Simplified Voltage and Frequency Controller Based on Droop Control for the Dynamic Analysis of a Microgrid

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***Abstract*—Due to various technical, economic and environmental concerns the concept of Microgrid has become popular in the electric energy industry. It's capability to operate in both grid-connected as well as an autonomous system in islanded mode is the distinct feature of the Microgrid concept. Hence, Microgrid control should provide seamless transition between grid-connected and islanded operations. Active-reactive (PQ) power control and voltage source inverter (VSI) control are two popular techniques employed in Microgrid control. This paper proposes a simplified VSI controller for dynamic analysis of the Microgrid operation. The proposed control algorithm is explained, modeled in MATLAB Simulink and the simulation results are presented for various operating scenarios to demonstrate the effectiveness of the proposed control scheme in providing a desirable dynamic performance for both the grid-connected and islanded operation mode of the Microgrid.**

***Index Terms*—Microgrid, Islanded operation, PQ control, VSI control.**

I. INTRODUCTION

MICROGRID (MG) is a low-voltage distribution network comprising various distributed generators, storage devices, and controllable loads that can operate either connected to or isolated from the main distribution grid as an autonomous entity [1]. The concept of MG is well accepted by the electric energy industry due their technical, economic and environmental benefits. MG consist of local power generation using non-conventional renewable energy sources such as wind power, solar photovoltaic cells, fuel cells, combined heat and power (CHP) systems and micro turbines etc. [2]. Hence, MGs help to reduce environmental pollution and global warming which are key factors for preferring renewable resources over fossil fuels. Reduction of physical and electrical distance between Microsource (MS) and loads contribute the improvement of reactive power support of the whole system, thus enhancing the voltage profile. It will further reduce the transmission and distribution feeder congestion and losses which will either reduce or postpone the new investments in the expansion of transmission and generation systems. Decentralized supply and better match of supply and demand improve the power quality and reliability of the system. The salient feature of a micro grid is its ability to respond to the changes in the power network. In many cases MGs can operate semi-autonomously. When an outage occurs on the main feeder; the MG is capable of supplying power to its captive loads without any interruption. A significant cost saving is achieved in MGs from utilization of waste heat in CHP mode of operation. Cost savings also influenced through integration of several MSs which generate electricity locally and shared among the local customers, which again reduce the need to import/export power to/from the main grid over longer feeders [3].

The control systems in MGs are designed to securely regulate the operation of the system in grid-connected and autonomous modes. If there are physical communications between MSs, then the control system is based on one central controller that regulates the operation of all MSs. Otherwise the control system is a part of each MS. In either case, the objective of the control system is to control the local voltage and frequency in the MG whenever the MG is disconnected from the utility, and ensure that these parameters remain within the acceptable limits. It also resynchronizes the MSs with the grid at the time of reconnection and regulates the output power from these sources based on defined set points for active and reactive power injecting /absorbing [4].

The rest of this paper is arranged as follows. Section II briefly describes the MG system under study and its modeling. Section III discusses the conventional active-reactive power flow controls and voltage source inverter control techniques applied in MG control. Furthermore, it explains the proposed simple VSI control for MG dynamic analysis. Simulation results are given in Section IV, followed by the conclusions made in Section V.

II. MICROGRID MODELING

A single line diagram of the MG which has been considered in this paper is shown in Fig.1. As it shows, the system consist of two renewable sources, a diesel generator and a battery bank, three types of local loads defined as critical load, non-critical load and a dump load. The system is connected to the grid through a static switch which can operate the system either connected with the grid or isolated from the grid. All the sources and loads are connected to the system through power converters.

A. Mirosources

MSs MS1 (300 kVA) and MS2 (200 kVA) represent the renewable energy based generation such as wind and solar system. Since the operation of such systems depends on the climate conditions, the output power is non-dispatchable in nature. Therefore, these sources can be modeled as current sources that inject a constant current. The output power from the renewable sources can be either DC, in case of PV systems and fuel cells or AC with variable frequency, in case of wind turbines. Therefore power converters are used to regulate the output of the renewable sources in the form required by the grid and the load. However, in dynamic analysis, detail model of the primary source and the inverter are not required unless the transients related to the commutation of the solid state switches in the inverters are considered [4]. Hence, in this study, MS1 and MS2 are represented by current sources controlled by the control functions of the system parameters. Furthermore, it is assumed that the output of the power converter is free from harmonics and losses.

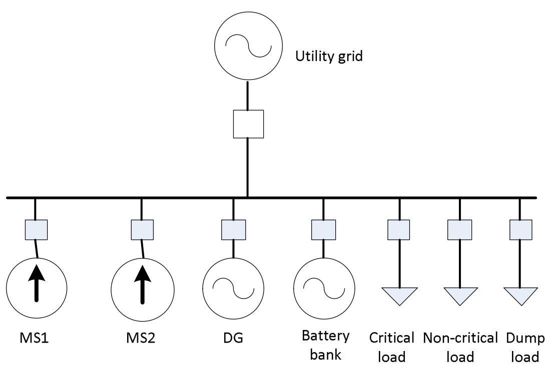


Fig. 1 Single line diagram of the MG under study

B. Microgrid loads

The critical and non-critical loads (1000 kW, 150 kVAr) are modeled as simple three phase RL branches where critical loads have the priority in the MS power. Throughout this analysis, they are assumed to be balanced and star-ground connected. Dumped load is modeled as a three phase variable resistor. The value of this resistor is to be changed automatically to dissipate the extra power, in a situation where the local generation is higher than primary load demand during islanded operation.

C. Utility grid

The utility grid (240±5% V, 50±1 Hz) is modeled simply as a three phase source with the associated feeder impedance corresponding to the fault level at the grid connection point. The static switch which controls the grid connection is modeled as a controllable three phase circuit breaker which operates according to the MG controller commands. Voltage controlled oscillator based PLL is used to derive the phase angle of the system voltage during both in grid connected as well as in isolated operation, which is required by the unit power controlled MS converters.

D. Battery bank

A battery bank (100 kVA) is installed in the MG system to ensure that the critical loads are continuously supplied even when there is no sufficient power from the renewable energy sources. It is connected to the MG network through a bi-directional converter that allows surplus energy to be stored whenever there is an extra power during light load condition. In case of a shortage of renewable sources supply, the battery bank has to release some of its energy so that the critical load is totally met. Furthermore, the converter connected to the battery bank will act as the grid forming inverter during islanded operation which controls the voltage and the frequency of the islanded system. In this study, the battery bank is modeled as an ideal voltage source and the power flows into and out of the battery bank is controlled by a circuit breaker. The battery bank comes into action only during the islanded operation in this simplified study.

E. Diesel generator

The diesel generator (150 kVA) in the MG system is a back-up power source. It operates only when the combined power from both the MSs and the battery bank cannot meet the critical load demand. Thus, the installation of a back-up power source, such as a diesel generator, is to guarantee that the critical load is securely supplied even if there is no sufficient power from the MSs and the battery bank to maintain required voltage and frequency. The diesel generator is also modeled as a voltage source in this study.

III. MICROGRID CONTROLS

The MG is centrally controlled and managed by a MicroGrid Central Controller (MGCC). The MGCC gather and analyses the data from load, grid-connection point and power sources and then send the set-points to MS controllers (MC) and load controllers (LC). However, these control commands are not used during dynamic operation [4]-[5]. Then, second hierarchical control level exist in the converters located at MSs and loads which provides the local control, enabling the plug and play capability to MSs and loads. Two kinds of control strategies are used to operate the MS converters; i.e. PQ inverter control and Voltage Source Inverter (VSI) control [6]-[8]. In this study, the PQ control is implemented only during grid connected operation. The controller in this configuration isolates the voltage source units and enforces the non-dispatchable MSs to inject a certain amount of their available power into the AC system. While the MSs inject the specified active and reactive power, the controller uses the voltage and frequency of the main grid as reference to regulate those of the MSs. The voltage source inverter control is implemented with the voltage source units when the utility grid is disconnected by the monitoring controller due to grid fault or power quality issues. The function of the controller in this situation is to keep the voltage and frequency of the system within acceptable limits.

A. Active-reactive power (PQ) inverter control

When the converter operates as a PQ inverter, the voltage and the frequency should be properly controlled in order to match with the system voltage and frequency. When the MG is operating in parallel with the utility grid, the control system uses the magnitude of the grid voltage as the reference and generates the instantaneous voltage accordingly. The frequency of the MG can be maintained to be the same as that of the grid by synchronizing the converter output with the grid voltage through a PLL. The MS converter is forced to supply the pre-specified active and reactive power by either MC or MGCC. The block diagram of the implemented PQ inverter controller is shown in Fig.2 [9]-[10].

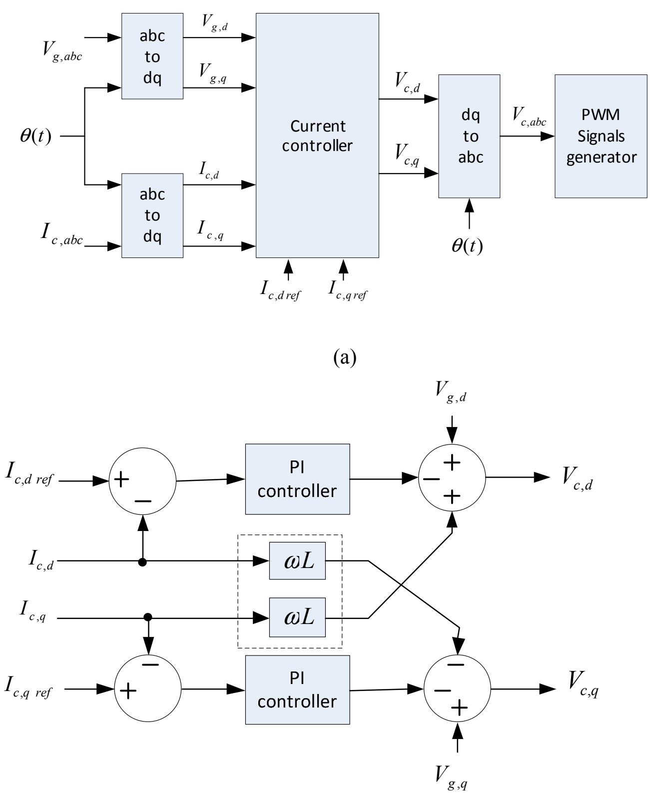


Fig. 2 Block diagram of the PQ inverter controller: (a) Overall controller (b) Expanded current controller [9]

The PQ control measures the system voltage and the converter current and transfer them into *dq* frame. The PLL is used to estimate the phase angle at the MS connection point and generate an angle which varies synchronously with the grid. The current quantities are then compared with the reference quantities in order to obtain the error signals. The error signals are applied to proportional-integral controllers to correct the errors and define the reference voltage signals. Overall, this process forces the inverter to inject the defined currents and at the same time it regulates the voltage at the connection point as measured from the grid side. It also compensates for the voltage drops in the cable by adding the dropped voltage values into the amplitude of the inverter's internal voltages, so that the voltage at the load is held to its specified value.

B. VSI control

VSI control is employed during islanded mode of operation which requires a control system that differs in its principles from those of the grid connected mode. In this mode the MG has already been disconnected from the main grid; consequently the voltage and the frequency are no longer regulated by the grid and have to be internally controlled. In this situation, the control system needs to regulate the voltage and frequency of the system within acceptable limits. The VSI control emulates the behavior of a synchronous machine, thus controlling the voltage and frequency on the AC system [11]. The VSI acts as a voltage source, with the magnitude and frequency of the output voltage controlled through droops, as described in the following equation.

$$\begin{aligned} \omega &= \omega_0 - k_P \times (P - P_0) \\ V &= V_0 - k_Q \times (Q - Q_0) \end{aligned} \quad (1)$$

where P and Q are the inverter active and reactive power outputs, P_0 and Q_0 are the active and reactive power at the reference values of angular frequency ω_0 and voltage V_0. k_P and k_Q are the droop slopes [12]-[13].

The authors in [14] propose a control method for autonomous operation of voltage source inverters based on a conventional power system control. As shown in the block diagram in Fig. 3, two blocks are used to calculate instantaneous active and reactive powers injected by the inverter. They are filtered before using the reactive power-voltage droop and active power- frequency droop to determine the required voltage and frequency.

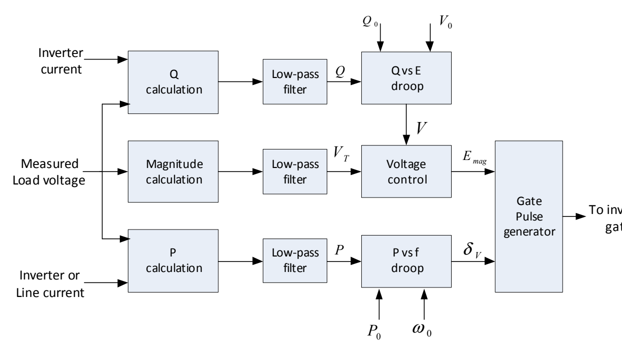


Fig. 3 Block diagram of the Voltage Source Inverter controller[14]

This controller can function perfectly in a MG system where the distribution cables are mainly inductive. However, distribution network cables consist of significant resistance and have higher R/X ratio. Hence, there will exist a coupling between active and reactive power flows disabling the independent active-reactive power flow control. Hence, some technique should be employed to decouple above interdependence. A simple and straightforward method is to add delay devices whose function is to delay the instantaneous measurements of the power, which is the technique used in this study. The modified version of the control technique shown in Fig. 3 is shown in Fig. 4. As figure shows, the low pass filter blocks are eliminated assuming that the inverters are equipped with well-designed filter that are able to filter out all unwanted harmonics, help to dampen any transients and produce pure sinusoidal waves at the specified frequency. Measuring devices are also assumed to be perfect and their measurements have no noise effects. Furthermore, the PI controller based voltage control block is also removed since desired voltage value can be directly taken from Q vs E droop block since the inverter has to adjust its output voltage based on this frame in all cases. Further, the droop gains are set such that each voltage source inverter inject the active and reactive power proportional to their rated capacities.

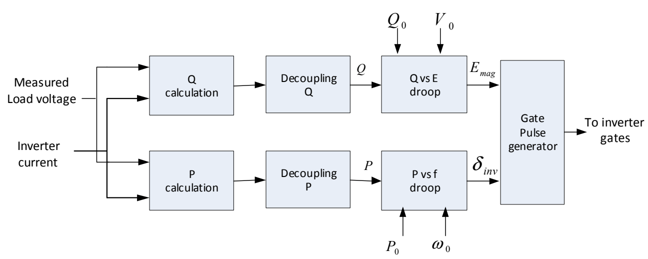


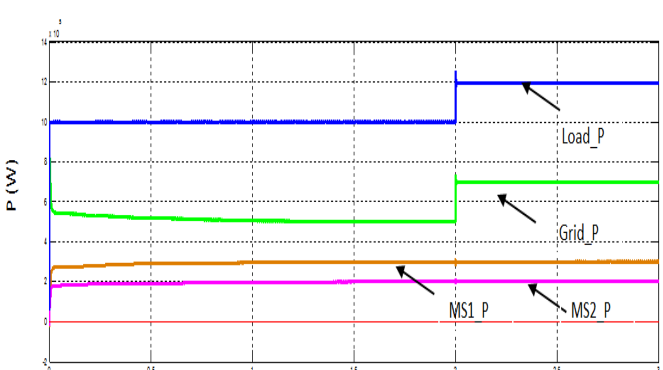
Fig. 4 Block diagram of the Simplified Voltage Source Inverter controller

IV. SIMULATION RESULTS

In order to evaluate the performance of the proposed power control strategies, a number of simulation studies have been carried out on the MG system shown in Fig 1. and the results are discussed below.

A. Scenario A: Parallel operation with utility grid

In this scenario, the load is supplied by both the MG local sources and the utility grid. The initial power references for the two MSs were set at 1 p.u. of active power. The reactive power demand of the load is supplied by the utility grid. The total load, including the non-sensitive load, was initially set at 1000 kW and 150 kVAr. At the time of 2 s, the load is increased by 200 kW and Fig. 5 shows active and reactive power variations of the load, grid, and the two MSs.



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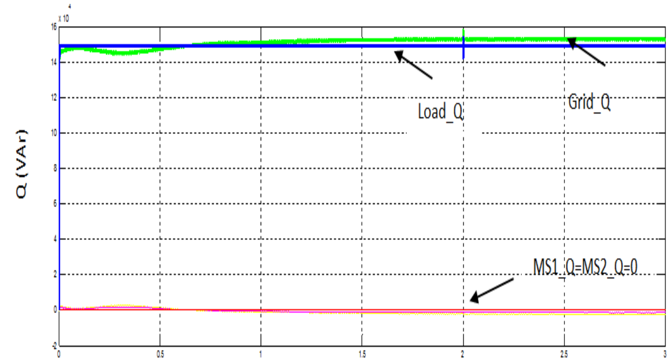

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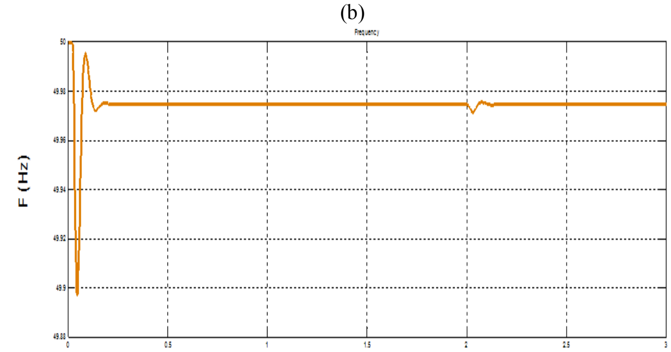


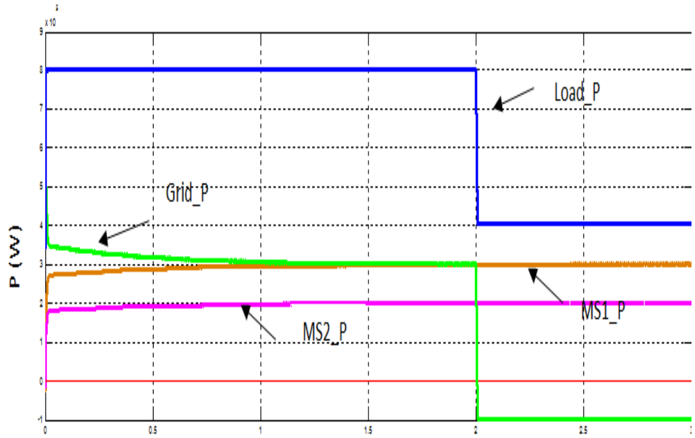
(C)

Fig. 5 Simulation results for scenario A: (a) Real power. (b) Reactive power (c) System frequency.

As can be seen in Fig. 5, the MSs track the output power reference values precisely. They inject the desired real power and left the reactive power of the load to be supplied by the grid. It can also be noticed that the output of the MSs remain constant throughout the simulation, despite the load variation. The variations of the load in both active and reactive powers were totally compensated by the utility grid.

The MG under test allows the power to be exchanged between the main grid and the MG. When the total real power generated by the MSs exceeds the load's demand, the excess real power will be transferred from the MG to the utility grid. The results shown in Fig. 6 illustrate this scenario. The load is initially set at 1000 kW and 150 kVAr and then reduced by 600 kW at t = 2 s. The negative sign during the load drop implies that the grid is receiving power from the MG. Instantaneous three phase voltage shown in Fig. 6 also indicates that the PLL implemented in Simulink is operating successfully in synchronizing the MG with the main grid.

This scenario demonstrates one of the MG benefits on the utility grid, i.e. when the generated power exceeds the local load, the MG can act as an active power system which may help the utility in sharing external loads during peak times.



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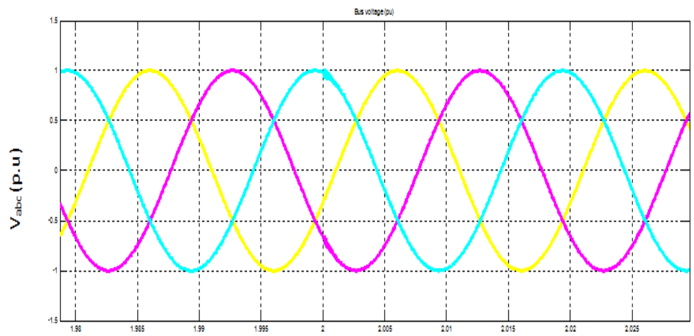
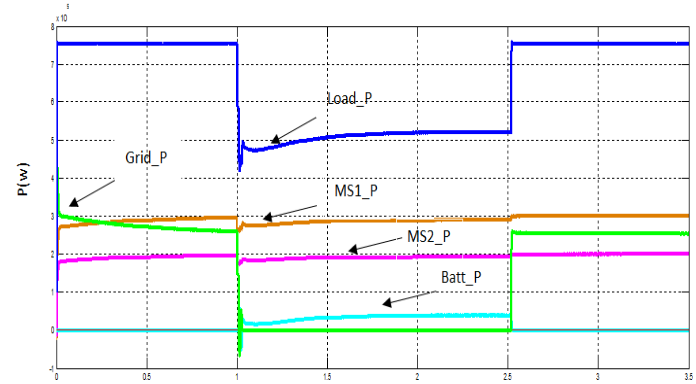


(b)

Fig. 6 Simulation results for scenario A: (a) Real power (b) Instantaneous 3-ph voltage of the system.

B. Scenario B: Transition from grid-connected mode to islanded mode

During the normal operation, the grid circuit breaker is closed and the two MSs are operating at rated power. Non-critical load is set at 200 kW, 100 kVAr and the critical load is set at 550 kW, 20 kVAr. At time t = 1 s, a voltage sag is applied at the grid side which drops the grid voltage from 240 Vrms to 212 Vrms. The voltage monitoring device detects the voltage drop which has reached the minimum allowable operating voltage (240-5% =228 V) and sent an instantaneous signal to the MG controller at around t =1.01 s. The MG controller responds with no time delay and in turn sent immediate commands to three circuit breakers. One command is sent to the grid CB to open, in order to remove the source of the disturbance and to make sure that the critical loads are not affected. The second command is received by the non-critical load's CB for load shedding. The third command is sent to the battery bank CB to turn it ON. As the grid is disconnected, the voltage and frequency references from the grid are lost and the MG uses battery bank's voltage and frequency as references needed by the MG while balancing the power inside the MG. At t = 2.5 s, the disturbance is cleared and MG controller is updated at around 2.51 s. Before the grid CB is tuned on, the controller synchronizes the MG with the grid and this takes approximately 0.01 s (half a cycle). The battery bank is disconnected and the non-critical loads are re-connected at t = 2.52 S. The simulation results during the transitions are shown in Fig. 7.



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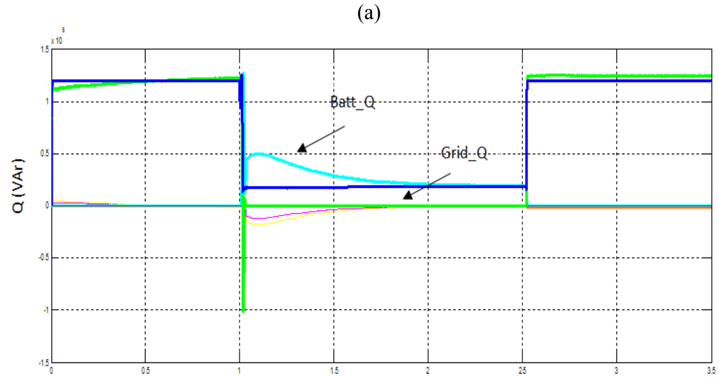

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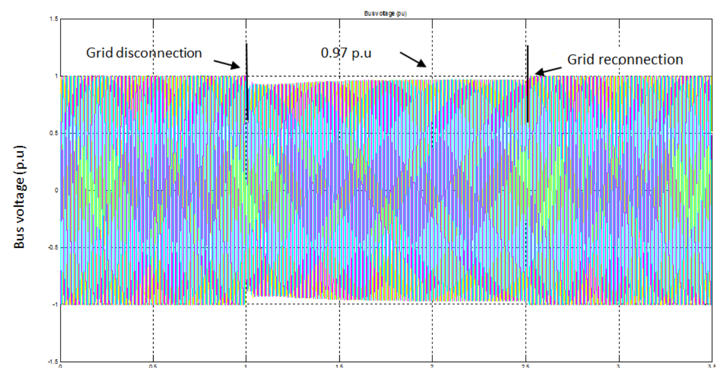

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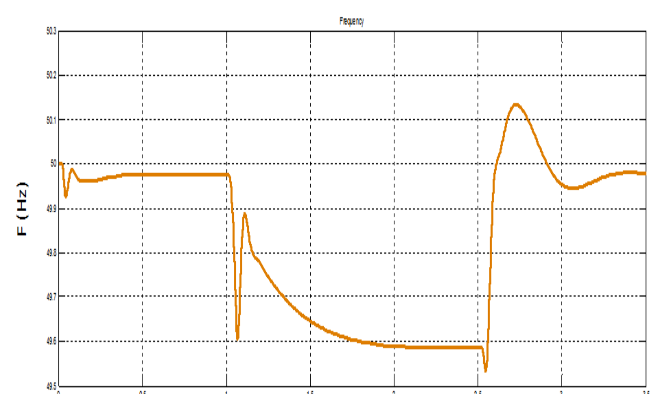


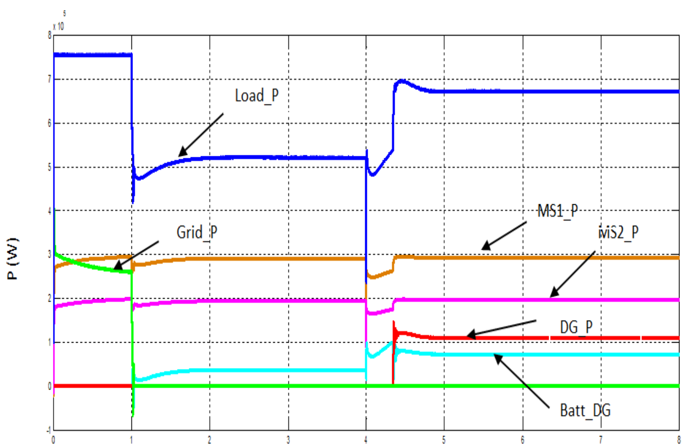
(d)

Fig. 7 Simulation results for scenario B: (a) Real power outputs (b) Reactive power outputs (c) Bus voltage in p.u. (d) System frequency

The results also show no significant oscillations in the output active and reactive power during the transitions. At the time of the transitions, the controller successfully synchronizes all the sources making the MG smoothly switch between the two modes of operation without significant disruptions in the power.

C. *Scenario C: Shortage in supply during islanded operation*

The power balance and load sharing between the battery bank and the diesel generator is investigated in this scenario. The MG is initially operating in parallel with the grid and due to a disturbance, the grid is disconnected at t = 1 s. During the islanded mode, the MG only serves the critical load of 550 kW and 20 kVAr. At t = 4 s, the critical load demand increases by 150 kW making the total load demand higher than the available power from the battery bank and the two MSs together. Therefore, the diesel generator is tuned on since an additional supply is required from the diesel generator to meet the demand of the critical load.



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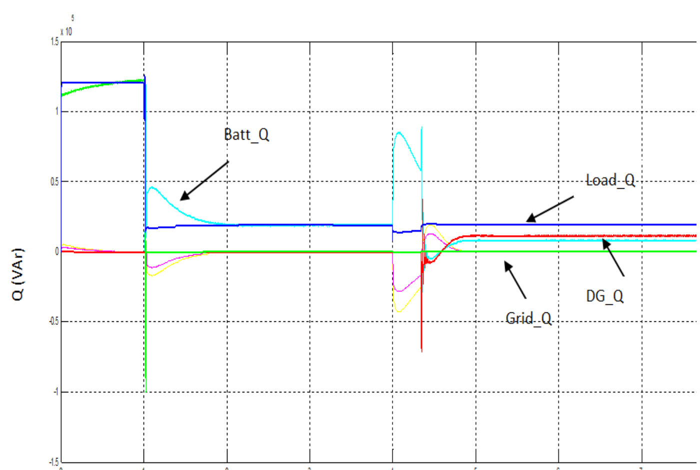

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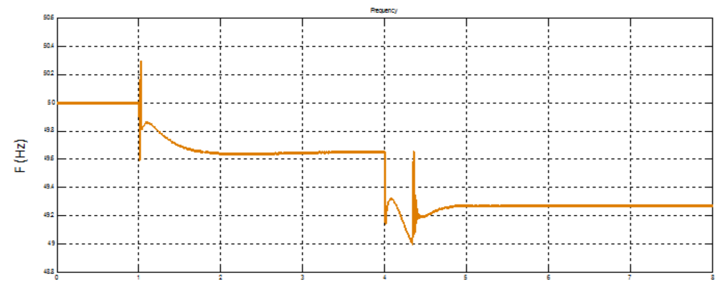
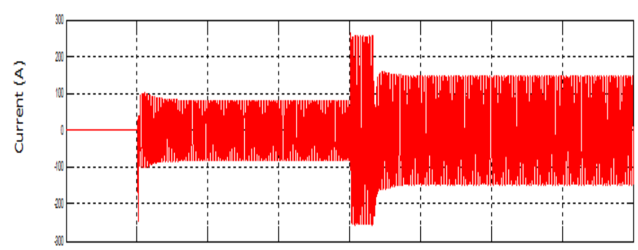


(c)

Fig. 8 Simulation results for scenario C: (a) Real power outputs (b) Reactive power outputs (c) System frequency.

The droop controllers have been designed such that voltages and frequencies at the terminals of voltage sources under no load conditions are to be at nominal values. If the diesel generator CB is closed with these values, massive oscillations would appear in the output powers of the battery inverter and the diesel generator due to the differences in the voltage phases and magnitudes. Therefore, the diesel generator voltage and frequency have to be sufficiently adjusted to the corresponding quantities of the battery inverter. This synchronization must be performed before the connection of the diesel generator in order to prevent an enormous transient.

The results in Fig. 8 (a) and (b) indicate that the droop techniques perfectly distribute the load demand between the diesel generator and the battery inverter according to their ratings. For instance, at t = 4 s, the MSs operate at maximum real power and leave around 200 kW of the load to be supplied by voltage sources. This 200 kW demand is shared between the diesel generator and the battery inverter as 120 kW and 80 kW respectively, which is equal to 80% of their rated capacities. This is clearly shown in Fig. 9, which shows the output current from the diesel generator and the battery inverter.



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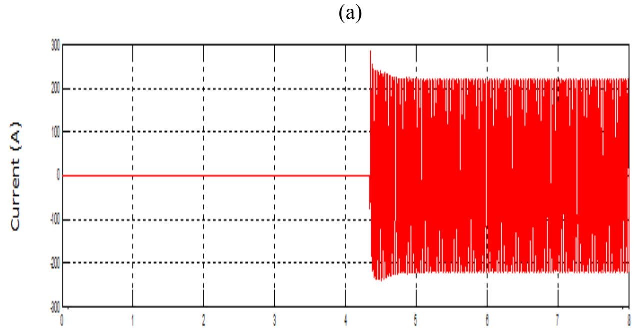


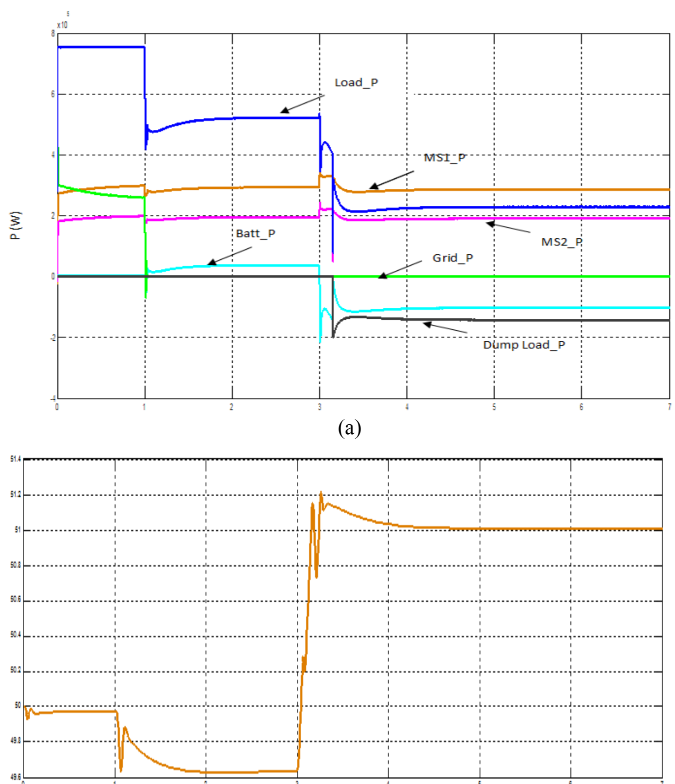
(b)

Fig. 9 Simulation results for scenario C (a) Output current from battery inverter (b) Output current from diesel generator

D. Scenario D: Excess power generation during Islanded operation

When the local generation is more than the load demand during islanded operation, the extra power has to be dissipated in a dump load in order to balance the power within the MG to prevent damages to equipment due to over voltage. If the battery bank is precisely modeled, the power transferred to the dump load is defined as the power from the MSs exceeding the load demand and being rejected by the battery bank since it is fully charged. However, the simple battery model in this proposed system has no knowledge of the battery state of charge. It is simply charged and discharged at different ratings for any required period of time. Therefore, the dump load power is considered as the power from the MSs that exceeds both load demand and the power needed to charge the battery bank at its rating

Above scenario is simulated to study the power dumping in the MGs. The results are shown in Fig. 10. The MG is operating in parallel with the utility grid and then disconnect at t = 1 s. During the islanded operation the total critical and non-critical load is set at 540 kW and 20 kVAr which are supplied by the two MSs and the battery bank. At t = 3 s, the load drops by 300 kW. The total load now becomes much less than the local generation. After fully supplying the load, the extra power is used to charge the battery bank. However, the excess power is higher than the battery inverter rating which causes the frequency of the system cross the maximum value. It then instantly switch on the dump load CB and adjusts its variable resistors so that it can dump the extra generation and maintain the frequency at 51 Hz.



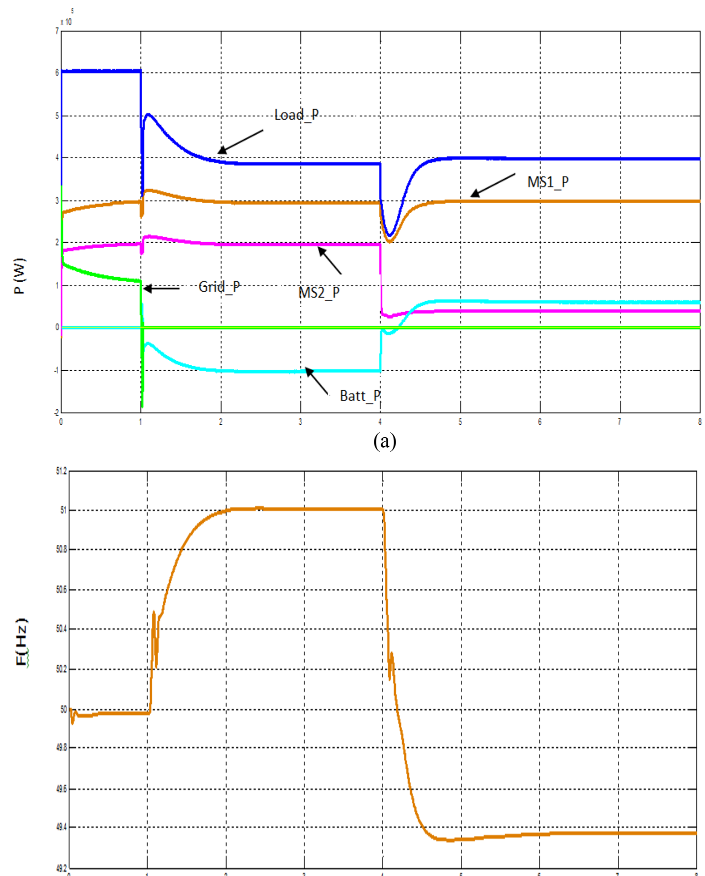
(a)

(b)

Fig. 10 Simulation results for scenario D: (a) Output power (b) System frequency

E. Scenario E: Sudden drop in microsources power during Islanded operation

The output of the renewable energy source based MSs is intermittent in nature since it depends on the environmental whether conditions. A situation where power drops from a MS is also investigated and the results are shown below. The MG is initially operating in parallel with the grid and then it is disconnected at t = 1 s. The battery bank CB closes and since the local generation is more than the load demand (400 kW), the battery bank is being charged. Both MSs operate at their maximum capacity until t = 4 s when the power of MS2 drops to 0.2 p.u. The transients due to above power drop are shown in Fig. 11.



(a)

(b)

Fig. 11 Simulation results for scenario E: (a) Output power (b) System frequency

It is evident from the results that a drop in MS2 power has caused a momentary dip in the load power supply. This is due to the voltage sag creates at the time of the power drop. When the power of MS2 drops instantly from 1 p.u. to 0.2 p.u., all the sources in the MG experience the drop in power as a voltage sag. This causes sag at each source's terminal voltage and does not affect the current supplied by rest of the sources. In real power systems voltage sag cannot be avoided and its severity and duration depend on the value of power being lost.

V. CONCLUSION

This study examined the MG concept and suggested control strategies that will reliably and efficiently operate on a balanced three phase low voltage MG both in grid connected and islanded modes of operation. Simplified models were used for modeling the MG elements such as MSs, loads and energy storages. However, the simulation results proved that the simplified MG model gives a useful insight into the dynamic behavior of an exact MG under various loading conditions, particularly when implementing the control strategies. A simplified droop control based voltage and frequency controller was implemented for the voltage source inverters. The simulation results confirmed that the loads shared among the voltage source units are proportional to their capacity. For the operation of the current source inverters, constant current control scheme was introduced and implemented. The simulation results have proved its robustness in regulating the output powers from the inverters as defined by the references. Delaying the active and reactive power estimation was successfully employed to decouple the interdependence of active and reactive power in a network with the impedance at high R/X ratio.

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