

# Detailed Analysis of Micro-Grid Stability during Islanding Mode under Different Load Conditions

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*Received January 21, 2011; revised March 4, 2011; accepted April 6, 2011*

## Abstract

Today, several types of DGs are connected together and formed a small power system called micro-grid (MG). MG is connected to the primary distribution network and usually operates in normal connecting mode. When a severe fault occurs in the primary distribution network, then the MG will transfer to islanding mode. In this paper a complete model is developed to simulate the dynamic performance of the MG during and subsequent to islanding process. The model contains of a solid oxide fuel cell (SOFC), a single shaft micro turbine, a flywheel, two photovoltaic panels and a wind generator system. All these micro sources are connected to the MG through inverters except the wind generation system. The inverters are modeled with two control strategies. The first strategy is PQ control which the inverter will inject a certain active and reactive powers. This type of inverter is used to interface micro turbine, fuel cell and photovoltaic panels to the MG. The second strategy is Vf control. This model is used to interface flywheel will act as the reference bus (slack bus) for the MG when islanding occurs. Two cases are studied: the first case discusses the effect of islanding process on frequency, voltage and active power of all micro sources when the MG imports active and reactive power from the primary distribution network. The second studied case, also, shows the effect of islanding on the previous quantities particularly when the MG exports active and reactive power to the primary distribution network. Results showed that the existence of storage device (flywheel) with appropriate control of its inverter can keep the frequency of the MG and the voltages of all buses within their limited levels. The developed model is built in *Matlab*<sup>®</sup> *Simulink*<sup>®</sup> environment.

**Keywords:** MG, Dynamic Performance, Islanding, Inverter and Distributed Generators

## 1. Introduction

Micro-scale Distributed Generators (DGs), or micro sources, are being applied increasingly to provide electricity for the expanding energy demands in the network. The development of micro DGs also help to reduce green house gas emissions and increase energy efficiency [1]. The MG usually consists of a cluster of micro DGs, energy storage system (e.g. flywheel, battery, ....) and loads, operating as a single controllable system. The voltage level of the MG at the load is about 400V or less. The architecture of the MG is formed to be radial with a few feeders. It often provides both electricity and heat to the local area. It can be operated in both grid-connected mode and islanded mode. From the customer point of view, the MG can provide both heat and electricity and

also can enhance the local reliability, reduce emissions, improve power quality (by supporting voltage and reducing voltage dip), and can potentially lower the costs of energy supply. From the utility point of view, application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities [2]. Clearly, distributed generations located close to loads can reduce the flows in transmission and distribution circuits with two important effects: loss reduction and substitute for network assets. Further, the presence of generations close to demand could increase the service quality for the end customers. The MG can provide network support in times of stress by relieving congestions and aiding restoration after fault occurrence [2].

Development of the MG can contribute to reduction of emissions and mitigation of climate changes. This is be

cause available and currently developing technologies for distributed generation units are based on renewable sources and micro sources that are characterized by very low emissions [2]. The new micro sources technologies (e.g. micro gas turbine, fuel cells, photovoltaic system and several kinds of wind turbines) used in the MG are not suitable for supplying energy to the grid directly [3-4]. They have to be interfaced to the grid through inverters. Thus, the use of power electronic interfaces in the MG leads to a series of challenges in the design and operation of the MG [5].

Technical challenges associated with the operation and control of the MG are immense. Ensuring stable operation during network disturbances, maintaining stability and power quality in the islanding mode of operation requires sophisticated control strategies development for the MG's inverters in order to provide stable frequency and voltage in the presence of arbitrarily varying loads. The aim of this paper is to demonstrate the transients of a MG due to intentional islanding process and to illustrate the maintenance of stability of the MG in the isolated mode of operation.

Reference [6] is discussed about the MG autonomous operation during and subsequent to islanding process however no renewable micro sources is included. In references [7] and [8], a control scheme based on droop concepts (to operate inverters feeding a standalone ac system) is presented. References [9] and [10] are discussed about the behavior of distributed generator (DGs) connected to distribution networks, however, the dynamics of the primary energy sources is not considered. The full picture of the MG long-term dynamic behavior, which is largely influenced by the micro sources dynamics, is also missing in this reference.

In the present paper, we developed a complete model to simulate the dynamic performance of the MG. All MG components are simulated in details. In our previous research [11] and [12], we developed a model for all MG components (each component operates in standalone mode). In reference [11], a detailed model is developed for inverter with three different control schemes. In reference [12], some models are developed for the micro sources exist in the MG (micro turbine, fuel cell, wind turbine and photovoltaic). This paper collects all individual models developed in references [11] and [12] in one complete model and apply a suitable control scheme which can arrange the operation of all models simultaneously. The developed model is general and can be used to study any disturbance which may occur in the MG. The model is built in *Matlab*<sup>®</sup> *Simulink*<sup>®</sup> environment.

The rest of the paper is organized as follows: Section 2 illustrates a single line diagram of the studied MG. Sec-

tion 3 gives a brief description of all MG components models. Section 4 presents a description of the complete model with the applied controls. Two studied cases with results and discussions are explained in Section 5. Conclusions are presented in Section 6.

## 2. Single Line Diagram of the Studied Micro-Grid

**Figure 1** shows the single line diagram of the studied MG [13]. It consists of 7 buses. Flywheel is connected to bus 1. Wind generation system is connected to bus 2. Two photovoltaic panels with rating 10 kW and 3 kW are connected to buses 4 and 5, respectively. A single shaft micro turbine with rating 30 kW is connected to bus 6. Bus 7 is provided with a solid oxide fuel cell (SOFC) with rating 30 kW. The loads and line parameters of the MG are given in the appendix.

## 3. Description of Micro-Grid Individual Components Models

### 3.1. Inverter Models

In reference [11], three different control models of the inverter are developed to interface micro sources to the MG. The first model is PQ model, which control the active and reactive power injected by the inverter into the MG. This model is suitable for interfacing micro turbine, fuel cell and photovoltaic panels. **Figure 2(a)** shows the terminal block diagram of PQ inverter model. The input terminals are active power ( $P$ ) and reactive power ( $Q$ ) produced by the micro sources, the output is the three phase terminals ( $V_a$ ,  $V_b$  and  $V_c$ ) which connected the inverter to the MG.

The second model is the PV model, which controls the active power ( $PI$ ) injected by the inverter and keep the voltage of the inverter bus ( $V$ ) at constant value as shown in **Figure 2b**. The third model is the Vf model, which keeps the voltage ( $V$ ) at constant value and return the frequency ( $f_o$ ) to its nominal after disturbance by controlling the amount of the active power injected in the MG. The Vf inverter is used to interface the flywheel to the MG and represents the reference bus (slack bus) of the MG during and subsequent to islanding occurrence (**Figure 2(c)**).

### 3.2. Micro Sources Models

In reference [12], detailed standalone models are developed for single shaft micro turbine, solid oxide fuel cell, photovoltaic panels and wind generation system. These

standalone models are described as follows.

**3.2.1. Single Shaft Micro Turbine (SSMT) Model**

**Figure 3(a)** shows the developed model of the single shaft micro turbine. In this figure, the input terminal  $P_{ref}$  represents the desired power. The output terminal is  $P_e$  (electrical power output from permanent magnet synchronous generator which coupled with micro turbine).  $P_e$  is connected to  $P$  input terminal of the PQ inverter.

**3.2.2. Solid Oxide Fuel Cell (SOFC) Model**

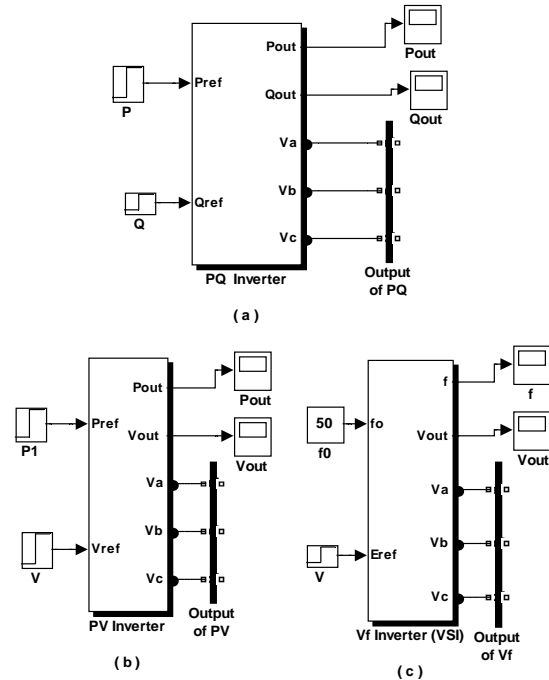
**Figure 3(b)** shows the developed model of the SOFC. In this figure, the input terminals are  $P_{ref}$  (desired power) and rated voltage ( $V_{rated}$ ). The output terminal is  $P_e$  which represents the electrical power output from fuel cell. This terminal is applied to  $P$  input terminal of the PQ inverter.

**3.2.3. Photovoltaic Model**

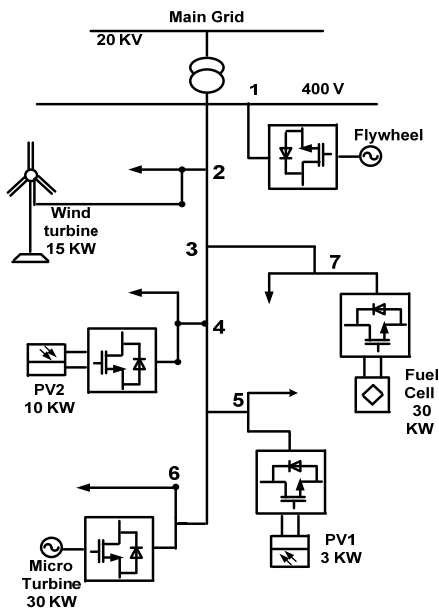
Photovoltaic model is shown in **Figure 3(c)**. Input terminals are Irradiance ( $G_a$  W/m<sup>2</sup>) and ambient temperature ( $T_a$  Kelvin). Maximum power point tracking (MPPT) is included inside the model. The output terminal is  $P_{max}$ , which represents the maximum output power developed by photovoltaic panel; this terminal is applied also to the input terminal of the PQ inverter.

**3.2.4. Wind Generation System Model**

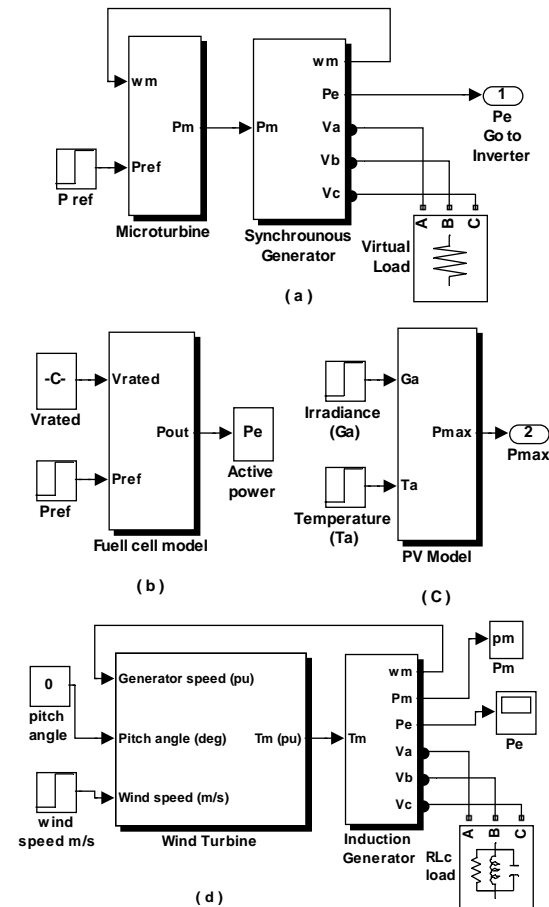
Wind generator system model is shown in **Figure 3(d)**. The wind turbine is coupled to a squirrel cage induction generator. The input terminals of the wind turbine are wind speed (m/sec.) and pitch angle of the turbine blades (degree). The output terminal of the wind turbine is me



**Figure 2. Inverter control models.**



**Figure 1. Single line diagram of the studied MG.**



**Figure 3. Micro sources standalone models.**

chanical torque ( $T_m$ ), which applied to the shaft of the induction generator. The terminals of the induction generator are connected directly to the MG.

### 4. Complete Model of the MG

The operation of the MG with several PQ inverters and a single voltage source inverter (Vf) is similar to the operation of the MG with synchronous machine as a reference bus (slack bus). The VSI provides the voltage reference for the operation of the PQ inverters when the MG is isolated from the main power grid. Acting as a voltage source, the Vf inverter requires a significant amount of storage capability in the DC link or a prime power source with a very fast response in order to maintain the DC link voltage constant. In other words, the power requested by a VSI needs to be available almost instantaneously in the DC link. In fact, this kind of behavior models the action of the flywheel system. Flywheel is connected at the DC bus of the Vf inverter to provide instantaneous power required. The Vf inverter is responsible for fast load-tracking during transients and for voltage control. During normal operation conditions (stable frequency at nominal value), the output active power of the Vf inverter is zero and only reactive power is injected into the MG for voltage control.

#### 4.1. Active Power Control in Each Micro Sources

During islanded (autonomous) operation, when an imbalance between load and local generation occurs, the grid frequency drifts from its nominal value. Storage devices (flywheel) keep injecting power into the network as long as the frequency differed from the nominal value. Micro turbine and fuel cell are controllable sources which the power output can be controlled. A PI controller (being the input of this controller the frequency deviation) which acts directly in the primary machine ( $P_{ref}$  of fuel cell and micro turbine) allows frequency restoration. After frequency restoration, storage devices will operate again at the normal operation point (zero active power output). This controller can not apply to wind turbine and photovoltaic panels because they are uncontrollable sources and their output power depend on wind speed, irradiance and ambient temperature. **Figure 4** shows the PI controller block diagram used to control the output power of fuel cell and micro turbine.

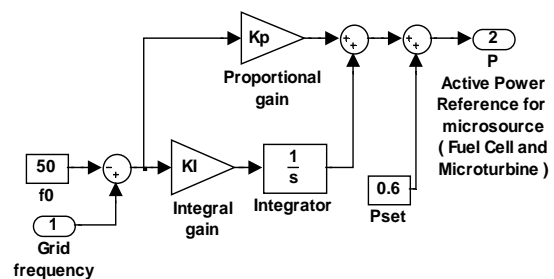
#### 4.2. Voltage and Reactive Power Control

In **Figure 5**, the adopted voltage control strategy is described. Knowing the network characteristics, it is possible to define the maximum voltage droop. To maintain

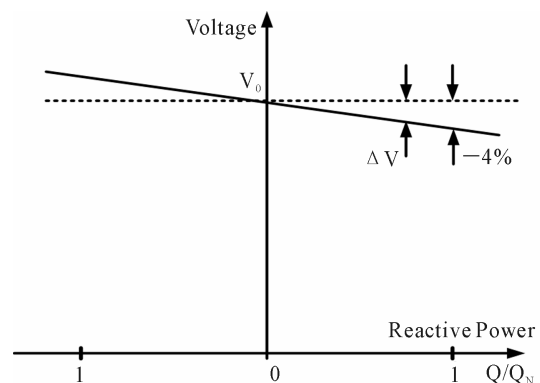
the voltage between acceptable limits, the voltage sources inverter (VSI) or Vf inverter connected to the flywheel will adjust the reactive power in the MG. It will inject reactive power when voltage falls from the nominal value and will absorb reactive power if the voltage rises above its nominal value.

#### 4.3. Frequency and Active Power Control

The transition to islanded operation mode and the operation of the network in islanded mode require micro generation sources to particulate in active power-frequency control, so that the generation can match the load. During this transient period, the participation of the storage devices (flywheel) in system operation is very important, since the system has very low inertia, and some micro sources (micro turbine and fuel cell) have very slow response to the power generation increase. As already mentioned, the power necessary to provide appropriate load-following is obtained from storage devices (flywheel). Knowing the network characteristics, it is possible to define the maximum frequency droop as shown in **Figure 6**. To maintain the frequency between acceptable limits, the Vf inverter connected to flywheel will adjust the active power in the network. It will inject active power when frequency falls from the nominal value and will absorb active power if the frequency rises above its nominal value.



**Figure 4.** Control of active power in controllable micro source.



**Figure 5.** Droop control of the inverter terminal voltage.

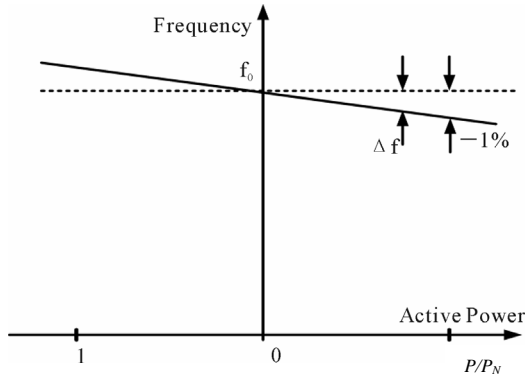


Figure 6. Frequency droop control of Vf inverter.

### 4.4. Complete Model of the MG

A complete model which collects all micro sources models, all inverter models and all control strategies is described in the previous sections and also shown in **Figure 7**. This model is general and can be used to describe any disturbances which may occur in the MG during connected and islanding modes.

### 5. Results and Discussions

In the simulation platform, the PV panels, a SOFC and a single shaft micro turbine are associated with a PQ inverter type. As the inverter control is quite fast and precise, it is possible to neglect the DC link voltage fluctua-

tions; if losses are also neglected, the output active power of a PQ inverter becomes equal to the output power of the associated micro source. Flywheel is connected to the Vf inverter.

#### Case1: MG Imports Active and Reactive Powers from the Main Grid

In this case, the amounts of active power and reactive power generated from micro sources are adjusted to make the MG imports 13 kW and 16 kVAr from the main grid. After finding suitable control parameters for the Vf inverter, disconnection of the upstream main grid is simulated at  $t = 60$  sec. and the simulation results are presented for the main electrical quantities (frequency, voltages, and active powers).

From the previous figures (**Figures 8-12**), the sequence of the events can be interpreted as follows:

- Before  $t = 60$  sec., the MG is at steady state and its frequency is at nominal value (50 Hz). The MG imports 13 kW and 16 kVAr from the main grid as shown in **Figure 12**.
- At  $t = 60$  sec., islanding occurred, the MG's loads are larger than the power generated by micro sources so that the frequency dropped to about 49.8 Hz and the voltages dropped to about 96% of their nominal values as shown in **Figures 8 and 9**, respectively.
- The difference between load powers (active and reactive) and generated power (active and reactive) is injected by flywheel as shown in **Figure 10**.

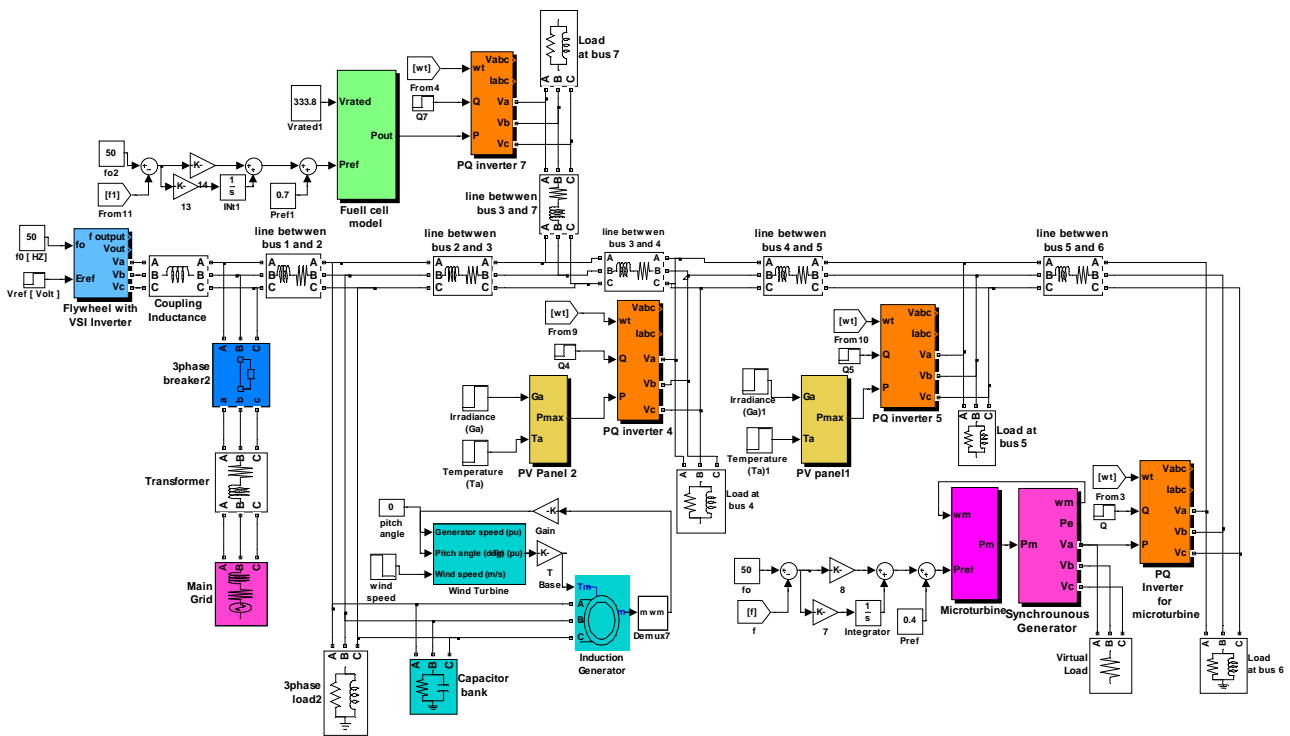


Figure 7. Complete system model.

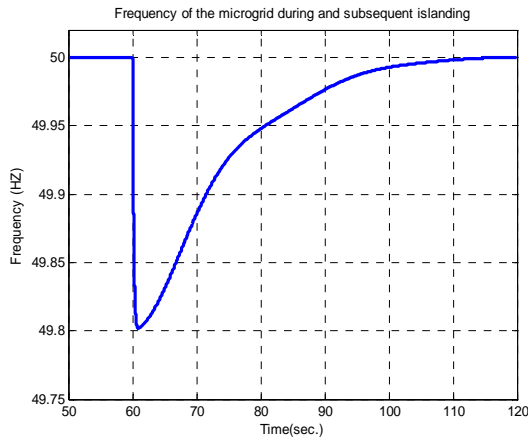


Figure 8. System frequency.

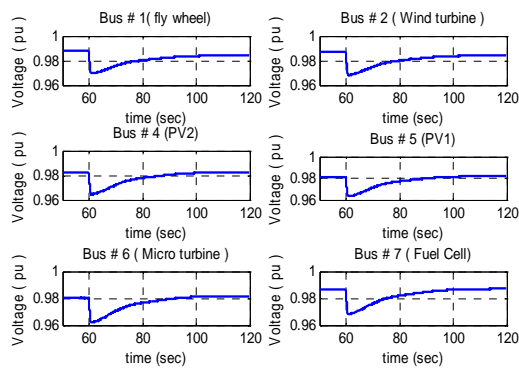


Figure 9. Voltages at all micro sources buses.

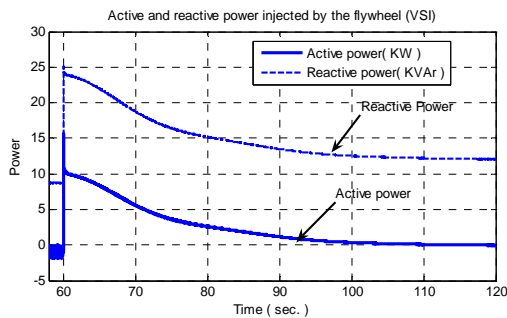


Figure 10. Flywheel (Vf) active and reactive powers.

- Due to frequency deviation, PI controllers connected to SOFC and SSMT increase the reference powers of those micro sources. The output powers of SOFC and SSMT begin to increase and help frequency restoration as shown in **Figure 11**.
- The powers produced by photovoltaic panels are constant because the ambient temperature and irradiance are assumed to be constant. This assumption is acceptable because the interval of simulations after islanding (50 sec) is small.
- Wind generator output power suffers from some fluctuations.

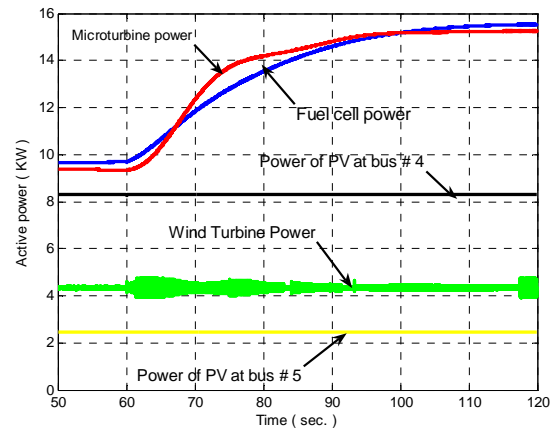


Figure 11. SOFC, SSMT, wind generator and photovoltaic panels active powers.

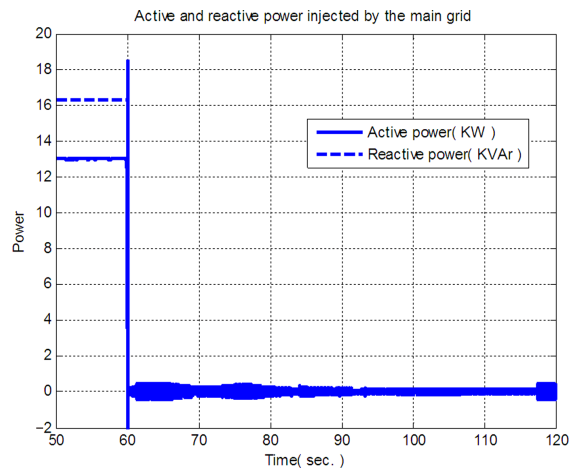


Figure 12. Active and reactive powers of the main grid.

- As the power generated by micro sources increases, the amount of power injected by flywheel decreases.
- When the power generated by the micro sources becomes equal to the demand by the load, active power injected by flywheel returns to zero and frequency returns to its nominal value.
- The dynamic performance of the studied MG needs about 50 seconds to return back to its steady state.
- Results proved that by using a storage device (flywheel) with a suitable rating, the MG can restore its stability after high disturbance (islanding) occurrence.
- In conclusions, MG is a very good solution for feeding sensitive loads and represents uninterruptable power supply for those loads.

**Case2: MG Exports Active and Reactive Powers to the Main Grid**

In this case, the reference powers of SOFC and SSMT are adjusted so that the amounts of active and reactive powers generated by all micro sources become greater than the demand. The MG exports about 21 kW and 20

kVar to the main grid. The disconnection of the upstream main grid simulated at  $t = 70$  sec., the simulation results are shown in the following figures.

From the previous figures (Figures 13-17), the sequence of the events can be interpreted as follows:

- Before islanding occurrence, the MG operates at its steady state and exports active and reactive powers to the main grid (Figure 17). The frequency of the MG

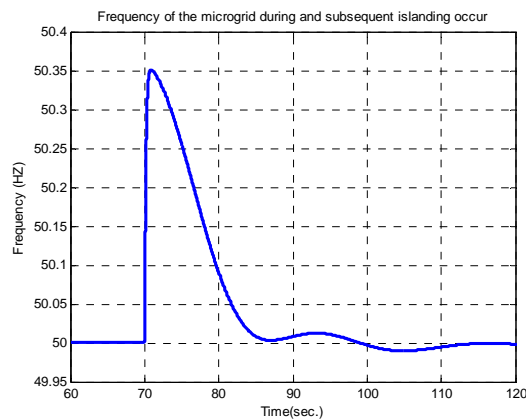


Figure 13. System frequency.

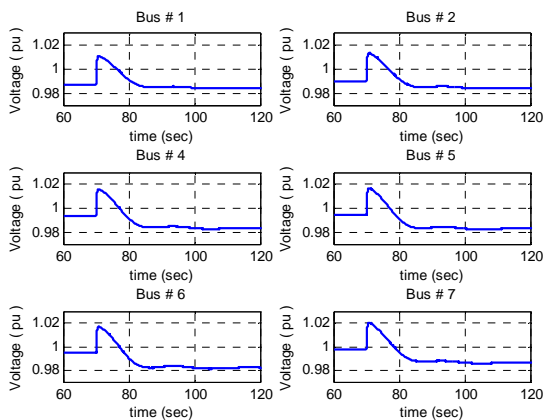


Figure 14. Voltages of all micro sources buses.

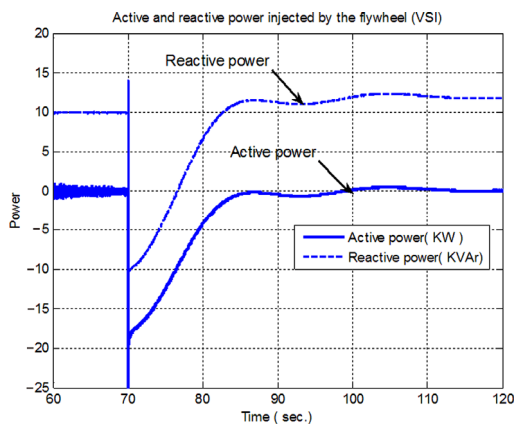


Figure 15. Flywheel (Vf) active and reactive powers.

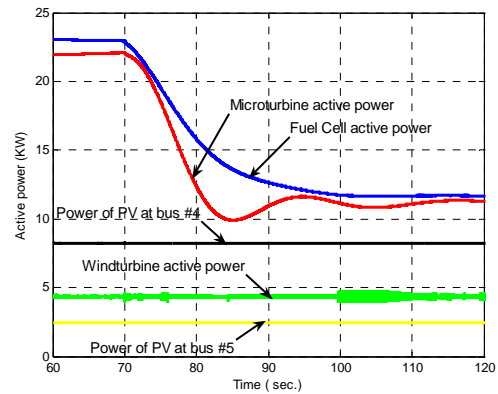


Figure 16. SOFC, SSMT, wind generator and photovoltaic panels active powers.

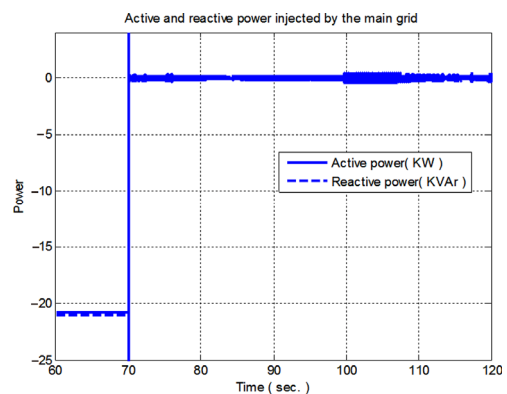


Figure 17. Active and reactive powers of the main grid.

is at its nominal value (50 Hz).

- Islanding occurs at  $t = 70$  sec., the MG loads are less than the power generated by micro sources which led the frequency increases to 50.35Hz. At this time, the voltages increases to about 102% of their nominal values as shown in Figures 13 and 14, respectively.
- The difference between load powers (active and reactive) and generated power (active and reactive) is absorbed by flywheel as shown in Figure 15.
- Due to frequency deviation, the PI controllers connected to SOFC and SSMT decrease the reference powers of those micro sources. The output powers of SOFC and SSMT begin to decrease and help frequency restoration as shown in Figure 16.
- By injecting a suitable amount of active and reactive power by the staorgae devices (flywheel), the frequency and voltages of the MG can be kept with the limited values.
- And when the power generated by the micro sources becomes equal to the power demand, the active power absorbed by flywheel returns to zero and the frequency returns to its nominal value. The MG needs about 40 seconds to restore to its steady state.
- In conclusions, by using a suitable control strategy

inside the MG, MG can keep its stability after islanding occurrence from the main grid under different load conditions.

## 6. Conclusions

This paper developed a complete model which can describe the dynamic behavior of the MG. All MG's components are modeled in detail. Two cases are studied: the first case investigates the dynamic performance of the MG during and subsequent to islanding when the MG imports active and reactive powers from the main grid. The second case shows the dynamic performance when the micro grid exports a large amount of active and reactive powers to the main grid. It was proved that the storage devices are absolutely essential to implement adequate control strategies for MG operation in islanded mode. The importance of storage devices due to the fact that the micro sources present in the MG have a very low inertia and slow ramp-up rates. A combination of droop control mode (applied to Vf inverter) together with an integral control loop (applied to controllable micro sources) are effective in controlling the frequency during islanded operation. It is found that appropriate control of Vf inverter coupled flywheel to the MG can keep the voltages and frequency within their acceptable limit values in the two studied cases. MG must contain at least one controllable micro source (fuel cell or micro turbine) to help frequency restoration when islanding occurs. If there are no controllable micro sources in the MG, the storage devices will still inject power in the MG until their energy are consumed and black out is occurred. Author's next step research aims to study the dynamic performance of the MG under different disturbances conditions such as failures of one micro source, load following, unbalanced loads, faults occur in MG feeders and so on.

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**Appendix**

Line Impedance				Loads		
Send Bus	Receive Bus	R (p.u)	X (p.u)	Bus	P (kW)	Q kVar
0	1	0.0025	0.01	2	10	2.5
1	2	0.0001	0.0001	4	19	11.7
2	3	0.0125	0.00375	5	10	2.7
3	4	0.0125	0.00375	6	19	11.7
4	5	0.0125	0.00375	7	6	2.7
5	6	0.0125	0.00375	Total	70	33.8
3	7	0.0218	0.00437			

The units of the lines impedances have been calculated in power base of 100 kVA and voltage base 400V. Bus 0 represents the main grid.