Centralized Control of Energy Storages for Voltage Support in Low-Voltage Distribution Grids

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***Abstract*—This paper presents a centralized voltage control scheme for unbalanced low-voltage grids experiencing over voltage problems due to high PV power penetration. Voltage control is primarily achieved by remotely controlling the active power of the distributed battery energy storage systems, which are owned by the customers. Reactive power capability of the converters are utilized for voltage control when sufficient kW capacity is not available. Distribution system operator has the control over these battery energy storage systems during the hours of high PV penetration. A method for fair utilization of battery energy storage systems by considering both rated power and energy capacity of the storage units is proposed. Delays caused by communication and computations are taken into consideration in the design of the real time controller. Results from a simulation study is presented to validate effectiveness of the real-time control scheme. The results show that the control scheme can successfully maintain the voltages at critical nodes within required limits. 1 minute computational and communication delay does not adversely affect the real time controller performance under the varying load and generation conditions considered in this paper. The utilization factor (total energy circulated through each battery units normalized to their rated energy capacity) justifies the fair utilization of battery storage units for voltage support.**

I. INTRODUCTION

Energy storage is becoming an essential element in the electrical power grid in order to ensure safe and reliable operation with the increasing share of non-controllable, intermittent renewable sources [1], [2]. It can play distinct roles at different levels of the grid. Applications of storage in distribution level include: voltage support, capacity support, and curtailment reduction [3]. Large integration of renewable sources particularly photovoltaic (PV) systems into the distribution grid has introduced several technical challenges, among them over voltage issues caused by reverse power flow is widely known. Active power curtailment, and reactive power support by PV inverters are two main solutions, which have been broadly discussed [4]–[7]. Distributed energy storage systems have advanced the voltage control capability in distribution grids further by providing a better solution in terms of both controllability and efficiency. This is because voltage regulation via active power control is much more effective than reactive power control due to the resistive nature of distribution grids [8]. Integration of communication infrastructure with the electrical power grid is an essential part of the development towards the Smart Grid, as it facilitates sophisticated real time monitoring and control of network elements. This improves reliability and quality of supply, and ensures optimal utilization of network elements [9]. Real time control of active power of distributed energy storage units is an effective solution for distribution grids experiencing over-voltage problems due to high PV penetration.

In this paper, we propose a centralized voltage control scheme for low-voltage (LV) distribution grids. Voltage control is primarily achieved by controlling active power of the distributed energy storage systems. The considered energy storage type in this work is battery energy storage (BES) systems. If available kW capacity is not sufficient then reactive power capability of the converters are utilized. In this work, the cause of the over-voltage problem is the active power, therefore active power is used as the primary voltage control option. Reactive power support comes at the cost of increased losses and increased reactive power capability in other parts of the grid, a cost which seems unnecessary given that BES units can source or sink active power, which is the root of the over-voltage problem in the first place. When the voltages in the distribution grid are within acceptable limits, the storage units can be used for other purposes such as peak shaving and economic energy dispatch.

II. METHOD

High power injection from PV systems can results over-voltage problem. The node that is located farthest away from the transformer is the one that usually experiences the largest deviation of the voltage from the nominal value. If the transformer supplies several feeders, then there can be more than one such critical node. Bringing down the voltage at critical nodes eventually bring the voltage profile of the line into the required limits. Here we assume voltage of the MV side of the distribution transformer is maintained sufficiently narrower range than that of LV network.

The control system consists of a central controller which calculates the active (P) and reactive (Q) power settings of the BES units. The smart meters that are located at the critical nodes notify central controller whenever they detect sustained over voltage. When the central controller receives over-voltage warning, it calculates P, Q settings of the BES units based on the real time critical nodes' voltage measurements and BES status. Then it transmit these set points to BES units' controllers. This approach is an event based triggered mechanism which starts whenever over voltage event is detected. We also included time based triggering in order to avoid operating at same P, Q settings over a long period of time.

European LV distribution systems are often three phase four-wire systems, and they accommodate both three- and single phase loads and DG units. Therefore, the system is usually unbalanced, to some extent. Connecting a single phase load or generator to a three phase four-wire balanced system results in a neutral point shift due to return current through the neutral conductor [10]. Because of that, a single phase generator injecting active power into the line results in an increase in the voltage (positive correlation) at the phase where it is connected, whereas the voltages in the other two phases are decreased (negative correlation) in grids having R/X ratio larger than 1. The positive correlation between voltage and power at the same phase, and the negative correlation between voltage and power at different phases permit voltage control by charging the BES units in one phase while discharging in other phases. This is an effective solution for unbalanced networks. Therefore, in the following, we treat the three phases separately and consider single phase BES units.

Using the voltage sensitivities w.r.t P and Q $\left(\frac{\partial V}{\partial P}, \frac{\partial V}{\partial Q}\right)$, the voltage change at node i, phase a for change in active and reactive power at nodes where BES units are connected can be written as follows.

$$\begin{aligned}\Delta V_{a,i} = &\sum_{k=1}^{N_a} \frac{\partial V_{ai}}{\partial P_{ak}}\Delta P_{a,k} + \sum_{k=1}^{N_b} \frac{\partial V_{ai}}{\partial P_{bk}}\Delta P_{b,k} + \sum_{k=1}^{N_c} \frac{\partial V_{ai}}{\partial P_{ck}}\Delta P_{c,k} \\ &+ \sum_{k=1}^{N_a} \frac{\partial V_{ai}}{\partial Q_{ak}}\Delta Q_{a,k} + \sum_{k=1}^{N_b} \frac{\partial V_{ai}}{\partial Q_{bk}}\Delta Q_{b,k} + \sum_{k=1}^{N_c} \frac{\partial V_{ai}}{\partial Q_{ck}}\Delta Q_{c,k}\end{aligned} \tag{1}$$

where $N_p : p = \{a, b, c\}$ is the total number nodes where BES units are connected in each phase, and $\Delta P, \Delta Q$ are the change in active and reactive power respectively. The method of calculating voltage sensitivities in an unbalanced system presented in [11] used in this work.

A. Active Power Allocation

In this study we consider utilizing multiple residential BES units for grid voltage support. Therefore, a fair utilization of participating units is of primary concern. We propose sharing the total active power involved in each phase in proportion to both the rated energy (kWh) and the rated power (kW) capacities of BES units. Sharing power in proportion to energy ratings ensures that battery degradation due to cycling for the purpose of voltage support is equal among the BES units. Sharing power in proportion to power rating avoids limiting usable kW capacity of a BES unit to the rated capacity of the BES unit having largest kWh rating, in case there exists BES units having larger kW capacity but lower kWh capacity compared to the one having the largest kWh capacity.

Assume that at a certain instant of time the required total active power transferred to (from) all the BES units that are connected to phases a, b, c are P_a, P_b, P_c respectively. We define the active power allocation coefficient (APAC) for phase a as follows. (Similar equations apply for phases b and c.)

$$K^P_{a,j} = \frac{P_{batRated,aj} \times E_{batRated,aj}}{\sum\limits_{k=1}^{N_a} P_{batRated,aj} \times E_{batRated,aj}} \; , \tag{2}$$

where $E_{batRated}$ and $P_{batRated}$ are rated energy and power capacity of the BES unit respectively. Subscripts a denotes phase a, j denotes the node where storage is connected, and superscript P denotes active power.

Then the active power settings for BES units are

$$P_{a,j} = K^P_{a,j}\, P_a \;\; ; \; P_{b,j} = K^P_{b,j}\, P_b \;\; ; \; P_{c,j} = K^P_{c,j}\, P_c \tag{3}$$

1) Voltage Unbalance: Besides solving over-voltage problem, BES units are utilized to minimize voltage unbalance. Here, we used the IEEE 112-1991 definition of voltage unbalance [12]. It is also known as phase voltage unbalance rate (PVUR) and is given by

$$\%\ \text{PVUR} = \frac{max|V_{a,b,c} - V_{avg}|}{V_{avg}} \times 100 \; , \tag{4}$$

where $V_{a,b,c}$ are the phase voltages in the three phases, and V_{avg} is the average phase voltage. We use this definition because it only considers voltage magnitudes. However, the true definition of voltage unbalance, which is known as voltage unbalance rate (VUR), is the ratio of the negative sequence voltage component to the positive sequence voltage component. The EN50160 standard states that the voltage unbalance shall be within the range 0 to 2 %.

2) Objectives: The active power settings of the BES units need to be found such that the total active power involved is minimized while still solving the over-voltage problem, and minimizing voltage unbalance. This requirement is converted to a non-linear constraint optimization problem where the objective function is as follows.

$$min\Bigg(\lambda_p \left(P_a^2 + P_b^2 + P_c^2\right) + \mu_p \left(\sum_{i=1}^{n} \text{PVUR}_i^2 - \beta^2\right)\Bigg), \tag{5}$$

where β is the statutory limit of voltage unbalance, n is the number of critical nodes, and λ_p and μ_p are the weightings provided for the two objectives in the objective function.

3) Constraints: The voltages at critical nodes should be within the limits after power allocation. The required voltage change at a critical node is calculated based on the real-time voltage measurements. These measurements are taken while BES units are in operation, i.e. P, Q settings of the BES units may not be zero while the measurements are being taken. Therefore, first we calculate the voltages at critical nodes without the presence of the BES units.

Adopted sign convention: Active power injection(discharging): Positive, Active power consumed (charging): Negative, Reactive power consumed: Positive, Reactive power injected: Negative.

The node voltage without the presence of BES units is given by

$$\begin{aligned}V_{ai,calc} = V_{ai,msred} &- \Bigg(\sum_{k=1}^{N_a} \frac{\partial V_{ai}}{\partial P_{ak}} P^o_{a,k} + \sum_{k=1}^{N_b} \frac{\partial V_{ai}}{\partial P_{bk}} P^o_{b,k} \\ &+ \sum_{k=1}^{N_c} \frac{\partial V_{ai}}{\partial P_{ck}} P^o_{c,k}\Bigg) - \Bigg(\sum_{k=1}^{N_a} \frac{\partial V_{ai}}{\partial Q_{ak}} Q^o_{a,k} + \sum_{k=1}^{N_b} \frac{\partial V_{ai}}{\partial Q_{bk}} Q^o_{b,k} \\ &+ \sum_{k=1}^{N_c} \frac{\partial V_{ai}}{\partial Q_{ck}} Q^o_{c,k}\Bigg),\end{aligned} \tag{6}$$

where $V_{ai,msred}$ is the measured node voltage, and $P^o_{a,k}, Q^o_{a,k}$ are P and Q settings of the k^{th} BES unit connected to phase a when measurements are being taken.

If the required change in three phase voltages at critical node are $\Delta V_{ai,req}, \Delta V_{bi,req}, \Delta V_{ci,req}$ then the node voltages after correction will be

$$\begin{aligned} &V_{ai,calc} - \Delta V_{ai,req} \\ &V_{bi,calc} - \Delta V_{bi,req} \\ &V_{ci,calc} - \Delta V_{ci,req} \end{aligned} \tag{7}$$

The values calculated from Eq. (7) is used in Eq. (4) to calculate the PVUR. The requirement of maintaining the voltage within allowable limits introduces following constraint into the optimization problem.

$$V_{ai,calc} - V_{max} \leq \Delta V_{ai,req} \leq V_{ai,calc} - V_{min} \ , \tag{8}$$

where V_{max} is the maximum limit and V_{min} is the minimum limit of the allowable voltage range.

Charging and discharging power of the BES units are limited to their rated values. This introduces the constraint

$$-P_{batRated,aj} \leq K^{P}_{a,j} \, P_a \leq P_{batRated,aj} \ , \tag{9}$$

The constraints given in Eqs. (8) and (9) apply for phases b, c as well.

The optimization problem is solved with the interior-point algorithm. Sometimes the problem may not have a feasible solution that satisfies the given constraints. In that case we relax the voltage constraints until the solution is feasible.

4) Clustering of BES units: If the LV network consists of one or several long laterals besides the main line, then there are more than one critical node. In that case, clustering of BES units based on which critical node each BES unit is supposed to support is required. This is because the voltage profile and the nature of voltage unbalance can be different in different laterals. For such networks, considering the total power involved in each cluster separately gives a better solution. Then, the number of variables in the optimization problem becomes 3 times the number of clusters. The total power involved in each cluster is shared among the BES units in each cluster according to Eq. (3). Although the clusters are being considered separately when sharing the power, the interaction between the clusters is taken in to account in Eqs. (4)-(8).

B. Reactive Power Allocation

If available kW capacity is not sufficient to maintain the nodes' voltages within statutory limits, then reactive power capability of the converters are utilized for voltage control. The reactive power settings of the converters are found such that the total reactive power involved is minimized while still solving the over-voltage problem, and minimizing voltage unbalance. The respective objective function is

$$\begin{aligned} min\Bigg(\lambda_q \left(\sum_{k=1}^{N_a} Q^2_{a,k} + \sum_{k=1}^{N_b} Q^2_{b,k} + \sum_{k=1}^{N_c} Q^2_{c,k} \right) + \\ \mu_q \left(\sum_{i=1}^{n} \text{PVUR}^2_i - \beta^2 \right) \Bigg), \end{aligned} \tag{10}$$

where $Q_{a,k}$ is the reactive power setting of the k^{th} BES unit's converter connected to phase a.

By solving the optimization problem in Section II-A we can find P settings of the BES units. These values are then substituted into Eq. (1) with $\Delta Q_{a,k} = \Delta Q_{b,k} = \Delta Q_{c,k} = 0$, to calculate the expected change in voltages ($\Delta V_{ai,expt}$) at critical nodes. Then the expected voltage at critical node is

$$V_{ai,expt} = V_{ai,calc} + \Delta V_{ai,expt} \tag{11}$$

Voltage constraint similar to the one described in Eqs. (7)-(8) is holds for this case as well, where $V_{ai,calc}$ should be replaced with $V_{ai,expt}$.

Q settings of each BES converter should be within the reactive power capability of each converter.

$$-\sqrt{S^2_{rated,aj} - P^2_{a,j}} \leq \ Q_{a,j} \ \leq \sqrt{S^2_{rated,aj} - P^2_{a,j}} \tag{12}$$

where $S_{rated,aj}$ is the kVA rating of the converter connected to phase a, node j.

The optimization problem is solved again using the interior-point algorithm. As in the previous case relaxation of the voltage constraints is done when required.

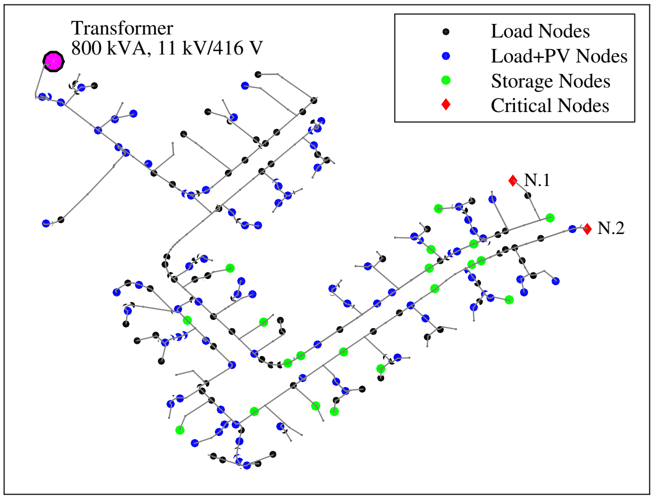


Fig. 1. Single phase layout of the LV network - IEEE European low voltage test feeder.

III. CASE STUDY

The proposed method is tested for IEEE European low voltage test feeder shown in Fig. 1. This network supplies 300 customers which includes both three phase and single phase connections. These customers were distributed symmetrically among the 3 phases. We considered 120 customers out of these 300 to have rooftop PV systems. Each of these systems are single phase with a capacity 4 kWp. We assume all loads/generations to be constant power loads. The daily domestic electric load profiles of a typical European household were obtained from IEA/ECBCS Annex 42 [13]. Power production from a 300 Wp PV module installed at a test station at the University of Agder in the town of Grimstad, Norway is used as the basis for PV production profiles [14], [15]. 30 different PV production profiles that can represent the spatial variability of solar irradiance were distributed randomly among 120 PV nodes. The resulting active power on the distribution transformer during the critical period is shown in Fig. 2.

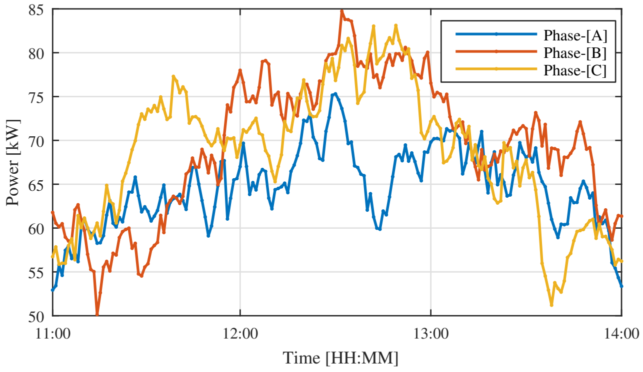


Fig. 2. Active power load on the distribution transformer. Positive values corresponds to power flow in the reverse direction.

TABLE I. CHARACTERISTICS OF BES UNITS.

Name	ST-1	ST-2	ST-3	ST-4	ST-5	ST-6	ST-7
kW	5	5	6	6	6	6	6
kWh	15	15	15	18	15	15	15
Name	ST-8	ST-9	ST-10	ST-11	ST-12	ST-13	ST-14
kW	6	6	6	6	6	6	6
kWh	15	12	20	18	18	18	18
Name	ST-15	ST-16	ST-17	ST-18	ST-19	ST-20	ST-21
kW	5	6	5	5	6	4	6
kWh	18	15	15	15	15	12	15

Regarding the BES units, we have assumed a case of residential BES units in which owners get financial incentives from the distribution system operator (DSO) for installing the BES unit, if the owner decides to participate in grid voltage support. The agreement between the DSO and the BES unit's owner states that the DSO has full control over the P, Q settings of the unit during a certain time interval of the day. In the following we call this time interval the critical period. In addition, the agreement states that the State of Charge (SOC) of the BES unit should not be above a certain limit at the start of the critical period. The DSO decides the critical period and the SOC limit. We considered 21 single phase BES units (7 units per phase) connected to the nodes indicated in Fig. 1. The rated power and the rated energy capacities of these BES units are listed in Table I. We can observe that this network consists of two long lines, and therefore has two critical nodes (N.1, N.2). Hence, clustering of BES units was done as shown in Table II.

IV. RESULTS AND DISCUSSION

Quasi-static time series simulations were performed with 1-minute time resolution. Over-voltage problems primarily occur during peak PV production hours, i.e. around solar noon. Therefore, the critical period was set to 1100-1400 hrs.The maximum SOC limit mentioned in Section III was set to 40 %. The time interval of time based triggering was set to 20 minutes. Time takes from originating the over-voltage warning to receive P, Q set points by BES units' controllers was considered as 1 minute (communication and computational delay).

TABLE II. CLUSTERING OF BES UNITS.

Cluster	Critical Node	BES
1	N.1	ST-1, ST-2, ST-3, ST-4, ST-5, ST-6, ST-7, ST-8, ST-9.
2	N.2	ST-10, ST-11, ST-12, ST-13, ST-14, ST-15, ST-16, ST-17, ST-18, ST-19, ST-20, ST-21.

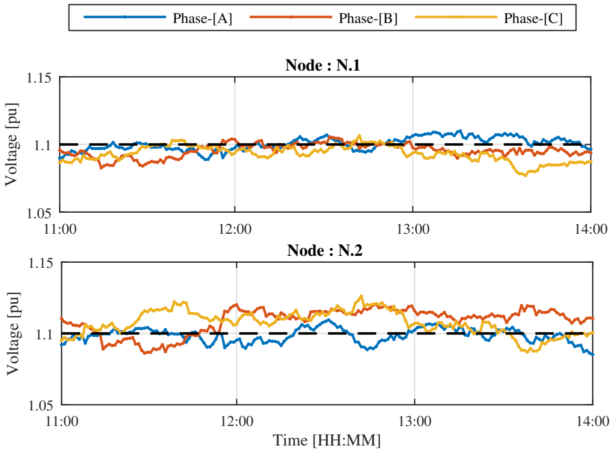


Fig. 3. Voltages at critical nodes during critical period without voltage control.

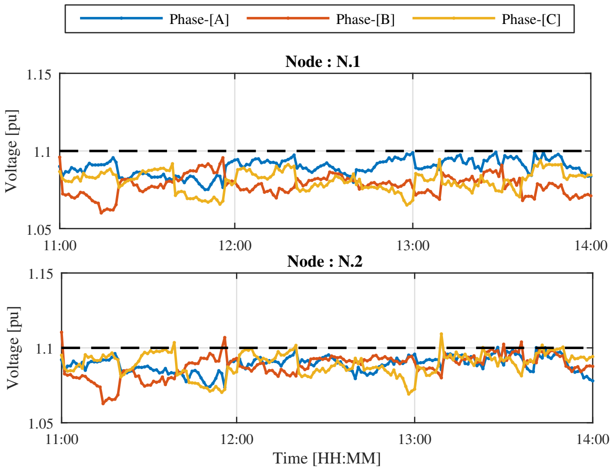
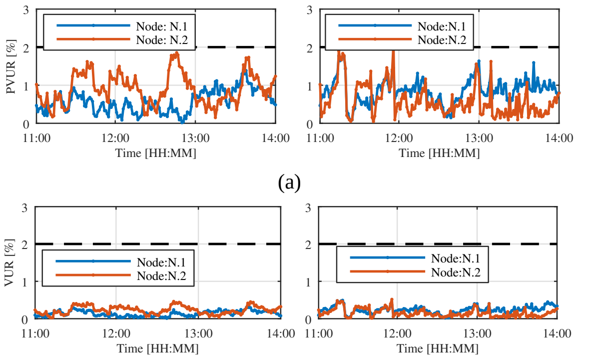


Fig. 4. Voltages at critical nodes during critical period with voltage control.

Fig. 3 shows voltage variation of the two critical nodes over time without any voltage control measures for a certain loading condition. As can be observed in the figure, both critical nodes experience over-voltages during this period. The nature of voltage unbalance in two nodes is significantly different. Fig. 4 presents the critical nodes' voltages with the centralized voltage control scheme. From the figure, it can be observed that the proposed scheme can successfully maintain the voltages in all three phases within the statutory limits. PVUR and the true VUR at the two critical nodes are shown in Fig. 5. From the figure, it can be seen that the IEEE 112-1991 definition of voltage unbalance (PVUR) deviates significantly from the true VUR. The IEEE 112-1991 definition usually gives larger values for voltage unbalance rate when compared to the true definition. Therefore, it is acceptable to adopt the IEEE 112-1991 definition in the objective function given in Eq. (5), because the true VUR will be always below the maximum limit as long as PVUR is. The calculated P, Q settings after receiving the over-voltage warning are sufficient to maintain the voltage within the statutory range over considerably long time interval even though the load and the PV generation



(a)

(b)

Fig. 5. Voltage unbalance at critical nodes without (figures on the left) and with (figures on the right) voltage control scheme. (a) Phase voltage unbalance rate (IEEE-112 1991 standard). (b) True voltage unbalance rate (EN50160 standard).

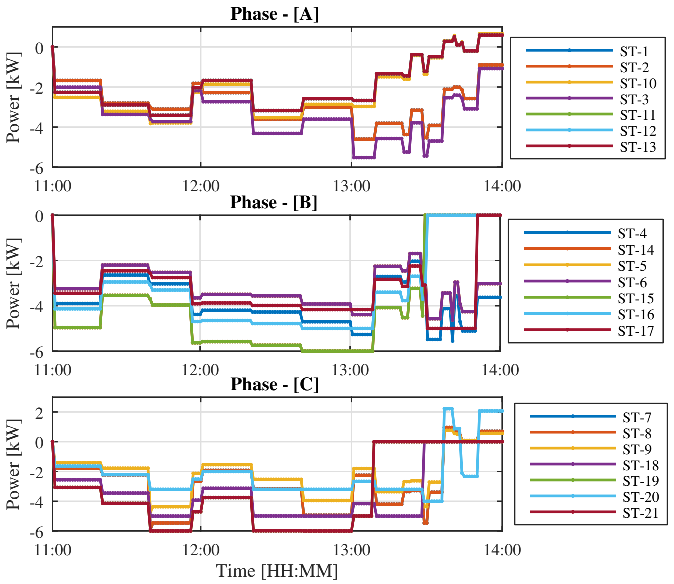


Fig. 6. Active power settings of BES units. Results are shown for the three phases separately. Positive values correspond to discharging while negative values correspond to charging.

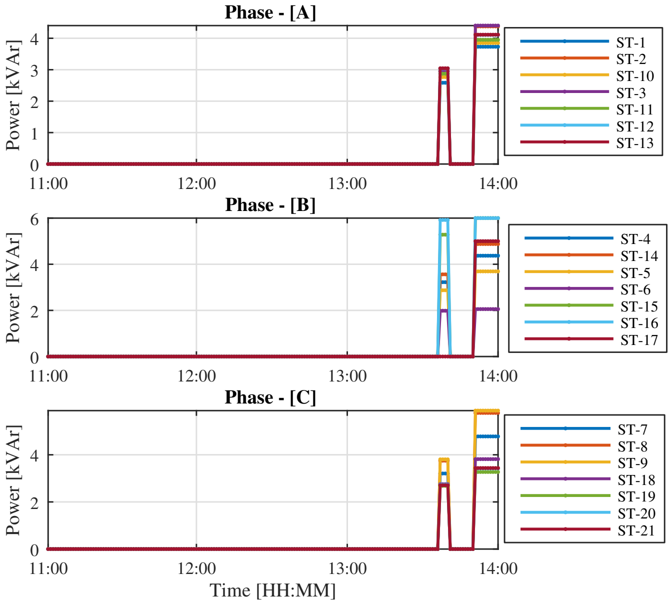


Fig. 7. Reactive power settings of the BES units' converters. Positive values correspond to reactive power consumed by the converters while negative values correspond to reactive power produced.

change over time. However, notice that these set points are not optimal because the load and the PV generation change all the time. It is important to solve over-voltage issues while transferring as little energy to the BES units as possible so that there will be kW capacity left for voltage support at a later time of the day. Moreover, reactive power involved need to be minimized so that the additional loss introduced due to the reactive power utilization is minimized. That is why it is required to calculate the optimal set points periodically (time based triggering) even without over-voltage warnings. However, it should be noted that so called optimal set points are not really optimal, because there is always a delay between getting measurements and receiving set points. Calculation of optimal set points is done based on the measurements and by the time the BES units receive these set points, the load and the generation have changed. Therefore, we can call these set points near optimal set points with respect to the current loading condition. Even though there is a delay (1 minute), the calculated set points are sufficient for maintaining the voltages within the required level. This implies that the considered communication and computational delay does not adversely affect the controller performance.

Fig. 6 presents active power settings of BES units connected to each phase. From the figure it can be observed that the time between 13:30h and 14:00h, the BES units connected to phases A and C are discharging while the BES units connected to phase B are charging. That is because the BES units, ST-14, ST-15 and ST-16 reach 100 % SOC by 13:30h results in insufficient kW capacity for voltage support in phase B-cluster 2. Hence first it try to lower the voltage in phase B by discharging the BES units connected to phases A and C while still maintaining the voltages in phases A and C within the limits. However, still it cannot solve over-voltage problem in phase B while satisfying all other constraints, therefore reactive power is utilized as shown in Fig. 7. Discharging BES units in one phase while charging BES units in the other phases are possible with single phase BES units. Also the optimal P, Q settings are different in three phases even the BES unit is connected to the same node. Therefore, single phase BES units are more effective in voltage control for unbalanced distribution grids.

Table. III lists the ratio of total circulated energy (kWh) in each BES unit during the critical period to the rated energy capacity of the BES unit. In this paper, this ratio is called as utilization factor of the BES unit. From the utilization factors shown in the table, it can be observed that BES units connected to each phase in each cluster are utilized fairly. However, if a certain BES unit's both rated power and energy capacities are lower compared to the others, then that BES unit will have a lower utilization factor, because active power is shared between BES units in proportion to the product of rated power and energy capacities.

Utilization of customer owned devices will avoid the need

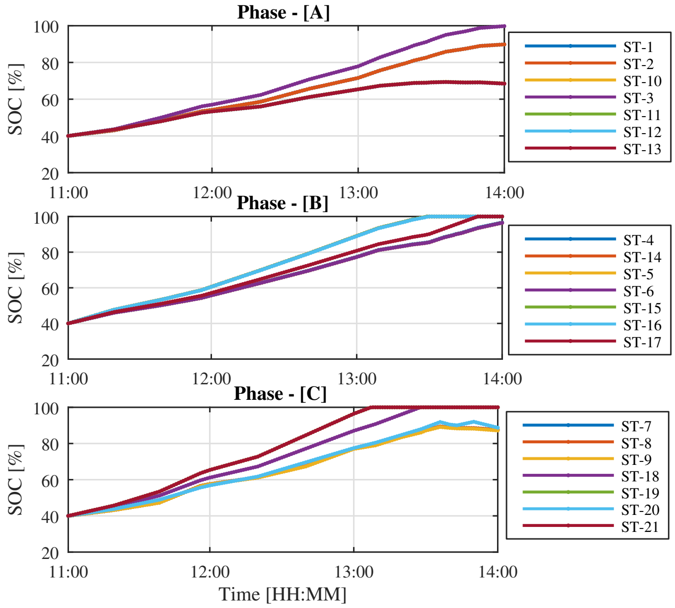


Fig. 8. State of Charge (SOC) variations of BES units.

TABLE III. UTILIZATION FACTOR OF BES UNITS.

Cluster	Phase [A]		Phase [B]		Phase [C]	
	Storage name	Util. factor	Storage name	Util. factor	Storage name	Util. factor
1	ST-1	0.50	ST-4	0.57	ST-7	0.51
	ST-2	0.50	ST-5	0.57	ST-8	0.51
	ST-3	0.60	ST-6	0.56	ST-9	0.51
2	ST-10	0.31	ST-14	0.60	ST-18	0.60
	ST-11	0.30	ST-15	0.60	ST-19	0.60
	ST-12	0.30	ST-16	0.60	ST-20	0.59
	ST-13	0.30	ST-17	0.60	ST-21	0.60

for the DSO to invest in larger energy storage systems in the LV network. Instead, proper incentive schemes can be implemented for residential storage units such as the one mentioned in Section III. This will not only motivate residential customers to install BES units but both parties will get benefits if the operation of these units is properly controlled. With the proposed incentive scheme for BES units, the DSO will have control over the units only during a limited time interval of the day. Therefore, during the rest of the time the BES units can be charged/discharged for increased self consumption or maximum revenue, considering the energy price.

V. CONCLUSION

Small residential energy storage units can be effectively utilized for centralized voltage control schemes of active LV-distribution grids experiencing over-voltage issues due to large integration of distributed generators. The proposed voltage control scheme, which uses residential BES units could successfully maintain the voltages of the LV nodes within the statutory limits in the case studied. The considered computational and communicational delay of 1 minute did not adversely affect the controller performance even though the load and the generation changes all the time. It has been shown that single phase BES units are more effective than three phase units, when used for voltage control in an unbalanced network due to the possibility of charging BES units in one phase while discharging in the other phases. Further, if a LV network has more than one critical node, then clustering of BES units based on which critical node each BES is supposed to support is required to ensure optimum utilization of power and energy capacity of BES units. Sharing active power in proportion to the product of rated power and energy capacity ensures better utilization of multiple BES units for voltage support.

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