Load sharing control of fuel cell based generation units in stand-alone distribution networks*

H Rastegar
Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

AA Ghadimi†
Department of Electrical Engineering, Faculty of Engineering, Arak University, Arak, Iran

ABSTRACT: *This paper proposes and investigates a control strategy for the distribution networks when isolated from a main utility in order to improve continuity of electricity to important loads. Specifically, the paper presents the operation and control of proton exchange membrane fuel cell based generation unit feeding to the islanded industrial network. The central controller defines all distributed generation units reference power and voltage with consideration of system and unit normal rating in order to maintain reliable and high quality power to the important loads. Simulation results verify that the proposed control scheme is effective for stable operation of the industrial islanded network with dynamic and variable loads.*

1 INTRODUCTION

Over the last few years, a number of factors – such as increase in gaseous emissions (mainly CO_2), transmission costs, energy efficiency or rational use of energy, deregulation or competition energy, diversification of energy resources, availability of modular generating plant, ease of finding sites for smaller generators, and short construction time – have led to an increased interest in distributed generation (DG) schemes (El-Khattam & Salama, 2004; Lasseter & Piagi, 2004; Marwali & Keyhani, 2004; Marwali et al, 2004). DG systems could be used to reduce demand charges of major commercial and industrial customers during grid connected mode. Also, DG systems can increase reliability by supplying power to critical loads during outage of utility (Lasseter & Piagi, 2000).

Typical distribution network with DG supporting units can be islanded from the main network because of a fault or a pre-planned disconnection from the main grid. To meet technical requirements, the DG unit must include protection, control and communication components enabling safe operation. Obviously, voltage and frequency in the islanded portion of the network must to be controlled. The main challenge in operating such a DG system is the coordination of the numerous generators for sharing the real and reactive power outputs, and control of system frequency and voltage.

Control of an islanded network can be achieved in different ways. The related work is addressed in Marwali et al (2004), Lasseter & Piagi (2000), Sao & Lehn (2005), Li et al (2004), Lopes et al (2006), Katiraei & Iravani (2006) and Engler et al (2000). In these studies, a concept was developed and improved using reactive power/voltage and active power/frequency droops for the power control of the inverters similar to those in utility grids. This method uses the grid quantities voltage and frequency for coordination of the components. The main advantage of this method is that it uses only local variables for controlling the system and is suitable for distribution network with long distance between DG units. However, as frequency will deviate after any load change, a secondary control loop is needed for stable and accurate frequency control. In addition, load sharing between generation units in order to have optimal condition in the network and maintaining all constraints in the system cannot be performed.

A system with a voltage source as master and additional controllable power sources is investigated and presented in Engler et al (2000). The proposed method uses a central control that is responsible for power distribution. This approach can be used in industrial networks where the communication

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† Corresponding author Dr Ali Ghadimi can be contacted at a-ghadimi@araku.ac.ir.

between all parts of system is possible and the central control knows the situation of loads and system at any specific time.

This paper is concerned with the control strategy for the parallel operation of DG systems in an industrial network after islanding from the main utility. In particular, the paper focuses on proper power sharing of each DG unit and maintaining the voltage profile. First of all, good load-sharing should be maintained under several disturbances. The key features of the proposed control method are that it only uses locally measurable feedback signals (voltages/currents), and uses relatively low bandwidth data communication signals between each generation system and central controller. Also, it is assumed that generation units in this network are the proton exchange membrane fuel cells (PEMFCs). The paper presents an effective method for using PEMFCs, characterised by slow transient response, in an industrial network with dynamic and variable loads.

To ensure good load-sharing, the central control should determine the outage of utility, and send suitable control signals to shed unimportant loads and control the DG unit in stand-alone mode. When the utility is reconnected, the central control must synchronise and reconnect the islanded system to the utility. This paper only focuses on island mode of operation and, hence, controller design and the scheme of transition between island mode and grid-connected mode are outside the scope of this study.

The rest of paper organised as follows. Section 2 shows industrial network under study configuration. Section 3 focuses on the modelling of PEMFCs, inverters, DC-DC converters and storage devices. In section 4, structure and features of the central controller are presented, and simulation results and discussion on a typical simulation system are described in section 5.

2 INDUSTRIAL STAND-ALONE SYSTEM STRUCTURE

A single line diagram of a low voltage cable type industrial distribution network that was used in this study for investigating the proposed island network controlling scheme is shown in figure 1. The system consists of four feeders that supply from utility via a 20/0.4 kV transformer, and data of all components of the system can be found in Appendices A and B. The important part of system consists of 9 buses and 8 loads in 2 radial feeders, and total power demand of this part is about 380 kW and 120 kVAR.

When the utility is available two DG units (DG 1 and DG 2) produce some part of the energy needed for the system in order to reduce demand charge. The system is considered to become islanded after the fault occurrence in the utility or according to the pre-planned disconnection of the system from the utility via turning the main switch off.

The system consists of two PEMFC-based DG units, DG 1 and DG 2. It contains PEMFCs, storage devices,

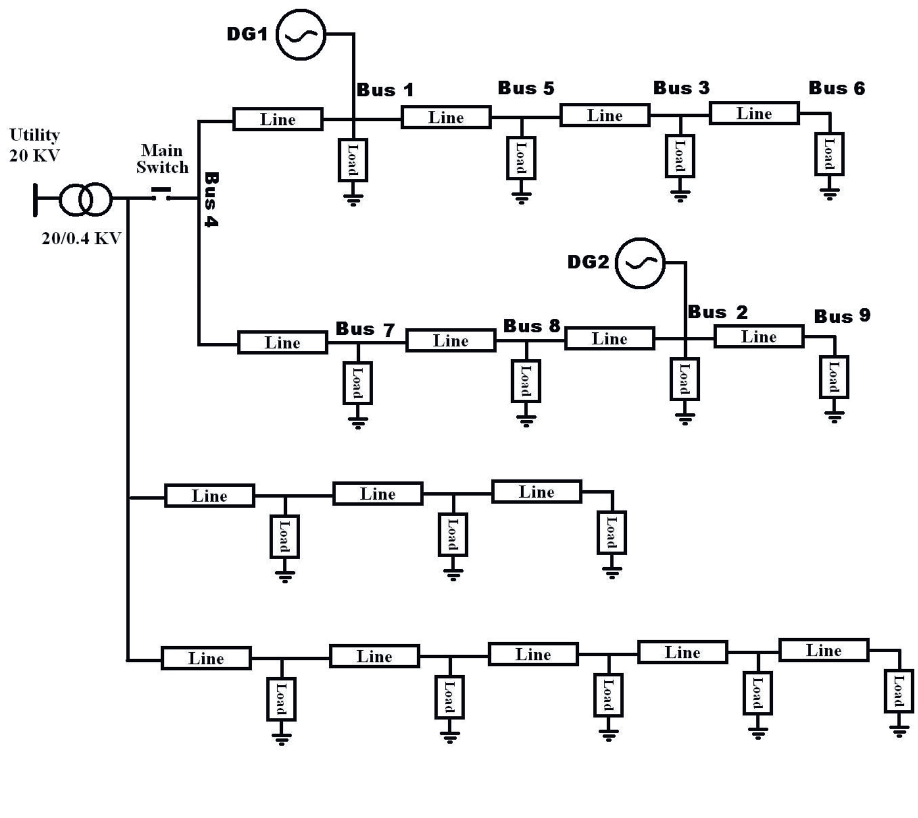

Figure 1: Single line diagram of the system under study.

a DC-DC converter, a DC-AC inverter, a filter and a transformer. Also loads, a local controller of the DG units and a central controller unit are other parts of system, which will be discussed in related subsections.

3 MODELLING OF DISTRIBUTED GENERATION SYSTEM COMPONENTS

In this section, a detailed model for all components of each DG units is presented, and the mathematical models will be used for designing the controller and simulation. Figure 2 shows a real system diagram of the fuel cell based DG unit that consists of a reformer, stack of the fuel cells (FC), storage device, a DC-DC converter, and a three-phase DC to AC inverter. Also all parts of the system have individual controllers that will be explained in following subsections. As shown in the figure, first the reformer produces hydrogen gas from the fuel cells and then provides it for the stack. Second, the stack with many unit cells in series generates the electrical power. Last, the power conditioning unit including storage device and power converters alters the low voltage DC from the fuel cell to a high voltage DC and/or a sinusoidal AC. The parameter description and values that is used in all block diagrams is defined in Appendices C, D and E.

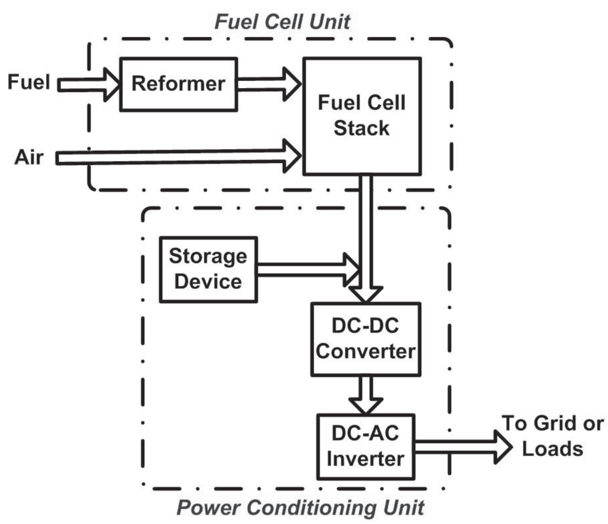

Figure 2: Block diagram of a fuel cell base DG unit.

3.1 Fuel cell

Among different types of the fuel cells categorised by the electrolyte used, three types are promising for DG systems: PEMFC, solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) (Jung & Keyhani, 2005; Sedghisigarchi & Feliachi, 2006; Wang et al, 2005). PEMFCs, one of the most developed fuel cells, show great promise both in transportation and in stationary power generation applications (Wang et al, 2005; 2006; El-Sharkh et al, 2004; Corrêa et al, 2003; Wang & Nehrir, 2007). The complete mathematical model of a PEMFC can be seen in El-Sharkh et al (2004; 2007), Corrêa et al (2003), Wang & Nehrir (2007), Uzunoglu & Alam (2006), Onar et al (2006) and Daryani et al (2006). Figure 3 shows a block diagram of the stack model according to mathematical model of a fuel cell.

In this paper, the model has been modified to simulate a 250 kW PEMFC and the parameters of the fuel cell are gained from El-Sharkh et al (2007) and are given in Appendix E.

3.2 Reformer

According to changes in power demand, the fuel cell consumes hydrogen, and the reformer should continuously generate hydrogen for stack operation. The mathematical form of the reformer model can be found in El-Sharkh et al (2004). To control the hydrogen flow rate according to the output power of the fuel cell, a proportional-integral (PI) control system is used, as shown in figure 4.

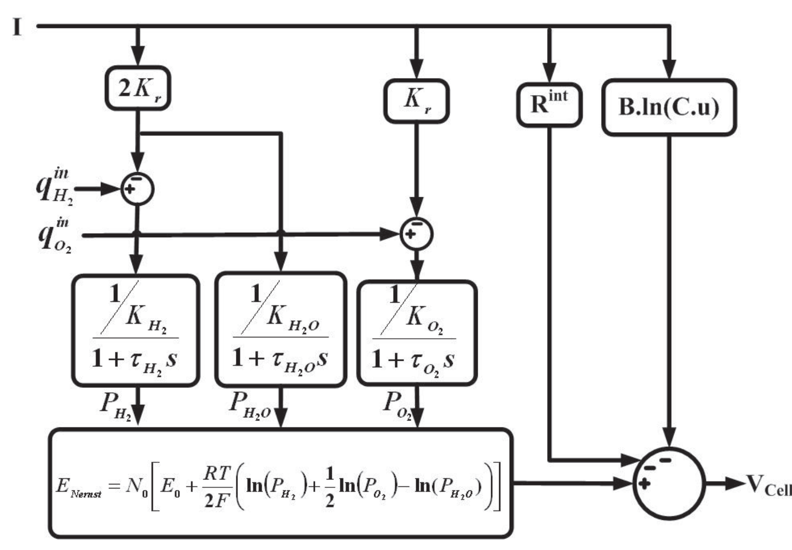

Figure 3: PEM fuel cell stack block diagram.

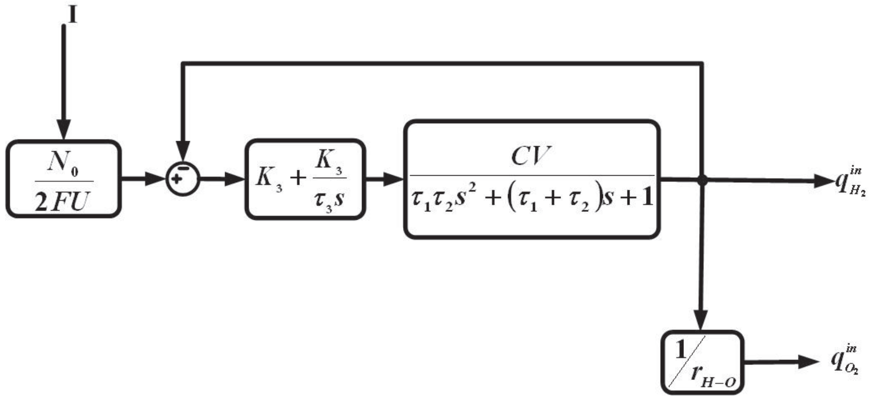

Figure 4: The reformer and its controller model.

3.3 Storage device

The fuel cell cannot immediately respond to power demand during start-up or sudden load changes due to its slow dynamics. Also, load transients can be harmful to them and will shorten their life (El-Sharkh et al, 2004; Corrêa et al, 2003; Wang & Nehrir, 2007). As a result, energy storage elements such as batteries, flywheels or ultra-capacitors (UCs) are needed to deliver the remaining power to the load for the transient times with the aid of power electronics devices.

Because of the high specific power and power density of UC banks and low output voltage of fuel cells, it may be possible to eliminate the DC-DC converter for voltage regulation and use UCs directly in parallel with the fuel cell, as shown in figure 5. The diode prevents the flow of reverse current from the UC bank into the fuel cell system. The direct integration of the UC bank is attractive, because it does not require a high power DC-DC converter, and so the complexity, cost, weight and volume of the system are significantly reduced (Onar et al, 2006; Daryani et al, 2006; Gao et al, 2005; Vielstich et al, 2003).

The capacity of the storage device is to be defined according to the dynamics of the fuel cell stack and the amount of power. Jung & Keyhani (2005) and Uzunoglu & Alam (2006) described how much storage is suitable and how to design it. In this study a UC is used as the storage device for the system and the model is shown in figure 6. The model consists of a capacitance (C), an equivalent series resistance (ESR) representing the charging and discharging resistance, and an equivalent parallel resistance (EPR) representing the self-discharging losses (Uzunoglu & Alam, 2006; Onar et al, 2006).

The power sharing between the fuel cell system and UC bank is determined by the total resistance between these two systems.

During low power demand periods, the fuel cell system generates up to its load limit, and the excess power is used to charge the UC. The charging or discharging of the UC bank occurs according to the terminal voltage of the overall load requirements.

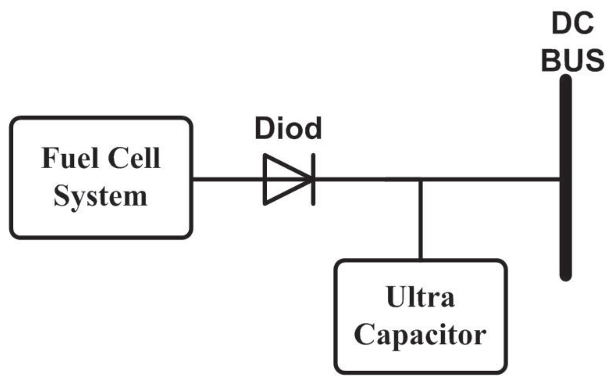

Figure 5: Arrangement of the fuel cell and ultra-capacitor.

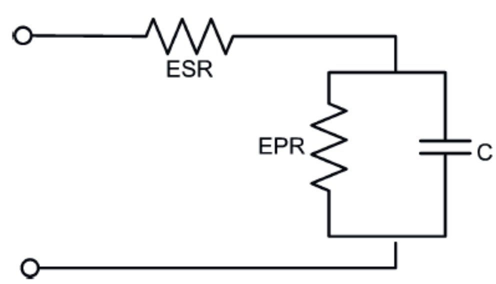

Figure 6: Equivalent model for the ultra-capacitor.

During high power demand periods, the fuel cell system generates the rated power and the UC is discharged to meet the extra power requirements that cannot be supplied by the fuel cell system. Also, short-time power interruptions in the fuel cell system can only be supplied by the UC bank.

3.4 DC-DC boost converter

Fuel cell systems normally need boost DC-DC converters to adapt the fuel cell output voltage to the desired inverter input voltage and smooth the fuel cell output current (Jung & Keyhani, 2005; Sedghisigarchi & Feliachi, 2006; Wang et al, 2005; 2006). For this purpose, a forward boost converter, a push-pull boost converter or an isolated full-bridge DC-DC power converter can be selected. Among these power converters, full-bridge converters are the most attractive topology for high power generation (Jung & Keyhani, 2005; Ghadimi et al, 2006).

In this paper, the full-bridge DC-DC converter large signal model that was adopted by Ghadimi et al (2006) is used for simulation and the small signal model used for designing controller. Figure 7 shows the controller block diagram for regulating the output voltage and changing it to a higher level. The controller parameter can be adjusted according to method presented by Ghadimi et al (2007).

As can be seen from figure 7, the control system uses feedback of the converter output and feed forward of input voltage, and define duty cycle of switches in order to regulate the output voltage in desires value.

The controllers for the boost DC-DC converters are designed to keep the DC bus voltage within an acceptable band (±5% in this paper). Therefore, the input to the three-phase inverter can be considered a fairly good constant DC voltage source.

3.5 DC-AC inverter

The output of the fuel cell, UC and DC-DC converter is DC, and is not suitable for supplying power directly to the AC grid and loads. Inverters are then needed to provide AC grid interface. Pulse-width modulated (PWM) voltage source inverters (VSIs) are widely used to interconnect a fuel cell energy system to a utility grid for real and reactive power control purposes (Wang & Nehrir, 2007; Mohan et al, 2003).

A circuit model of a three-phase DC to AC inverter with LC output filter is further described in figure 8. As shown in the figure, the system consists of a DC voltage source (V_{dc}), a three-phase PWM inverter and an output filter (L_f and C, with considering parasitic

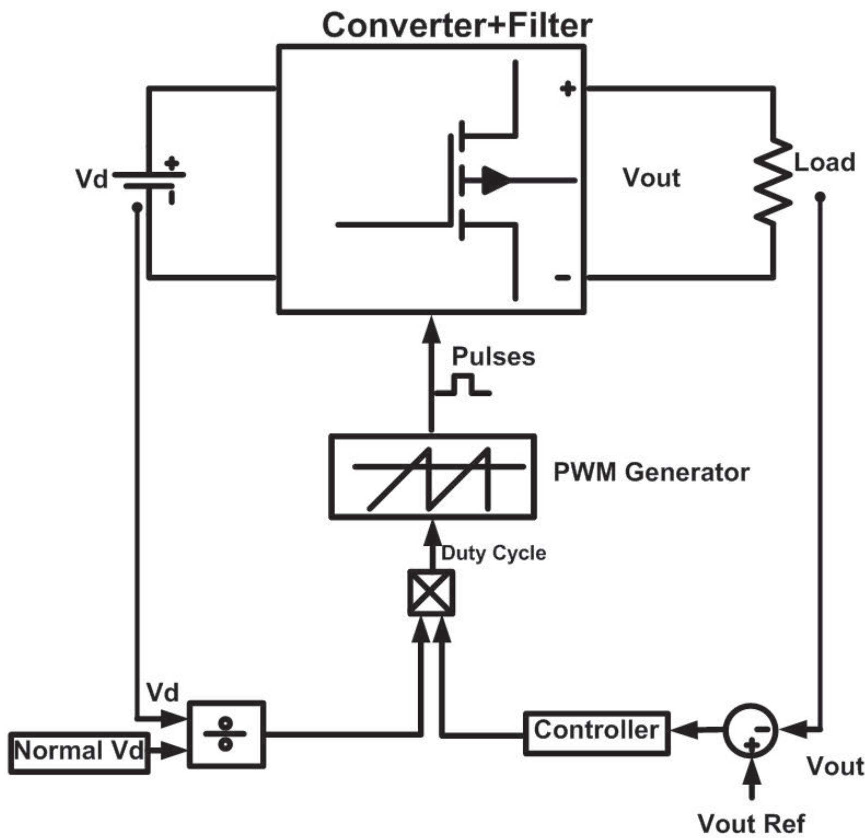

Figure 7: Block diagram of the full-bridge DC-DC converter controller.

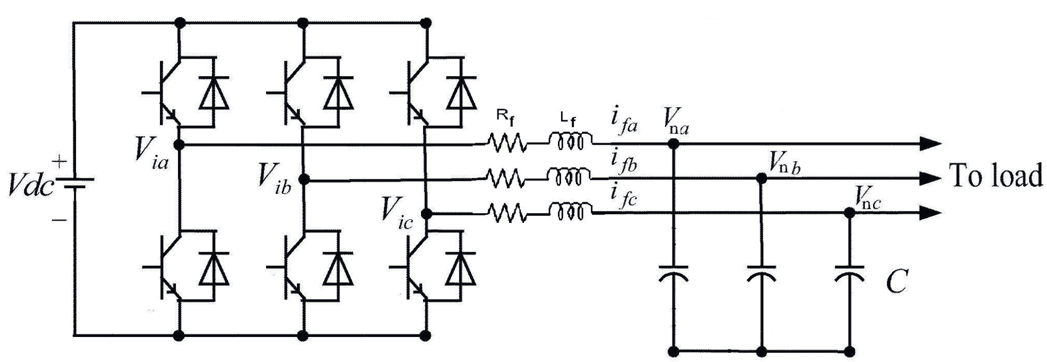

Figure 8: PWM inverter circuit diagram.

resistance of filter R_f). Sometimes a transformer may be used for stepping up the output voltage and hence L_f can be transformer inductance.

There are two ways for controlling an inverter in a DG system (Lopes et al, 2006; Katiraei & Iravani, 2006; Engler, 2000):

3.5.1 PQ inverter control

This type of control is adopted when the DG unit system is connected to an external grid or to an island of loads and more generators. In this situation, the variables controlled by the inverter are the active and reactive power injected into the grid, which have to follow the set-points P_{ref} and Q_{ref}, respectively. These set points can be chosen by the customer or by a central controller.

The PQ control of an inverter can be performed using a current control technique in the *q-d* reference frame, where the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power (Bertani et al, 2004). The inverter controller block diagram for supplying reference value of P_{ref} and Q_{ref} is as figure 9.

For the current controller, two PI regulators have been chosen in order to meet the requirements of stability of the system and to make the steady-state error be zero.

When the output voltage is needed to be regulated, the PV control scheme can be used. This scheme is similar to PQ mode with feedback of voltage that used to adjust Q_{ref}.

3.5.2 Vf inverter control

This controller has to act on the inverter whenever the system is in island mode of operation. In fact, in this case, it must regulate the voltage value at a reference bus bar and the frequency of the whole grid. The regulators work in order to keep the measured voltages upon the set-points. Moreover, the frequency is imposed through the modulating signals of the inverter control by means of an oscillator. A simple PI controller can regulate bus voltage in reference value with receiving feedback of real bus voltage, as it is shown in figure 10.

Designing of the PI controller in the control loop of both inverters is done with the method presented in Bertani et al (2004), and with consideration of inverter ratings and circuit parameters.

4 PROPOSED ISLANDED SYSTEM CONTROLLER

If a group of DG units is operated within a distribution system and the main power supply is connected, all the inverters can operate in the PQ mode because a voltage and frequency reference is available. In this grid-connected mode, similar to a conventional utility system, each DG unit can be controlled to generate pre-specified real and reactive power components (PQ-bus) or generate pre-specified real power and regulate its terminal voltage (PV-bus). The utility grid is expected to support the difference in real/reactive power requirements and maintain the frequency (Lopes et al, 2006; Katiraei & Iravani, 2006), like a slack bus generator in traditional systems.

However, when the utility is lost and the network becomes islanded, the whole system must be shut down and all DG units must be disconnected because of the lack of frequency support. If there are some important loads that should be supplied at all times, then it is important to find a solution to supply them and guarantee continuity of electricity supply.

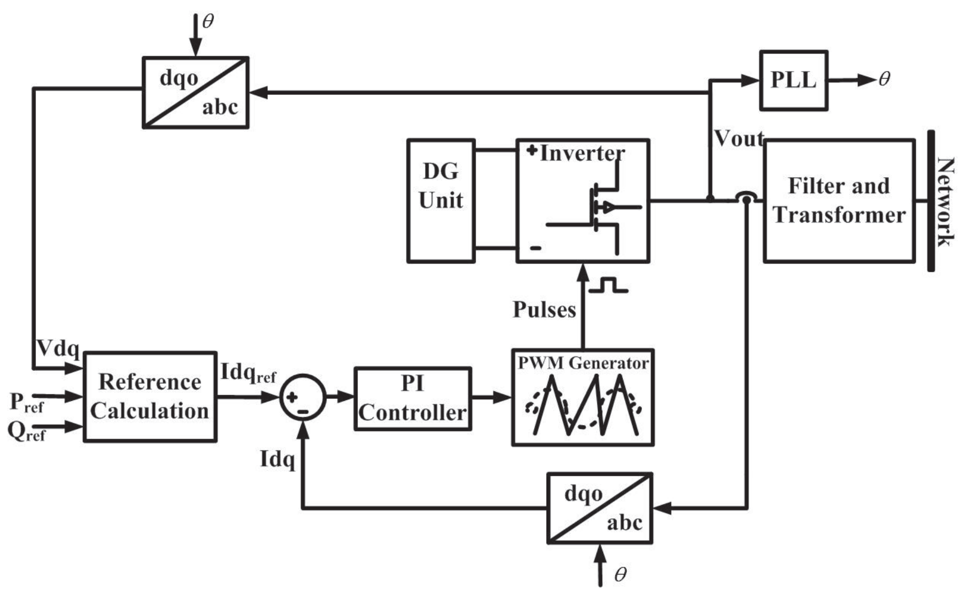

Figure 9: PQ control scheme of inverter with current control loop.

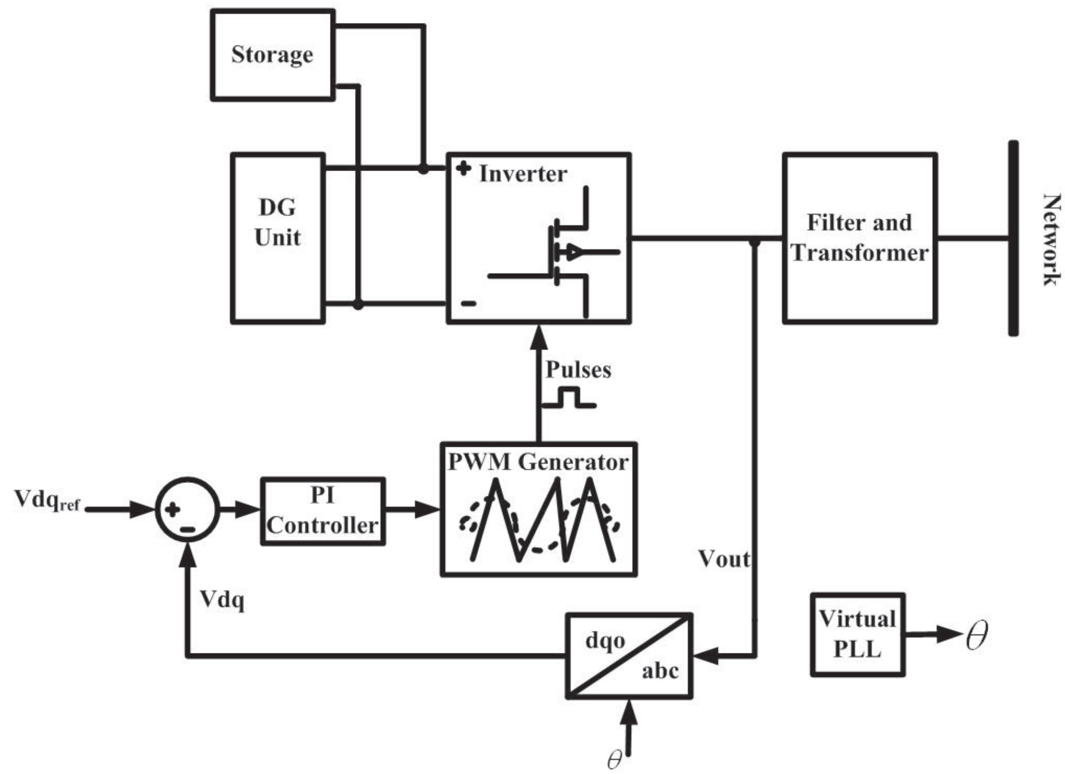

Figure 10: Vf control scheme of inverter.

Since usually there is no synchronous generator in industrial networks to balance demand and supply, inverters should be responsible for controlling frequency and balancing loads during islanded operation. A voltage regulation strategy is also required for power quality satisfaction. Also, sometimes a load shedding scheme must be applied to match generation and load demand during transients.

In this case, at least one of the DG units must act as voltage reference, and then it will be possible to obtain an exact balance between load and generation. That unit, called the Master DG unit in this study, has the duty of providing the reference voltage and frequency. The other DG units can work in PQ or PV mode, and they are not expected to contribute to transient changes in loads and may be used for long-term load balance.

Such a Master DG unit should be coupled with a storage device of suitable capacity in order to be able to compensate natural load and production variations. This is an important issue for successful load balancing in islanded operation with DG units.

The whole system must be centrally controlled and managed by a central controller that can be installed at the substation. The main criteria that should be met by the system controller are as follows:

- Identify outage of utility and disconnect unimportant load, and change control scheme of all DG units to island mode of operation with one Master unit and others in PV or PQ mode.
- Maintain stability and restore the system during and after load change or transients.
- Load sharing among DG units with consideration limits of each DG unit, including type of the DG unit, cost of generation, maintenance period and environmental impacts.
- Maintain the power quality and voltage profile at the standard values.
- Prepare island network to reconnect to the utility after reconnection of utility.
- Change the control scheme of all DG units to grid-connected mode after reconnecting this important load to utility

These goals should be performed by a suitable controller. Two levels of controller is suggested for this purpose:

1. *Local controller:* At the first level, inverter current is controlled according to desired active and reactive powers, and with consideration of inverter and switch ratings. It is obvious that the related DC-DC converter should control its output voltage at the desired value, and alsothe hydrogen flow controller must control the input rate of the reformer during any change in any DG unit output power.
2. *Central controller:* This level of controller defines the reference values of active and reactive/ voltage of each inverter. Also, this controller defines the state of controllable loads if they exist. The controller manages network operation by providing set-points to both loads and generation units. Commands are at format of power and voltage references for DG units, and load shedding for controllable loads.

Figure 11 shows a general overview of the control strategy that is proposed for a stand-alone system in this paper.

Since, in this study, an industrial network is considered as an islanded system, it is obvious that the load profile is known, and the DG unit variable can be measured and transmitted to central control with the existing communication facility in the network. So, the central controller has the knowledge of the system at all times, and can decide the proper load sharing to control the system effectively.

The amount of data to be exchanged between network controllers includes mainly messages containing set-points to the DG units. Also, information about the state of loads and measurement signals of system can be monitored and can be used for advance load forecasting.

5 SIMULATION RESULTS AND DISCUSSION

To validate the effectiveness of the proposed control strategy in the stand-alone AC power system, a simulation test bed using Matlab/Simpower Toolbox is constructed for an AC 220 V (L-N)/50 Hz system, which its single line diagram is showed in figure 1. A low voltage DC output of the fuel cell is used along with the full-bridge DC-DC converter and a UC for backup is connected in parallel to the DC bus. According to system powers, voltages and other parameters, all parts and related controllers are designed properly with the method discussed in section 3, and parameters of all components are given in Appendices A to E.

It is considered that DG 1, a PEMFC generator with UC storage, is the Master DG Unit, and it acts like a synchronous generator for producing voltage and frequency reference, and also compensates for rapid load change. The other unit, DG 2, synchronises itself with the main unit via phase-locked loop. It works at PQ mode of operation, and its power can change with pre-plan and in a sluggish response. It is considered that DG 2 does not have a storage device, and produces energy with a slow response because of its slow dynamics and reformer time constants. So for proper working of the fuel cell system, step change on DG 1 can be used, but for DG 2, the power reference must change slowly. In this study, we consider ramp type increment in reference power of DG 2 between two operating points. Also it is considered that DG 2 injects constant reactive power value of 50 kVAR. In fact this unit is responsible for active power only.

The whole system is simulated under some changes and under various conditions, and the simulation results of the system are shown in figures 12 to 28. Initially with aim of a load flow calculation, it is considered that power reference of DG 2 is set to 170 kW and 50 kVAR. It can be seen from figure 12

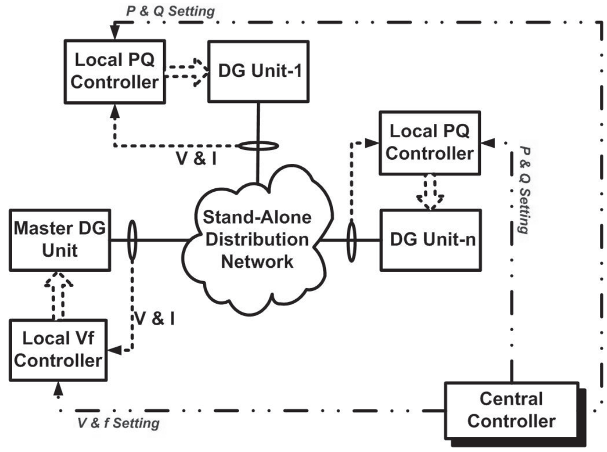

Figure 11: Overview of proposed control strategy.

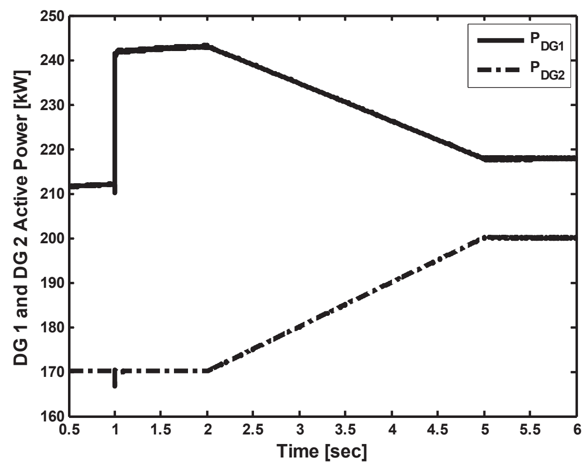

Figure 12: DG 1 and DG 2 output active power.

that in this case the controller adjusted output power of DG 2 in desired value and as expected remaining needed power supplied by the Master Unit, DG 1.

At t = 1 second, load in bus 9 increased about 100% and it can be seen from figure 12 that the increased power was supplied by Master Unit DG 1, while DG 2 worked in constant power at predefined reference value. The amount of increased load supplied by the Master Unit was as expected.

As the central controller knows this increase in load because of the factory production schedule, at t = 2 seconds, it decides to increase the reference value of DG 2 to 200 kW. Since DG 2 does not have a storage device, its power is increased slowly from initially 170 kW to finally 200 kW in a ramp manner with rate of 10 kW/s. It is obvious from figure 12 that the power of DG 2 goes up and the power of Master Unit DG 1 reduces as it prepares for the next disturbance.

Figure 13 shows all bus voltages in this simulation period. As it can be seen, all bus voltages are at standard values (±5%). The figure shows that in this industrial network with short cables, regulating the voltage in DG unit buses guaranteed standard voltage profile for other buses. If any bus voltage deviates from standard value, then a voltage regulation scheme and compensators should be considered.

Figure 14 shows the reactive power output of each DG unit. As expected and considered in the system controller, the reactive power demand supplied by the Master Unit and, since the distances are short in the study, system voltage remain in standard value, as shown in figure 13.

For illustrating working conditions and the parameters of fuel cell generators, simulation results of fuel cell parameter are shown in the next figures. Figure 15 shows output power of the DG 1 fuel cell stack, and it can be seen from figure 16 that during load changes, the UC supplies the system load and Fuel Cell 1 output power increases slowly with small amounts that guarantee the safe operation of the fuel cell stack.

It is obvious that during load change, in 1 second the UC supplies the amount of needed power (figure 16) and so the load can be supplied continuously. After that, fuel cells will produce the whole DG 1 system power, the UC will charge from the fuel cells, and finally its current will go to zero and it will be prepare for the next disturbances.

Since the DG 2 power command is applied in a slow rate and its amount is small (30 kW means 12% nominal power), it can be seen from figure 17 that Fuel Cell 2 tracks the desired power reference approximately.

Figures 18 to 23 show Fuel Cell 1 parameters. It is obvious from figures 18 and 19 that when powers demand is increased, output voltage drops and fuel cell current increases to satisfy the needed power. Also, figure 20 shows that fuel cell are working in safe conditions because its hydrogen utilisation rate is in a suitable range (0.7-0.9) (Sedghisigarchi & Feliachi, 2004) that is not harmful for the stack.

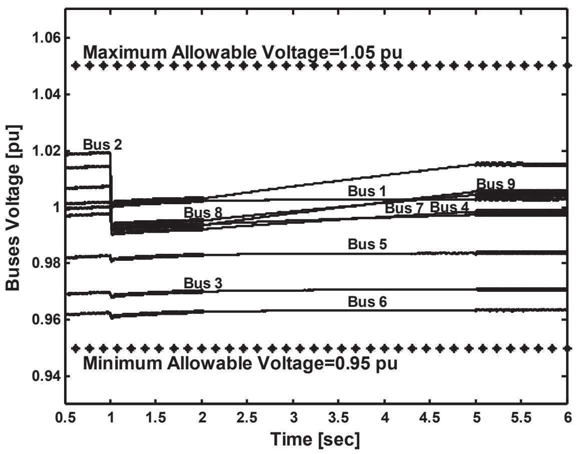

Figure 13: Islanded network bus voltage.

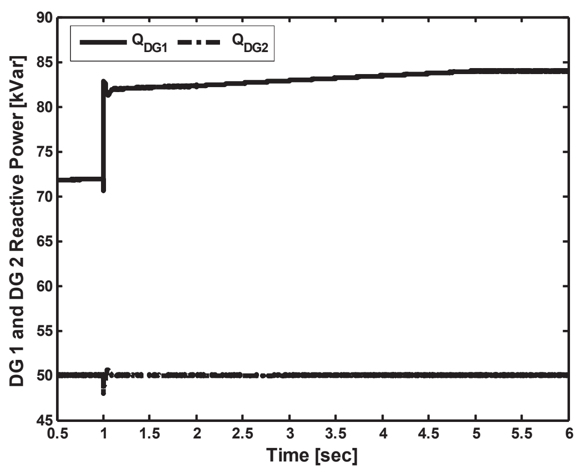

Figure 14: DG 1 and DG 2 reactive power.

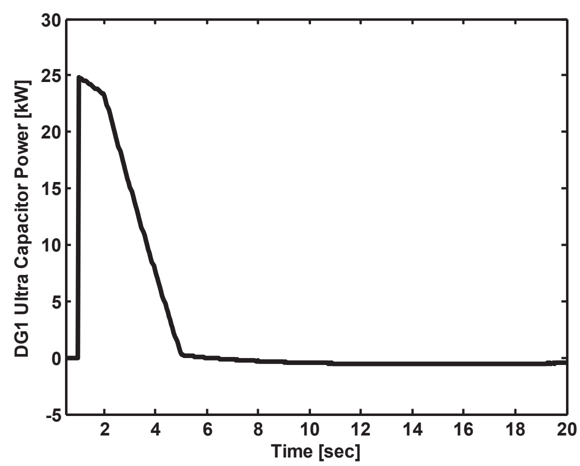

Figure 16: Ultra-capacitor output power.

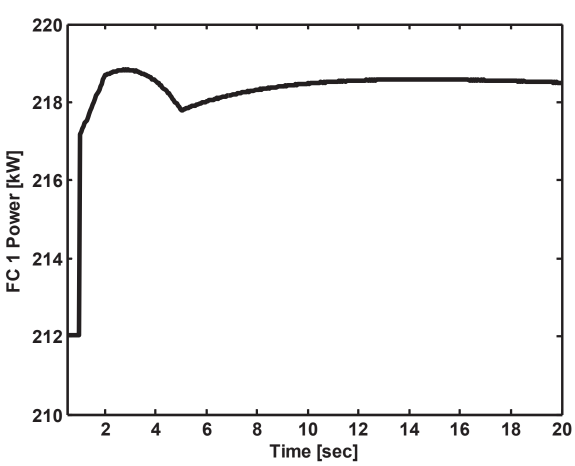

Figure 15: Fuel Cell 1 output power.

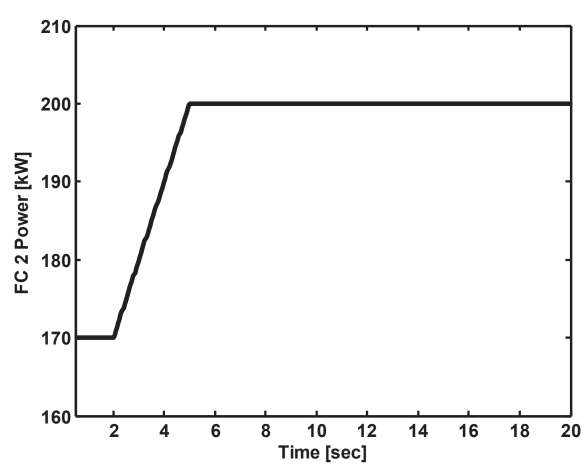

Figure 17: Fuel Cell 2 output power.

According to the change in fuel cell output power and current, input of the reformer will increase and it will produce more hydrogen, according to figure 21, which shows the increment of hydrogen flow rate after load change.

Also, figures 22 and 23 show hydrogen and oxygen partial pressure changes due to power increments. As it can be seen from the fuel cell model in figure 3, hydrogen and oxygen partial pressure are related to fuel cell current with a first-order transfer function, which models the fuel feeding pipes in the stack. So the response of hydrogen and oxygen partial pressure in figures 22 and 23 to the load change is gained after constant times of τ_{H2} and τ_{O2}, which is given in Appendix E for the fuel cell under study.

The initial fast drop in pressures is due to the fast consumption of hydrogen in the stack and the time needed for the reformer to produce the needed hydrogen according to load levels. After supplying proper hydrogen, the hydrogen and oxygen pressures in the stack reach the higher level, as can be seen in figures 22 and 23.

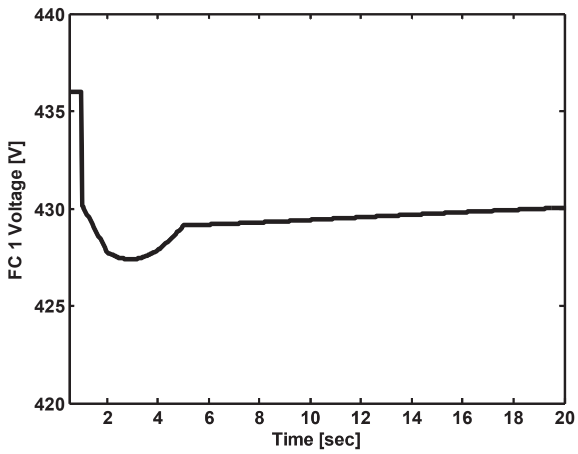

Figure 18: Fuel Cell 1 stack voltage.

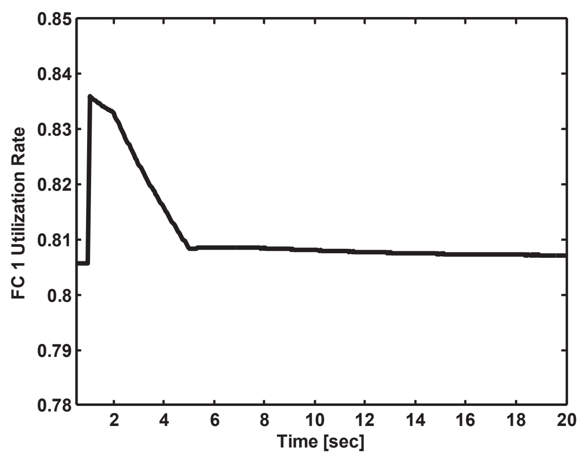

Figure 19: Fuel Cell 1 stack current.

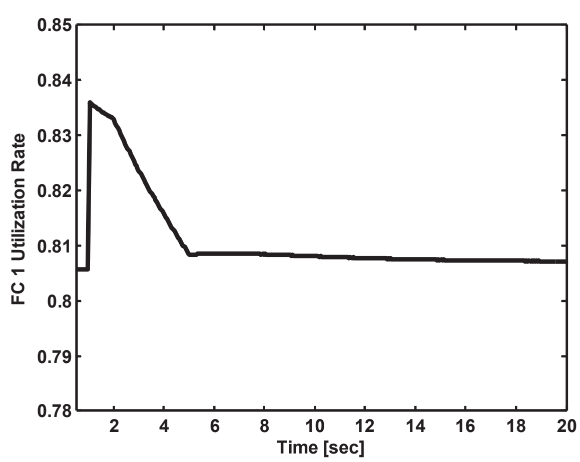

Figure 20: Fuel Cell 1 hydrogen utilisation rate.

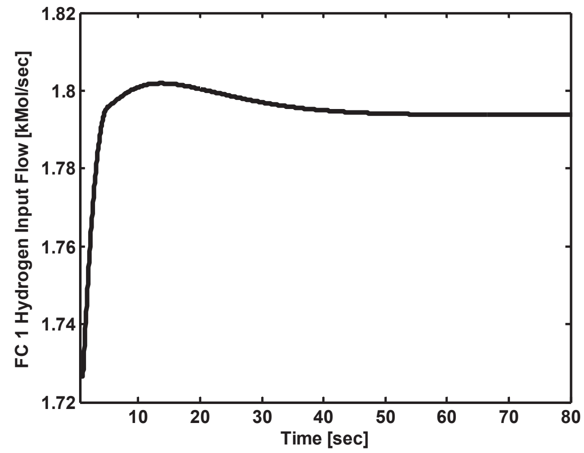

Figure 21: Fuel Cell 1 hydrogen flow.

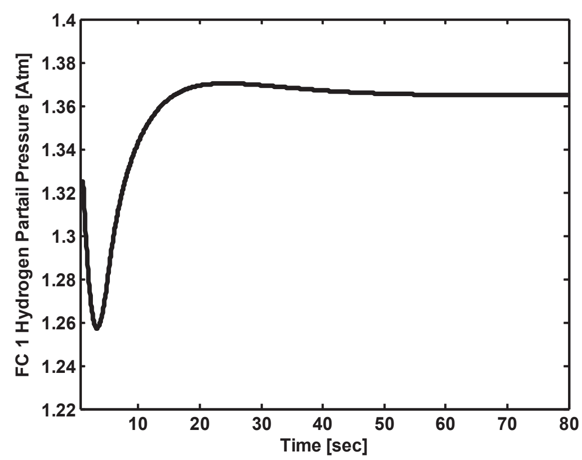

Figure 22: Fuel Cell 1 hydrogen partial pressure.

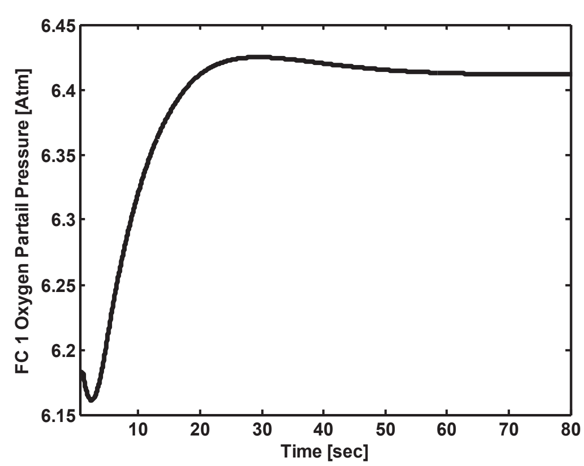

Figure 23: Fuel Cell 1 oxygen partial pressure.

Figures 24 and 25 show Fuel Cell 2 voltage and current. Like Fuel Cell 1, when power increases, output voltage drops and fuel cell current increases; and also hydrogen flow rate, and hydrogen and oxygen pressure increases accordingly, as figures 26 to 28 indicate.

Similar to Fuel Cell 1, loads increasing in a ramp manner causes the hydrogen and oxygen pressures to reduce, firstly because of lack of hydrogen needed to overcome the needed current. When the hydrogen is produced with the reformer, the internal pressures go to a higher level, which supports the higher load level.

Also with slow changing of output power, the fuel cell works in suitable utilisation rate and in safe working condition, as showed in figure 29.

As it is clear from the simulation results, the proposed method for controlling DG units is effective and can respond to the network needs during islanding. It means that when the utility is disconnected, this control strategy guarantees continuous power supply

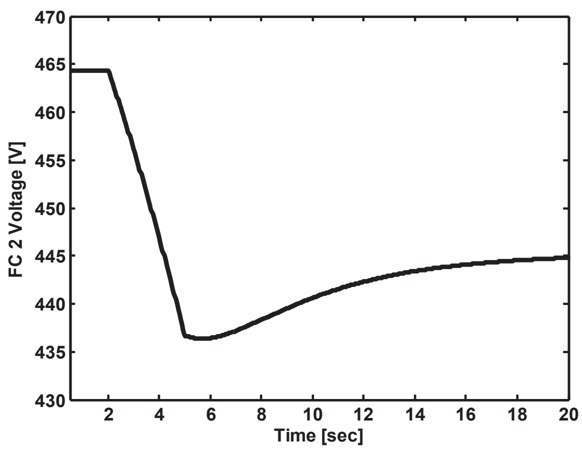

Figure 24: Fuel Cell 2 stack voltage.

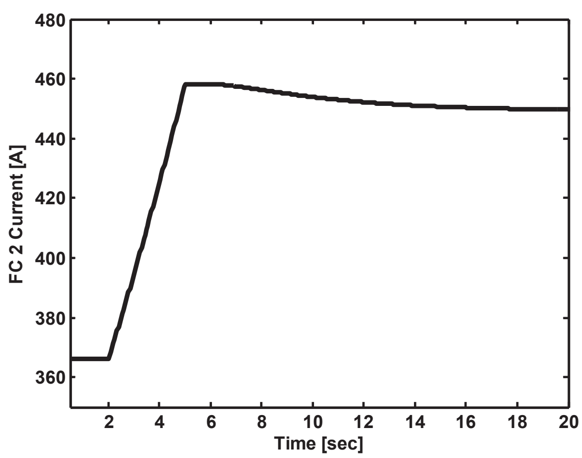

Figure 25: Fuel Cell 2 stack current.

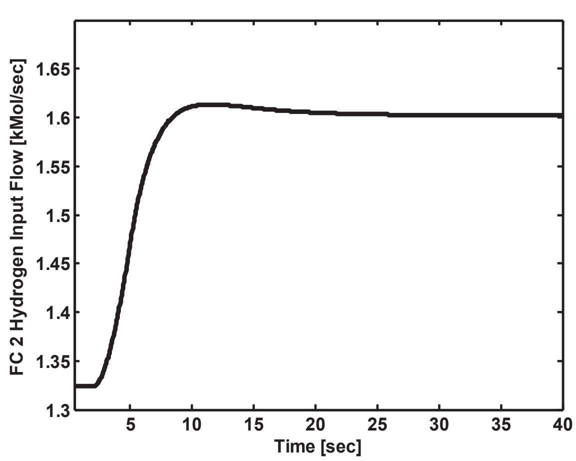

Figure 26: Fuel Cell 2 hydrogen flow.

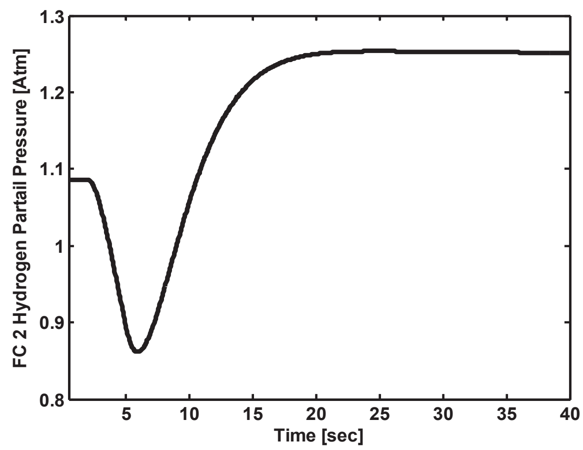

Figure 27: Fuel Cell 2 hydrogen partial pressure.

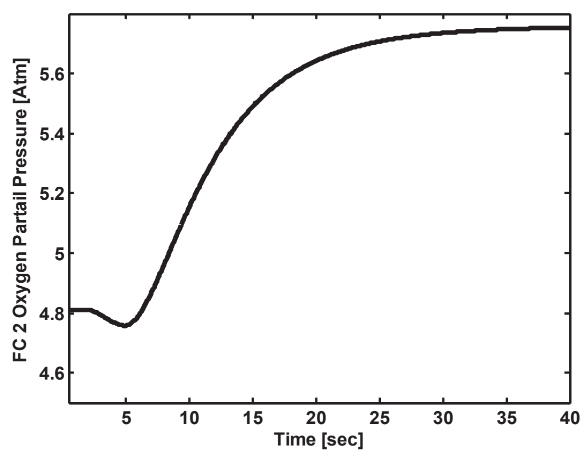

Figure 28: Fuel Cell 2 oxygen partial pressure.

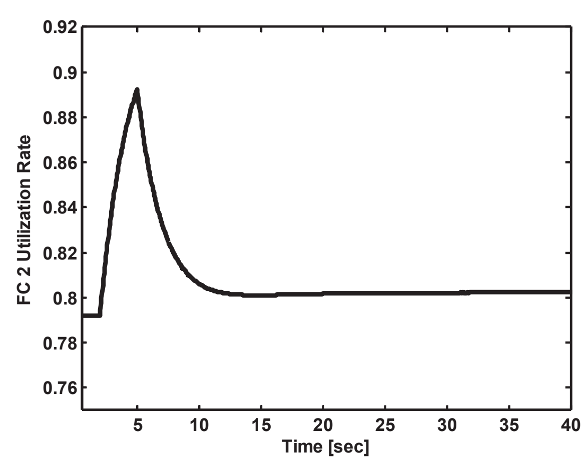

Figure 29: Fuel Cell 2 utilisation rate.

to the loads, and when the utility comes back, the islanded system can be reconnected to the grid.

6 CONCLUSION

This paper has presented the control strategy needed for successful load sharing in an islanded industrial network. To manage these goals, the system should include one large capacity inverter-based energy storage unit, which acts as a voltage and frequency reference and supports the network during transients. The other DG units just supply reference value of power to the network. It is clear that when storage devices are combined with fuel cells, this clean and efficient power source can be used for supplying reliable and high quality energy to important loads during outage of a utility.

Simulation results showed that the system controller is able to keep the system stable and all bus voltages in standard value, and also the ability of fuel cells to be installed in industrial stand-alone networks for decreasing demand charge and guarantee continuity of power supply.

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APPENDIX A: DISTRIBUTION SYSTEM DATA

All lines are similar with the following data.

Cable resistance: $R = 0.164\ \Omega/\text{km}$

Cable inductance: $L = 0.26\ \text{mH/km}$

Table 1: Distribution line data.

Line no.	From bus	To bus	Length (m)
1	4	1	100
2	1	5	200
3	5	3	150
4	3	6	210
5	4	7	160
6	7	8	200
7	8	2	180
8	2	9	220

Table 2: Buses load data.

Bus no.	P (kW)	Q (kVar)
1	80	25
2	36	12
3	25	12
5	90	33
6	60	12
7	36	12
8	56	32
9	96	42

APPENDIX B: DG UNITS DATA

Table 3: DG units data.

DG	Nominal power (kVA)	Control mode	P-gain	I-gain
DG 1	400	vf	1.1	3.23
DG 2	280	PQ	6.0	0.12

APPENDIX C: DC-DC CONVERTER DATA

Filter capacitance: $C = 330\ \mu\text{F}$

Filter inductance: $L = 7\ \text{mH}$

Transformer power = 300 kVA

Switching frequency = 2000 Hz

Switches on resistor = $5 \times 10^{-3}\ \Omega$

P-gain of PI controller = 1.05

I-gain of PI controller = 2.34

APPENDIX D: ULTRA-CAPACITOR PARAMETER

$C = 20$ F

ESR = 0.001 Ω

EPR = 450 Ω

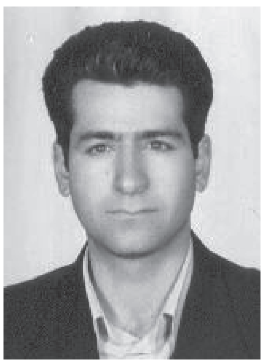
APPENDIX E: FUEL CELL AND REFORMER DATA

Table 4: Fuel cell and reformer data.

Parameter	Notation	Value	Unit
Fuel cell nominal power	P	250	kW
Stack temperature	T	343	K
Faraday's constant	F	96484600	C/kmol
Universal gas constant	R	8314.47	J /(kmol K)
No load voltage	E_0	0.8	V
Number of cells per stack	N_0	550	
Number of stacks	N_{stack}	6	
K_r constant	$= N_0/(4F)$	1.4251×10^{-6}	kmol A/s
Utilisation factor	U	0.8	
Hydrogen valve constant	K_{H2}	4.22×10^{-5}	kmol /(s atm)
Water valve constant	K_{H2O}	7.716×10^{-6}	kmol /(s atm)
Oxygen valve constant	K_{O2}	2.11×10^{-5}	kmol /(s atm)
Hydrogen time constant	τ_{H2}	3.37	s
Water time constant	τ_{H2O}	18.418	s
Oxygen time constant	τ_{O2}	6.74	s
Reformer time constant	τ_1	2	s
Reformer time constant	τ_2	2	s
Reformer PI gain	K_3	0.25	
Conversion factor	CV	2	
Activation voltage constant	B	0.04777	A^{-1}
Activation voltage constant	C	0.0136	V
Internal resistance	R^{int}	0.2778	Ω
External line reactance	X	0.05	Ω
PI-gain constants	$C2$, $C3$	0.15, 11.4	
Hydrogen/oxygen flow ratio	$r_{H/O}$	1.168	
Current delay time constant	T_d	3	s

HASSAN RASTEGAR

Hassan Rastegar received his BSc, MSc and PhD degrees from AmirKabir University of Technology (Tehran Polytechnic), Tehran, Iran, in 1987, 1989 and 1998, respectively, all in power engineering. Currently, he is Assistant Professor and research member in Department of Electrical Engineering at AmirKabir University of Technology (Tehran Polytechnic), Tehran, Iran, since 1989. He has been working in the field of renewable energy, power system dynamics, distributed generation, and application of computational intelligent in power systems.



ALI GHADIMI

Ali Asghar Ghadimi received his BSc, MSc and PhD degrees in Power Engineering in 1999, 2002 and 2008, respectively. He is currently Assistant Professor and research member in Department of Electrical Engineering at Arak University, Arak, Iran. His research interests are in the area of distributed generation, fuel cell, simulation and analysis of power system, power quality, and high voltage transmission lines.