Control Strategies for Residential Battery Energy Storage Systems Coupled With PV Systems

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***Abstract*—This paper presents, and compares the performances of four control strategies for residential battery energy storages coupled with photovoltaic (PV) energy systems. The control strategies are: 1) rule based control, 2) optimization based control without utility constraints, 3) optimization based control with utility constraints, and 4) distributed control. The first two methods only concern about fulfilling the battery owner's requirements. In the other two methods, the utility is involved in controlling the operation of the batteries into certain extent. Therefore, the batteries intentionally contribute to lower the over-voltage risks while fulfilling the customers' needs. From the simulations it is shown that a significant reduction in reactive power support required from the converters can be achieved with optimization based control with utility constraints and distributed control schemes. Distributed control scheme shows best performance in terms of reduction in reactive power requirement, reduction in line losses and decreasing voltage unbalance. All these can be realized with little impact on the battery owner's desired objectives.**

I. INTRODUCTION

The number of installations of small scale rooftop solar photovoltaic (PV) systems are increasing dramatically worldwide. In some areas it can be observed that the rooftop PV systems are geographically concentrated. This has created over-voltage issues in the period around the solar noon due to reverse power flow caused by high production and the low load condition in this period [1], [2]. Reactive power support from the PV inverters is currently being used in such distribution grids for solving the over-voltage problems [3], [4]. Energy storage systems such as batteries have recently gained attraction by the residential customers as the cost of such systems are becoming affordable. Due to increasing electricity price and decreasing feed-in-tariff, residential customers are more concerned about increasing self-consumption rather than selling excess energy to the grid. Residential PV systems coupled with storage units 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. Proper charging of storage greatly reduces the reactive power requirement from the PV inverters for regulating the node voltages.

References [5] and [6] present control strategies for residential energy systems with PV and batteries, based on model predictive control (MPC). MPC relies on prediction of load and generation over a certain time horizon into the future and find the optimum schedule of the battery over that period which can minimize a desired objective. Proposed control strategies concern on minimizing the aggregate impact of the residential energy systems on the distribution grid. Reference [7] proposes a method for voltage regulation in distribution feeders using residential energy storage units. In the proposed method charging and discharging rates of the batteries are a function of the voltage at the point of common coupling.

Utility friendly charging strategies might adversely affect the primary need of the storage owner. Therefore, battery owners might hesitate to let the utility to influence the operation of their storage, unless reasonable incentives are given. It is required to develop proper charging/discharging strategies, which can help the utility to solve over-voltage problems with little effect on the owner's main requirements. This way the utility can also get optimal benefits from the residential storage units. This paper presents four control strategies for residential battery energy storages (BES) coupled with PV systems. Among the four control strategies presented, two strategies only concern about fulfilling the BES owner's objectives while other two intentionally contribute to lower the over-voltage risks. A compression of the performances of these four methods is presented.

II. METHOD

The residential energy system consists of an inelastic load, a PV system and a BES unit. The discrete representation of the system for the i^{th} user at discrete time t is

$$\begin{aligned} \text{Discharge: } P_{pv,i}(t) =& P_{load,i}(t) + P_{grid,i}(t) - \eta_{conv,i}\ P_{bat,i}(t) \\ \text{SOC}_i(t) =& \text{SOC}_i(t-1) - P_{bat,i}(t)\Delta t/\eta_{bat,i} \\ \text{Charge: } P_{pv,i}(t) =& P_{load,i}(t) + P_{grid,i}(t) - P_{bat,i}(t)/\eta_{conv,i} \\ \text{SOC}_i(t) =& \text{SOC}_i(t-1) - \eta_{bat,i}\ P_{bat,i}(t)\ \Delta t \end{aligned} \tag{1}$$

where $P_{pv,i}$ is the power production from the PV system, $P_{load,i}$ is the local demand, $P_{bat,i}$ is charging/discharging power of the battery (charging is considered negative in sign convention) and $P_{grid,i}$ is the power supplied by/to the grid. These are the average values over a Δt time interval. $\eta_{conv,i}$ and $\eta_{bat,i}$ are the efficiencies of the battery converter and the battery respectively. SOC is the state of charge of the battery.

The charging/discharging power of the battery is constrained to the dc side rated capacity of the battery converter ($P^{dc}_{conB,rated}$) and the SOC is maintained within certain limits.

$$-P^{dc}_{conB,rated} \leq P_{bat,i}(t) \leq P^{dc}_{conB,rated} \tag{2}$$

$$SOC_{min} \leq SOC_i(t) \leq SOC_{max} \tag{3}$$

The control strategies presented in this paper are, 1) rule based control, 2) optimization based control without utility constraints, 3) optimization based control with utility constraints, and 4) distributed control. In rule based control method, charging/discharging power set points are decided locally in real-time based on certain rules. In other three methods, 24-hour ahead power set points are calculated by each system individually using an optimization algorithm. The objective function is locally decided, however requirement from the utility concerning over-voltage issue is included in third and fourth control methods. In optimization based control without utility constraints method, the objective is to satisfy solely the BES owner's needs. The optimization is based on the forecasts of the load and the PV production over the considered planning horizon. The difference between the optimization based control with utility constraints and the distributed control methods is that, in optimization based control with utility constraints method, power set points are decided locally while in distributed control the already decided set points could be adjusted by a central entity if needed. All four control strategies use reactive power support from the PV inverters when charging of storage is not sufficient for solving the over-voltage problem completely.

A. *Rule Based Local Control Method*

The objective is to store excess energy available from the PV system and use that later to supply the local load when there is no production from the PV system. The battery is charged when the power production from the PV system exceeds the local demand. The charging continues until the battery is fully charged. If there is excess energy available after fully charging the battery, that is injected to the grid. The battery starts to discharge in the evening for supplying the local load.

B. *Optimization Based Control Without Utility Constraints*

The objective function is chosen to maximize the economic benefits for the BES owner assuming electricity selling price is lower than the buying price. If the selling price is higher than the buying price it makes no sense to install a battery unless the customer is eager to have storage in his premises. In that case the objective function can be changed to maximizing the self-consumption. The optimization problem is formulated as follows for the i^{th} user.

$$min \sum_{t=1}^{T} -\Big\{C_i(t) - 2\alpha \, \mathrm{BDC}_{cyl,i}(t)\Big\}, \tag{4}$$

where $C_i(t)$ term represents the cost of electricity, which is reflected in the electricity bill. T is the total samples per planning horizon. $\mathrm{BDC}_{cyl,i}(t)$ is the battery degradation cost due to cycling and α is a control parameter.

Battery degradation cost is calculated as follows.

$$\mathrm{BDC}_{cyl,i}(t) = \gamma_{bat,cyl} \, |P_{bat,i}(t)| \Delta t$$

where $\gamma_{bat,cyl}$ is the battery degradation cost per kWh of energy charged/discharged from the battery due to cycling.

$$\gamma_{bat,cyl} = \frac{\mathrm{BC}}{\mathrm{E}_{bat,ltpt}},$$

where BC is the installation and maintenance cost of the BES system over its lifetime and $\mathrm{E}_{bat,ltpt}$ is the lifetime throughput of the battery.

Battery degradation cost is included in the objective function in order to avoid charging from the grid and discharging stored energy into the grid. Charging from the grid is only economical if the savings made by consuming the stored energy that is originally bought from the grid is higher than the cost of buying that energy from the grid plus the battery degradation cost during charging and discharging that energy. Similarly, discharging energy into the grid is only economical if the earnings made by selling stored energy to the grid is higher than the earnings that could have made by selling that energy directly to the grid without storing in the battery plus battery degradation cost for cycling that energy.

The control parameter α is set to 1 if the battery is charging from the grid or discharging to the grid. It is set to zero otherwise due to the reason mentioned before. Battery degradation cost due to charging from the PV system and discharging for supplying the local load is disregarded. That is because the purpose of having the battery at the first place is to store the excess energy from the PV system for supplying the local load.

The cost of electricity of the i^{th} user is given by

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

where γ_{FiT} and γ_{buy} are the sell back price and the buying price of the electricity.

C. *Optimization Based Control With Utility Constraints*

In optimization based control with utility constraints method, additional requirement concerning the over-voltage issue is added in to the optimization problem. The over voltage issues mostly occur during the period around the solar noon. In the following this period is called the critical period. The battery is forced to charge only during this period when the excess energy available from the PV system during this period is sufficient to fully charge the battery. This is achieved by setting a limit on the power that can be injected to the grid during the critical period ($\Delta T_{critical}$).

$$P_{grid,i}(t) \leq P_{grid,max} \quad : t \in \Delta T_{critical} \tag{5}$$

Initially $P_{grid,max}$ is set to zero, which means that all the excess power available from the PV system during the critical period is 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, this limit is increased until a feasible solution is found. The optimization problem is solved using dynamic programming.

D. *Distributed Control Method*

In distributed control method, the dc side charging/ discharging set points of the battery is found by solving the same optimization problem as in the optimization based control with utility constraints method. However, a central controller can adjust these set points in real time when needed. In this study we consider storage units, which are connected to the grid via three phase converters. It is assumed that this converter can control power in each phase independently. The central controller can adjust power in each phase, however the three phase sum or the dc side power set point should not be changed. Distribution grids are usually unbalanced into some extent due to single phase loads and generators. Therefore, power adjustment among the phases not only improves this power unbalance but also can solve over-voltage issues in cases when the voltage of one/two phase(s) are outside the statutory limit while voltages in other phase(s) is within the limit.

The quality of the voltage is monitored by meters located at strategic nodes in the network. In the following these nodes are called critical nodes. The central controller is notified by these meters, if they detect sustained over-voltage. When the central controller receives a warning it calculates the required adjustments at each storage unit that can minimize the power unbalance seen by the transformer.

$$min\ (P_{TR,a}-P_{TR,b})^2+(P_{TR,b}-P_{TR,c})^2+(P_{TR,c}-P_{TR,a})^2\ , \tag{6}$$

where $P_{TR,ph}, ph \in \{a,b,c\}$ is the active load on the transformer. The active power in each phase of the transformer is calculated using the power balance. Here, the line losses are neglected.

$$P_{TR,ph} = P_{TR,ph}^{msrd} + \sum_{i=1}^{N_{bat}} P_{ph,i}^{msrd} - \sum_{i=1}^{N_{bat}} P_{ph,i} \tag{7}$$

where $P_{TR,ph}^{msrd}$ is the measured active load of the transformer, $P_{ph,i}^{msrd}$ is the measured ac side active power set point of the battery converter, $P_{ph,i}$ is the new ac side active power set point of the battery converter and N_{bat} is the total number of BES units in the system.

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. This introduces the constraint

$$P_{bat,i} = \eta_{convB,i}(P_{a,i} + P_{b,i} + P_{c,i}) \tag{8}$$

where $\eta_{convB,i}$ is the efficiency of the battery converter.

The capacity constraint of the converters:

$$-P_{conB,rated}^{ac} \leq P_{ph,i} \leq P_{conB,rated}^{ac} \tag{9}$$

Moreover, the new set points should be able to maintain the critical node voltages within the statutory limits, if feasible.

$$[\Delta V]_{min} \leq [\Delta V]_{req,P} \leq [\Delta V]_{max} \tag{10}$$

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

$$[\Delta V]_{req,P} = \left[\frac{\partial V}{\partial P}\right][P] \tag{11}$$

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

$$\begin{aligned}[\Delta V]_{max} &= [V]_{msrd} - \left[\frac{\partial V}{\partial P}\right][P]_{msrd} - \left[\frac{\partial V}{\partial Q}\right][Q]_{pv,msrd} \\ &\quad - [V]_{min} \\ [\Delta V]_{min} &= [V]_{msrd} - \left[\frac{\partial V}{\partial P}\right][P]_{msrd} - \left[\frac{\partial V}{\partial Q}\right][Q]_{pv,msrd} \\ &\quad - [V]_{max}\end{aligned} \tag{12}$$

where $[V]_{msrd}$ is the measured critical node voltages, $[P]_{msrd}$ and $[Q]_{pv,msrd}$ 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 [8], [9]. 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

$$\begin{aligned}[V]_{exptd} = [V]_{msrd} - \left[\frac{\partial V}{\partial P}\right][P]_{msrd} - \left[\frac{\partial V}{\partial Q}\right][Q]_{pv,msrd} \\ + [\Delta V]_{req,P}\end{aligned} \tag{13}$$

E. Reactive Power Control of Converters

If charging of storage units is not sufficient to maintain the voltages within the statutory limits, reactive power support from the PV inverters are utilized. The meters located at critical nodes send requests to the PV inverters asking to decrease the power factor when they detect sustained over-voltage. When the 10-minute moving average of the critical node voltage drops below a certain safe limit the meter again send a request to release the reactive power support by increasing the power factor. This method need neither information about the network nor the PV inverters. It only needs one way communication between the meters located at the critical nodes and the PV inverters. Therefore, this method is used in corporation with rule based control, and optimization based control with and without utility constraints for solving over-voltages completely.

In distributed control, the network model is known and two way communication is needed. Therefore, the required reactive power from the PV inverters are calculated in real-time by the central controller by solving an optimization problem with the objective of minimizing the total reactive power requirement. 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

$$min \sum_{i=1}^{N_{pv}} \sum_{ph}^{a,b,c} Q_{ph,i}^2 \tag{14}$$

subjected to the constraint

$$pf \geq pf_{min} \tag{15}$$

where $Q_{ph,i}$ is the reactive power set point of the converter, N_{pv} is the total number of PV inverters and pf is the power factor of the PV inverter.

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 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

$$\%\Delta Q_{total,ph} = \frac{Q_{total,ph} - Q_{total,avg}}{Q_{total,avg}} \times 100$$

$$Q_{total,avg} = \frac{Q_{total,a} + Q_{total,b} + Q_{total,c}}{3}$$

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

The voltage constraint

$$[\Delta V]_{min} \leq [\Delta V]_{req,Q} \leq [\Delta V]_{max} \tag{16}$$

where

$$\begin{aligned} [\Delta V]_{max} &= [V]_{exptd} - [V]_{min} \\ [\Delta V]_{min} &= [V]_{exptd} - [V]_{max} \end{aligned} \tag{17}$$

$$[\Delta V]_{req,Q} = \left[\frac{\partial V}{\partial Q}\right][Q]_{pv}, \tag{18}$$

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

III. CASE STUDY

Modified IEEE European low voltage test feeder shown in Fig. 1 is used for testing and comparing the performance of the above mentioned control strategies. It is considered that this network supply 56 customers, among them 28 customers have only PV systems, and 12 customers have both PV and BES units. The load and the PV generators were represented by load and PV production profiles measured by smart meters installed in a Italian low voltage network located in the city Brescia [10]. Identical PV and BES systems were considered. The capacity of a PV system is 3 kWp and the battery ratings are 9 kWh/4.5 kVAr with 80% maximum depth of discharge. Charging/discharging efficiencies of the batteries are 95%. The considered electricity tariff is shown in Fig. 2. The battery degradation cost $(\gamma_{bat,cyc})$ is 0.2 \$/kWh. The two nodes, N.1 and N.2 indicated in the figure were identified as the critical nodes from the off-line power flow.

IV. RESULTS

Time period of 24 hours starting from 08:00 a.m. in the morning was chosen as the planning horizon. Hourly average forecasts ($\Delta t = 1$ hour) of the load and PV productions were used for calculating the optimum schedule of the battery. Then, the power flow simulations were performed with 1 minute time resolution along with the proposed on-line active and reactive power support methods. Hourly averages cannot represent the short term fluctuations (in this case 1 minute) of the load and the production. Therefore, the following real-time mechanism is adopted for compensating the short term fluctuations.

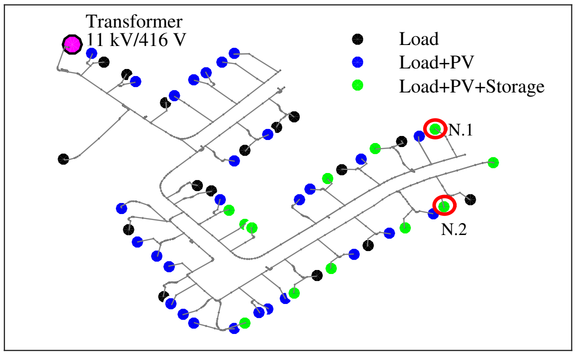

Fig. 1. Single phase layout of the low voltage network, modified IEEE European low voltage test feeder.

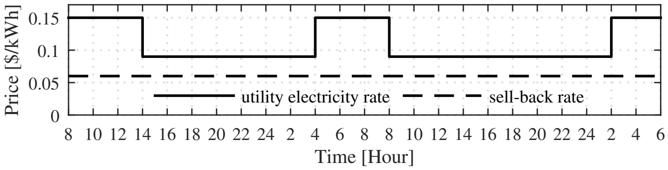

Fig. 2. Electricity tariffs.

1: P_{grid} set points were calculated from the optimization.
2: The battery set points, that can maintain P_{grid} at desired set points were re-calculated in real-time operation.
3: The new battery set points are subjected to the conditions:
    – Short term fluctuations of the load and PV should not results charging the battery from the grid at any instant of time when charging from the grid is not recommended by the optimization.
    – In order to prolong the battery cycle life, it is discharged only after it reaches maximum possible SOC over the planning horizon. Any fluctuation of the net load that can result discharging of the battery before it reaches to maximum SOC is compensated by the grid.

Fig. 3 shows the voltage profile and the voltage unbalance rate (the ratio between the negative sequence voltage and the positive sequence voltage) at one of the critical node (N.2) without any BES units. As can be observed in the figure, during the period from 10:00-14:00h the voltages in phase-[A] go above the maximum limit of 1.1 pu. Further, the voltages are significantly unbalanced due to single phase loads and generators even though the voltage unbalance rate is below the limit of 2%. The voltage profiles with the proposed control strategies are shown in Fig. 4. All four control strategies are successfully able to maintain the critical node voltages within the statutory limits. Fig. 5 shows the required reactive power support from the PV inverters with different battery control strategies. As the figure shows, highest amount of reactive power support is needed when batteries are controlled with rule based method. Least amount of reactive power support is needed with distributed control scheme. In this case, it is zero. Active power adjustment among the phases is sufficient for maintaining the voltage profile within the limits for this case. Because the voltage in only one phase goes above the maximum limit.

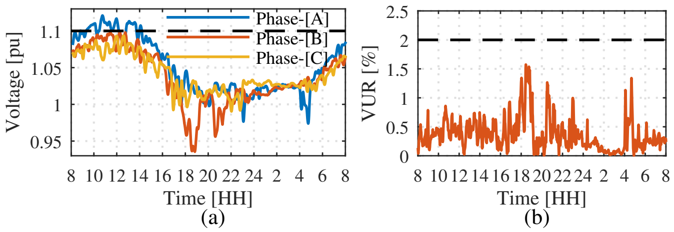

Fig. 3. Quality of the voltage at the critical node (N.2) without BES units in the system (a) supply voltage variation, (b) Voltage unbalance rate.

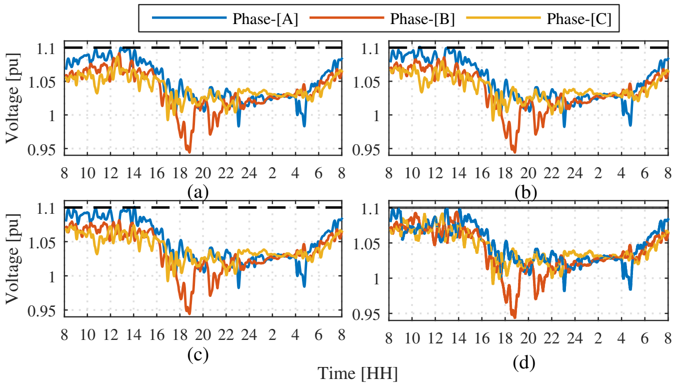

Fig. 4. Supply voltage variation at the critical node (N.2) with BES units, (a) rule based control, (b) optimization based control without utility constraints, (c) optimization based control with utility constraints, (d) distributed control.

The behaviour of one of the system among 12 customers with BES are shown in Fig. 6. It shows the load profile, PV production profile, battery charging/discharging profile and the power supplied by/to the grid. The resolution of the data is 1 minute. The local controller maintains P_{grid} at the set points calculated by the optimization algorithm. However, short-term fluctuations of net-load can result discharging the battery when it is supposed to charge, in order to maintain the P_{grid} at the set points calculated by the optimization. Short-term fluctuations can also result charging from the grid even though it is not supposed to charge from the grid. In this study, short charge/discharge cycles of the battery is avoided in order to prolong the battery life. The battery starts to discharge only after it reaches to the maximum possible SOC over the planning horizon. Therefore, the grid acts as the sink for absorbing the fluctuations. As a result, sometimes P_{grid} set points are modified as shown in the figure. In the rule based method, the battery charges whenever there is excess energy available from the PV system. Charging of the batteries has lowered the voltage profile below the maximum limit, therefore, little reactive power support is needed from the PV inverters. Half of the BES units reaches 100% SOC by 12:30h (not shown), therefore reduces the possibility of diverting the excess power into the batteries without injecting into the grid. This results utilizing reactive power support from the PV inverters for solving over-voltage issues. In the optimization based method without utility constraints, there is no constraint on the time the battery should charge. Therefore, the battery can be charged at any time when ever there is excess energy. Only concern is, charging the battery so that later it can be used to supply the local load and/or injecting to the grid. As a results the batteries can be charging at any time. In the results shown, the battery starts charging at 08:00h, continue charging at certain power levels while injecting part of the excess energy to the grid. It reaches 100% SOC by 14:00h. In optimization based method with utility constraints, power injection into the grid is constrained during the critical period. Therefore, the battery has to be charged during the critical period as shown in the Fig. 6(c). This results injecting less power into the grid during the most critical period compared to the optimization based without utility constraints method. Therefore, less reactive power is needed for completely solving the over-voltage problem. There is no difference in the battery or grid set points with distributed control method and the optimization based with utility constraints method. Here the assumption is that the customer is billed for the net three phase power. Then only power adjustment among the phases does not affect the electricity bill.

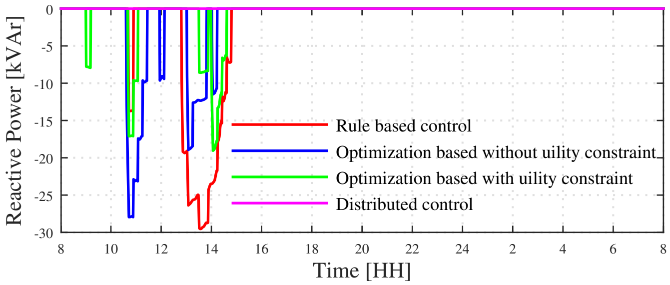

Fig. 5. Total reactive power support provided by the PV inverters.

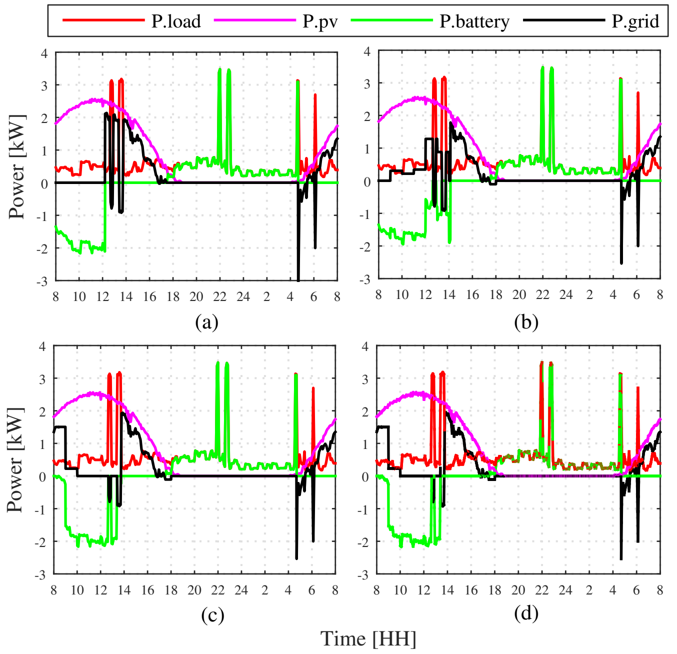

Fig. 6. Power flow (a) rule based control, (b) optimization based control without utility constraints, (c) optimization based control with utility constraints, (d) distributed control.

In order to evaluate the impact of different control strategies on the customer's electricity bill and quantify the benefits for the utility, simulations were carried out for a period about a month. First, simulations were performed over a year without

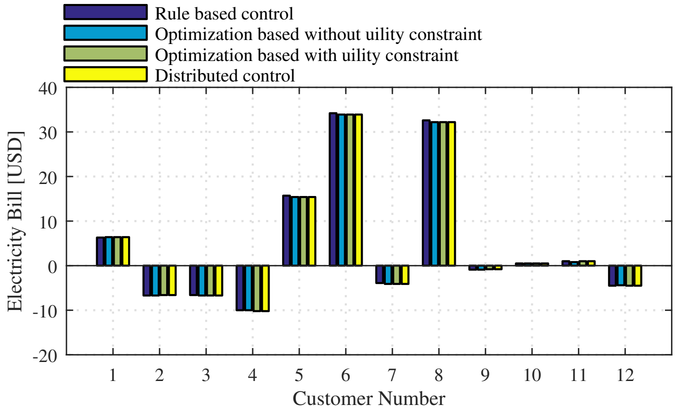

Fig. 7. Electricity bill of the customers having BES (negative values represent net earnings).

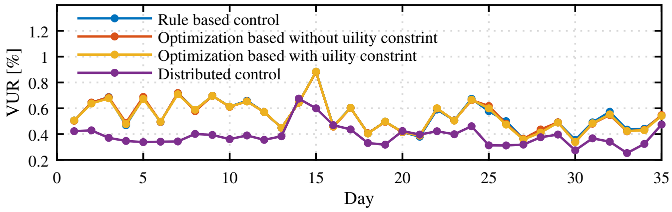

Fig. 8. Average voltage unbalance rate during critical periods at critical node-N.2.

BES units to identify the month(s) experiencing notable over-voltage issues. From this simulation, the period from 1^{st} June to 5^{th} July was identified and chosen for simulating with the batteries. The electricity bills of the customers over this month were calculated. Fig. 7 shows the results for different control strategies. Table I lists the total required reactive power support from the converters and the power loss over the considered period. From these results, it can be observed that the difference of the electricity bill of different control strategies is so little, hence can be ignored. However, the reduction of reactive power support required when compared with the methods which do not account the voltage quality of the grid is significant. Further, loss has also reduced. The distributed control method shows the best performance in terms of reduction in reactive power required and the power loss. Because it accounts the state of the whole network when calculating the required adjustments among the three phases of batteries' set points and reactive power set points of the PV inverters. The average voltage unbalance rate over the critical period during the simulated days is shown in Fig. 8. As can be seen in the figure, the voltage unbalance rate can also be improved with the distributed control scheme. From the results, it is evident that the utility friendly charging strategies do not adversely affect the battery owner's local objectives.

V. CONCLUSION

The comparison of four different control strategies reveals that the residential storage units can effectively contribute to solve possible over-voltage issues created by high PV penetration if charging/discharging schedule is managed properly. Additional requirements concerning the voltage quality of the grid should be included when scheduling the battery instead of only concerning on the customers requirements. It is shown that the additional constraints introduced by the utility do not significantly affect the electricity bill of the battery owner. Among four different methods compared, the distributed control method shows best performance in terms of reduction in reactive power support, power loss, and improving the voltage unbalance.

TABLE I. PERFORMANCE COMPARISON OF DIFFERENT CONTROL STRATEGIES.

Method	Required reactive power from the converters [kVArh]	Network power loss [kWh]
Rule based control	1164	583
Optimization based without utility constraints	1167	589
Optimization based with utility constraints	937	575
Distributed control	37	532

ACKNOWLEDGMENT

The authors thank H. Hafezi and Prof. R. Faranda from Politecnico di Milano for provision of load and PV production data sets.

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