Distributed Control Scheme for Residential Battery Energy Storage Units Coupled With PV Systems

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Abstract

A distributed control method for residential battery energy storage (BES) units coupled with photovoltaic (PV) systems is presented. The objective is to utilize customer owned BES units for solving the over-voltage issues caused by high PV penetration without significantly affecting the BES owners local objectives. 24 hour ahead active power set points of the BES unit are calculated by an optimization based scheduling algorithm. The objective function is locally decided and the optimization is performed at the local level. The BES units are charged from the excess energy from the PV systems mostly during the period the grid is under risk of over-voltage. If the set points that were calculated by the optimization, turn out not to be able to maintain the voltages within the statutory limits in real time operation, the active power set points are modified. Reactive power is also utilized when active power is not sufficient. The new set points are calculated by a central controller. The performance of the proposed method is validated in a simulation study. It is shown that the residential BES units can successfully be utilized for solving over-voltage issues without significantly affecting the primary needs of the BES owners.

Keywords: Battery energy storage, distributed control, optimization, PV systems, voltage regulation

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Nomenclature

t	discrete time index: $t > 0, t \in \mathbf{N}$
i	BES index
ph	phase index: $ph = \{a, b, c\}$
$T, \Delta t$	total number of discrete intervals per planning horizon and sampling interval
$\Delta T_{critical}$	critical period
$P_{load,i}(t)$	average load forecast over the time step Δt
$P_{pv,i}(t)$	average PV forecast over the time step Δt
$P_{bat,i}(t)$	battery P set points decided by the local controller
$P_{grid,i}(t)$	average power drawn or injected to the grid over the time step Δt
$\eta_{convPV,i}$	PV inverter efficiency
$\eta_{convB,i}$	battery converter efficiency
$P_{conB,rated}^{dc}$	dc side rated capacity of the battery converter
$P_{conB,rated}^{ac}$	ac side per phase rated capacity of the battery converter
$SOC_i(t)$	State of charge of the battery
SOC_{min}, SOC_{max}	minimum and maximum SOC level
$\eta_{chrg,i}, \eta_{dichrg,i}$	charging and discharging efficiencies of the battery
$Q_{nom,i}$	nominal Ah capacity of the battery bank
$I_{bat,i}(t)$	battery bank current
$V_{bat,i}(t)$	battery bank voltage
$V_{bat,min}, V_{bat,max}$	minimum and maximum allowed battery voltage
N_{bat}	number of three phase BES units
N_{pv}	number of PV systems
$P_{grid,max}$	maximum power that can be injected to the grid
$P_{a,i}, P_{b,i}, P_{c,i}$	ac side active power set points of the battery converter in phases a, b and c
$P_{ph,i}^{msrd}$	measured ac side P set points at the BES converter
pf, pf_{min}	power factor of the converter, minimum power factor
$P_{TR,ph}^{msrd}$	active power measured at the transformer
$Q_{ph,i}$	reactive power set point of the PV inverter

1. Introduction

Increased penetration of power from distributed generators (DG) provides numerous benefits such as a reduction in the need for large infrastructure upgrades, a reduction in the pressure on transmission lines, improved efficiency, and lower CO_2 emissions when renewable energy sources are used. The latter comes at a price of intermittency, hence energy storage is becoming an essential element in the electrical power grid in order to ensure safe and reliable operation [1, 2]. Storage can play distinct roles at different levels of the grid. Applications of storage at the generation and transmission levels include energy arbitrage, capacity firming, curtailment reduction, frequency and voltage control, and black starting. In the distribution level, storage can provide capacity support, peak shaving, curtailment reduction and voltage support [3].

Large scale integration of renewable sources, particularly photovoltaic (PV) systems, into the distribution grid has introduced several technical challenges for the network operators [4]. Among them, the most common problem is the over-voltage issues caused by reverse power flow [5, 6]. The bi-directional power flow caused by DGs has made voltage regulation more challenging when using traditional methods such as on load tap changers (OLTC). This is because reverse power flow can cause over-voltage problems in one feeder while some nodes in another feeder with no DGs can experience under-voltage problems. In such a situation, the OLTC is not able to regulate the voltage. Therefore, voltage support solutions at the low levels of the grid are required to deal with such problems efficiently. The local solutions for the over-voltage problem that have been broadly discussed are static/dynamic active power curtailment and reactive power support by PV inverters [7–11]. Various coordinated and centralized solutions based on reactive power support from the PV inverters have also been proposed [12–14].

Recently, there has been a growing interest for battery energy storage (BES) units in the residential sector, especially coupled with PV systems. According to recent studies, a rapid growth is expected in this sector in the coming years [15, 16]. Detailed modelling and control of grid connected and standalone PV systems coupled to BES unit are discussed in [17–19]. The BES units are used at the residential level mainly to increase self-consumption along with decreased electricity bill. Residential storage units can not only increase the self-consumption for the user, but also can help the utility to solve over-voltage problems if charging of the storage is properly controlled. A local control method for residential storage units that can maximize the economic benefits for the storage owner while supporting the grid to lower the over-voltage risk is presented in [20]. Proper charging of the BES units can reduce the reactive power requirement from the PV inverters for regulating the node voltages. However, it is important to satisfy the primary needs of the BES owners; otherwise they might hesitate to let the utility to involve in controlling their BES units. Therefore, the objective of this work has been to propose a method for controlling the residential BES units to provide voltage support to the grid without significantly affecting the primary needs of the BES owner.

Several authors have presented different control methods for distributed energy storage units that are

used for providing voltage support to the grid. Ref. [21] presents a coordinated control method of distributed energy storage for managing node voltages and thermal constraints. Active power (P) from the storage is controlled for managing the network loading, whereas reactive power (Q) is used for voltage regulation. The method uses the energy storage system closest to the voltage violated node for the voltage regulation. Ref. [22] presents a coordinated voltage control scheme with the use of energy storage units and the transformer OLTC. In the proposed method, the selection of voltage control device(s) is based on the voltage cost sensitivity factor, which is defined as the ratio of the required voltage change at a selected node to the operating cost of a voltage control device. The device having the highest voltage cost sensitivity is selected first, and the required P, Q settings are calculated using voltage sensitivity coefficients with respect to P and Q. In the case where sufficient capacity is not available, a second device is chosen. Ref. [23] presents a similar approach, but the selection is based on both voltage sensitivities and the remaining cycle life of the battery. A centralized controller selects the storage unit(s) to be used and notifies that to the local controller. Having received the command from the centralized controller, the local controller determines the P, Q set points based on a local voltage measurement. A real time voltage control scheme with P, Q control of super capacitor bank(s) has been presented in [24]. P, Q settings of the storage unit(s) are found by solving an optimization problem with the objective of minimizing the total P, Q adjustments from the scheduled values, and the difference between expected and nominal voltages at all critical nodes. This method suggests closed loop control, hence continuous data transmission between the central controller and the selected nodes (critical voltage nodes and storage nodes) is required.

In this paper, we propose a new control strategy for residential BES units, which is aimed to support the grid for solving over-voltage issues without adversely affecting the local objectives of the storage owner. The proposed control strategy is based on the distributed control concept. Unlike the methods mentioned above, in this method, most of the decisions are taken locally with the use of local information, while information exchange and decision making via a central entity occurs only when needed. This allows the local controllers to decide the charging/discharging set points of the BES units, and therefore the primary objective function can be chosen by the BES owner. Besides, the BES scheduling algorithm in the local controller attempts to charge the BES unit mostly during the period of high reverse power flow in the grid. This reduces the risk of over-voltage problems. Active power adjustment and use of reactive power for voltage support is only used when the BES set points decided by the local controllers are not able to solve the over-voltage problem completely. This lowers the amount of required reactive power for voltage support, and therefore reduces the distribution losses.

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 [25]. Smart meters and smart grid enabled converters are some of the examples from today that

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have interfaces to communicate with an external party. In the near future, such smart grid technologies will be more and more common; therefore, in this paper we assume the communication infrastructure to be available.

The rest of the paper is organized as follows. Section 2 explains the proposed method for voltage control in detail, and in Section 3 the case study which is used to validate the method is presented. Results from the simulations are provided in Section 4 along with a discussion, before the Conclusion.

2. Method

Customers expect reduction in their electricity cost along with increase in self-sufficiency of local PV generation from their BES units. The BES unit can store the excess energy from the PV system without selling it to the grid for a low price. This energy can be used later to supply the local demand. Customers who are subjected to a time-of-use electricity tariff can utilize the stored energy preferably during high tariff periods. An optimization based energy management system can maximize the economic benefits for the customer [20]. Considering voltage quality, if these BES units charge during the period when the over-voltage problems occur and discharge during the time when the distribution grid is heavily loaded, the voltage quality can be improved and transformer over-loading issues can be mitigated. The over-voltage problem usually occurs around solar noon, because in this period PV systems inject large amount of power into the grid compared to the rest of the hours. In this paper we call this period the critical period. The capacity of the BES units are limited, and therefore they can reach 100% state of charge (SOC) well before the critical period ends. If that happens, the active power support from the BES units is no longer available for solving the over-voltage problem. However, a certain minimum amount of power should be transferred to the BES units during this period in order to solve the over-voltage problem completely. Therefore, both the availability of the BES units for charging during the critical period, and the amount of power transferred to the BES units are equally important when charging power is controlled for improving the grid voltage. In the proposed method, an optimization based local energy management system (EMS) calculates the active power set points of the BES unit. The BES owner decides the objective function. The charging of the BES is controlled such that the BES charges mostly during the critical period. In addition, it is ensured that the BES does not reach 100% SOC before the critical period ends.

The idea is to use the available active power capability of the BES systems maximally for improving the voltage quality. The optimization problem is solved by each residential system with PV and BES units individually by their local controllers. The output of the optimization is the active power set points of the BES unit over the planning horizon. The voltage profile during the critical period will be improved due to charging of BES units. However, when the cumulative energy capacity and/or the power capacity of the BES units are not sufficient, the over-voltage issues may not be completely solved. In that case, a secondary
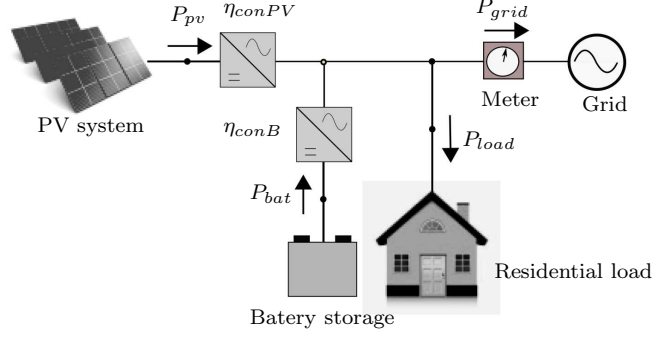
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Figure 1: AC-coupled configuration of a PV and battery energy storage system. Arrows indicate the direction of positive power flow.

solution is needed. The proposed secondary solution is based on the centralized control concept. A central controller determines the set points based on the real-time measurements whenever the controller is triggered. The central controller adjust the locally decided active power set points and/or utilizes the reactive power support from the converters for voltage regulation. The proposed control method is a distributed control approach. Because, the active power set points are locally decided using the local information. The central controller modifies the active power set point or asks for the reactive power support when only the locally decided active set points are not able to satisfy the network constraints.

2.1. Local Scheduling of BES Units

Two different configurations of residential PV systems coupled with BES can be found: DC- and AC-coupled systems. In this study we consider the AC-coupled configuration shown in Figure 1. The system consists of an inelastic load, a PV system, a BES unit and power electronic converters.

The discrete representation of the system for the ith user at discrete time t is

$$
\begin{aligned}
\text{Discharging:} \quad & \eta_{conPV,i}P_{pv,i}(t) = P_{load,i}(t) + P_{grid,i}(t) - \eta_{conB,i}\ P_{bat,i}(t) \\
\text{Charging:} \quad & \eta_{conPV,i}P_{pv,i}(t) = P_{load,i}(t) + P_{grid,i}(t) - \frac{P_{bat,i}(t)}{\eta_{conB,i}}
\end{aligned}
\tag{1}
$$

where $P_{bat,i}$ is positive when the battery is discharging and $P_{bat,i}$ is negative when the battery is charging. $P_{grid,i}$ is positive when power is injected to the grid and $P_{grid,i}$ is negative when power is drawn from the grid.

The state of the charge (SOC) of the battery is calculated from the coulomb counting method [26, 27].

$$
\begin{aligned}
\text{Discharging:} \quad & SOC_i(t) = SOC_i(t-1) - \frac{I_{bat,i}(t)\ \Delta t}{\eta_{dischrg,i}\ Q_{nom,i}} \\
\text{Charging:} \quad & SOC_i(t) = SOC_i(t-1) - \frac{\eta_{chrg,i}\ I_{bat,i}(t)\ \Delta t}{Q_{nom,i}}
\end{aligned}
\tag{2}
$$

where $I_{bat,i}$ is positive when the battery is discharging and $I_{bat,i}$ is negative when the battery is charging. In this work, we considered lithium-ion battery bank. The self-discharge rates of lithium-ion batteries are generally very small, therefore the self-discharge rate is neglected.

The battery bank current is

$$I_{bat,i}(t) = \frac{P_{bat,i}(t)}{V_{bat,i}(t)} \tag{3}$$

$V_{bat,i}$ is the terminal voltage of the battery bank. It is given by [28]

$$V_{bat,i}(t) = E_o - K\left(\frac{Q_{nom,i}}{Q_{nom,i} - q}\right)q - K\left(\frac{Q_{nom,i}}{Q_{nom,i} - q}\right)|I_{bat,i}(t)| + Aexp(-Bq) - R_{bat}I_{bat,i}(t) \tag{4}$$

where

$$\begin{aligned} q &= Q_{nom,i} \, SoC_i(t) \,, & \text{Discharging } (I_{bat,i} \geq 0) \\ q &= Q_{nom,i} \, (1 - SoC_i(t)) \,, & \text{Charging } (I_{bat,i} < 0) \end{aligned} \tag{5}$$

and E_o is the battery constant voltage, K is the polarization voltage, A is exponential zone amplitude, B is exponential zone time constant inverse, R_{bat} is the internal resistance of the battery.

The state of charge should be maintained within a safe region in order to prolong the battery lifetime and to avoid safety issues [29].

$$SOC_{min} \leq SOC_i(t) \leq SOC_{max} \tag{6}$$

The charging/discharging rate of the battery should be within the rating of the battery converter.

$$-P_{conB,rated}^{dc} \leq P_{bat,i}(t) \leq P_{conB,rated}^{dc} \tag{7}$$

The optimization algorithm in the local controller schedules the battery over a certain time horizon using the forecasts of local demand and PV production. In this study, the primary need of the customer who own the BES unit is to maximize the economic benefits . Here we consider the case where the feed-in-tariff for PV is lower than the utility electricity price. The main concerns when scheduling the battery are as follows.

- The main purpose of having the BES is to store the excess energy available from the PV system for later utilization. Therefore, charging from the grid should be avoided whenever sufficient excess energy is available from the PV system.

- If the excess energy from the PV system is not sufficient to charge the battery fully, the EMS should consider charging from the grid. Charging from the grid is only economically attractive if the savings made by consuming the stored energy which is originally bought from the grid, is higher than the cost of buying energy, plus the cost of losses plus the battery degradation cost due to cycling of the battery.

- If the excess energy available from the PV system during the critical period is sufficient to fully charge the battery, it should be charged only during the critical period. Otherwise, charging outside the critical period should be allowed.

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• The battery should not reach 100% SOC before the critical period ends.

Considering the above requirements and constraints, the optimization problem is mathematically formulated for the ith user as shown below.

Objective function:

$$min \sum_{t=1}^{T} -\Big\{ C_i(t) - \alpha \, \text{BDC}_{cyl,i}(t) + \beta \, \gamma_{comp} \, |P_{bat,i}(t)| \Big\},$$ (8)

where $C_i(t)$ term represents the cost of electricity, which is reflected in the electricity bill, $\text{BDC}_{cyl,i}(t)$ is the battery degradation cost due to cycling, γ_{comp} is a fictitious cost that is used to promote charging during the critical period and α, β are control parameters. The fictitious cost γ_{comp} can take any value greater than the maximum difference between the electricity buying rate (γ_{buy}) and the electricity selling rate (γ_{sell}). The control parameter β is set to 1 during the critical period if the battery is charging from the excess energy from the PV system, otherwise it is set to 0.

$$\beta = \begin{cases} 1; & t \in \Delta T_{critical} \ \& \ P_{grid,i}(t) \geq 0 \ \& \ P_{bat,i}(t) < 0 \\ 0; & \text{otherwise} \end{cases}$$

In this study, we consider time-of-use electricity tariff schemes for energy bought from the grid and flat rate for the energy sold to the grid. The cost of electricity can then be calculated from the following equations.

$$C_i(t) = \begin{cases} P_{grid,i}(t) \, \Delta t \, \gamma_{sell}(t); & P_{grid,i}(t) > 0 \\ P_{grid,i}(t) \, \Delta t \, \gamma_{buy}(t); & P_{grid,i}(t) \leq 0 \end{cases}$$ (9)

A method for calculating an approximated value for battery degradation cost using the data provided in the battery data sheet is explained below. The battery degradation cost per kWh due to cycling of the battery is calculated from the equation

$$\gamma_{bat,cyl} = \frac{\text{BC}}{\text{E}_{bat,ltpt}},$$ (10)

where BC is the battery installation and maintenance cost over its lifetime. $\text{E}_{bat,ltpt}$ is the lifetime throughput of the battery. Lifetime throughput is the total amount of energy (kWh) that can be delivered from the battery during its lifetime. Battery ageing tests have been performed in [30] for several battery types to observe the battery capacity loss due to cycling over the time. The results have shown a linear relationship between the capacity loss and the number of full equivalent discharge cycles. Based on this linear capacity loss, the lifetime throughput of a battery sized to operate with minimum depth of discharge of DoD_{min} is found as follows.

$$\text{E}_{bat,ltpt} = \left(\frac{\text{E}_{bat,nominal} + \text{E}_{bat,end}}{2} \right) \times \text{DoD}_{min} \times \text{Number of cycles to failure},$$ (11)

where $E_{bat,nominal}$ is the nominal capacity of the battery when it was new and $E_{bat,end}$ is the end of life capacity of the battery. The number of cycles to failure of the battery for a given DoD can normally be found in the data sheet of the battery.

The battery degradation cost when cycling certain amount of energy from the battery is

$$\text{BDC}_{cyl} = \gamma_{bat,cyl} \; E_{bat} \tag{12}$$

where E_{bat} is the amount of energy cycled through the battery.

Inclusion of battery degradation cost can however decrease the self-consumption rate when the cost of battery capacity loss due to cycling a certain amount of energy generated from the PV system is higher than the cost of buying the same amount of energy from the grid when needed. The purpose of coupling the BES to the PV system in the first place is to maximally utilize the self generated energy. Since the electricity cost has been chosen as the objective function, we need to increase the self consumption rate in such a way that the cost of electricity over the planning horizon is minimized. Therefore, the battery capacity loss cost due to cycling of energy generated from the PV system to supply the local load is considered zero. The battery capacity loss cost is included or the control parameter α is set to 1 when: i) the battery is charged from the grid, and ii) the stored energy in the battery is fed-in to the grid. Because, in these two cases, there is the possibility to i) buy energy directly from the grid to supply the local load without cycling the battery, and ii) sell excess energy directly to the grid without cycling the battery. For all other cases, the battery capacity loss cost is neglected by setting the control parameter α to 0. These cases include, i) the battery is charged from the PV system, ii) the battery is discharged to supply the local load.

The local controllers do not have any information about the network. Therefore, they try to reduce the over-voltage risk by charging the BES units mostly during the critical period. The requirement of not reaching 100% SOC before the critical period ends, is achieved by setting a limit on the power that can be injected to the grid. This limit is only active during the critical period.

$$P_{grid,i}(t) \le P_{grid,max} \quad : t \in \Delta T_{critical}. \tag{13}$$

Initially, this limit is set to zero, which means that all the excess energy available from the PV system during the critical period should be transferred to the battery. If either the rated kW capacity or the energy capacity is not enough, it is not possible to transfer all the excess energy to the battery. In that case, the limit is increased until a feasible solution is found.

The non-linear constrained optimization problem is solved using dynamic programming. Ref. [20] contains more details about the application of dynamic programming for solving this problem. The output from the optimization is the average active power set points at discrete time intervals over the considered time horizon.

2.2. Centralized Control of BES Units

The local controllers schedule the BES units with the aim of reducing the power flow in reverse directions during the time when the network is prone to over-voltage risks. However, as mentioned before, when the power transferred to the BES units is not sufficient, the voltage issues may not be completely solved. In order to optimally utilize the available resources for effective voltage regulation, the centralized control concept is adopted. The central controller adjusts active power set points and/or utilizes reactive power support from the converters for solving the over-voltage problem completely. Reactive power support can be provided by both PV inverters and the battery converters. In this study we consider that the PV inverters connected to the network are responsible for providing reactive power support when requested by the utility.

The utility monitors the quality of the supply voltage by measuring the voltages at strategic nodes in the network. In the following those nodes are called critical nodes. The meters located at these nodes generate warnings when they detect sustained over-voltage. The central controller is triggered either by these warnings or an internal time based signal. When the central controller is triggered, it requests the following information from the network: voltage measurements of all three phases of the critical nodes, the availability of the BES units for voltage support via active power, the current and scheduled set points at the next time step of the BES units, current Q set points of the PV inverters and the active power measurements at the transformer. Having received this information, the central controller calculates the new set points of the BES converters and PV inverters that can maintain the voltages at critical nodes within the statutory limits and improve the power unbalance among the phases.

2.2.1. Active Power Adjustment

The new P set points of the battery converters are found by solving an optimization problem with the objective of minimizing the active power unbalance among the phases at the distribution transformer.

$$min \ (P_{TR,a} - P_{TR,b})^2 + (P_{TR,b} - P_{TR,c})^2 + (P_{TR,c} - P_{TR,a})^2 \ , \tag{14}$$

where active power in each phase of the distribution transformer is calculated using the power balance. Here the line losses are neglected.

$$P_{TR,ph} = P_{TR,ph}^{msrd} + \sum_{i=1}^{N_{bat}} P_{ph,i}^{msrd} - \sum_{i=1}^{N_{bat}} P_{ph,i} \tag{15}$$

The central controller adjusts the active power set points of the three phases by keeping the three phase sum at the value decided by the local controller. Here we consider a three phase converter that can control the power in each phase independently. This introduces the constraint

$$P_{bat,i} = \eta_{convB,i}(P_{a,i} + P_{b,i} + P_{c,i}) \tag{16}$$

The capacity constraint of the converters:

$$-P^{ac}_{conB,rated} \leq P_{ph,i} \leq P^{ac}_{conB,rated} \tag{17}$$

Power balancing among the three phases not only improves the voltage unbalance, but also can solve the over-voltage problems in certain cases when the grid is significantly unbalanced. For example, when the voltages of one or two phases are outside the limits while the voltage in the other phase(s) is within the limit. Therefore following voltage constraint is added. This is only active when the solution is feasible.

$$\left[\Delta V\right]_{min} \leq \left[\Delta V\right]_{req,P} \leq \left[\Delta V\right]_{max} \tag{18}$$

where $\left[\Delta V\right]_{req,P}$ is the required change in voltages at critical nodes with P support, and $\left[\Delta V\right]_{max}$ and $\left[\Delta V\right]_{min}$ are the maximum and minimum limit of the required voltage change at the critical node(s).

$$\left[\Delta V\right]_{req,P} = \left[\frac{\partial V}{\partial P}\right]\left[P\right] \tag{19}$$

where $\left[P\right]$ is the new P set points of the battery converters that needs to be calculated by solving the optimization problem.

$$\left[\Delta V\right]_{max} = \left[V\right]_{msrd} - \left[\frac{\partial V}{\partial P}\right]\left[P\right]_{msrd} - \left[\frac{\partial V}{\partial Q}\right]\left[Q\right]_{pv,msrd} - \left[V\right]_{min}$$
$$\left[\Delta V\right]_{min} = \left[V\right]_{msrd} - \left[\frac{\partial V}{\partial P}\right]\left[P\right]_{msrd} - \left[\frac{\partial V}{\partial Q}\right]\left[Q\right]_{pv,msrd} - \left[V\right]_{max} \tag{20}$$

where $\left[V\right]_{msrd}$ is the measured critical node voltages, $\left[P\right]_{msrd}$ and $\left[Q\right]_{pv,msrd}$ are the P set points of the BES converters and Q set points of the PV inverters when measurements are being taken. $\frac{\partial V}{\partial P}$ and $\frac{\partial V}{\partial Q}$ are the sensitivities of critical node voltages to the active and reactive power at the nodes where BES units and PV inverters are connected. V_{max} and V_{min} are the maximum and minimum limits of the allowable voltage range.

The expected critical node voltage with new P set points is given by

$$\left[V\right]_{exptd} = \left[V\right]_{msrd} - \left[\frac{\partial V}{\partial P}\right]\left[P\right]_{msrd} - \left[\frac{\partial V}{\partial Q}\right]\left[Q\right]_{pv,msrd} + \left[\Delta V\right]_{req,P} \tag{21}$$

2.3. Reactive Power Control of Converters

If active power balancing is not able to solve the over-voltage problem, the central controller utilizes the reactive power support from the PV inverters for voltage regulation. The optimal reactive power set points of the inverters, which results in minimum total reactive power supplied by the network are found by solving the optimization problem

$$min \sum_{i=1}^{N_{pv}} \sum_{ph}^{a,b,c} Q^2_{ph,i} \tag{22}$$

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subjected to the constraint

$$pf \geq pf_{min} \tag{23}$$

The reactive power support from the converters regulates the voltage amplitudes, but also affects the voltage angles. From the above optimization, we seek a solution with the objective of minimizing the total reactive power involved in the system. Consider a case where there are significant number of single phase PV systems and the network is significantly unbalanced. In such situation, the optimum solution would be unequal reactive power support from the three phases (sum of the reactive power support provided by the single phase inverters connected to each phase will be different). Even though this corrects the voltage amplitudes, it can worsen the voltage unbalance due to the unequal effect on the voltage angles in the three phases. Therefore, the difference of the reactive power sum between the phases are constrained.

$$|\%\Delta Q_{total,ph}| < \varepsilon$$

where

$$
\begin{aligned}
\%\Delta Q_{total,ph} =& \frac{Q_{total,ph} - Q_{total,avg}}{Q_{total,avg}} \times 100 \\
Q_{total,avg} =& \frac{Q_{total,a} + Q_{total,b} + Q_{total,c}}{3}
\end{aligned}
\tag{24}
$$

$$Q_{total,a} = \sum_i Q_{a,i}, \; Q_{total,b} = \sum_i Q_{b,i}, \; Q_{total,c} = \sum_i Q_{c,i} \tag{25}$$

The voltage constraint

$$\left[\Delta V\right]_{min} \leq \left[\Delta V\right]_{req,Q} \leq \left[\Delta V\right]_{max} \tag{26}$$

where

$$
\begin{aligned}
\left[\Delta V\right]_{max} =& \left[V\right]_{exptd} - \left[V\right]_{min} \\
\left[\Delta V\right]_{min} =& \left[V\right]_{exptd} - \left[V\right]_{max}
\end{aligned}
\tag{27}
$$

$$\left[\Delta V\right]_{req,Q} = \left[\frac{\partial V}{\partial Q}\right] \left[Q\right]_{pv}, \tag{28}$$

$\left[Q\right]_{pv}$ is the new Q set points of the PV inverters.

The central control algorithm was developed in Matlab. The non-linear Matlab solver "fmincon" was used to solve the optimization problem described above.

3. Case Study

3.1. Distribution Network

The proposed method is tested using the modified IEEE European low voltage test feeder shown in Figure 2. We considered 56 customers located at the nodes shown in the figure. Among these 56 customers,
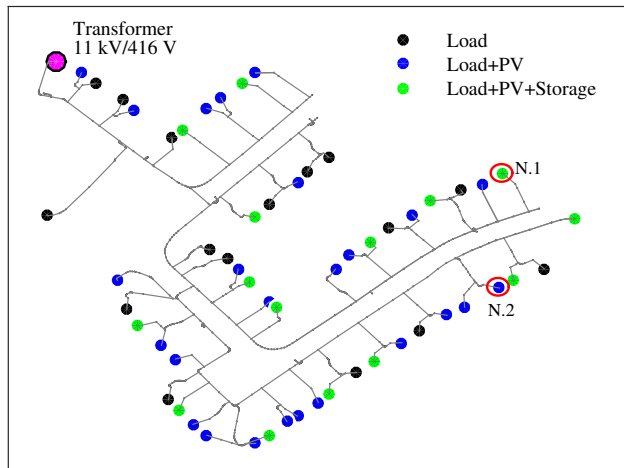
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Figure 2: Single phase layout of the low voltage network, a modified IEEE European low voltage test feeder.

we assume 40 customers own 4 kWp rooftop PV systems. The daily domestic electric load profiles of a typical European household were obtained from IEA/ECBCS Annex 42 [31]. The loads were represented by 56 different load profiles. The load power factor was set to 0.98. The secondary side fixed tap setting of the transformer was set to 1.04 pu to prevent the under-voltage problems. 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 [32, 33]. The time resolution of both of these data sets is 1 minute. We considered 15 customers who own PV systems to have BES units. The customers who own BES units are indicated in Figure 2. All these BES units are identical and Table 1 lists the characteristics of these systems.

Table 1: Parameters of the BES system.

Parameter	Value
Nominal capacity	9 kWh/ 170 Ah
$\eta_{chrg,i}, \eta_{dischrg,i}$	95%
$\eta_{conB,i}$	95%
E_o	52.0 V
R_{bat}	0.025 Ω
A, B, K	4.078 V, 0.3214 Ah^{-1}, 0.0024 V
SOC_{min}, SOC_{max}	20%, 100%
$P^{dc}_{conB,rated}$	4.5 kW
battery degradation cost	0.4 \$/kWh
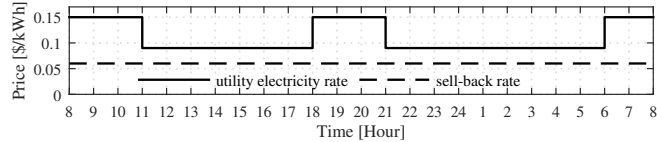
Figure 3: Electricity tariff.

3.2. Simulation Study

The local scheduling algorithm and the central control algorithm were implemented in Matlab. The optimization problem in the local scheduling algorithm was solved using dynamic programming [34], whereas the optimization problems in centralized control of BES units and the reactive power control of converters were solved using the Matlab non-linear solver "fmincon". The distribution network was modelled in openDSS [35] to run the power flow at each time step. The control set points calculated from the Matlab code were sent to openDSS at each time step and the results obtained from running the power flow were then sent back to Matlab for calculating the set points at the next time step.

It is assumed that the hourly forecasts of load and PV production over a 24 hour time period are available for all the households with PV and BES system. Two nodes, N.1 and N.2 indicated in Figure 2, were identified as the critical nodes from the off-line load flow. The critical period was set to 10:00-15:00h. The considered electricity tariffs are shown in Figure 3. The optimization was run for each household individually at the start of the planning horizon, for scheduling the BES for the next 24 hours. The start of the planning horizon was set to 08:00h. From the optimization, the hourly dc side power set points of the BES systems and the SOC variations were calculated. The results from the optimization are the hourly average set points of the BES units. However, power flow is performed with 1 minute time resolution. Short term fluctuations of the load and PV cannot be detected in hourly averages. Therefore, an error correction algorithm was included to take care of the short term fluctuations. The error correction algorithm avoids unnecessary charging from the grid, discharging to the grid, and make necessary adjustments to follow the expected SOC variation. Further, a peak shaving algorithm was included to restrict the power taken from the grid to 3 kW.

The time setting of the internal time based triggering of the central controller was set to 30 minutes. That means the central voltage control scheme is triggered by an internal signal if the central controller has not been triggered over the last 30 minutes. The limit of the unbalance among the sum of reactive power support provided by the inverters in each phase was set to 10%. The voltage profiles have been compared with the base case voltage profiles, that would have occurred without any BES units or reactive power support from the PV inverters.

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4. Results and Discussion

Figure 4 illustrates the sharing of power among the different elements of the residential energy systems and Figure 5 shows the SOC variation of the BES units. All the BES units start charging at the beginning of the critical period, and reach the fully charged state by the end of the critical period. The local controllers ensure that the BES units are being charged during the whole critical period. This reduces the risk of over-voltages over the critical period. The BES units discharge mostly during the high tariff period (18:00-21:00h). The BES supplies the local demand during the low tariff period when the local load during the high tariff period is lower than the stored energy in the battery. Further, the power drawn from the grid is limited to 3 kW by the peak shaving algorithm. Discharging of the battery before it reaches 100% SOC is not allowed to prolong the battery lifetime. Therefore, the BES perform one cycle over a 24 hour interval.

When charging, BES charges at highest rate at the solar noon resulting lowest power injection to the grid at solar noon. Power injection to the grid is controlled in a way such that the grid injection is inversely proportional to the excess power available from the PV system. As the PV systems without BES inject the highest amount of power at solar noon, this charging strategy flatten out the load at the transformer during the critical period. Figure 6 illustrates the effect of this charging strategy on the transformer load. As can be seen from the figure, the peak is clipped at about 25 kW over the critical period.

Figure 7 shows the voltage variations and the voltage unbalance rates (the ratio between the negative sequence voltage and the positive sequence voltage) at the two critical nodes without BES units. According to the European standard EN50160, 10-minute average values of the supply voltage should be within the range of ±10% of the nominal voltage. As shown in the figure, the voltages go above the limit during the critical period. Further, voltages are significantly unbalanced even though the voltage unbalance rate is below the limit of 2%. The voltage variations and the voltage unbalance rate with the proposed distributed control approach are shown in Figure 8. With this method, the over-voltage issues are completely mitigated. Further, the voltage unbalance during the time when the storage is charging has also improved.

The sum of the active power transferred via each phase to the BES units are shown in Fig 9. As the BES units start charging at 10:00h, the central controller adjusts the active power among the phases but the three phase sum of each BES unit remains unchanged. The voltages are significantly unbalanced at that time. Therefore, active power coordination among the three phases not only improves the voltage unbalance but also effectively solves the over-voltage problem. As the voltage of phase-[A] is the highest among the three phases, the highest amount of power is transferred to the BES units via phase-[A]. Power adjustment among the phases is not done in the evening as the voltages are within the acceptable range at that times. The local controller maintains the same power sharing ratio among the phases ($P_{a,i} : P_{b,i} : P_{c,i}$) over time even though the dc side set point changes. This ratio is determined based on the last set points received by the central controller. It is either changed by a new set point from the central controller or a change in
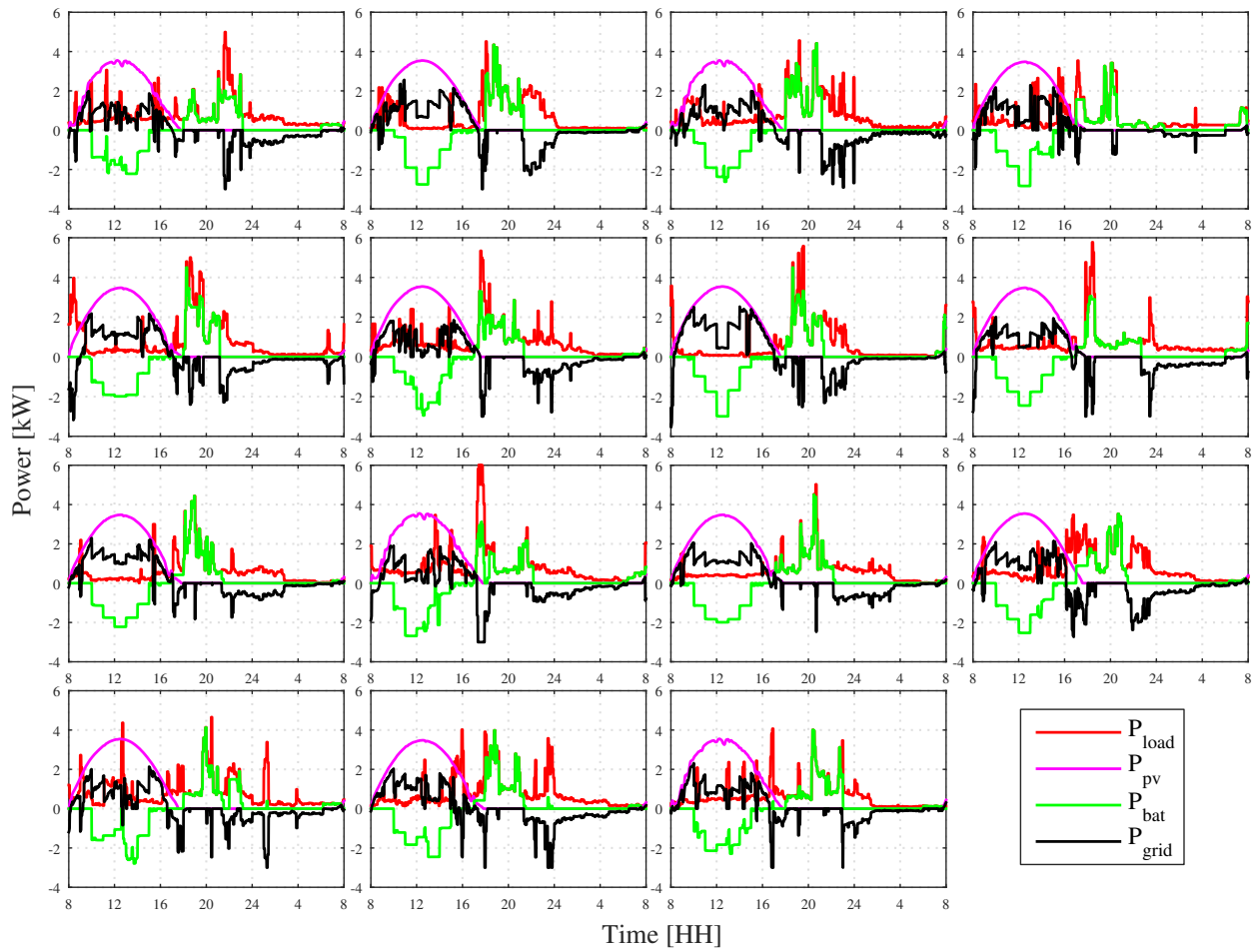
Figure 4: Performance of the 15 residential energy systems with the proposed distributed control scheme.
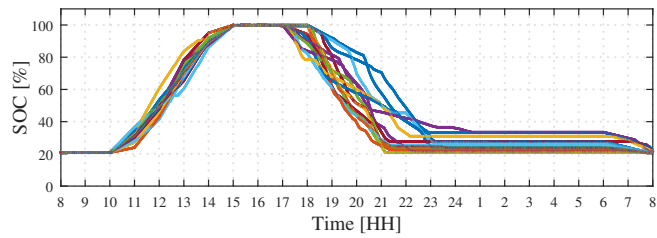

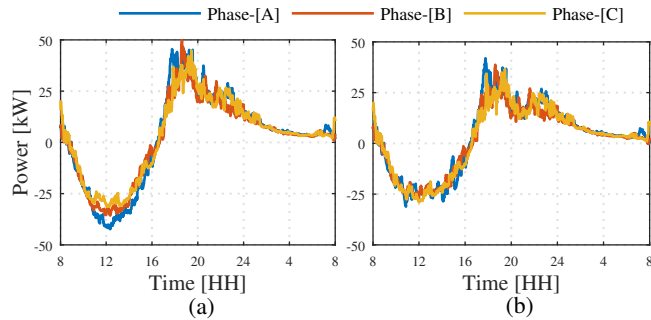Figure 5: State of charge variation of the battery banks.

Figure 6: Active load on the transformer (a) without BES units (b) with BES units.

operation of the battery from charging to discharging. For the simulated case the over-voltage problem is solved without using any reactive power support from the PV inverters.

In order to illustrate the performance of the voltage control via reactive power support, we simulate the same case by deactivating the active power adjustment algorithm. In that case, the charging power of the BES units are shared equally among the phases. Figure 10 shows the required reactive power support from the PV inverters for maintaining the critical node voltages within the statutory limits. As shown in the figure, the total reactive power support required is minimized with unequal reactive power support from the inverters located at different nodes. The inverters having lowest electrical distance to the critical nodes provide higher reactive power support. Some of the inverters were discarded because of the high electrical distance from their location to the critical node. The reactive power support from those inverters does not improve the critical node voltage significantly. Figure 11 shows the resulting reactive load on the transformer. A significant reactive power support from the inverters are required for solving the over-voltage problem. This is because of the high R/X ratio of the distribution grids. The active power adjustment strategy was able to reduce this required reactive power support to zero. However, when the active power adjustment is not able to solve the over-voltage problem, reactive power support from the converters has to be used.

In the proposed distributed control method, the ac side P set points of the converters are adjusted without affecting the battery set points on the dc side. Therefore, the SOC variation of the battery is not affected. The central controller does not change the net three phase power. Therefore the electricity cost of the customer is not affected, except for a marginal impact on the total system efficiency. The proposed centralized control does not affect neither the battery cycling nor the customer's electricity bill, but still helps the utility to improve the voltage quality issues related to supply voltage variations and voltage unbalance. Utilization of customer owned devices will reduce the need for the utility to invest in larger energy storage systems in the low voltage network. Instead, proper incentive schemes can be implemented for residential storage units. 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.
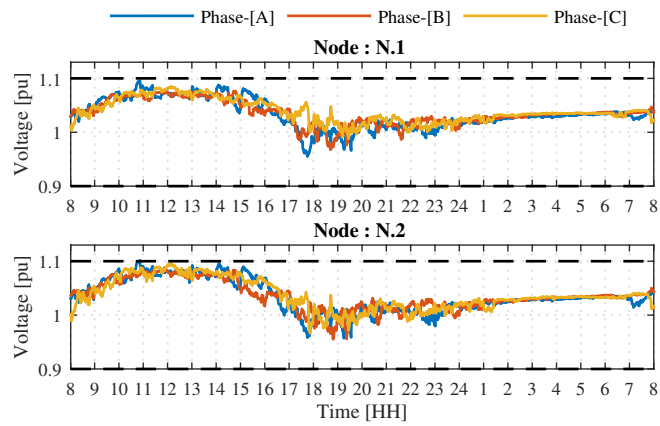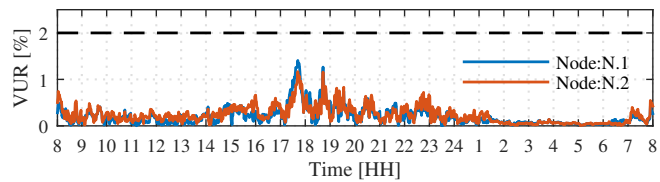
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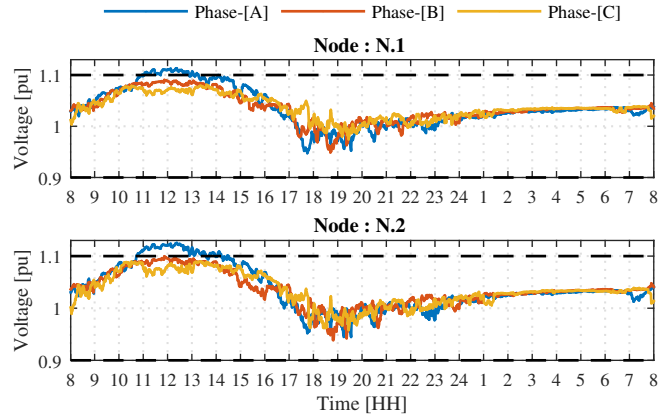
(a) Supply voltage variations.
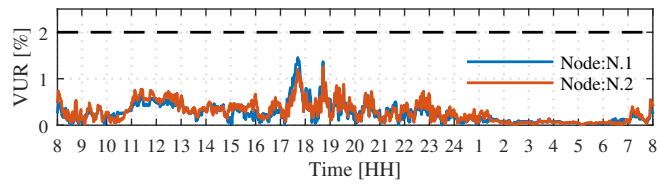
(b) Voltage unbalance rate.

Figure 7: Quality of the voltage at the critical nodes when there are no BES units in the system.

(a) Supply voltage variations.

(b) Voltage unbalance rate.

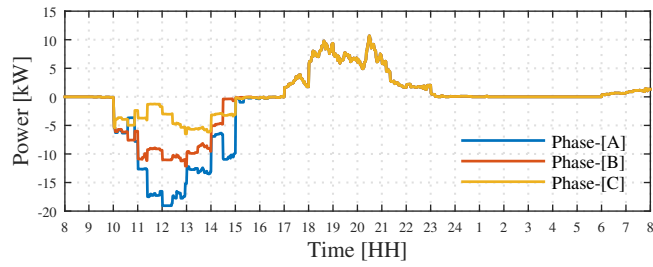Figure 8: Quality of the voltage at the critical nodes with distributed control of BES units.

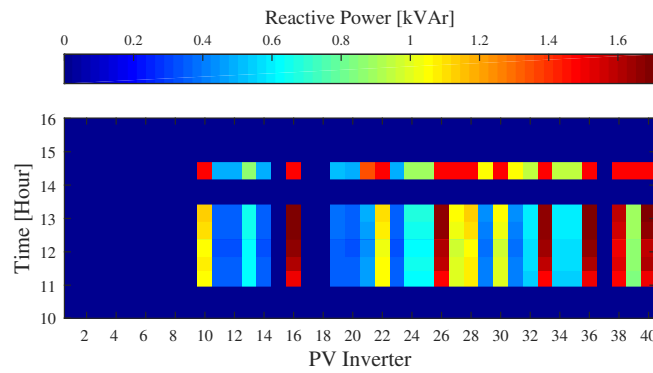Figure 9: Total sum of active power supplied to/from the BES units via three phases.

Figure 10: Reactive power support provided by the PV inverters. Results are only shown for the period from 10:00-16:00h, because outside this period the reactive power support provided by all the inverters are zero.
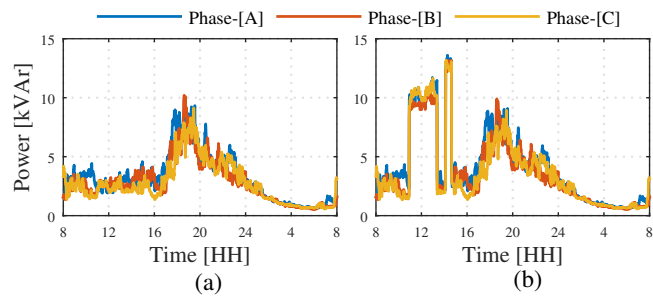

Figure 11: Reactive load on the transformer (a) without reactive power support from the PV inverters (b) with reactive power support from the PV inverters.

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5. Conclusion

The distributed control scheme for residential BES units coupled with PV systems presented in this paper is able to help the utility to solve the over-voltage issues caused by high PV penetration. As the optimization problems are solved locally, the customers can decide the main usage of their storage. It could be increasing the self-consumption or increasing the savings in the electricity bill. Whatever the main purpose is, the storage is constrained to charge only during the critical period whenever the excess energy available from the PV system during this period is sufficient to fully charge the BES. Further, the local controller ensures that the storage does not reach 100% SOC before the critical period ends. This lowers the risk of over-voltages over the critical period. The central controller ensures that the voltages are maintained within the limits when the locally decided active power set points are not sufficient to solve the voltage problems. The central controller either adjusts the active power set points among the three phases and/or utilizes reactive power. The charging/discharging schedule of the battery is not affected by the involvement of the central controller, because the central controller only adjusts the active power set points among the three phases by keeping three phase sum fixed at the value decided by the local controller. Therefore, the customers' primary objectives for using BES are not affected, except for a marginal impact on the total system efficiency. As primary decisions are taken locally, there is no requirement of frequent information sharing between the central controller and the local controllers. This greatly reduces the communication burden and avoids the need for the utility to solve a complex optimization problem.

Acknowledgment

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