On Stability of Islanded Low-Inertia Microgrids

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***Abstract*—As the number of distributed energy sources (DERs) increases in a microgrid (MG), the likelihood of frequency and voltage instabilities increases. In particular, the control of frequency and voltage becomes a challenge in an islanded mode due to the inherent low-inertia feature of DERs compared to a grid-tied mode where there is a grid support. This instability problem becomes worse for low or medium voltage low-inertia MGs, where the line impedance is dominantly resistive. The goal of this paper is to demonstrate the stability and power quality problems that can occur in islanded medium voltage MGs. PSCAD/EMTDC simulation results for an MG with a high share of low-inertia power generation units illustrate the importance of the frequency and voltage stability as power utilities adopting more DERs.**

***Index Terms*—droop control, microgrids, power quality, power systems, smart grids.**

I. Introduction

The reliable operation of MGs on modern power systems have become a major concern as more renewable energy sources such as wind turbines and photovoltaic (PV) arrays are employed as power generation units. Integration of these power generation units has brought several challenges regarding stability, protection, and power quality issues in modern power systems. As the number of distributed energy sources (DERs) increases, supervisory control schemes are required to provide an allocating share of energy between DER units. Also, MGs can run in two different modes of operation, namely grid-tied and islanded modes that require different control strategies. An MG similar to a distributed energy source can operate either tied to the grid or isolated from the grid, and the transition between these modes of operation must be performed with slight or no distraction to the loads [1]. Isolation from the main grid is required due to scheduled or unscheduled events. Scheduled events are because of grid maintenance, and unscheduled events can be due to critical events such as faults, voltage collapses, blackouts, and voltage fluctuations. Moreover, an MG should have the ability to reconnect to the main grid seamlessly once the grid stability is restored. Typically, the main grid provides the frequency and voltage reference signals during a grid-tied mode, where DERs are in an active-reactive power control mode. In the islanded mode, however, there will be no main grid to regulate the frequency and voltage of the system, thus, the MG control system should itself regulate these quantities. In this situation, new concerns due to the *low-inertia* of DERs arise. Since the inertia of the DERs is not comparable to the inertia of synchronous generators, a change in the balance between the power supply and demand can result in frequency and voltage fluctuations [2], [3].

The organization of this paper is as follows. In Section II, MG control challenges are briefly discussed. MG stability and power quality issues are addressed in Section III. Representative simulation results are illustrated in Section IV to demonstrate the stability problems due to the low-inertia of DER units.

II. Microgrid Control Schemes

An MG can be identified as DERs, energy storage systems (ESSs), power lines and loads. A DER can be a renewable source such as wind turbine and photovoltaic array; and a non-renewable source such as fuel cell and diesel generator. Also, an ESS can be a flywheel and/or a battery system. MGs can be operated in any of the three different modes of operation as (*i*) grid-tied, (*ii*) islanded, and (*iii*) isolated. An MG may need to transfer from grid-tied mode to islanded mode due to some scheduled events such as grid maintenance or unscheduled events such as faults or some other main grid power failures.

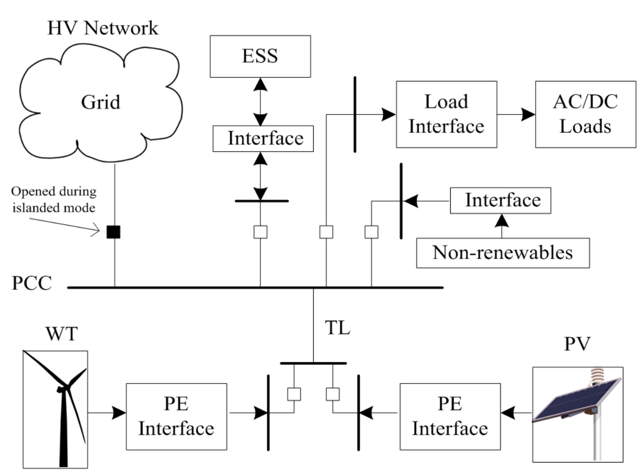

Fig. 1. MG network

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Seamless transfer during critical situations is an important aspect of the control scheme of MGs to prevent voltage and frequency instabilities. Fig.1 illustrates an MG connected to the main grid network at the point of common coupling (PCC) bus. Most DER technologies in MGs are not suitable for direct connection to the electrical network due to the characteristics of the energy produced. Thus, DERs in an MG are connected to the power grid by power electronic (PE) interfaces, i.e. inverters, as shown in Fig.1.

MGs bring several benefits to the power systems; however there are some control and energy management concerns that need to be addressed as the number of DERs increases. For example, a need for communication between DERs becomes essential. An effective communication solution would provide handling power balance in an optimal manner. The MG can be centralized or decentralized regarding communication aspects [4]. In the centralized mode, a vast amount of communication between all of DER units is required. The data monitored is concentrated at a single location and the control signals are accordingly generated and the command signals are sent back to DER units. In the decentralized mode, however, every DER has their control, and there is no need to communicate between DER units. Both of the schemes have their cons and pros, however, none of them are completely feasible at the technical perspective since the first approach needs a high bandwidth for data communication, whereas the latter has the problem of overlapping zones.

In comparison with synchronous generator based power plants, inverter-based DER units have zero or very low inertia and their output frequency is internally set by a reference signal [5], [6] therefore the frequency does not inherently vary with the active power. However, for a grid-tied DER unit, droop controllers for steady-state and small-signal stability concerns are implemented as $\Delta f = -R_p \, \Delta P$ and $\Delta V = -R_Q \, \Delta Q,$ where ΔP and ΔQ are the deviations of active and reactive power, and Δf and ΔV are the deviations of frequency and voltage. It should be noted that the droop controllers can be implemented for the power grids with inductive impedance, i.e. $2\pi f L \gg R$, and a large amount of inertia. In distributed systems, low and medium voltage grids, where $2\pi f L \cong R$, e.g. a city with high share of rooftop PV units, the voltage and active power are related, i.e. $\Delta V = -k \, \Delta P$ [7].

III. MICROGRID CHALLENGES

The presence of PE interfaces arises a new type of power system as compared to the traditional systems with synchronous generators. In this sense, the planning and

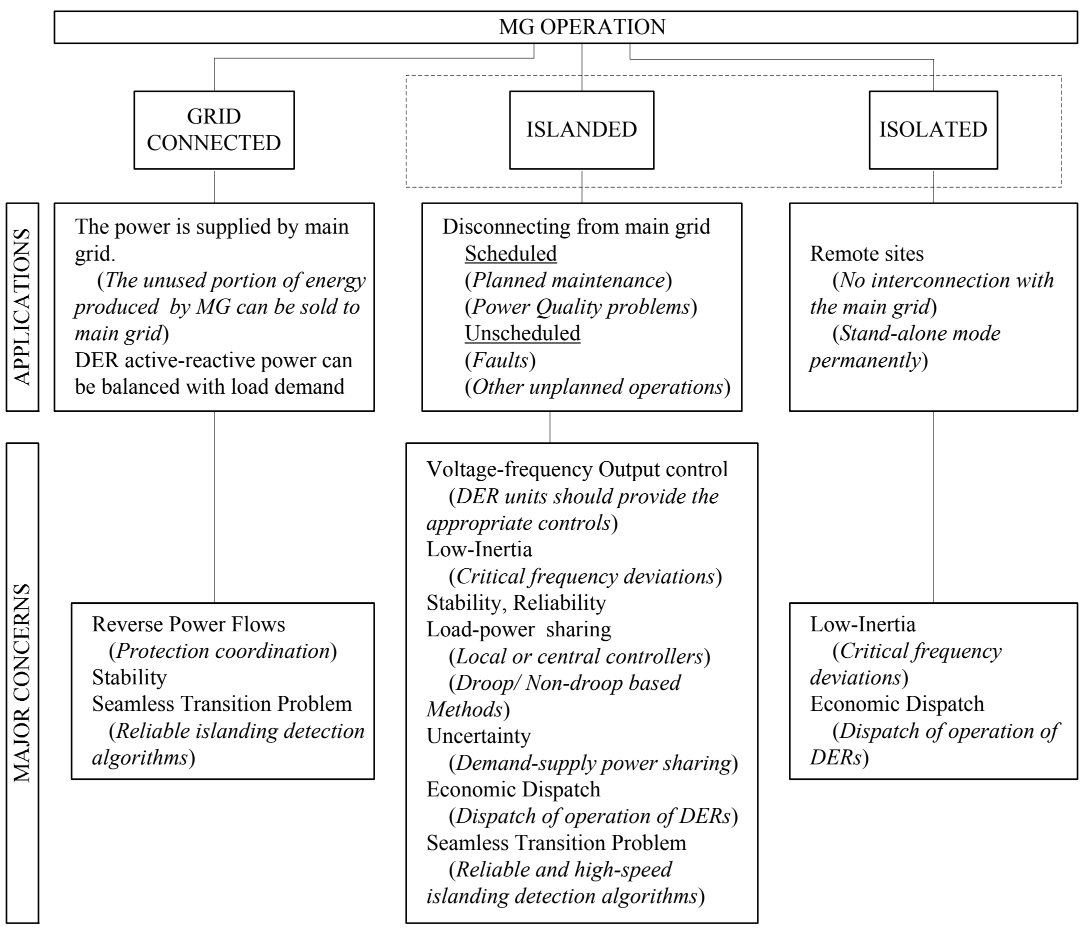


Fig. 2. MG operation modes and concerns

operation of such MGs require dealing with some issues that are summarized in Fig.2.

A. Stability Challenges

Low-inertia is an important concern for MGs. The behavior of an MG with low-inertia is different from conventional power systems. Traditional power systems have the opportunity to store energy on the rotating masses of synchronous generators. However, MGs need some form of energy storages to deal with transients during islanded mode. An efficient frequency control procedure demands load-shedding strategies and storage approaches since the inertia in an MG is low. The rate of change of speed and frequency deviation is inversely proportional to inertia. Power grids can maintain frequency and voltage during disturbances by the large inertia and control of synchronous generators. Synchronous generators can store a large amount of kinetic energy in their high inertia rotors. When an increase in load occurs, the imbalance between electrical and mechanical power in a synchronous generator initiates speed deceleration. The kinetic energy stored in the rotor is initially used to compensate the difference between supply and demand powers. Then, the governor increases the mechanical input power to match mechanical and electrical powers. Finally, system stabilizes at a new steady-state operating point. Voltage regulation during reactive power demand can be achieved in a similar manner. Voltage source inverters (VSI) in the DERs, on the other hand, are not dynamic and do not have rotating masses. Droop control and current limitation on inverter switches make inverters have a virtual low inertia. Thus, voltage and frequency regulation during disturbances cannot be achieved by these sources. As a result, MGs with VSI sources have the voltage and frequency instability issue due to low-inertia. Control methods for inverters based on virtual inertia are proposed in the literature. These studies aimed to improve the frequency response of MGs under disturbances involving large frequency deviations [8]. The techniques can also achieve a reduction of unwanted load shedding in an islanded MG.

Regarding the capacity comparison between DERs and conventional power generation plants, for the same capacity, the inertia of DERs is typically less. In the case of a doubly fed induction generator (DFIG)-based wind farms, for example, if DFIG-based wind farms replace some conventional plants in the power system with the same capacity, the total installed capacity of the grid is still unchanged. However, the total kinetic energy is reduced because the kinetic energy of the variable speed wind turbines does not naturally contribute to the system inertia. Thus, operating a large number of DFIG-based wind turbines in place of conventional plants can significantly reduce the effective inertia of the overall system. On the other hand, if newly installed wind farms are added to the power system without changing the conventional plants, the total kinetic energy remains unchanged. However, the effective inertia of the system is still reduced [9].

For MGs connected to the grid, active and reactive powers are typically provided by the main or host grid. However, bidirectional power flow is also possible using smart meters. Therefore, extra power generated in an MG can be retailed to the host grid. When an MG is operated in grid-tied mode, frequency and voltage references will be provided by the main grid. The control of multiple MGs can be also achieved by a coordination controller, whereas a supervisory control scheme can accomplish the power dispatch between DERs in each MG. The loads in an MG receive power from both the grid and DERs in grid-tied mode. During loss of the grid, the MG should seamlessly transfer to islanded mode by reducing the demand or increasing the power generation. The loss of the main grid can result in changes in voltage phase angles at each DER unit, and also a frequency drop. If an appropriate level of power generation is not provided; this leads to the loss of stability in the MG.

In islanded operation, PV- and wind- based DERs are much faster than synchronous generators, therefore, a reduction in the power generated by PV-based DERs due to partial shading cannot be compensated as quickly as the PV-based power decays. Also, load-tracking problems arise in islanded mode as micro turbines have relatively slow response in a low-inertia MG. The prime movers output power time constants range from 10 to 200 secs, which is too slow for most loads. In case of a traditional power system, energy balance (when a new load is connected to the grid) is satisfied by system inertia. A system with clusters of micro-sources (e.g. DERs, diesel generators, etc.) operated in islanded mode however, must provide some energy storage to insure this energy balance [10].

For the stability of a MG, providing a seamless transition from grid-tied mode to an islanded mode requires fast and accurate islanding detection. It is important since a failure in islanding detection can harm generators and loads. There are different techniques for islanding and anti-islanding detection problems in the literature [11]. Isolated mode is a standalone mode where a MG is at a remote location and there is no connection with the main power grid. This mode has similar concerns as islanded mode. Due to small inertia, there may be rapid reflection to frequency deviation in case of power fluctuation. To suppress this situation, high-speed frequency detection is required. The tracking ability of high frequency change can provide improved performance.

B. Power Quality Challenges

The power generated by PV- and wind-based DESs varies and can result in power quality issues. Also, these power sources can inject a high level of harmonics to the system due to power electronics interfaces. The pulse-width modulation (PWM) inverters are used to connect the renewable energy sources with variable voltage and frequency to a MG with fixed frequency and voltage. However, the output voltage waveforms of these inverters contain many harmonics that must be reduced the standard total harmonic distortion (THD) limitation [12]. One possible approach for harmonic reduction from voltage waveforms is the selective harmonic elimination technique [13], [14]. There are also other techniques based on signal processing [15], [16] and artificial intelligence [17-19].

In summary, the power quality challenges in MGs can be listed as follows:

- The harmonics produced by the widely used power electronic switches and inverters [20],
- Voltage fluctuation and flicker due to the intermittence nature of the photovoltaic cells, wind turbines and other distributed generators [21],
- Negative-sequence currents due to the asymmetry of nonlinear loads [22].

Other concerns are; current spikes (due to slight variations in phase and amplitude) which can be generated by a DG connected to an MG, node voltage distortion due to the propagated harmonic current injections through the grid, voltage regulation and stability problems.

It should be noted that identification and mitigation of the power quality issues are important as they can degrade the performance of the power system.

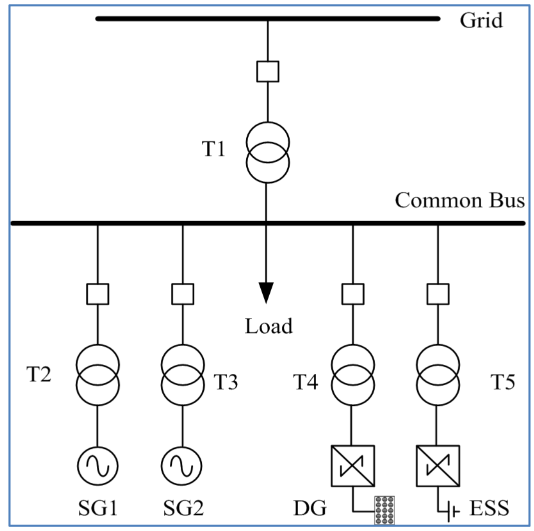


Fig. 3. PSCAD/EMTDC layout of MV MG

IV. Simulation Results

In this section, power quality and stability problems are illustrated in a medium-voltage (MV) MG shown in Fig.3. The case study power system was modeled by the PSCAD/EMTDC simulation software as shown in Fig.4. All DG units were equipped with the droop control strategy. The loads were considered as a combination of constant impedance and a constant power load. Feeder was supplied by the adjacent DG units. A variety of case studies were simulated in order to demonstrate the issues of low-inertia DGs.

The rating of machines, loads and droop constants of inverters are provided in Table I and Table II, respectively.

TABLE I. Parameters Of Microgrid

Nominal Ratings	**SG1**	**SG2**	**DG (PV)**	**Load**
Active Power (kW)	500	300	300	300
Reactive Power (kVar)		100		

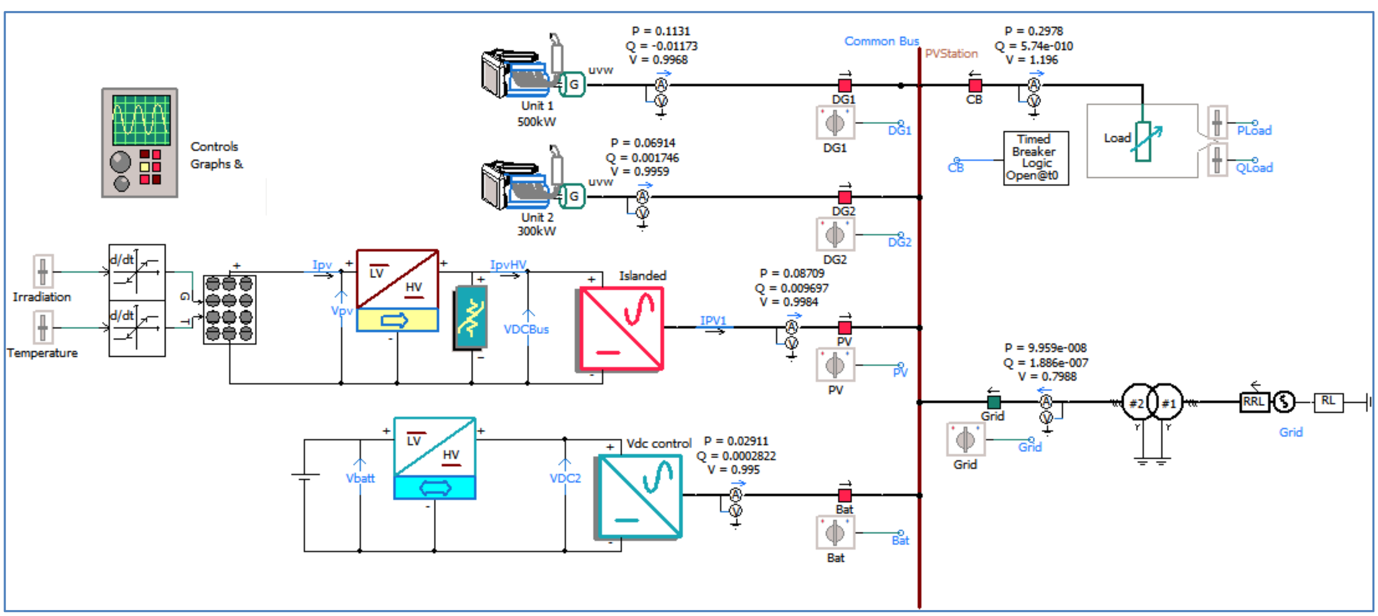


Fig. 4. The case study medium voltage MG

TABLE II. DROOP CONSTANTS

Inverter DC Voltage	0.8 kV
P-w droop gain-SG1, SG2	0.03 (<0.05)
Q-V droop gain-SG1, SG2	0.03 (<0.05)
P-w droop gain-DG	0.03 (<0.05)
Q-V droop gain-DG	0.03 (<0.05)

The traditional droop control method assumes that the line impedance of a high voltage transmission system is mostly inductive. On the other hand, for low/medium voltage MG, the feeder is mostly resistive. Traditional droop method is not valid due to the real and reactive power coupling among ESSs. This will reduce system transient response and steady-state performance [23]. Several control methods were proposed to solve the problem of traditional droop method [24-29]. The following case studies show the reduced stability and power quality due to low-inertia in such MV MGs.

A. Case 1: Short-Circuit Disturbance in Islanded- mode with Inertia:

The aim of this case was to analyze the frequency response of the islanded MG in the presence of short-circuit faults. Load active and reactive powers are 510 kW and 110 kVar, respectively. A symmetrical three-phase short-circuit fault with duration of 0.4 sec was occurred at t =0.6 sec in the islanded-mode. Fig.5 illustrates the frequency response, active and reactive load share by the synchronous generators and inverters. It is clearly seen from Fig.5 that the frequency is stabilized to 60 Hz following the clearing of the short-circuit fault. The synchronous generators and inverters shared the total load according to their droops after clearing the fault.

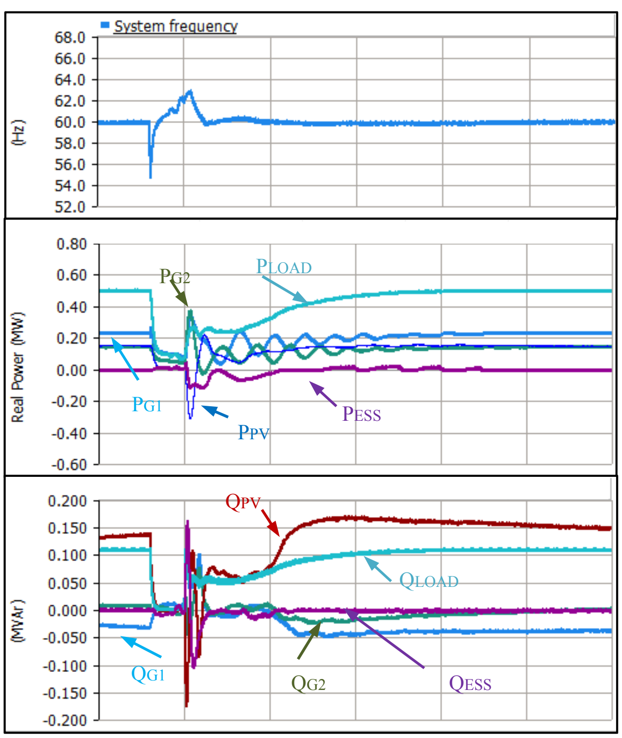


Figure 5. Load Sharing and Frequency for Case 1

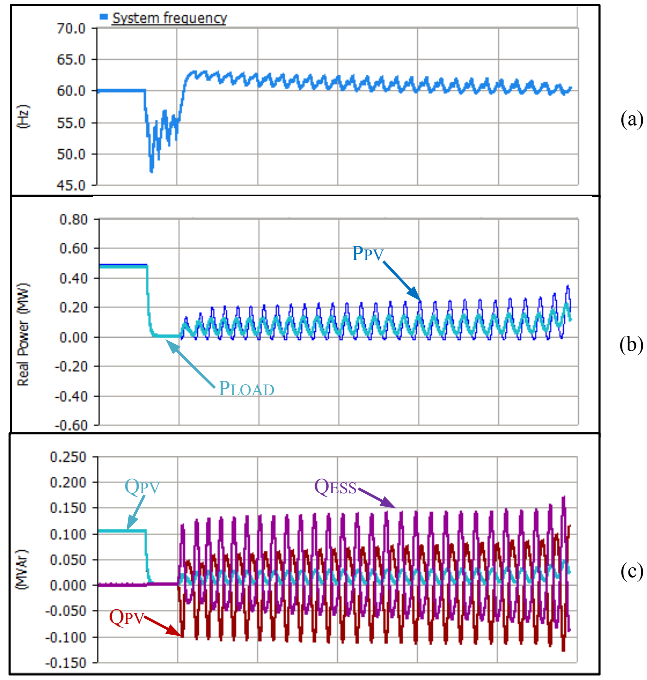


Figure 6. Load Sharing and Frequency for Case 2

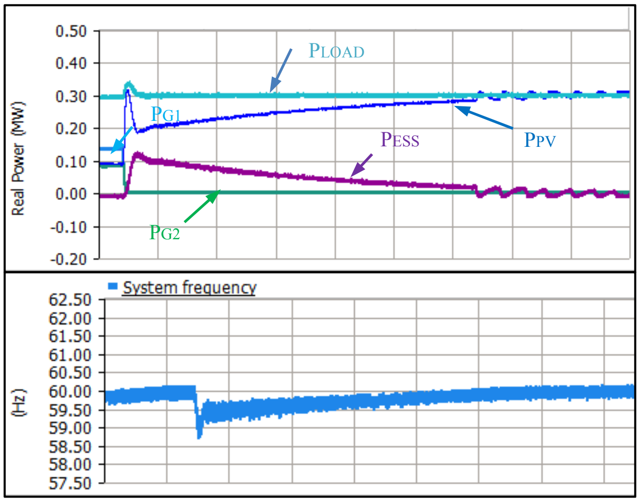
B. Case 2: Short-Circuit Disturbance in Islanded-mode with no Inertia:

The analysis in Case 1 was repeated when the diesel generators SG1 and SG2 were disconnected from the islanded MG. A symmetrical three-phase short-circuit fault of 0.4 sec duration was occurred at t =0.6 sec. Fig.6 represents the frequency response, active and reactive load share by the inverters. It is clearly seen from Fig.6-(a) that short-circuit caused higher frequency drop in comparison to the case in Fig.5-(a). In addition, a 3% frequency oscillation was produced; following the clearance of the short-circuit fault after 0.4 sec. Fig.6-(b) and Fig.6-(c) also illustrate the out-of-stability in terms of active and reactive power supplied to the load. The simulations for different SC types, as symmetrical and unsymmetrical SC faults, yielded similar results.

This simulation shows that the inertia of the PV-ESS system is insufficient to tolerate the disturbance such as short-circuit fault; in comparison to the same simulation with diesel generators which have relatively high inertia.

C. Case 3: Loss of Generation in Islanded-mode:

For this simulation, when the load was supplied by SG1, SG2 and PV; SG1 and SG2 were disconnected at t =1 sec. After the diesel generators were disconnected, the output power of PV was increased by its droop control. In addition, the energy storage system (ESS) supplied energy to the system to balance the load demand. The role of ESS is critical in this situation, since it stands as a source of inertia to supply the sudden change of load when the SG with mass inertia was disconnected from the power system. The duration of recovery time is 16.5 sec for Case 3. As it is seen from Fig.7-(a), a 17%



(a)

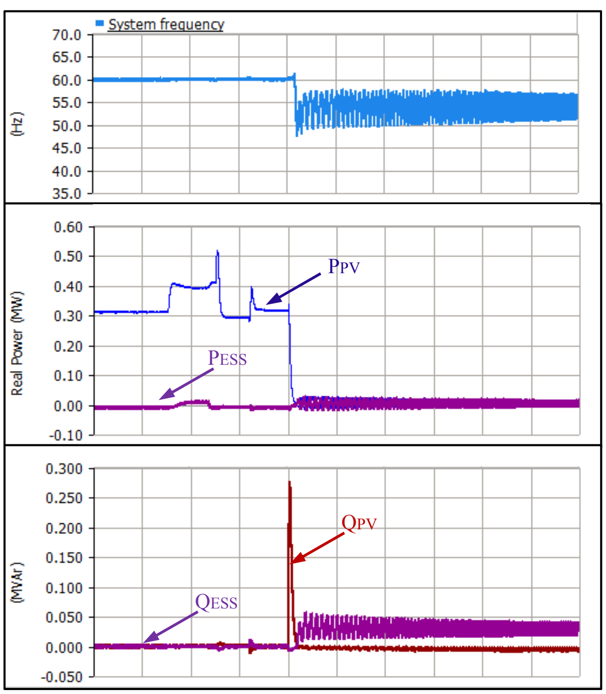
(b)

Figure 7. Load Sharing and Frequency for Case 3

oscillation was generated. Although, ESS supplied inertia to the system, this is not comparable to inertia of diesel generators; thus a larger fluctuation is generated. Fig.7-(b) shows the frequency response. As can be seen, the frequency recovers in less than 0.16 sec. If the microgrid follows IEEE 1547 recommendations, all of the sources must get disconnected from the microgrid when $t \geq 0.16$ sec [23]. This may lead to a complete blackout in the system.

D. *Case 4: Maintaining System Stability in case of load variations:*

Providing system stability in spite of load variations is one of the several challenges associated with MGs. To demonstrate the response of the system to load variations with only PV-ESS



(a)

(b)

(c)

Figure 8. Load Sharing and Frequency for Case 4

source, SG1 and SG2 were disconnected from the MG. Then several load variation scenarios were created for the purpose of observing how the low-inertia system would respond to the fluctuations in the demand power. In the first scenario, the PV and ESS supplied a load with 310 kW power. Then, at t =1.5 sec the active power demand was increased to 400 kW. At t =2.5 sec the load power decreased to 300 kW, and it was set to its original value at t =3.2 sec. As a last scenario, reactive power demand was increased to 150 kVar at t =4 sec. Fig.8 shows the frequency, as well as active and reactive power variations.

It has been observed from Fig.8-(b) and (c) that PV active power supply and reactive power supply were lost at t =4 sec; following the increase of reactive power demand. In addition, Fig.8-(a) also shows that there is instability in terms of frequency. This simulation verifies that, load fluctuations may lead to power quality and stability issues since the inertia of islanded MG is smaller in comparison to the main grid. Proper ESS control is required to maintain stable frequency and voltage [30].

V. Conclusion

This paper focused on the stability issues of islanded MG systems with a low-inertia characteristic, especially if there is a significant share of power generated by electronic-interfaced distributed generation (DG) units. The low-inertia can lead to severe frequency deviations in islanded mode if some proper control mechanisms are not implemented for power sharing purposes. In this respect, the stability issues in both grid-tied and islanded modes have been discussed. PSCAD/EMTDC simulations have been performed to reveal the instability problems regarding frequency deviations. Some scenarios were performed in islanded mode for the purpose of demonstrating the response of a low-inertia system to several cases that can be encountered in power systems. In the first scenario, a symmetrical three-phase short-circuit fault case has been simulated with and without inertia. It has been observed that lack of inertia produced some instability problems. Also, power quality problems such as oscillations in active and reactive powers have been observed in this study. In the second scenario, the aim was to observe the ability of the PV-ESS system in case the generators were disconnected (due to a fault or maintenance). It was seen that, following the loss of diesel generators, a power quality problem remained even though the frequency was stabilized. As a final scenario, the response of power system to load variations was simulated which may be created due to load shedding and load recovery in the event of system failures. It has been observed that the PV-ESS system may not be adequate to fulfill the load demand, and both frequency instability and loss-of-supply may be encountered. The simulations also showed that when a low-inertia DER (instead of a conventional plant) is connected to the islanded MG, the VSI of the DG may not tolerate the load demand in the system and may not provide active and reactive power in some conditions. This may lead to instability. These results point to the importance of a proper controller that is required to compensate the low-inertia nature of the DGs.

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