Article

Voltage Control Strategy for Energy Storage System in Sustainable Distribution System Operation

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Abstract: Due to the increasing penetration of distributed energy resources (DERs) required for the sustainable distribution system, new voltage control strategy is needed by utilities. Traditional voltage control strategy can not support the increasing number of DERs in a coordinated and scalable manner to meet the operational voltage regulation requirement. Supported by the power electronics converter, the energy storage system can provide fast, smooth, and flexible voltage control services. In this paper, an effective and easy to implement sensitivity-based voltage control strategy is developed for the energy storage system. The developed control strategy is validated using an industrial feeder data in Northwest Washington. The proposed strategy can mitigate the voltage unbalance issue, improve the voltage profile, and correct power factors while supporting sustainable distribution system operation.

Keywords: voltage control; smart distribution system; energy storage system; DERs; storage management

1. Introduction

Many conventional generators are approaching their lifespan and are planned to be replaced by renewable energy given the push for sustainable power systems. Around 2000 MW of conventional generators will be retired in the Washington and Oregon states [1] by end of 2020 and are being replaced by renewable and distributed energy resources (DERs) like photo-voltaic (PV) and wind turbines [2]. Enhanced integration of DERs could significantly impact the system voltage profile and the operations of the voltage regulation devices [3]. Variation in energy output may also increase the voltage unbalance rate of the system [4]. The voltage unbalance rate in the distribution system is usually larger than that in the transmission system due to the unbalanced network configuration. Imbalance voltages may damage equipment like induction motors [5], lead to an even higher unbalanced phase current [6] and introduce more losses and heating effects [7]. Therefore, maintaining a low voltage unbalance rate could help to improve the power quality and increase the reliability of the distribution system.

Traditionally, devices like regulators or capacitors are utilized to do Volt/Var control in the distribution system. Authors in [8] propose a multi-objective Volt/Var control method to optimize the operation of capacitor banks and tap changing transformers in the distribution network. In [9], an integrated voltage control method is introduced to minimize energy losses with capacitors and regulators. Using data from measurement and communication infrastructure, the control scheme shows good coordination among voltage regulators and capacitor banks and thus provides an effective Volt/Var control. Another strategy that aims to control capacitors through communication among remote terminal units is presented in [10]. An online Volt/Var optimization application that runs
at the utility control center is described in [11]. Authors in [12] develop a voltage control method to minimize the line losses by adjusting the transformer tap position. An intelligent voltage control algorithm to maximize total energy savings in the distribution system is discussed in [13]. In [14], wireless distributed processing units are utilized to control the voltage control devices through performing power flow analysis. Authors in [15] propose a hybrid genetic-fuzzy algorithm to control the voltage profile, reactive power flow, and total harmonic distortion.

Since frequently switching these traditional voltage control devices will shorten their lifespan [16], there is a need for fast response and flexible operation devices. Supported by the power electronics-based four-quadrant operation, the energy storage system (ESS) becomes a promising option and could provide active and reactive support to the grid [17,18]. ESS is usually used to provide active power support like load shedding and peak shaving. An ESS-based active power management scheme is proposed for PV capacity firming and energy time shift in [19]. The authors in [20] utilize a multi-agent ESS frequency schedule to regulate the active power. Another fuzzy active power control method is introduced for ESS to reduce the operating cost and power exchange. Due to the relatively high installation cost of ESS, utility companies show growing interest in investigating the potential benefits of ESS in addition to the active power support. For example, ESS is mainly used to manage the adjacent PV station in Marshall Steam Station Energy Storage Project. However, Duke Energy uses ESS to provide both active and reactive power support, such as peak shaving, energy time-shift, capacity firming, and voltage control [21]. In the research field, researchers are also investigating how to design a control strategy that can utilize ESS’ reactive power capacity on top of real power capacity. For example, Kashem and Ledwich design a P-I controller for ESS for real and reactive power support [22]. Under the Q mode, ESS can inject reactive power from the converter for low voltage correction. Similar to other P-I controllers, it may suffer from high starting overshoot and sensitive to controller gains [23]. In [24], an optimization-based ESS control strategy is proposed to ensure the voltage quality requirements in an low voltage grid with high PV penetration. This strategy requires frequently power flow solutions to get the voltage value from critical nodes. Similarly, authors in [25] propose an ESS control strategy in middle voltage level distribution systems to provide peak load shaving and voltage support. This method takes into account power flow, bus voltage, and associated ESS control parameters. Notice that the above optimization-based ESS control strategy usually need a continuous power flow solution to control the reactive power output. For a relatively large industrial distribution system, an accurate and high-frequency power flow solution is not always available. Besides, the voltage unbalance issue is not fully investigated with ESS control.

In the eastern Washington area, Avista deployed an ESS to provide a continuous power supply to a local manufacturer customer for enhanced reliability. Avista is also interested to use ESS to provide frequency regulation and voltage control services [26]. The modeling of the feeder with this ESS is done in [27], and the ESS real power control strategy for frequency support is provided in [26]. The local ESS reactive power control strategy is developed in [28]. In addition to our previous work in [28], a sensitivity-based coordinated voltage control strategy is developed for ESS to mitigate the voltage regulation issues along the feeder and help to reduce voltage unbalance rate under varying load conditions and varying installed PV capacity. The contributions of this paper are summarized as follows: (1) Comparing to our previous work in [28], the proposed strategy can further reduce voltage unbalance rate under varying conditions. (2) Comparing to optimization-based control strategies, the proposed strategy does not require regular distribution power flow solutions results to control the reactive power output. (3) The simulation results are tested and validated with a real industrial feeder model and actual field data. The local utility company can easily validate the performance of the proposed strategy with its own energy management systems.
2. Voltage Sensitivity-Based ESS Control Scheme

2.1. Voltage Control Scheme in Distribution System

Voltage control is an important distribution energy management application, which can provide voltage support based on the measured data [29]. A typical voltage control scheme in the distribution system is explained in Figure 1. The overall goal is to improve voltage profile and reduce the total network losses [30,31]. The voltage control scheme can be implemented by centralized or decentralized approaches with load tap changers, voltage regulators, capacitor banks, and etc. Each approach includes a specific problem algorithm to achieve the required network targets. The centralized control scheme can achieve a theoretical global optimal object through a series of control actions. However, this approach requires an accurate distribution model and reliable power flow and state estimation results. The network changes will also impact the results. On the other hand, a decentralized control scheme uses real-time local measurements to control a certain one or a group of voltage control devices to achieve a specific objective. Although it may not produce the "optimal" control steps like the centralized scheme, this approach is not limited by the power flow results and can produce fast voltage support.

In order to enable ESS to provide support in presence of the above existing control scheme, a new voltage control strategy for ESS is needed. Usually, utilities hesitate to do large scale control scheme change due to large scale field testing requirement and safety concerns, so a control strategy that can help to improve distribution system operation with minimal coordination problem with other control devices is preferred.

To meet the need of utilities, a sensitivity based control strategy is proposed. The control scheme is presented in Figure 2. Based on the voltage sensitivity analysis method [32], the sensitivity factor estimator will utilize the system model and smart meter data to generate the sensitivity factor for this system. In real-time operation, the ESS controller can control the reactive power output based on the measured voltages and the sensitivity factor.

Figure 1. The voltage control scheme in the distribution system.

Figure 2. The scheme of the proposed energy storage system (ESS) control strategy.
2.2. Sensitivity Factor Estimator

The sensitive factor estimator will generate the sensitivity factor through off-line simulation. To get the sensitivity factor of the studied system, the general power flow equations are introduced first:

\[ P_k = \sum_{n=1}^{N} |V_k| |V_n| Y_{kn} \cos(\delta_{kn} + \delta_n - \delta_k) \]  \hspace{1cm} (1)

\[ Q_k = \sum_{n=1}^{N} |V_k| |V_n| Y_{kn} \sin(\delta_{kn} + \delta_n - \delta_k) \]  \hspace{1cm} (2)

where \( P_k \) and \( Q_k \) represent the injected active and reactive powers at node \( k \); \( V_k \) and \( V_n \) represent the voltage magnitude for node \( k \) and \( n \). \( \delta_k, \delta_n \) represent the voltage angle at nodes \( k \) and \( n \). \( Y_{kn} \angle \theta_{kn} \) is the admittance between nodes \( k \) and \( n \). For a given nominal operation point, the above equations can be linearized as:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\
\frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}
\end{bmatrix}
\cdot
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix}
\]  \hspace{1cm} (3)

The inverse of the Jacobian matrix is the sensitivity matrix. \( S_{\delta p}, S_{\delta q}, S_{vp}, S_{vq} \) describe the relationship between the voltage angle, magnitude and the active, reactive power.

\[
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix} =
\begin{bmatrix}
S_{\delta p} & S_{\delta q} \\
S_{vp} & S_{vq}
\end{bmatrix}
\cdot
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]  \hspace{1cm} (4)

For a given operational point, the voltage change for each node can be calculated with changed reactive power. Assuming the ESS is installed at node \( k \). If the reactive power output of ESS is changed by \( \Delta Q_B \), the voltage changes (\( \Delta V_i \)) at node \( i \) can be calculated as:

\[ \Delta V_i = S_{vq}(i, k) \cdot \Delta Q_B \]  \hspace{1cm} (5)

Since the focus of this study is Volt/Var control strategy, the real power control is not included here. The ESS real power output \( \Delta P_B \) is zero and \( S_{vp}(i, k) \) is neglected. The sensitivity factor is defined as the inverse of \( S_{vq}(i, k) \).

\[ k = \frac{1}{S_{vq}(i, k)} \]  \hspace{1cm} (6)

Noticing that for any \( i \neq k \), \( S_{vq}(i, k) \leq S_{vq}(k, k) \), so the reactive output of the ESS has the highest effectiveness on the installed node [33].

The sensitivity factor can be calculated through two off-line simulations using the feeder model and collected field data. In each case, ESS will provide a constant reactive power output during the entire period, namely \( Q_{B1} \) and \( Q_{B2} \). The output difference should be small and meet the linear approximation criteria. The sensitivity factor for each snapshot \( k_t \) can be calculated.

\[ k_t = \frac{\Delta Q_B}{\Delta V_B} = \frac{Q_{B2} - Q_{B1}}{V_{B2} - V_{B1}} \]  \hspace{1cm} (7)
where \( V_{B1} \) and \( V_{B2} \) is the average voltage measured at the ESS terminal from the above two scenarios. Depending on the simulation time interval (\( \Delta T \)) and total simulation time \( T \), there will be \( N = T/\Delta T \) sensitivity factors generated from the simulation. Finally, we get the average sensitivity factor \( K \) from averaging them using Equation (8).

\[
K = \frac{1}{N} \sum_{t=1}^{N} k_t
\]  

(8)

2.3. ESS Controller

The ESS controller will control the reactive power output for each phase based on the calculated sensitivity factor from the sensitive factor estimator and the measured voltage value at the ESS terminal. In order to change the voltage to the desired target voltage \( (V_T) \) from the current measured voltage \( (V_B) \), the total required reactive power \( Q_B \) is determined by Equation (9), whereas, \( Q_B \) should vary within the reactive power output limits (\( Q_{\text{min}} \) and \( Q_{\text{max}} \)).

\[
Q_B = K \cdot (V_T - V_B) \quad (9)
\]

\[
Q_{\text{min}} \leq Q_B \leq Q_{\text{max}} \quad (10)
\]

Once the total required reactive power is determined, it will be allocated to each phase properly to mitigate the voltage unbalance issue. The reactive power for each phase is calculated using Equation (11).

\[
Q_B^p = \frac{(V_T - V_B^p)}{\sum_p (V_T - V_B^p)} \times Q_B \quad (11)
\]

where \( Q_B^p \) is reactive compensation needed for each phase \( p \) from ESS and \( V_B^p \) is the measured phase voltage at the ESS node. The voltage sensitivity analysis method is initially derived for the transmission system. To validate the proposed method for the distribution system which normally has an unbalanced charter and has a relatively lower \( X/R \) ratio \([34,35]\), a detailed feeder model is needed. For our feeder model, each phase is explicitly modeled. The electromagnetic coupling between phases is also included. The resistance and reactance of each component are considered as well. Applying the sensitivity analysis method on this detailed distribution model, we demonstrate that the measured average voltage at ESS bus with the proposed strategy is very close to the pre-set target voltage, which proves the feasibility of this method.

3. Simulation Results and Analysis

In this section, several simulation cases have been conducted to present the benefits of the proposed control strategy.

3.1. Simulation Environment and Evaluation Metrics

The simulation system is developed based on an actual feeder in Pullman with gridlab-D. The configuration of the feeder is presented in Figure 3. This system has over 300 nodes and the load data is collected from smart meters. The studied 1.31 MVA/3.2 MWh ESS has 65–70% AC round trip efficiency. The ESS inverter has 5s charge/discharge lock time and 97.5% efficiency. The model detail and model validation process is present in our previous work in \([27,28]\).
In this paper, two metrics are utilized to quantify the impact of ESS on voltage unbalance mitigation and voltage profile improvement. The phase voltage unbalance rate (PVUR) defined by the Institute of Electrical and Electronics Engineers (IEEE) [4] is used to evaluate the voltage unbalance rate. The PVUR is defined as

$$PVUR = \frac{V_D}{V_A} \times 100\%$$ (12)

where $V_D$ represent the max voltage deviation from the average phase voltage and $V_A$ is the average phase voltage. For the voltage drop improvement, we evaluate the mean voltage magnitude changes at the feeder end using Equation (13).

$$IMP = \frac{V_{wo} - V_w}{V_{wo}} \times 100\%$$ (13)

where $V_w$ and $V_{wo}$ is the mean voltage with/without the proposed method.

### 3.2. Simulation Results for One Specific Day

The performance of the three-phase Volt/Var control strategy is tested on a typical winter day on 16 January 2017. The voltage profile along the feeder without ESS at 18:00 is shown in Figure 4a. Since Feeder I is a relatively short feeder, the voltage drop along the feeder is relatively small. However, due to the nature unbalanced characteristics of the distribution system, the voltage unbalance rate is noticeable and gets worse at the feeder end. Based on the measured voltage at the ESS node, ESS will inject reactive power to the feeder as shown in Figure 4b. According to the control algorithm, the lower the measured phase voltage, the higher the injected reactive power. ESS will inject more reactive power to phase B and C at 18:00. As a result, the average voltage drop improvement is 30.9%, and the maximum voltage unbalance rate in terms of PVUR can decrease from 0.2415% to 0.1225%.
3.3. PVUR Mitigation

The proposed ESS control strategy can help to mitigate high voltage unbalance rate along the feeder and quantified in terms of PVUR improvement. The original PVUR for each three-phase node without ESS on 16 January is plotted in Figure 5a. Due to the physical structure of the feeder, the node at the feeder end tends to have a higher PVUR. However, the highest PVUR rate is not always at the feeder end. PVUR is also varying with time, usually higher PVUR is during morning and night peak time. Typically, less than 1% PVUR is recommended [37] and the feeder is operated within the range. With the help of ESS, the PVUR can be future reduced to improve the power quality. The PVUR for each three-phase node with ESS on the same day is plotted in Figure 5b. Compared with feeder without ESS, the PVUR is decreased significantly, especially during peak hours. The average PVUR decreases from 0.074% to 0.053% and the maximum PVUR decrease from 0.241% to 0.160%. The PVUR for all testing days are listed in Table 1. For all testing days, the PVUR improvement ranges from 9.65% to 43.84%.
Table 1. Maximum PVUR improvement from ESS controller.

| Season | Data             | No ESS | With ESS | Improvement |
|--------|------------------|--------|----------|-------------|
| Summer | 22 August 2016   | 0.22%  | 0.19%    | 13.07%      |
|        | 23 August 2016   | 0.20%  | 0.18%    | 12.82%      |
|        | 24 August 2016   | 0.20%  | 0.18%    | 9.93%       |
|        | 25 August 2016   | 0.20%  | 0.18%    | 9.65%       |
| Autumn | 12 October 2016  | 0.23%  | 0.19%    | 19.18%      |
|        | 13 October 2016  | 0.28%  | 0.21%    | 24.72%      |
|        | 14 October 2016  | 0.21%  | 0.17%    | 18.59%      |
|        | 15 October 2016  | 0.27%  | 0.21%    | 21.90%      |
| Winter | 12 January 2017  | 0.25%  | 0.18%    | 30.47%      |
|        | 13 January 2017  | 0.24%  | 0.14%    | 43.84%      |
|        | 14 January 2017  | 0.23%  | 0.15%    | 34.21%      |
|        | 15 January 2017  | 0.22%  | 0.14%    | 35.80%      |
|        | 16 January 2017  | 0.24%  | 0.16%    | 33.70%      |

3.4. Power Factor Correction and Voltage Profile Improvement

Power factor correction is another benefit of the ESS controller. The improvement for one simulation case on 15 October is plotted in Figure 6a. The improvement is relatively low in the morning and high during the rest of the time. For days with higher reactive power demand like this testing day, ESS can help to improve the power factor from 0.93 to 0.956. Minimum power factor correction for all testing days is presented in Figure 6b. For different loading conditions, all testing days show power factor improvement from ESS.

![Power factor improvement on 15 October](image1)

![Minimum power factor correction for all testing days](image2)

(a) Power factor improvement on 15 October

(b) Minimum power factor correction for all testing days

ESS could also help to improve voltage profile through increasing the voltage magnitude along the feeder for all three phases. The power loss and transferring capacity can benefit from such improvement. The voltage profile with and without the proposed control strategy on 14 January is presented in Figure 7a. Under different load conditions, the improvement varies from 2.2% to 38.1%, but the average improvement is about 30% as shown in Figure 7b.
3.5. Control Strategy Comparison

Compared to the original ESS control strategy proposed in [28], named as Strategy I, the new strategy, named as Strategy II, can provide a better voltage unbalance rate mitigation and a similar level of voltage profile improvement at the same time. The maximum PVUR for all nodes on 16 January 2017 is plotted in Figure 8. Visually, Strategy II is more efficient in voltage unbalance rate mitigation during the entire testing day. Strategy I is not designed for PVUR mitigation and ESS will inject reactive power equally to each phase, so the PVUR rate is only slightly better than the benchmark case without ESS. In comparison, the new control strategy II will provide a different level of reactive power compensation at each phase based on the measured voltage. As a result, PVUR can be further reduced. Especially, during the morning and night peak period, strategy II can help to reduce the PVUR much higher than strategy I.

3.6. Impact of PV on PVUR

Deeper PV penetration could cause the voltage unbalance issues. For example, when the PV size increases to 750 kVA, the PVUR increases significantly during noontime as shown in Figure 9a. Originally, the maximum PVUR is 0.241% and happened at 20:00. Due to the effect of PV, the maximum PVUR is 0.359% and happened at 13:00. PV generators not only increase the overall PVUR along the feeder but also creates new peak PVUR hours during the noontime. For the current penetration level, a 75 kVA PV has a limited impact on PVUR. However, when the penetration level reaches 750 kVA, the impact will become quite obvious. To test the influence of high-level PV penetration on the voltage control strategy, one test case is conducted on 16 January with a 750 kVA PV system. The new PVUR profile for this feeder is plotted in Figure 9b. Compared with the system without
ESS control, the maximum PVUR decreases from 0.359% to 0.175%. The noon PVUR peak caused by PV is almost fully mitigated.

![Graph showing PVUR profile without ESS control](a) PVUR profile without ESS control

![Graph showing PVUR profile with ESS control](b) PVUR profile with ESS control

Figure 9. PVUR mitigation under high photo-voltaic (PV) penetration scenario.

### 3.7. The Impact of Load Level on Voltage Control Performance

Since there is a certain reactive power output limit for the ESS, it may not increase the voltage as desired under heavy load conditions. As shown in Figure 10a, the demand on 12 January is significantly higher than that on 14 January. During the test, the reactive output from ESS on 12 January capped at 1.2 MVar after 6:00 am as shown in Figure 10b. Therefore, it is beneficial to find a suitable size of ESS for a certain feeder through simulation.

![Graph showing real and reactive power demand](a) Real and reactive power demand

![Graph showing reactive power output of ESS](b) The reactive power output of ESS

Figure 10. The impact of load level on voltage control performance.

### 4. Conclusions

This paper proposes a sensitivity-based voltage control strategy for the real-time operation of sustainable distribution systems with a high DER penetration rate. The proposed method utilizes only measured voltage at the ESS terminal to determine the reactive power output for each phase, which can reduce voltage unbalance rate under varying conditions on top of voltage profile improvement and power factor correction. Under a high DERs penetration case, the maximum PVUR is reduced significantly. The new PVUR peak dur-
ing noon-time caused by PVs is properly mitigated. The developed technique has been validated using a detailed feeder model based on real field data. The utility company can easily validate the proposed strategy with its energy management systems. Future work includes extending the proposed algorithm for the four-quadrant operation of converters and coordination with distributed energy resources such as PV and wind.

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