ISESCO Science and Technology Vision
Volume 5 - Number 8 - November 2009 (46-55)

# Improvement of Transient Dynamic Response of Micro-Grid Subsequent Islanding and Failure of Micro Sources by Connected Two Nearby Micro-Grids

Rashad. M. Kamel, Aymen Chaouachi and Ken Nagasaka
Environmental Energy Engineering, Department of Electronics & Information Engineering,
Tokyo University of Agriculture and Technology
2-24-16, Nakamachi, Koganei-shi, Tokyo, Japan
Phone and fax: +81-42-388-7481
r_m_kamel@yahoo.com;
a.chaouachi@gmail.com;
bahman@cc.tuat.ac.jp

## Abstract

*With Solving global warming problems by reducing $CO_2$ emissions in electricity generation field has led to increase interesting in Micro-Grid (MG) especially one which included renewable sources. MG normally operates in the normal interconnected mode and connects with the main grid. If a large disturbance happens in main grid, MG transfers to islanding mode. This paper deals with connecting two nearby Micro-Grids (MGs) for enhancement transient dynamic response of the two MGs subsequent two large disturbance occurrence (Two MGs island from main grid followed by failure of a dominant micro source in the first MG). Three cases are investigated. First case investigated the dynamic response of the two MGs (subsequent the two disturbances) when there is no tie line connection between them. Second case, studied dynamic performance of the two MGs when there is a private line connects the two MGs during emergency conditions, while the third case is close to the second case in addition to automatic generation control (AGC) applied upon each MG to return frequency to its nominal value and control tie line power to be with its scheduled value. Results proofed that when two nearby MGs are connected by private line and facing huge and multiple disturbances, dynamic response of the two MGs improved well. When there is no connection, one of the two MGs turns to blackout after second disturbance occurrence. In the three studied cases, frequency and voltages deviations of the two MGs are very small when the two MGs interconnected with each other if compared with the first case (no interconnection between the two MGs). Tie line connection between two MGs enables them to withstand against multiple and huge disturbances and keep their stability. All components inside the two MGs (Wind generation systems, fuel cells, photovoltaic panels, micro turbines, inverters, controllers, …etc.) are dynamically modeled in detail. All models and controllers are built in Matlab® Simulink® environment.*

***Keywords:*** *Micro-Grid, dynamic response, islanding, micro source failure, tie line, nearby MGs and automatic generation control.*

## 1. Introduction

Economic, technology and environmental incentives are changing the face of electricity generation and transmission. The need of reducing $CO_2$ emissions in the electricity generation field, recent technological developments in micro generation domain in addition to electricity business restructing are the main factors responsible for the growing interest in the use of micro generations [1-2]. Energy investors and utility operators are attracted to the MG role and associated industry for the following foreseen opportunities [3]:

- Distributed generators (DGs) installed inside MG can be fueled by locally available renewable and alternative mix of fuel sources. Greater independency from importing petroleum fuel can be achieved by incorporating MG that is powered by various fuel sources.
- MG can support future increase in demand without investment in the expansion of existing distribution network by installing the MGs very close to the new load centers.
- MG can be used in reducing intermittent and peak supply burdens on utilities grid by injecting power during peak periods.

- MG could contribute in decreasing vulnerability of the electric distribution system to external threats and hidden undetected faults that may cause wide scale blackout by feeding power to the sensitive infrastructure.

In fact, connection of small generation units (micro sources) with power rating less than a few tens of kilowatts- to low voltage (LV) networks potentially increases the reliability to final consumers and brings additional benefits for global system operation and planning, namely, regarding investment reduction for future grid reinforcement and expansion [4]. In this context, a MG can be defined as a low voltage network (e.g. a small urban area, a shopping center, or an industrial park) plus its loads and several small modular generation systems connected to it, providing both power and heat to local loads. MG is intended to operate in the following two different operating conditions:

- **Normal Interconnected Mode:** MG is connected to a main grid (distribution network), either being supplied by it or injecting some amount of power into the main system.
- **Islanding Mode:** MG operates autonomously, in a similar way to physical islands, when the disconnection from the upstream distribution network happens.

The development of MG can contribute to the reduction of emissions and the mitigation of climate changes; this is because available and currently developing technologies for distributed generation units are based on renewable sources and micro sources that are characterized by very low emissions [5]. The new micro sources technologies (e.g. micro gas turbines, fuel cells, photovoltaic panels and several kinds of wind turbines) used in MG are not suitable for supplying energy to MG directly. They have to be interfaced with the MG through an inverter. Thus, the use of power electronic interfaces in the MG leads to a series of challenges in the design and operation of the MG [6].

### *A. General Overview of MG Dynamic Response*

Reference [4] described and evaluates the feasibility of control strategy to be adopted for the operation of the MG when it becomes isolated. Reference [5] studied the MG during both connected and islanded modes of operations. Reference [7] investigated preplanned switching events and fault events that cause islanding of the MG. The feasibility of the MG islanding mode concept was laboratory tested in a prototype installed in National Technical University of Athens (NTUA) which compromises a photovoltaic (PV) panel, storage battery, loads and a controlled interconnection to LV grid [8]. In [9] and [10], the behavior of micro sources connected to distribution networks has been addressed.

All the previous mentioned references besides all other works available in the literature dealt with dynamic response of one MG only. The next few years will see integration of many MGs inside the same distribution network. At that time, if the nearby MGs are connected with each other by a private line (following fault or high disturbance occurrence in the distribution network), the transient dynamic response of all interconnected MGs will highly improved. This paper dealt with the investigation of transient dynamic response of two interconnected MGs after islanding from the distribution network occurs following by failure of a dominant micro source (fuel cell with high rating) installed inside the first MG. To deals with the proposed study, the following three issues are described.

1) Investigating transient dynamic response of two MGs subsequent islanding occurrence from the main grid and failure of a dominant micro source if the two MGs have no interconnection between each other (no private line connects the two MGs after disturbances occurrence).
2) Investigating transient dynamic response of the two MGs subsequent islanding occurrence from the main grid and failure of a dominant micro source when the two MGs are connected with each other through a private tie line after disturbances occurrence.
3) Third case is close to the second case in addition to automatic generation control (AGC) is applied upon each MG to return frequency to its nominal value and control tie line power to its scheduled value when the transient state finished.

The rest of the paper is organized as follow. Section II describes architecture of the two investigated MGs and conditions which cause the two MGs to transfer to the islanding mode. Section III presents a brief description of models of the micro sources which installed inside the two MGs. Section IV describes the three studied cases and the control scenarios proposed for improvement the dynamic performance of the two adjacent MGs. Results and discussion are presented by section V. Conclusions are summarized in section VI.

## 2. Architecture of the Two MGs Developed System

Architecture of the two MGs developed system is shown in ***Figure 1***. That system consists of two MGs, each MG connected to the main grid (distribution network) through a separate transformer ($T_1$ and $T_2$). The two MGs have the same structure but with different loading and micro sources rating. Each MG comprises low voltage network, loads, both controllable and non controllable micro sources and storage device (flywheel). Controllable micro sources are the micro sources which can control their output generated power like micro turbine and fuel cell, while the non controllable micro sources are the micro sources which their outputs depend on weather conditions like wind generation system and photovoltaic panels. As shown in ***Figure 1*** each MG consists of 7 buses. Flywheel (storage device) is connected to bus 1. Wind generation system is located at bus 2. Two photovoltaic panels with different rating are connected to buses 4 and 5. Single Shaft Micro Turbine (SSMT) is connected to bus 6. Bus 7 is provided with Solid Oxide Fuel Cell (SOFC). Rating of all micro sources and loads installed in the two MGs are shown in the figure. All micro sources in the two MGs are interfaced through inverters except the wind generation system directly coupled. As indicated in the figure, in steady state the two MGs are connected to the distribution network (main grid). If fault occurs in main grid as shown, the two MGs will be isolated from the main grid as soon as possible by $CB_1$ and $CB_2$, While $CB_3$ immediately connects the two MGs with each other. As we will see in the results, this proposed strategy has a large effect in enhancement the transient dynamic response of the two MGs subsequent emergency conditions.

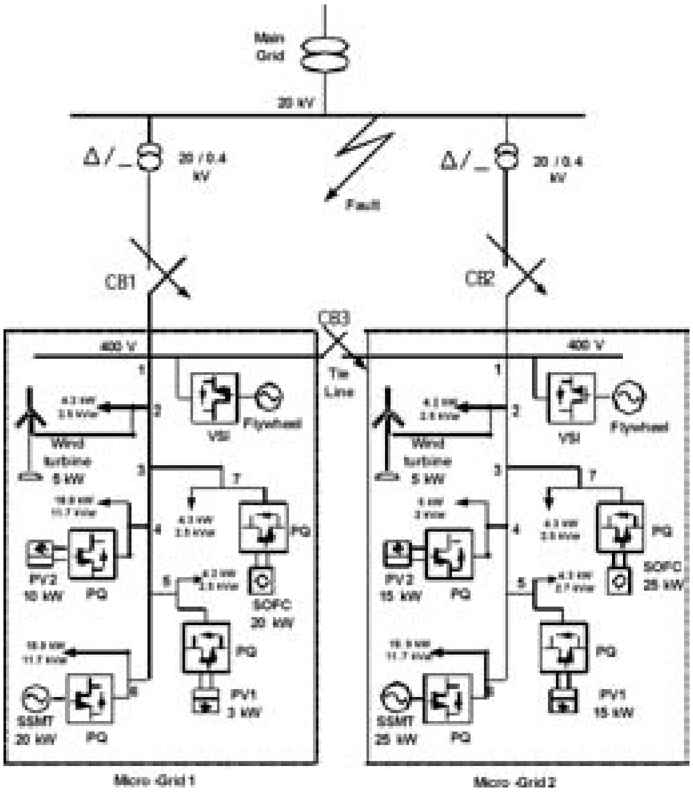

**Figure 1.** *Single line diagram of the two MGs developed system.*

## 3. Dynamic Modeling of MG's Components

All MGs's components are modeled in detail using *Matlab® Simulink®* environment. Detailed standalone models for inverter with different control strategies, Single Shaft Micro Turbine (SSMT), Solid Oxide Fuel Cell (SOFC), wind generation systems and photovoltaic panels models are developed in our previous work and can be found in references [11-12]. All models developed in references [11-12] are based on description and mathematical equations presented by references [13-15]. Here we briefly describe about inverters's control strategies used in this paper, wind generation systems and storage devices (flywheels) modeling beside the three investigated cases and control strategies which adopted to improve the performance of the two MGs after disturbances.

### A. Inverters Modeling

Inverters play a vital role in the system which interference of micro sources with MG. Two kinds of control strategies are developed in this study to control all inverters installed inside the two MGs.

1) ***PQ Inverter Control:*** This type of inverter is used to inject a certain active and reactive power set-value. PQ inverter type in this paper is used to interface SSMT, SOFC and the two photovoltaic panels. Basic structure of inverter's PQ controller is shown in ***Figure 2***. $P_{ref}$ in ***Figure 2*** represents active power produced by the micro source which interfaced to the MG by that inverter. $P_{ref}$ represents amount of reactive power injected to or absorbed from the MG at inverter's bus.
2) ***Voltage Source Inverter (VSI) Control:*** This inverter is controlled to feed load with predefined values of voltage and frequency. Depending on the load, the VSI active and reactive powers are defined. VSI in this paper is used to interface the storage device (flywheel) to the MG and represent the reference bus (slack bus) for each MG during islanding mode. VSI emulates behavior of synchronous machine, thus controlling voltage and frequency on the AC system. VSI acts as a voltage source, with the magnitude and frequency of the output voltage controlled through droops, as described in the following equation:

$$\begin{aligned} f &= f_o - k_p * P \\ V &= V_o - k_Q * Q \end{aligned} \qquad (1)$$

Where, $P$ and $Q$ are inverter active and reactive output powers, $k_P$ and $k_Q$ are the frequency and voltages droop slopes (positive quantities) respectively, and $f_o$ and $V_o$ are the idle values of the frequency and voltages (nominal frequency and nominal voltage). A three-phase model of a VSI implementing the droop concepts described by equation (1) was developed as shown in ***Figure 3***. In this model amount of active and reactive power injected to or absorbed from MG will control voltage and frequency of the MG (like synchronous generator).

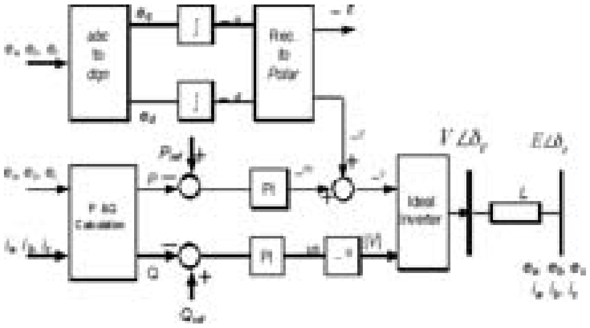

**Figure 2.** *Basic structure of the PQ inverter control scheme.*

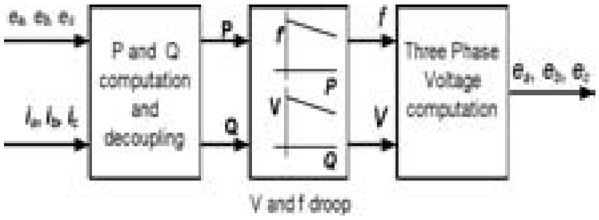

***Figure 3.*** *Voltage source inverter (VSI) control model.*

### *B. Storage Devices Modeling*

Due to large time constants of responses of some micro sources, such as fuel cell and micro turbine, storage device must be able to provide the amount of power required to balance MG following disturbances and/or significant load changes. Storage devices, such as flywheel and batteries, are modeled as constant DC voltage source using power electronic interfaces to be coupled with the electrical network. Storage device used in this paper is a flywheel and is connected to the VSI. Active and reactive power needed to balance generation and consumption inside the MG which injected to or absorbed from MG are proportional to frequency and voltage deviation (frequency and voltage droops) described by equation (1).

### *C. Wind Generation System Model*

Generators used in this paper are squirrel-cage induction generators that directly connected to the MG. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine are combined with those of the generator coupled to the turbine. Output power of the turbine can be calculated by the following equation [16]:

$$P_m = C_P(\lambda,\beta)\frac{\rho A}{2}v_{wind}^3 \qquad (2)$$

Where:

$P_m$: Mechanical output power of the turbine (Watt), $C_P$: Performance coefficient of the turbine, $\rho$: Air density (kg/m$^3$), $v_{\text{wind}}$: Wind speed (m/s), $\lambda$: Tip speed ratio of the rotor blade tip speed to wind speed, $\beta$: Blade pitch angle (deg.) and A : Turbine swept area (m$^2$).

A generic equation which used to model $C_P$ ($\lambda$, $\beta$) is:

$$c_P(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \qquad (3)$$

with: $$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

The coefficients $C_1$ to $C_6$ are found in reference [16]. The wind turbine characteristics used in this study is shown in ***Figure 4*** for different values of $\beta$.

For induction generator, the 4th order $d_q$ model, expressed in the arbitrary reference frame and rotating with an angular velocity $\omega$ is used and described in the following equations [17]:

$$u_{sd} = -r_s.i_{sd} - \omega.\psi_{sq} + p\psi_{sd} \qquad (5)$$

$$u_{sq} = -r_s.i_{sq} + \omega.\psi_{sd} + p\psi_{sq} \qquad (6)$$

$$u_{rd} = 0 = r_r.i_{rd} - (\omega - \omega_r).\psi_{rq} + p\psi_{rd} \qquad (7)$$

$$u_{rq} = 0 = r_r.i_{rq} + (\omega - \omega_r).\psi_{rd} + p\psi_{rq} \qquad (8)$$

Where, $p = \frac{1}{\omega_0}\frac{d}{dt}$, and $\omega_o$ is the base angular electrical frequency.

The electromagnetic torque is given by:

$$T_e = \psi_{qr}.i_{dr} - \psi_{dr}.i_{qr} \qquad (9)$$

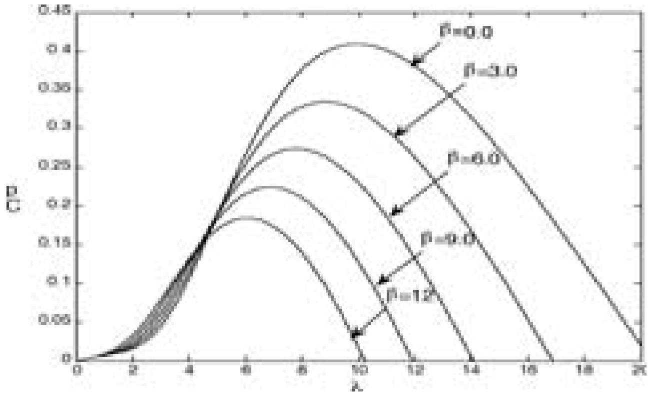

***Figure 4.*** *$C_P$- λ curves of the wind turbine for different pitch angles.*

## 4. Control Strategies of the Two MGs Subsequent Islanding From the Main Grid and Failure of Micro Source

In presence of unplanned events like severe faults in the main grid indicated in ***Figure 1***, MG separation from the main grid must occurs as fast as possible. If there are no synchronous machines to balance the demand and supply (as our case), inverters must be responsible for frequency and voltage control during islanding operation. During connected mode (connected with main grid), all inverters can be operated in *PQ* mode, in which voltage and frequency references (main grid) are available. In this case, a sudden disconnection from the main grid would lead to the loss of the MG, because load/generation balancing and therefore frequency and voltage control is not possible. However, by using a VSI connected to the flywheel to provide a reference for voltage and frequency as explained in equation (1), it is possible to operate the MGs in islanding mode.

In three cases which will described in the following subsections (A, B and C), the two MGs are facing two high disturbances. The first disturbance is fault occurrence in the main grid forces the two MGs to transfer to islanding mode, while the second disturbance is failure of dominant micro source with high rating (SOFC) installed in the first MG.

### A. Two MGs Separated From Each Other Subsequent Disturbances Occurrence

In this case there is no interconnection between the two MGs when islanding from main grid happens. During this situation, the voltage source inverter (VSI) connected to the flywheel is responsible for frequency and voltage control in each MG as described by equation (1) and shown in ***Figure 5***. However, those devices (flywheels) with high capabilities for injecting power during small time intervals have a finite storage capacity. Therefore, correcting permanent frequency deviations during any islanded operation conditions should then be considered as one of the key objectives for any control strategy. In order to promote adequate secondary control aiming to restore frequency to nominal value after disturbances, local frequency control by using a PI controller at each controllable micro source (SSMT and SOFC) is used to control active power outputs of the primary energy sources based on the frequency deviation error as shown in ***Figure 5***. As indicated in ***Figure 5***, flywheel with its VSI acts as primary frequency control (acts as inertia of synchronous machine installed in conventional power plant) and the controllable micro sources (SSMT and SOFC) acts to balance the load and generation inside each MG. In addition, the VSI connected to the flywheel controls voltage of the MG (by controlling reactive power injected to or absorbed from MG) and acts like automatic voltage control in conventional power plant as indicated in ***Figure 5***. When fuel cell installed in $MG_1$ fails, $MG_1$ loses active and reactive power supplied by that micro source. Also, VSI connected to flywheel in $MG_1$ must compensate shortage of the active and reactive power and secondary frequency control acts upon SSMT (only controllable micro source in $MG_1$ after failure of SOFC) installed in $MG_1$ to return frequency to its nominal value. $MG_2$ not feel with this disturbance (failure of SOFC in $MG_1$) because there is no connection between the two MGs in this case.

### B. Two MGs Connected With Each Other by a Private Tie Line Subsequent Disturbances Occurrence

For this case, there is a private tie line connects the two MGs immediately subsequent islanding from main grid. The value of power flowing through the tie line depends on the difference between the two MGs's frequencies ($\Delta f_1$-$\Delta f_2$) as shown in ***Figure 6***. Also, as discussed in case A, Flywheel with its VSI will control voltage and frequency (primary frequency control beside voltage control) and controllable micro sources (SSMT and SOFC) acts as secondary frequency control as indicated by ***Figure 6***. In this paper, at the instant of islanding from main grid, $MG_1$ has heavy loads and little generation, so that $MG_1$ was imported certain amount of power (about 15 kW) from the main grid before transfer to islanding mode, while $MG_2$ has lightly loads and high generation which force $MG_2$ to export some power to the main grid (9 kW) before islanding occurrence. During second disturbance (failure of SOFC in $MG_1$), VSI connected to flywheel in $MG_2$ will support some power (active and reactive) to compensate power shortage in $MG_1$. Also, secondary frequency control will acts upon SSMT of $MG_1$ in addition to SSMT and SOFC of $MG_2$ to balance loads and generations inside the two MGs.

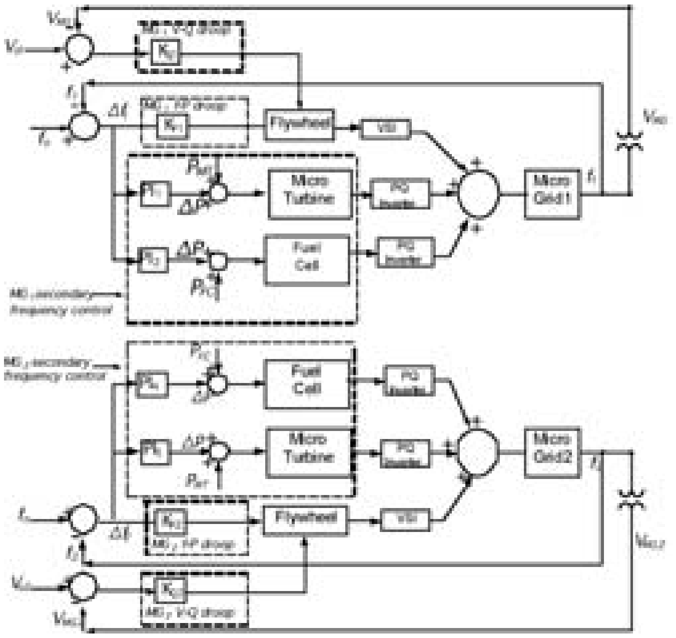

***Figure 5.*** *Control scheme of the two MGs (Two MGs are separated).*

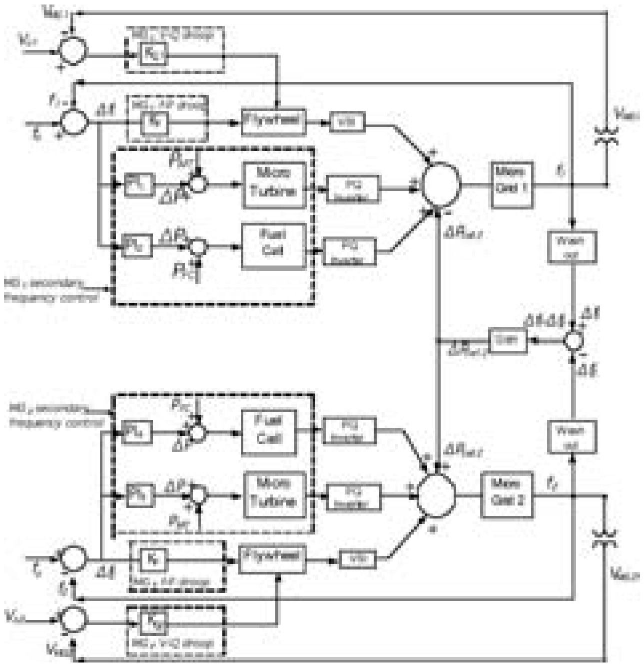

***Figure 6.*** *Control scheme of two interconnected MGs without AGC.*

### C. Two MGs Connected to Each Other By A private Tie line following Disturbances and Automatic Generation Control Applied upon Each MG

This case is close to the second case in addition to frequency bias tie line control (discussed later) is applied inside each MG as shown in ***Figure 7***. Frequency bias tie line controller will acts on the reference power of the controllable micro sources inside each MG (SSMT and SOFC) to correct the frequency deviation (return the frequency to its nominal value) and also control tie line power to its scheduled value. In this study, the scheduled value of tie line power is zero. This means that the two MGs exchanges powers (active and reactive) during transient state only. After transient period finished, each MG will feed its loads and the tie line power (active and reactive) returns to its value before disturbance occurrence.

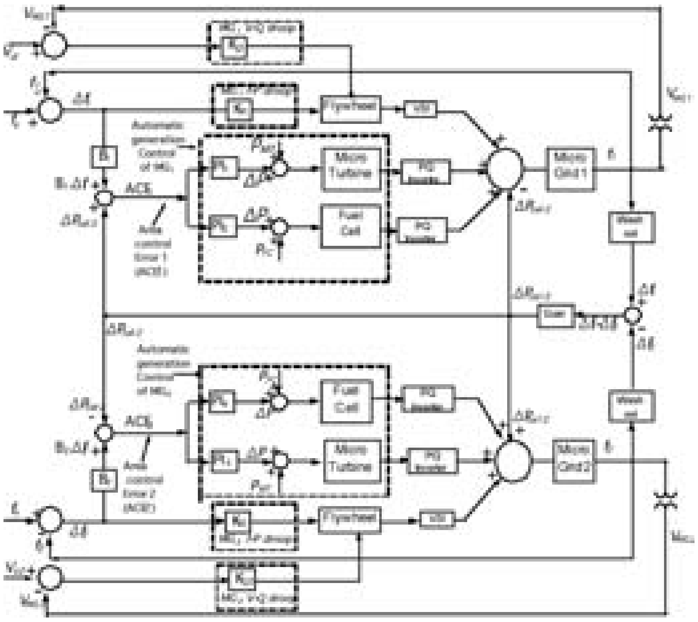

***Figure 7.*** *Control scheme of two interconnected MGs with AGC.*

### *Frequency Bias Tie Line Control*

The basic objectives of frequency bias tie line control are to restore balance between each MG's loads and generations. This is met when the control action maintains:

- Frequency at the nominal value.
- Net interchange power with neighbouring Micro-grids at scheduled value.

The supplementary control (frequency bias tie line control) in a given MG should ideally correct only for changes in that MG. In other words, if there is a change in $MG_1$'s load, there should be supplementary control action only in $MG_1$ and not in $MG_2$ (after the transient state passed). To execute that supplementary control inside each MG, a control signal consisted of tie line flow deviations ($\Delta Ptie_{12}$) added to frequency deviation weighted by a bias factor would accomplish the desired objectives. This control signal is known as Area Control Error (ACE) in bulk conventional power system [18]. The same technique is used in our study for controlling the tie line power exchanges between the two MGs.

Based on above discussions, Area Control Error of $MG_1$ ($ACE_1$) is given by the following equations:

$$ACE_1 = \Delta P_{Tie12} + B_1 \Delta f_1 \qquad (10)$$

$B_1$ is the bias factor for $MG_1$, and given by the following equation:

$$B_1 = K_{P1} + D_1 \qquad (11)$$

Where, $K_{P1}$ is frequency droop gain of $MG_1$ given in equation (1) used for controlling flywheel installed in that MG. $D_1$ represents percentage of load change inside $MG_1$ due to frequency deviation from its nominal value.

Similarly for $MG_2$, Area Control Error ($ACE_2$) is given by:

$$ACE_2 = \Delta P_{Tie21} + B_2 \Delta f_2 = \Delta P_{Tie12} + B_2 \Delta f_2 \qquad (12)$$

$B_2$ is the bias factor for $MG_2$, and is given by the following equation:

$$B_2 = K_{P2} + D_2 \qquad (13)$$

Where, $K_{P2}$ is the frequency droop constant of $MG_2$ used for controlling flywheel installed in that MG. and $D_2$ represents percentage of load variation in $MG_2$ due to frequency deviation from the nominal value subsequent disturbance.

ACE for each MG represents the required change in MG generation. The block diagram in ***Figure 7*** illustrates how Automatic Generation Control (AGC) implemented inside each MG using ACE signal which applied to the reference power of the controllable micro sources installed inside each MG (SOFC and SSMT).

## 5. Results and Discussions

Disconnection from the upstream main grid followed by failure of SOFC which installed in $MG_1$ was simulated in order to understand the dynamic behavior of each MG in the three studied cases. As we discussed before, SSMT and SOFC are the controllable micro sources used for secondary frequency control in the first two studied cases as shown in ***Figures 5*** and ***6***, and used for AGC in third case as shown in ***Figure 7***. In all three studied cases, wind speed and solar irradiance are assumed varying continuously. Wind speed and solar irradiance data are available in reference [4]. Simulation results are presented for the main quantities (Frequency, voltage, power, tie line power, …..etc).

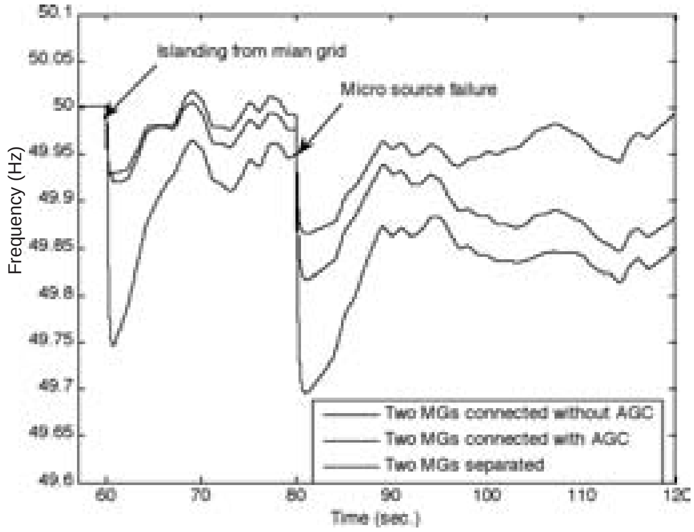

***Figure 8.*** *Frequency of MG$_1$ before and during disturbances for the three studied cases.*

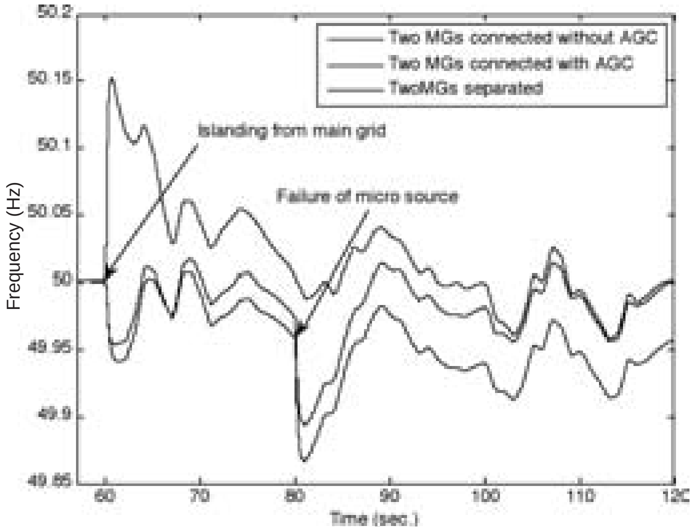

***Figure 9.*** *Frequency of MG$_2$ before and during disturbances for the three studied cases.*

Frequency (Hz)

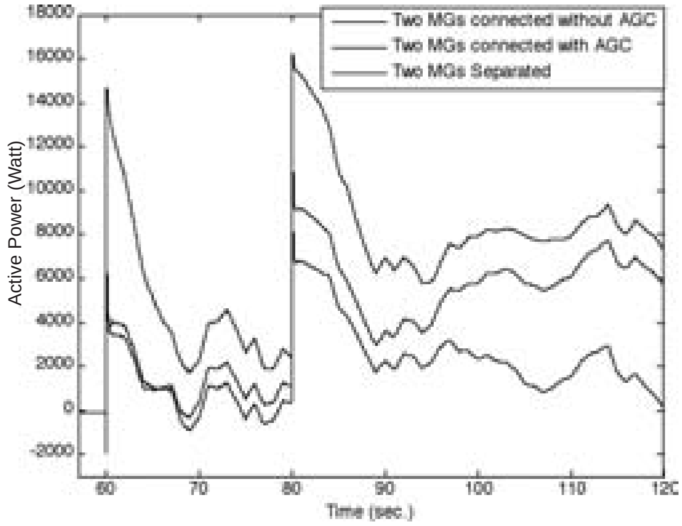

***Figure 10.*** *Active power injected by VSI connected to flywheel installed in MG$_1$.*

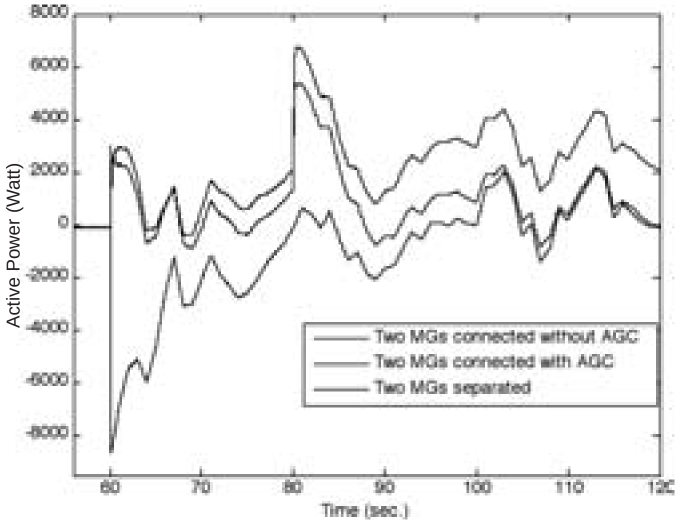

***Figure 11.*** *Active power injected by VSI connected to flywheel installed in MG$_2$.*

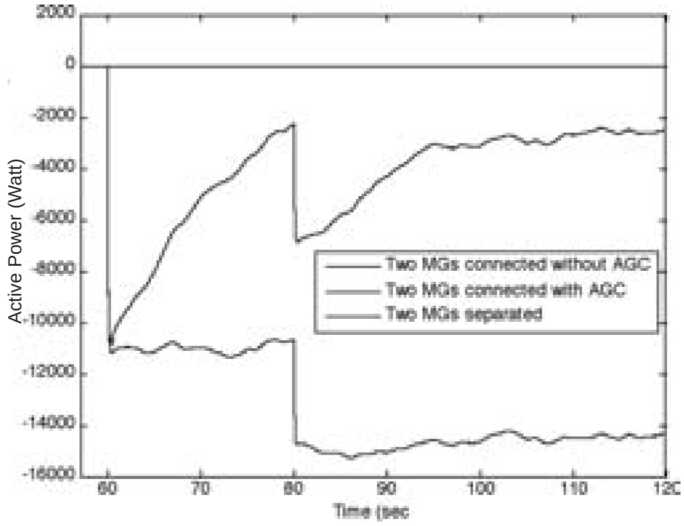

***Figure 12.*** *Tie Line active power exchanges between the two MGs ($\Delta Ptie_{12}$).*

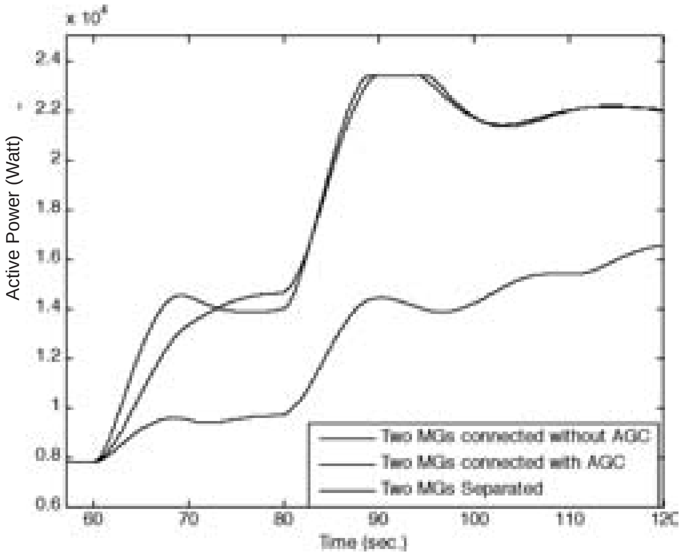

***Figure 13.*** *Active power generated by SSMT installed in MG$_1$.*

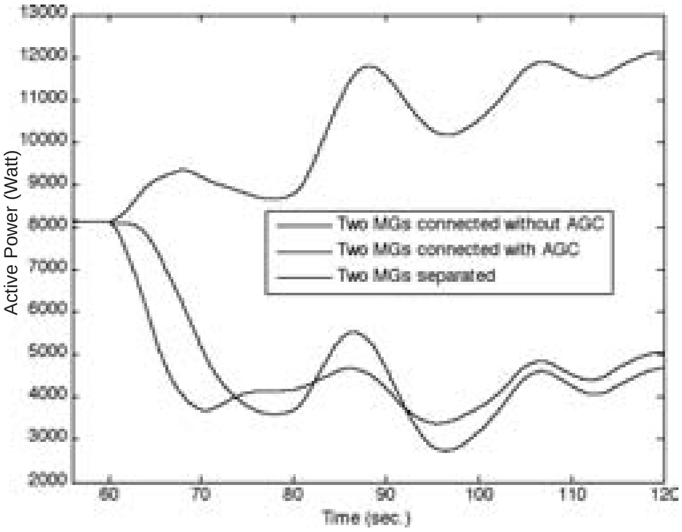

***Figure 14.*** *Active power generated by SSMT installed in $MG_2$.*

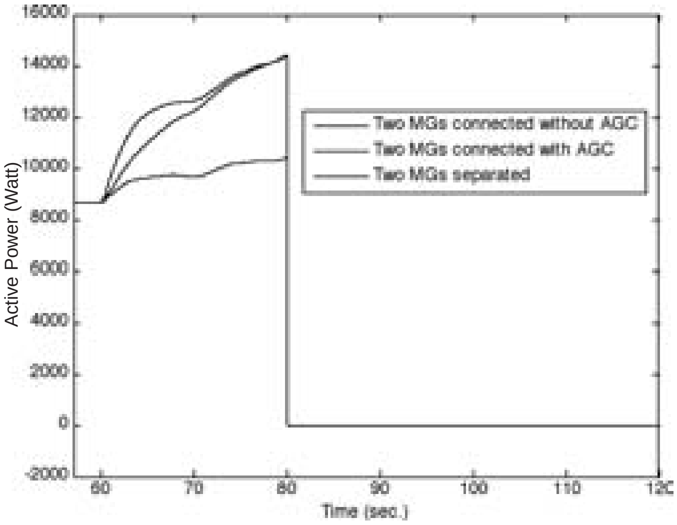

***Figure 15.*** *Active power generated by SOFC installed in $MG_1$.*

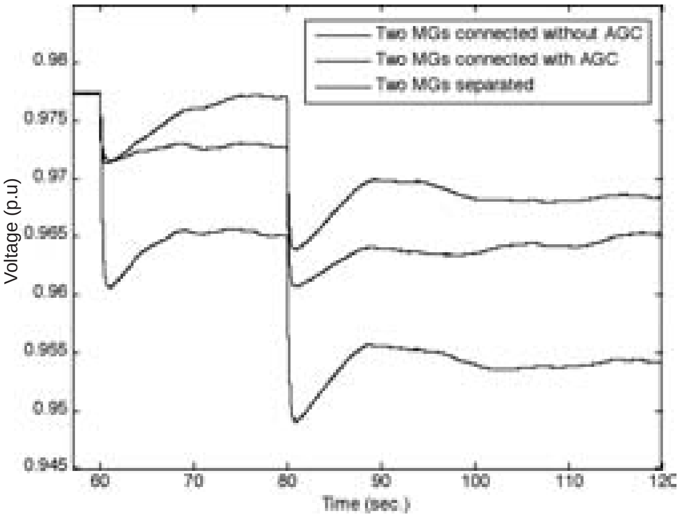

***Figure 16.*** *Voltage at bus # 6 of $MG_1$.*

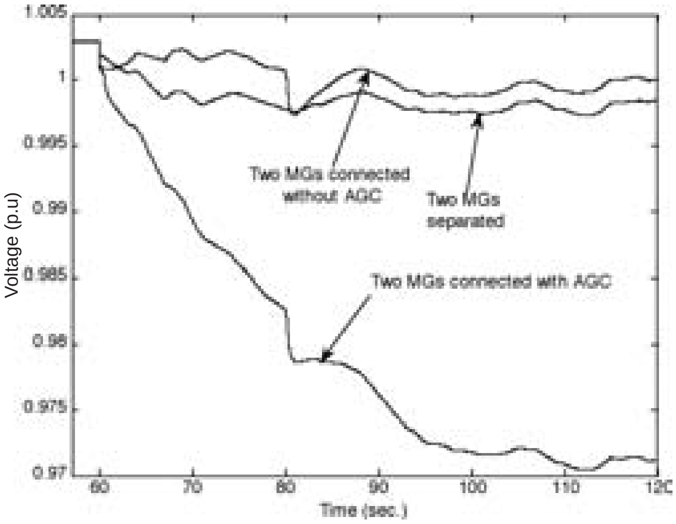

***Figure 17.*** *Voltage at bus #6 of $MG_2$.*

From ***Figures (8-17)***, the following points can be summarized:

### *For the First Case (Two MGs Separated)*

- Before islanding occurs, the two MGs are in their steady state. The frequency of the two MGs is at the nominal value (50Hz). Any load change inside each MG can be compensated by the main grid and no need for secondary frequency control applied to the controllable micro sources inside each MG (i.e secondary frequency control not activated when the two MGs connected to main grid).
- When islanding happened at t=60 sec., the two MGs islanded from main grid. For this case (no interconnection between the two MGs), each MG performs alone as electrical island. VSI connected to the flywheel in each MG acts as synchronous generator to control the voltage and frequency of inside each MG.
- Frequency deviation in each MGs acts on reference power set points of controllable micro sources and try to balance generations and loads inside each MG. Due to power deficit in $MG_1$, frequency dropped to about 49.75 Hz as shown in ***Figure 8***, while due to power surplus in $MG_2$, frequency jump to about 50.15Hz as shown in ***Figure 9***. Frequency deviation acts to increase the power of SSMT and SOFC of $MG_1$, while it acts to decrease the power of SSMT and SOFC of $MG_2$ as shown in ***Figure 13*** and ***Figure 14***, respectively.
- In order the two MGs can keep their stability subsequent islanding occurrence from the main grid, the flywheel of MG1 must inject about 15 kW and the flywheel of MG2 must absorb about 9 kW as shown in ***Figure 10*** and ***Figure 11***, respectively.
- Fluctuation of powers generated by the renewable source (wind turbine and photovoltaic panels) due to change of

wind speed and solar irradiance cause fluctuations in the frequency of the two MGs (***Figures 8*** and ***8***) and the VSI connected to the flywheel must compensate those fluctuations (***Figures 10*** and ***11***) until the controllable micro sources can balance the load and generation inside each MG.

- The voltage of MG1 buses shows high drop (***Figure 16***) due to deficit of power (active and reactive), while voltage of $MG_2$ buses shows very small drop (***Figure 17***) due to lost some reactive power which was supplied by the main grid before islanding occurrence.
- After 20 sec. from islanding occurrence, the two MGs nearly back to their steady state. At this moment, SOFC installed inside $MG_1$ failed and became out of service. $MG_1$ facing a very huge emergency state due to lost high amount of power (active and reactive) and its frequency and voltages dropped to 49.69 Hz and 0.95 p.u as shown in ***Figures 8*** and ***16*** respectively. VSI connected to flywheel of MG1 must inject about 16 kW to balance load and generation in $MG_1$. Frequency deviation acts on SSMT of $MG_1$ (the only controllable micro source still exist in $MG_1$) and try to balance load and generation. Unfortunely, at t=90 sec. SSMT installed in $MG_1$ reached its rated and became overrated (120 % of its rated value) and not able to inject any power more. However, frequency of $MG_1$ still has some deviation from the rated values (49.85 Hz), flywheel continues injecting power until its storage energy consumed, at this instant $MG_1$ forces to go to black out unless load shedding strategy is used.
- Failure of SOFC installed in $MG_1$ has no effect in $MG_2$ response because there is no connection between the two MGs at this case.

### *For the Second Studied Case (Two MGs connected with each other without AGC)*

- For this case, the two MGs have the same conditions of the first case, but the two MGs connected with each other subsequent islanding occurrence from the main grid. In this case due to existence of the tie line between the two MGs, power surplus in $MG_2$ will support power deficit in $MG_1$ and the frequency deviation of the two MGs shows small deviation compared with the first case. As shown in ***Figure 8***, frequency $f_1$ dropped only to about 49.93 Hz compared with 49.75 Hz in the first case, while the frequency $f_2$ dropped to about 49.93 Hz compared with 50.15 Hz in the first case as shown in ***Figure 9***.
- Amount of active power required to be injected by flywheel of $MG_1$ about 4 kW compared with 15 kW in the first case (***Figure 10***), while the active power required from flywheel of $MG_2$ about 3 kW compared with -9 kW in the first case (***Figure 11***). This means that when the two MGs connected with each other following islanding occurrence, rating of the required storage devices (flywheels) and accompanied inverters (VSI) is small compared with separated MGs.
- Voltage of $MG_1$ has fewer drops (0.97 p.u) in the second case compared with the first case (0.955 p.u) due to power (active and reactive) flows from $MG_1$ through the tie line.
- At t=80 sec., failure of SOFC installed in $MG_1$ has small effect in the dynamic responses of the two MGs compared with the first case. This is because, power shortage due to fail of SOFC will be compensated by the two flywheels of the two MGs, SSMT of $MG_1$ and SOFC and SSMT of $MG_2$. No one of those micro sources reached its rated, and the two MGs can restore their steady state. Tie line connects the two MGs keep two MGs away from black out subsequent two huge disturbances occur.
- As shown in ***Figures 8-17***, dynamic response of the two MGs can be highly improved if the nearby MGs installed in the same distribution network are connected with each other by a private line subsequent disturbances occurrence (islanding from main grid, failure of any micro source, micro sources reaching the rated values,…etc.). Also, this interconnection between the adjacent MGs will be very important if one dominant micro source fails inside any MGs. For instance, if VSI accompanied with flywheel fails in any MG (after islanding from main grid), that MG will transfer to blackout unless the interconnection between the MGs exist. Also, this interconnection between the nearby MGs may be very important if the controllable micro sources inside any MG reached their nominal power and can not produced any additional power. During those conditions, interconnection between adjacent MGs is necessary to keep the stability of the heavy loaded MG and keeps it far from blackout.

### *For third case (Two MGs connected with each other with AGC)*

- This case has performance almost close to the performance of the second case, however, AGC inside each MG acts on controllable micro sources to return the tie line power to its scheduled value (zero in our case) besides returns frequency to its nominal value as shown in ***Figures 8***, ***9***, and ***12***.
- After second disturbance (failure of SOFC of $MG_1$), if AGC applied, this will lead to black out in $MG_1$, because SSMT of $MG_1$ reached its rated power ( at t=90 sec) and the frequency $f_1$ is still lower than its nominal value.
- Applying AGC inside each MG requires high rating of the controllable micro sources (***Figure 13***) to enable the MGs feed their loads locally and reduced the tie line power to zero as shown in ***Figure 12***.
- For this case, voltage of $MG_2$ is less than the two previous cases (***Figure 17***). This is because, when AGC applied

in $MG_2$, this MG must reduce its power (active and reactive) to restore the tie line power to zero value. Reducing power generation inside $MG_2$ leads to some drop in its voltages.

- AGC is not used to enhance the dynamic responses of the two interconnected MGs, but it is necessary when contract between the owners of the two MGs states that the two MGs only support each other during transient state. After the transient state passed, each MG must feed its loads. In this case, tie line improved reliability and security of the two MGs. Also, reducing the tie line power to zero after the transient state finished, will reduce the losses inside the two MGs. This is because each MG feeds its loads locally and no power circulating from one MG to the other.

## Conclusions

This paper dealt with improvement dynamic response of two nearby MGs when the two MGs connected through a private line subsequent islanding from the main grid occurs and failure of a dominant micro source in the first MG. It is noted from the results that the dynamic performance will gain a highly improvement by connected the two nearby MGs. Frequency deviations is highly reduced. It is noted from the results that instead of the frequency of $MG_1$ drops to 49.75 Hz without interconnection between the two MGs, it will only drop to 49.93Hz. For $MG_2$, frequency dropped to about 49.93 Hz instead of jumping to 50.15 Hz. Also, amount of active power required to be injected by each flywheel highly reduced. After the second disturbance, $MG_1$ forced to blackout if there is no interconnection between the two MGs. AGC is applied to return the frequency of the two MGs to its nominal value and control the tie line power to its scheduled value according to the contract signed between the owners of the two MGs. Tie line connected the two MGs will be necessary in some emergency situations like failure of a dominant micro source inside any MG or reaching rated power of controllable micro sources inside one of the MGs. Such conditions will force one of the MGs to blackout if tie line absent. Finally we can conclude that connecting two nearby MGs with a private tie line when transfer to islanding mode from main grid or facing a large disturbance is very effective method to increase the reliability and security of both MGs. Of course more improvement can be achieved if more nearby MGs connected with each others (three, four …etc). Connecting more than one MG in islanding mode produces more strong MGs system when the MGs isolated from main grid due to large disturbance (fault) occurs in the main grid.

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