrative how an output filter for the SOFC power plant in an isolated system can be designed. The examples are based on the experimental data given in Appendix A. The proposed filter design is verified using the simulation tool MATLAB/SIMULINK.

Based on the discussion in Chapter 4, the fuel valve is assumed to be controlled under constant fuel utilization manner where the FC steady state operating status is described by the line $u_s = 0.8$ shown in Figure 4-3. From (3-16), it can be calculated that V_{dc} will have the maximum value $V_{dc,max} = 344.63\text{V}$ when the DC power is $P = 28.78\text{ kW}$, the minimum value $V_{dc,min} = 330.91\text{V}$ when $P = 100\text{ kW}$. The load is assumed to be at its rated voltage when the FC is operating at the rated output with the maximum modulation index $m_{max}=0.8$, i.e., the load voltage is $0.5mV_{dc,min} / \sqrt{2} = 93.6\text{ V}$ (phase). The minimum m that maintains the output voltage constant is $m_{min} = m_{max}V_{dc,min} / V_{dc,max} = 0.766$. The maximum THD of inverter output voltage h_{max} is corresponding to the condition $m_{min}=0.766$. It can be calculated using the method described in [76], that is $h_{max} = 0.8973$.

The switching frequency for the PCU is chosen as $f_c = 4650\text{ Hz}$, i.e., the frequency modulation is $m_f = 93$ for the fundamental frequency of 50Hz. From [76], it can be calculated that the harmonic voltage coefficients $A_{(i)}$ dominate between the order of $(m_f - 2)$ or 91 and $(4m_f + 7)$ or 379. Those harmonic orders above the $5m_f$ are very small and can be neglected.

Suppose the minimum load power factor $(\cos \varphi_{LD})_{min} = 0.9$ and is assumed constant. The load real power is within the FOA, i.e., it is assumed in the range $30\text{ kW} < P_{LD} < 100\text{ kW}$.

Given $V_{LD, rated} = 93.6\text{V}$, from $Z_{LD(1)} = (\sqrt{3}V_{LD(1)})^2 / \sqrt{P_{LD(1)}^2 + Q_{LD(1)}^2}$, $Z_{LD(1)}$ can be calculated and is shown to be within the range of $0.236\Omega \leq Z_{LD(1)} \leq 0.778\Omega$.

The desired values of load voltage THD ε_v , inverter output current THD ε_i and the filter power loss factor ε_p are specified as 5%, 5% and 2% respectively.

Based on the above initial data and using the filter design method described in Section 5.3, one possible set of the filter parameters can be obtained through an iterative process. They are $R_F=0.0052\Omega$, $L_F=67\mu\text{H}$ and $C_F=300\mu\text{F}$. This corresponds to $\omega_f = 7055\text{rad/sec}$ and $Q_f = 91$.

Figure 5-4 Load voltage and spectrum at minimum load impedance

Figure 5-5 Load current and spectrum at minimum load impedance

When the load has the minimum impedance value, Figure 5-4 and Figure 5-5 show the waveforms and spectra of the load voltage and current. From the simulation, the load voltage THD is determined to be 4.8%, current THD is 2.7% and the power loss is 1.86%. All are within permissible range.

As the filter is designed on the most onerous condition, it is expected to perform within the design specifications on other operating conditions. When the load has the maximum impedance, the corresponding load-side voltage THD has been determined and it is 3.6%, current THD is 2.2% and the power loss is 1.92%. All are again within permissible range. In addition, Q_f in this particular example is still high. A smaller Q_f can be obtained by relaxing the design specifications. If ε_p changes at 5% while ε_v and ε_I remain at 5%, the other possible set of the filter parameters can be calculated as $R_F = 0.013\Omega$, $L_F = 100\mu\text{H}$ and $C_F = 196\mu\text{F}$. This corresponds to $\omega_f = 7120\text{rad/sec}$ and $Q_f = 55$. Further simulation results show that the load-side voltage THD is now 4.1%, current THD is 2.7% and the power loss is 4.9% when the load has the maximum impedance. When the load has the minimum impedance value, the corresponding load-side voltage THD is 4.7%, current THD is 3.2% and the power loss is 4.8%. All are within permissible range.

5.5 Conclusions

From the FC steady-state operation characteristics, a passive low-pass output filter design method suitable for the FC power plant in an isolated system is presented. In the stand-alone operation, a filter at the PCU output side becomes indispensable due to high contents of harmonics produced by the inverter. The THD of the load voltage, inverter output current and the filter power loss can be kept below acceptable values by the application of the second-order low-pass filter. The range of the FC terminal voltage variations, the expected ranges of load impedance and power factor changes are seen as critical factors in determining the values of filter components. A simple design procedure has been derived and its effectiveness has been demonstrated by numerical examples. With the analytical design method, the load-side power quality can be improved through the control of the harmonic current flow originated from the PCU.

Chapter 6

Power Flow Control of SOFC in a Grid-Connected System

6.1 Introduction

Having studied how a FC power plant can be designed to improve power quality in an isolated system, applications of the DG in the grid-connected condition will be discussed in this and next chapters. In the grid-connected condition, the FC power plant is assumed connected to an external system which is considered much larger in capacity. Due to the FC smaller capacity and relative slow response compared to (say) a conventional synchronous generator, the capability of the FC to control system voltage is limited. The inherent dynamic characteristics of the FC make it more suitable to solve power quality problems such as that encountered during the natural changing of the load level. Indeed, FC has become a promising option to provide stationary power supply at the load side. The slow load variation can be easily monitored and tracked by the local DG. Power system benefits from the load-tracking ability of the DG in terms of larger spinning reserve, higher power factor, reduced transmission losses, among other factors.

In the literature, FC has been studied in conjunction with the other DG to solve the load-tracking problem in a grid-connected system. The other DG could take the form of a photovoltaic (PV) or microturbine (MT). It then constitutes a hybrid power system. Rahman *et al.* in their series of papers studied the operation and control scheme of a 3 MW PV-FC hybrid system [28, 81, 82]. The 1 MW PV was controlled by a neural network controller which could help the PV track the sunlight and produce the maximum available power. As PV might experience large variance of its output power under variable weather conditions, the output of the hybrid system would fluctuate. To smooth out the power fluctuation and meet system demand, a real/reactive power controller (RRPC) was introduced to control a 2 MW FC. The RRPC contained three PI controllers which controlled the phase shift and modulation index of the PCU as well as the natural gas input of the fuel valve. Although the controller design method was not given, the simulation results shown that the FC could change its real power from 500

kW to 2 MW within 1 second. However, as the dynamic characteristics of the FC were not examined in these papers, the capability of whether the FC could safely afford such real power change needs further exploration. In a later paper, Zhu *et al.* studied the load-tracking performance of a MT and FC hybrid system [35]. The paper provided the dynamic models of MT and FC. The proposed MT dynamic model included the control system, turbine and induction generator. The FC dynamic model was based on the work in [34] and included a first order fuel processor system. The 100 kW MT and the 100 kW FC stand-alone dynamic performances were evaluated. Finally, the hybrid system used for load-tracking in a distribution network was simulated. Although the detailed control method on the hybrid system was not given, the paper gave some valuable suggestions on FC operation. From the above discussions, it can be concluded that it is important to find a suitable control scheme for DG to track the varying load. The control scheme must consider the dynamic characteristics of the studied DG.

In view of the above and to study the behavior of the FC power plant in tackling the load-tracking problem, it is necessary to find the fastest and yet prudent way of changing the output power in a grid-connected condition. In addition, as the FC power plant can also regulate the reactive power injected to the external system, the method of manipulating the reactive power should also be examined. It is also important that, as introduced in Chapter 3, any control scheme must guarantee the FC operating states stay within the FOA. Particularly, the cell fuel utilization must be in the range of 0.7 and 0.9. Or the FC life will be reduced, which is unacceptable. In this chapter, it will be shown that the fluctuations of the utilization factor in the transient state due to a change in operating power level can be constrained to the allowable range by strategically controlling the current drawn by the PCU. According to measured variables (hydrogen input, stack current, FC terminal voltage and external system voltage) and dynamic characteristics of the fuel processor, four strategies of controlling current are compared to arrive at the strategy that results in minimum transient time for a given power change. The proposed control schemes are verified through computer simulations. Some of the results described in this chapter also appear in one of the author's publications [83].

6.2 SOFC in a Grid-Connected Network

Unless the load supplied by the FC plant is of DC type, as described in Chapter 2, the power generated by the FC stack has to be converted to an AC form by using a Power-Conditioning Unit (PCU). Recently, there has been much interest in designing suitable PCU for the FC plant [23, 28, 33, 36, 84-88]. Some of the topologies use a boost-type DC/DC converter in cascade with a conventional Voltage Source Inverter (VSI) to interface the FC with the AC-grid [23, 84, 85]. Some authors omit the DC/DC converter and suggest instead, the use of specially designed inverter such as the Z-source inverter which has voltage boosting capability [86-88]. In a third category, the conventional VSI is used directly, without the DC/DC converter, when the terminal voltage variations of the FC stack are within a range that can be handled by the VSI [28, 33, 36]. As seen from Section 4.3 and Figure 4-3, the operation of the SOFC with a constant utilization factor in steady-state typically results in limited terminal voltage variations. Since such variations can be readily handled by the conventional Pulse-Width Modulated (PWM) VSI through the change of the modulation index, the PCU considered in this project will therefore consist only of the conventional PWM VSI connected directly to the FC stack terminals. Sinusoidal Pulse Width Modulation (SPWM) technique with the two control variables modulation index (m) and the phase shift (δ_f) are used in the VSI. Detailed SPWM switching scheme can be referred to Section 2.6.

Figure 6-1 Schematic diagram of a FC power plant interconnected to an AC-grid

Figure 6-1 shows a schematic diagram of the FC power plant interconnected to the external grid. Typically, the output voltage V_{dc} of the FC stack is relatively low compared to the operating voltage of the grid $\dot{V}_s$. It is very likely that a step-up transformer would be used to interconnect the VSI to the grid. In Figure 6-1, the link impedance X_f represents the total per-phase series reactance of the transformer and the

associated feeder. X_f is assumed a known constant. In order to avoid transformation of variables across the transformer, all the electrical variables used in the following sections are expressed as per-unit values. It is also envisaged that the capacity of the FC would be much smaller than that of the upstream grid system. Therefore, the grid bus could be considered as relative “stiff” with voltage V_s and operating at a constant frequency. $\dot{V}_s$ is assumed measurable and is treated as the reference phasor in controlling the phase shift δ_f of the VSI. The power delivered at the grid bus is denoted as $P_r + jQ_r$. In the following discussion, only the fundamental components are considered: the ripples generated due to the switching of the inverter would be neglected. As was described in Chapter 5, the ripples can be lowered to desired levels by connecting filter on the DC and AC sides. In any case, the ripple does not contribute to the transfer of real power, which is the focus of this chapter. Losses in the switching devices, transformer and the feeder are also considered negligible.

6.3 Power Flow Control

In the SOFC system under study, three control variables can be used to control the generation and transfer of real and reactive power. As it shown in Figure 6-1, these are the input flow rate of natural gas N_f to the fuel processor, the modulation index m and phase shift δ_f associated with the VSI.

6.3.1 Control of fuel input to the stack

According to (3-23), the operation of the FC stack with a fuel input (N_f) proportional to the stack current (I_{FC}) results in a constant utilization factor (u_s) in the steady state. Furthermore, such a constant utilization factor operation results in very small deviations in the terminal voltage due to changes in stack current, as can be seen in Figure 4-3 and in [34]. In this way, the initial and final operating points in Figure 4-3 related to a change in the output power are at the intercepts of the corresponding constant power curves at the two power levels with the u_s line. Based on this control scheme, the FC steady-state operating point will be located along the preset u_s line. Discussions in

Chapter 4 show that the constant fuel utilization method is a simple fuel input regulating method and it can be implemented easily.

6.3.2 Control of PCU

Figure 6-2 Phasor diagram of $\dot{V}_f$, $\dot{V}_s$ and $\dot{I}_f$

Figure 6-1 shows that the output voltage of the cell stack is V_{dc} . If the SPWM switching method is used, from (4-2), the p.u. voltage at the inverter output is given by $V_f = mV_{dc}$. The current that PCU sends to the system bus is $\dot{I}_f$. The relationship between $\dot{V}_f$, $\dot{V}_s$ and $\dot{I}_f$ is shown in the phasor diagram of Figure 6-2. The projection of $\dot{I}_f$ on the d and q axis are $\dot{I}_{df}$ and $\dot{I}_{qf}$ respectively. The voltage at the grid-bus $\dot{V}_s$ is treated as the reference phasor.

It then follows that the p.u. fundamental frequency component of line current $\dot{I}_f$ in p.u. can be expressed in terms of its d and q components as

$$I_{df} + jI_{qf} = \frac{(V_f \angle \delta_f - V_s \angle 0)}{jX_f}$$

It can be readily shown that the delivered real and reactive power at the grid bus in steady state is given by

$$P_r = V_s I_{df} = \frac{mV_{dc}V_s \sin \delta_f}{X_f} \quad (6-1)$$

$$Q_r = V_s I_{qf} = \frac{m V_{dc} V_s \cos \delta_f - V_s^2}{X_f} \quad (6-2)$$

Since power losses in the VSI, transformer and feeder have been neglected, the real power received at the grid bus is equal to the power drawn from the FC stack, i.e., $P_r = V_{dc} I_{FC}$. Substitute this last equation into (6-1), it is easily seen that

$$I_{FC} = \frac{m V_s \sin \delta_f}{X_f} \quad (6-3)$$

6.3.2.1 Control of PCU for constant power factor operation

In controlling the PCU, the required reactive power could be realized through the VSI to achieve different operating conditions on the AC-side such as constant power factor, constant voltage or constant reactive power operation. As the capacity of the DG is considered to be small compared to that of the upstream power system, the constant power factor operation appears to be the likely option in most cases. Under such an operating condition, suppose the SOFC real power output needs to be set to P_{ref} with a power factor angle φ . From (6-1)-(6-3), the two control variables of the VSI would be governed by the following equations:

$$\delta_f = \tan^{-1} \left[\frac{P_{ref}}{V_s^2 / X_f + P_{ref} \tan \varphi} \right] \quad (6-4)$$

$$m = \frac{I_{FC} X_f}{V_s \sin \delta_f} \quad (6-5)$$

From (6-4) and (6-5), it is seen that the control variable m is dependent on δ_f . Furthermore, as the variables on the RHS of the above equations are readily measurable or known, δ_f and m can be determined and applied to the VSI to inject the desired amount of real power to the grid bus and at the desired power factor. Note that due to a transient in the hydrogen input to the FC stack, the values of V_{dc} and I_{FC} still can change while keeping their product constant.

6.3.2.2 Control of PCU during power changes

During a change in the operating power level of the FC, the utilization factor will deviate from its steady-state value u_s even when its fuel input is controlled in the manner described in Chapter 4. This is because of the delay associated with the fuel processor operation. Therefore, it is necessary to ensure that u is within the allowable range during the transient state as well. This can be accomplished by controlling the PCU to draw a current from the stack to follow a set reference current $I_{FC,ref}$. The manner in which $I_{FC,ref}$ is derived will be discussed in next section. Since the transient periods of an SOFC power plant are much longer than the electrical time constants on the AC-side, the steady-state power transfer equations derived as (6-1) and (6-2) can still be used during the changes of the power level without any significant loss of accuracy. By replacing P_{ref} in (6-4) and (6-5) with $V_{dc}I_{FC,ref}$, the VSI is controlled during a power change as,

$$\delta_f = \tan^{-1} \left[\frac{V_{dc} I_{FC,ref}}{V_s^2 / X_f + V_{dc} I_{FC,ref} \tan \phi} \right] \quad (6-6)$$

$$m = \frac{I_{FC,ref} X_f}{V_s \sin \delta_f} \quad (6-7)$$

In this way, $I_{FC,ref}$ will be continuously adjusted until the FC output reaches the desired power P_{ref} . Once P_{ref} has been attained, the PCU is controlled as constant power operation. However, due to the action of the fuel controller, u will then recover to its steady-state operating value u_s . During this period, both V_{dc} and I_{FC} would undergo further adjustments.

6.3.3 Overall control scheme

Based on the control criteria of the three control variables described in the preceding sections, the overall control block diagram of the power plant can be depicted as in Figure 6-3. In the figure, the SOFC power system and its control system are delineated into two distinct parts. The components which constitute the SOFC power system are as described earlier in Section 3.2. The control system consists of:

Figure 6-3 Block diagram depicting the proposed SOFC control scheme

Fuel Controller: The fuel valve is tuned according to the feedback stack current with the proportional gain $2K_r/u_s$, as described by (3-23).

u Calculation Block: From the on-line measurement of $N_{H_2}^{in}$ and I_{FC} , u can be determined using (3-12) and in real time.

Strategy Block: According to the on-line u and power error information, the stack current reference signal $I_{FC,ref}$ will be generated. $I_{FC,ref}$ should be adjusted in a manner as will be described in the next section.

VSI Controller: The transient period due to a change in the output power can be divided into two distinct parts. During the initial stage, the output power level is forced to reach the desired value P_{ref} so that the utilization factor is constrained to the allowable range. During this stage (6-6) and (6-7) are used together with the $I_{FC,ref}$ generated from the strategy block to determine the appropriate values of δ_f and m . The second stage begins when the output power level reaches the desired level P_{ref} . The control equations are changed to (6-4) and (6-5) to tune the VSI so that it maintains the real power output at P_{ref} at a constant power factor for the subsequent periods. With the onset of this stage, the utilization factor begins to recover from its transient value and finally achieves the steady-state value u_s .

Note that the control scheme depends only on the on-line terminal information of the FC stack. It does not require the knowledge of the internal state of the stack. Hence, any possible loss of accuracy such as in ignoring the activation and concentration losses and in the variations of stack temperature will not affect significantly the effectiveness of the proposed control scheme.

6.4 Strategies of Generating Reference Current

The Strategy block is the most important part in the proposed control scheme. A proper $I_{FC,ref}$ will not only achieve the power demand in minimum time but also guarantee that all the FC transient operating points stay within the FOA. The different strategies of generating the reference current signal are explored below.

From (3-12), the small-signal relationship between Δu , ΔI_{FC} and $\Delta N_{H_2}^{in}$ about their initial steady-state values u_s , $I_{FC,0}$ and $N_{H_2,0}^{in}$ can be written as,

$$\Delta I_{FC} = \frac{N_{H_2,0}^{in}}{2K_r} \Delta u + \frac{u_s}{2K_r} \Delta N_{H_2}^{in} \quad (6-8)$$

Under constant u control, substituting (3-24) into (6-8), and (6-8) can be rewritten as

$$\Delta u = \frac{u_s}{I_{FC,0}} \frac{\tau_f s}{1 + \tau_f s} \Delta I_{FC} \quad (6-9)$$

where $I_{FC,0}$, the initial stack current, is related to the initial $N_{H_2,0}^{in}$ through (3-23). By denoting $\Delta I = \Delta I_{FC} / I_{FC,0}$,

$$\Delta u = u_s \frac{\tau_f s}{1 + \tau_f s} \Delta I \quad (6-10)$$

It is seen from (6-10) that the dynamics of Δu is a function of the initial stack current, fuel processor time constant and the way how I_{FC} is manipulated to cater for the real power demand variation. Whichever manner I_{FC} is manipulated, u should not be greater than the maximum allowable value u_{max} (say 0.9) or less than the minimum allowable value u_{min} (say 0.7). The possible strategies to generate the reference current signal in response to the external power change through the manipulation in I_{FC} are as follows.

6.4.1 Step change in $I_{FC,ref}$

If the desired power change (ΔP) is to be achieved as a step change in current, with the magnitude of the step expressed in terms of the initial steady-state current i.e., $\Delta I(t) = k_s I_{FC,0}$, substituting $\Delta I(s) = k_s / s$ into (6-10), it yields

$$\Delta u(t) = u_s k_s \exp(-t / \tau_f) \quad (6-11)$$

It is seen from (6-11) that u will have a maximum change equal to $u_s k_s$ initially, then u will decay in an exponential manner and has the same time constant as the fuel processor. By defining a parameter ε_u as,

$$\varepsilon_u = \begin{cases} (u_{\max} - u_s) / u_s & \text{for positive } I_{FC} \text{ step} \\ (u_{\min} - u_s) / u_s & \text{for negative } I_{FC} \text{ step} \end{cases} \quad (6-12)$$

Then from (6-12), the initial change in u shall have to be constrained such that

$$k_s \leq |\varepsilon_u| \quad (6-13)$$

Hence, the maximum allowable step change in current as a ratio of the initial stack current $I_{FC,0}$ is $|\varepsilon_u|$. Considering the typical values $u_s = 0.8$, $u_{\min} = 0.7$ and $u_{\max} = 0.9$, from (6-13) the maximum safe step of current is 12.5% of $I_{FC,0}$. As the step change in I_{FC} is constrained, the allowable FC maximum instantaneous real power change is also limited. During the initial period, the FC EMF E can be assumed unchanged, i.e., from (3-15), $\Delta E = 0 = \Delta V_{dc} + r \Delta I_{FC}$. The real power change can then be written as

$$\begin{aligned} \Delta P &= V_{dc,0} \Delta I_{FC} + I_{FC,0} \Delta V_{dc} \\ &= (V_{dc,0} - r I_{FC,0}) \Delta I_{FC} \end{aligned} \quad (6-14)$$

where $V_{dc,0}$ is the initial terminal voltage of the stack. As $V_{dc,0} \gg r I_{FC,0}$, and from (6-13), (6-14) can be rewritten to show that ΔP must satisfy the following relationship

$$\Delta P \leq |\varepsilon_u| I_{FC,0} V_{dc,0} \quad (6-15)$$

Inequality (6-15) gives the maximum real power change that the FC can provide without violating the u constraint. If the desired power change ΔP is less than $|\varepsilon_u| I_{FC,0} V_{dc,0}$, the demand for the power change (ΔP) can be achieved instantaneously by a single step. For larger changes of power that cannot be achieved safely by a single step, one of the strategies discussed in the following sections may be applied.

6.4.2 Ramp change in $I_{FC,ref}$

If the stack current is changed in a ramp manner with a constant rate k_r , then $\Delta I(s) = k_r / s^2$. Substituting it into (6-10),

$$\Delta u(t) = u_s k_r \tau_f (1 - \exp(-t / \tau_f)) \quad (6-16)$$

It is seen from (6-16) that u will start from u_s and change in an exponential manner. The ramp change is to continue until such time the desired power level P_{ref} is reached. If the duration of the ramp is much larger than τ_f , the final steady state change in u is $u_s k_r \tau_f$. Since the constraint $u_{min} \leq u \leq u_{max}$ has to be satisfied, the limit of the ramp rate k_r is given by

$$k_r \leq |\varepsilon_u| / \tau_f \quad (6-17)$$

However, if the required power change is smaller, the period of the ramp can be comparable to the time constant τ_f . In such cases, the ramp rate can be increased beyond the limit in (6-17) and up to a limit calculated using (6-16). It is also obvious from (6-16) that with the ramp change in I_{FC} , u cannot reach either u_{max} or u_{min} instantaneously. Hence, it can be concluded that this strategy alone will not produce the effect of reaching the intended power level in minimum time.

6.4.3 Simultaneous application of a step and a ramp in $I_{FC,ref}$

From the discussion of the effects of step and ramp strategies shown in the preceding sections, it can be concluded that the fastest and yet safe way to achieve a given real power change is to maintain u at the maximum allowable value, i.e. $u = u_{max}$ during a

power increase, and at its minimum allowable value, i.e. $u = u_{min}$ during a power decrease. This means that ΔI should cause u to experience a step change such that $\Delta u = |\varepsilon_u|/s$. Conversely, the way how I_{FC} should be varied can be obtained by substituting $\Delta u = |\varepsilon_u|/s$ into (6-10). That is

$$\Delta I = |\varepsilon_u| \left(\frac{1}{s} + \frac{1}{\tau_f s^2} \right) \quad (6-18)$$

To reach the demanded power level in minimum time, (6-18) shows that ΔI should consist of a step change with the magnitude $|\varepsilon_u|$ superimposed with a ramp change with the fixed ramp rate $|\varepsilon_u|/\tau_f$. However, as (6-18) has been derived on the basis of small-signal linearization, the strategy can be expected to perform well only for small changes of power. During larger power changes, u may not be maintained at the desired extreme value, u_{max} or u_{min} .

6.4.4 On-line control of $I_{FC,ref}$

If the real power demand change (ΔP) is large, the above three strategies based on the small-signal analysis may no longer be suitable. In order to reach the desired power level P_{ref} in minimum time, u should therefore be instantaneously driven from u_s to its appropriate limit value u_{max} or u_{min} and maintained at the same value until the desired power level is reached, as depicted in Figure 6-4. In this case, the reference current $I_{FC,ref}$ is not given by a pre-determined formula. Instead $I_{FC,ref}$ is adjusted on-line by a feedback control action based on the measured real-time value of u . Hence this control strategy has the added advantages that it not only accommodates power changes of large magnitude but also is independent of the model of the fuel processor.

Figure 6-4 Expected u loci before the FC reaches the target power

6.5 Illustrative Examples

The examples in this section will be used to illustrate how an SOFC power plant in the grid-connected condition can be controlled to change its output power level through the control scheme discussed in Sections 6.3 and 6.4. The example is based on the 100 kW SOFC plant data given in [34, 35], which are shown in Appendix A. The base values used in the examples are 100kW, 330V at the FC stack terminals and 100 kW, 400V at the grid side of the step-up transformer. The total reactance due to the transformer and feeder is taken as 5% based on the base values. It is also assumed that it is desirable to operate the SOFC power plant at unity power factor at the system terminal (i.e., $Q_r = 0$). The controller to the hydrogen fuel is to achieve a constant utilization factor $u_s = 0.8$. For illustration purposes, u_{max} and u_{min} are chosen as 0.9 and 0.7 respectively. Therefore, from (6-12), it exists $|\mathcal{E}_u| = 0.125$ in this case.

The effectiveness of the design is verified through simulation using the non-linear model shown in Figure 3-1. The simulation tool is MATLAB/SIMULINK. The intention is to show how the SOFC plant can meet the desired power demand through the generation of the appropriate $I_{FC,ref}$ and the control of the PCU. In the following illustrative cases, the power demand is increased to its rated value at $t = 30$ s and then restored to its original value at 130s. The purpose is to demonstrate the transient response of the SOFC-grid system during both the increase and decrease of the real power.

6.5.1 Simulation results

The four strategies discussed in Section 6-4 are used here to achieve different power demands.

Case 1: Step change in $I_{FC,ref}$: P_{ref} changes between 0.85 p.u. and 1 p.u.

Without limiting the step magnitude, the power change is attempted to be met by a step change in $I_{FC,ref}$. Figure 6-5 shows the profiles of u , V_{dc} , I_{FC} and P_r . Although the real power demand can be met instantaneously, it is clearly seen from Figure 6-5 that the utilization factor is not constrained to the allowable region during the transient periods.

In fact, according to (6-13), the maximum safe step size is 0.125 of the initial power level. Therefore, power can only have a maximum safe step of 0.11 p.u. when the initial power level is 0.85 p.u.

Figure 6-5 Power flow control by a step change in $I_{FC,ref}$ when P_{ref} changes between 0.85 p.u. and 1 p.u.

Figure 6-6 Power flow control by a ramp change in $I_{FC,ref}$ when P_{ref} changes between 0.85 p.u. and 1 p.u.

Case 2: Ramp change in $I_{FC,ref}$: P_{ref} changes between 0.85 p.u. and 1 p.u.

In order to prevent the FC's transient operating points from straying outside of the FOA, a ramp change strategy can be attempted with the ramp determined using (6-17). In the studied example, this corresponds to the ramp rate of 6.35A/s for the power increase and 7.53A/s for the power decrease. Figure 6-6 shows the profiles of u , V_{dc} , I_{FC} and P_r . It is seen that indeed, u remains within the allowable range throughout the transient process. However, due to the small period of ramp resulting from small magnitude of power change, the desired power level is attained even before u reaches its limit. It indicates that it is still possible to reduce the transient time by increasing the ramp rate as determined using (6-17).

Case 3: Simultaneous application of a step and a ramp in $I_{FC,ref}$: P_{ref} changes between 0.85 p.u. and 1 p.u.

To achieve the desired power level in the minimum possible time, the stack current can be increased by application of a step and a ramp, as shown by (6-18). Figure 6-7 shows the profiles of u , V_{dc} , I_{FC} and P_r . It is clear that u remains on its limit of u_{max} or u_{min} until the FC output reaches the target power. As can be seen in the comparison of strategies in Table 6-1, this strategy achieves the target power in much shorter time compared to the ramp strategy.

Case 4: Simultaneous application of a step and a ramp in $I_{FC,ref}$: P_{ref} changes between 0.5 p.u. and 1 p.u.

For a power change as large as half of the SOFC rating, the step and ramp strategy (6-18) is applied to reach the target. Figure 6-8 shows that u can stay at the limit of the FOA at the initial stage. As time progresses, however, u will deviate outside the limit value. In particular, the utilization factor deviates from the allowable range when the real power decreases. This case clearly shows that the simultaneous step and ramp rate strategy can only be applied successfully for a limited range of power changes of the order of 20%. To meet the demand for larger power changes, the $I_{FC,ref}$ must be continuously adjusted.

Figure 6-7 Power flow control by simultaneous step and ramp change in $I_{FC,ref}$ when P_{ref} changes between 0.85 p.u. and 1 p.u.

Figure 6-8 Power flow control by simultaneous step and ramp change in $I_{FC,ref}$ when P_{ref} changes between 0.5 p.u. and 1 p.u.

Case 5: On-line control of $I_{FC,ref}$. P_{ref} changes between 0.5 p.u. and 1 p.u.

Based on the on-line calculation of u using the measured hydrogen input and the stack current, $I_{FC,ref}$ is initially set to drive u to its appropriate limit value u_{max} or u_{min} instantaneously. When u starts to deviate from the limit value by more than a set margin, $I_{FC,ref}$ is adjusted to force u back to its limit value. Unlike Case 4 in which the u constraint is violated during the decreasing power, the profiles in Figure 6-9 show that u stays on its limit value until the FC reaches the target power level. The trade-off is an increase the time period required to reach the lower power level. Thus, it is clearly seen that the on-line control of $I_{FC,ref}$ strategy is capable of safely changing the power output of SOFC plant in large proportions and in minimum possible time.

Figure 6-9 Power flow control using on-line control of $I_{FC,ref}$ when P_{ref} changes between 0.5 p.u. and 1 p.u.

6.5.2 Comparison of strategies

Table 6-1 compares the times taken to achieve the different power changes considered in the preceding section.

Table 6-1 A comparison of the strategies

Case	Strategy	ΔP (p.u.)	Time(s)
1	Step	0.15	0
		-0.15	0
2	Ramp	0.15	6.9
		-0.15	6.4
3	Step and Ramp	0.15	2.8
		-0.15	1.7
4	Step and Ramp	0.5	34.7
		-0.5	19.1
5	On-line Control	0.5	26.4
		-0.5	24.5

6.6 Conclusions

The strategies of changing the output power level of an SOFC power plant connected to an AC grid through a PCU were explored. The objectives are to minimize the time needed to achieve the power changes while guaranteeing the safe operation of the plant. After identifying the feasible operating area of the FC stack in steady state and considering the power transfer characteristics through a PCU, concepts were formulated to manipulate the three control variables of the power plant. The fuel input to the plant was controlled proportionally with the current to operate the stack with a constant utilization factor in steady state and reduced terminal voltage variations. The phase shift and modulation index control variables of the PCU are utilized to regulate the stack current and to keep the power factor of the plant constant for all power levels. Different manners in which the stack current can be changed are studied to achieve the objectives of minimizing the transient time while maintaining the utilization factor in the allowable region. Through the analysis, it was found that the maximum safe step in stack current as a ratio to the initial stack operating current is equal to the maximum allowed excursion of the utilization factor, as a ratio to the steady-state utilization factor. Any power change larger than this safe limit can be achieved as a combination of the maximum safe

step and a ramp with a fixed or variable rate. For very large power ranges, the ramp rate should be varied by on-line estimation of the utilization factor to maintain it at the limit value until the target power level is achieved. For this method of control, the controller is independent of the model of the fuel processor. Furthermore, with all the strategies of current control, the controller is independent of the model of the FC. Computer simulations have verified the accuracy of the theoretical analyses and predictions.

Chapter 7

The Role of SOFC in a Voltage Sag Ride-Through Scheme

7.1 Introduction

In Chapter 6, attention has been focused on the load tracking capabilities of the SOFC where the power plant is assumed connected to an external bus. In practical applications, the SOFC DG would be sited close to the loads in a distribution network. The voltage at the Point of Common Coupling (PCC) may no longer be constant at all times because of disturbances and network changes. For example, a fault in the neighboring feeder or the starting of a large induction motor, will result in the PCC voltage level being depressed. Often this depressed voltage, also called voltage sag, lasts for 3~30 cycles. Indeed, voltage sag has become an important power quality issue with the increased use of non-linear loads, computer systems and sensitive electronic circuit. Most of these loads are sensitive to voltage variations.

Solutions to mitigate the voltage sags are of great interest to the utility industry. Various power quality enhancement devices such as that described in Chapter 2 can be considered to mitigate the sags to cater for customers' requirements. Among all these possible power quality improvement candidates, the FC-based DG could be a viable option. Under normal state, FC can operate as a stationary power source and support the local loads. As analyzed in Chapter 3, however, the SOFC is too slow to respond to the short-duration disturbance such as voltage sag. Its internal EMF is almost constant during this short period. From the discussions in Chapter 6, it is also seen that the FC can only achieve a limited step real power change due to the fuel utilization constraint. On the other hand, the fast-acting PCU of the SOFC DG can regulate its output real and reactive power quickly. Therefore, the SOFC DG system may still have the capability to provide some assistance in achieving quality power.

In recent years, deregulation in the utility industry has made it possible to introduce competitive supply prices for customers. In the past, power quality implied that the

power would be available when needed at an acceptable voltage level. Today the definition of power quality depends on the load and its sensitivity to voltage changes [2]. In distribution networks, customers can usually accept the loss of residential lighting loads for a short duration. The power supply quality need not be high so long as it is economical. Some industry loads such as induction motors can tolerate a slight voltage sag (say 0.9 p.u.) for sustained operation. These loads need higher power quality. Thus voltage sag mitigation solutions should be introduced to maintain the minimum acceptable voltage level for the motors. Yet some loads such as wafer processor are very sensitive to voltage change. A slight voltage sag (say below 0.9 p.u.) for a short period would cause substantial financial losses. Again novel voltage sag mitigation schemes should be introduced to protect these sensitive loads from all possible voltage depression. Such premium power quality supply may therefore command the highest tariff. The concept to supply multi-quality power is called unbundled power quality service [89].

7.2 Power Quality Control Center

Figure 7-1 An illustrative PQCC system

In the context of the above consideration, Power Quality Control Center (PQCC) embedded with the DG technologies has been described by several researchers. References [89-91] described several possible systems. An illustrative UPS-type PQCC system described in [89] is shown in Figure 7-1. The authors of [89] assumed that the upstream power source supplied power to the downstream PQCC through Feeder 1 and a step down transformer. In the scheme designed, there were three levels of AC supply in the PQCC, namely, Ordinary Quality (OQ) load, High Quality (HQ) load and Super Premium (SP) Quality load. The first two level loads were connected to the transformer

low voltage side directly. The SP load was supplied by two back-to-back connected inverters, Inv.1 and Inv.2. A DG was connected to the DC bus.

Through the proposed PQCC, unbundled power quality supply is to be provided. If a fault occurs in Feeder 1, the OQ load will be disconnected by the solid-state relay instantaneously. Feeder 1 will be turned off by the hybrid transfer switch HTS1. At the same time, the backup Feeder 2 will be connected to the upstream source through the turn on of HTS2. The total downstream load is then transferred from Feeder 1 to Feeder 2. During the disturbance, the HQ load voltage could experience a short duration of depression. However, the SP load voltage will be improved by the PQCC and remains the same at the pre-disturbance level. The authors in [89] considered only conceptual schemes centered on the PQCC while detailed dynamic response of the DG was not analyzed. Furthermore, it is obvious that in practice, the number of fault incidents on the directly-connected feeder will be negligible compared to those originating on the much more extensive upstream transmission/distribution system. Hence, it is doubtful whether the installation of the HTS would be an economically viable proposition in practical systems.

Figure 7-2 A simplified PQCC system in [92]

Alternative scheme described in [92] has been proposed using the PQCC to help the sensitive load ride through the voltage sag. Figure 7-2 shows a simplified version of the PQCC scheme studied in [92]. The upstream power system was represented by an equivalent voltage source $V_s \angle 0$, connected to Inv.1 through a linking impedance jX_L . The authors introduced SOFC DG in their studies. Under steady-state condition, upstream source and DG supply the downstream SP load simultaneously. Inv.1 is to operate at a current less than its rated value $I_{inv1,rate}$. When a sag occurs, the PQCC is to operate in one of three stages by avoiding the over-loading of Inv.1. For a shallow sag, it is possible to make sure the DC bus voltage $V_{dc,0}$ and output of FC will not change. This

is called Stage 1 operation. By allowing Inv.1 operating current to reach $I_{inv1,rate}$, the real power supplied from the upstream source can be forced to be the same as that before the fault. Stage 2 is designed for compensating more severe sags. In this scenario, Inv.1 operating current will be fixed at $I_{inv1,rate}$ during sag. Downstream power shortfall will be provided by the FC. By controlling the DC bus post-fault voltage V_2 to satisfy $V_{dc} > V_2 > 0.9V_{dc}$, the FC could increase its power to balance the load power demand. It was shown in [92] that Stage 2 could compensate for a voltage deviation of approximately double that under Stage 1. For even more severe sags which could not be compensated under Stage 2, Inv.1 will be tuned off and the PQCC would operate in an isolated mode. The total downstream load could be supplied by the FC for a short period of time. When the disturbance is over, the PQCC would be re-connected to the upstream source and the FC output power is returned to the pre-fault value. The simulation result shown in [92] verifies the proposed ride-through scheme. In their study, the FC was modeled as a constant EMF in series with a constant resistor during the sags. The FC was assumed to have the capability to support a required step real power change of (say) from 100 kW to 200 kW. However, as the authors did not examine the fuel utilization factor u in their study, the feasibility of the proposed scheme should be re-examined. In addition, only the SP load was considered in [92]. To further investigate the possibility of unbundled power quality supply, the other loads of different quality levels should be included. Based on the work described in [92], this chapter will re-examine the ride-through ability of the PQCC under voltage sag. Some of the results described in this chapter also appear in one of the author's publications [93].

7.3 System Description

In this project, the UPS-type PQCC studied in [92] is also adopted here for further investigation. Figure 7-3 shows the interior structure of the UPS-type PQCC which consists of back-to-back PWM controlled inverters (Inv.1 and Inv.2) and an SOFC DG. The upstream power system is represented by an equivalent voltage source $V_s \angle \delta_s$. The PCC voltage and the front-end voltage of Inv.1 are $V_p \angle 0$ and $V_f \angle \delta_f$ respectively. Observed at the PCC bus, the equivalent system and the PCC-Inv.1 interconnection

impedances are represented as $R_s + jX_s$ and jX_f respectively. The short circuit capacity of the upstream is assumed to be much higher than that of the total PQCC load.

Figure 7-3 Structure of the UPS-type PQCC system

Working in conjunction with the upstream system and as described earlier, four types of loads can be supplied: OQ load, HQ load, SP load and DC load. In the normal state, the OQ and HQ loads are connected directly to the PCC. Therefore, they have the same level of waveform quality. However, the OQ load has the lowest supply priority and it can be switched off quickly by the solid-state relay shown in Figure 7-3 if required. In this scheme, the SP load has the highest level of waveform quality improved by the two inverters and DG simultaneously. Under steady state, suppose the power supply from the upstream system and that of the FC are $P_s + jQ_s$ and P_{dg} respectively. The PQCC injects to the PCC a power contribution $P_r + jQ_r$. The SP, DC, OQ and HQ loads are $P_{SP} + jQ_{SP}$, P_{DC} , $P_{OQ} + jQ_{OQ}$ and $P_{HQ} + jQ_{HQ}$ respectively. Hence, in this scenario, the SOFC would be providing support to the SP and DC loads, and parts of the HQ and OQ loads.

7.4 Steady State Operation

7.4.1 Normal state

In Figure 7-3, it is seen that all loads have two supply options. It can be envisaged that the SOFC DG will play an important role. Unlike conventional battery-based UPS which is typically used as a limited-duration energy buffer, the DG can continuously track the downstream SP and DC loads and supply any surplus real power to the upstream OQ

and HQ loads through Inv.1 so long as fuel supply is available. One should keep in mind the FC should be operated within the FOA in which the fuel utilization u constraints ($u_{min} \leq u \leq u_{max}$) and the output power P_{dg} constraints ($P_{min} \leq P_{dg} \leq P_{max}$) limit the FC operating regime. It is known from Chapter 6 that the operating status of a grid-connected FC can be guaranteed to remain within the FOA by adopting the constant fuel utilization (u_s) scheme. In this way, power flow between the FC and the distribution network shown in Figure 7-3 can be regulated by properly controlling Inv.1 through the two control variables m and δ_f . Suppose the total downstream real power is defined as $P_{SD} = P_{DC} + P_{SP}$. From (3-16), (6-1) and (6-2), the steady-state operating point of the PQCC can be obtained as,

$$P_{dg} = V_{dc} I_{FC} \quad (7-1)$$

$$\left(\frac{1}{u_s} - 1\right)^2 \left(\frac{2}{u_s} - r_{H-O}\right) = \frac{\exp(\gamma + 2r I_{FC} / E_f)}{I_{FC}} \quad (7-2)$$

$$P_r = P_{dg} - P_{SD} = \frac{m V_{dc} V_p \sin \delta_f}{X_f} \quad (7-3)$$

$$Q_r = \frac{m V_{dc} V_p \cos \delta_f - V_p^2}{X_f} \quad (7-4)$$

It is seen from (7-1) to (7-4) that the PQCC can regulate the power flow $P_r + jQ_r$ in the distribution network by the control of Inv.1 through adjustments in m and δ_f . Of course, such power flow control has to take into consideration the capacity of the DG and Inv.1. P_{dg} should be within the minimum and maximum values determined by the FOA, i.e.,

$$P_{min} \leq P_{dg} \leq P_{max} \quad (7-5)$$

Furthermore, perhaps due to contractual reason, reverse power, i.e., $P_s < 0$, to the upstream grid may not be allowed.

Based on the above initial operating condition, the FC will possess a limited ability to accommodate sudden load change as described in Chapter 6. From (6-15), in order to prevent the transient operating points from straying out of the FOA, the FC maximum instantaneous allowable real power increase ΔP_{dg} must satisfy the equation

$$\Delta P_{dg} \leq |\varepsilon_u| P_{dg,0} \quad (7-6)$$

Thus, the maximum step power change that the FC is able to provide is $|\varepsilon_u|$ times of its initial power level $P_{dg,0}$. Such constraint will limit the PQCC operating mode and its ability to ride through disturbance. This aspect will be discussed in later sections.

Apart from regulating P_r in the distribution network, Inv.1 can be sized to supply all the reactive power required by the OQ and HQ loads under steady state. Power factor at the point “A” in Figure 7-3 will be unity. By doing so, the voltage drop across the equivalent impedance $R_s + jX_s$ can be reduced, thus allowing an increased level of real power be transferred from the upstream power system to the PCC. In adopting this strategy and from (7-3) and (7-4), if Inv.1 control variables will be set such that

$$\delta_f = \tan^{-1} \left(\frac{P_r}{Q_{OQ} + Q_{HQ} + V_p^2 / X_f} \right) \quad (7-7)$$

$$m = \frac{P_r X_f}{V_{dc} V_p \sin \delta_f} \quad (7-8)$$

If the capacity of FC is larger than the total downstream load demand, both SP load and DC load can be totally supplied by the FC and the loads can enjoy the intended high-level of supply. In this way, the upstream power system will act as a back-up source only when the FC is out of operation. Any surplus real power from the FC, i.e. P_r , can be sent to the PCC. The control variable δ_f in (7-7) will be positive and Inv.1 will be operated under the inversion mode.

Next, it is necessary to determine at what level P_r can assume. In the event when point “B” in Figure 7-3 is suddenly open, P_r will decrease to 0 almost instantaneously. The FC will be affected in that its utilization factor u will decrease until such time the fuel input can be re-adjusted. In order to guarantee the FC to remain operating within the FOA transiently, the initial value of P_r ($P_{r,0}$) must be constrained to be less than ΔP_{dg} , as governed by (7-6), i.e. $0 \leq P_{r,0} \leq \Delta P_{dg}$, or

$$0 \leq P_{r,0} \leq |\varepsilon_u| P_{dg,0} \quad (7-9)$$

In this way, the SOFC can only supply a fraction of real power demand of the OQ and HQ loads. Furthermore,

$$P_{dg,0} = P_{SD} + P_{r,0} \quad (7-10)$$

where as defined earlier, $P_{SD} = P_{SP} + P_{DC}$.

Substituting (7-10) into (7-9) and re-arranging terms, it is seen that,

$$0 \leq P_{r,0} \leq \frac{|\varepsilon_u|}{1 - |\varepsilon_u|} P_{SD} \quad (7-11)$$

Equation (7-11) therefore establishes a feasible operating range for $P_{r,0}$ in terms of the total downstream load demand P_{SD} . Note that $P_{r,0} \geq 0$ signifies that the DG is supplying part of the HQ and OQ loads. Hence the proposed scheme calls for that in addition to the SOFC supplying all the SP and DC loads, Inv.1 can make use of (7-7) and (7-8) to adjust m and δ_f such that $P_{r,0}$ satisfies (7-11).

It may be reasonable to adjust the power flow $P_{r,0}$ such that it equals to the upper limit of (7-11), if it is economically attractive to operate SOFC in this manner. Thus, from the maximum value of $P_{r,0}$ given in (7-11), back substituting it into (7-10). The resulting $P_{dg,0}$ so obtained must still be less than the SOFC rating, P_{max} , in view of power constraint $P_{min} \leq P_{dg} \leq P_{max}$. Re-arranging terms, the following constraint equation on P_{SD} , the total downstream the DC and SP loads can be obtained:

$$(1 - |\varepsilon_u|) P_{dg,0} \leq P_{SD} \leq P_{dg,0} \quad (7-12)$$

When the SOFC output is at its rated value P_{max} , from (7-12), the minimum P_{SD} will be $(1 - |\varepsilon_u|) P_{max}$. Also, the maximum real power the PQCC can supply to the PCC is

$$P_{r,max} = |\varepsilon_u| P_{max} \quad (7-13)$$

7.4.2 Operation under outage of SOFC

In the event of internal fault or mal-operation of the FC, SOFC may be disconnected from the PQCC. In order to provide the supply quality needed for the downstream load, the upstream power system must meet the load demand as rapidly as possible. Under this condition, Inv.1 will operate under the rectifier mode by importing real power from the PCC.

7.4.3 Inv.1 Rating

In order to perform the proposed operating scheme, current rating of Inv.1, denoted as $I_{inv1, rated}$, should be examined. $I_{inv1, rated}$ should be chosen according to the maximum possible current flow through Inv.1. From the above discussion, the rating of Inv.1 depends on the following two conditions. The first condition is when the FC is out of service. From (7-12), the maximum downstream load real power demand P_{SD} will not be above P_{max} . The total downstream reactive power Q_{SP} can be provided by Inv.2. Therefore, current I_l from the PCC to Inv.1 will only have real component and its maximum value is

$$I_{max1} = \frac{P_{max}}{V_p} \quad (7-14)$$

where V_p is the PCC rated voltage.

The second condition is when the PQCC satisfies the unity power factor at point “A” in Figure 7-3 and supplies the total reactive power of OQ and HQ loads. From (7-13), the maximum power injected from Inv.1 to the PCC will be $|\mathcal{E}_u| P_{max} + j(Q_{HQ, max} + Q_{OQ, max})$. Therefore, the maximum current I_{max2} from Inv.1 to PCC will be,

$$I_{max2} = \frac{\sqrt{(|\mathcal{E}_u| P_{max})^2 + (Q_{HQ, max} + Q_{OQ, max})^2}}{V_p} \quad (7-15)$$

$I_{inv1, rated}$ must be larger of the values of I_{max1} and I_{max2} , i.e.,

$$I_{inv1, rated} \geq \max(I_{max1}, I_{max2}) \quad (7-16)$$

7.5 Voltage Sag Ride-Through Scheme

As described earlier, in the event of an upstream fault, a voltage sag incident would result. The SP and DC loads may be mitigated somewhat from the voltage sag due to the power support provided by the SOFC, and Inv.1, Inv.2 actions. However, the OQ and HQ supply quality will be degraded because the PCC voltage V_p will be depressed during the sag. Due to the complexity and extensiveness of the upstream system, only balanced voltage sags will be considered at this stage. It is also assumed that the sag magnitude remains constant over the duration of the sag.

Before a ride-through scheme for the PQCC loads under voltage sag is proposed, it would be useful to firstly refer to the ITI/CMEMA curve shown in Figure 7-4. The curve shows that there are two voltage boundaries limiting the time that the load is capable of continuous operation. Under a voltage sag, the duration T_d under which the loads can safely operate depends on the voltage magnitude. The more severe the sag is, the shorter T_d . The lower boundary of the ITI/CMEMA curve describes this relationship. T_d would be infinite for those sags which result in a standing voltage above a minimal level (V_{min}): V_{min} is the lowest acceptable voltage level for prolonged operation of the load.

Figure 7-4 ITI/CMEMA curve showing load ride-through capability [38]

In the context of the PQCC, suppose such voltage-time capability curve is available for the HQ and OQ loads. Therefore if the sag duration were less than the specified T_d for a given sag, the HQ and OQ loads are expected not to be adversely affected. Conversely, if the sag duration exceeds T_d the loads could be damaged unless corrective actions are taken. In the design of the PQCC, therefore, there are two scenarios once an upstream voltage sag has been detected.

7.5.1 Scenario 1: $t \leq T_d$

Under this scenario, the OQ and HQ loads can still be connected to the PCC and obtain supply from the upstream source and the PQCC continuously. In maintaining the supply, however, it is prudent not to disturb the SOFC. It is desirable to maintain the FC output at the pre-sag level. Through the actions of Inv.1 and Inv.2 in maintaining the DC and SP the load terminal voltages constant at their pre-sag values, power demands of the DC and SP loads would also remain the same as that at the pre-sag level. It is therefore necessary to maintain the real power flow through X_f at the pre-sag level $P_{r,0}$. In order to prevent reverse power flow to the upstream grid, power flow at point “A” in Figure 7-3 is continuously monitored. If reverse power flow to the upstream grid occurs, Inv.1 will automatically decrease P_r . Note that since $P_{r,0}$ is set according to (7-11), the operating status of the FC is guaranteed to be within the FOA even when P_r is reduced to 0. Detailed PQCC control scheme to decrease P_r will be introduced in a later section. In addition, reverse reactive power is also prohibited. Under voltage sag, reactive power demands of loads connected at the PCC will vary according to the PCC voltage $V_{p,sag}$. If the injected reactive power $Q_{r,sag}$ from the PQCC is regulated such that it matches exactly the reactive power of OQ and HQ under sag, the power factor at point “A” in Figure 7-3 will also be unity. During the voltage sag, the total reactive power demand of OQ and HQ load is:

$$Q_{OQ,sag} + Q_{HQ,sag} = V_{p,sag}^{\beta} (Q_{OQ,0} + Q_{HQ,0}) \quad (7-17)$$

In this study, the OQ and HQ loads are assumed to be characterized by the load reactive power-voltage sensitivity index β . $Q_{OQ,0}$ and $Q_{HQ,0}$ correspond to the reactive power demand at the pre-sag voltage of $V_{p,0}$. This is a general form of describing static load

behavior. For example, if the load is of constant-impedance type, then $\beta = 2$ whereas if the load is a constant-power type, then $\beta = 0$. β typically ranges from 0 to 3.5 [94].

7.5.2 Scenario 2: $t > T_d$

If the sag duration were to exceed T_d , it is proposed that the solid-state relay of the OQ load would operate at the first available instance to disconnect the OQ load from the PCC. After the shedding of the OQ load, if the PCC voltage recovers to above V_{min} , the PQCC would revert to the Scenario 1 control scheme described earlier but without the OQ load. If the PCC voltage fails to recover to a value of at least V_{min} , the circuit breaker (CB) at point “A” in Figure 7-3 would open (say) one cycle later. The PQCC system is then operating in an isolated mode. The reason for disconnecting the OQ load is because it only requires the lowest level of supply quality amongst the loads. It is also not intended to have the SOFC supply the OQ load under the isolated state.

Although the OQ load can be shed, the HQ load would still be energized and supplied by the PQCC under this isolated stage. The initial power supplied by the SOFC to the upstream load, $P_{r,0}$, is unlikely to match the post-sag HQ load requirement exactly. The output power of the SOFC has to be regulated following the islanding. The reserve power of the FC, as shown in (7-6), can be used to support the HQ load. This amounts to a step change of $\Delta P_{dg} = |\varepsilon_u| P_{dg,0}$. While Inv.1 still operates in inversion mode, it is proposed that its role is changed from controlling $P_r + jQ_r$ (as it does under normal state) to controlling V_p and maintaining the PCC bus frequency. The objective is to maintain the PCC voltage at V_{min} . Hence, following the islanding, the HQ load will draw a power level $P_{HQ,iso}$ which should be limited as,

$$0 \leq P_{HQ,iso} \leq P_{r,0} + \Delta P_{dg} \quad (7-18)$$

Again if the real power demand of the HQ load is characterized by the real power-voltage index α , therefore,

$$P_{HQ,iso} = V_{min}^\alpha P_{HQ,0} \quad (7-19)$$

where $P_{HQ,0}$ denotes the pre-sag HQ load demand. α is the real power- voltage index [94] of the HQ load. Typically, $0 \leq \alpha \leq 2$.

In considering (7-6), (7-18) becomes

$$P_{HQ,iso} \leq P_{r,0} + |\epsilon_u| P_{dg,0} \quad (7-20)$$

Substituting $P_{dg,0}$ from (7-10) into (7-20) and re-arranging, one obtains the following relationship

$$\frac{P_{HQ,iso} - |\epsilon_u| P_{SD}}{1 + |\epsilon_u|} \leq P_{r,0} \quad (7-21)$$

(7-21) establishes a lower bound on $P_{r,0}$ in terms of the HQ, SP and DC loads that can be supported under this scheme. It may now be combined with the constraint equation (7-11) to establish a new feasible operating range for $P_{r,0}$:

$$\frac{P_{HQ,iso} - |\epsilon_u| P_{SD}}{1 + |\epsilon_u|} \leq P_{r,0} \leq \frac{|\epsilon_u|}{1 - |\epsilon_u|} P_{SD} \quad (7-22)$$

Clearly

$$\frac{P_{HQ,iso} - |\epsilon_u| P_{SD}}{1 + |\epsilon_u|} \leq \frac{|\epsilon_u|}{1 - |\epsilon_u|} P_{SD}$$

From the last expression, the following constraint relationship between the HQ and total SP and DC loads is obtained:

$$P_{HQ,iso} \leq \frac{2|\epsilon_u|}{1 - |\epsilon_u|} P_{SD} \quad (7-23)$$

Finally, under the isolated mode, the output power of the SOFC must be within the limits given by (7-5), i.e.,

$$P_{\min} \leq P_{HQ,iso} + P_{SD} \leq P_{\max} \quad (7-24)$$

It is seen that in order for the power change to be met by the SOFC instantaneously and without violating the u and output power limits, the post-fault HQ, SP and DC load levels must comply with equations (7-23) and (7-24). The result of the above derivation can be summarized graphically in Figure 7-5. It shows the PQCC feasible operating zone under Scenario 2. The lower output power boundary is shown by the boundary line 'RS', the upper output power boundary is shown by the line 'UT' and (7-23) is shown as the line 'RU'. Clearly, in order for the SOFC to meet any instantaneous power change when point 'A' open, the only feasible load regime is within the area 'RSTUR'. From Figure 7-5, the maximum HQ load that can be supplied in the isolated mode corresponds to point 'U'. It can be determined by solving (7-23) and (7-24) simultaneously to yield

$$P_{HQ,iso\ max} = \frac{2|\varepsilon_u|}{1-|\varepsilon_u|} P_{max} \quad (7-25)$$

The HQ load as obtained from Figure 7-5 can then be translated to its corresponding pre-fault value by applying (7-19), viz:

$$P_{HQ,0} = \frac{P_{HQ,iso}}{V_{min}^\alpha} \quad (7-26)$$

where $P_{HQ,0}$ and $P_{HQ,iso}$ denote the pre-fault and post-fault HQ load power demands respectively.

Figure 7-5 PQCC feasible operating zone under Scenario 2

Based on the above analysis, the unbundled power quality provided by the PQCC system can be summarized in Table 7-1.

Table 7-1 Power quality levels of Loads in the PQCC

Load type	Quality level	Supply reliability
SP	Highest	Improved by Inv.1 and Inv.2. SOFC tracks the load, with the upstream power source acting as backup.
DC	High	Improved by Inv.1. SOFC terminal voltage variation will cause load voltage to vary but typically of $\pm 5\%$.
HQ	Medium	Two sources to supply load under Scenario 1. PCC voltage maintains at V_{min} by PQCC only if sag duration exceeds T_d .
OQ	Low	Two sources to supply load in Scenario 1. Shed when sag duration is larger than T_d .

7.6 Control Scheme

Control scheme for the various PQCC operating conditions is considered next. As described earlier with reference to Figure 7-3 when the PQCC is connected to the upstream system, Inv.1 is used to control the power flow $P_r + jQ_r$. This can be realized by regulating Inv.1 current i_f through the control of Inv.1 phase angle (δ_f) and modulation index (m). Since this power flow control is applied under the interconnected state, which includes normal steady-state, SOFC DG outage state and upstream voltage sag (Scenario 1), the Inv.1 controller configuration is therefore the same under all the above operating conditions. The only difference is in the reference value of i_f . In this section, the controller design and the generation of the reference current would be examined.

7.6.1 Control scheme under interconnection state

Consider firstly the AC link between the PCC and Inv.1. Its voltage-current relationship can be written as,

$$L_f \frac{d}{dt} \dot{i}_f = \dot{V}_f - \dot{V}_p \quad (7-27)$$

where $\dot{i}_f$, $\dot{V}_f$ are the vectors of the AC link line currents and Inv.1 front-end voltages as functions of time. $\dot{V}_p$ and $\dot{V}_f$ can be written as [95],

$$\dot{V}_p = \sqrt{\frac{2}{3}} V_p \begin{bmatrix} \sin \omega t \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (7-28)$$

$$\dot{V}_f = \sqrt{\frac{2}{3}} V_f \begin{bmatrix} \sin(\omega t + \delta_f) \\ \sin(\omega t + \delta_f - \frac{2\pi}{3}) \\ \sin(\omega t + \delta_f + \frac{2\pi}{3}) \end{bmatrix} \quad (7-29)$$

As the switching frequency is much higher than the fundamental frequency, the fundamental component of the voltage can be represented by its average value and also, $V_f = mV_{dc}$. As described in Section 2.6, $\dot{V}_f$ can be regulated through Inv.1 control variables m and δ_f . Assuming no mutual coupling exists between phases and using the Park transformation matrix,

$$p = \sqrt{\frac{2}{3}} \times \begin{bmatrix} \sin \omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos \omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (7-30)$$

Equation (7-27) can be transformed into d-q frame and rewritten as,

$$L_f \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & \omega L_f \\ -\omega L_f & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{fd} - V_p \\ V_{fq} \end{bmatrix} \quad (7-31)$$

where $[i_d, i_q]^T$ and $[V_{fd}, V_{fq}]^T$ contain the d-q components of i_f and V_f respectively. In this chapter, the fundamental components are the main focus and the switching harmonics due to Inv.1 are not considered. Such simplification is reasonable as the cross-over frequency of the control system to be designed for Inv.1 would be much below Inv.1 switching frequency. Applying the Park transformation (7-30) to (7-29)

$$\begin{bmatrix} V_{fd} \\ V_{fq} \end{bmatrix} = p \dot{V}_f = \begin{bmatrix} \cos \delta_f \\ \sin \delta_f \end{bmatrix} m V_{dc}$$

V_{dc} , V_{fd} and V_{fq} relationship can then be described by the algebraic equations

$$\begin{aligned} V_{fd} &= m V_{dc} \cos \delta_f \\ V_{fq} &= m V_{dc} \sin \delta_f \end{aligned} \quad (7-32)$$

Equations (7-31) and (7-32) show that the system dynamic is nonlinear. Cross-coupling exist between the state variables i_d , i_q and the control variables m , δ_f . In this investigation, the decoupled control scheme described in [95] has been used to overcome these design difficulties. Let the reference voltage of Inv.1 be given by $V_f^* = [V_{fd}^*, V_{fq}^*]^T$. Since $V_f = m V_{dc}$, the control variables of Inv.1 can then be determined as,

$$\begin{aligned} m &= \sqrt{(V_{fd}^*)^2 + (V_{fq}^*)^2} / V_{dc} \\ \delta_f &= \arctan(V_{fq}^* / V_{fd}^*) \end{aligned} \quad (7-33)$$

On the RHS of (7-31), i_d , i_q , V_p , V_{fd} and V_{fq} can be measured or determined on-line. One can therefore achieve decoupled control if the following reference voltages are generated,

$$\begin{aligned} V_{fd}^* &= V_{fd} - V_p + \omega L_f i_q \\ V_{fq}^* &= V_{fq} - \omega L_f i_d \end{aligned} \quad (7-34)$$

Substituting (7-34) into (7-31),

$$\begin{aligned} L_f \frac{di_d}{dt} &= V_{fd}^* \\ L_f \frac{di_q}{dt} &= V_{fq}^* \end{aligned} \quad (7-35)$$

Hence the reference voltage signals can be generated through a current control loop as,

$$\begin{aligned} V_{fd}^*(s) &= G(s)(i_d^* - i_d) \\ V_{fq}^*(s) &= G(s)(i_q^* - i_q) \end{aligned} \quad (7-36)$$

where $G(s) = k_{PI} + k_{II}/s$ is a Proportional-Integral (PI) controller whose parameters are yet to be determined. The proposed control scheme is as shown in Figure 7-6. By assuming the inverter is capable of reproducing the reference voltage exactly at its output, the block representing the inverter in Figure 7-6 can be omitted from this diagram. It should be noted that the small time delay of the inverter and the harmonics at its output are neglected in this process. With the inverter block omitted, the cross-coupling terms on the two sides of the inverter cancel out, leaving only the two single-input single-output decoupled closed-loop systems as shown in Figure 7-7.

Figure 7-6 Control scheme of Inv.1 under interconnection state

Figure 7-7 Equivalent d-q current control schemes for Inv.1

From Figure 7-7, Inv.1 and the AC link is represented by the first order model $1/(L_f s)$. In order to track the current references properly, the closed-loop systems must achieve satisfactory dynamic response (bandwidth) with adequate stability (phase) margin.

However, as the switching actions of Inv.1 may affect the dynamic performance of the PQCC, it is then proposed for the bandwidth (ω_l) of the compensated system in Figure 7-7 be set at $1/5 \sim 1/2$ of the switching frequency. The open-loop transfer functions of Figure 7-7 can be set to provide the desired phase margin (ϕ_l) at ω_l , i.e.

$$G(s) = (k_{p1} + \frac{k_{I1}}{j\omega_1})(\frac{1}{jL_f\omega_1}) = \exp[j(-180^\circ + \phi_l)] \quad (7-37)$$

Solving for the real and imaginary parts of (7-37), the PI-controller parameters can then be determined:

$$\left. \begin{aligned} k_{p1} &= \omega_l L_f \cos \phi_l \\ k_{I1} &= \omega_l L_f \sin \phi_l \end{aligned} \right\} \quad (7-38)$$

7.6.2 Control scheme under isolated mode (Scenario 2)

Under Scenario 2, the PQCC is disconnected from the upstream power system. Inv.1 changes from controlling $P_r + jQ_r$ to controlling V_p magnitude and system frequency. Since $P_{r,0}$ satisfies the condition (7-22) such that the SOFC is able to accommodate the sudden disconnection, the PQCC is now tasked to supply power to the SP, DC loads and HQ loads. Under this islanding mode, the phase angle δ_f is set equal to 0. From (7-32), Inv.1 front-end voltage becomes $V_f = mV_{dc}$. The main control function of Inv.1 will be to maintain V_p . This is achieved by adjusting the only control variable available, i.e. its modulation index m .

Under this isolated condition, from (7-19), the PCC voltage variation will cause $P_{HQ,iso}$ to change:

$$\Delta P_{HQ,iso} = \alpha V_p^{\alpha-1} P_{HQ,0} \Delta V_p \quad (7-39)$$

As the SP and DC load are kept constant, the FC output real power variation will be equaled to the AC-side real power change, i.e. $\Delta P_{dg} = \Delta P_{HQ,iso}$. Also, during the voltage sag, the FC EMF can be assumed constant. Therefore, $\Delta V_{dc} = -r\Delta I_{FC}$ and one obtains the relationship

$$\Delta P_{dg} = V_{dc,0} \Delta I_{FC} + I_{FC,0} \Delta V_{dc} \approx (I_{FC,0} - V_{dc,0} / r) \Delta V_{dc} \quad (7-40)$$

Neglecting the relative small voltage drop across X_f , $V_f \approx V_p = m V_{dc}$, hence,

$$\Delta V_p \approx \Delta V_f = m_0 \Delta V_{dc} + V_{dc,0} \Delta m \quad (7-41)$$

where $V_{dc,0}$, m_0 are the initial values of V_{dc} and m respectively.

Since $\Delta P_{dg} = \Delta P_{HQ,iso}$, from (7-39)~(7-41), therefore

$$(I_{FC,0} - V_{dc,0} / r) \Delta V_{dc} = \alpha V_p^{\alpha-1} P_{HQ,0} (m_0 \Delta V_{dc} + V_{dc,0} \Delta m)$$

Rearranging the above equation, the relationship between ΔV_{dc} and Δm is,

$$\Delta V_{dc} = \frac{\alpha V_p^{\alpha-1} V_{dc,0} P_{HQ,0}}{I_{FC,0} - V_{dc,0} / r - \alpha V_p^{\alpha-1} m_0 P_{HQ,0}} \Delta m \quad (7-42)$$

Substituting (7-42) into (7-41), the relationship between ΔV_p and Δm can be represented by the transfer function G_{iso} as

$$G_{iso} = \frac{\Delta V_p}{\Delta m} = k_{iso} \quad (7-43)$$

where $k_{iso} = V_{dc,0} + \alpha V_p^{\alpha-1} m_0 V_{dc,0} P_{HQ,0} / (I_{FC,0} - V_{dc,0} / r - \alpha V_p^{\alpha-1} m_0 P_{HQ,0})$.

Equation (7-43) shows that m change will cause a proportional change in V_p . The sensitivity parameter, k_{iso} , is a function of the PQCC initial condition. In order to maintain V_p at V_{min} and to avoid any control action to be affected by Inv.1 switching noise, a PI type controller is used. Figure 7-8 shows the proposed control scheme and just like that under the interconnected mode, the controller is $G_v = k_{p2} + k_{I2} / s$. G_v introduces a pole and zero to reshape the new open-loop system in Figure 7-8 so that it will have the desired bandwidth of ω_2 and phase margin ϕ_2 . This requirement can be translated as at ω_2 , the open-loop feed-forward transfer function is given by

$$G_v G_{iso}(j\omega_2) = k_{iso} (k_{p2} + \frac{k_{I2}}{j\omega_2}) = \exp[j(-180^\circ + \phi_2)] \quad (7-44)$$

Whence by equating the real and imaginary parts of (7-44), the control parameters are

$$\left. \begin{aligned} k_{P2} &= -\cos \varphi_2 / k_{iso} \\ k_{I2} &= \omega_2 \sin \varphi_2 / k_{iso} \end{aligned} \right\} \quad (7-45)$$

It can be seen from (7-45) that since $k_{P2} > 0$ and also $k_{iso} > 0$, a necessary condition is that the phase margin $\varphi_2 > \pi/2$. Also, a larger value of k_{iso} will lead to a smaller phase margin i.e. a more onerous operating condition. Since k_{iso} is governed by the initial PQCC operating condition, therefore one can design the PI-controller on the basis of the most onerous operating condition by selecting the largest conceivable k_{iso} . From the definition of k_{iso} in (7-43), as $V_{dc,0} \gg rI_{FC,0}$, the maximum k_{iso} is equal to $V_{dc,max}$ when $P_{HQ,0} = 0$ and the SOFC stack current is $I_{FC,m}$, as is shown in Figure 3-2. The controller designed this way will guarantee closed-loop stability at any other operating conditions.

Figure 7-8 Control scheme for Scenario 2

The case of the loss of the AC interconnection between the PCC bus and Inv.1 would not require the control action of Inv.1. Rather Inv.2 will be called upon to regulate the SP load terminal voltage. The design of Inv.2 controller is similar to that used in conventional inverter. Hence its design is not described in this thesis.

7.6.3 Determination of current reference

Having examined the controller design, the current references for the different operation states will now be given.

- **Current reference under normal state**

Under steady state, the PCC line voltage is $V_{p,0}$. Inv.1 transfers real power $P_{r,0}$ from the DC-side to the AC system and also supplies all the reactive power required by the HQ and OQ load. Therefore, the current reference is given by

$$\begin{aligned} i_d^* &= P_{r,0} / V_{p,0} \\ i_q^* &= (Q_{OQ,0} + Q_{HQ,0}) / V_{p,0} \end{aligned} \quad (7-46)$$

- **Current reference under sudden loss of SOFC**

In the event of the internal fault of SOFC, SOFC must be switched off quickly. Under the SOFC outage condition, Inv.1 changes from inversion mode to rectifier mode. Inv.1 carries the total real power demand of the DC and SP loads, with $Q_r = 0$. Thus,

$$\begin{aligned} i_d^* &= -(P_{DC} + P_{SP}) / V_{p,0} \\ i_q^* &= 0 \end{aligned} \quad (7-47)$$

- **Current reference under voltage sag (Scenario 1)**

Under this scenario, suppose the PCC voltage drops to $V_{p,sag}$. Inv.1 transfers the same amount of real power ($P_{r,0}$) as before the sag from the DC to the AC system while at the same time provides all the reactive power needs of the OQ and HQ loads. Therefore,

$$\begin{aligned} i_d^* &= P_{r,0} / V_{p,sag} \\ i_q^* &= (Q_{OQ,sag} + Q_{HQ,sag}) / V_{p,sag} \end{aligned} \quad (7-48)$$

Note that in generating the current references, the PQCC loads would be expected to vary as part of the normal operating condition. Hence, i_d^* and i_q^* will have to be adjusted continuously to track the load changes.

7.7 Simulation Examples

7.7.1 System description

The examples in this section will be used to illustrate how the PQCC can be controlled to help the load ride through disturbances, using the proposed schemes discussed in Sections 7.4 and 7.5. The SOFC dynamic model shown in Figure 3-1 is used for study. The SOFC data used in these examples are the same as that used in the previous chapters and shown in Appendix A. The base values used in the examples are 200 kVA, 330V at the FC stack terminals and 150V at the grid side. The PQCC is directly connected to the

PCC through X_f . The SOFC is controlled under constant fuel utilization factor where u_s is set to 0.8. Just like in Figure 4-3, the upper and lower u boundaries are set to 0.9 and 0.7 respectively. Therefore, ε_u can be calculated from (6-12) as 0.125. From (7-6), the maximum allowable step real power change of the SOFC is $0.125P_{dg,0}$. As only the fundamental components are of interest in this chapter, the PCU is modeled as idealized switches and the ripples generated during the switching are neglected. The PCU is assumed to use the SPWM switching method and the switching frequency is 4 kHz. The simulation tool is MATLAB/SIMULINK.

In the distribution network shown in Figure 7-3, it is assumed that the upstream power system short circuit capacity at the PCC is 20 MVA. Suppose the equivalent X_s is 3 times of R_s , thus it can be shown that $R_s = 0.0032$ p.u., $X_s = 0.0095$ p.u. Furthermore, the reactance $X_f = 0.1$ p.u. This was obtained when the short circuit capacity of the PQCC at the PCC was assumed to be 2 MVA. Under steady state, the SOFC output is $P_{dg,0} = 0.45$ p.u. where the total downstream load real power is $P_{SD} = 0.4$ p.u. and the surplus real power sent to the PCC is $P_{r,0} = 0.05$ p.u. The OQ and HQ loads connected at the PCC are $P_{OQ} = 0.875$ p.u. and $P_{HQ} = 0.125$ p.u. at 0.95 lagging power factor. The HQ and OQ loads are assumed to be constant impedance type: i.e., $\alpha = \beta = 2$. Their withstand voltage-time characteristic is assumed to be governed by the ITI/CBEMA curve shown in Figure 7-4 with $V_{min} = 0.9$ p.u. With the above assumptions, the SOFC DG can accommodate a $0.125 \times 0.45 = 0.056$ p.u. step change in real power. When this step change is added to the initial P_r , i.e., $P_{r,0} = 0.05$ p.u., the real power that the PQCC can supply to the HQ load in the isolated mode is larger than the required amount of $(0.9)^2 \times 0.125 = 0.1$ p.u. Therefore, the PQCC operates within the feasible zone shown in Figure 7-5.

From (7-14) and (7-15), it can be calculated that $I_{max1} = 0.5$ p.u. and $I_{max2} = 0.33$ p.u. Therefore, the current rating of Inv.1 should be the larger of the two, i.e. $I_{inv1, rated} = 0.5$ p.u. Inv.1 controller bandwidth can be chosen as 1/4 of the switching frequency, i.e. $\omega_1 = \omega_2 = 2000\pi$ rad/sec. By selecting $\phi_1 = 45^\circ$, the corresponding PI controllers for Inv.1 when the PQCC is operating under interconnected condition can be obtained from (7-38) as $G(s) = 0.05 + 0.05/s$. In designing the PI controller for the isolated condition, it can be seen from (7-43) that the value of k_{iso} when V_{dc} is maximum can be calculated from

(3-16): i.e. when $V_{dc,max} = 1.04$ p.u., $P_{dg} = 0.14$ p.u. If one selects $\varphi_2 = 100^\circ$, from (7-45), the corresponding PI controller is $G_v = 5 \times 10^{-4} + 6/s$. It ensures the new open-loop system has the desired bandwidth and phase margin.

7.7.2 Simulation results

In order to verify the effectiveness of the proposed schemes, four simulation cases are provided, namely: upstream system source undergoes voltage sags to 90%, 60% of its nominal values, PQCC under the loss of SOFC and the loss of AC link (point “B” in Figure 7-3 is open). The corresponding simulation results are shown in Figure 7-9~Figure 7-12.

Figure 7-9 System operation under a 10% voltage sag (Scenario 1)

Before the disturbance, it is shown in Figure 7-9 that PCC extracts 0.05 p.u. real power (P_r) and 0.33 p.u. reactive power (Q_r) from the PQCC. The pre-sag power factor at point “A” in Figure 7-3 is unity. As soon as the 0.9 p.u. voltage sag occurs, from the ITI/CBEMA curve both the HQ and OQ loads can still be connected at the PCC for a sustained operation. With the proposed control scheme, Inv.1 will still transfer 0.05 p.u. real power but at the reduced reactive power of $(0.9)^2 \times 0.33 = 0.27$ p.u. to the PCC. The power factor post-sag at point “A” remains at unity. It is seen from Figure 7-9 that the

SOFC is not disturbed and u is almost unchanged during the disturbance. As the moving windows method is used to calculate rms value, the PCC voltage waveform is shown continuous at the instance of the disturbance.

Figure 7-10 System operation under a 40% voltage sag (Scenario 2)

When a more severe sag occurs which brings the operation outside the HQ and OQ load voltage-time tolerable range, the PQCC has to be disconnected from the upstream system and operates in an islanding mode. Figure 7-10 shows such an example. In this case, the PCC voltage is assumed to drop to 0.6 p.u. From the ITI/CBEMA curve, the maximum duration the HQ and OQ loads could tolerate (T_d) for a 60% sag is less than 20 ms. Therefore in the simulation the OQ load is assumed successfully disconnected by the action of the solid-state relay 10 ms after the incipient of the sag. As the simulation result shows that the PCC voltage remains below V_{min} after the load shedding, the PQCC system is then disconnected from the upstream power system half a cycle later. Thereafter, $P_s=Q_s=0$. The operating mode of Inv.1 is changed from controlling the power flow to regulating V_p and bus frequency. Figure 7-10 shows that the PCC voltage can indeed be restored to 0.9 p.u. during this isolated mode operation. The SOFC output

power increases to its rated value and the step power change is within the FOA of the SOFC. The increased power is supplied to the HQ load. The SOFC fuel utilization factor u increases but it is still less than u_{max} . The FC terminal voltage decreases slightly following the disconnection.

Figure 7-11 System operation under sudden loss of SOFC

Figure 7-11 shows the system response under the sudden loss of the SOFC. In order to protect the DC and SP loads, the upstream system is controlled to meet all the real power load demand rapidly and Inv.1 is therefore changed from the inversion to rectification operating mode. It is seen that V_{dc} decreases at the instance of the DG disconnection. However, it recovers rapidly because of the support from the upstream system. The downstream loads are almost unaffected.

The simulation results under sudden loss of the AC link (point 'B') are given in Figure 7-12. It is seen that as soon as the fault incident occurs, $P_{r,0}$ decreases to 0 rapidly and the upstream loads are totally supplied by the upstream system. Since $P_{r,0}$ was chosen to satisfy (7-22), the sudden power change would not damage the SOFC: the SOFC utilization factor is within its limit during the fault event. With the AC link opened, the

downstream SP and DC loads are supplied by the SOFC. V_{dc} increases slightly and u recovers to u_s slowly from u_{min} .

Figure 7-12 System operation under sudden loss of AC link (point 'B')

7.8 Conclusions

The role of the SOFC in an interconnected system is examined, in the context of power quality enhancement. Under normal state, the SOFC in the PQCC could be used to track slow load changes. To supply unbundled power quality, the control scheme of PQCC is further investigated. Operation schemes of PQCC under steady state, voltage sag state and the DG fault state have been presented in which the SOFC DG is embedded. Unlike previous works on PQCC, the role of the DG and the inverters in the PQCC is examined with regard to mitigating the impacts of the fault disturbances on loads. By taking into consideration the ability of the SOFC to track load changes, it is proposed that the SOFC supplies all the downstream loads under steady state. Upstream voltage sag is dealt with in accordance to the severity of the sag. Two scenarios are possible in which the criteria

is to provide maximum support for load ride-through while maintaining the unbundled power quality supply feature of the PQCC. The operating state of the SOFC DG can be guaranteed within the FOA. The proposed scheme exploits more fully on the control of the inverters and the SOFC to mitigate the voltage sag effect, rather than rely on the use of alternative feeder and the transfer switches as was suggested by earlier researchers. Analysis of the power system dynamics and the design of the control system of the PQCC have also been presented. The efficacy of the scheme is verified by the simulation results.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

In this project, technical problems associated with the SOFC DG for stationary power generation are investigated. In particular, the design of the operational schemes of the SOFC and to use them to mitigate power quality problems are the main concern of the research. Detailed analysis and studies include the introduction of the concept of FOA, control of the SOFC and output filter design in an isolated condition, real and reactive power control of the SOFC power plant in a grid-connected system, design of the PQCC to help load to ride through voltage sag and provide unbundled power quality.

Starting from an available SOFC model suitable for power system analysis, the concept of the FOA is introduced. This is one of the main contributions of this thesis. Fuel utilization factor and output power are two main constraints on the FC: any operating state outside of the FOA will harm the cell life and is unacceptable. From the derived analytical expression which describes the steady state relationship between the cell stack current, terminal voltage and fuel utilization factor, it is found the steady-state operating points of the FC cannot satisfy the constant fuel utilization factor (u) and constant terminal voltage (V_{dc}) simultaneously. Also based on the SOFC dynamic model, the derived small-signal SOFC dynamic model under constant fuel input and constant u operating conditions indicates that the FC is a slow power source in nature. The SOFC cannot make any fast stack current change by quickly varying its EMF. When a load current step change occurs, the FC terminal voltage variation is examined under the condition when the FC is connected in parallel with a capacitor bank. It is shown, from the numerical results, that the derived simplified SOFC models have the desired accuracy. Compared to the constant fuel input condition, FC under constant u scheme will undergo a smaller V_{dc} variation, compared to the case of without the installation of the shunt capacitor.

SOFC could be applied to track load in an isolated condition. In an isolated system, the PCU has fast but limited AC-side voltage regulation ability. In this way, when the external load is increasing, the PCU could soon reach its regulation limit and the load voltage may drop. Therefore, it is necessary to regulate the natural gas input (H_2 fuel) to track the external load. The natural gas input can be controlled to constrain the operating point within the FOA, using either the proposed constant u or constant V_{dc} control scheme. With the constant u scheme, the stack current is fed back with a simple proportional gain $2K_f/u_s$. When the external load current varies with a step (say 0.1p.u.) and different ramp-rate change, the FC steady state operating states will settle along the preset u_s line while the V_{dc} variation is small (say less than 5%). This could help the PCU maintain the AC side voltage constant readily. Using the stack current feedback as an inner current loop, the FC terminal voltage can also be fed back to regulate the fuel valve. With this two-loop control scheme, the FC terminal voltage can be maintained at a reference value, which in turn will also guarantee the FC operating points stay within the FOA after the load variations. Based on the well-known frequency response analysis, the analysis shown in the thesis indicates that the system would have the smallest phase margin when the load is the lightest. Hence, the controller is designed according to this most onerous condition to achieve the required stability margin. Compared to the constant V_{dc} scheme, it is found that constant u scheme would undergo a smaller u excursion when load has a step change under the light load condition. Therefore, the simple constant u scheme for the SOFC is more suitable for practical applications.

In an isolated system, the harmonics generated by the PCU power switches will degrade the load power quality. Based on the FC operating scheme, the reliable, low-cost second-order low-pass output filter could be used to mitigate the harmonic problem. The analysis shows that the selection of the filter quality factor and cut-off frequency are related to the limits set on the load voltage THD, PCU output current THD and the power loss in the filter. The filter parameters can be determined through the proposed iterative process.

In a grid-connected condition, FC can regulate the real and reactive power to the external grid by controlling its three control variables i.e. natural gas input, modulation index and phase shift angle. Constant u scheme can still be used to tune the natural gas

input. Based on the proposed strategies, FC can achieve the target power level according to a series of on-line generated modulation index and phase shift angle information. These control variables for the PCU will depend on the reference stack current used. Hence one objective of the investigation is to determine the proper reference stack current generation strategies. This is with the view to minimize the time needed to achieve the power changes while guaranteeing the FC operating states within the FOA. Through the analysis, it is found that the maximum safe step in stack current as a ratio to the initial stack operating current is equal to the maximum allowable u excursion, as a ratio to the desired steady-state u . Due to the u constraint, the capability of the FC to achieve the step real power change is only fraction of its initial power. Any power change larger than this step change limitation can be achieved as a combination of the maximum safe step and a ramp with a fixed or variable ramp rate. For very large power change ranges, the ramp rate should be varied by on-line estimation of the u to maintain u at the limit value until the target power level is achieved. For this method of control, the controller has the very desirable property that it is independent of the model of the fuel processor. Furthermore, with all the strategies of current control, the controller is also independent of the model of the FC. This eliminates the possible degradation in the controller performance due to model inaccuracies.

PQCC embedded with a FC-based DG forms a conceptual distribution network. FC can not only deal with the normal slow-varying load changes but also help PQCC to provide unbundled power quality supply. It can assist the loads ride through short-duration voltage disturbances. Under steady state, the FC power plant can be designed to satisfy the total DC and SP loads. Surplus real power of the FC together with the reactive power generated by Inv.1 will be fed to the upstream OQ and HQ loads by adjusting Inv.1 controls. The upstream source will supply power at unity power factor at the PCC. When an upstream voltage sag occurs, the PQCC is designed to operate under two scenarios. In Scenario 1, PQCC will be connected to the PCC for a time period T_d , which is determined from the standard ITI/CBEMA curve. The output power of the FC is not changed during the disturbance. In Scenario 2, if the sag is deep, OQ will be shed firstly. If the PCC voltage cannot recover to the acceptable threshold voltage V_{min} , PQCC will be disconnected from the upstream source after T_d . In the isolated mode, PQCC control schemes must satisfy some constraints to guarantee the FC operating points within the

FOA. These operating constraints form a feasible operating zone. During the disturbance, HQ load in this zone can operate with V_{min} . As the FC may experience a step increase, DC load voltage may have a slight drop (say less than 5%). However, the SP load voltage waveform is always not changed. In this manner, the FC power plant in the PQCC plays an important role of helping to provide unbundled power quality supply.

8.2 Recommendations

Notwithstanding the progress described in the thesis, the following areas are suggested as the possible areas for further investigations. With view of making practical applications, these possible areas could help to improve the proposed schemes in this thesis.

In Chapter 3, the FOA and the small-signal dynamic models are derived based on the available SOFC model, which has the accompanying assumptions. For example, the output gases partial pressures in the Nernst equation are strongly related to the structure of the FC stack. With a different structure, the assumptions such as the single interior pressure in the stack and the choked orifice may not be valid. This may affect the dynamic processes in the stack, output gases partial pressures and the FC EMF. The SOFC dynamic model would then need to be changed. An improved version of the FOA may be obtained which would make the control scheme more realistic. Similarly, the model of the fuel processor is also most approximate. A more accurate processor model will lead to a superior control scheme of the SOFC. Depending on the type of problem of interest, the SOFC power plant model could include aspects of material, thermodynamic and electro-chemistry. Non-linear control methods such as that based on the fuzzy control theory which are less sensitive to the FC model may be used. The robustness of the fuzzy controller should be verified.

In considering the output filter design in Chapter 5, much attention has been focused on alleviating the PCU-caused harmonic problems on the AC-side. However, as introduced in Chapter 2, the FC is alternatively connected to the external system through the PCU. During the switching process, the stack current will contain ripples on the DC-side. The

ripples may cause the FC operating states to deviate from the FOA. In order to generate harmonic-free DC power, harmonic mitigation solutions must be found. The relationships between the cell stack, harmonic mitigator, PCU and the external systems would need to be derived.

The PQCC capability to help loads ride through disturbances is a fruitful area for future study. As shown in Figure 7-5, the capability of the PQCC as a shunt compensator is limited within the area of 'RSTUR'. If the upstream HQ load is of such value as to be outside of this area, the HQ load cannot be protected for sustained operation by the PQCC. One possible ride-through scheme is by installing shunt compensators such as a capacitor bank. However, as described in [58], the size of the shunt compensator must be very large in order to maintain the PCC voltage to be within acceptable level. On the other hand, upstream system source is always the first option to provide power. In order to help the loads ride through the disturbance, a series compensator (SC) can be considered. In this manner, the DG and the SC can share the same DC bus. Real power from the DG can be controlled to provide the energy needed by the SC, thus the area of 'RSTUR' can be expanded. There would be coupling effects between the PQCC and the SC. This may affect the transient operating behaviour of the SOFC during the mitigation period. Further analysis and simulation works are needed to verify this new scheme.

Combined Heat and Power (CHP) is one promising application area for the DG technology. As introduced in Chapter 2, heat generated by the SOFC can be recycled and used by the other DG such as a microturbine. The efficiency of the generation set can be improved. When the SOFC is in parallel operation with the other forms of DG, the electrical interactions between the generators need to be quantified. These interactions may affect the SOFC dynamic performance during the load-tracking and voltage sag mitigation processes. New prudent control scheme suitable for the operation of the SOFC need to be explored.

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Appendices

Appendix A

Typical 100 kW SOFC Power Plant Experimental Data Used for Simulation Studies

Table A-1 100 kW SOFC power plant data [23, 34,35]

Symbol	Representation	Value
P_{rate}	Rated power	100kW
$V_{dc, rated}$	Rated FC terminal voltage	330V
T	Operation temperature	1273 °K
E_0	Ideal standard potential	1.18V
N_0	Number of series cells in the stack	384
K_r	Modeling constant	$0.993 \times 10^{-3} \text{ mol}/(\text{s.A})$
u_s	Fuel utilization factor setting	0.8
K_{H_2}	Hydrogen valve molar constant	0.843 mol/(s.atm)
K_{H_2O}	Water valve molar constant	0.281 mol/(s.atm)
K_{O_2}	Oxygen valve molar constant	2.52 mol/(s.atm)
τ_{H_2}	Hydrogen flow response time	26.1s
τ_{H_2O}	Water flow response time	78.3s
τ_{O_2}	Oxygen flow response time	2.91s
r	Ohmic loss	0.126Ω
τ_f	Fuel processor response time	5s
r_{H_2O}	Ratio of hydrogen and oxygen	1.145
b_{act}	Tafel slope	0.11
a_{act}	Tafel constant	0.05
a_{con}	Concentration loss constant	10^{-4} V
b_{con}	Concentration loss constant	8×10^{-3}

Note: The first 14 parameters, from P_{rate} to r , are given in [34]. Parameters τ_f and r_{H-O} are given in [35]. The last 4 parameters are given in [23].

Appendix B

Derivation of (4-8) and (4-9)

Substituting $\Delta N_{H_2}^{in}(s) = [\Delta N_r(s) + 2K_r/u_s \Delta I_{FC}(s)]/(1 + \tau_f s)$ and the initial steady-state output partial pressures in (3-6) into (3-19), the relationship between the EMF, fuel regulation signal and stack current is:

$$\begin{aligned} \Delta E(s) &= P(s)\Delta N_r(s) + Q(s)\Delta I_{FC}(s) \\ &= \frac{RTu_0}{I_{FC,0}} \cdot \frac{1}{1 + \tau_f s} \cdot \left(\frac{1}{1 - u_0} \cdot \frac{1}{1 + \tau_{H_2} s} + \frac{1}{2 - u_0 r_{H-O}} \cdot \frac{1}{1 + \tau_{O_2} s} \right) \Delta N_r(s) \\ &\quad + k \left[\frac{u_0}{1 - u_0} \cdot \frac{1}{1 + \tau_{H_2} s} \cdot \left(\frac{1}{1 + \tau_f s} \cdot \frac{1}{u_s} - 1 \right) + \frac{u_0 r_{H-O}}{2(2 - u_0 r_{H-O})} \cdot \frac{1}{1 + \tau_{O_2} s} \cdot \right. \\ &\quad \left. \left(\frac{1}{1 + \tau_f s} \cdot \frac{2}{u_s \cdot r_{H-O}} - 1 \right) + \frac{1}{1 + \tau_{H_2 O} s} \right] \Delta I_{FC}(s) \end{aligned} \quad (B-1)$$

From (B-1), $P(s)$ and $Q(s)$ (4-8) can be written as

$$P(s) = K \frac{[(2 - u_0 r_{H-O})\tau_{O_2} + (1 - u_0)\tau_{H_2}]s + 3 - u_0 - u_0 r_{H-O}}{(1 + \tau_f s)(1 + \tau_{O_2} s)(1 + \tau_{H_2} s)}$$

$$Q(s) = k_0 \frac{b_3 s^3 + b_2 s^2 + b_1 s + b_0}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}$$

$$K = \frac{RTu_0}{I_{FC,0}(1 - u_0)(2 - u_0 r_{H-O})}$$

$$k_0 = \frac{E_f}{I_{FC,0}}$$

where

$$a_4 = \tau_f \tau_{O_2} \tau_{H_2} \tau_{H_2O}$$

$$a_3 = \tau_f \tau_{O_2} \tau_{H_2} + \tau_f \tau_{O_2} \tau_{H_2O} + \tau_f \tau_{H_2} \tau_{H_2O} + \tau_{O_2} \tau_{H_2} \tau_{H_2O}$$

$$a_2 = \tau_f \tau_{O_2} + \tau_f \tau_{H_2O} + \tau_f \tau_{H_2} + \tau_{O_2} \tau_{H_2} + \tau_{O_2} \tau_{H_2O} + \tau_{H_2} \tau_{H_2O}$$

$$a_1 = \tau_f + \tau_{O_2} + \tau_{H_2} + \tau_{H_2O}$$

$$a_0 = 1$$

$$b_3 = \tau_f \tau_{O_2} \tau_{H_2} - \frac{u_0 \tau_f \tau_{O_2} \tau_{H_2O}}{1 - u_0} - \frac{0.5 u_0 r_{H-O} \tau_f \tau_{H_2} \tau_{H_2O}}{2 - u_0 r_{H-O}}$$

$$b_2 = \tau_f \tau_{O_2} + \tau_f \tau_{H_2} + \tau_{O_2} \tau_{H_2} - \frac{u_0 [\tau_f (\tau_{O_2} + \tau_{H_2O}) - (1/u_s - u_s) \tau_{O_2} \tau_{H_2O}]}{1 - u_0} \\ - \frac{u_0 r_{H-O} [\tau_f (\tau_{H_2} + \tau_{H_2O}) - 0.5 (2/u_s r_{H-O} - 1) \tau_{H_2} \tau_{H_2O}]}{2 - u_0 r_{H-O}}$$

$$b_1 = \tau_f + \tau_{O_2} + \tau_{H_2} - \frac{u_0 [\tau_f - (1/u_s - 1) (\tau_{O_2} + \tau_{H_2O})]}{1 - u_0} - 0.5 u_0 r_{H-O} [\tau_f - (2/u_s r_{H-O} - 1) (\tau_{H_2} + \tau_{H_2O})]$$

$$b_0 = 1 + \frac{u_0 (1 - u_s)}{u_s (1 - u_0)} + \frac{0.5 u_0 (2 - u_s r_{H-O})}{u_s (2 - u_0 r_{H-O})}$$

By substituting (3-15), $\Delta V_{dc} = R_l \Delta I_{FC}$, $P(s)$ and $Q(s)$ into (4-9), it can obtain

$$M(s) = \{[(2 - u_0 r_{H-O}) \tau_{O_2} + (1 - u_0) \tau_{H_2}]s + 3 - u_0 - u_0 r_{H-O}\} (1 + \tau_{H_2O} s)$$

$$N(s) = d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s + d_0$$

$$d_4 = (1 + r / R_l) a_4$$

$$d_3 = (1 + r / R_l) a_3 - k_0 b_3 / R_l$$

$$d_2 = (1 + r / R_l) a_2 - k_0 b_2 / R_l$$

$$d_1 = (1 + r / R_l) a_1 - k_0 b_1 / R_l$$

$$d_0 = 1 + r / R_l$$

Vita

Li Yonghui was born in P. R. China, in 1973. He received his B.E. and M.Eng. degrees from the Huazhong University of Science and Technology, China, in 1994 and 1998, respectively, all in Electrical Engineering.

He worked as a lecturer in Wuhan University from 1998 to 2001. His research areas include SCADA/EMS, Power System Stability and Power Quality.

Research related to this thesis has result in the following publications:

[1] Y. H. Li, S. S. Choi and S. Rajakaruna, "An analysis of the control and operation of a solid oxide fuel cell power plant in an isolated system," IEEE Transactions on Energy Conversion, Vol. 20, No. 2, pp. 381 - 388, Jun. 2005.

[2] Y. H. Li, S. Rajakaruna and S. S. Choi, "Control of a solid oxide fuel cell power plant in a grid-connected system," In print, IEEE Transactions on Energy Conversion. Paper No: TEC-00199-2004.

[3] Y. Q. Zhan, Y. H. Li, S. S. Choi, S. Rajakaruna and D. M. Vilathgamuwa, "The design of power quality control center to realize unbundled power quality supply," In print, IEEE Transactions on Power Delivery. Paper No: TPWRD-00045-2005.

[4] Y. H. Li, S. S. Choi and S. Rajakaruna, "Solid oxide fuel cell power plant application in an isolated system". The 6th International Power Engineering Conference (IPEC03), Vol. 1, pp. 347-352, Nov. 27-29, 2003, Singapore.

[5] Y. H. Li, S. S. Choi and S. Rajakaruna, "The design of the inverter output filter of a fuel cell power plant in an isolated system". The 5th Power Electronic and Drive System Conference, Vol. 1, pp. 548-553, Nov. 17-20, 2003, Singapore.

[6] Y. Q. Zhan, Y. H. Li, S. S. Choi, S. Rajakaruna and D. M. Vilathgamuwa, "Some recent results on the design of power quality control center", The 7th International Power Engineering Conference (IPEC05), TM-1.4, pp. 1-6, Nov. 29 – Dec 02, 2005, Singapore.