Voltage Regulation in a Microgid with Hybrid PV/Wind Energy

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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. The potential for using energy storage promise to have a major impact on schemes for voltage control in a microgrid. A hybrid Particle Swarm Optimization/Gravitational Search Algorithm (PSOGSA) based approach is used in this paper to contemplate the optimum size and location of energy storage to reduce voltage variations and feeder losses caused by PV/wind energy integrated in a microgrid. Effectiveness of the proposed method is implemented through a quasi-static time sequence analysis over a 24-hourly simulation period on autonomous Microgrid system. The corresponding voltage profile is analyzed under different operating conditions, with high penetration level of PV/wind energy. Test results show that the energy storage causes reduction in system losses and enhances system capability to maintain voltages within the permissible limits.

Keywords: energy storage, microgrid, PSOGSA, solar PV, voltage profile, wind turbine

1. Introduction

Smart grids (SGs) will have a fundamental role in transforming today's power grids. The objective is to address growing demand; renewables, intermittent, and distributed generation (DG); and environmental concerns. Microgrids are a key element in this transformation (Schmitt, Kumar et al. 2013). 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 (Shahidehpour and Khodayar 2013). 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.

A hybrid system is an integral part in the composition of modern day microgrids integrated in the utility grid. 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 (Petinrin and Shaaban 2013). However, variable nature of solar irradiance and wind speed, resulting in intermittent output energy, could lead to voltage rise, particularly when PV/wind generation is high and demand is low. Schroeder in (Schroeder 2011) presented that energy (ES) and demand response (DR) are essential grid technologies in operation of utility grid by avoiding capacity shortages. For instance, there can be deferment of grid reinforcement at some voltage level without affecting system security because the system voltage will still be kept within the permissible voltage bounds. In addition, the effect of DR will be stronger with more flexible demand using electric vehicle (Poudineh and Jamasb 2014).

Deployment of ES throughout the grid from generation to end-users presents an opportunity to transcend the real-time power balance paradigm between supply and demand. ES was reportedly used with small solar arrays to even out the power flow as clouds pass over, and in ancillary service provision, such as frequency regulation (Petinrin and Shaaban 2013).

Various approaches have been developed in literature to solve the problem of voltage regulation in a grid system using ES. A matrix real-coded genetic algorithm (GA) technique was proposed to optimally coordinate the power production of DGs and ES to minimize the operational costs of a MG (Chen, Duan et al., 2011). A neural network was used to forecast the energy output of the PV sources, and battery energy storage was modeled aggregately. The paper, however, assumes identical batteries based on the size of the PV system. In other words, the size and location of the ES were not studied.

A heuristic tool using the GA with simulated annealing was described in (Crossland, Jones et al. 2014), to locate distributed ES in low voltage (LV) networks. Monte Carlo simulations were utilized to randomly site the PV systems at full power and the highest voltage is determined. The heuristic tool is then applied to find out the storage needed. Nonetheless, a single time step load flow is performed to evaluate the worst-case scenario.

Alam (Alam, Muttaqi et al., 2012), proposed distributed energy storage (DES) to mitigate voltage rise problem caused by solar PV in a distribution system (DS). The method employed enable DES to absorb excess energy at noon day to mitigate the reverse power flow as a result of high PV output. The stored energy is then discharged to support the voltage in the evening peak period. The method considered an over-simplified charge/discharge ES cycle with the assumption of no voltage problem except noon day and evening peak period. However, a preventive control frame work is required to continuously monitor current and voltage at the PCC to establish a real-time equivalent circuit of the DS. This will guide against any changes in load pattern, most especially during holidays, or else application of such model might be detrimental for the DS.

Optimal sizing and siting of the ES is necessary to improve the voltage profile in the DS and reduce losses. Different methods have been employed in the literature for optimal sizing and siting of ES/DG to mitigate the problems associated with uncertainties of renewable generation (RG). Gravitational search algorithm (GSA) and particle swarm optimization-gravitational search algorithm (PSOGSA) are used to determine multiple DG capacity and location in DS in (Khan, Ghosh et al., 2013) and (Tan, Hassan et al., 2013) respectively. An OPF-based algorithm for siting the aggregated capacity of ES was developed to decrease the wind energy curtailment and cost of energy supply in (Atwa and El-Saadany 2010). A coordinated control of DES systems with LTC for voltage rise mitigation under high PV penetration is proposed in (Liu, Aichhorn et al., 2012). However, none of the reviewers above employed the hybrid PSOGSA for their search technique on energy storage.

This paper presents a comprehensive architecture that do not only take into consideration the coordination of hybrid PV/wind energy, but also manages storage facilities in an hourly operation fashion. This gives the MG operator options in selecting appropriate and effective voltage control measures. Hybrid PSOGSA is employed for sizing and location of ES. The importance of ES in voltage regulation in a MG with high penetration of PV/wind energy is demonstrated.

2. Problem Formulation

Multifaceted opportunities are provided with deployment of ES in a MG for significant benefits to MG system, electricity supply, utility customers, ancillary services, and integration of renewables (Roberts and Sandberg 2011). Their key function in modern MGs is to counterbalance the intermittency introduced by integrating variable renewables at the point of common coupling (PCC). Such effect of the ES is likely to minimize the overall losses and improve the system voltage profile. Therefore, the problem of finding the optimal location and size of the ES can be cast as a mathematical programming problem, where the objective is to minimize hourly energy losses and voltage deviations across all network nodes. This can be expressed mathematically as:

$$\text{Min} \quad F = w_v \sum_{i=1}^{N} \sum_{t=1}^{24} \left\| V_{i,t} - V_{ref} \right\|^2 + w_l \sum_{i=1}^{N} \sum_{t=1}^{24} P_{L_{i,t}} \Delta t \tag{1}$$

Where w_v and w_l are the weighted-coefficients of voltage and loss minimization respectively. $V_{i,t}$ and V_{ref} are the voltage of bus i at time t and magnitude of voltage reference respectively, obtained from the power flow. V_{ref} is considered unity in this paper. $P_{L,t}$ is the system loss at time t. Δt is 1 hour time interval and N is the number of buses.

The first term of (1), corresponds to the squared norm of voltage deviations over the given period of time, whereas the second term represents the total system losses at time t.

The total power losses due to the ES is given as (Shaaban and Petinrin 2013):

$$P_{Li,t} = \sum_{j=1}^{N} \left[\alpha_{ij,t} \left(P_{i,t} P_{j,t} + Q_{i,t} Q_{j,t} \right) + \beta_{ij,t} \left(Q_{i,t} P_{j,t} + P_{i,t} Q_{j,t} \right) \right] \quad i \in N$$

(2)

Where, $\alpha_{ij} = \dfrac{r_{ij}}{V_{i,t} V_{j,t}} \cos\left(\delta_{i,t} - \delta_{j,t} \right)$, $\beta_{ij} = \dfrac{r_{ij}}{V_{i,t} V_{j,t}} \sin\left(\delta_{i,t} - \delta_{j,t} \right)$, and $Z_{ij} = r_{ij} + x_{ij}$ is the ijth element of [Zbus] matrix.

$$P_{i,t} = P_{Gi,t} \pm P_{ESi,t} - P_{Di,t}, \quad Q_{i,t} = Q_{Gi,t} \pm Q_{ESi,t} - Q_{Di,t}.$$

$P_{i,t}$ and $Q_{i,t}$ are the net active and reactive power injection at the bus i at time t, $P_{Gi,t}$ and $Q_{Gi,t}$ are the active and reactive powers generated from the PV/wind energy systems at time t. $P_{ESi,t}$ and $Q_{ESi,t}$ are the active and reactive power charged/discharged by the ES at bus i at time t, while $P_{Di,t}$ and $Q_{Di,t}$ are the load active and reactive powers at bus i at time t respectively.

The constraints include power flow equality constraints represented as:

$$P_{i,t} = V_{i,t} \sum_{j=1}^{N} V_{j,t} \left[G_{i,j} \cos\left(\delta_{i,t} - \delta_{j,t} \right) + B_{i,j} \sin\left(\delta_{i,t} - \delta_{j,t} \right) \right]$$

(3)

$$Q_{i,t} = V_{i,t} \sum_{j=1}^{N} V_{j,t} \left[G_{i,j} \sin\left(\delta_{i,t} - \delta_{j,t} \right) - B_{i,j} \cos\left(\delta_{i,t} - \delta_{j,t} \right) \right]$$

(4)

Where $V_{i,t}$ is the voltage at bus i at time t, $G_{i,j}$ and $B_{i,j}$ are the conductance and susceptance of the line between buses i and j respectively, whereas $\delta_{i,t}$ is the voltage angle at bus i at time t.

a) Voltage limits:

$$V_{\min} \leq V_{i,t} \leq V_{\max}$$

(5)

b) Storage physical and operating limits:

$$\sum_{t=1}^{24} - P_{Es_{i,t}} \Delta t \eta_i \leq E_{ES_i}^{\max} - E_{ES_i}^{0}$$

(6)

$$\sum_{t=1}^{24} P_{ES_{i,t}} \Delta t \eta_i \leq E_{ES_{i,t}}^{0}$$

(7)

$$E_{ES_i}^{\min} \leq E_{ES_{i,t}} \leq E_{ES_i}^{\max}$$

(8)

$$P_{ES_i}^{\min} \leq P_{ES_{i,t}} \leq P_{ES_i}^{\max}$$

(9)

c) Power loss constraint:

$$P_{Li,t}^{\,with\,ES} \leq P_{Li,t}^{\,without\,ES}$$

(10)

Where η is the energy storage round-trip efficiency, E_{ES} is the energy stored in the ES, and E^0_{ESi} is the initial energy stored at bus i, where the ES is located. E^{min} and E^{max} are the minimum and maximum energy capacity of the storage respectively.

Equation (6) and (7) denote the maximum and minimum amount of the energy absorbed or injected from the ES respectively. Similarly, (8) and (9) are the maximum and minimum ES capacity with the relevant active power rating. Equation (10) guarantees that integration of the ES improves the network-wide losses. The formulation from (1) to (10) gives a complete description for the modeling of energy storage required to mitigate the impact of the hybrid PV/wind generation on voltage deviation and network losses.

d) Weighting Factor

A composite objective function is molded as the weighted sum of the objectives to avoid multiobjective programming and produce an equivalent single-objective optimization problem. A weight for an objective is directly proportional to the penchant weighted factor allocated to that specific objective. Thus, secularizing an objective vector into one composite objective function changes the multi-objective optimisation problem into one objective optimization problem (Deb 2001). When such a composite objective function is optimized, in most cases it is possible to get one particular trade-off solution. Each objective function is multiplied by scalar coefficients called weighting factors. The weighting factors are usually normalized as:

$$\sum_{k=1}^{K} W_k = 1 \tag{11}$$

Therefore, $w_v + w_l = 1$.

The convergence criterion of the maximum number of generation is checked after the fitness of each individual in a population is evaluated by the following fitness function.

$$Fitness = \left[w_v \sum_{t=1}^{T} \sum_{i=1}^{N} \left(V_{i,t} - V_{ref} \right)^2 + w_L \sum_{t=1}^{T} \sum_{i=1}^{N} P_{L_{i,t}} \right] \tag{12}$$

3. Test Results

The proposed method is tested on autonomous microgrid system of an actual 5MVA, 115 kV/4.16 kV 50-Hz where bus 150 is used as point of common coupling to the utility grid. The total load is distributed among commercial and residential energy consumers.

The MG as shown in Figure 1, consists of three-phase overhead or underground primary feeders and double-phase or single-phase line sections near the end of the feeder laterals. The MG has 91 loads of different types, including constant current, constant impedance and constant power. The voltage at bus 450, line 99 is monitored on hourly basis. That particular bus is selected due its high voltage sensitivity. It is a point on the feeder that responds quickly to any changes in system conditions.

The weighting factors were determined as $w_v = 0.55$ and $w_l = 0.45$ for voltage deviation and power losses respectively, after numerous simulation studies. Lower emphasis was given to the energy loss, as compared with the voltage, due to its dependency on voltage deviations. These weighting factors improve the overall system performance. The proposed method has been implemented in MATLAB, and examined on the MG system for 24 hours using quasi-static time sequence analysis.

The size and location of the ES are found using the PSOGSA-based optimization approach, as listed in Table 1. It is evident from the Table that, the proposed approach is capable of estimating the storage size at a single location or multiple locations with comparable sizes.

Table 1. Results for the sizing and location of ES

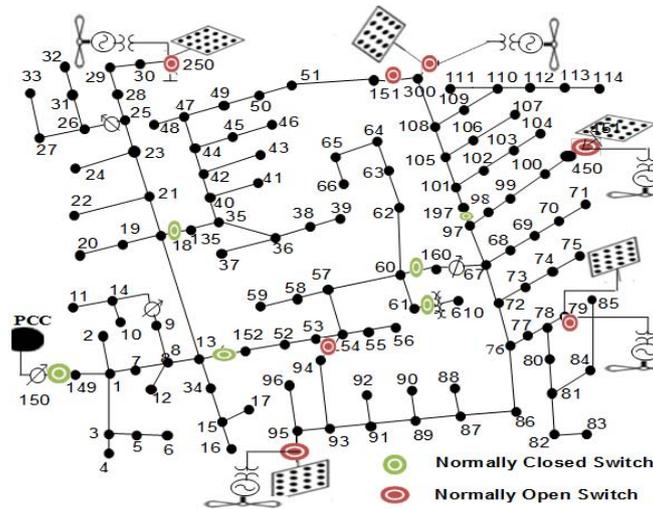| Centralized Energy Storage (CES)		Distributed Energy Storage (DES)	
Bus	Rating (MW)	Bus	Rating (MW)
		81	2.264
81	4.473	70	1.035
		78	0.485
		43	0.693

Figure 1. Autonomous microgrid bus feeder

a) Case I Hybrid Solar PV/Wind for Voltage Regulation in a Microgrid
    Due to variable sunshine hours as regards to solar PV, 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. Each of the RGs is integrated into the feeder independently and power flow simulation is carried out. Finally, the hybrid PV/wind energy is integrated into the feeder and power flow is carried out to determine the voltage profile of the MG. There is high-power blocking diode between the solar PV and wind turbine to prevent bi-directional current flow in the hybrid. Hybridization of solar PV with wind therefore form a very reliable RG in this scenarios, wind can provide energy in both day and night (where there is availability of wind blowing) and solar PV acts as back up energy during peak hour of the day (Habeebullah Sait and Arul Daniel 2011). Wind speed generally tends to increase in the evening during the same time that solar PV begins to decrease. Three scenarios are considered in the proposed approach are 1) Standalone PV generation; 2). Standalone Wind generation and 3) Hybrid solar PV/wind generation.
    A 30% PV penetration is distributed in a modified peak load feeder of 10 MW with the wind turbine isolated. The output voltage of the MG at different hour of the day with the integration of solar PV is shown in Figure 2. The dotted line, for PV, shows a maximum voltage magnitude of 1.01 pu at the 13.00 hour of the day and a minimum voltage magnitude of 0.95 pu with corresponding losses of 1.28 MW as shown in Table 2.
    A 30% wind penetration without PV is also distributed in the feeder. The output voltage with the wind turbine connected independently to the MG is shown with dashed line in Figure 2. Its maximum voltage is 1.01 pu at the 5.00 hour of the day and the minimum is 0.97 pu and corresponding losses is 1.59 MW. It is clear that both PV and wind could not maintain the voltage at 1.0 pu at every hour of the day, albeit still within the acceptable voltage boundary of 0.95 pu to 1.05 pu. The voltage injection of the solar PV appears to be zero in the night as far as the hourly voltage profile is concerned; in comparison with the ones resulting from the wind turbine generator. The wind appears to exhibit more bounded excursions through the day.
    In the third scenario, a total of 15% PV and 15% wind hybrid together as shown in Figure 1 is distributed in the feeder. The output voltage of the MG at different hour of the day, at bus 450, with the combination of the hybrid solar PV/wind turbine is shown solid line in Figure 2. The solid line shows a maximum voltage magnitude of 0.99 pu at the 13.00 hour of the day and 0.96 pu as minimum voltage and corresponding losses is 1.05 MW. There is appreciable system loss reduction and minimum voltage deviation in the hybrid PV/wind turbine as compared to the independent use of both solar PV and wind turbine. This underscores the improvement of the voltage profile offered by the hybrid system over the independent use of PV and wind energies. Security of supply is displayed as the wind generation offer supply when the solar PV could not and the solar PV acts as a back-up where the wind generation drops in the day.
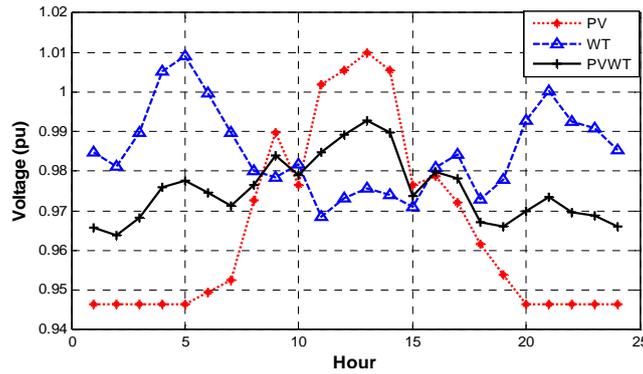
Figure 2. Hybrid PV/wind voltage output

In these scenarios, wind can provide energy in both day and night (while wind blows) and solar PV panel systems can provide back-up energy for peak hours of the day when appliances are on and work is in progress in offices (Habeebullah Sait and Arul Daniel 2011). Although, the two RGs can be made to operate in 100% redundancy; while the solar PV is made to operate during the day, the wind turbine is made to operate in the night. It is evident in Figure 2 that the application of a hybrid system offers appreciable voltage regulation, reduces (if not eliminate) the cost of ES system and the storage capacity of ES system, compared to standalone wind turbine or PV system (Katiraei and Iravani 2006, Katiraei, Iravani et al. 2008). The hybrid system provides the benefits of peak load shaving, mitigation of peak-valley difference, improves the voltage profile quality and offers active power adjustment capacity for the MG (Qing, Nanhua et al. 2013) which ES could have provided if employed.

The power delivered by each of the RG is presented in Figure 3. This highlights the fickle characteristics of the renewable energy system; either solar or wind system. Nonetheless, Figure 3 suggests that the variability of solar PV is somewhat less than that of the wind generation; albeit dropping to zero at night. While the degree of variation is site-dependent, short-term fluctuations are smaller in the case of PV. Therefore the total losses and voltages are slightly better than the wind generation as depicted in Table 2.
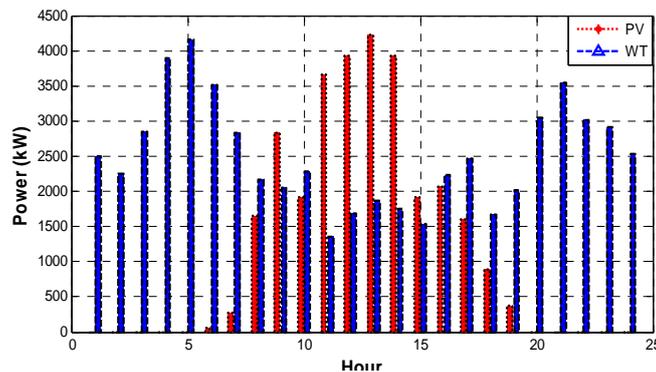

Figure 3. PV and wind generation power injection

Table 2. Voltage ranges and incurred losses

RG	Min pu Voltage	Max pu Voltage	Voltage deviation	Losses, MW	% Losses Reduction
Base case	0.9466	0.9466	-	2.182	-
PV	0.9466	1.0100	0.0634	1.278	41.43
Wind	0.9684	1.0089	0.0405	1.586	27.31
PV/Wind	0.9640	0.9929	0.0289	1.053	51.74

The above results underscore the improvement of the voltage control offered by the hybrid system over the independent use of PV and wind energies. The coordination between RGs 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.

b) Case II Energy Storage for Voltage Support in Hybrid PV/Wind Energy System

In this scenario, both the solar PV and the wind generator delivered their full capacity (30% penetration each) due to load increase in the MG from 10MW to 14MW. It is expected that bus voltage magnitude in the feeder is maintained within acceptable limit of 0.95 pu and 1.05 pu. Figure 4 illustrated the effect of the hybrid PV/wind system on the voltage profile of the MG. Here, the independent uses of solar PV and wind turbine energy have the voltage below the acceptable voltage bounds. Except at 11th to 14th hour of the day for the PV (dotted line) and 5th to 7th and 21st hour of the day for wind energy (dashed-dotted-dashed line). The voltages are within the range of 0.918 pu – 0.961 pu for solar PV and 0.935 pu - 0.960 pu for wind energy. Nonetheless, the hybrid PV/wind turbine (solid line) managed to increase the voltage (0.9397 pu – 0.981 pu) and nearly keeps it within the acceptable boundary. There is appreciable voltage increase in the hybrid PV/wind turbine as compared to the independent use of both solar PV and wind turbine. However, 9 hours are still below the statutory limits in the night.

A total energy storage (ES) of 4.473MW as determined by PSOGSA based optimization is distributed in the MG at their respective optimal locations. The ES systems are divided into two sections because the maximum charging and discharging rate is 6 hours each. Section 'A' comprises only the ES on bus 81 of 2.264MW capacity while section 'B' comprises of ES integrated at buses 70, 78 and 43 with total size of 2.214MW. The integration of the ES is to inject power into the MG as voltage support and absorb power during high generation for voltage levelling.
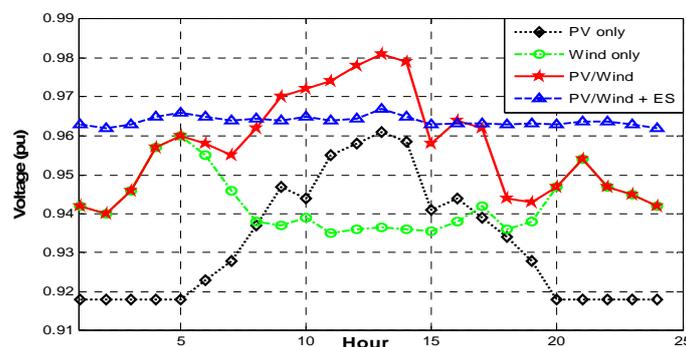

Figure 4. Energy storage for voltage support

There is a remarkable improvement in the voltage profile as compared with the hybrid PV/wind energy. The voltage is maintained within 0.962 pu and 0.967 pu with voltage deviation of 0.005. This case emphasizes the role of ES as a remedy to the voltage depression problem in a MG, when the coordination of other control devices fell short in restoring the voltage within its prescribed bounds. The integration of ES in the feeder was able to absorb and inject power into the buses as deem fit, thereby demonstrated the benefits of peak load shaving and mitigation of peak-valley difference. This has effectively assists to harness intermittent renewable energy resources, reduced energy loss, improve the voltage profile and bring the voltage within statutory limit.

3. 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 developed a framework for voltage regulation in autonomous microgrids that is capable to operate under

wide range of operation modes and conditions. Solar PV and wind turbine size and locations in the microgrid were preselected, however, the size and location of the energy storage was determined using PSOGSA optimization approach. 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 coordination of the hybrid PV/wind energy system with energy storage, a feature of the smart microgrid, were apt to bring the voltage back within statutory limits.This improves the voltage profile quality and offers active power adjustment capacity to the DS. The efficacy of real-time pricing (RTP) demand response tool in shaping load demand is suggested for further studies which will not only greatly minimizes the peak load, but also the load demand variation).

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