

Review Article

Real-Time Pricing and Energy Storage for Voltage Improvement in a Distribution Feeder

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To cite this article:J. O. Petinrin, M. A. Sanusi, M. A. Tijani, A. K. Adebayo, M. O. Abolarin. Real-Time Pricing and Energy Storage for Voltage Improvement in a Distribution Feeder. *International Journal of Mechanical Engineering and Applications*. Vol. 5, No. 1, 2017, pp. 41-46.

doi: 10.11648/j.ijmea.20170501.15

Received: September 13, 2016; **Accepted:** January 10, 2017; **Published:** February 24, 2017

Abstract: Increasing demand on electrical energy coupled with lack of new distribution facilities create a potential threat that can eventually sprawl to jeopardize the distribution system reliability. The variability characteristics of wind energy sources present a fundamental problem to its smooth integration in the distribution feeders, in a large proportion. Energy storage (ES) systems and demand response (DR) technique have the potential to improve the flexibility of distribution network, by allowing two ways of freedom for the distribution network operator (DNO), to support mitigation of demand-supply balance issues, and thereby the share of renewable energy sources (RESs) or improve penetration levels of renewables. By shifting electricity supply and customer demand patterns, this paper applies real time pricing and energy storage not only to significantly increase the penetration of wind energy, but also to offer other important value to shifts demand to times of relatively high renewable energy resources and low load; and by storing energy during off-peak, with less line losses, and redispatching this energy when needed. The results show that real time pricing and energy storage can effectively provide demand-supply benefits to the distribution network and customers.

Keywords: Energy Storage, Real Time Pricing, Peak-Valley Levelling, PSO GSA, Wind Energy

1. Introduction

Energy storage (ES) systems and demand response (DR) technique have the potential to improve the flexibility of distribution network, by allowing two ways of freedom for the distribution network operator (DNO), to support mitigation of demand-supply balance issues, and thereby the share of renewable energy sources (RESs) or improve penetration levels of renewables [1] (Alharbi and Bhattacharya 2013). The coordination of DR and ES enable high levels of (RESs) penetration than currently possible, by providing such flexibility in distribution network operation. For instance, the main benefits are related to maintaining grid balance, loss reduction for the DNO and capacity support. The benefits are in terms of reliability improvements, reduction in time-of-use tariffs, and load charges for the electricity users.

Deployment of ES throughout the grid from generation station to customers present an opportunity to transcend the

power balance paradigm by storing energy during off-peak, with less line losses, and redispatching this energy when needed [2, 3] (Roberts and Sandberg 2011), (Petinrin and Shaaban 2013). ES system is essential for grid support so as to lead to a higher synergy between electricity consumers and variable renewable energy. DR is one of smart grid tools that empowers customers and offers them with opportunity to interact with utilities. It has the potential to reduce overall plant and capital cost investments and postpone the need for network upgrades [4] (Venkatesan, Solanki et al. 2012). Real time pricing (RTP), one of the DR tools used in this paper is more flexible because its price varies on hourly basis [5] (Chen and Lan 2014).

Energy storage system and demand response are among a limited set of options in the latter category of smart grid tools. ES and DR provide means to better align renewable generation (RG) with electricity demand patterns as shown in figure 1: ES stores excess RG for use in times of relatively low

RG and high load, while DR shifts demand to times of relatively high RES and low load.

By shifting electricity supply and customer demand patterns, ES and DR can not only significantly increase the penetration of RG, but also can offer other important sources of value such as provision of firm capacity, which can

remove the necessity for conventional peaking capacity [6, 7]. In addition to providing load shifting, both ES and DR can also offer operational flexibility. This paper seeks to address the extent to which ES and DR can provide demand-supply benefits to the distribution network and customers.

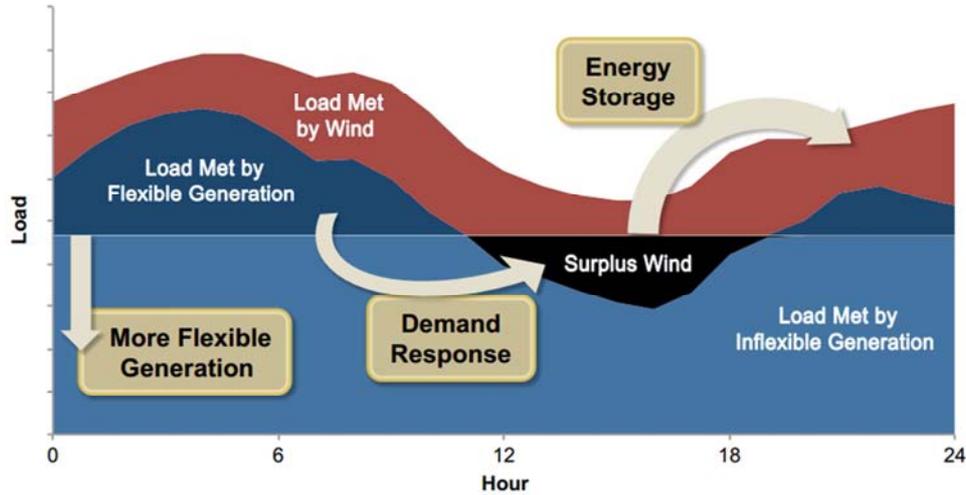


Figure 1. Renewable generation with electricity demand patterns.

2. Methods and Materials

The proposed method is tested on a sample circuit taken from the IEEE 123 bus feeder of an actual 115 kV/4.16 kV 50-Hz distribution feeder as shown in figure 2. The total load is modified and is distributed among commercial and residential energy consumers. The existing control devices already ingrained in the feeder are utilized to the full extent in this paper. Loads with dissimilar types including constant current, constant impedance and constant power are modeled at the system buses. The feeder is supposed to have a unity power factor. Therefore, the power injections of the wind

energy systems have been represented by voltage-independent active injections with zero reactive power. The voltage at bus 450, line 99 is monitored on hourly basis. That particular bus is selected because of its high voltage sensitivity. It is a location in the feeder which responds fast to any changes in system conditions. The optimal consumer’s electricity consumption scheduling is determined for the four zones using hybrid particle swarm optimization-gravitational search algorithm (PSOGSA). A 30% wind energy is distributed in the modified peak load feeder of 16 MW. OpenDSS interfacing with Matlab is used to carry out voltage and loss analysis in this paper.

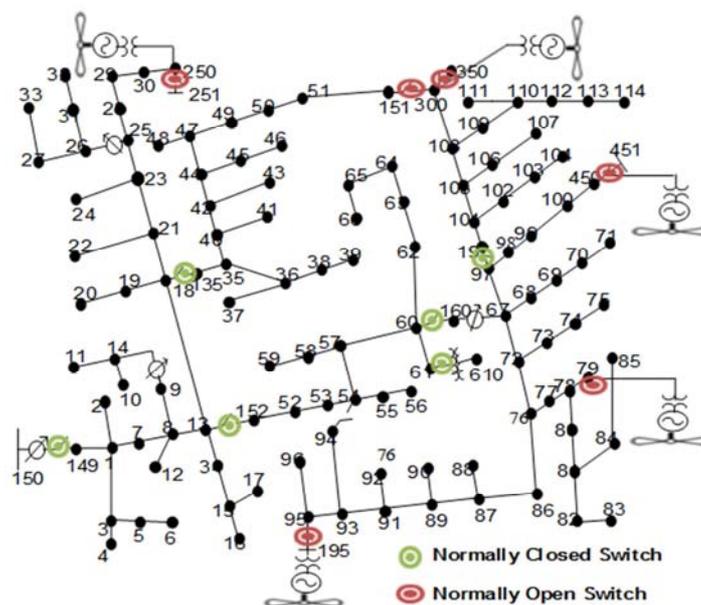


Figure 2. Modified IEEE 123 bus test feeder.

3. Results and Discussions

Voltage analysis results by [4] shows that DR has a great potential to increase the DS voltage at nearly all the critical nodes.

The popular option in dynamic pricing, one of the DR tools are real-time pricing (RTP), critical-peak pricing (CTP) and time-of-use pricing (ToUP). RTP is more flexible because its price varies on hourly basis [5] and it is very effective in shaping the load demand, peak-load reduction and reduction of load demand variation. However, RTP may cause the load demand to be deferred to hours with low electricity price, which would result in higher peak electricity demand and peak-to-average ratio during the low electricity price time [8]. In [9], a novel voltage sensitivity matrix based on voltage sensitivity analysis is proposed. The voltage sensitivity is due to customers' load participation in DR program. The result shows that load curtailment reduces voltage drop across the

DS and improve voltage profile. However, the cost of incentives to participating customers are not considered. The effect of incentive-based DR on distribution system voltage profile was carried out in [4]. A demand-price elasticity matrix was modeled for participating customers. However, the model lacks the control option to carry out the incentive-based DR program. Real time pricing is employed as one of the DR tool in this case study. Publicly available wholesale market data as shown in figure 3 [10] (Monitoring Analytics 2013), is used in this paper to estimate the system-level costs incurred by the Distribution System Company (DISCO). With the introduction of RTP, consumers control their elastic loads based on the electricity price released by DISCO. A load limit is set $0 \leq P \leq 385 \text{ kW}$, so that any consumer that goes beyond the load limit will receive a fine. That is, making extra payment for the extra load.



Figure 3. 24-hour electricity price.

The distribution feeder is divided into four zones, representing the DR participating customers. The zones were defined by network mapping based on location (Venkatesan, Solanki et al. 2011). The proposed algorithm has been implemented in MATLAB Com OpenDSS, and examined on the test system for a multiperiod of 24 hours. The optimal consumer's electricity consumption scheduling is determined for the four zones using PSO-GSA.

The test feeder consists of 20kW load, 40 kW load and 75 kW load and above. It is assumed that 20 kW and below are inelastic load, loads above 20 kW to 40 kW are assumed to be controllable loads while any load above 40 kW is assumed to be shiftable load. Loads are taken in the proportion of ratio 20%, 50% and 30% for inelastic, controllable and shiftable load respectively. Load reduction was applied to controllable loads while the shiftable loads are shifted from hour t to t' , that is, from day to night.

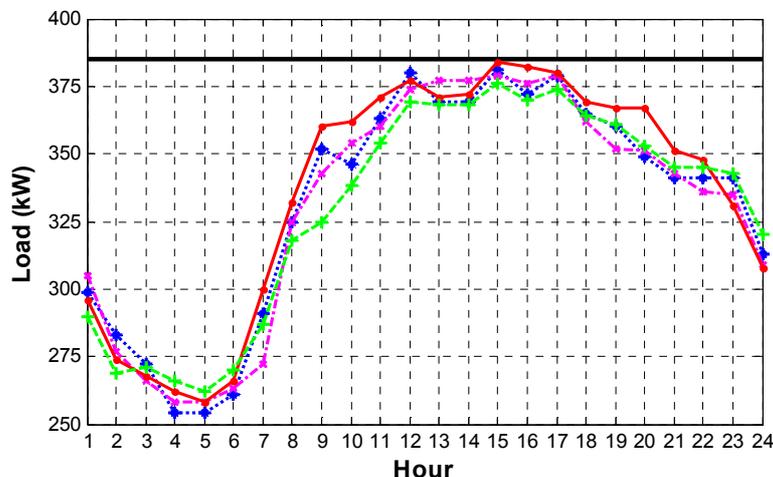


Figure 4. 24-hour power usage (load) scheduled curve.

An hourly consumer’s scheduled load curve using PSO-GSA is as shown in figure 4 for the zones. At 15th hour, the customer's load in Zone C (solid line) is very close to the point of maximum load limit because some critical load at this hour could not be shifted to another time. Every customer managed their load not to exceed the maximum load limits. There is load reduction in the day because some loads are shifted from day to night due to low electricity price per kWh energy consumption.

A 30% wind energy is distributed in the modified peak load feeder of 16 MW. OpenDSS interfacing with Matlab is used to carry out voltage and loss analysis in this paper. The power flow is executed in daily (24-hour) mode. A 24-hourly simulation with each zone electricity consumption scheduling is carried out with the voltage of the distribution feeder monitored at each zone. The output voltage of the distribution feeder at different hour of the day is illustrated in figure 5 for the zones. A peak-valley levelling is observed in figure 5 with a better voltage profile. There is a wide gap between minimum

and maximum pu voltage without the DR. However, the application of the DR has reduced the voltage deviation and brings significant improvement in the voltage profiles. The result of the proposed algorithm is compared to price elasticity matrices used in [4] (Venkatesan, Solanki et al. 2012). Both results shows that the load reduction/shifting due to the implementation of the RTP reduced the system line losses causing improvement in the feeder voltage profile. The RTP one of the DR tools was able to alleviate the disparity of energy consumption by reducing the energy usage at peak period and increase it at off-peak hour. Thus, the efficacy of RTP in shaping load demand is illustrated in not only greatly minimizes the peak load, but also the load demand variation. This shows the effectiveness of RTP in not only improving the voltage profile during peak-load period but also during off-peak period. It infers that the RTP did not only mitigate voltage drop as a result of peak load but voltage rise as a result of wind gush and bring further improvement to overall voltage profile.

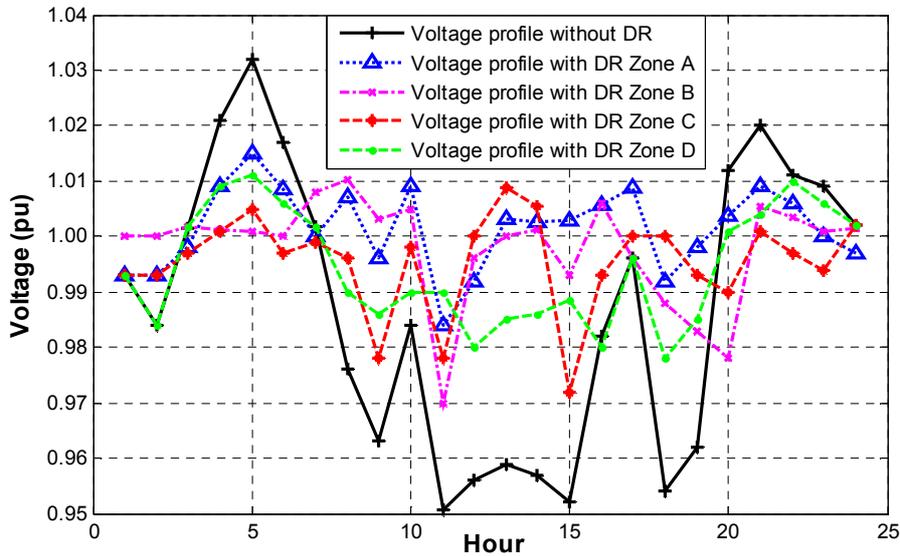


Figure 5. Application of dynamic pricing for voltage control.

Table 1. Voltage deviation with and without demand response.

Description	Zone	Max Voltage (pu)	Min Voltage (pu)	Voltage Deviation
No DR		1.0320	0.9507	0.0813
Application of DR	A	1.0150	0.9840	0.0310
	B	1.0100	0.9700	0.0400
	C	1.0088	0.9720	0.0368
	D	1.0110	0.9780	0.0330
Application of DR and ES	A	1.0090	0.9915	0.0175
	B	1.0100	0.9930	0.0170
	C	1.0088	0.9900	0.0188
	D	1.0085	0.9900	0.0185

However, it is observed that Zone B has the highest voltage deviation out of the four zones as shown in Table 1. There

were points in time when the load cannot be further curtailed or shifted in order not to impair the customer satisfaction level as it occurred at 11.00 hour in Zone A; 15.00 hour and 18.00 to 20.00 hour in Zone B; 9.00, 11.00 and 15.00 hours in Zone C; and up to nine (9) hours in Zone D (figure 5).

It is assumed that higher pu voltage magnitude is required at these hours. Batteries energy storage (BES) can be considered as the most developed and widely utilized energy storage out of all the energy storage technologies [10]. Therefore, the optimum solution for distribution system operator (DSO) to maintain grid power quality, flexibility and security, is the use of the battery ES for their fast response, mobility and flexibility. These qualities afford battery energy storage to be connected at different locations in the grid from generation to end-users to ensure efficiency and security [12].

For improved voltage at these hours, a 0.5kW, 1.2kW, 2.5kW and 3kW battery energy storage is integrated in Zone A,

Zone B, Zone C and Zone D respectively to inject more power to the zones at these hours in order to meet customers' satisfaction. An iterative method based on voltage sensitivity is used to identify the best storage location in [13], sensitivity analysis is used to find the optimal, gas-fired distributed generation capacity locations in the distribution system in [14], while Gravitational Search Algorithm (GSA) and PSOGSA are used to determine multiple distributed generation capacity and location in DS in [15] and [16] respectively. An OPF-based algorithm for siting the aggregated capacity of energy storage was developed to decrease the wind energy curtailment and cost of energy supply in [17]. A coordinated control of distributed energy storage systems with load tap changer for voltage rise mitigation under high PV penetration is proposed in [18]. Battery energy storage capacity for each Zone is determined using hybrid PSOGSA in this paper. The distribution of the energy storage injected power in each zone at these hours and levelled up the valley as shown in figures 6-9. This smoothing the voltage profile and thereby further reduces the voltage deviation as it is illustrated in Table 1. This shows the effectiveness of energy storage in smoothing, peak shaving and load levelling. The integration of the energy storage has warranted voltage profile improvement which will cause energy loss reduction and bring the voltage within statutory limit.

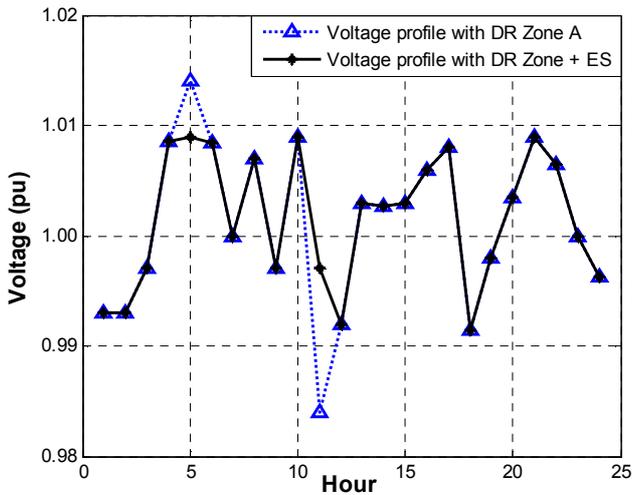


Figure 6. Application of ES in peak-valley levelling-Zone A.

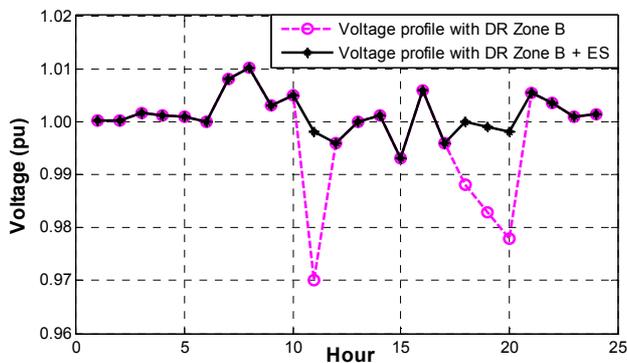


Figure 7. Application of ES in peak-valley levelling-Zone B.

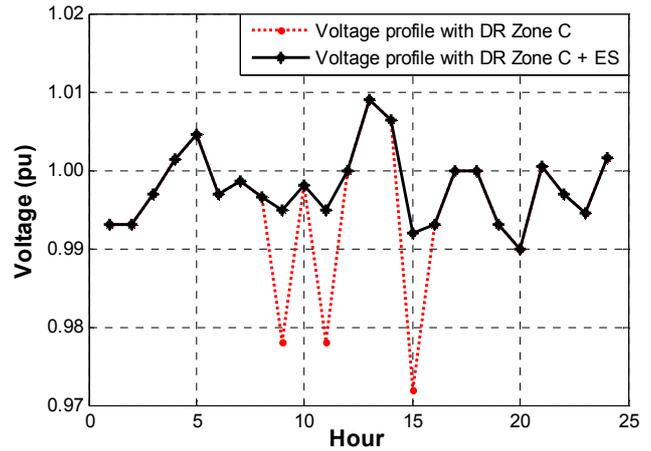


Figure 8. Application of ES in peak-valley levelling-Zone C.

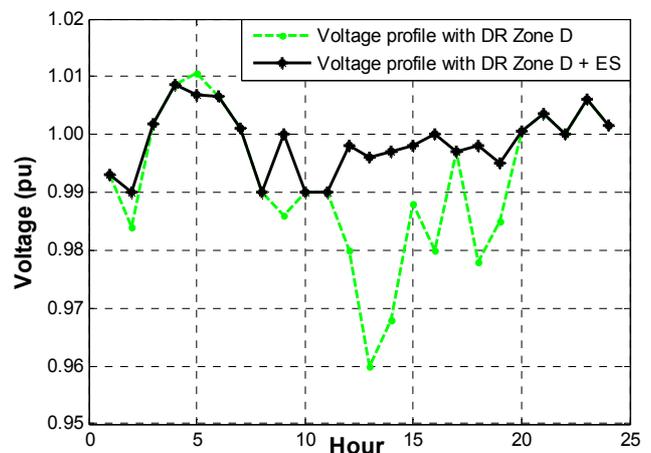


Figure 9. Application of ES in peak-valley levelling-Zone D.

4. Conclusion

The variability characteristics of wind energy sources present a fundamental problem to its smooth integration in the distribution feeders, in a large proportion. Test results show that the application of real time pricing, one of demand response tools and energy storage cause reduction in peak load, energy losses and enhance system capability to maintain voltages within the statutory bounds.

The application of real time pricing, contributes to voltage control and allowing increased integration of wind energy (renewable generation) in distribution feeders. Real time pricing is demonstrated in this paper as a remedy to the voltage dip/rise problem in distribution feeders with high penetration of wind energy. The distribution of energy storage on the other hands provides a leveling functionality of the system voltage profile. This enhances the system flexibility to hedge against fluctuations of wind energy.

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