Local Power Controller Based Load Shedding Scheme in Islanded Microgrids

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Abstract- To decrease the blackout risk due to the large disturbances, it is recommended to intentionally create islanded conditions in power systems. In this event, system elements will be insulated and the supply for creating the islands can be preserved. To do so, resources and generations in the islands are discharged and loads should be shed in case it is required. In this condition, voltage and frequency stay in their limits. In this paper, a priority-based load shedding technique is proposed using a Local Power Controller (LPC) for islanded microgrids. The suggested method utilizes frequency and rate of change of frequency (ROCOF) based approaches to activate the shedding procedure. Moreover, the proposed approach controls the islanded microgrids for developing a support for the main grid in the case of frequency deviation events whereas supplying the local critical loads is mandatory. The advantages of method are minimum equipment requirement and suitability for end-users with critical loads. In the proposed methodology, a load addition mechanism is also considered. This mechanism automatically switches the shed loads when the system frequency recovers to a certain level. The proposed method scheme is verified and validated in a laboratory microgrid test bench under two operation modes, specifically allowing load shedding procedure in advance of and consequent to the islanded situation. In both cases, the results demonstrate that the scheme is able to sustain the islands.

Keywords Local power controller, islanded microgrid, load shedding method, smartgrid.

1. Introduction

Making islands in the system is one of solutions for decreasing the risk of occurrence or possible amount of the blackout. In these conditions, the disturbed features of the system are separated and the source to the created islands can be continued [1-10]. To avoid frequency degradation and support the sustaining created islands, load shedding is an optimum choice [3]. Different researches have been done in the improvement of load shedding methods [3-20]. Among these researches, references [3], [5-7] and [9] denote load shedding patterns that sustenance with the balancing of power generation and demand between created islands. Although, there are a few load shedding techniques in the area islanded condition (before or after entering the islanded microgrid), so that the top levels of support to the network can be recognized while supporting the local supply. Also, the performances of most of the methods are simply confirmed and tested using simulations [21-26].

This paper presents a Local Power Controller (LPC) that reports the challenge of preventing overall blackout by managing local networks properly with distributed generators (DGs), which are often called microgrids. The LPC is equipped with a priority-based load shedding scheme that allows loads with low priorities to be shed first while ensuring supply to most critical loads – there may also be commercial arrangements among suppliers, network operators and customers that would also explain the priority list used. This method develops a frequency and rate of change of frequency (ROCOF) based approach which needs minimum equipment. A load addition mechanism is also provided with the proposed approach when the system frequency recovers to a certain level. The mechanism automatically switches the shed loads. The proposed scheme has been evaluated and validated in a laboratory microgrid test bench under two operation modes: enabling the load shedding process in advance of and subsequent to the local system being islanded. The experimental validation results for both situations are developed and compared later in the paper. Such a scheme is mainly appropriate for end-users with critical loads and emergency backup generators.

Recent progresses in smart grid technologies, e.g. smart metering, rather than completely shedding them, offer possibilities to further improve of the scheme by controlling loads. Flexible loads could be controlled to further reduce the supply interruption (even for low-priority loads) with no obvious impact on consumers. This paper investigates the potential enhancement of the scheme by incorporation of such demand-side management elements. Future accomplishments to examine the communication necessities to sustenance the practical implementation of the scheme and the effect of communication problems on the method performance are also deliberated.

The paper is structured as follows. Section II offers an outline of the LPC system and presents the proposed load shedding procedure. In Section III, the tests and demonstrations of the load shedding scheme in a laboratory microgrid test bench are obtainable and the results are analyzed and discussed. Section IV presents a comparative assessment between the proposed method and three well-known approaches. And finally, Section V presents the future work on the developments of the scheme and the study of communication necessities to upkeep the load shedding structure.

2. Local Power Controller (LPC) based Load Shedding method

2.1. Overview of the LPC

The LPC is deliberated for the managing the microgrids and covers a suite for control and protection algorithms. The LPC can provide main network support during system instabilities while certifying high level of security for supplying the local loads. This is mainly achieved by operating the potential microgrids in either grid-connected or islanded mode to cater for various system conditions, properly dispatching the local DG(s), and shedding loads when necessary. In [11], the functionalities of the LPC are presented and the ways that functional elements are coordinated to sustain microgrids during large system disturbances are demonstrated. In this paper, focus is placed on the demonstration of the load shedding scheme within the LPC and the analysis of the impacts upon the local and main networks when the scheme is enabled either before or after the local system is islanded.

As mentioned before, the load shedding scheme is priority-based. There is currently provision for loads with nine different priority levels. This is shown in Fig. 2 later in the paper, where load 0 has the highest priority and should always remain on while load 8 has the lowest priority and will be shed first when needed.

The load shedding algorithm is largely a standalone element within the LPC. The main function of the element is to monitor the frequency of the local power system, and to shed loads as in the way it is needed to keep the generator within its sustainable power range and switch on the shed loads when the system frequency recovers to a predefined level. There are two main operational modes for the load shedding scheme:

- ➢ enabling the load-shedding function in advance of an islanding event, and
- ➢ After an island is created, i.e. islanded mode.

2.2. Load shedding in advance of an islanded event

In the first mode, the network frequency and ROCOF are determined by the entire network and do not necessarily represent the balance between local load and local generation capacity. Therefore, a simple power-balancing network model is used to predict performance of the local network which would result if it became islanded. This is done by predicting the per-unit power output of the local generator, and its drooped frequency, based upon the known local load consumption and the known droop slope.

If the predicted generator power is >1pu, i.e. if the present load demand is higher than the generator active power rating, then loads will be shed using a slow load shedding process: i.e. shed one load (from the lowest-priority loads) at a time if a hold-off time of 3 s has elapsed since last load was shed.

The load shedding scheme is also equipped with a reconnection mechanism. If the generator power is <1pu, then the predicted drooped frequency in islanded mode is checked against the reconnection frequency threshold (typically 49.98 Hz). If frequency is above this value, and ROCOF is positive, loads would be reconnected one at a time with a minimum time interval between individual connections (typically 3 s).

Local loads can therefore be shed or reconnected even when the local system is still connected to the grid. This allows the local generation and loads to be matched as closely as possible prior to any islanded condition so that the impact of islanded on the islanded system would be minimal. This may lead to the risk of failure in detecting unexpected islanded conditions from only electrical measurements, but this can be addressed using advanced island detection methods, such as that reported in [12].

2.3. Load shedding subsequent to an islanded event

The islanded load shedding algorithm works by using thresholds of frequency and ROCOF to decide whether relatively slow load reduction, fast load reduction or load addition with a fixed (but configurable) interval is required. The actions are performed individually and sequentially, and a minimum wait time between actions is applied to allow the system to settle before the next action is permitted – the wait time and actions are flexible and can be configured. This is necessary due to the response times of the prime mover controllers and any inertia in the generation and/or load systems.

This mode of operation only allows shedding of loads when islands have been created, so the impact of islanded could be relatively more significant, potentially resulting in large ROCOF and frequency deviations in the island immediately following the island formation.

The islanded load shedding algorithm implemented in the LPC is illustrated in Fig. 1, and can be summarized as follows:

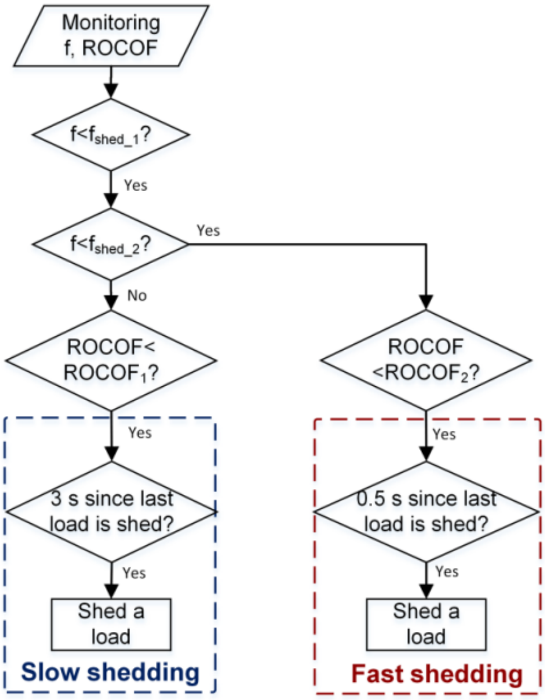

Fig. 1. The load shedding algorithm implemented in the LPC

- ➢ The frequency (*f*) and ROCOF are continuously monitored.
- ➢ If the frequency falls below f_{shed_1} (typical set as 49.2 Hz) but above f_{shed_2} (typically 48 Hz), and ROCOF is smaller than $ROCOF_1$ (typically -0.05 Hz/s), a slow load shedding process is triggered, i.e. shed one load (from the lowest-priority loads) at a time if a hold-off time of 3 s has elapsed since last load was shed.
- ➢ If f falls below f_{shed_2}, and ROCOF is negative (smaller than $ROCOF_2$, which is typically 0 Hz/s), the fast load shedding process is triggered i.e. shedding loads with much smaller time interval (0.5 s in this case).

A reconnection mechanism is also available in this mode of load shedding, where if the frequency recovers to above a certain limit (typically 49.98 Hz) and ROCOF is positive, loads would be reconnected one at a time with a time interval between individual connections (typically 5 s).

3. Demonstration of the Load Shedding Scheme

3.1. *Overview of the demonstration*

The developed load shedding scheme presented in Section 2 has been tested in a laboratory microgrid environment, and a test schematic is shown in Fig. 2. The LPC requires measurements of voltages and currents at only two local points, i.e. at the DG terminals and at the point of common coupling (PCC). For the operation of the load shedding scheme, only measurements at the DG terminals are required. The algorithms reported in [13] have been used for the measurement function in system reported here. The LPC is implemented and executed on an MVME5500 processor card [14], which is embedded with a multi-processor rack [15] that allows logging of performance [11].

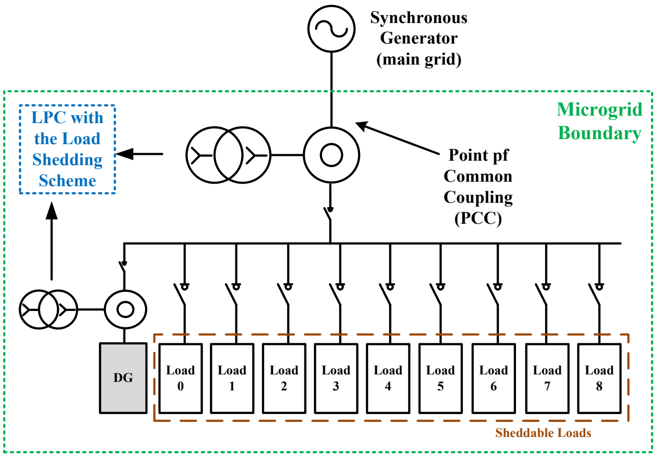

Fig. 2. Overview of laboratory arrangement for the demonstrations

In this arrangement, an 80 kVA synchronous generator (a controllable motor-generator set) is used to represent the main distribution grid where the microgrid is connected. By closely controlling the synchronous generator, appropriate voltages and frequencies can be produced to emulate disturbance events for the test scenarios. A load of 2 kW is permanently applied to this grid source to provide additional stability to the control of the 80 kVA generator. Between the grid source and the microgrid, impedance is inserted to represent the transformer that interfaces the microgrid to the main grid. For the tests demonstrated in this section, the impedance is 16 mH per phase. This represents an impedance of 6.25 % at the 2 kVA level, and is therefore a realistic impedance to simulate an 11 kV to 400 V transformer at the microgrid to main grid interface, using power flows of the order of 2 kVA (the total load is around 2200 W, which is discussed later in this section).

Within the microgrid, there is a converter-interfaced DG with a maximum power output of 1500 W, which has been specially designed to behave as a synchronous generator and is capable of operating under islanded and grid-connected conditions. More details on this are reported in [16].

The local loads used are commensurate with the size of the generator. There are two main scenarios that may potentially be experienced by the microgrid in practice, i.e.

the local load is smaller or larger than the DG's capacity. In this paper, the scenario where the total load is substantially larger than the DG capacity is presented. The load is made up of a fixed load of 453 W and 8 sheddable loads of varying sizes, all at a notional power factor of 0.9 lagging. The total load is approximately 2200 W, of which the 4 lowest-priority loads must be shed in order to bring the total load below the nominal DG power output of 1500 W to preserve island stability.

In the demonstrations, a worst-case scenario is presented, where the local DG is not in operation when the disturbance occurs. Such a scenario is considered as the worst case since the DG is required to be dispatched "from cold", which is more difficult to manage than the scenarios where DG is already dispatched and synchronized with the network.

3.2. Demonstration 1: load shedding enabled before islanded

In this experiment, the method for load shedding is started before islanding happens, i.e. the technique is permitted to shed loads when the frequency and ROCOF fall into a pre-configured variety, even when the microgrid continues connected to the core network.

As shown in Fig. 3, the 80 kVA synchronous generator is organized to "play" the pre-defined frequency profile (50-47- 50 Hz frequency sag, with a fall time of 60 second), a hold time of 10 second, and a rise time of 30 second to mimic a system frequency disturbance incident.

At around 23 second, the frequency sag will be lower than 49.2Hz (while the microgrid is connected to the distribution network), and the slow load shedding procedure is started, where loads are shed consecutively with 3 s of hold-off time. As shown in Fig 4, it is obvious that there are four load stages resultant to four loads being shed. Meanwhile, the DG is transmitted by the controller in the LPC so that it can afford to help the main grid. It can be seen from Fig. 4 that, from 28 second forwards, the local load is nearly equivalent to the local DG generation. So, the microgrid is preparing to help the main network by introducing minimum power from the grid.

As it can be seen in Fig.3, after the frequency of the microgrid is improved quickly to around 49.7 Hz, although the frequency in the main network remains to decrease, the frequency endures to decrease below 47 Hz and the local system is deliberately islanded at around 48 second. This planned islanding method permits the local frequency and voltage (as shown in Fig. 5) to be retained within suitable levels.

As declared before, the local load and generation have been thoroughly coordinated before the islanding process. So, the conversion method from grid-connected approach to islanded manner is smooth, which is obvious from reflection of the frequency and voltage profiles as shown in Fig. 3 and Fig. 5 correspondingly.

The frequency of the network improves to 49.75 Hz at around 105 second, and the local system is resynchronized and relinked to the network, i.e. it leaves islanded state. Afterward, as the frequency remains to improve, a load reconnection procedure is begun. As shown in Fig. 4, the loads are reconnected from around 110 s individually and sequentially, also the local DG stands down.

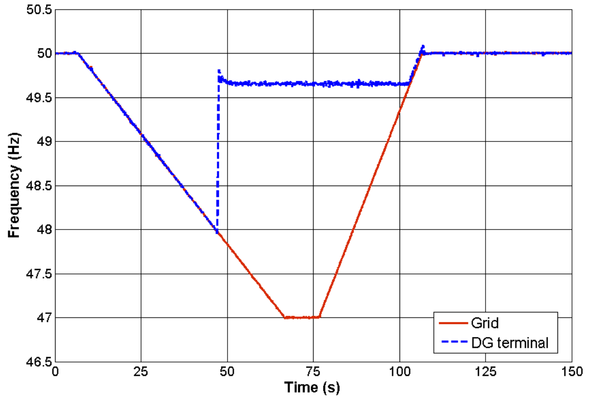

Fig. 3. The frequencies at the main grid and the DG terminal: load shedding before islanded

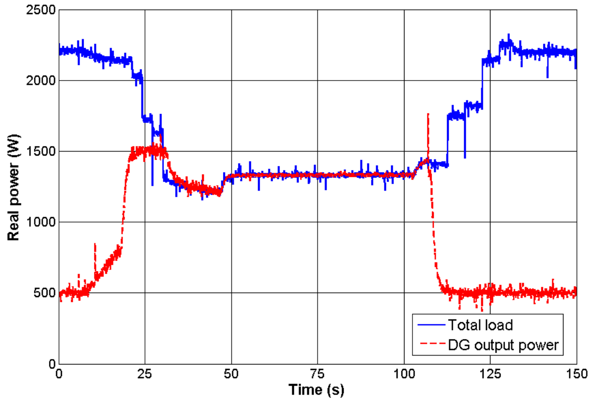

Fig. 4. The DG power output and the total load in the microgrid: load shedding before islanded

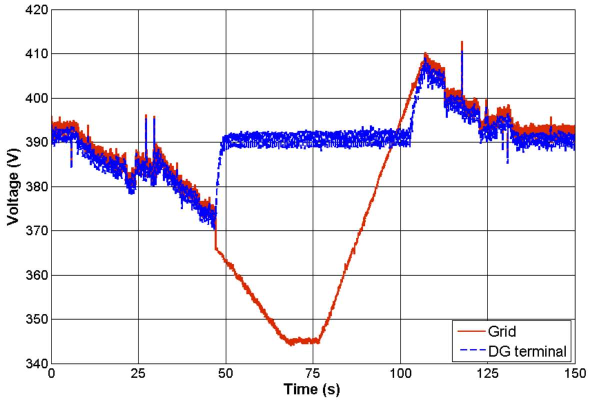

Fig. 5. The voltages at the main grid and the DG terminal: load shedding before islanded

From this experiment, it is obvious that the microgrid can afford helping the main network by diminishing the power importation before going to islanded situation with dispatching the local DG and applying the suggested load shedding structure appropriately. If such a stage is not adequate for the network to improve, the local system will travel to islanded state flawlessly as the local load and generation is matched as near as possible before the islanding action is started. The resource to the most critical loads (load 0-4) inside the microgrid has been sustained. it should be noted that in this event, the synchronous generator imitating the main grid is organized to “play” the pre-defined frequency profile and there is only one microgrid is being experienced, so the maintenance from the microgrid to the network frequency by shedding low-priority loads is not recognizable. However, if there are multiple microgrids contained in the procedure and the power released by the total shed loads in all these microgrids is similar to the loss of generation that origins the disruption, such support to the main network would be more noticeable and could possibly assist to convey the system back to a normal situation minus the need for islanded process.

3.3. Demonstration 2: load shedding enabled subsequent to the islanded event

In this representation, the load shedding scheme is tested under the same frequency disturbance event, but is only enabled when the local system is islanded from the main network.

As shown in Fig. 6 and Fig. 7, when the frequency drops below 49.2 Hz at around 220 s, the local DG is dispatched to provide support to the main network. Although, the load shedding process is not initiated. The islanded operation is performed at around 245 s, and there is a power mismatch of around 700 W between the total local loads the DG output in the island when this islanded occurs. When the local network gets islanded, the DG is switched to the islanded control mode and tries to increase its output to meet the local loads. However, since the load is significantly larger than the generator’s capacity, loads (4 local loads in total) have to be shed until the local system can be maintained stable. As shown in Fig. 6, it takes longer time for the local frequency to recover than in the scenario presented in the before, and the frequency recovery process involves multiple stages, which correspond to the steps where the loads are shed. Similar results can be observed in the voltage profile as shown in Fig. 8.

The reconnection process is similar to the previous scenario, where the local system is re-synchronized and reconnected to the main system when the frequency in the main network recovers above 49.75 Hz, after which the loads are reconnected and the DG stands down.

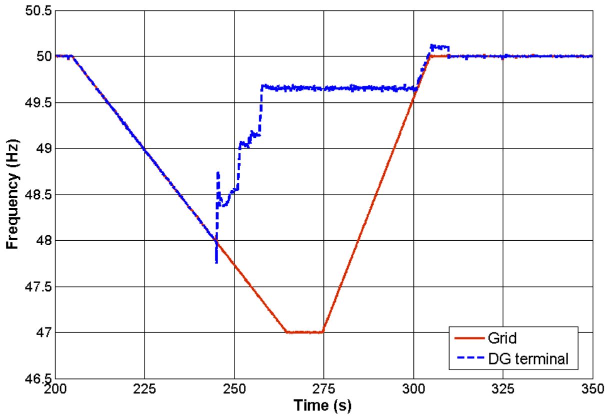

Fig. 6. The frequencies at the main grid and the DG terminal: load shedding after islanded

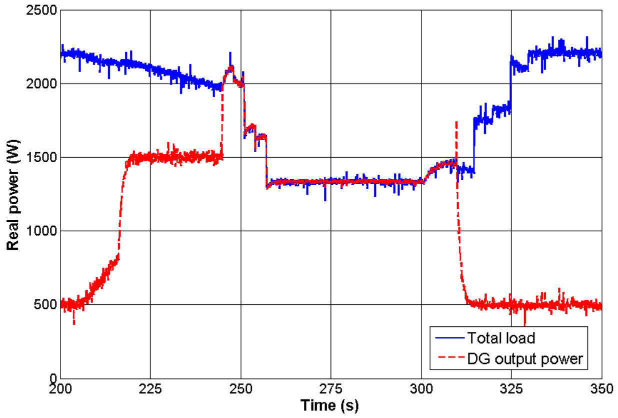

Fig. 7. The DG power output and the total load in the microgrid: load shedding after islanded

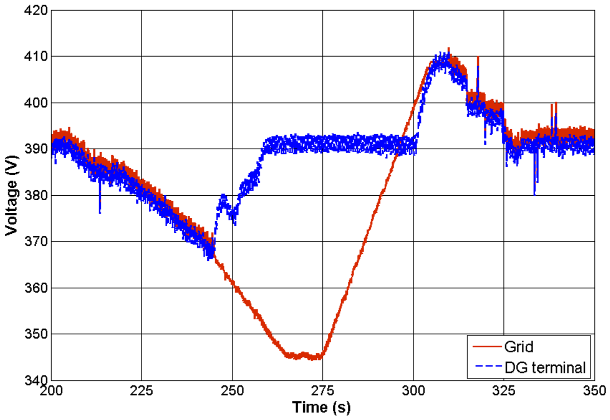

Fig. 8. The voltages at the main grid and the DG terminal: load shedding after islanded

3.4. Discussions of the demonstrations

From each of the two demonstrations presented in this paper, it is clear that the LPC is capable of maintaining the supply to the microgrid with the aid of the developed load shedding scheme. Although four low-priority loads have to be shed in both cases, the continuous supply to the most critical loads has been achieved.

In the first demonstration, the loads are shed before the island is created, so that the local load is matched as closely as possible to the generation within the "potential island", which provides support to the main network by minimizing power import from the network. This also allows a seamless transition to islanded mode. The disadvantage of this mode of operation is that some low- priority loads must be shed "early", i.e. before the island is created, and sustained operation with these loads shed may not be desirable, as islanding may not occur in practice.

In the second demonstration, the loads are only shed when the island is created. This is beneficial in the cases where the main network is capable of recovering itself after a short period of time and the system is not required to switch to islanded mode, because the supply to all loads can be maintained. However, in a large system disturbance, as demonstrated in this paper, such an approach provides less support to the network since no loads are shed until the island is created. Furthermore, when transiting to the islanded mode, the local system may potentially experience a longer period of voltage and/or frequency instability before the system can settle.

In practice, these two modes of operation need to be selected carefully to meet the local microgrid's needs. For example, if the critical loads in the microgrid are sensitive to frequency and/or voltage instability and shedding low-priority loads is tolerable when considering the importance of the critical loads, shedding loads before the creation of islands is more suitable.

4. Comparative Assessment

To evaluate the performance and accuracy of the proposed method, it is compared with some other approaches. The studied methods are briefly reviewed as follows:

A. Plug-and-Play selective load shedding method [24]: In this scheme, a method based on a single measurement of the frequency across the power system is suggested. This approach approximates online the certain structure of the nonlinearities of the swing equation of the power system and adaptively bounds the load disturbances and the functional approximation errors of the nonlinearities.

B. Centralized adaptive load shedding controller [25]: This method is incorporating a distribution state estimator to estimate the power consumption of the demand. In parallel to this, the actual active power imbalance in the microgrid is estimated by simultaneously monitoring the system frequency and its rate of change. The centralized controller uses these two variables to determine the correct amount of load to be shed.

C. Dynamic load shedding method [26]: In this methodology, dynamic load shedding is formulated as a

D. stochastic optimization problem, where the uncertainties induced by intermittent energy sources and load are incorporated whereas the objective is to maximize the economic performance of the microgrid. Limits on the generation resources and operational constraints are also considered. Then, a model based on Markov decision process (MDP) is developed for the problem. A solution method for the MDP model is proposed to obtain the optimal load shedding strategy.

In the following, the performance of the proposed technique is compared with the aforementioned methods based on following four criteria:

- Accuracy
- Computational burden
- Real time application
- Required average time for load shedding

In Table 1, the proposed algorithm is compared with these methods using the mentioned indices. From this table, it is obvious that the proposed method is accurate to determine the amount of load shedding, reliable for practical applications and efficiently applied in modern and complex power systems. Also the method is fast enough with simple procedure to operate in real power systems.

5. Conclusions and future works

This paper has presented a LPC based load shedding technique designated to help the supervision of microgrids through accurate shedding and reconnecting loads. Such a scheme wants minimum equipment for action (only requiring measurement at the DG terminals), and is appropriate for end-users with critical loads and DGs. The objective of the LPC is to afford support to the main grid and guarantee high security level of supply for the microgrid.

The proposed load shedding scheme has been verified and validated in a laboratory microgrid test bench under two operation modes, i.e. enabling the shedding of the loads before and after the island is created, and the results have been presented and compared. It has been shown that the load shedding scheme is capable of assisting sustaining the microgrid during large system disturbances in both modes. Shedding loads before entering islanded mode results in low-priority loads being disconnected relatively early, but can provide support to the main network by minimizing the power import from the grid. This also allows a seamless transition to the island mode, which is most suitable for local systems with critical loads that are very sensitive to frequency and/or voltage instability.

Table 1. Results for comparison with previous methods

Method	Accuracy	Real time application	Computational burden	Average time for load shedding
A	Low	No	High	**Around 15 s**
B	High	No	Very high	**Around 10 s**
C	Medium	No	Low	**More than 8**
Proposed method	**High**	**Yes**	**Low**	**Around 3 s**

Enabling load shedding after the island is created may avoid the disconnection of any loads if the main system recovers before the local system gets islanded, but it would potentially experience longer period of voltage and frequency instability when transiting to islanded mode during large system disturbances.

Future work will focus on the improvement of the developed load shedding scheme so that a faster responding time can be achieved and interruption to the supply can be minimized through the control of flexible loads. Communication requirements and their potential impacts to the load shedding scheme will also be analyzed.

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