FREQUENCY CONTROL OF MICROGRIDS BY DEMAND RESPONSE

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ABSTRACT

This paper investigates the use of electricity demand response as a new measure for fast reserves inside of an autonomous (islanded) microgrid during different operating conditions including frequency controlled disturbance and normal ones. It is worth noting that demand response programs using under-frequency relays to shed the loads is used in the past, but these programs have, however, mainly focused on large-size industrial loads. This paper proposes novel approaches to stabilize the frequency in normal and emergency conditions based on the new bilateral communicating infrastructure within a microgrid. Demand reserves are used based on a pre-scheduled scenario instead of shedding loads or applying generation resources, hence the ease and priority of the customers are guaranteed and full exploitation of generating resources are provided.

INTRODUCTION

Frequency is a parameter indicating the balance of generation and consumption in a power system. Ancillary services are referred to frequency and voltage control, which are essential parts of a power system. In conventional ancillary services, the frequency is primarily controlled by adjusting the generation side resources including extra capacities from large generators and interconnection [1].

In severe stability conditions and lack of sufficient spinning reserve, load shedding is used as the last resort. It is worth noting that generation and demand can be equally applied to the frequency control. Demand response is defined as: "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" by Federal Energy Regulatory Commission (FERC) [2].

Intermittent renewable generation amount is progressively increasing and the flexible conventional generating units are decreasing proportionally, hence, demand response can be very well exploited with increasing penetration of such energy resources [3]-[4].

Actually, conventional primary frequency control is a distributed control system that operates on the imbalance between load and generation through measuring the frequency deviations. Indeed, each generating unit respond to the frequency excursions by its droop characteristic without any communicating signal from the control center. In other words, the generating units that are responsive to frequency changes are self-regulatory units that help to improve the frequency locally without any commanding signal. Secondary and tertiary control loops need communication to and from the control center; mainly for better economic optimization and network security. This means that responsive loads could participate in the frequency control without the insurmountable obstacles of two-way communications between many loads and the control center. However, the newly developed smart grids are moving progressively toward a comprehensive communication infrastructure in order to establish a bilateral electricity and information network. Construction of an advanced communication infrastructure enhances the methods for active participation of electricity consumers in demand response programs. The inherent monitoring potentials of smart grid can overcome the prejudices against demand side resources [5].

Accordingly, microgrid is a new paradigm that is defined as a cluster of renewable/conventional energy resources and loads that have the salient feature of operating in grid-connected or autonomous mode [6]. Frequency control in microgrids is different from the conventional power systems. When the microgrid is connected to the utility-grid, the frequency of the microgrid is the same as that of the main grid, however, the frequency regulation in autonomous mode is an issue, particularly in the absence of ancillary services, like spinning/non-spinning reserves and in the presence of renewable power generation sources with intermittent nature [7].

The utilization of demand as reserve can be largely applied in microgrids, because many electricity demands with small capacities like household appliances including electric heating, refrigerators, freezers, and water heaters are ideal candidates to be used as fast reserves due to their considerable volume and the possibility of instantaneous switching on and off as frequently, and rapidly as needed. This kind of demand can respond autonomously to frequency variation and provide fast reserve to the system by equipping them with frequency sensors and appropriate control intelligence. Demand frequency reserve can deliver the same service plus additional benefits like faster response speed, potentially lower costs, well-dispersed in distribution network and pollution free in comparison with traditional reserves [8]. This is particularly important for networks where lack of balancing resources is foreseen as the major challenge; the best example could be microgrids, when they are operating in autonomous (islanded) mode. It is worth noting that demand-management programs using under-frequency relays to control loads is used in the past, but these programs have mainly focused on large size industry loads.

In this paper the demand within a microgrid is used to respond to the frequency deviations in a manner similar to the generators. Simulation results show that, using this approach, the demand side can make a significant and reliable contribution to primary frequency response while preserving the benefits that consumers derive from their supply of electric energy. The merits of new bilateral communicating infrastructure within a microgrid to stabilize the frequency in normal and emergency conditions by using demand reserve is also discussed. It is indicated that frequency control could be performed by a pre-scheduled scenario instead of generation resources; hence the ease and priority of the customers are guaranteed.

SAMPLE POWER SYSTEM

Figure 1 shows a sample microgrid with one main feeder. It is similar to the LV network proposed in [9], but with some changes and modifications. The network comprises three feeders: one serving a primarily residential area, one industrial feeder serving a small workshop, and one feeder with commercial consumers. The power factor of all loads is assumed to be equal to 0.85 lagging. A variety of DG sources, such as a microturbine, a solid-oxide fuel cell (SOFC), a non-directly coupled wind turbine, and several photovoltaics are installed in the residential feeder. It is assumed that all DG sources produce active power at unity power factor, i.e., neither requesting nor producing reactive power. Minimum and maximum of different microsources are mentioned in Table 1.

Table 1: Installed DG sources

Unit	Unit ID	Min Power (kW)	Max Power (kW)
Microturbine	MT	6	30
Wind Turbine	WT	0	15
Photo Voltaics	PV	0	30
Solid-oxide Fuel Cell	SOFC	3	20

The technical minimum of the microturbine is obtained from [9], so that its operation is stable for an interconnected operation. Its maximum startup time is slightly above 2 min. The Solid-Oxide Fuel Cell (SOFC) type usually used in residential sector installations, also presents fast startup characteristics lower than the time step considered.
As mentioned in the introduction, the role of primary frequency control is very important in initiating moments of a major disturbance in a power system in order to prevent system from collapsing. In this sample system, a major disturbance could be the separation of the microgrid from the utility-grid. Therefore, a coordinated and robust scheduling of frequency responsive generation is needed to bring the microgrid to an equilibrium point.

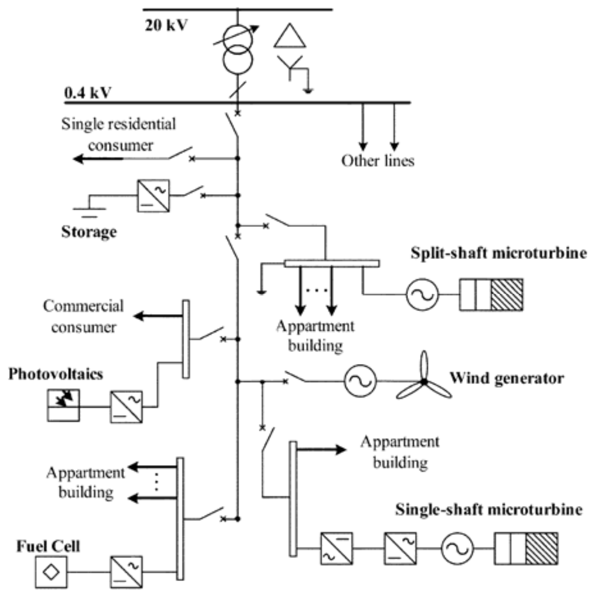

Figure 1: Sample power system

Traditionally, the generating units are partially loaded to provide enough spinning reserve to cope with the transition from utility-grid connection to autonomous mode. This means the microsources could not be used with full capacity. This concept is sometimes referred to "adequacy constraint" [10]. As Figure 1 shows, the opening of the circuit breaker at the beginning of the main feeder transfers the microgrid to the islanded mode. Since the generating units have mechanical governors with slow response, a storage device is needed to stabilize frequency and voltage. In this sample microgrid, some kind of battery is used as storage device.
Normally, the balance of generation and demand in microgrids is performed by importing a portion of the generation from the utility grid. During grid disturbances, the microgrid would be disconnected, so there would be lack of generation, hence a reliable strategy is required to maintain an equilibrium operating point.
Figure 2 shows the variation of the frequency of the microgrid after its transition. At t=5s, the main feeder circuit breaker opens and the frequency drops due to the imbalance between the generation and consumption. The battery performs appropriately to supply the demand for a short time allowing the partially-loaded units to increase their outputs and compensate the generation deficiency. The battery output gradually decreases by increasing the generation. This is the normal operation of a suitably-designed microgrid. It is assumed that the wind turbines and PVs are delivering their maximum output, hence no more extra capacity is expected from them, but other units such as microturbine and SOFC would increase their outputs to compensate the required generation amount. As can be deduced from Figure 2, the frequency drop is not so high due to the intervention of the storage device.

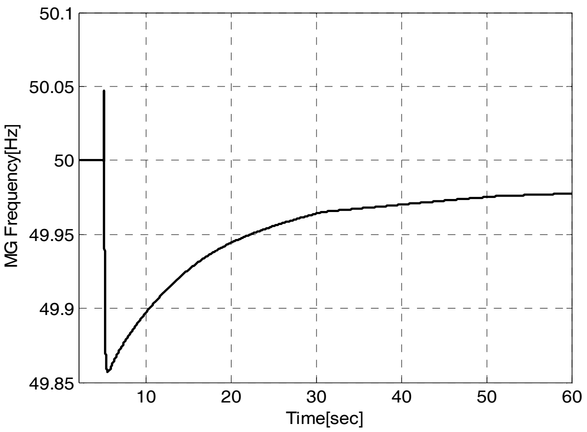

Figure 2: Frequency variation in transition from utility-grid connected mode to autonomous mode

Figure 3 shows the microsources outputs for the mentioned traditional frequency compensation. As can be deduced from this figure, the PVs and wind turbine outputs are intact, while the microturbine and SOFC have increased their outputs. The operation of the storage device (battery) is also very interesting. It shows that the battery delivers a large amount of energy in a very short time to stabilize the frequency, while its output starts to decrease after the intervention of the generating units that are designed to respond to frequency changes.
It is worth noting that microturbine output has increased more than 50% and SOFC output has also increased considerably. This means that adequacy constraint is a remarkable point that forces the microsources within the microgrid to be loaded only by a fraction of their outputs. The adequacy can be well adapted by using the inherent potential of the demand response. This could be very well behaved in such an application. The proposed method is based on the participation of consumers to compensate the imbalance of generation and demand by switching on or off the pre-specified appliances.

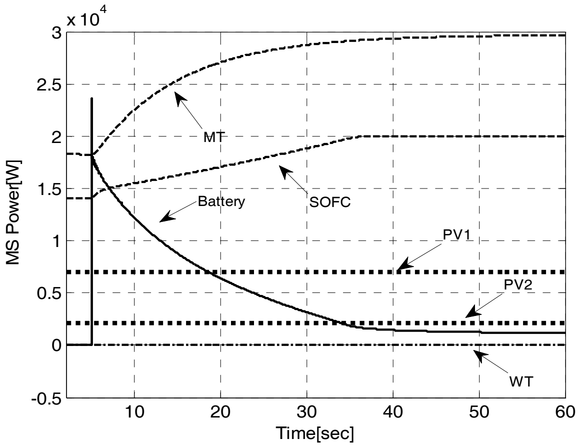

Figure 3: Output of generating microsources after transition of microgrid from utility-grid connection to autonomous mode.

DEMAND RESPONSE TO STABILIZE FREQUENCY

There are two ways to control the power consumed by a load in order to simulate the droop characteristics similar to a generator:

1) Continuous control by power electronics controller if the load is supplied by such a device;
2) Switching on and off the responsive loads whose utility to the consumer is a function of the energy consumed over a period of time rather than their instantaneous power consumption.

The first groups of loads are rare and very expensive, while the second groups have minimal inconvenience for the consumers. The best candidates of the second group are heating, ventilation and air conditioning equipment, tumble dryers, immersion water heaters, and pumping devices because these kinds of cycling loads can handle short interruptions that would be acceptable for the users [5]. It means individual appliances which are essentially energy users rather than power users can participate in the frequency regulation program. Their participation could be in two ways:

1) The candidate appliances to be equipped with some kind of frequency modules to command the load to be switched on with the frequency upwards drift and switched off with the frequency downwards drift.
2) A bilateral communication link to be foreseen in order to send and receive commanding signals to connect and disconnect loads based on a central control, usually managed by an aggregator.

A recent survey in Europe showed that the residential electricity consumption amounts to about 30% of the total electricity demand, meanwhile, the domestic electricity demand could be sorted in descending order as follows [11]:

1) Space heating loads 22%;
2) Refrigerators and freezers 15%;
3) Storage water heaters 9%.

These above values indicate that there is sufficient potential for load-frequency control in many of those domestic appliances. Similar approaches can be applied in some process plants for heating and cooling needs of large buildings.
Different manufacturers have presented devices for controlling domestic loads without the necessity of communication links. A load controller for use on small power grids that have very high penetrations of variable renewable generation has been developed by Econnect Ltd [12]. This is a U.K.-based company active in the integration of renewable electricity. As Frequency control is a challenging task on micro-grids, the Econnect devices

monitor system frequency and use fuzzy logic to decide when to switch resistive loads (such as space and water heating) in order to maintain frequency stability [4]. ResponsiveLoad Ltd is also a U.K. firm developing a frequency dependent load controller similar which uses various frequency limits having the ability to move into different modes of operation, depending on the grid frequency at the time [12].

APPLICATION OF DEMAND RESPONSE IN THE SAMPLE MICROGRID

The sample microgrid of Figure 3 is used to show the performance of the responsive loads to regulate the frequency. The microsources are all set as constant-power units, hence they do not participate in frequency regulation. It means that the generations curves of microturbine and SOFC are flat the same as PVs and wind tiurbines. The battery system as a storage device is working as before, i.e., it delivers energy to compensate the generation deficiency, but the responsive loads start to switch off based on an assumption of maximum 15% of such loads.

Switching the loads is based on a time-grading for frequency deviations analogous to an inverse time over-current relay characteristic as in [5].

The simulation results show that the frequency is recovered step by step with switching the responsive loads, but the loads are switched off at one step if a load aggregator is applied, meanwhile the storage system output decreases in proportion to the demand decreasing.

CONCLUSIONS

In this paper the demand within a microgrid is used to simulate the droop characteristics of a generator by responding to the frequency deviations. It is shown that traditionally, the generating units are partially loaded to provide enough spinning reserve to cope with the transition from utility-grid connection to autonomous mode in a microgrid. However, applying demand response allows the microsources within a microgrid to be fully loaded without the necessity to foresee spinning reserve to cope with the power imbalance during transition from utility-grid mode to autonomous mode. The proposed approach can make a significant and reliable contribution to primary frequency response while preserving the benefits that consumers derive from their supply of electric energy. The merits of new bilateral communicating infrastructure within a microgrid could be used to centrally stabilize the frequency in normal and emergency conditions by using a load aggregator.

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