A Hybrid Solar PV/Wind Energy System for Voltage Regulation in a Microgrid

J.O. Petinrin and Mohamed Shaaban
Centre of Electrical Energy Systems (CEES)
Faculty of Electrical Engineering, Universiti Teknologi Malaysia
81310 UTM, Johor Bahru, Malaysia

Abstract—**Autonomous operation of a microgrid system hinges on the efficient combination of various energy resources to maintain self-sustainability of energy supply. Furthermore, it is equally important to coordinate the resources to regulate the microgrid voltage profile. The problem becomes more complicated if these resources have intermittent characteristics such as solar PV and wind turbines. This paper presents a hybrid solar PV/wind turbine system for voltage regulation in a microgrid. Demand response (DR) is employed to control the total energy consumption, so as to maintain the system security and enhance the microgrid's voltage profile. The singular use of solar PV and/or wind generation is tested and compared to the coordinated hybrid case. Investigation is carried out on an autonomous microgrid bus feeder to validate the effectiveness of the proposed system. It is shown that the coordination between the two variable renewable energy resources is much more effective in regulating the voltage throughout the microgrid.**

Keywords— microgrid; voltage profile; wind turbine; solar PV

I. INTRODUCTION

Smart grids will have a fundamental role in transforming today's power grids. The objective is to address growing demand; renewable, intermittent, and distributed generation; and environmental concerns. Microgrids are a key element in this transformation [1]. A Microgrid (MG) is a contiguous section of the grid which consists of one or multiple DG units (in electrical closeness to one another) capable of operating either in parallel with, or autonomous from, a power utility grid, while providing reliable power to multiple loads and consumers. A MG can be connected to/or disconnect from the grid to enable operation in both grid-connected mode or autonomous mode [2]. It should be also capable of riding through between the two modes if necessary. A MG can be strategically placed at any site in a power system, most especially at the grid system for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system reliability, integrity, and efficiency.

Although, variable renewable generation (VRG), such as solar and wind energies, integrated on a MG system have undeniably brought forward some positive impacts as far as sustainable energy development is concerned, it retains serious drawbacks. In particular, their inability to guarantee continuous energy supply, due to their intermittent and fluctuating nature, is the most imminent one [3]. Therefore, voltage regulation is essential, if suitable voltage level at the customer's point of common coupling (PCC) is to be maintained. Due to variable sunlight hours to which solar PV is exposed, and relatively fickle cut-in wind speeds, solar PV or wind turbines may not produce usable energy for considerable portion of time during the year.

Hybridization of solar PV with wind, therefore, improves the reliability of a VRG, where the wind acts as back up during low PV output [4]. Hybrid systems are basically a combination of two or more, complementary though, different energy supply sources at the same site [5]. A hybrid system is an integral part in the composition of modern-day microgrids. In weak grids, the hybrid PV/wind system is better than the independent use of PV or wind energy, since it suppresses rapid changes in the output power of the independent source [5]. Hybrid systems provide relatively constant electricity at an affordable cost, even when one of the supply systems is shut down [6]. Application of a hybrid system can reduce the storage capacity of batteries and the total cost of the system, compared with standalone PV or wind generation system [6], [7].

Demand response (DR) relates to the changes of electric energy usage by end customers to shift from their normal consumption patterns, in response to specific financial incentives. It can help in load reduction during times of peak demand. DR is designed to minimize the total energy consumption increase, hence maintaining network safety and reliability, and increasing energy efficiency of the MG [8].

This paper presents a hybrid solar PV/wind energy system for voltage regulation in an autonomous MG. Demand response is employed to minimize the total energy consumption, to maintain network security and integrity, and enhance the voltage profile. Investigation is carried out on an autonomous MG bus feeder to validate the effectiveness of the proposed system. Test results, carried out on the MG bus feeder, are presented and analyzed.

II. POWER MANAGEMENT OF THE MICROGRID

From a system-wise point of view, MGs should increase the overall efficiency of the power system by integrating larger amounts of distributed generations (DGs), including renewables, reducing system losses and greenhouse gas (GHG) emissions, as well as enhancing system reliability. Nonetheless, proper coordination of the MG's generation and storage operation as well as its effects on the connected grid, is a critical issue [9].

The work is supported by the Malaysian Ministry of Higher Education, under the Fundamental Research Grant Scheme (FRGS).

When a MG operates in the grid-connected mode, it balances its loads by purchasing or importing power from the main grid it is connected to. However, if it is in the standalone or islanded mode, *i.e*, isolated from the upstream distribution grid, MG uses its own generation resources to supply power to the customers. A microgrid thus requires a power and energy management (PEM) strategy to guarantee coordination between DG units and the main grid to achieve reliable and economic operation [6].

The main objective of the PEM strategy is to minimize MG's operating costs, including fuel costs if it has conventional generation, and cost of energy purchased from the main grid. The criteria required to meet such objective are [7]:

- Load sharing among DGs to minimize the power losses in the system;
- Considering factors that affect limits of DG units; such as type of DG, generation cost, maintenance interval, and environmental impacts;
- Preserving the power quality including voltage profile and harmonic distortion;
- Maintaining stability margin and improving the dynamic response as well as restoring voltage/frequency of the system during and following transients.

The main control functions for DGs, within a MG, are voltage and frequency controls, in addition to active and reactive power control. Using specified reference values for real power dispatch and reactive power support, control of dispatchable units can be carried out [6]. Storage is an important component in MGs, since it can maintain the balance between generation and load at the instant of system separation. It also provides a 'firming' capacity for VRGs [10]. Electric energy storage are required to supplement the generators during low voltage transient on the MG or, when in autonomous operation [1]. With the complementary characteristics between solar and wind energies for a sustainable energy output, a hybrid PV/wind power generation systems with demand response feature can offer a highly reliable source of energy that is suitable for microgrids in the standalone mode and reduces the energy storage required [11].

Load/generation shedding is often required in MG standalone mode to maintain power balance, where the output power must meet the total load demand. Hence, the operating strategy of a MG must ensure that critical loads of the MG receive service priority, whereas noncritical loads may need to be dropped; unless there is sufficient generation and storage provided in the MG to cover all needs. In practice, part of noncritical, controllable loads can be entered into a demand response (DR) control strategy to both reduce the peak load and smooth out the load profile. The non-controllable part of the noncritical loads is eligible for load shedding [6].

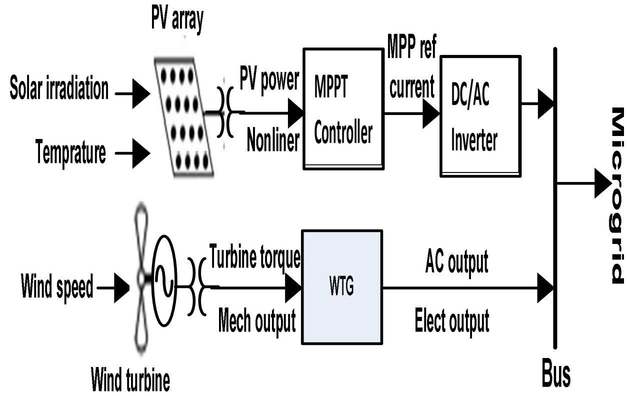

Fig. 1. Block diagram of PV/Wind hybrid system

The block diagram in Fig. 1 shows a hybrid PV/wind energy system. Each VRG is represented by its supply. Inverter power controllers regulate the power outputs, by providing reference values for the output voltage magnitude and phase. The real power droop of particular interest here is characterized by a frequency setpoint and a droop gain while the generator rating limits the extent to which the droop is applicable [5], [7]. In this study the PV and wind generators are combined together in parallel at the same bus to share real power demand according to their combined droops, and to suppress rapid changes in the output power. An energy management system, in real time, can adjust the PV and wind generators droop settings relative to each other to implement a particular droop operating point with a certain power sharing at a chosen frequency.

III. DEMAND RESPONSE IN A MICROGRID

There is always an issue of supply-demand mismatch in the presence of VRGs such as solar PV and wind turbine in the MG. Introducing a backup system such as diesel generator may be expensive and is not favored environmentally. The supply-demand mismatch is better reduced by incorporating demand response techniques at the distribution end of the power system.

Demand response (DR) is concerned with reducing consumption during peak hours and shifting demand to off-peak hours [11]. DR brings active participation of both producers and consumers of electrical energy in network operation via shifting/shaving load profiles, or allowing direct load control. The customer in return gets incentives with respect to electricity price [12]. DR promotes the interaction of the customers with the energy system which can not only lead to economic benefits to all stakeholders (customers and the utility), but also can reduce capital cost investments and postpone the need for grid upgrades [13].

Demand response tools include rate-based or price DR, incentive or event-based DR, and demand reduction bids. Types of the price DR options include time of use (TOU) rates, critical peak pricing (CPP), and real time pricing (RTP). Demand reduction bidding is a financial tool to allow customers to offer bids to curtail their loads if the electricity market price is high [13].

DR can be enabled through a two-way communication network that can provide remote control of individual loads. Incentive-based DR options allow the direct control of noncritical loads such as air conditioners, water heaters, ovens, heat pumps water storages, and freezers. The on/off times of noncritical loads can be determined by the distribution system operator (DNO) based on the consumer willingness to participate and receives incentive payments. Customers can adjust their demands through setting the operating time of some of the domestic appliances, based on real time price and weather conditions to shift their consumption, save energy and reduce costs [11], [14].

In this paper, DR is applied by curtailing portion of the peak loads at some buses in the MG, in order to minimize the total energy consumption. This would expectedly have a positive effect on the MG, particularly when operating in autonomous mode, where the hybrid solar PV/wind energy system is unable to meet its local load demand. DR may also be applied to grid-connected MG operation mode, if the upstream grid has hard limits due to some contractual obligations [6].

IV. Test Results

The proposed method is tested on an autonomous MG bus feeder of an actual 115 kV/4.16 kV 50-Hz distribution circuit. The total load is 3.866 MW and is distributed among commercial and residential energy consumers. The autonomous MG bus feeder, shown in Fig. 2, consists of a three-phase overhead/underground primary feeders and double-phase and single-phase line sections near the end of the feeder laterals. The model is taken from the IEEE 13 feeder test system. Loads with different types including constant current, constant impedance and constant power are modeled at the system buses.

The hybrid system is supposed to have a unity power factor. Therefore, the power injections of the PV and wind turbine is connected as illustrated in Fig. 2, whereas the details of the connection follows the block diagram shown in Fig. 1. The hybrid system was represented by voltage-independent active injections with zero reactive power. The VRGs are integrated into the distribution feeder at bus 9 for the simulation. Bus 9 is chosen, as in [15], based on a design criterion. However, any bus can be used depending on the amount of feasible energy harvested at a particular site, as dictated by the available resource, and subject to dominant meteorological conditions.

The base case power flow without any VRG is carried out first to determine the voltage magnitude at bus 14. Then, each of the VRGs is integrated into the microgrid independently and power flow simulation is carried out. Finally, the hybrid PV/wind energy is integrated into the MG and power flow is conducted again to determine the voltage profile of the MG system. The voltage at bus 14 is monitored on an hourly basis. Bus 14 is a non-visible bus representing concentrated point load of the distributed loads in line 1 and 4. It is located at 1/3 the distance from bus 1.

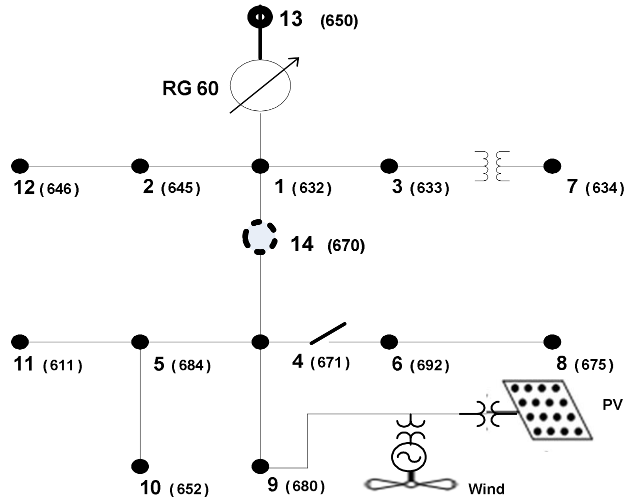

Fig. 2. Autonomous MG bus feeder

A. Combination of Hybrid Solar PV and Wind Turbine

The base case power flow without any of the VRG, gives a voltage magnitude of 0.9861 pu at bus14. The output voltage of the microgrid system at different hours of the day, due to the integration of solar PV is shown in Fig. 3. The dashed red-colored line, for the PV, shows a maximum voltage magnitude of 0.9982 pu and a minimum voltage magnitude of 0.9870 pu with corresponding losses of 118.6 kW as shown in Table I. Meanwhile, the output voltage with the wind turbine connected independently to the microgrid is shown in Fig. 3. Its maximum voltage is 0.9972 pu and the minimum is 0.9933 pu and corresponding losses of 116.2 kW.

It is clear that both PV and wind could not maintain the voltage at 1.0 pu, albeit still within the acceptable voltage bounds of 0.95 pu to 1.05 pu. The voltage regulation of the solar PV appears to be more fluctuating as far as the hourly voltage profile at bus 14 is concerned; in comparison with the one resulting from the wind generator. The wind appears to exhibit more bounded excursions throughout the day. The power delivered by each of the VRG is presented in Fig. 4. This highlights the fickle characteristics of the VRG system; whether solar or wind systems. Nonetheless, Fig. 4 suggests that the variability of wind generation is somewhat less than that of the solar PV one; albeit dropping to almost zero at 6:00 pm. While the degree of variation is site-dependent, short-term fluctuations are smaller in case of wind; therefore the total losses and voltages are slightly better than the solar PV.

The solid line, in Fig. 3, shows a 1.0071 pu of maximum voltage and a 0.9941 pu as minimum voltage with 122.5 kW system losses as depicted in Table 1. The increase in system losses due to hybrid PV/wind turbine is a result of a minor increase in its size. The losses on distribution system reduce to a minimum as the DG increases in size up to an optimal level. However, the losses start to increase if the size of the DG is further increased. It may even overshoot the base case losses [16]. There is appreciable voltage increase in the hybrid PV/wind compared to the individual use of solar PV and wind.

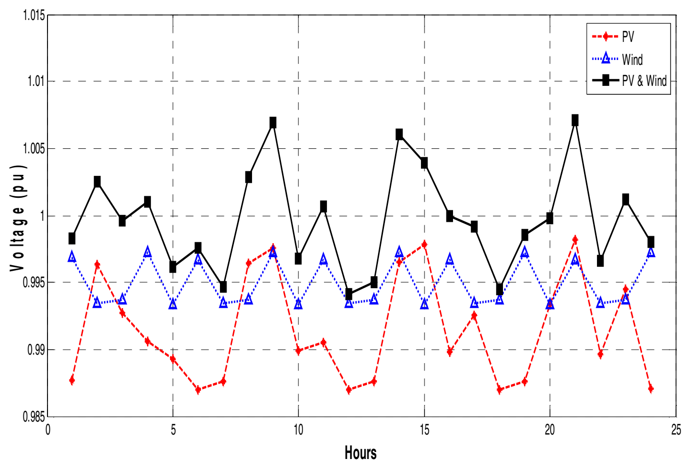

Fig. 3. Hourly voltages at bus 14 due to PV, wind and hybrid PV/wind

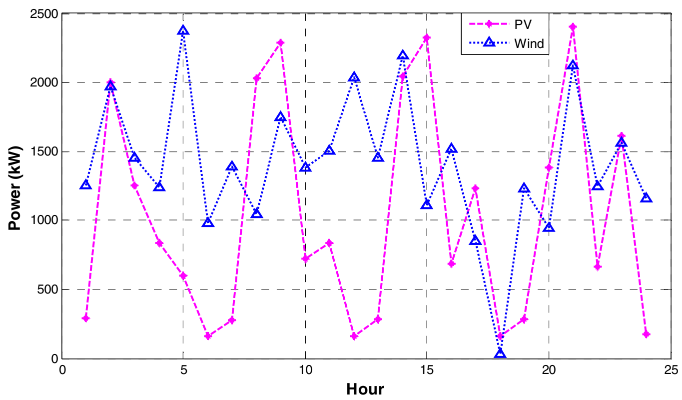

Fig. 4. PV and wind power outputs throughout the day

TABLE I. VOLTAGE RANGES AND INCURRED LOSSES

VRG	Min Voltage, pu	Max Voltage, pu	Losses, kW	% Losses
Base case	0.9861	0.9861	237.5	4.69
PV	0.9870	0.9982	118.6	2.33
Wind	0.9933	0.9972	116.2	2.28
PV/Wind	0.9941	1.0071	122.5	2.45

The above results underscore the improvement of the voltage regulation/profile offered by the hybrid system over the independent use of PV and wind energies. The coordination between VRGs can make the best use of the latter in the long-time period and can contend with the inherent intermittency of each of them acting alone. This can, in turn, enhance the reliability of supply with minimum operation costs.

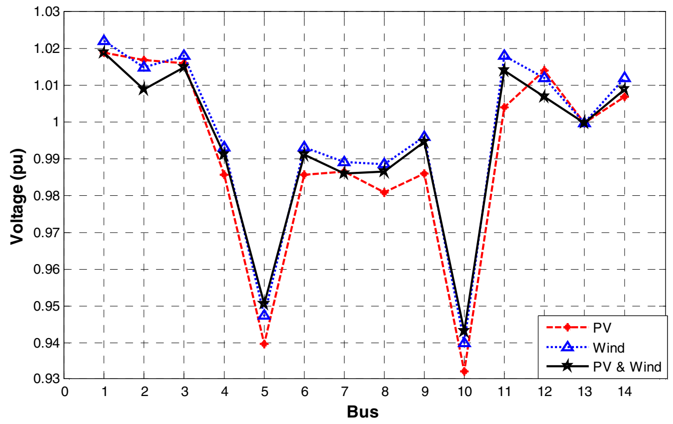

Fig. 5. Voltage magnitudes at various buses at 01:00 pm

The output voltage of the MG system at 1.00 pm corresponding to all system buses is depicted in Fig. 5. The peak load recorded at this hour of the day was 3.443 MW. The graph confers that while improvement in the overall system voltage profile can be improved on a diurnal basis, it may not be necessary true on every hour of the day at all system nodes.

B. *Effect of Incorporating Demand Response*

The total load of the microgrid is increased by 45%. It is expected that bus voltage magnitude in the MG should be within acceptable limits between 0.95 pu and 1.05 pu. Fig. 6 illustrates the effect of the hybrid solar PV/wind turbine system in maintaining the voltage within acceptable limits, when the load is increased. Again, the independent use of solar PV and wind turbine generator render the voltage below the acceptable voltage bounds. The voltages are within the range of 0.9421 pu – 0.9528 pu and 0.9482 pu - 0.9516 pu for solar PV and wind generation respectively. Nonetheless, the hybrid PV/wind turbine combination manages to increase the microgrid system voltage to (0.9500 pu - 0.9577 pu) and keeps it within the acceptable bounds.

Demand response is applied in order to improve the voltage further. The requirement for DR utilization is that the loads can be modulated and controlled when the need arises. It is assumed that, as the case of a MG in the standalone mode, DR can be implemented by shifting some of the peak loads into off peak hours of operation.

Some of the peak loads at buses 8, 9 and 11 were curtailed and the result is as shown in Fig. 7. There is a remarkable improvement in the voltage regulation/profile as compared with the independent PV, wind and even hybrid PV/wind energy. The voltage is maintained within 0.9976 and 1.0100 pu. That is, around 1.0 pu. These results highlight the improvement in the MG voltage profile at critical nodes [17]. This case emphasizes the role of DR as a remedy to the voltage depression problem in a MG, when the coordination of variable renewable energy resources fell short in restoring the voltage within its prescribed bounds.

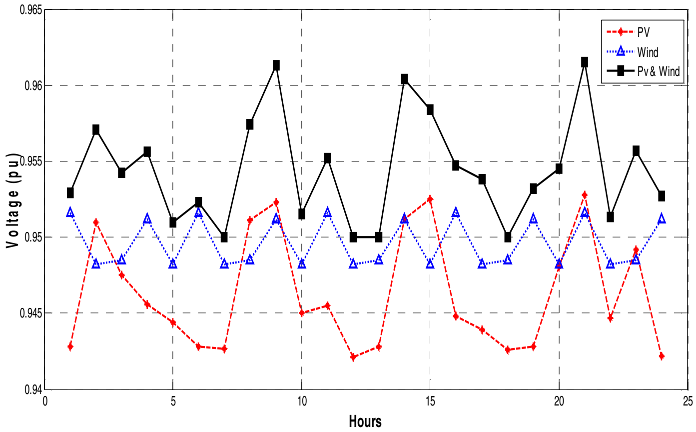

Fig. 6. Hourly voltage variations at bus 14 due to 45% load increase

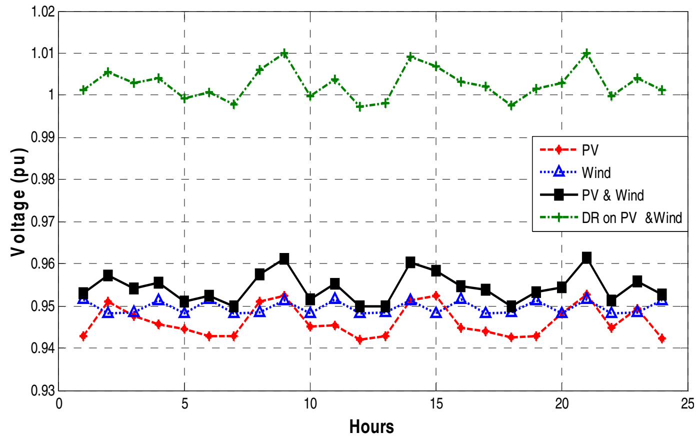

Fig. 7. Effect of demand response at bus 14 on system hourly voltage profile

V. Conclusion

Accelerated installation of variable renewable generation coupled with the introduction of the smart grid, have created an increased interest in microgrids. This paper has demonstrated the voltage regulation in a microgrid system comprising hybrid solar PV/wind turbine in the autonomous operation mode. Solar PV and wind turbine size and locations in the microgrid were preselected. Simulation studies were carried out on a microgrid system to test the impact of various individual and variable renewable energy (solar/wind) combination. The hybrid solar PV/wind generation provided more effective voltage regulation to the microgrid system as compared with each of the solar PV/wind turbine acting alone. Furthermore, when the voltage variation fell beyond the capabilities of the hybrid system, the combination of demand response (DR), a feature of the smart microgrid, with the hybrid PV/wind system were apt to bring the voltage back within statutory limits. Voltage drop across the distribution feeders reduce in the case of load curtailment due to DR, causing an increase in the voltage at the far end of the MG's feeder system.

Further research is needed to work out a framework for voltage regulation in microgrids that is capable to operate under wide range of operation modes and conditions.

Acknowledgement

The first author acknowledges the support of The Federal Polytechnic, Ede, Osun State, Nigeria.

References

[1] L. Schmitt, J. Kumar, D. Sun, S. Kayal, and S. Venkata, "Ecocity upon a hill: microgrids and the future of the European city," *IEEE Power and Energy Magazine,* vol. 11, pp. 59-70, 2013.

[2] M. Shahidehpour and M. Khodayar, "Cutting campus energy costs with hierarchical control: the economical and reliable operation of a microgrid," *IEEE Electrification Magazine,* vol. 1, pp. 40-56, 2013.

[3] J. O. Petinrin and M. Shaaban, "Overcoming challenges of renewable energy on future smart grid," *TELKOMNIKA Indonesian Journal of Electrical Engineering,* vol. 10, pp. 229-234, 2012.

[4] H. Habeebullah Sait and S. Arul Daniel, "New control paradigm for integration of photovoltaic energy sources with utility network," *International Journal of Electrical Power & Energy Systems,* vol. 33, pp. 86-93, 2011.

[5] C.-M. Hong and C.-H. Chen, "Intelligent control of a grid-connected wind-photovoltaic hybrid power systems," *International Journal of Electrical Power & Energy Systems,* vol. 55, pp. 554-561, 2014.

[6] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power and Energy Magazine,* vol. 6, pp. 54-65, 2008.

[7] F. Katiraei and M. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Transactions on Power Systems,* vol. 21, pp. 1821-1831, 2006.

[8] A. J. Roscoe and G. Ault, "Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response," *IET Renewable Power Generation,* vol. 4, pp. 369-382, 2010.

[9] A. K. Basu, S. Chowdhury, S. Chowdhury, and S. Paul, "Microgrids: energy management by strategic deployment of DERs—a comprehensive survey," *Renewable and Sustainable Energy Reviews,* vol. 15, pp. 4348-4356, 2011.

[10] M. Montoya, R. Sherick, P. Haralson, R. Neal, and R. Yinger, "Islands in the storm: integrating microgrids into the larger grid," *IEEE Power and Energy Magazine,* vol. 11, pp. 33-39, 2013.

[11] K. Hamilton and N. Gulhar, "Taking demand response to the next level," *IEEE Power and Energy Magazine,* vol. 8, pp. 60-65, 2010.

[12] Y. Wang, I. R. Pordanjani, and W. Xu, "An event-driven demand response scheme for power system security enhancement," *IEEE Transactions on Smart Grid,* vol. 2, pp. 23-29, 2011.

[13] P. Siano, "Demand response and smart grids—a survey," *Renewable and Sustainable Energy Reviews,* vol. 30, pp. 461-478, 2014.

[14] P. Wang, J. Huang, Y. Ding, P. Loh, and L. Goel, "Demand side load management of smart grids using intelligent trading/metering/billing system," in *IEEE PowerTech 2011 Trondheim*, 2011, pp. 1-6.

[15] M. Shaaban, and J. O. Petinrin, "Sizing and siting of distributed generation in distribution systems for voltage improvement and loss reduction," *International Journal of Smart Grid and Clean Energy,* vol. 2, pp. 350-356, 2013.

[16] N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," *International Journal of Electrical Power & Energy Systems,* vol. 28, pp. 669-678, 2006.

[17] N. Venkatesan, J. Solanki, and S. K. Solanki, "Residential demand response model and impact on voltage profile and losses of an electric distribution network," *Applied Energy,* vol. 96, pp. 84-91, 2012.