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Energy Storage Disposition for Voltage Control in Distribution Systems with Renewable Energy

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Abstract – The integration of renewable energy (RE) have gained substantial interest recently, due to continued advancement in renewable energy technologies and their effectiveness as a local power source; where generation is in close proximity to loads or consumers. Such integration imposes new challenges to the distribution system over centralized conventional generation due to their intrinsic variability and fluctuating characteristics, thus hampering the ability of the grid to accommodate more renewables. This paper presents techniques using energy storage to offset the variability of renewable energy sources, mitigate their effect on voltage rise and maintain the feeder voltage within statutory limits. The paper further coordinate the VAr control devices and Energy Storage using times series analysis applied to the IEEE 123 bus distribution feeder system. Test results have confirmed the capability of the energy storage as an effective remedy for voltage variability and uncertainty under decentralized operation paradigms.

Keywords: Energy storage, Renewable energy, Solar PV, Variability, Voltage rise.

1. Introduction

There is dramatically a change in electrical power generation globally in recent time due to integration of renewable energy resources such as wind and solar energies. Renewable energies (REs) integrated in the distribution system impose some challenges due to their variability and uncertainty. More so RE may not be available when and where needed. In order to allow high penetration of RE, a proffered countermeasure of balancing supply and demand is to distribute energy storage (ES) in the distribution system. ES with long life cycle and fast response has the capability to store energy during high generation or low demand and dispatching it during low generation or high demand,

In addition [1]. ES has several attractive significance schemes such as solution for the intermittence of renewable source power generation, management of distributed power generation, meeting peak electrical load demands, aid smart grids technologies, reducing electrical energy import during peak demand periods, electric vehicle load needs, etc. Apart from the economic benefits, the load curve are also smoothed [2].

Without distributed ES, integration of RE would be back up with fossil fuel that releases carbon dioxide emission and runs at low efficiencies which contradicts the benefits and purpose of RE. Energy storage system with power electronics that interfaces the utility grid and ES has enormous impact and a great technical application on distribution system. This results in many benefits for managing the variability in electricity generation as well as energy consumption [3].

However, RE can be revolutionized using any of these technologies if they become main stream and accomplish low costs. Some important factors to be considered in choosing an appropriate ES option for integration are Size of storage devices, type of application, total energy required and power/unit of weight, specific power and specific energy, etc. Potential environmental impacts, level of technological maturity, and reliability are essential considerations. Integration of ES throughout distribution system from generation to customers presents a prospect to transcend the power balance pattern by storing energy during high generation, with less line losses, and re-dispatching the energy when desired [2, 3]. ES is necessary for grid support so as to lead to a higher synergy between RE and electricity consumers.

Optimal location and sizing of the ES is essential to improve the voltage profile in the distribution system and reduce losses. Different approaches have been engaged in the literature for optimal location and sizing of ES to mitigate the uncertainties of RE integration in distribution system [5]. Developed an iterative technique based on voltage sensitivity to ascertain the best storage location. An Optimal Power Flow (OPF)-based algorithm for ES location was developed using OPF-based algorithm to decrease the RE curtailment in [6][7]. Liu, et.al, proposed a coordinated control of ES system with Load Tap Changer (LTC) Transformers for voltage rise mitigation under high RE penetration [8]. A two-stage iterative technique for the siting of a pre-determined size of ES in the distribution network, using a Genetic Algorithm (GA) in the first stage and an Optimal Power Flow (OPF) in the second stage, was employed in [9]. A heuristic tool using GA with simulated annealing was proposed to locate ES in low voltage networks [10]. However, the sizing of the ES was not considered in most of the previous investigations.

2. Energy Storage Modeling

Flexibility of the distribution system can be increased through the distribution of ES in the distribution system. ES enables high penetration of variable RE. It is also of good benefit to deferral of network upgrade and load leveling [11]. The operational and physical bounds of the ES are: [12]:

$$P_{i,t} = P_{G_{i,t}} - P_{D_{i,t}} \pm P_{ES_{m,t}} \quad m \in M, \quad M \subseteq N \tag{1}$$

$$\sum_{t=1}^{24} P_{Es_{i,t}} \Delta t \, \eta_i \le E^{0}_{ES_{i,t}} \tag{2}$$

$$\sum_{t=1}^{24} - P_{Es_{i,t}} \Delta t \, \eta_i \le E^{\max}_{ES_i} - E^{0}_{ES_i} \tag{3}$$

$$E^{\min}_{ES_{m,t}} \le E_{ES_{m,t}} \le E^{\max}_{ES_{m,t}} \tag{4}$$

$$P^{\min}_{ES_{m,t}} \le P_{ES_{m,t}} \le P^{\max}_{ES_{m,t}} \tag{5}$$

$$\left(P_{ES_{m,t}}\right)^2 + \left(Q_{ES_{m,t}}\right)^2 \le \left(C^{\max}_{ES_{m,t}}\right)^2 \tag{6}$$

- Power loss constraint:

$$P_{L_{i,t}}^{with\,ES} \le P_{L_{i,t}}^{withoutES} \tag{7}$$

where η is the energy storage charge-discharge cycle efficiency, EES is the energy stored in the energy storage, and $E^{0}_{ES_{i,t}}$ is the initial energy stored at bus i and time t. Emax and Emin are the maximum and minimum capacity of the storage respectively. Cmax is the power capability limit of the energy storage and M is the number of storage elements. The storage could be positive or negative signifying charging or discharging cycles respectively. Storage units are only connected at a few locations in the system.

Equation (1) presents the power balance at the ES node m. Since the ES cannot be charging and discharging simultaneously. Equations (2) and (3) respectively denote the maximum and minimum amount of the energy stored or discharged from the energy storage. Similarly, (4) and (5) are the maximum and minimum energy storage capacity respectively with the relevant active power rating. Based on the assumption that the energy storage is interfaced with the distribution network through efficient power electronic converters, Eq. (6) models the capability curve of the energy storage. Equation (7) confirms that the system with the energy storage produces less energy losses.

The above formulation gives a complete mathematical programing description for the modeling of energy storage necessary to counterbalance the impact of the variable RE on system losses and voltage profile. On the other hand, selecting the size and location of the ES represents a large-scale, complex mixed-integer, nonlinear optimization problem; since selecting the node number, where the storage should be located, is intrinsically an integer problem. Hybrid Particle Swarm Optimization - Gravitational Search Algorithm (PSOGSA) used in [13] is employed to solve the resulting combinatorial problem. The size and location of the ES is determined based on the algorithm is as shown in Table 1. The RE and ES are distributed in a modified IEEE feeder as shown in figure 1.

Table 1 Sizing and siting of energy storage

Bus	**Size (MW)**
81	1.258
70	0.575
78	0.270
43	0.385

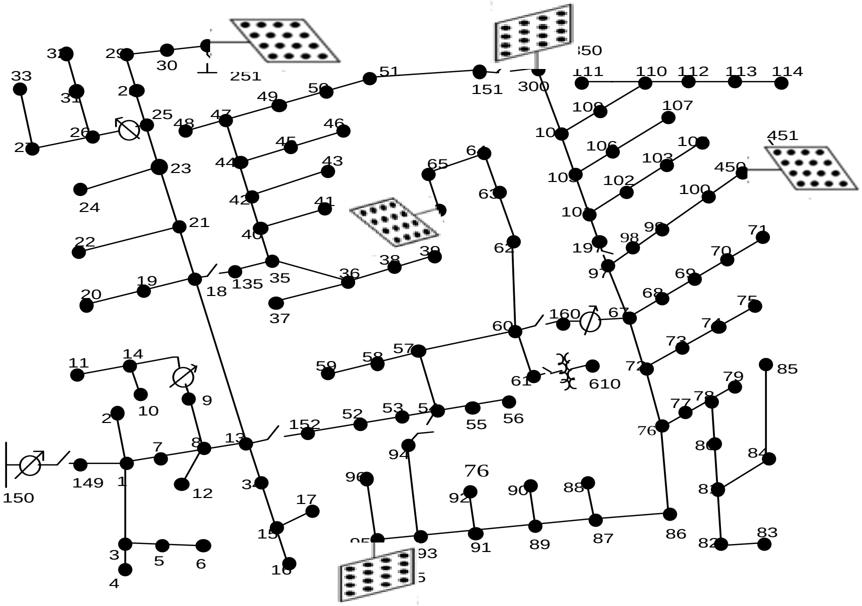

Fig. 1 Modified IEEE 123 test feeder

3. Impact of Renewable Energy Penetration on Voltage Profile and Load Tap Changer Operations

Effect of RE penetration on voltage profile and LTC tap changer is verified. The regulator setting is set at 0.9 - 1.1 pu while the permissible voltage limit is set at 0.95 - 1.05 pu. The tap range is ± 10% of rated value, step voltage is 0.625% (0.00625) and the dead band is 2 V. Solar PVs are integrated in the modified IEEE 123 bus feeder with 15% penetration at 3.866 MW peak load. The power flow here is done on a snap shot and voltage profile of some selected buses are recorded so as to compare them to the paper in [14] for justification. The result is as shown in Fig. 2. The accuracy of the proposed LTC algorithm incorporated in the distribution system using OpenDSS is validated in this paper since the voltage profiles are almost coincided.

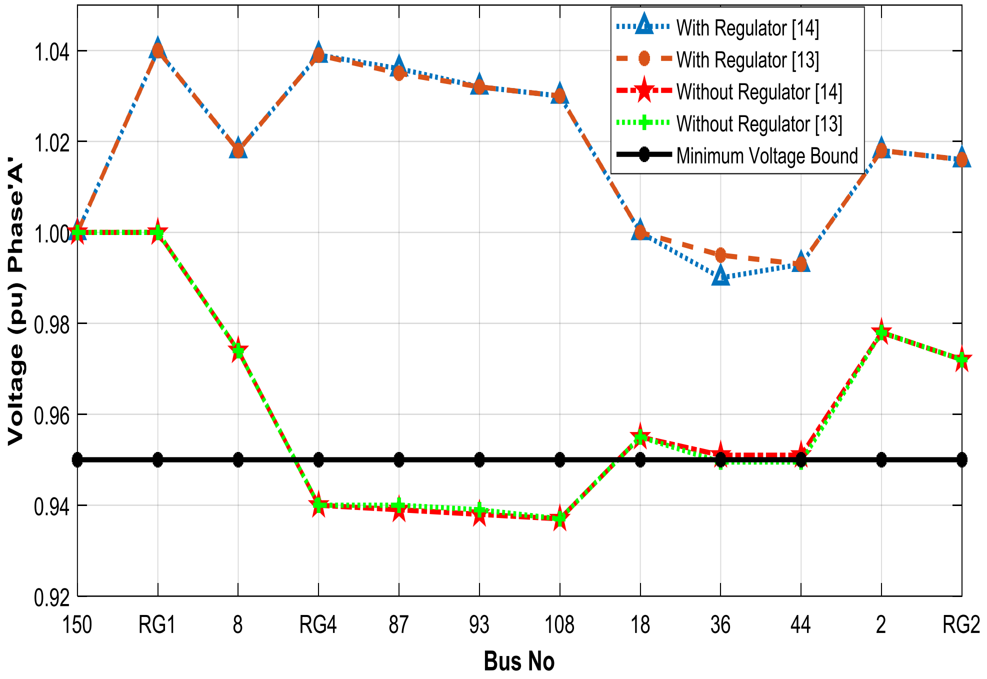

Fig. 2 Voltage profile of IEEE 123 feeder phase (A) with and without regulation

The impact of RE penetration on voltage profile and LTC movement is determined in this scenario. Variable PV is integrated at different locations into the distribution feeder, with high penetration levels. The base case power flow without the connection of RE is first considered at a modified peak load of 12 MW. The solar PV is integrated in the IEEE 123 bus feeder at buses 450, 300, 250, 95 and 79 as shown in Fig. 1 at different penetration level. In this scenario, PVs amounted to 10%, 30% and 50% of 12 MW peak load are distributed at 5 different locations in the feeder. Each bus location has equal PV capacity connected to it. A 24-hourly power flow carried out resulted in pu voltages and regulator ranges with its corresponding losses of the PV depicted in Table 2.

Then, the PVs were replaced with wind energy of the same size and at same location and different penetration level as that of the PV, 10%, 30% and 50% of 12 MW peak load. The result of the wind energy indicating the pu voltages, operation of the LTC and line losses were investigated. The two scenarios confirmed that the higher penetration of the RE results in more reverse power flow. Therefore the more the RE penetration increases, the more the voltage increases and the more the LTC tap movement (either up or down) to bring the voltage to permissible limits. Table 2 illustrates the comparison between the PV and wind energies showing their pu voltages and regulator ranges with its corresponding losses at each penetration level. The power loss is high when RE is not connected as shown in the table. The integration of the RE minimizes the losses as it can be seen in the Table 2.

Table 2: Voltage profile, LTC regulator and feeder losses at RG penetration level

	Base Case (No RG)	PV			Wind		
		10%	30%	50%	10%	30%	50%
Min Voltage (pu)	0.9641	1.0036	1.0036	1.0036	1.0081	1.0125	1.0183
Max Voltage (pu)	0.9641	1.0181	1.0340	1.0430	1.0178	1.0334	1.0420
No. of Tap	1	5	8	11	3	6	10
Tap steps	10	9-11	4-11	0-11	9-10	4-7	0-6
Losses (kW)	1031	913.28	587.62	429.09	916.25	593.74	434.71
Loss Reduction (%)	-	11.42	43.00	58.38	11.13	42.41	57.84

4. Effect of Energy Storage on Renewable Energy in Distribution System

Integration of ES systems is used to improve the voltage profile and enhance system performance in this text case. This underlines the importance of attaching ES, as an exemplar of smart grid technologies, with RE such as solar and wind energy to maintain acceptable system performance. This is used to capture the fickle inherent characteristics of variable RE. It is a framework which accounts for the time-varying characteristics of renewables to minimize the energy losses, rather than the power losses, and enhances the voltage profile, in a given time horizon. The LTCs and the capacitor banks are coordinated with the ES for smooth operation to achieve the desired objectives in this paper. The ES is integrated to decouple the timing of generation production (or absorb the variability of the RE) from the consumption of electric energy. The LTC is coordinated with the ES to make sure the voltage profile as a result of the PV penetration is within the permissible limits. The size and location of the ES is determined based on the proposed algorithm.

The per unit voltage of the chronological 24-hourly simulation of the system with 12 MW peak load, 30% PV penetration is carried out. Five scenarios are involved in the case study. In the first scenario, the regulator devices are disabled and the voltage profile is monitored and recorded. The voltage output is in the range between 0.80 and 0.84 pu, shown with dashed-dotted line in Fig. 3 falls below the accepted voltage limits. When the OLTC is enabled in the second scenario, the voltage profile is propped up. The increased value is between 0.88 and 0.93 pu (dashed line); yet, still below the voltage limits. The voltage is regulated within the limits 0.95 - 1.0 pu (bold line) when the SVRs are enabled in the third scenario. The voltage is very close to the border limit at some hours of the day. Any slight increase in the load can push the system off, of the boundary limit.

In the 4th scenario, switching ON the capacitor banks increases the voltage profile between 0.9793 and 1.0173 pu (bold line) as depicted in Fig. 3. This maintains the distribution system security as the voltage profile gets flattened off. The capacitors, expectedly, have great influence on the reactive power flow. Line current is drastically reduced, thereby reducing the line voltage drop. The more the capacitor banks are connected, the more the losses get reduced and the more the voltage profile is improved. The capacitors, therefore, have compensated for the line voltage drop and kept the voltage close to 1.0 pu.

Finally, total energy storage of 2.485 MW is distributed in the feeder at their respective optimal locations as indicated in Table 1.. The dispatch operation of the energy storage charging and discharging integrated with the PV in the feeder is shown dashed line in Fig. 3. The voltage profile is between 0.9842 pu and 1.001 pu. The integration of the ES has warranted voltage profile improvement, particularly when the voltage was low at night. The voltage deviation is substantially lowered from 0.063 pu without energy storage to 0.018 pu with energy storage. This illustrates the effect of energy storage along with PV. The use of ES effectively assists to harness intermittent renewable energy resources, accommodate higher proportion of them, mitigate the voltage rise as well as voltage drop and provide additional flexibility to the system to hedge against the fluctuations of variable renewable energy output.

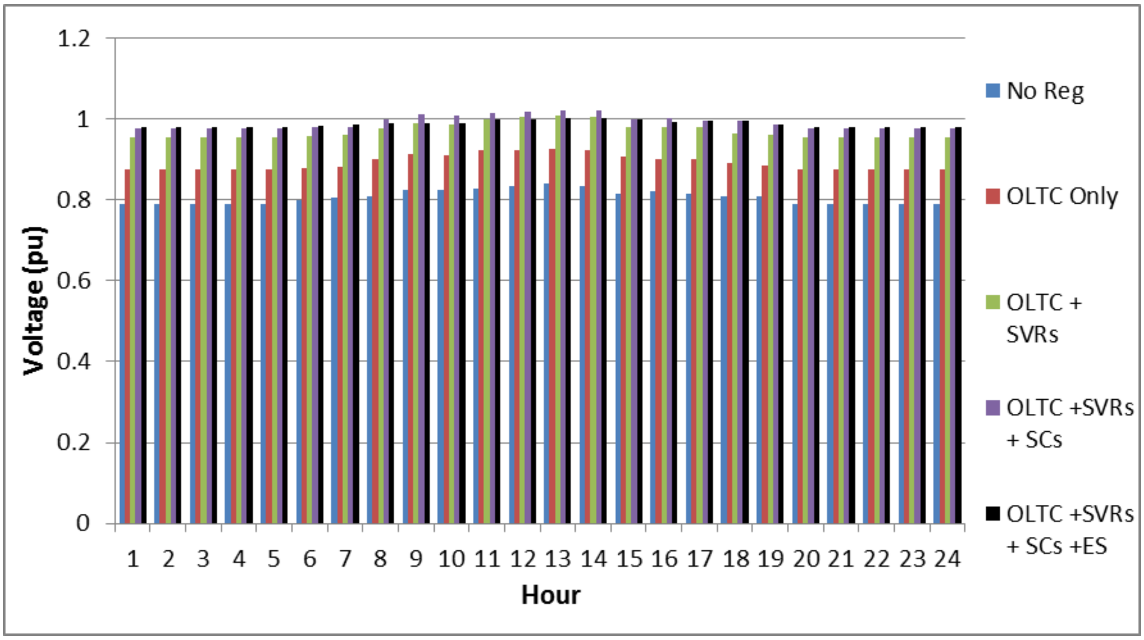

Fig. 3 Application of control devices at 30% PV penetration

5. Conclusion

The paper has highlighted the inherent challenges associated with the integration of intermittent RE into the distribution system, where the location and size are dictated by merits of resource availability and appropriate metrological conditions. Higher penetration of RE can potentially cause voltage rise problems. Furthermore, the indelible uncertainty associated with these variable RE sources can disrupt the normal operation of voltage regulation devices in medium and low voltage distribution systems.

This paper has presented a framework that coordinates VAr control devices, including LTC transformers and switched capacitors, along with ES to mitigate the voltage variations resulting from high penetration of RE units in distribution feeder. Results indicate that the coordinated operation of the VAr control devices causes reduction in system losses and enhances system capability to maintain voltages within the permissible bounds. Coordination control of tap changers makes it possible to completely eliminate, or at least reduce the number of tap operations. Consequently, the number of voltage spikes due to OLTC operation reduced.

The use of energy storage effectively assists to harness intermittent RE resources, accommodate higher proportion of them, mitigate the voltage rise as well as voltage drop and provide additional flexibility to the system to hedge against the fluctuations of variable RE output. The developed platform is not only competent in regulating the system voltage, regardless of the proportion of the integrated RE or the location where it is connected at, which is the ultimate premise of the smart grid, but also is extendable to integrate other smart grid tools or market instruments to enhance the grid operation.

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