The Application of Demand Response for Frequency Regulation in an Islanded Microgrid with High Penetration of Renewable Generation

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***Abstract*—Increasing the penetration of variable generation sources, such as wind and solar, potentially threatens the stability of the power systems. Past studies have shown that 15-20% renewable penetration is the largest amount the power systems can handle using conventional control. To overcome the challenge that variable renewable generation presents, this paper proposes that real-time demand response (DR) be used for ancillary services (AS). The impact of varying the amount of DR on the performance of a microgrid-configured distribution feeder is evaluated in this study. Simulation results have shown that a proper amount of DR resources can help to achieve higher penetrations of renewable generation while maintaining the desired system frequency.**

***Index Terms*—Adaptive hill climbing (AHC), automatic generation control (AGC), demand response (DR), frequency stabilization, governor droop control, microgrid, thermostatically controlled appliances (TCA)**

I. Introduction

As a feature of smart grid, variable renewable generation is projected to achieve a high penetration in the future power system. Many countries have stated goals to increase the amount of renewable energy penetration considerably in years to come. Past studies have revealed that renewable energy penetration greater than 20% will potentially result in grid instability when using conventional control techniques, such as governor droop control and automatic generation control (AGC) [1], [2]. In order to overcome this challenge, more ancillary services are needed, specifically during peak hours. Recently, studies have focused on using demand response (DR) as an ancillary services (AS) provider [3]. Many aspects of DR have been researched, such as DR markets and cost/benefit analysis [4] and DR modeling [5], [6], [7] and aggregation [8]. This paper is a continuation of the study reported in [1], where DR is applied to stabilize the frequency of a microgrid-configured distribution feeder.

DR is fundamentally achieved by varying the load so that the power consumed matches the power generated; therefore, the grid frequency will always operate at its reference value. The traditional way to maintain a balance between load and generation is to vary generation to meet demand (i.e., load following). The distinct difference when using load frequency control through DR is that the load is varied to meet the available generation (i.e., generation following).

Past studies have shown that loads, such as electric water heaters (EWHs), can be controlled to smooth out the demand curve while maintaining customer comfort [8], [9], [10]. EWHs make up 11% of residential loads and can increase to 30% during peak hours [11]. Therefore, the control of aggregated EWHs can be a viable option for DR. In this paper, no individual load is considered as a responsive load (DR resource). The generic load used can consist of EWHs, HVAC, or other thermostatically controlled appliance (TCA).

In this paper the simplified grid model (SGM) proposed in [1] will be further modified to include AGC. For this paper adequate frequency regulation is defined as maintaining a grid frequency within 60±0.05 Hz, which is the Federal Energy Regulatory Commission (FERC) standard. An adaptive hill climbing (AHC) control technique has been shown to control fluctuations in grid frequency and will be used during this study to implement DR [3]. Then various methods to control frequency, including, governor droop control, governor droop control with AGC, and governor droop control with DR will be examined. The objective here is to show the effectiveness of DR to provide AS in an islanded microgrid (MG) setting in comparison to traditional AS (governor droop control and AGC). In addition, various latencies will be studied to analyze the effect of communication delay on the performance of DR. Also, slow and fast AGC will be examined. Simulation results have shown that DR with governor droop control can yield adequate frequency stabilization in the microgrid-configured distribution feeder.

The rest of this paper is organized in the following manner: Section II discusses the proposed control strategy. Section III shows the system studied, Section IV presents the simulation results. Section V suggests some possible future work, and Section VI concludes the paper.

II. The Proposed Control Strategy

The need to balance generation and demand at all times through control action is a necessary process for a power

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system. Any load or generation variation can cause a mismatch between the two and result in unwanted frequency deviation. The traditional frequency correction action includes generator inertia (as an unintentional control), frequency droop control (known as primary control), and AGC (known as secondary control). In this paper all three of these control actions are modeled. The primary frequency correction comes from those generators that are outfitted with governor droop controllers where droop can vary from 4%-20%, shown in Fig. 1. A generator outfitted with a 4% droop means that a 4% drop in frequency would result in a 100% increase in that generators output. Fig. 1 shows the block diagram of a synchronous generator (SG) with droop and excitation control. The constant K_i shown in the figure is the integral control constant of the secondary frequency control (AGC), which is set to zero when only droop control is active. We used the combination of the SG, droop control, AGC, and excitation control, shown in Fig. 1, as a simplified grid model (SGM) to show frequency variation in the distribution system studied.

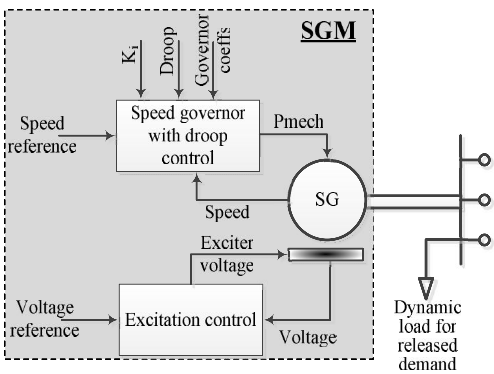


Fig. 1. The proposed SGM with governor droop control and AGC

The required reserves for AGC are usually provided by fossil-fuel based power plants as either spinning or non-spinning reserve, which are normally not available for islanded MGs. In this study, the impact of AGC is presented by an equivalent model of all available traditional regulation providers by a single generator (Fig. 1 when droop value is zero) with an integral controller (K_i), shown in Fig. 1. The speed of the AGC controller can be increased by increasing the integrator coefficient, K_i. In addition, the capacity of the generator can be changed to represent available regulation services in the MG.

Since AGC is not commonly available for MGs, as a viable alternative, DR is proposed in this study to replace the AGC controller (Fig. 2). The DR strategy in this study includes an AHC technique, introduced in [3]. In order to obtain the percent frequency variation *L(t)* at each step, the system frequency is measured and compared to a reference frequency (60Hz) in order to generate the frequency error (Δf). This frequency error (Δf) is then multiplied by a gain term, M, which is finally added to the percent frequency variation at the previous time step, *L(t-1)*, as follows.

$$L(t) = L(t-1) + M \times \Delta f \quad (1)$$

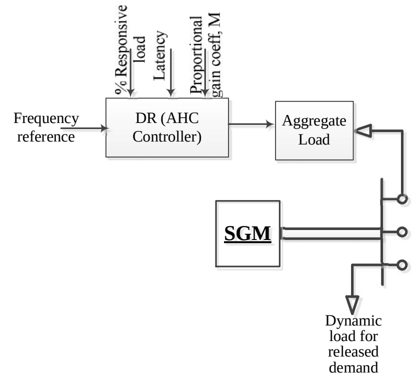


Fig. 2. Block diagram of the proposed DR controller

Increasing the gain leads (*M*) to faster response but introduces a larger overshoot. It is important to avoid ringing in power system control so that the generators are not oscillating, which puts undue torque and stress on the machines and can decrease their serviceable lifetime. It was determined that for the system under study, the best response was achieved by setting the gain, M, to 2.5.

The percent frequency error, *L(t)*, represents the percentage of load that needs to be manipulated. If *L(t)* is positive then frequency is rising and load must be increased, whereas if *L(t)* is negative the frequency is dropping and load needs to be curtailed. The AHC controller attempts to always achieve $\Delta f = 0$ by continuously changing the value of df/dt and move it toward zero. This is similar to the maximum power point tracking (MPPT) method for PV cells, which attempts to make $dP/dV = 0$ [12].

Latency delay was also considered for the DR control strategy. Previous studies have shown that a latency of 20 to 50 seconds can be associated with traditional AGC control [13]. This latency is due to communication delay and mechanical processes that must take place, such as opening or closing steam valves. It can take on the order of 30 minutes to an hour for the frequency to settle back to its reference frequency after a disturbance occurs [14]. Therefore, a latency period of approximately 30 minutes is used in this study to model the current response time of AGC control. However, a MG operating as a small-scale regional power system will experience much faster two-way communication (smaller latency period on the order of several hundred msec). According to the study reported in [15], latency of 500msec or less is achievable with current Internet infrastructure. Furthermore, wireless communication can achieve much smaller latency periods. In this study, latencies of 100ms and 500ms were used for implementing DR.

III. Systems Studied

The system studied during this research resembles an islanded micro-gird. MGs can function without assistance from the main grid and operate in islanded mode. The MG includes distributed generators that may be controlled from a central location. The control may also be decentralized using distributed agents [16], [17]. A MG may not have the benefit of AS, such as governor droop and AGC control, to regulate frequency. Therefore, another means of control such as DR must be used.

Long term dynamic simulation in MATLAB/Simulink® is very slow, so that modeling an entire distribution feeder was not possible in this study. To solve this problem, only a part of the feeder is modeled in detail and the rest of it is modeled by equivalent generation sources (SGM) and aggregated load. The SGM includes a 17 MVA generator with governor droop control and excitation control. The SGM with governor droop control is complemented with the proposed AGC discussed in Section II. This system also includes a 7.5 MW of concentrated PV farm, 13 MW/9.75 MVAr base load, and a distribution feeder, shown in Fig. 3. The distribution feeder shown in Fig. 3 is approximately 0.837MW/0.626MVAr (1.06 MVA). Although AGC is used in large-scale power systems, we have modeled the AGC in the SGM to show its impact on the system frequency behavior.

Although energy storage is foreseen as a part of a MG, it is not the primary concern of this paper, as the focus is to regulate system frequency with DR, and therefore is not included in the MG. Only responsive loads, such as EWHs and HVAC, become virtual energy storage (buffer) for the power system, which allows them to provide negative and positive reserve. When generation exceeds load, EWHs can be turned ON to absorb the excess power, which is stored as heat in the hot water tanks. Then during periods of peak demand the stored energy in the hot water tanks can be released [8], [9], [10].

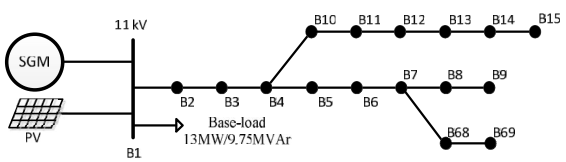


Fig. 3. Schematic of the microgrid-configured distribution feeder

For this study the PV penetration was set to a maximum of 25% meaning that 25% of the total generation capacity available is from PV. The system studied has been previously used in [1] without AGC. The solar data for this research was obtained from the National Renewable Energy Laboratory (NREL) for a site in Oahu, Hawaii, USA on June 18, 2010. The solar irradiation and the temperature data for the hours 12:36–15:06 were used to obtain the output of the PV farm, shown in Fig. 4. The PV output power data was reported in one second intervals and was input directly into the simulation.

IV. Simulation Results

The system introduced in Section III is implemented in MATLAB/Simulink®. The first part of the simulation is for proof of concept and includes the proposed model and controllers without the feeder model. In this section the impact of the proposed DR strategy with different latencies is compared with traditional AGC control. The second part of this section, sub-section B, is devoted to the MG system including the feeder. For these simulations, variable PV generation is also added and the simulations are carried out for 2.5 hours.

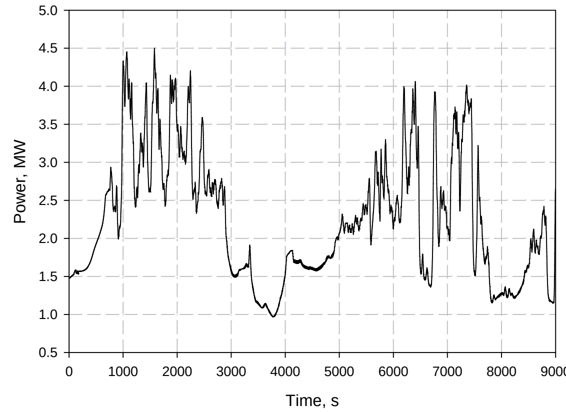


Fig. 4. PV power generation in Oahu, Hawaii, USA

A. System Performance Using Load Step Change

In this section, several simulations are carried out to reveal the different features of DR application for frequency stabilization compared to the conventional AGC. For these simulations the feeder and variable solar power are eliminated. The load was 10MW for the first 60 seconds, at which point the load was instantly increased by 20% to 12MW. The integral gain, K_i, for the AGC control and the proportional gain, M, for the AHC controller are determined throughout these simulations. These simulations also prove the hypothesis that applying DR through an AHC controller outperforms the conventional frequency regulation using governor droop control with AGC.

For conventional power systems, AGC is known as slow control which takes place in several minutes to bring the frequency back to 60Hz. In the first simulation study, the AGC responses with different speeds (gains) are compared with responses of the governor droop control and the DR with 25% of available responsive loads, shown in Fig. 5. It can be seen that the droop control response has a large steady-state error and does not bring the frequency to the acceptable range. Further, the frequency regulation performance with DR outperforms the conventional AGC, even the fastest AGC with K_i=4. Since the system under study is a small islanded power system, the AGC control is assumed to be fast. However, the objective of this figure is to show that load frequency control using DR is still faster than the fastest AGC control.

Fig. 6 shows the impact that varying the amount of responsive load has on the system frequency. As it can be seen from this figure, 15% of responsive load is not enough for adequate frequency regulation. More responsive load should participate in DR to bring the frequency back to its nominal value. Once available DR is increased to 25%, the system frequency is stabilized and zero steady-state error is achieved. Frequency stabilization is achieved faster with 50% DR (compared to 25% of DR), but a frequency overshoot is observed. The overshoot, increases as the percentage of responsive load available increases. The controller switches the status of a greater number of devices than necessary to quickly react to a frequency deviation, which can result in nuisance curtailment. A past study has shown that a step-by-step controller can be used to correct this problem [17].

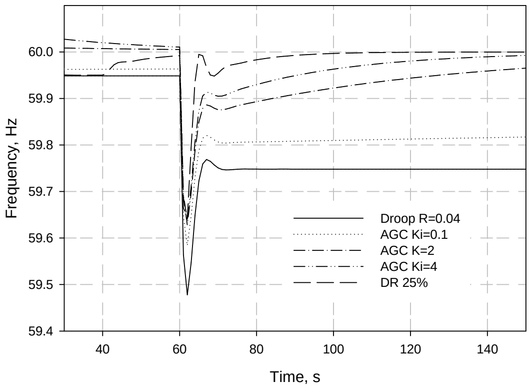


Fig. 5. Load step change with variable integrator gain

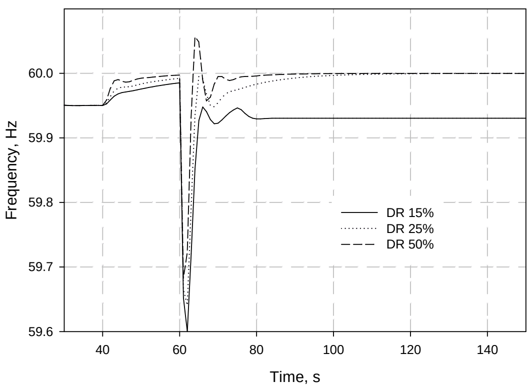


Fig. 6. Load step change with variable responsive load

The system frequency behavior was also evaluated under different communication latencies to ensure that the system frequency remains stable under such latencies. Fig. 7 shows the impact that different latencies associated with DR have on system frequency, where 25% of responsive loads are available. As it can be seen from Fig. 7, larger latencies result in oscillations in the system frequency since it takes longer for the central controller commands to be received by the loads. However, the system frequency is stabilized for latencies of up to 2 sec, which is well within the range of typical communication delays. According to [15], communication with 500 msec delay is achievable by the Internet today, and with that delay, the system frequency behavior is well within the acceptable range.

B. *Impact of the PV Farm*

In these simulations, the output power of the PV farm was added into the system and the simulations were carried out for 2.5 hours. 15% and 25% PV penetration is considered to show the effectiveness of DR in providing frequency regulation for a generic distribution feeder. All other parameters and coefficients are the same as those in sub-section IV.A except the parameters whose variability is being analyzed. For all simulations the AGC integral gain, K_i, is 0.1, which stabilizes system frequency in approximately 30 minutes.

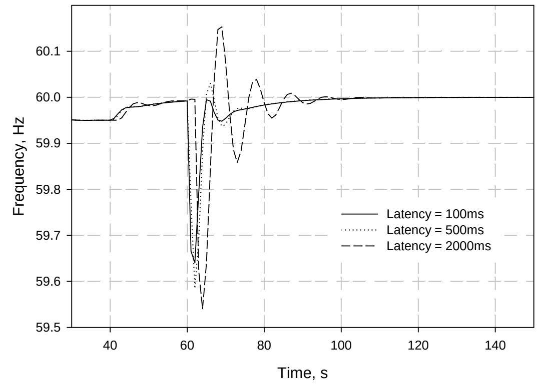
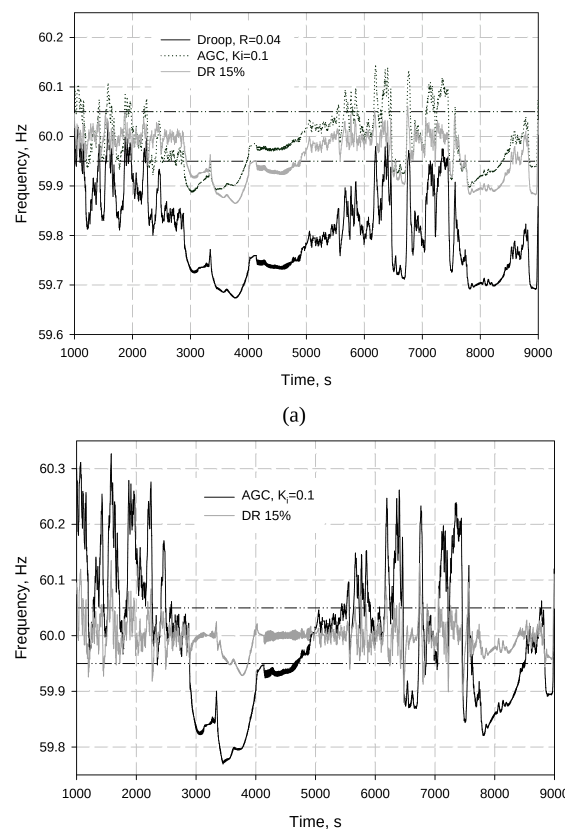


Fig. 7. Load step change with different DR latencies

Fig. 8 shows the frequency response with the three different control strategies discussed above for 15% and 25% of PV penetration. Fig. 8(a) shows the system frequency behavior with droop control, AGC, and DR with PV penetration of 15%. It is clear from the figure that the droop control is not capable of bringing the frequency to the acceptable range. Although the DR performance is better than AGC, both methods are not able to keep the frequency in the desired range, as shown in Fig. 8(a). However, the DR control performance is superior in the case of 25% PV penetration, Fig. 8(b).



(b)

Fig. 8. System frequency response with (a) 15%, (b) 25% PV penetration

Fig. 9 shows the impact of 15% and 25% responsive load on the system frequency. The PV penetration is 25% in both cases. It is clear that when 25% responsive load is available for DR, the frequency deviations are within the acceptable range most of the time. Therefore, an increase in the amount of responsive load results in significant decrease in the frequency fluctuations magnitude. In addition, the average, standard deviation, and root mean square error (RMSE) of frequency deviation are better with 25% DR as compared with 15% available DR, as shown in Table I.

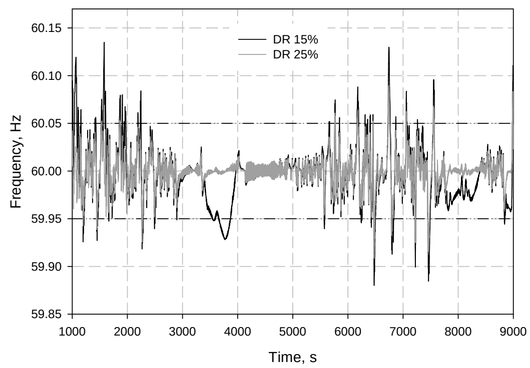
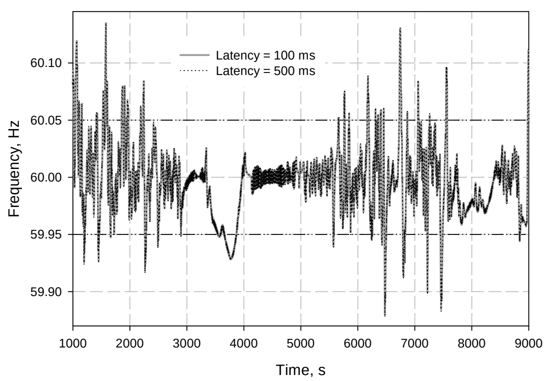
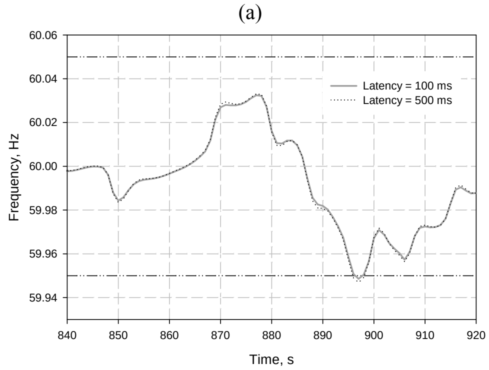


Fig. 9. System frequency response with variable responsive load with 25% of PV penetration

Fig. 10 shows the impact of 100 msec and 500 msec DR latency on the system frequency, where 15% of responsive loads is considered for DR. There is no discernible difference between the system frequency responses with latencies of 100 msec and 500 msec and therefore the two curves are laid on top of each other. Fig. 10(b) is a zoomed-in view of a portion of Fig. 10(a).



(a)



(b)

Fig. 10. (a) System frequency response with 25% PV penetration, (b) zoomed-in view

Table I shows the minimum and maximum frequency, and standard deviation, and RMSE of frequency (compared to 60 Hz) for governor droop control, AGC and 15% and 25% DR. It is again clear that in all cases, DR outperforms the other methods, and 25% DR is better than 15% DR. The values are calculated using the results obtained between 1000 sec and 9000 sec. The values before 1000 sec were excluded from the statistical analysis because the system had yet to reach steady state from its initial value.

TABLE I
SYSTEM FREQUENCY STATISTICS FOR THE THREE CONTROL METHODS IN 9000 SEC SIMULATION FOR 25% PV PENETRATION

	Minimum Frequency (Hz)	Maximum Frequency (Hz)	Average Frequency (Hz)	Standard Deviation (Hz)	RMSE (Hz)
Governor	59.74	60.33	59.95	0.140	0.149
DR-15%	59.88	60.13	59.99	0.030	0.030
DR-25%	59.91	60.09	60.00	0.017	0.017
AGC	59.77	60.32	59.99	0.120	0.121

V. FUTURE WORK

This study showed that frequency control using the AHC method can help to stabilize system frequency. In the future a variable aggregated load, instead of a fixed load, will be implemented to more accurately simulate a real world environment. Also, a dynamic model of EWHs will be used to show the impact of DR on customer comfort level. Finally, real-world PV and wind data, recorded during the same time of day, will be implemented together to determine whether diverse generation has a positive effect on system frequency.

VI. CONCLUSIONS

In this study, DR has been utilized to stabilize the system frequency with high penetrations of variable PV generation. Different simulation results have revealed the effectiveness of the proposed DR strategy in comparison to AGC. It also has been observed that the system frequency improved as the amount of available responsive load increased. It was also noticed that long communication delays in load controls could negatively impact the system frequency. However, the system performance was acceptable for communication delays of up to 500 msec.

REFERENCES

[1] S.A. Pourmousavi, A.S. Cifala, M.H. Nehrir, "Impact of high penetration of PV generation on frequency and voltage in a distribution feeder," In Proc. *North American Power Symposium (NAPS)*, Champaign, IL, 2012, pp. 1-8.

[2] K. Kawamura, R. Kato, S. Bando, M. Takahashi, “Avoided cost of effects of voltage control by demand response in a distribution network with high integration of rooftop PV,” In Proc. *Innovative Smart Grid Tech. IEEE PES.*, Washington DC, 2013, pp. 1-6.

[3] S.A. Pourmousavi, M.H. Nehrir, "Demand response for smart microgrid: Initial results," In Proc. *Innovative Smart Grid Tech. IEEE PES.*, Anaheim, CA, 2011, pp. 1-6.

[4] J.A. Taylor, J.L. Mathieu, D.S. Callaway, K. Poolla, “Price and capacity competition in zero-mean storage and demand response markets,” In Proc. *50th Annual Allerton Conference on Communication, Control, and Computing*, , Monticello, IL, 2012, pp. 1316-1323.

[5] N. Navid-Azarbaijani, M.H. Banakar, “Realizing load reduction functions by aperiodic switching of load groups,” *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 721-727, May 1996.

[6] K.Y. Huang, H.C. Chin, Y.C. Huang, “A model reference adaptive control strategy for interruptible load management,” *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 683-689, Feb. 2004.

[7] D. Westermann, A. John, “Demand matching wind power generation with wide-area measurement and demand-side management,” *IEEE Trans. Energy Covers.*, vol. 22, no. 1, pp. 145-149, March 2007.

[8] 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*, 39th North American Power Symposium (NAPS ’07), pp. 492-497.

[9] M.H. Nehrir, B.J. LaMeres, V. Gerez, "A customer-interactive electric water heater demand-side management strategy using fuzzy logic," In Proc. *IEEE PES Winter Meeting*, vol. 1, New York, NY, 1999, pp. 433-436.

[10] S.N. Patrick, “Control of aggregate electric water heaters for load shifting and balancing intermittent renewable energy generation in a smart grid environment,” M.S. Thesis, Department of Electrical and Computer Engineering, Montana State University, Bozeman, 2011.

[11] N. Lu, S. Katipamula, "Control strategies of thermostatically controlled appliances in a competitive electricity market," In Proc. *2005 IEEE PES General Meeting*, 2005, pp. 202-207.

[12] W. Xiao, W.G. Dunford, “A modified adaptive hill climbing MPPT method for photovoltaic power systems,” In Proc. *IEEE 35th Annual Power Electronics Specialists Conference*, vol. 3, 2004, pp. 1957-1963.

[13] X. Yu, K. Tomsovic, “Application of Linear Matrix Inequalities for load frequency control with communication delays,” *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1508-1515, Aug. 2004.

[14] Y.G. Rebours, D.S. Kirschen, M. Trotignon, S. Rossignol, “A survey of frequency and voltage control ancillary services-Part I: Technical features,” *IEEE Trans. Power Syst., vol. 22, no. 1, pp. 350-357, Feb. 2007.*

[15] A. Brooks, E. Lu, D. Reicher, C. Spirakia, B. Weihl, “Demand dispatch: using real-time control of demand to help balance generation and load,” *IEEE Power & Energy Mag.*, vol. 8, no. 3, pp. 20-29, May-June 2010.

[16] C.M. Colson, “Toward real-time power management of microgrids for power system integration: A decentralized multi-agent based approach,” Ph.D. Dissertation, Montana State University, 2012.

[17] C.M. Colson, M.H. Nehrir, “Comprehensive real-time microgrid power management and control with distributed agents,” *IEEE Transactions on Smart Grid*, Vol. 4, No. 1, March 2013.

[18] S.A. Pourmousavi, M.H. Nehrir, “Real-time central demand response for primary frequency regulation in microgrids,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1988-1996, Dec., 2012