



A New Adaptive Load-Shedding and Restoration Strategy for Autonomous Operation of Microgrids: A Real-Time Study

M. Farzinfar^{*a}, N. K. C. Nair^b, M. Bahadornejad^c

^a School of Engineering, Damghan University, Damghan, Iran

^b Power Systems Group of Department of Electrical and Computer Engineering at University of Auckland, Auckland, New Zealand

^c Unitec Institute of Technology, Auckland, New Zealand

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ABSTRACT

Islanding operation is one of the main features of a MicroGrid (MG), which is realized regarding the presence of distributed energy resources (DERs). However, in order to deal with the control challenges, which an MG faces during island operation, particularly when the transition is associated with certain excessive load, an efficient control strategy is required. This paper introduces a Central Management Agent (CMA) which maintains the stability of the MG, once it is islanded, by controlling an Energy Storage System (ESS) and a Central Synchronous Generator (CSG). Further, this paper proposes a new adaptive load-shedding/restoration schemes that calculates the amount of power imbalance based on frequency measurements combined with the mean value of the frequency gradient. The primacy of the proposed scheme over existing schemes, like instantaneous frequency gradient-based load shedding scheme, is its robustness against frequency oscillations. Moreover, the proposed method acts compatible with the control routine of DERs and the intermittent nature of the PV plant. As another salient feature of this paper, a Hardware In the Loop (HIL) testbed for real-time simulation is developed under which the proposed scheme and related communication with CMA along with other components are evaluated. The obtained results show that the control strategy can confidently conserve the stability of the MG in islanded mode and meet smooth reconnection to the grid-connected mode.

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1. INTRODUCTION

In general, a low voltage MicroGrid (MG) is described as a localized group of distributed energy resources (DERs) and a number of loads, which normally operates in connection with a main utility grid. [1]. Most common DERs include renewable sources of energy, like solar Photovoltaic (PV), synchronous generators, and distributed energy storage devices. A DER unit may be interfaced to the grid either directly through a rotating machine or through an inverter [2, 3]. With the embedded control strategy, MGs can operate in parallel with the utility grid, i.e. grid-connected mode, or as an autonomous grid, i.e. island mode [4]. Hence, one of the key features of an MG is its ability to separate itself from the rest of the grid in order to continue supplying the islanded portion, especially the critical load. Transition

of the MG into islanded mode can be due to disturbances, such as power quality issues, or due to preplanned switching events [5]. However, for a successful operation of the MG in different modes, various issues should be dealt with. In recent times, extensive researches have been undertaken to address and improve the technical challenges facing MG paradigm, such as energy management, control, protection schemes, and power quality issues in MG [6-12].

To realize stable operation of the MG in autonomous mode, and for a smooth transition between the islanded and the grid-connected mode, an appropriate control strategy should be devised. In fact, due to the limited capacity of the DERs, lack of rotational inertia of the MG, and also limited fault ride through (FRT) capability of the inverter-based DERs, the stability of the islanded MG, in facing voltage and frequency variations caused

*Corresponding Author Email: m.farzinfar@du.ac.ir (M. Farzinfar)

by the fault may get affected [1, 13]. In this regards, the control approaches based on either embedded as autonomous parts of each DER, or utilizing a central controller have been addressed in recent publications [6, 14-16]. Despite the merits of the presented control methods in literature, it should be noted that these techniques are only effective if the balance between load and generation is conserved after islanding. Nevertheless, it is very common that the transition is usually associated with an excessive load (or generation). Under this condition, the MG will not be able to ride through the islanded mode and therefore would be subjected to the instability. Generally, utilization of the energy storage devices or load-shedding schemes, which are the main topics of the present paper, are effective ways to safeguard the MG from instability.

As mentioned, different control techniques have been presented in recently published papers. In [15] a local control approach based on active power sharing and regulation capability of inverter-based DERs has been presented. Based on control algorithms utilized in [17-19], each DER regulates its output power coordinately to deal with the voltage/frequency variation and to maintain the stability of the MG. Satapathy *et.al.* (2018) focus on the frequency stability of the island MG, and present droop control and virtual synchronous generator control to maintain the MG frequency [20].

Although the above articles present a full range of control techniques, however, they are not effective if the balance between load and generation is lost after islanding. Nevertheless, it is very common that the transition is usually associated with an excessive load (or generation). In such situation, the frequency of the islanded MG is subject to changes that can lead to instability if not controlled in a timely and robust manner. To address this issue, utilization of the energy storage device has been presented in [6, 21, 22] to ensure initial power balance in islanded MG. Other effective way to safeguard the MG from instability is load-shedding schemes, which has been widely investigated in [23-28].

In [23] a two-stage load-shedding scheme is presented, according to the control response of the inverter-based DERs, estimates the required load at each stage to be shed. In [26-28] adaptive Under Frequency Load-Shedding (UFLS) scheme is proposed, which disconnects predefined loads based on predetermined frequency threshold values. Adaptive UFLS schemes have been further improved by using both frequency and Rate Of Change Of Frequency (ROCOF) in determination of load-shedding requirement [26, 29, 30]. Nevertheless, ROCOF can differ for system disturbances in PCC and may vary in time due to transition to islanded mode leading to malfunction. In addition, the ROCOF based schemes are severely affected by frequency fluctuations and may have inappropriate performance under these conditions.

In view of the shortcomings of the existing schemes, a novel adaptive load-shedding scheme that calculates the amount of power imbalance based on frequency measurements combined with mean value of the frequency gradient is proposed in this paper. The proposed method acts compatible with the control routine of DERs and the intermittent nature of the PV plant as per its Maximum power point tracking (MPPT) technique. Another aspect of the proposed scheme is load-restoration which is triggered in conformity with frequency passing its thresholds and by equating the rate of mean change of frequency between its relevant thresholds.

To implement the proposed schemes, a Central Management Agent, named CMA, is modeled that activates the load-shedding/restoration scheme once the MG gets islanded to restore the balance between the load and available DERs, and thereby prevent the frequency instability. In addition to load-shedding strategy, a control routine based on utilization of both Energy Storage System (ESS) and Central Diesel Generator (CSG) is presented which under supervision of the CMA, plays an important role in maintaining stability of the MG during both modes of operation. These DERs not only supply dynamic active and reactive need of MG after transition to islanded mode, but also increase the total inertia of the MG.

Another salient feature of this work is real-time simulation of MG on the OPAL-RT platform. In order to analyze behavior of an MG and the employed control strategy before actual implementation, real-time digital simulation is an in-dispensable and beneficial tool. For this purpose, a Hardware In the Loop (HIL) testbed for real-time simulation is developed under which the proposed scheme and related communication with CMA and other components are evaluated.

2. THE MICROGRID PROTOTYPE

The MG prototype under study in this paper, which is based on MG presented in [31] is shown in Figure 1. In order to implement the strategy proposed in this paper, the MG prototype is assumed to have different types of DERs (synchronous based generator and PV) and an ESS that supplies four loads. Loads, which are the model of feeders load, have been classified into four categories by taking into account the priority of them in the islanded mode, i.e., Load 1 (most priority), Load 2, Load 3, Load 4 (less priority). As can be seen, the MG is connected to the utility grid via Point of Common Coupling (PCC) where transition between grid-connected and islanded modes is made. All components of the MG are connected via circuit breakers that are controlled by a CMA. The CMA is able to interact with any component of the MG such as PCC CB, DERs, energy storage devices and

controllable loads, to change the operating status of the component as per the requirement. In Figure 1, red/blue lines show schematic communication link between CMA and various component. In addition, the allocated subsystems for real-time simulation have been shown via dashed orange color. The realization of the real-time study will be explained in Section 4.

3. PROPOSED CONTROL STRATEGY

When the MG operates in the grid-connected mode, the utility grid, which acts as an infinite bus, does the control of frequency and voltage of the MG, and so it can maintain the required level of voltage and frequency easily. However, immediately after disconnection of the MG from the main network, the MG requires a governing scheme to maintain nominal values of frequency and voltage, and so the safety and stability of the MG. In this regard, the following control schemes, including the proposed strategy of the paper, are utilized.

3. 1. Energy Storage System The concept of a smart MG also contains an energy storage system, which is used to store energy when it is in excess. This gives the consumers the flexibility to store the energy when the prices of electricity are low, and use it when the prices are high. In addition, to ensure uninterrupted supply to priority loads, operation of energy storage devices like battery, flywheels and ultra-capacitors can be controlled. In the MG under study, a 1000v Lithium-Ion battery as the ESS element is used. As some DERs, like PV, have low inertia or ride-through capability and they are generally operated with adopted control strategy of constant power factor, the ESS also helps in supplementing the MG during low voltage transients on the distribution system, or short-term overloads, especially for autonomous operation. It should be

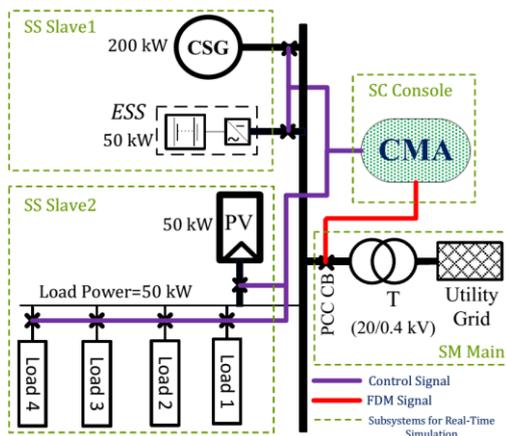


Figure 1. Simplified scheme of the MG under study

however noted that as per the size and capability of the used ESS, it is not able to guarantee the stability of the MG after sever disturbances, and the ESS is generally used for compensating voltage sags or small disturbances in the islanded mode [4].

In the present study, when the MG is in grid-connected mode, the ESS operates in the charging status to store energy, while in the islanded mode, the ESS supplies power to the MG to help stable operation of the MG (discharging status). In order to integrate ESS into the MG, an AC-DC converter is required to convert the AC voltage from the grid to charge the battery of the ESS, and a DC-AC inverter is required when the battery supplies the MG in discharging period. The detailed structure of the utilized ESS has been described in [32, 33].

3. 2. Frequency and Voltage Control by Central Synchronous Generator

In the present study, a CSG is employed to acts as a swing bus and be responsible to control the MG. The CSG would rapidly react to fluctuations to return the voltage and/or frequency within acceptable ranges in a short time. In fact, due to the following reasons, utilizing the CSG is essential for control and stability of the MG in the stand-alone mode:

- The generation capacity of DERs generally is low and in the case of severe disturbances, they might not be able to compensate the required amount of power. Apart from that, due to the intermittent nature of some of them, like PV, the declared net capacity is less than the nameplate capacity.
- Inverter-based DERs have very low inertia as they are decoupled from the MG by the inverter. Therefore, in the MG with high penetration level of inverter-based DERs, the frequency may change rapidly during a disturbance as the rate of frequency change depends upon the inertia of the MG. In such situation, the DER might be disconnected from the MG as per its fault ride-through (FRT) capability that endangers the stability of the MG. In the present study, the FRT capability has been set for PV based on [16] to fully model the MG and its components.

According to aforementioned issues, the CSG makes it a critical part of the MG as it adjusts its output depending upon the need of the MG. In other words, the control strategy of the CSG is characterized as grid forming function in the islanded condition to manage its own active/reactive output in response to the frequency/voltage of the MG after transition to islanded mode.

However, once the MG is reconnected to the utility grid, the CSG output is reduced to the minimum possible level, and its control strategy is switched to a constant

power factor (known as grid following function). It is worth noting that the importance in utilizing the CSG is its fast response to help maintaining the stability of the MG. The detailed information regarding undertaken control strategy of the CSG has been modelled based on the presented model in [34], and so the detailed information are not given here.

3. 3. Central Management Agent The overall control and management of the MG should be implemented through an intricate device interlinked through real-time communication channels. Therefore, in this paper, a CMA is presented at the top level of the MG control to perform functions like control of MG in both grid-connected and islanded mode, energy management, metering and protection of the MG. In other words, in the present study, the MG is managed and controlled as if it is one entity, and based on that all the protection/control routines are achieved through the CMA. In order to implement the proposed strategy and to achieve correct sequence of operation, the CMA has possibility of real-time communication with the MG components including PCC circuit breaker, DERs controller, and load breakers to send proper command signals to all the equipments. As a side note, it is important to mention that various management functions, like synchronism-check unit, is also embedded in the CMA. However, they are not reported in detail here as they are beyond the scope of the present study. Three main functional modules of the proposed CMA are:

-Fault Detection Module (FDM)

Protection system of a MG must be designed to ensure stable operation of the MG during any contingency. The issue of MG protection has already been addressed in many papers by proposing different protection schemes [8, 10, 16]. In this paper, a simple protection strategy based on current and voltage protection functions [10] is embedded in the FDM for the purpose of fault detection. In other words, whenever there is a fault in the utility grid, FDM detects it firstly and sends a signal to disconnect the MG from utility grid resulting in islanding. In this paper, an external fault input has been integrated for the sake of real-time simulation, which will be explained in Section 4 of the paper.

-Control Module

This module executes the overall control of the MG by providing calculated setting of control schemes, as already mentioned, and most importantly performs the proposed load-shedding strategy to prevent MG collapse after islanding. This function, which is the main novelty of this paper, is discussed in Section 3.4.

- Seamless transition from islanded to grid-connected mode

Once the upstream fault is cleared, the MG can be reconnected to the utility grid. However, synchronization on both sides of the PCC is necessary before closing PCC

circuit breaker, which is one of the important functions of the CMA in the present study. In this regard, the CMA checks frequency, voltage magnitude and voltage phase of the two grids from the accurate matching to prevent transients. In this way, seamless transition from islanded mode to grid-connected mode is guaranteed. Further, the CMA communicates with the ESS to change its statuses from discharging to charging, and also changing the control mode of the CSG in the time of grid restoration.

3. 4. Proposed Load-shedding and Restoration Strategy

-Load-Shedding

The control methods outlined above are only effective if the balance between load and generation is maintained after islanding. However, it is very common that the transition is usually associated with an excessive load (or generation). Under this condition, the MG frequency drops or increases rapidly according to imbalance in load and generation, which can lead to instability of the MG. The most common way to safeguard the MG from instability is to shed share of the load/generation to rebuild the balance between load and generation.

This paper proposes a robust load-shedding scheme that shed/restore the loads regarding frequency measurements combined with average rate of frequency change. The proposed method acts compatible with the control routine of DERs and the intermittent nature of the PV plant as per its Maximum power point tracking (MPPT) technique. The instantaneous frequency gradient (df/dt) method, which has been used in some papers, can differ for system disturbances in the PCC and may vary in time due to transition to islanded mode. Moreover, it is severely affected by frequency fluctuations and may have inappropriate performance under these conditions. Therefore, to overcome this issue this paper proposes measuring and considering the mean value of the frequency gradient for implementation of the load-shedding scheme. In this scheme, the CMA activates the load-shedding scheme once the MG is islanded to restore the balance between the load and available generation, and thereby, prevents the frequency collapse. In fact, the CMA collects both frequency and mean value of the frequency gradient in real-time manner to check whether they exceed or fall below the set thresholds. Finally, if both conditions are satisfied, the CMA initiates a signal to trip the loads assigned priority 1 (stage 1).

Figure 2 shows the operation of the proposed load-shedding strategy schematically.

As per Figure 2, the $\frac{\Delta f}{\Delta t}$ function of the proposed scheme is active only below a frequency threshold f_{th1} , and afterwards a timer is started (setting value Δt in periods). When the measured system frequency drops under tripping value f_T within the time Δt , the CMA

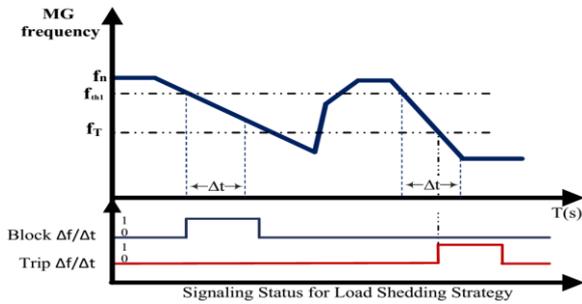


Figure 2. Operation of the proposed load-shedding strategy with mean value of the frequency gradient (for first stage)

immediately initiates a signal to trip the loads assigned priority 1. The tripping value f_T results from settings Δf , f_{th1} and Δt :

$$\Delta f = \frac{f_{th1} - f_T}{\Delta t} \quad (1)$$

$$f_T = f_{th1} - \Delta f \times \Delta t$$

If the frequency goes further down, the next stage of the loads will be shed and this will continue until the frequency returns to its nominal value. Obviously, if the actual frequency does not fall below f_T within Δt , load-shedding does not occur.

The primacy and advantage of the proposed scheme over existing schemes, like instantaneous frequency gradient-based load shedding scheme, is its robustness against frequency oscillations. In other words, if the frequency drops continuously over time, the proposed scheme will be activated to shed the assigned loads, but if the frequency fluctuation, which probably results in the frequency exceeding the threshold frequency value in Figure 2, the CMA will reset the scheme again to avoid unnecessary shedding of the load within frequency fluctuations.

Moreover, in the proposed scheme, to avoid MG instability due to probable slow frequency drifts, time delayed back up load-shedding function, which operates regardless of the mean value of the frequency gradient, is provided at each stage of the load-shedding scheme. The schematic representation of the designed load-shedding scheme and set thresholds is depicted in Figure 3.

- Load Restoration

If the load-shedding scheme has been successfully implemented, the MG frequency will stabilize and then will recover to the nominal frequency. The CSG in this step will assist this recovery. Therefore, the recovery of MG frequency to the normal value is likely to be slow deposit its decline. Based on the proposed load restoration scheme of the paper, the CMA monitors the frequency changes continuously and as the MG frequency approaches the normal value; restoration of the

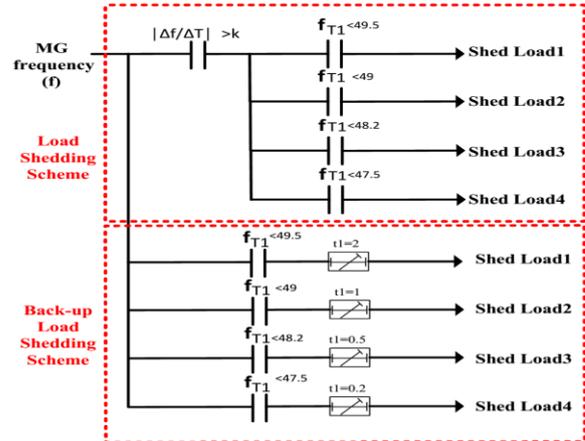


Figure 3. Schematic representation of the proposed load-shedding strategy

loads that have already been shed is initiated automatically. In the load restoration program, the amount of load that can be restored in each stage is determined by the ability of the MG based on the available generation.

However, in the case of serious change of MG frequency, there is a possibility to oscillate between shedding and restoration, which is one of the main challenges in load-shedding/restoration programs. Hence, to overcome this issue, the load restoration operations are triggered in conformity with passing frequency its thresholds and by equating the rate of mean change of frequency between its relevant thresholds. In this way, reconnecting loads in each stage minimizes power swings within the MG and thereby minimizes the possibility of starting a new disturbance.

4. REAL-TIME STUDY

4. 1. MG Model for Real-time Simulation

The realization of the proposed strategies and the possibility for fast exchanging information between different components is one of the major challenges faced by the MGs in providing the required services. The realizations of this issue needs a high-speed communication system and can be achieved by using a real-time simulation testbed [35, 36]. For verifying this matter, the behavior of the MG is tested through a real-time simulator. In fact, in this study a HIL testbed for real-time simulation is developed under which the proposed scheme and related communication with the CMA and other components are evaluated. The real-time simulation is conducted using eMEGAsim RTDS developed by OPAL- RT Technologies Inc. OPAL-RT simulators, equipped with the OP5600 chassis, is a complete simulation system containing a powerful real-time target computer

equipped with up to 12 parallel processor cores, a flexible high-speed front-end processor and a signal conditioning stage [13]. Figure 4 shows the experimental real-time simulation testbed developed in this work. In the designed testbed, oscilloscope displays input and output from the front panel. Host RT-LAB command station PC is used to load the MG model on OP5600. RT-LAB target PC is used to display outputs from console. The LEDs are used to represent automatic under frequency priority based load-shedding process in the MG. Additional external fault is added in the model to test FDM and behavior of MG prototype in both modes of operation (grid connected and islanded) in real-time. To do so, an external analog input from OP5600 is used to control a 3-phase fault in utility grid line. Fault occurrence and clearance are controlled by an external switch (See Figure 4)

In the real-time model of this study, the MG is first modelled into MATLAB, as the OPAL-RT eMEGAsim is integrated with MATLAB/Simulink, and is then converted to RT-LAB for testing in real-time. RT-LAB software provides parallel processing on OPAL-RT’s CPUs for fast real-time simulation.

To execute the real-time model on several cores, the MG is reorganized in different subsystems (so-called: master, slave, and console) for compilation by RT-Lab. The separated subsystems for performing real-time study have been illustrated in Figure 1, based on which reorganization of the studied MG in RT-LAB are demonstrated in Figure 5. The real-time reorganization consists of four subsystems; one master, two slaves, and one console. In OPAL-RT, the master and slave subsystems are assigned to different processors by RT-LAB for faster computation. The master subsystem

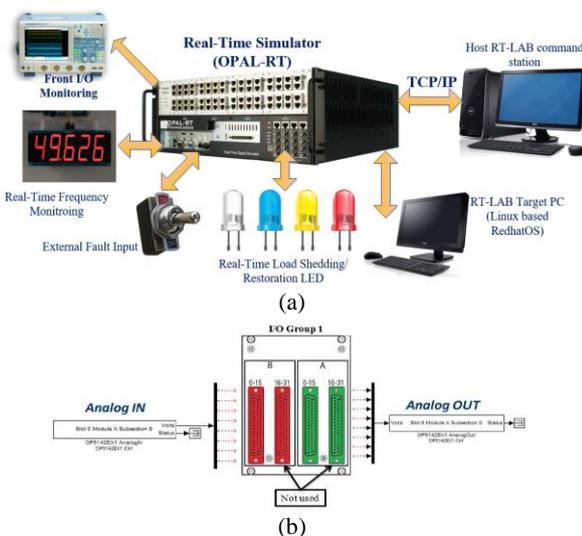


Figure 4. (a) Real-time hardware in the loop simulation test bed (b) RT-LAB blocks used in this paper to assign their respective analog input and output ports on OP5600 panel

includes utility grid, while the slave subsystem includes CSG, ESS, PV and the loads. The allocation of each elements, pre-fixed with “SM_”, “SS_” and “SC_”, have been specified in Figure 5. The load-shedding/restoration scheme and power management computational blocks are placed in master subsystem because it has highest priority for processing. Console subsystem consists of scopes and displays, and its function is to display output on host computer.

For multi-core computation purpose, “Stubline” decouples different subsystems from each other. Stubline block is a decoupling tool from Artemis library, which makes the computation processes faster. In the real-time modelling of this paper, other than the necessary blocks, additional OpComm and OpMonitor, OpTrigger, fault set are included. OpComm block, which enables communication between subsystems, is installed in all subsystems of the prototype, as all the signal inputs between the subsystems are required to pass through Opcomm block. Integrator and memory blocks are also installed at output points of every subsystem to maximize the processing speed of real-time simulation. The OpMonitor block is used to add real-time monitoring capacity for simulation.

4. 2. Real-time Hardware in the Loop (HIL) Simulation

OpComm block from RT-LAB library was installed in all subsystems of the prototype, as all the signal inputs between the subsystems are required to pass through OpComm block in RT-LAB. OpComm enables communication between subsystems. Integrator and memory blocks from RT-LAB library were installed at output points of every subsystem to maximize the processing speed of real_time simulation.

The analog inputs and outputs were assigned to FPGA ML605 using input and output blocks from RT-LAB I/O library. The blocks from RT-LAB and their respective input and output ports in I/O Group 1 has been shown in the Figure 4.(b). Only I/O group 1 of OP5600 was used in this paper.

In this paper, the analog outputs signals are used for the following:

- To turn on four LEDs that represent loads in the system, these LEDs also depict the load-shedding process.

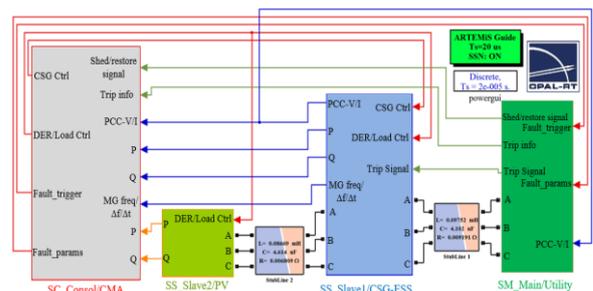


Figure 5. Representation of MG model in RT-LAB

- To display the operating frequency of the system on external LCD via used microcontroller.
- The analog inputs signals are used for the following in this paper:
- To receive an external control signal from a switch to control the 3-phase fault in the main grid.

5. REAL-TIME SIMULATION RESULTS

Verification of the proposed algorithm is carried out by comprehensive real-time simulation studies on the MG shown in Figure.1. The MG data, which some of them, like DER capacity, have been inserted in Figure. 1, are given in [31]. The real-time performance of the MG is evaluated by real-time simulation based on the explained OPAL-RT testbed (Figure. 4). This section contains selected real-time simulation results that validate model design and the control strategies proposed to maintain system stability in islanded mode. For this purpose, within the first three seconds of simulation external fault input in ON. Therefore, the FDM module detects the fault in utility grid and automatically causes islanding of the MG. After the external fault is removed, if the synchronization conditions are met, the MG is reconnected to the utility grid.

To verify the effectiveness of the proposed strategy, two scenarios are simulated. The first one is the case where no load-shedding scheme is utilized, while in the second scenario the load-shedding scheme is implemented. In the present study, the threshold value of the frequency and the frequency gradient are assumed 49.5 HZ and 60, respectively.

Scenario 1: Based on the control routine, when the MG is operated in islanded mode the CSG, ESS and PV supply energy to the loads. In this paper, PV operates under constant power factor and so it does not participate in voltage/frequency control. In such a case, the CSG, as the main controller, tries to balance the mismatch between the generation and demand to counteract voltage/frequency variation. However, when the MG starts operating in the islanded mode, the demand of loads is assumed greater than maximum power generation capacity of PV, CSG and ESS. Consequently, despite the CSG attempts at control of the MG, the frequency of the MG starts to dip due to instability. Figure 6 demonstrates the MG frequency under this situation. As can be clearly seen, the synchronization unit of the CMA does not allow connection of the MG to the utility as the MG frequency is too low. In this figure, the signaling statues of the FDM performance, which is governed by the CMA is also depicted.

Scenario 2: Figure 6 shows the primacy of the utilization of the load-shedding strategy. To overcome this issue, the proposed load-shedding scheme automatically starts to shed the loads as per the frequency value and the mean change of frequency variation. In Figure 7, the frequency

variation and $\Delta f / \Delta t$ function as well as the performance of the proposed strategy in Scenario 2 are demonstrated. In this figure, high signal on the graph represents that the load is restored to the MG, while the low signal shows that the load is shed at that point of time. The different loads are shown in increasing order of priority from top to bottom with Load 1 being the least important one, and Load 4 being the most important one.

From the real-time simulation result, it can be seen that Load1 and Load 2, due to their considerably low priority, are the first loads to be shed and last ones to be reconnected. The power output of the DERs and utility grid in this scenario are also shown in Figure 8. As can be seen in this figure, during the fault period, no power is generated by the utility grid and the CSG alter its output in accordance with load change and tries to maintain generation/demand balance within the MG, as the ESS and the PV are constant output sources. The swing capabilities of the CSG can also be observed in Figure 8 at 1.75 seconds, where the CSG ramps its output to compensate for decrease in power output of PV due to change in irradiance input of PV.

As per Figure 8, after 3 seconds the fault is cleared and the MG is reconnected to the utility grid, thus PV and grid supply all the power to the loads. In this time, the CSG is disconnected from the MG and the ESS stops discharging. On contrary, during the grid-connected mode of the MG, the ESS will be operated in the charging cycle as a load, however, as Figure 8 demonstrates the output generated power of DERs, the charging curve (as a load consumption) is not depicted in this figure. In this figure, a comparison between load consumption (of load 1-4) and generated active power (via utility grid and PV and CSG) obtains the amount of ESS power consumed.

Further, as can be seen in this figure, a seamless transition to grid-connected mode occurs which the most important reason is the adding of pre-synchronization unit in the proposed control routine. Nonetheless, the MG undergoes a transient state with load-shedding before achieving the new stable operating point or in the time of reconnecting to the grid. This is because of the switching action of the DERs, which produces transient distortion.

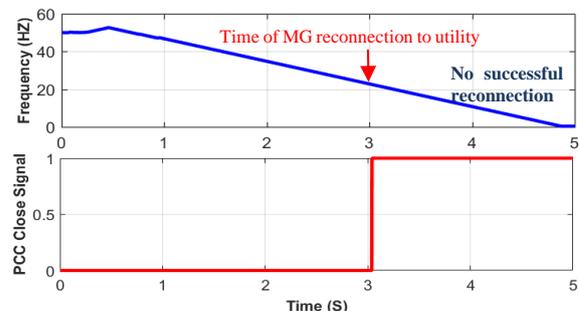


Figure 6. MG frequency under fault condition and reconnection signal (Scenario 1)

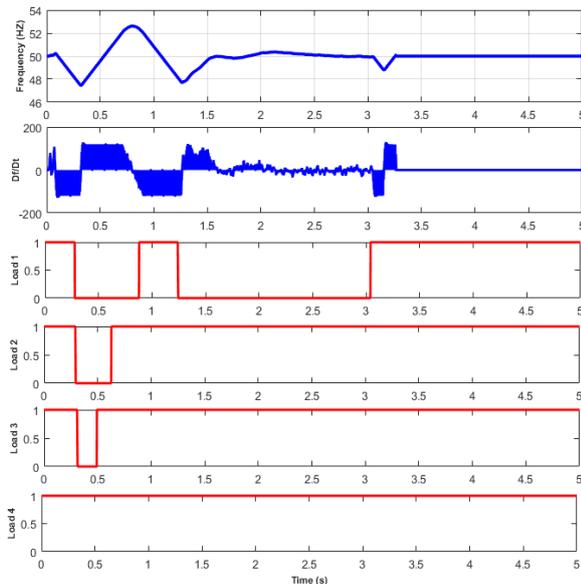


Figure 7. MG frequency and performance of the load-shedding/restoration scheme (Scenario 2)

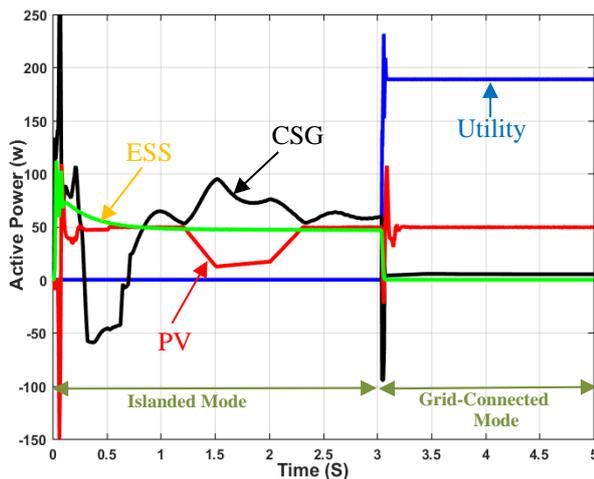


Figure 8. Power output of DERs during islanded and grid connected mode

6. CONCLUSION

One of the main issues in stable operation of the MG, particularly after transition to islanded mode, is the occurrence of voltage/frequency fluctuation. This matter shows the importance of utilization of an efficient control strategy in MG. This paper presents a Central Management Agent (CMA), which by controlling an Energy Storage System (ESS) and a Central Synchronous Generator (CSG) could maintain the stability of the islanded MG. However, to deal with imbalance of generation/demand a novel load-shedding/restoration was proposed to conserve stability of the MG. In this regard, the CMA utilizes frequency measurements

combined with average rate of frequency change of the MG to perform the load-shedding/ restoration strategy. The salient feature of the proposed scheme over existing schemes, like instantaneous frequency gradient-based load shedding scheme, is its robustness against frequency oscillations. Finally, to evaluate such a complex system a hardware-in the loop testbed for implementing real-time simulation was developed in this paper. The real-time obtained results confirmed the effectiveness of the proposed strategy.

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A New Adaptive Load-Shedding and Restoration Strategy for Autonomous Operation of Microgrids: A Real-Time Study

M. Farzinfar^a, N. K. C. Nair^b, M. Bahadornejad^c

^a School of Engineering, Damghan University, Damghan, Iran

^b Power Systems Group of Department of Electrical and Computer Engineering at University of Auckland, Auckland, New Zealand

^c Unitec Institute of Technology, Auckland, New Zealand

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یکی از ویژگی‌های یک ریزشبکه عملکرد جزیره‌ای آن است که با توجه به حضور منابع تولید پراکنده محقق می‌گردد. باین‌حال، به‌منظور حل چالش‌های کنترلی که یک ریزشبکه در مد جزیره‌ای، به‌ویژه هنگامی که گذر به این مد همراه با بار اضافه می‌باشد، یک استراتژی کنترلی کارآمد نیاز است. در این مقاله یک سیستم مدیریت مرکزی با کنترل هم‌زمان یک سیستم ذخیره‌ساز انرژی و یک ژنراتور سنکرون مرکزی پایدار ریزشبکه در مد جزیره‌ای را حفظ می‌کند. همچنین، این مقاله یک طرح جدید قطع و بازیابی بار ارائه می‌دهد که بر اساس اندازه‌گیری مرکب دو پارامتر فرکانس و مقدار متوسط گرادیان فرکانس مقدار عدم تعادل بار را محاسبه می‌کند. مقاوم بودن در برابر نوسانات فرکانسی ریزشبکه برتری روش پیشنهادی بر طرح‌های موجود قطع بار، همانند طرح مبتنی بر گرادیان لحظه‌ای فرکانس، می‌باشد. علاوه بر این، روش پیشنهادی مقاله سازگار با استراتژی کنترلی منابع تولید پراکنده و رفتار متغیر نیروگاه خورشیدی می‌باشد. یکی دیگر از ویژگی‌های برجسته این مقاله پیاده‌سازی یک میز تست شبیه‌سازی سخت‌افزار در حلقه به‌منظور ارزیابی روش پیشنهادی و ارتباطات سیستم مدیریت مرکزی با اجزای ریزشبکه به کمک شبیه‌سازی زمان واقعی است. نتایج زمان واقعی به‌دست‌آمده نشان می‌دهد که استراتژی کنترلی این مقاله پایدار ریزشبکه در مد جزیره‌ای را حفظ و امکان بازگشت هموار آن به مد متصل به شبکه را تضمین می‌کند.

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