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Efficient Control of Energy Storage for Increasing the PV Hosting Capacity of LV Grids

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Abstract— **Photovoltaic (PV) systems are among the renewable sources that electrical energy systems are adopting with increasing frequency. The majority of already-installed PV systems are decentralized units that are usually connected to low-voltage (LV) distribution grids. The PV hosting capacity of an LV grid is usually limited by overvoltage, and the efficient control of distributed electrical energy storage systems (EESSs) can considerably increase this capacity. In this paper, a new control approach based on the voltage sensitivity analysis is proposed to prevent overvoltage and increase the PV hosting capacity of LV grids by determining dynamic set points for EESS management. The method has the effectiveness of central control methods and can effectively decrease the energy storage required for overvoltage prevention, yet it eliminates the need for a broadband and fast communication. The net power injected into the grid and the amount of reactive power absorbed by PV inverters are estimated using the PV generation forecast and load consumption forecast, and the dynamic operating points for energy storage management are determined for a specific period of time by solving a linear optimization problem. Simulations performed on a realistic LV feeder of the Danish island Bornholm verify the performance of the proposed method.**

Index Terms—**Energy storage, overvoltage prevention, photovoltaic, reactive power, dynamic set point.**

I. Introduction

BY increasing the penetration of grid-connected photovoltaic (PV) units in electrical energy systems, the concern regarding the effect of these units on grid operation increases as well. A considerable proportion of PV units already installed in some countries are residential PVs that are usually connected to low voltage (LV) distribution systems [1], [2]. Since the maximum PV generation happens simultaneously with low residential load consumption, high PV penetration may cause reverse power flow in the grid, which can potentially cause overvoltage, especially in weak grids [3]-[7].

Different methods have been proposed to mitigate the voltage rise caused by high PV penetration such as grid reinforcement, demand-side management (DSM) and reactive power absorption by PV inverters. The cost associated with grid reinforcement is high [8], and as the controllable domestic loads are not necessarily used on a daily and continuous basis, DSM cannot be considered as a reliable solution [9]. Moreover, in some LV grids the R/X ratio is high; as a result the reactive power absorption by PV inverters is not sufficient to prevent the overvoltage [10].

In recent years, the concept of using electrical energy storage systems (EESS) for overvoltage prevention in high PV penetration conditions has been addressed. Although battery technologies have developed in recent years, the main concern about the application of EESS is still the initial investment in the system, and a strategy to optimize the size of energy storage units in the distribution system is required. A sizing strategy for optimizing the size of energy storage units in a distribution system is proposed in [11], and the EESS life time, the effect of energy storage utilization on operation cost of transformer with on-load tap-changer (OLTC), and the effects of EESS on reduction of peak power generation cost are considered. In [12], a sizing strategy is developed to calculate the EESS capacity required for prevention of voltage rise and voltage drop in LV grids with residential PVs and electric vehicles (EVs). In [13] a method is proposed to determine the minimum EESS required to be installed at different locations of an LV residential distribution system in order to prevent overvoltage in the network. The uncertainties associated with PV generation and load consumption are modeled for sizing the EESSs in this study.

Although the EESS utilization in high PV penetration conditions is an effective solution to prevent overvoltage, advanced methods are needed to control these units as efficiently as possible. In [14], different local control strategies for PV storage systems are proposed to increase the self-consumption in LV grids while preventing overvoltage in the grid. A recent study [15] suggests a locally controlled EESS strategy using a fixed common power threshold, which is determined under worst-case conditions of maximum PV generation and no load consumption, for triggering the activation of EESSs in the grid in order to transfer the EESS charging period to high PV generation hours. In [13], a locally control approach is applied to determine the EESS operating points according to calculated fixed set points. These local control strategies for voltage control act only according to the local measurements and do not need broadband networks. However, they are not as effective as central control approaches due to a lack of broader information. Specifically, efficient control of EESS for overvoltage prevention cannot be

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performed when the reactive power absorption methods are applied to some PV inverters, or DSM strategies are applied to some loads. It is worth mentioning that the majority of decentralized PVs and EESSs in LV grids are customer-owned units, and the economic efficiency of each individual owner has to be considered in the strategy of overvoltage prevention.

The centralized methods usually provide better performance for EESS control [16]. A central controller can send commands to PVs, EESSs, smart loads, and other controllable units in the grid. These methods usually rely on monitoring the grid and receiving feedbacks from controllable units, which require two-way communication [17]. Providing ancillary services to the medium voltage grid using EESSs [18], and coordinated control of EESS charging and PV inverter reactive power [19] can be performed more effectively using central control approaches. Although central schemes can deliver the best possible performance, voltage control using these approaches requires high speed and fast computers and broadband networks, all of which imply substantial investment specifically in LV grids with large numbers of small units [20].

In this paper, a new control approach is proposed for energy storage management to prevent the overvoltage in the high PV penetration condition. The net power injected into the grid and the amount of reactive power absorbed by locally controlled PV inverters are estimated using the PV generation forecast and load consumption forecast, and by using a linear optimization problem, the dynamic operating points for EESS control are determined for a specific period of time. The communication is one-way communication and also new set points are not frequently sent to the EESSs. The method is based on the voltage sensitivity analysis, and the sensitivity matrix of an entire LV grid is used to increase the efficiency of the method compared to the locally calculated sensitivities.

The structure of the paper is as follows. First, the procedure for evaluating the voltages of grid using voltage sensitivity analysis is presented in section II. In section III, using the process explained in section II, a simplified two-bus system is presented and the methods for mitigating the overvoltage and the need for efficient management of EESS are discussed. In section IV, the proposed method for EESS management is described and then, in section V, the simulation results associated with a realistic LV feeder are presented for different PV penetration conditions. Finally, the major contributions of the paper are summarized in section VI.

II. Voltage Analysis Using Voltage Sensitivity Analysis

In this paper the voltage sensitivity matrix derived from power flow equations is used for the grid voltage calculation. Sensitivity analysis can effectively decrease the computational time in optimization problems [21], [22]. Reactive power management of PV inverters for voltage control in LV grids is amongst the applications of voltage sensitivity analysis [23], [24]. The procedure is described here [13].

Consider an N-bus LV grid with the following power flow equations at bus k:

$$\begin{cases} P_k = \sum_{n=1}^{N} V_k V_n Y_{kn} \cos(\theta_{kn} + \delta_n - \delta_k) \\ Q_k = -\sum_{n=1}^{N} V_k V_n Y_{kn} \sin(\theta_{kn} + \delta_n - \delta_k) \end{cases} \quad (1)$$

where P is the active power, Q is the reactive power, V is the magnitude of bus voltage phasor, δ is the angle of bus voltage phasor, Y is the magnitude of Ybus, and θ is the angle of Ybus. Expanding these two equations in a Taylor series for the initial estimate, and neglecting all higher order terms, results in the following set of linear equations:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \underbrace{\begin{bmatrix} \left[\frac{\partial P}{\partial \delta}\right] & \left[\frac{\partial P}{\partial V}\right] \\ \left[\frac{\partial Q}{\partial \delta}\right] & \left[\frac{\partial Q}{\partial V}\right] \end{bmatrix}}_{Jacobian} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (2)$$

By solving the previous equation, the voltage sensitivity matrix can be extracted as follows:

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{vmatrix} [S_{\delta P}] & [S_{\delta Q}] \\ [S_{VP}] & [S_{VQ}] \end{vmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (3)$$

where S_{VP} and S_{VQ} are the sensitivities of the bus voltage magnitudes to the active and reactive powers, respectively, and $S_{\delta P}$ and $S_{\delta Q}$ are the sensitivities of the bus voltage angles. The magnitude of the voltage at bus k can be calculated using the following equation:

$$V_k = V_S + \sum_{n=2}^{N} \left(S_{VP,k,n} P_n + S_{VQ,k,n} Q_n \right) \quad (4)$$

where V_s is the voltage at the connection point to the grid. Based on this equation, the active power feed-in at any location in the grid will increase the voltage in all buses. These increases differ for different locations and depend on the sensitivity of the connection points to the active power. As a result, in order to control the grid voltage efficiently, an advanced method is required for the grid management.

III. Overvoltage in High PV Penetration Condition and Mitigation Methods

To examine a worst-case scenario concerning overvoltage, let us simplify a radial distribution feeder to a two-bus system conditioned that all PVs are collected at the end of the feeder, as shown in Fig. 1. Bus 1 is considered a slack bus. The voltage sensitivity matrix can be extracted using (1)-(3) as $S_v = \left[R/V_1 \quad X/V_1 \right]$. The magnitude of the voltage at bus 2, using (4), can be calculated as follows:

$$V_2 = V_1 + S_{VP} P_2 + S_{VQ} Q_2 = V_1 + \frac{RP_2 + XQ_2}{V_1} \quad (5)$$

According to (5), the active power feed-in by PV increases the voltage at the connection point of PV and in high PV

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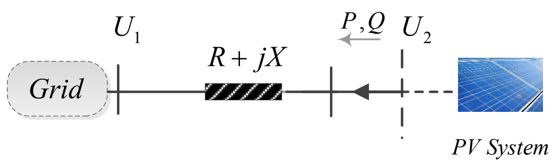

Fig. 1. A typical PV system connected to the grid.

generation condition the voltage may increase to an unacceptable level. In this situation, a part of active power generated by PV units has to be curtailed to prevent the overvoltage. By controlling the maximum power point tracker (MPPT) of the PV inverter, the output power can be curtailed at a specific level. Curtailment strategies can be divided into static and voltage dependent methods. In the static methods, the output power of PV inverters is curtailed at a specific level. Compared to the static active power curtailment methods, voltage dependent methods have higher efficiency and less active power loss [7], [25]-[27]. However, the benefits to customers located at the electrically weak nodes may be decreased [6]. Since the PV output is green and free energy and high amount of energy loss may increase the payback period for PV investors, other solutions need to be investigated for overvoltage prevention. It is worth mentioning that the active power curtailment of customer-owned PVs is not allowed in certain countries, as in Denmark.

An important solution for mitigating the overvoltage is to implement the reactive power absorption by PV inverters by using the droop control methods, which are currently applied in the new small-scale and residential PV inverters [23], [28]-[29]. Based on (5), the reactive power absorption by PV inverter can decrease the voltage at the PV connection point to the grid. Two main droop control methods for reactive power management of PV inverters are power factor as a function of injected active power (*PF(P)*), and reactive power as a function of voltage in the PV connection point (*Q(U)*). In the *Q(U)* method, the voltage at the PV connection point is considered as a reference for the droop control and the PV inverter absorbs the reactive power only when the terminal voltage is higher than a specific value. In the *PF(P)* method, the reactive power is a function of the generated active power. The schematics of these methods are shown in Fig. 2.

Another effective method for overvoltage prevention is active power management. By using the intelligent and controllable loads, the load consumption can be transferred to high PV generation hours and decrease the net power injected into the grid by PVs. As the controllable domestic loads are not necessarily used on a daily basis, DSM is not a reliable method for overvoltage prevention [9]. Utilizing EESS is the other active power management solution to limit the injected power into the grid. Although EESS utilization is an effective solution, advanced methods need to be applied for controlling these units as efficiently as possible. For instance, the domestic EESSs are usually controlled using a simple local control approach that is based on activation of the energy storage units when the PV generation is higher than local consumption [9]. Using this control approach, these units are

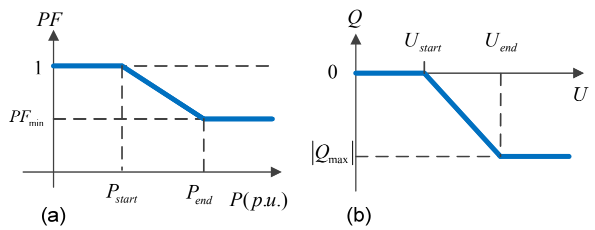

Fig. 2. The schematics of local reactive power absorption methods; a) PF(P), b) Q(U)

usually fully charged during morning hours on sunny days; therefore they cannot be considered as reliable voltage support tools.

By determining a fixed power threshold for EESS activation, the net power injected into the grid can be curtailed at a specific level. This curtailment level has a considerable effect on the need for energy storage, and curtailing the active power at lower levels results in higher EESS need and vice versa. To illustrate this, consider a PV unit with maximum output power of 4 kW. The daily active power generation of this PV system in a summer day is shown in Fig. 3. By adjusting the control system to start storing the energy when injected power into the grid exceeds specific level, the maximum injected power into the grid is curtailed at that level. The required EESS capacities for different curtailment levels are also shown in this figure. As can be seen, the active power curtailment level has a considerable effect on the need for energy storage. For example, by setting the power threshold at 3 kW, less than 4 kWh EESS is required. To curtail the output power at 2 kW, the required EESS increases to more than 10 kWh. Therefore, the EESS operating points have to be managed in order to minimize the energy storage that is required for overvoltage prevention.

IV. Proposed Method

As discussed before, the curtailment levels have considerable effects on the need for energy storage, and curtailing the active power at lower levels results in higher EESS need and vice versa. By determining a fixed operating point for controlling EESSs, which has to be determined under worst-case conditions of maximum PV generation and no load consumption [15], the effect of reactive power absorption by PV inverters and the effects of local consumption cannot be considered.

This paper proposes a new method to determine dynamic operating points for EESS control in LV grids. Using the proposed method, the effects of reactive power absorption by PV inverters are considered as well as the load consumption. The procedure for determining the dynamic set points based on the proposed method is as follows.

A. Estimation of PV generation and load consumption

PV generation and load consumption for the next specific period of time are estimated. The PV output depends on different parameters such as the irradiance level and temperature, and can be estimated using weather forecast data

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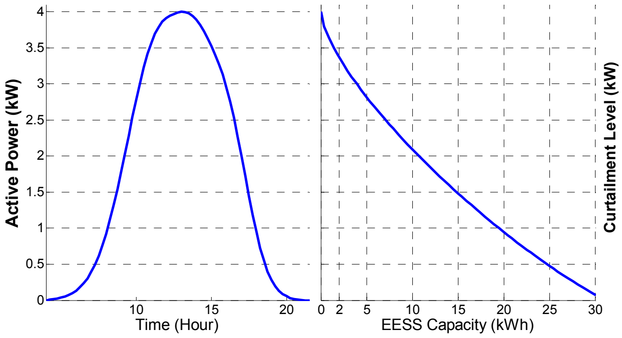

Fig. 3. Effect of different power thresholds on energy storage need.

[30], [31]. As the standard deviation of forecast error increases with time, a short prediction horizon, e.g. 10 minutes, is considered in the method. Although the estimation is carried out for a short period of time, the real PV generations may differ with the forecasted values because of fast variation of solar irradiance caused by cloudy-clear or clear-cloudy sky ramps, which are short-term events, or error caused by forecast tools.

The clear-cloudy sky ramps caused by passing clouds decrease the output power of PV panels as well as voltages at the connection points of PVs; therefore, no extra action is usually required regarding overvoltage. The cloudy-clear sky ramps can quickly increase the PV output power and the voltage at the PV point of connection. The voltage rise caused by these ramps can be limited by controlling the ramp-rate of PV systems or adding some controllers to EESSs [32]-[34]. In addition, according to the standards applying to LV grids, such as EN50160 [35], the 10-minute average voltages have to be measured and evaluated, and for the transient events usually a higher voltage increase is acceptable. Therefore, short-term events caused by clouds can be neglected in the calculations. It is worth mentioning that the probability of flicker caused by passing clouds is low, as the PVs are usually distributed along LV feeders.

The error caused by forecast tools is inevitable. Suppose that the real PV output is P_r^{PV} ; therefore:

$$P_f^{PV,min} < P_r^{PV} < P_f^{PV,\max} \tag{6}$$

where the $P_f^{PV,min}$ and $P_f^{PV,\max}$ are the minimum and the maximum forecasted values for PV output, respectively. Any value between these minimum and maximum forecasted powers can be considered as the output power of PV. If the average of $P_f^{PV,min}$ and $P_f^{PV,\max}$ is considered for the calculations, then:

$$P^{PV} = \begin{cases} P_r^{PV} - P_{un}^{PV,error} & if\ underestimated \\ P_r^{PV} + P_{ov}^{PV,error} & if\ overestimated \end{cases} \tag{7}$$

where $P_{un}^{PV,error}$ and $P_{ov}^{PV,error}$ are the errors caused by underestimation and overestimation of the PV output, respectively, and P^{PV} is the average value.

Load consumption can be estimated using historical data and the electricity price as it is expected that the load consumption is decreased when the electricity price is high [36]-[38]. Similar to the PV generation forecast, the estimated load consumption may contain errors. Suppose that the real load consumption is P_r^L ; therefore:

$$P_f^{L,min} < P_r^L < P_f^{L,\max} \tag{8}$$

where $P_f^{L,min}$ and $P_f^{L,\max}$ are the minimum and the maximum estimated values for load consumption, respectively. Any value between these minimum and maximum can be considered in the calculations. If the average of $P_f^{L,min}$ and $P_f^{L,\max}$ is considered, then:

$$P^L = \begin{cases} P_r^L - P_{un}^{L,error} & if\ underestimated \\ P_r^L + P_{ov}^{L,error} & if\ overestimated \end{cases} \tag{9}$$

where P^L is the average value, and $P_{un}^{L,error}$ and $P_{ov}^{L,error}$ are the errors caused by underestimation and overestimation, respectively. The second-based load variations are neglected as the minute-based average voltages are usually considered in the grid codes and standards related to the overvoltage in LV grids.

B. Estimation of reactive power absorbed by PV inverters

Using the estimated PV generation and load consumption values, and based on the method used for the reactive power control of PV inverters, the amounts of reactive power absorbed by each PV inverter are estimated. In the case of using *PF(P)* method, the reactive power absorption is determined on the basis of the generated active power by PVs, and the grid voltage does not affect the reactive power absorbed by PV inverters. The reactive power absorbed by PV_i can be calculated as:

$$\begin{cases} Q_s^{PV} = 0 & P < P_{start} \\ Q_s^{PV} = P\tan\left(\cos^{-1}\left(PF\right)\right) & P_{start} < P < P_{end} \\ Q_s^{PV} = P\tan\left(\cos^{-1}\left(PF_{\min}\right)\right) & P > P_{end} \end{cases} \tag{10}$$

where P_{start} is the power in which the reactive power absorption is started, and P_{end} is the power in which the minimum power factor, PF_{min}, is applied. P_{start}, P_{end}, and PF_{min} are defined in the droop that is applied to the PV inverter.

In the case of using *Q(U)* method, the voltage of the PV connection point is considered for controlling the reactive power; therefore both PV generation and load consumption affect the reactive power absorbed by PV inverters. After estimating the reactive power absorbed by *PF(P)* controlled PV inverters, an estimation of the grid voltage at the Q(U) controlled PV_j is obtained using the following equation:

$$V_j^{PV} = V_S + \sum_{r=2}^{R}\left(S_{VP,j,r} P_r^L + S_{VQ,j,r} Q_r^L\right) + \\ \sum_{s=2}^{S}\left(S_{VP,j,s} P_{mop} + S_{VQ,j,s} Q_s^{PV}\right) + \sum_{u=2}^{U}\left(S_{VP,j,u} P_{mop} + S_{VQ,j,u} Q_u^{PV}\right) \tag{11}$$

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where R is the number of customers without PV, S is the number of customers with *PF(P)* controlled PV inverters, and U is the number of customers with *Q(U)* controlled PV inverters in that LV grid. P_{mop} is the maximum power that can be injected into the grid by each customer and is determined in the next step. To initiate the procedure, P_{mop} can be replaced by P_s^{PV} and P_u^{PV}. The reactive power absorbed by PV_u can be calculated as:

$$\begin{cases} Q_u^{PV} = 0 & V_j^{PV} < U_{start} \\ Q_u^{PV} = \dfrac{|Q_{\max}|}{U_{start} - U_{end}} (V_j^{PV} + U_{start}) & U_{start} < V_j^{PV} < U_{end} \\ Q_u^{PV} = Q_{\max} & V_j^{PV} > U_{end} \end{cases} \quad (12)$$

where U_{start} is the voltage in which the reactive power absorption is started, and U_{end} is the voltage in which the maximum reactive power, Q_{max}, is absorbed. These values are determined in the droop that is applied to the PV inverter. The voltage and the reactive power have to be estimated for all Q(U) controlled PV systems. By considering the reactive power absorbed by each Q(U) controlled PV system, voltages at the connection points of other PV systems are changed; therefore, the calculation of grid voltage as well as the absorbed reactive power have to be repeated until the deviations of calculated values decrease to an acceptable level.

C. Determining the EESS set points

After estimating the reactive power supplied by PV inverters, the magnitudes of the voltages at all PV points of connection in the grid are estimated by (4). If the voltage at any point of the grid exceeds the maximum allowed value, all the EESSs have to be activated in order to prevent the overvoltage. The maximum power that can be injected into the grid by each customer can be determined by solving the following linear equation:

$$Maximize\, P_{mop}(t)$$
$$s.t.$$
$$\begin{cases} V_s + \sum_{i=2}^{M} S_{VP2,i} \times P_{mop}(t) + \sum_{i=2}^{M} S_{VQ2,i} \times \left(Q_i^{PV}(t) + Q_i^{L}(t)\right) + \\ \quad \sum_{j=2}^{R} \left(S_{VP2,j} \times P_j^{L}(t) + S_{VQ2,j} \times Q_j^{L}(t)\right) < V_{\max} \\ V_s + \sum_{i=2}^{M} S_{VP3,i} \times P_{mop}(t) + \sum_{i=2}^{M} S_{VQ3,i} \times \left(Q_i^{PV}(t) + Q_i^{L}(t)\right) + \\ \quad \sum_{j=2}^{R} \left(S_{VP3,j} \times P_j^{L}(t) + S_{VQ3,j} \times Q_j^{L}(t)\right) < V_{\max} \\ \quad .... \\ V_s + \sum_{i=2}^{N} S_{VPn,i} \times P_{mop}(t) + \sum_{i=2}^{N} S_{VQn,i} \times \left(Q_i^{PV}(t) + Q_i^{L}(t)\right) + \\ \quad \sum_{j=2}^{R} \left(S_{VPR,j} \times P_j^{L}(t) + S_{VQR,j} \times Q_j^{L}(t)\right) < V_{\max} \end{cases} \quad (13)$$

where P_{mop} is the maximum power that can be injected into the grid by each customer without overvoltage occurrence, and $V_{\max}$ is the maximum allowed voltage at the connection point of PV. In the case of using *Q(U)* method and by considering the active power of EESSs, voltages at the connection points of PV systems as well as the absorbed reactive powers are changed; therefore, the states B and C have to be repeated until the deviation of calculated P_{mop} decreases to an acceptable level.

After determining the P_{mop} and communicating this value to all customers, they have to store the excess power into their EESS units, conditioned that the state of charge (SOC) of EESSs are less than the maximum state of charge of the batteries, SOC_{max}, and the battery converters are able to absorb the excess power. The minimum power that has to be absorbed by $EESS_k$ to prevent active power curtailment of PV_k can be determined using the following equation:

$$P_k^{st}(t) = P_k^{PV}(t) - P_k^{L}(t) - P_{mop}(t) \quad (14)$$

where P_k^{st} is the minimum absorbed power by $EESS_k$. If the SOC of $EESS_k$ is more than SOC_{max}, or the converter capacity of $EESS_k$ is less than P_k^{st}, a part of generated power by PV_k has to be curtailed. As mentioned before, the active power curtailment can be performed by controlling the MPPT of the PV inverter. The output power of PV_k has to be limited according to the following equation:

$$P_k^{PV,Curtailed}(t) = P_k^{st}(t) + P_k^{L}(t) + P_{mop}(t) \quad (15)$$

where $P_k^{PV,Curtailed}$ is the operating point of PV_k. According to (15), when a customer does not have EESS, the PV output power of that customer has to be limited to the sum of the local consumption and P_{mop}. The stored energy in EESSs can be used to increase the self-consumption, trade power in the electricity markets, charge EVs, and participate in the primary frequency control [39]-[42]. To have a more cost-efficient operation, combination of different services can be considered [43]-[45]. The procedure for determining the EESS dynamic operating points is shown in Fig. 4.

As the P_{mop} is calculated using the estimated PV generation and load consumption, it may contain error. When the output power of PV is overestimated (↑) or underestimated (↓), the estimated reactive power can also be affected as follows:

$$P^{PV} \uparrow \Rightarrow \begin{cases} Q(U) \Rightarrow Voltage \uparrow \Rightarrow Q \uparrow \\ PF(P) \Rightarrow Q \uparrow \end{cases} \qquad P^{PV} \downarrow \Rightarrow \begin{cases} Q(U) \Rightarrow Voltage \downarrow \Rightarrow Q \downarrow \\ PF(P) \Rightarrow Q \downarrow \end{cases} \quad (16)$$

Overestimation and underestimation of load consumption can also affect the estimated reactive power as follows:

$$P^{L} \uparrow \Rightarrow \begin{cases} Q(U) \Rightarrow Voltage \downarrow \Rightarrow Q \downarrow \\ PF(P) \Rightarrow Q\ fixed \end{cases} \qquad P^{L} \downarrow \Rightarrow \begin{cases} Q(U) \Rightarrow Voltage \uparrow \Rightarrow Q \uparrow \\ PF(P) \Rightarrow Q\ fixed \end{cases} \quad (17)$$

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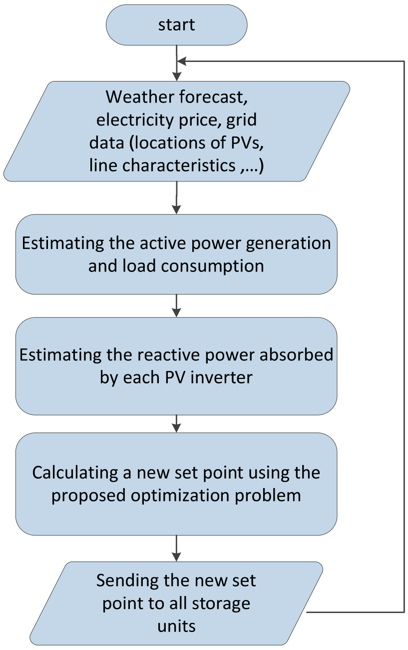

Fig. 4. The procedure for determining the EESS dynamic operating points.

If the reactive power is underestimated, the P_{mop} is underestimated and is calculated less than its real optimal value; therefore EESSs are charged more than required and they may be fully charged sooner. On the other hand, if the reactive power is overestimated, the P_{mop} is overestimated and is calculated more than its real optimal value. This may cause curtailment of PV output in weak points of the LV grid. With a precise forecast, the proposed method acts similar to the centrally controlled EESSs with real-time feedbacks; however, even if overestimated set points are considered, the EESS need for overvoltage prevention is less than that of a fixed power threshold as the effect of reactive power absorption by PV inverters and the load consumption are considered. The optimization problem can be solved by DSOs or aggregators for each LV grid. An overview of locally controlled PV systems and EESSs controlled by DSO/Aggregator is depicted in Fig. 5. As can be seen the communication is one-way communication. In addition, new set points are not frequently communicated to EESSs; therefore, a broadband and fast communication is not required.

V. Simulation Results

A three-phase LV feeder of the Danish island Bornholm with 52 customers and 23 buses is selected for the simulations. The line-diagram of the test system is depicted in Fig. 6. The transformer and cables parameters can be found in [13]. The maximum allowed voltage increase in the system is considered to be 5%. Simulations are carried out for 50, 75, and 100% PV penetration. It is assumed that all customers had the same installed PV capacity (kWp) and for 100% PV penetration this capacity is set at 5.2 kWp. Accordingly, 50% PV penetration means that all customers have installed PVs with 2.6-kWp capacities. All PVs are connected to the grid

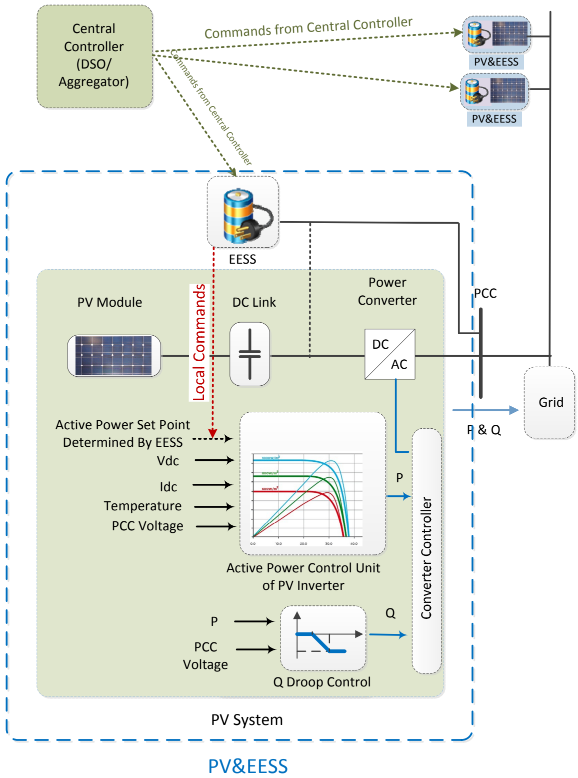

Fig. 5. An overview of locally controlled PV systems and EESSs controlled by DSO/Aggregator.

through three-phase inverters and the system is considered as a balanced three-phase system. EESSs are connected to the AC terminals of PV inverters. The maximum reactive power that can be absorbed by PV inverters is set to 48% of nominal active power for both PF (P) and Q (U) methods. The related droops are shown in Fig. 7. Real PV generation data and load consumption data are used for the simulations. Matlab is used to model the selected LV feeder.

Simulations show that the amount of active power that can be injected into the grid without overvoltage occurrence is considerably increased by using the proposed method. This injected power in the condition of 75% PV penetration is shown in Fig. 8. In the case of using a fixed power threshold, the active power injected into the grid is curtailed at a value of around 1.5 kW in order to prevent overvoltage in the grid. By using the proposed method and assuming that the *PF (P)* method is applied to the PV inverters, the injected active power can be increased to 2.5 kW without overvoltage occurrence during hours with high PV generation. The reason for this is that the maximum reactive power injection happens simultaneously with the maximum active power generation by the PV inverters. Using the *Q (U)* method, each inverter in the grid absorbs different amounts of reactive power according to the voltages at the connection point of that PV; as a result, the maximum active power that is allowed to be injected into the grid is not the same as that of the PF (P) method. The amount of reactive power absorbed by each PV inverter when *PF(P)* method is applied, and the amount of reactive power absorbed by each *Q(U)* controlled PV inverter located at buses 3, 11, and 23 are shown in Fig. 9.

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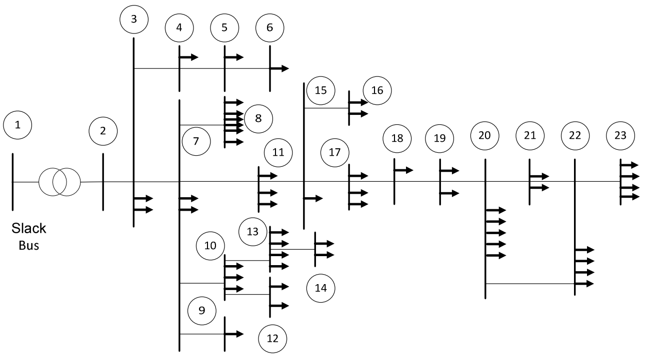

Fig. 6. Single-line diagram of the LV grid used for simulations.

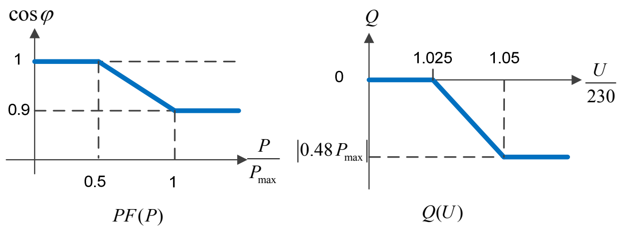

Fig. 7. The reactive power droops used for simulations.

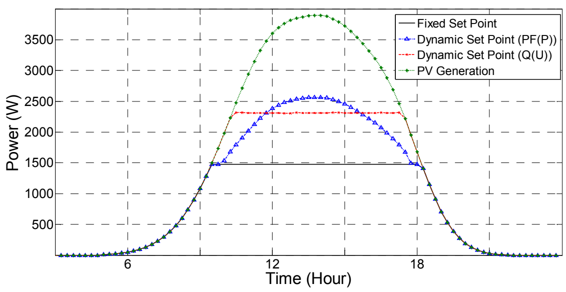

Fig. 8. Amount of active power that can be injected into the grid without overvoltage occurrence in the condition of 75% PV penetration.

By increasing the amount of active power that can be injected into the grid without overvoltage occurrence, the power absorbed by the EESS is considerably decreased. The active power absorbed by the EESS in the condition of 75% PV penetration is shown in Fig. 10. It can be seen that the maximum active power absorbed by the EESS in the condition of using a fixed power threshold is around 2.4 kW, which is about two-times more than that of using dynamic set points.

The EESS need for overvoltage prevention in the conditions of 50%, 75%, and 100% PV penetration is shown in Fig. 11. As can be seen, in the condition of 50% PV penetration and by using the fixed power threshold, the EESS capacity that is required for overvoltage prevention is around 5.5 kWh per customer. A lower EESS installation can cause overvoltage in the grid; therefore, the output power of the PV units has to be curtailed for overvoltage prevention. This EESS need can be decreased to less than 1 kWh by applying dynamic set points that is around 20% of the required EESS capacity with a fixed power threshold control approach. In the condition of 75% PV penetration, the EESS that is required for overvoltage prevention is around 14 kWh and 5 kWh per customer by using a fixed power threshold and dynamic set points,

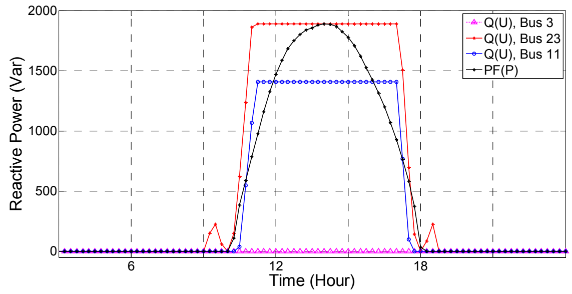

Fig. 9. Amount of reactive power absorbed by each PV inverter

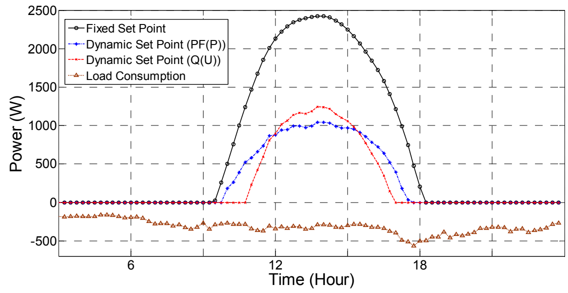

Fig. 10. Absorbed power by EESS in the condition of 75% PV penetration.

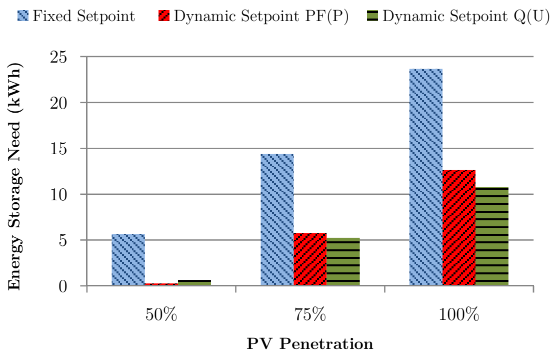

Fig. 11. The EESS need for overvoltage prevention in the conditions of 50%, 75%, and 100% PV penetration.

respectively. It can be concluded that by installing 5 kWh EESS per customer and using a fixed power threshold, the maximum PV penetration can be increased to around 50% without overvoltage occurrence; however, by using the proposed method and determining the dynamic set points, the PV penetration can be increased to around 75%. By increasing the PV penetration to 100%, in the case of using a fixed power threshold, the required EESS for voltage support increases to around 23.5 kWh. Using the proposed method, the EESS need decreases by around 50%, and 12.5 kWh EESS installation is enough for the grid voltage support. In addition, the *PF(P)* method is more efficient in lower PV penetration and the *Q(U)*method shows better efficiency in higher PV penetration. It is worth mentioning that the required EESS for overvoltage prevention may differ for different days during the year as the PV generation and load consumption are stochastic. The PV generation, load consumption, power absorbed by EESS, and the EESS capacity that is required for overvoltage prevention during 14 successive days in June, 2013 in the condition of 100% PV penetration are shown in Fig. 12. As can be seen,

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the required EESS differs for these days; however, the EESS need is less in the proposed method compared to that of a fixed set point method in all cases. It is worth mentioning that the optimized EESS capacity for each customer depends on various factors, including the electricity price, the grid regulatory specifications, the PV capacity and its orientation and inclination, the consumption pattern of an individual customer, the EV charging patterns, the battery price and technology, the grid structure, and the like. Therefore, a decision making procedure is required to determine the optimized EESS capacity for each customer and it is out of scope of this paper.

VI. Conclusion

In this paper, a new control approach was proposed for energy storage management to prevent the overvoltage in LV grids. To this aim, dynamic set points were determined for EESS control considering the effects of reactive power absorption by PV inverters and the local load consumption. Simulations were performed on a realistic LV feeder of the Danish island Bornholm to determine the EESS capacity required to prevent overvoltage in the network considering two reactive power control methods, namely, reactive power as a function of voltage (Q (U)) and power factor as a function of injected active power (PF (P)). The results indicated that by using the proposed method, the customers' voltage remained less than the predefined value in all locations of the grid and in all operation modes. In addition, compared to the fixed power threshold method, the energy storage that is required for overvoltage prevention was considerably decreased. Simulations showed that by considering 5-kWh EESSs and applying the proposed method, the PV penetration in the grid could be increased to around 75%. In the same condition, by using a fixed set point for energy storage control, the PV penetration had to be limited to around 50%. In addition, simulations indicated that in the selected LV grid, the *PF(P)* method was more efficient in lower PV penetration and the *Q(U)* method showed better efficiency in higher PV penetration.

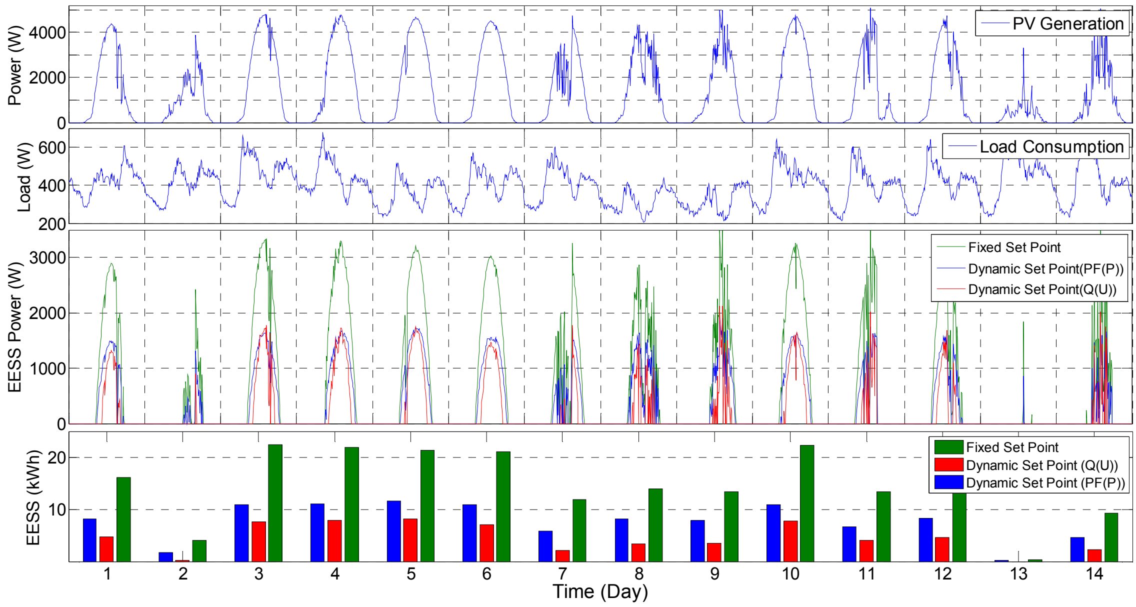

Fig. 12. The PV generation, load consumption, power absorbed by EESS, and the EESS capacity required for overvoltage prevention during 14 successive days.

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