Providing Ancillary Services through Demand Response with Minimum Load Manipulation

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***Abstract*—This paper presents a demand response (DR) algorithm for regulating system frequency using responsive customer loads, while minimizing the amount of manipulated loads. The dynamic model for a small islanded microgrid and an improved hill climbing controller are developed in MATLAB/Simulink® to show the proof of concept. Simulation results show that the improved DR control strategy provides frequency and voltage regulation while minimizing the amount of manipulated responsive loads. As a result, customer quality-of-service (QoS) is not compromised, while a higher percentage of responsive loads (more non-spinning reserve) would be available for additional control for responding to unexpected disturbances.**

***Index Terms*—Adaptive hill climbing, ancillary service, demand response, microgrid, smart grid, step-by-step control.**

I. INTRODUCTION

PERFECT balance between generation and demand in real time is key to reliable operation of the electric power systems. Traditionally, this balance has been provided by changing the amount of generation whenever it was required based on generation or demand variations [1], however, this is expected to change in the deregulated power market, and emphasis on smart grid and microgrid technologies. In the smart grid era, demand response (DR), i.e. control of responsive customer loads in real-time, will play an important role in maintaining balance between generation and demand. According to a USDOE report [2], the economic benefits from demand bidding range from about \$80 M to about \$800 M annually, depending on the level of need. Also, the economic benefits from emergency DR range from about \$85 M to more than \$300 M annually. From a technical perspective, power consumption of responsive residential and commercial controllable loads, such as electric water heaters (EWHs), can easily be controlled by a command signal, which can increase or decrease reserve and provide frequency regulation to keep the utility area control error (ACE) near zero.

Various Demand Side Management programs have been introduced for peak load shaving, load shifting and contingency services since early 1970s [3]. However, a new opportunity for DR is available in the smart grid environment, where two-way communication with residential appliances and some industrial loads is available, thus making centralized and decentralized load control possible. As a result, more controllable loads are accessible for the utilities for providing ancillary services. However, most of the studies on DR have dealt with economic and market-based implementation of such programs, and few have been reported on the impact of these programs on frequency and power balance [4]-[7].

The authors have shown the effectiveness of DR using an adaptive hill climbing (AHC) control strategy for frequency regulation of an islanded microgrid [8]. This paper is a continuation of [8], where a step-by-step algorithm is proposed to minimize the amount of responsive load needed, and therefore improve customer QoS. The proposed control strategy is applied to the small islanded microgrid used in [8] (Fig. 1), to show proof of concept. A diesel generator, which is equipped with governor and exciter, is the primary generation source in the microgrid.

The simulation model was developed in MATLAB/Simulink®; simulation results show improved performance of the proposed DR strategy compared to that reported in [8]. In the remainder of this paper, the system description is presented, the proposed DR control strategy is described, simulation results are given, and future direction of work is discussed.

II. SYSTEM DESCRIPTION

The small islanded microgrid used in this study (Fig. 1) includes a 3.125-MW, 2.4-kV diesel generator (DG), equipped with speed governor and exciter, along with fixed and active dynamic (responsive) loads. This system is the same as that used in [8], so that we can compare the system performance with the proposed DR control strategy with the original one reported in [8], in order to show its effectiveness and new features.

In general, a storage device is also a part of a microgrid; however, since the purpose of this paper is to show the applicability of the new controller for frequency and voltage stabilization, storage devices are not included in the simulation studies and not shown in Fig. 1. The controller described in [8] takes the frequency deviation signal ($\Delta f = f - f_{ref}$) as input , and based on that signal, it determines the amount of the responsive load which needs to be disabled or enabled to keep the frequency within the desired thresholds.

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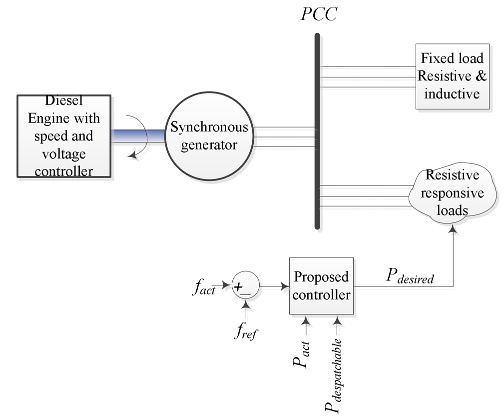


Fig. 1. Configuration of the test system.

The proposed approach will also be effective for voltage stabilization, as will be shown in Section IV. This is because the output voltage of the generator depends on the amount of power demanded from the generator. Thus, by controlling the active responsive load, both the frequency and output voltage of the microgrid are regulated at the same time.

This study focuses on resistive load regulation for frequency stabilization at the distribution level, where microgrids normally operate. The proposed control scheme (described in Section III) is applied to regulate the frequency by controlling the system responsive loads at the beginning of a disturbance (step 1); it then minimizes the amount of manipulated load (step 2) when the frequency has already been stabilized in step 1. Simulation results show the effectiveness of the proposed DR strategy for frequency and voltage regulation, while minimizing the amount of responsive load. The responsive load is assumed to be 15% of the total load, i.e. 15% of the total load is available to be controlled if needed. Each responsive load is assumed to be a 4.5 kW EWH, which could be either in the “ON” or “OFF” state.

The details of the dynamic model for the diesel engine and how the dynamic load is simulated in MATLAB/Simulink® are presented in [8].

III. THE PROPOSED CONTROL STRATEGY

The proposed control strategy consists of AHC control, as in [8], and a step-by-step controller used to minimize the amount of manipulated load at steady-state, as shown in Fig.2.

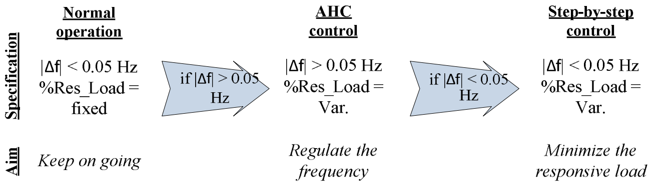


Fig.2. Concept of the proposed control strategy.

During normal operation, the frequency is assumed to be within the desired dead-band $\Delta f = f_{desired} \pm 0.05\ Hz$. Under a disturbance, the system frequency will increase or decrease depending on the type of disturbance. When the frequency deviation exceeds the pre-defined dead-band, the AHC controller will start to regulate the frequency by changing the amount of responsive loads [8]. The flowchart of the AHC controller is shown in Fig. 3. The frequency, measured at the point of common coupling (PCC) of the microgrid, is the input variable to the controller. If the frequency deviation falls outside the dead-band, a percentage of the dynamic load will change based on the sign and magnitude of the frequency deviation as follows:

$$\%Load(k) = \%Load(k-1) + \Delta f \times M \tag{1}$$

When the frequency is higher than acceptable, a percentage of the responsive loads (that are OFF) will turn ON, and when it is lower than acceptable, a percentage of the responsive loads (that are ON) will turn OFF. The perturbation parameter is $M*\Delta f$, where M is a constant, used to scale down the frequency deviation. More detail on the AHC algorithm is provided in [8].

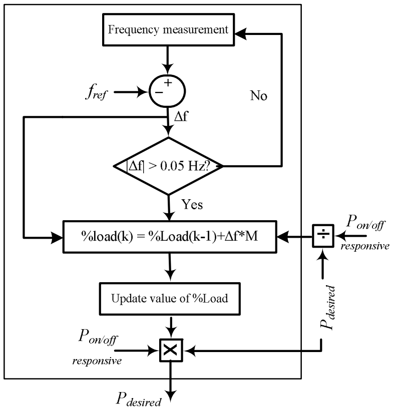
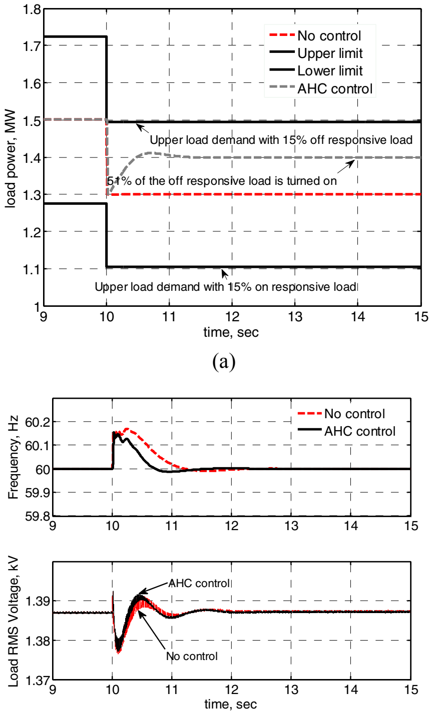


Fig. 3. The flowchart of the AHC control [8].

The AHC controller acts faster than the speed governor of the diesel generator because of the rapid nature of control, since the power consumption status of EWHs and other resistive loads can be changed instantaneously by the ON or OFF command signal they receive. This way, more dynamic loads will be manipulated at the beginning of the disturbances than required at steady-state. As a result, a higher percentage of the responsive loads are manipulated at steady-state, which is more than needed.

To illustrate the concept explained above, a set of results from [8] is shown in Fig. 4. In this figure, 1.5 MW of load is suddenly switched to 1.3 MW at t=10 sec. The upper and lower limits of the responsive loads are shown in Fig. 4(a). In this case, as shown in Fig. 4(b), the governor of the diesel generator is able to regulate the frequency without turning ON any responsive loads (the “no control” case). With “AHC control”, 51% of the responsive loads are turned ON to improve the transient frequency response. However, this percentage of responsive loads remains ON for the rest of the simulation, while they could ideally be OFF at steady-state.



(a)

(b)

Fig. 4. System response due to a step down load change: (a) Responsive load power, (b) Frequency and RMS value of the voltage. P_{load} is changed from 1.5 MW to 1.3 MW.

In order to assure that the minimum required amount of responsive load is changed, the "step-by-step" control, introduced in Fig.2, is used. Once the frequency is stabilized by the AHC controller, the step-by-step controller will start operating to minimize the amount of manipulated responsive loads. Using the step-by-step controller, the manipulated responsive load will be decreased by 5% at each one-second time-step according to Eq. (2) until the frequency exceeds the desired dead-band.

$$\%Load(k) = 0.95 \times \%Load(k-1) \tag{2}$$

According to Eq. (2), the responsive load variation depends on its previous value. Therefore, the load control strategy begins with large variations in load which decrease with time, making the "step-by-step" control strategy non-linear with large variations at the beginning and small changes at the end. As a result, the proposed control strategy minimizes the amount of responsive loads that need to be manipulated at steady-state to keep the system frequency within the desired range. The advantage of this strategy is that a lower percentage of responsive loads are manipulated at steady-state, which improves customers' QoS. As a result of this improvement, a higher percentage of customer loads will be available for future control, if needed.

In an actual system, there are two possibilities of delay in the response; one is related to the dynamic response of the loads and the other related to the delay in communication. Both delays should be considered in DR control algorithms to prevent unnecessary switching of the responsive loads. Purely resistive loads (such as EWHs considered in this study) respond instantly to the changes to their input voltage instantly. Therefore, it can be assumed that there is no delay in their response to the changes [10]. The communication delay, often referred to as latency, is the length of time from when a request is made by a control entity to when the electrical device receives the request and acts on it. Latency should be shorter than 500 ms with the existing internet infrastructure [11]. In this study, a wireless network with a latency of less than 20 ms. is considered as the communication protocol between the control entities and loads.

IV. SIMULATION RESULTS

Simulation studies were conducted using the proposed control strategy under different loading conditions, the same as in [8], in order to be able to compare results. The objective of the simulations is to keep the frequency within ±0.05 Hz (or ±0.083%) of 60 Hz. As expected, the transient response of the system with the proposed control strategy is the same as the results with AHC control only, reported in [8]. However, noticeable improvements are observed at steady-state, where fewer responsive loads need to be controlled. In both cases, the responses of the "no control" case are the same.

A. No Control

Fig. 5 shows the frequency response of the microgrid system under light loading in the absence of the AHC or the proposed controller. In all cases, the load is changed from 1.6 MW to the level shown in the figure at t=10 sec. Because of the availability of excess generation, the frequency initially exceeds its rated value (60 Hz). When the load is 1.3 MW or higher, the speed governor of the DG is effective in stabilizing the frequency. However, when the load goes down to 1.2 MW or lower, the speed governor of the DG fails to stabilize the frequency.

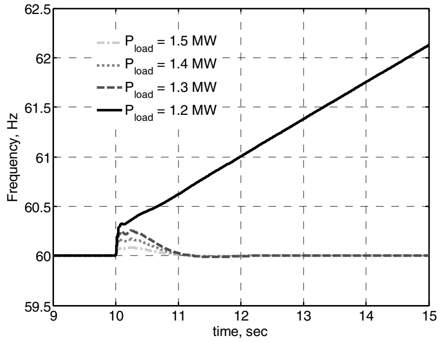


Fig. 5. Rising frequency under light loading – no control.

The system frequency response in the heavy loading case is shown in Fig. 6. The load increases from 1.6 MW to the values shown in the figure. The DG's speed governor is able to stabilize the frequency up to a load of 3.2 MW. Beyond this load, i.e. at 3.3 MW or more, the speed governor fails to stabilize the frequency.

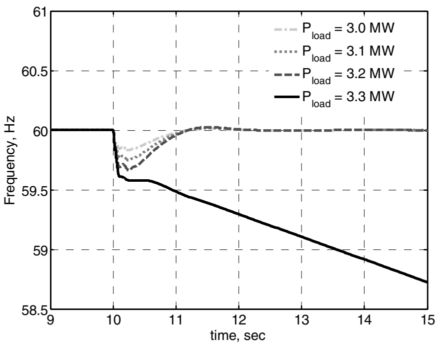


Fig. 6. Falling frequency under heavy loading – no control.

B. *Controller enabled*

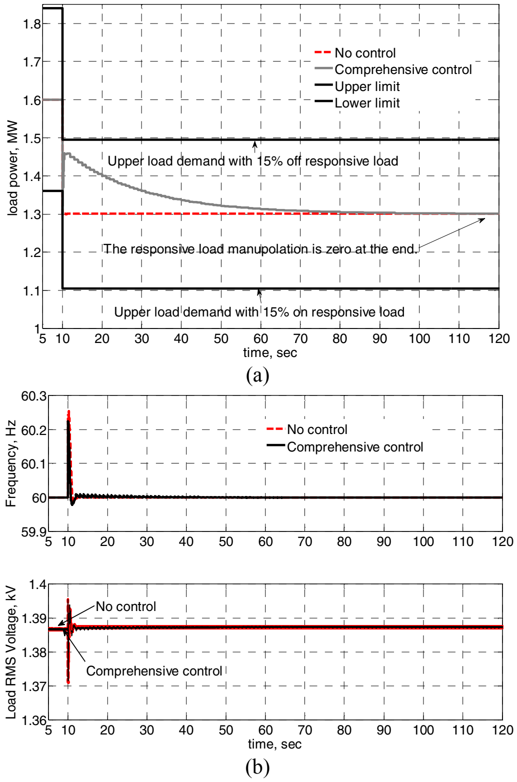
In this section, the system performance when the proposed comprehensive controller is enabled is compared with those when either only the AHC controller is enabled or all controllers are disabled. As it was discussed earlier, the transient responses of the system for the two controlled cases (AHC and comprehensive) are the same and can be seen in [8]. It has been shown in [8] that the transient frequency response of the microgrid is improved with DR compared to the DG's speed governor control. In the following subsections, we focus on the system performance at steady-state with the AHC controller alone, and with the step-by-step controller acting after the AHC. Simulation results show the effectiveness of applying the "step-by-step" control right after the AHC controller. In all cases, it is assumed that the ON/OFF responsive loads are 15% of the total load.

Case 1:Light loading – decrease in load

As shown in Fig. 7 (a), a 1.6 MW load is suddenly switched to 1.3 MW at t=10 sec. The upper and lower limits of the responsive loads are also shown in the figure.

As shown earlier, when only the AHC controller is enabled, 51% of the responsive loads are gradually turned on by the AHC to stabilize the frequency. However, the "step-by-step" control strategy gradually reduces the required responsive load to zero since the speed governor is able to adjust the output power of the DG to match the generation with demand at steady-state. Therefore, the AHC and responsive loads are needed to improve the frequency response during the transient period, but no manipulation of responsive loads is needed at steady-state (100 seconds after the disturbance), as a result of the step-by-step controller. The frequency and voltage profiles under the above disturbance are shown in Fig. 7(b). It is clear that the frequency and voltage stay within the desired limit when the "step-by-step" control strategy is in operation.

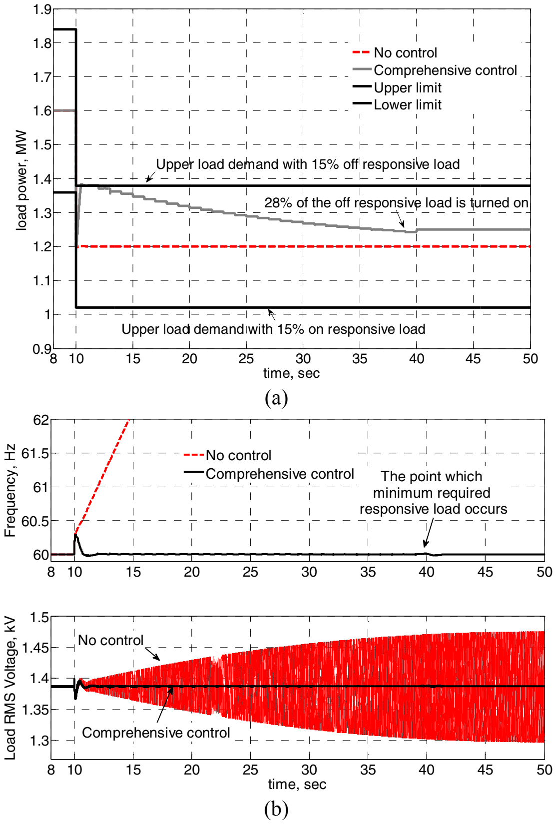
Fig. 8(a) shows the required decrease in load as well as the upper and lower limits of load demand due to a sudden change in demand from 1.6 MW to 1.2 MW at t = 10 sec. Also, the generator frequency and voltage response are shown in Fig. 8(b). It can be seen that the responsive loads appropriately increase or decrease in order to stabilize the frequency and voltage.



(a)

(b)

Fig. 7. System response due to a step down load change: (a) Responsive load power, (b) Frequency and RMS value of the voltage. P_{load} is changed from 1.6 MW to 1.3 MW.



(a)

(b)

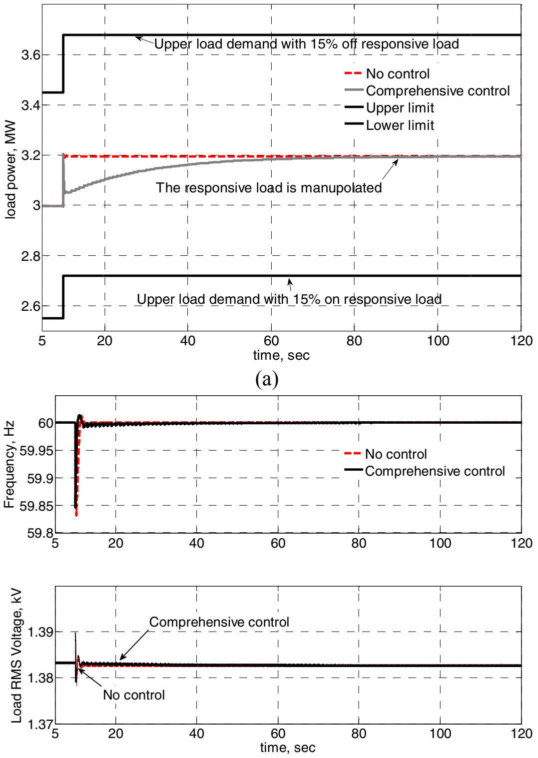
Fig. 8. System response due to a step down load change: (a) Responsive load power, (b) Frequency and RMS value of the voltage. P_{load} is changed from 1.6 MW to 1.2 MW.

It is shown in [8] that when the AHC controller is in operation alone, 79% of the responsive loads (which were in the OFF state) are turned ON in order to stabilize the frequency to the desired level in the transient stage, whereas the frequency will go out of range under no control, Fig. 8(b). However, with the proposed comprehensive (AHC + step-by-step) control strategy, the amount of manipulated load has been reduced to 27.7% after almost 40 seconds, as shown in Fig. 8(a). Therefore, the proposed controller improves the transients and minimizes the responsive load manipulation required at steady-state, while keeping the system frequency within the desired dead-band.

Case 2:Heavy loading – increase in load

In this case, the load is suddenly increased from 3.0 MW to 3.2 MW, Fig. 9 (a). The load demand for both cases with no control and with the comprehensive controller is also shown. It is shown in [8] that, with the AHC controller, 29% of the responsive loads (which were ON) are disabled to improve the frequency response at the beginning of the disturbance. However, with the comprehensive controller, once the AHC controller stabilizes the frequency, the "step-by-step" controller starts operating to minimize the amount of manipulated responsive loads. It can be seen from Fig. 9(a) that no responsive load is really needed at steady-state to regulate the frequency, because the speed governor can handle the deficiency in the generation at steady-state. Note that the transient response is improved by applying the AHC controller at the beginning of the disturbance, and then all responsive loads are returned to their original OFF mode using the "step-by-step" controller. It is clear from Fig. 9(b) that the frequency stays within the range during the "step-by-step" control process.

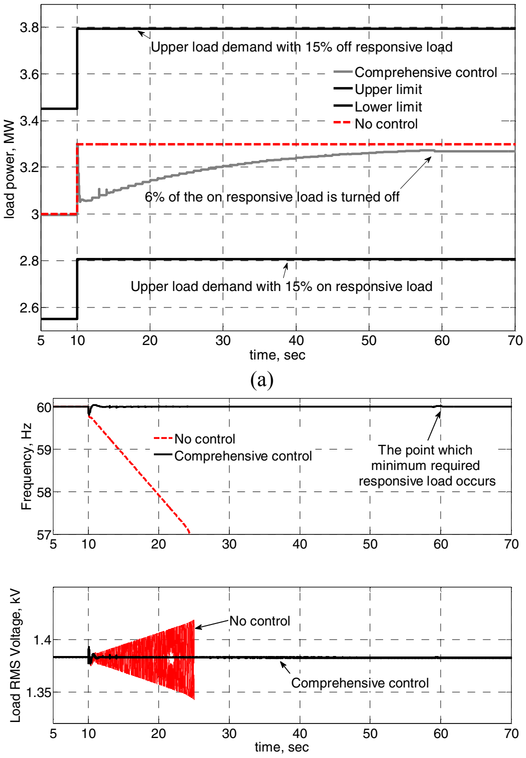
As shown in Fig. 10 (a), a 3.0 MW load is suddenly increased to 3.3 MW. The upper and lower limits of the load demand considering the 15% responsive load, along with the load demand for both the no control case and with the comprehensive controller, are also shown in the figure. As shown in [8], 56% of the responsive loads (which were ON) are turned OFF to keep the frequency within range. However, when the "step-by-step" control strategy is in operation, the amount of manipulated responsive load necessary to keep the frequency within range is reduced to 6.26%, Fig. 10 (a). Fig. 10(b) shows the frequency and voltage profile of the system. The proposed AHC controller stabilizes the frequency at the beginning of the simulation by manipulating (in this case, turning OFF) a large percentage of responsive loads. Nevertheless, most of the manipulated loads are returned to their ON state at the end of the "step-by-step" control. It is also noticed that the frequency goes out of range and the voltage becomes unstable when the controller is not enabled. As in the previous cases, the voltage is stabilized when the comprehensive controller is operating.



(a)

(b)

Fig. 9. System response due to a step up load change: (a) Responsive load power, (b) Frequency and RMS value of the voltage. P_{load} is changed from 3.0 MW to 3.2 MW.



(a)

(b)

Fig. 10. System response due to a step up load change: (a) Responsive load power, (b) Frequency and RMS value of the voltage. P_{load} is changed from 3.0 MW to 3.3 MW.

V. FUTURE WORK

In this study, a comprehensive DR strategy is introduced to determine the minimum percentage of responsive loads required to regulate the frequency. As intermittent renewable power could be a part of the generation mix in future microgrids, the variable generation can result in significant mismatch between generation and demand. One way to reduce the impact of the variable generation is generation following using DR. Future work will include applying the proposed DR strategy for stabilizing microgrid frequency in the presence of variable wind generation. Another part of our future work related to this project is to apply the proposed load control strategy to an IEEE distribution system benchmark.

VI. CONCLUSION

A comprehensive demand response-based frequency control strategy is proposed in this paper for an islanded microgrid, which minimizes the amount of the manipulated responsive loads after each disturbance. It is shown that the comprehensive DR strategy minimizes the amount of manipulated responsive loads while improves transient frequency response. The proposed approach is suitable for smart grid applications, where control of responsive loads will be achievable through robust two-way communication.

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VII. REFERENCES

[1] M. H. Albadi, E. F. El-Saadany, "A Summary of Demand Response in Electricity Markets," *Electric Power Systems Research*, vol. 78, no. 11, Nov. 2008, pp. 1989-1996.

[2] U.S. Dept. of Energy, Office of Electric Transmission and Distribution, "Grid 2030: A National Vision for Electricity's Second 100 Years," July. 2003, available at www.ferc.gov/eventcalendar/files/20050608125055-grid-2030.pdf

[3] V. Hamidi, F. Li, F. Robinson, "Demand Response in the UK's Domestic Sector," *Electric Power Systems Research*, vol. 79, no. 12, pp. 1722-1726, 2009.

[4] D. Trudnowski, M. Donnelly, E. Lightner, "Power-System Frequency and Stability Control using Decentralized Intelligent Loads," *Proceedings,* IEEE PES Transmission and Distribution Conference and Exhibition, pp. 1453-1459, 2005.

[5] S. Doolla, T.S. Bhatti, "Load Frequency Control of an Isolated Small-Hydro Power Plant with Reduced Dump Load," *IEEE Transactions on Power Systems*, vol. 21, no. 4, pp. 1912-1919, 2006.

[6] J.A. Short, D.G. Infield, L.L. Freris, "Stabilization of Grid Frequency Through Dynamic Demand Control," *IEEE Trans. on Power Systems*, vol. 22, no. 3, pp. 1284-1293, 2007.

[7] Shuai Lu, et al, "Centralized and Decentralized Control for Demand Response," *Proceedings,* 2011 IEEE Innovative Smart Grid Technologies Conference, Anaheim, CA.

[8] S.A. Pourmousavi, M.H. Nehrir, "Demand Response for Smart Microgrid: Initial Results," *Proceedings,* 2011 IEEE Innovative Smart Grid Technologies Conference, Anaheim, CA.

[9] N. Lu, S. Katipamula, "Control strategies of thermostatically controlled appliances in a competitive electricity market," *Proceedings,* Power Engineering Society General Meeting, vol. 1, pp. 202 – 207, 2005.

[10] R. Jia, M.H, Nehrir, D.A. Pierre, "Voltage Control of Aggregate Electric Water Heater Load for Distribution System Peak Load Shaving Using Field Data," *Proceedings,* 2007 North American Power Symposium, pp. 492-497.

[11] A. Brooks, E. Lu, D. Reicher, C. Spirakis, B. Weihl, "Demand Dispatch: Using Real-Time Control of Demand to Help Balance Generation and Load," *IEEE Power and Energy Magazine*, vol. 8, Issue. 3, pp. 20-29, 2010.