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Comparison of point-of-load versus mid-feeder compensation in LV distribution networks with high penetration of solar photovoltaic generation and electric vehicle charging stations

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Abstract: Increasing use of distributed generation (DG), mainly roof-top photovoltaic (PV) panels and electric vehicle (EV) charging would cause over- and under-voltage problems generally at the remote sections of the low-voltage (LV) distribution feeders. As these voltage problems are sustained for a few hours, power electronic compensators (PECs) with input voltage control, i.e. electric springs cannot be used due to the unavailability of non-critical loads that can be subjected to non-rated voltages for a long duration of time. However, PECs in output voltage control mode could be used to inject a controllable series voltage either somewhere on the feeder (mid-feeder compensation, MFC) or between the feeder and each customer (point-of-load compensation, PoLC) both of which are effective in tackling the voltage problem without disrupting PV power output and EV charging. In this study, a comparison between the MFC and PoLC option is presented in terms of their voltage control capability, required compensator capacity, network losses, PV throughput, and demand response capability. The criteria for selection of the optimal location of these compensators are also discussed. Stochastic demand profile for different types of residential customers in the UK and a typical European LV network is used for the case study.

1 Introduction

Voltage violations caused by roof-top photovoltaic (PV) generation [1, 2] and/or charging of electric vehicle (EV) [3] could limit utilisation of low-voltage (LV) distribution network assets (i.e. feeders, transformers etc.). Various voltage control measures (e.g. onload tap-changers, power electronic compensators (PEC)) could be deployed in such cases to minimise or to defer the need for network reinforcement.

Fast response of power electronic compensation is preferred to deal with the volatility in loads and PV generation, in particular. However, sizing and siting of the PEC has to be considered carefully so that only the minimum required power is processed through power electronics to keep the losses down while achieving the required flexibility in voltage control. For example, in LV feeders, over-voltage due to PV generation and under-voltage due to EV charging typically occurs towards the remote section. It is, therefore, adequate (although not necessarily optimum) to install a PEC at the point on the feeder beyond which voltage violation start to occur to minimise the rating (and losses) of the PEC. Such an arrangement is known as mid-feeder compensation (MFC) [4, 5].

There is, however, limited flexibility with MFC as the individual load voltages cannot be controlled. This can be overcome by decoupling each load (say, individual residential customers) from the feeder using a PEC which is smaller but operationally similar as in the case of MFC. This arrangement is henceforth referred to as point-of-load compensation (PoLC). For PoLC, individual load voltages could be regulated anywhere within the stipulated limits (0.94–1.1 p.u.) if the PECs are adequately rated. Thus, PoLC provides larger flexibility for load voltage regulation which can also be exploited to exercise voltage-driven demand response [6] to tackle grid frequency problems during future low inertia scenarios [7, 8]. However, the overall rating of the PECs required for PoLC would be larger compared to MFC which can take advantage of the load diversity factor.

In this paper, a comparison between PoLC and MFC is presented in terms of (i) voltage regulation capability, (ii) reserve provision for voltage-driven demand response, (iii) required capacity of PEC, (iv) losses (in network and PECs), and (v) PV throughput. This is substantiated through a case study on IEEE European LV network considering the stochastic demand profile of typical residential customers in the UK [9].

The traditional approach to PoLC is to use a dynamic voltage restorer (DVR) or unified power quality conditioner (UPQC) [10] for only the critical industrial/commercial customers to regulate the supply voltage precisely. In recent years, some papers have been published on PoLC using Electric Springs focusing on regulating the feeder (line) side voltage while allowing wider variation (up to 20%) of the voltage across the non-critical loads to modulate their power consumption [11–14]. The problem with the use of ES is that these over- and under-voltages are sustained for long periods of time. Non-critical loads cannot be subjected to voltages different from rated voltages for longer durations. Also, the idea of using wider voltage tolerance for non-critical loads especially, over longer time scales (minutes to hours) is subject to regulatory clearances and is unlikely to be adopted by the industry any time soon. ESs are only effective in dealing with frequency and/or voltage problems that are transient in nature. The availability of the non-critical load at the time of the disturbance is another issue which makes the ESs approach less viable.

This paper recommends the approach of regulating the load side voltages where the PEC is operated in an output voltage control mode. Unlike previous papers on the topic, in this paper, no distinction is, therefore, made between critical and non-critical loads and the voltages across all loads have been maintained within the stipulated limits of 0.94–1.10 p.u [15]. Also, unlike the previous papers on PoLC using Electric Spring which considered specific load types (e.g. constant impedance with 0.95 power factor [16, 17]), here a stochastic demand profile for typical residential customers in the UK [9] is used to capture the variability in load types and their dependence on terminal voltage, and the corresponding impact on the effectiveness of PoLC. No assumptions were made about the availability of a particular type

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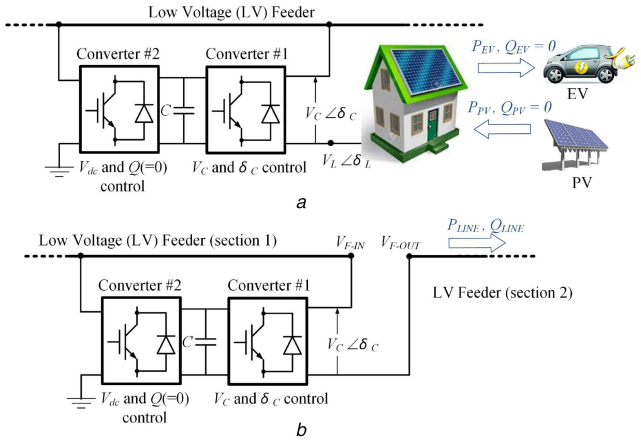


Fig. 1 *Series–shunt converter arrangement for* ***(a)*** PoLC and, ***(b)*** MFC

of load and the dependence of power consumption on the terminal voltage. This paper presents a novel solution for tackling sustained over-voltages in the LV system and draws a comparison between the two available options (MFC already proposed and PoLC which is proposed in this paper). It also presents a better way of choosing the optimal location for MFC compared to the existing recommendation [4]. Moreover, there is no need for coordination using droop control [13] or otherwise as the loads are decoupled from the feeder through the PECs.

Traditionally, voltage control is exercised by using a combination of static and dynamic control devices. Static voltage control devices provide a fixed amount of reactive power. They include shunt reactors and capacitors. While the dynamic voltage control devices can provide a changing reactive power out based on the system voltage [1]. Some of these dynamic devices can change their reactive power output without relying on a measurement, while others work in a closed-loop configuration where the reactive power is injected based on the difference between the terminal voltage and the desired terminal voltage. Typical dynamic voltage control devices include generators, synchronous compensators, static synchronous compensators [18–21] and static var compensators [22, 23]. All these devices have different operating speeds. Sufficient dynamic voltage control is essential to contain and recover the voltage after a disturbance and to manage the real-time change in reactive power requirements of the loads. Traditionally, all these devices are installed by the distribution utility to provide a constant voltage to the customers. MFC will have to be installed by the distribution service provider, while PoLC can be installed by the customers if some sort of incentive is provided to participate in the demand response. However, this is beyond the scope of this paper. This paper only focuses on the merits and demerits of both techniques.

2 PEC for voltage control

Voltage problems in the distribution network could be tackled effectively by injecting a controllable series voltage using PECs. As PECs are less efficient than conventional electromagnetic voltage regulators (e.g. transformers with on-load tap changers), only the minimum required an amount of power should be processed through the PECs. In LV feeders, e.g. over- and under-voltage typically occurs towards the remote section. It could therefore, be adequate to install a PEC at the point on the feeder where voltage violation starts to occur to optimise the rating of the PEC. Such an arrangement is known as mid-feeder compensation (MFC) [4]. There is, however, limited flexibility with MFC as the individual load voltages cannot be controlled. This can be overcome by decoupling each load from the feeder using PEC smaller but otherwise similar as in the case of MFC. This arrangement is henceforth referred to as PoLC.

Both for PoLC and MFC, a PEC that is capable of injecting a series voltage with controllable magnitude and angle provides maximum flexibility [10, 17]. For tackling over- or under-voltage problems, the required series voltage is generally a fraction of the rated feeder/load voltage. Hence, a shunt–series converter arrangement connected back-to-back through a DC link (similar to a UPQC [10]) is suitable (shown in Fig. 1 without the transformers and interface filters) to keep the PEC rating down to a fraction of the power flowing through it. The series converter (converter 1) is set to control the magnitude (V_C) and the phase angle (δ_C) of the injected voltage, while the shunt converter (converter 2) supports the active power exchanged by the series converter by maintaining the DC-link voltage. The shunt converter is usually operated at unity power factor to minimise its apparent power rating.

In this paper, such a series–shunt converter arrangement in considered for PEC in case of both PoLC and MFC, as shown in Fig. 1. For MFC, the series converter decouples zone of voltage violation from rest of the feeder by injecting a voltage to maintain the voltage at the remote end of the feeder within the stipulated limits. This series voltage (V_C) is determined either through line drop compensation approach [6] using local voltage measurements or communication from the remote sections.

For PoLC, the PEC decouples each individual load (i.e. individual residential customer) from the feeder as shown in Fig. 1*a*. The load voltages (V_L) can be regulated anywhere within the stipulated limits (0.94–1.1 p.u.) by injecting appropriate voltage through the series converter.

3 Location of MFC and PoLC

It is important to find the location of PECs for both MFC and PoLC. The rating of PEC for MFC depends on the location of installation. If we install it near the far end of the feeder, close to the boundary node after which the voltage limits are violated, we get a smaller device rating due to the smaller series current flowing in the PEC. We cannot install the PEC just at the voltage on-set point as the compensation action will change the voltages of the nodes behind the PEC and can cause them to go out of the limits. This is explained in detail in this section.

In [4], it is recommended that the PEC for MFC should be placed at the location where we have 50% of the total voltage drop across the feeder. This eliminates the problem of node voltage behind the compensator going out of the allowed limit as a result of the compensation action. However, it requires a much larger PEC rating compared to the PEC if it is to be placed closer to the boundary node towards the far end of the feeder. Similarly, additional PECs current in case of PoLC can cause the boundary node to change as a result of the compensation. In this section, it is shown how the optimal location of the compensator can be chosen without violating the voltage limits.

For analysis, consider a simple radial distribution feeder fed by a constant substation voltage $V_S \angle \delta_S$ and N equally spaced loads ($L_1, L2, \ldots, L_N$) as shown in Fig. 2*a*. The total feeder impedance is $Z_T \angle \theta_o$, while the impedance of each section is $Z_o \angle \theta_o$. The PEC used for MFC installed at the node k can be modelled as shown in Fig. 2*b*. The series converter is modelled by a series voltage source that inserts a voltage $V_{\text{MFC}} \angle \delta_{\text{MFC}}$ in series with the feeder. A parallel dependent current source with a current $I_{\text{MFC}} \angle \delta_{Fk}$ represents the active power consumed by the shunt converter (to maintain the DC-link voltage) to provide active power transfer capability to the series converter. The magnitude of this current depends on the series voltage that is inserted. As the shunt converter operates on unity pf, the phase angle of the current I_{MFC} is the same as the phase angle of the feeder voltage (δ_{Fk}). The PECs used in a PoLC are modelled in the same way using a voltage source and a dependent current source (Fig. 2*c*). The only difference is that now the voltage is inserted between the feeder and the load, instead of inserting it in series with the feeder.

Using the above system model, the location of PEC for MFC and onset node after which all loads must have PECs for PoLC are calculated for different types of loads. For simplicity of analysis, the feeder impedance is considered to be predominantly resistive ($R \gg L$), which is a valid assumption for an LV distribution feeder. Also, all the PECs insert a voltage in phase or anti-phase with the feeder voltage as it will ensure the minimum converter rating.

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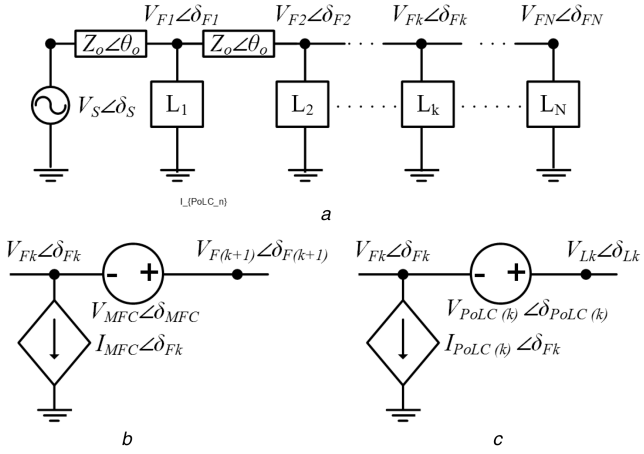


Fig. 2 *Equivalent models for*
(a) Radial LV system, ***(b)*** MFC, and ***(b)*** PoLC equivalent models

Calculations are shown here for the under-voltage condition. However, the same equations are valid for the over-voltage condition if you consider current is flowing in the opposite direction and the voltage drops have a negative sign.

3.1 Constant current loads

If all loads are of a constant current type and the total load current is given I_T, the expression for voltage drop from the substation up-to a node k, where $k \in \mathbb{W}$ and $1 \leq k \leq N$, is given by

$$\Delta V_k = \sum_{n=N-k+1}^{N} n\frac{Z_T I_T}{N^2} = \frac{Z_T I_T k}{N}\left(1 - \frac{k-1}{2N}\right) \tag{1}$$

It can be re-arranged as

$$(I_T Z_T)k^2 - (2NI_T Z_T + I_T Z_T)k + 2N^2\Delta V_k = 0 \tag{2}$$

If the maximum allowed voltage drop is given by ΔV_{LIM}, the boundary node after which the voltage limits will be violated (under no compensation) can be found by solving (2) (and ignoring the factitious root), as shown below:

$$k = \left\lfloor \left(N + \frac{1}{2}\right) - \sqrt{\left(N + \frac{1}{2}\right)^2 - 2N^2\frac{\Delta V_{\text{LIM}}}{I_T Z_T}} \right\rfloor \tag{3}$$

In the case of MFC, this boundary node will change due to the additional current I_{MFC} flowing in the feeder. This additional current can be calculated by considering the active power exchange of the series converter. If PEC for MFC is to be installed at the node k, the new equation for total voltage drop up-to node k is calculated by using superposition, as shown below:

$$\Delta V_k = \frac{Z_T I_T k}{N}\left(1 - \frac{k-1}{2N}\right) + \frac{Z_T k I_{\text{MFC}}}{N} \tag{4}$$

$$= \frac{Z_T I_T k}{N}\left(1 - \frac{k-1}{2N} + \frac{(N-k)V_{\text{MFC}}}{NV_k}\right) \tag{5}$$

Also, the voltage at the last node N is given by

$$V_N = V_k + V_{\text{MFC}} - \sum_{n=1}^{N-k} n\frac{Z_T I_T}{N^2} \tag{6}$$

$$= V_k + V_{\text{MFC}} - \frac{I_T Z_T (N-k)(N-k+1)}{2N^2} \tag{7}$$

The new boundary node k at which the PEC for MFC should be installed, to avoid voltage limit violations, can be calculated by (5) by considering $\Delta V_k = \Delta V_{\text{LIM}}$, and $V_k = V_S - \Delta V_{\text{LIM}}$, for a given V_{MFC} from (7), that is needed to bring V_N within the allowed range ($V_N \geq V_S - \Delta V_{\text{LIM}}$).

Similarly, if PECs for PoLC are installed between the nodes k to N, there will be additional currents $I_{\text{PoLC}(k)}, I_{\text{PoLC}(k+1)}, \ldots, I_{\text{PoLC}(N)}$ flowing in the feeder. As a result, the equation for the voltage drop up-to node k can be modified as

$$\Delta V_k = \frac{Z_T I_T k}{N}\left(1 - \frac{k-1}{2N}\right) + \frac{Z_T k}{N}\sum_{n=k}^{N} I_{\text{PoLC}(n)} \tag{8}$$

$$= \frac{Z_T I_T k}{N}\left(1 - \frac{k-1}{2N} + \frac{1}{N}\sum_{n=k}^{N}\frac{V_{\text{PoLC}(n)}}{V_{F(n)}}\right) \tag{9}$$

where $V_{F(n)}$ is the feeder voltage and $V_{\text{PoLC}(n)}$ is the PEC voltage inserted at node n (where $n \in \mathbb{W}$ and $k \leq n \leq N$). If all loads are to be kept at 1.0 p.u., we can consider $V_{\text{PoLC}(n)} = 1.0 - V_{F(n)}$. The feeder node voltages can be calculated as

$$V_{F(n)} = V_k - \sum_{j=N-n+1}^{N-k}\frac{jI_T Z_T}{N^2} - \frac{Z_T}{N}\sum_{i=k+1}^{n}\sum_{j=i}^{N} I_{\text{PoLC}(j)} \tag{10}$$

$$= V_k - \frac{I_T Z_T (k-n)(k+n-2N-1)}{2N^2} - \frac{Z_T}{N}\sum_{i=k+1}^{n}\sum_{j=i}^{N}\frac{V_{\text{PoLC}(j)}}{V_{F(j)}} \tag{11}$$

Equations (9) and (11) can be solved to calculate the node k after which PECs for PoLC are required by considering $\Delta V_k = \Delta V_{\text{LIM}}$, $V_{\text{PoLC}(n)} = 1.0 - V_{F(n)}$, and $V_k = V_S - \Delta V_{\text{LIM}}$, just like the case of MFC.

3.2 Constant impedance loads

If PEC for MFC is installed at the node k and the change in the load voltages due to MFC is given by $\Delta V_{\text{MFC}}(j)$, we can express the equation for voltage drop from source to the node k as

$$\Delta V_k = \frac{Z_T}{NZ_L}\sum_{i=1}^{k}\sum_{j=i}^{N}(V_{F(j)} + \Delta V_{\text{MFC}(j)}) + \frac{Z_T k}{N} I_{\text{MFC}} \tag{12}$$

and

$$V_N = V_K + V_{\text{MFC}} - \frac{Z_T}{NZ_L}\sum_{i=1}^{N}\sum_{j=i}^{N}(V_{F(j)} + \Delta V_{\text{MFC}(j)}) \tag{13}$$

If PECs for PoLC are installed from nodes k to N, the equation for voltage drop to the node k is modified as shown below:

$$\Delta V_k = \frac{Z_T}{NZ_L}\sum_{i=1}^{k}\sum_{j=i}^{N} V'_{F(j)} + \frac{Z_T k}{NZ_L}\sum_{i=k}^{N}\frac{V_{\text{PoLC}(i)}}{V'_{F(i)}} \tag{14}$$

3.3 Constant power loads

For constant power loads, if P_T is the total power, the equation for voltage drop with no compensation can be expressed as

$$\Delta V_k = \frac{Z_T P_T}{N^2}\sum_{i=1}^{k}\sum_{j=i}^{N}\frac{1}{V_{F(j)}} \tag{15}$$

while $V_{F(n)}$ can be calculated by setting up a load flow problem and considering the source to be the slack bus.

With MFC, the voltage drop equation is modified to

$$\Delta V_k = \frac{Z_T P_T}{N^2}\sum_{i=1}^{k}\sum_{j=i}^{N}\frac{1}{V_{F(j)} + \Delta V_{\text{MFC}}(j)} + \frac{Z_T k}{N} I_{\text{MFC}} \tag{16}$$

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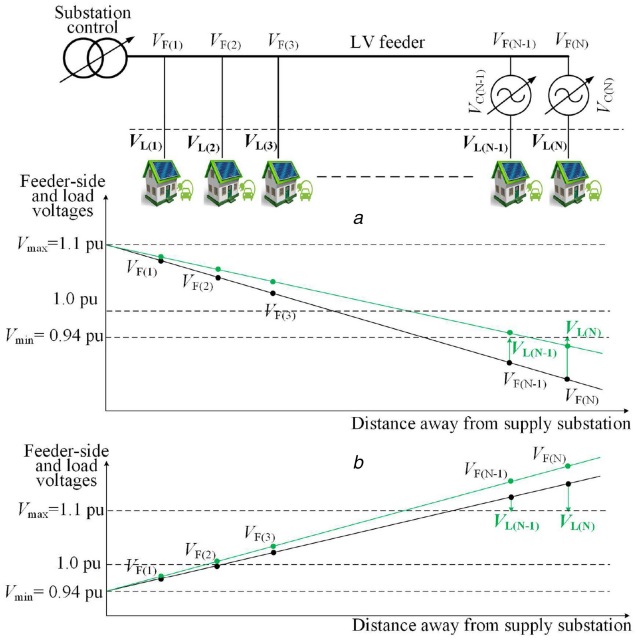


Fig. 3 *Typical voltage profile across the LV feeder using PoLC for* ***(a)*** Under-voltage and, ***(b)*** Over-voltage conditions

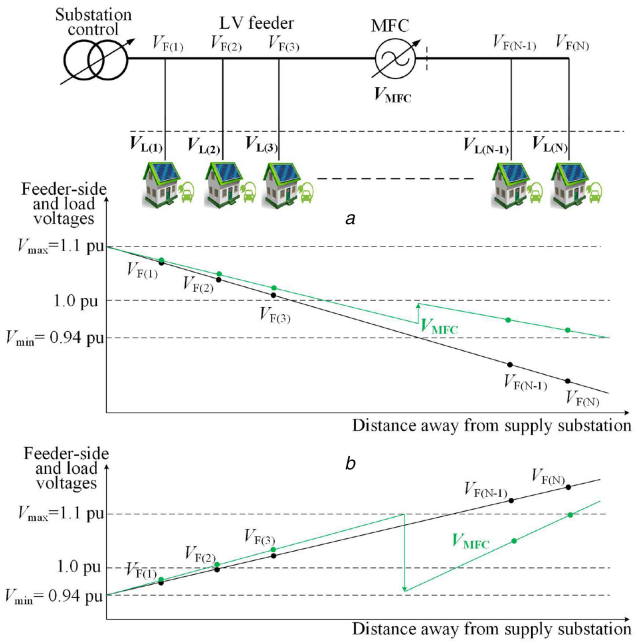


Fig. 4 *Typical voltage profile across the LV feeder using MFC for* ***(a)*** Under-voltage and, ***(b)*** Over-voltage conditions

where $\Delta V_{MFC}(j)$ is the change in the bus voltages due to MFC and I_{MFC} is the MFC current.

The equation for PoLC is given by

$$\Delta V_k = \frac{Z_T P_T}{N^2} \sum_{i=1}^{k} \sum_{j=i}^{N} \frac{1}{V'_{F(j)}} + \frac{Z_T P_T k}{N^2} \sum_{i=k}^{N} \frac{V_{PoLC(i)}}{V'_{F(i)}} \quad (17)$$

4 Point-of-load versus MFC

Typical feeder voltage profiles are shown for PoLC and MFC in Figs. 3 and 4, respectively, for both over- and under-voltage conditions. The loads are considered to be predominantly of constant power type in case of both over- and under-voltage conditions. This is a valid assumption as the worst over-voltage occurs during the daytime when the PV generation is close to its peak value while EV charging causes worst under-voltage during the night. Both PV and EV interface inverters can be considered to be of constant power type [2, 24].

4.1 Load and feeder voltages

Under-voltage: It is caused by charging of EVs which is commonly done in constant power mode. If PoLC is used to increase the load (including PV and EV) voltage within limits, the current drawn for EV charging would reduce resulting in a smaller voltage drop across the feeder (17). As a result, the feeder side voltages are improved throughout including the zone where PECs for PoLC are not required. The current drawn by the EVs in that zone would reduce (due to improved voltage) which helps improve the feeder voltages further. The same is true in the case of MFC. However, the feeder side voltages actually get worse if all the loads are of constant impedance type (13) and (14).

Over-voltage: It is caused by PV generation which, when held at their maximum power point act as constant power sources at a given point in time. For PoLC, the PECs decouple the residential customers from the feeder and can regulate individual load voltages (V_L) anywhere within the stipulated limits, preferably close to 1.0 p.u. As a result, the current injected by the corresponding PVs increase resulting in a larger voltage drop across the feeder, as shown by (17). It means the zone of voltage limit violation with PoLC could be larger than the nominal case (no PoLC). The feeder side voltages can become worse under compensation as compared to the case of no compensation. Although, constant current and constant impedance loads will counteract the increase in feeder voltage (9) and (14). Due to these opposing effects, the resulting increase in the feeder side voltage might not necessarily be worse than the nominal (without PoLC) case. However, in order to determine the zone in which PECs for PoLCs are to be installed, the worst-case scenario should be considered and all loads should be considered to be of constant power type.

For MFC, the PEC inserts a voltage in series with the feeder to maintain the voltages (feeder and load voltages are the same in this case) within the stipulated limits. Similar to the case of PoLC, voltages on the substation side of the MFC could be outside the stipulated limits for the over-voltage condition, if the location of MFC is not chosen carefully. It is important to solve (16) carefully for the worst over-voltage condition (considering all loads to be constant power) while choosing the location of MFC.

4.2 Compensator capacity

The rated capacity of individual PECs for PoLC would have to be a fraction of the net peak demand/generation of each residential customer depending on the desired voltage regulation capability and load type. Typically, the load voltages could be regulated to around 1.0 p.u. for most of the time of the day (as shown later) using about 5% (of peak demand/generation) capacity each for the series and shunt converters. For MFC, a single PEC (with same shunt–series arrangement) caters for a large number of loads and thus requires less overall rating (than the equivalent groups of PECs for PoLC) due to the load diversity factor. In case of PoLC, a PEC has to be placed at the connection point of each house. As a result, it has to be rated as a fraction of the peak household load that occurs for a very should duration during the day. In order to reduce the PoLC rating, it can be controlled to give-up the compensation action for a few mins during the peak domestic load. It can result in a much smaller PoLC ratting. However, in this paper, PECs for PoLC were considered to be operational for all load scenarios.

4.3 Reserve for voltage-driven demand response

The PoLC offer largest flexibility in regulating individual load voltages to minimum/maximum stipulated voltage. Hence, it can provide maximum reserve for voltage-driven demand response. With MFC, it is not possible to regulate the load voltages individually, which results in less reserve than PoLC depending on the location of the MFC and the existing loading condition.

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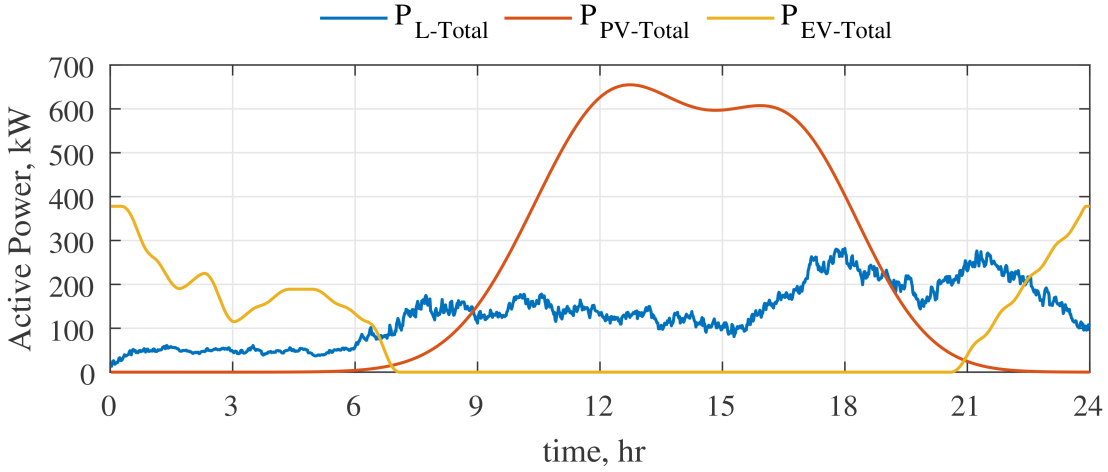


Fig. 5 *Variation in total demand, total PV generation and total EV charging power over 24 h of a typical summer weekday*

4.4 Losses

The PECs involved in PoLC and MFC would incur additional semiconductor losses which need to be considered. Typically, these losses are around 2% per converter for PoLC and 1.5% per converter for MFC which operates at higher power levels [25]. The overall losses would depend on the actual power processed by the PECs in each case which among other things is dependent on the loading profile.

4.5 PV throughput

The obvious way to tackle the over-voltage problem caused by PV generation is to control (curtail) the active power injected by the PV. However, this results in 'spilling' of PV power which is economically and environmentally unattractive. By using MFC and/or PoLC, the over-voltage could be tackled without having to 'spill' PV power. As both MFC and PoLC control the load voltages and hence the load power consumption in different ways, it is important to consider the overall PV throughput (which is the PV power flowing back to the grid through the substation) in each case to compare their effectiveness. The PV throughput would include the losses in PECs and the feeder which are different for MFC and PoLC.

In this section, a comparison between PoLC and MFC is presented general and qualitative terms. To account for the variability in loads, a case study on the IEEE European LV test feeder in presented next considering a stochastic demand profile for typical residential customers in the UK [9].

5 Test case

5.1 Study network

The IEEE European LV test feeder [26] is chosen for this study. It is a 416 V three-phase radial network with 55 single-phase residential customers (loads) connected across the three phases. As studying unbalance is not the focus here, only one particular phase with 21 residential customers is considered for the study. The rated capacity of the system is close to 600 kVA. The LV network is fed by a distribution transformer with an on-load tap-changer connected at the substation whose medium-voltage (MV) side is considered to be held at 1.0 p.u. To accommodate a larger number of residential customers in order to capture wider variability in residential load profiles, 9 such LV networks with 189 residential customers in total were considered to be connected to the substation.

5.2 Customer/load model

Stochastic demand profiles for the residential customers in the UK are generated using the tool developed by the Centre for Renewable Energy Systems Technology (CREST) [9] based at the University of Loughborough. Power consumption of each residential customer is obtained with 1 min resolution by randomising the occupancy level and the appliances used. This is based on a bottom-up modelling approach considering the active occupancy and daily activity profiles derived from survey data. Power–voltage dependence of each customer at a given time was determined from the power–voltage relationship of the appliances that are turned on. This eliminates the assumptions of constant impedance type non-critical loads that was made in the previous studies published on electric spring type compensators. It also eliminates the assumption that the non-critical load is available all the time. As the loads are not subjected to voltages outside the normal stipulated limits, we do not have to divide the load into critical and non-critical types. The load diversity factor is nearly 2.50. As, load operating voltages are always within the allowed range, these compensation techniques can be used for sustained voltage problems.

5.3 Voltage problems

To simulate the over-voltage condition, PV panels with a peak power of 3.5 kW were connected to each residential customer. An EV charging facility of 4.0 kW was considered at every alternate customer to create the under-voltage condition. A typical daily PV generation profile was obtained using an average solar irradiation data with a resolution of 1 min. A constant power charging scheme was assumed for the EVs [24].

The PV generation, EV charging the load variations for a typical summer weekday in the UK are shown in Fig. 5. Over-voltage occurs during the daytime when the PV generation is close to its peak value while EV charging causes under-voltage during the night. To simulate worst over- and under-voltage conditions, no overlap was considered between the hours of PV generation and the EV charging. It is to be noted that the feeder capacity was sufficient to accommodate peak PV generation and EV charging. The maximum reserve power flow through the substation is close to the total peak load demand (including EVs).

5.4 Power electronic compensator

For the simulation study, the controllers for converters were assumed to be ideal. In practice, non-ideal behaviour of the phase-lock-loop, finite response time of the converter control and the DC-link dynamics of the DC link would cause the voltage magnitude and phase angle to deviate from their reference values under transient conditions. As only the steady-state values are reported for each time instant, the above aspects were neglected. The location of PECs is chosen based on the equations provided in Section 3.

6 Voltage control

The test case described in Section 5 was simulated in MATLAB to highlight the limitation of using an onload tap-changer (OLTC)

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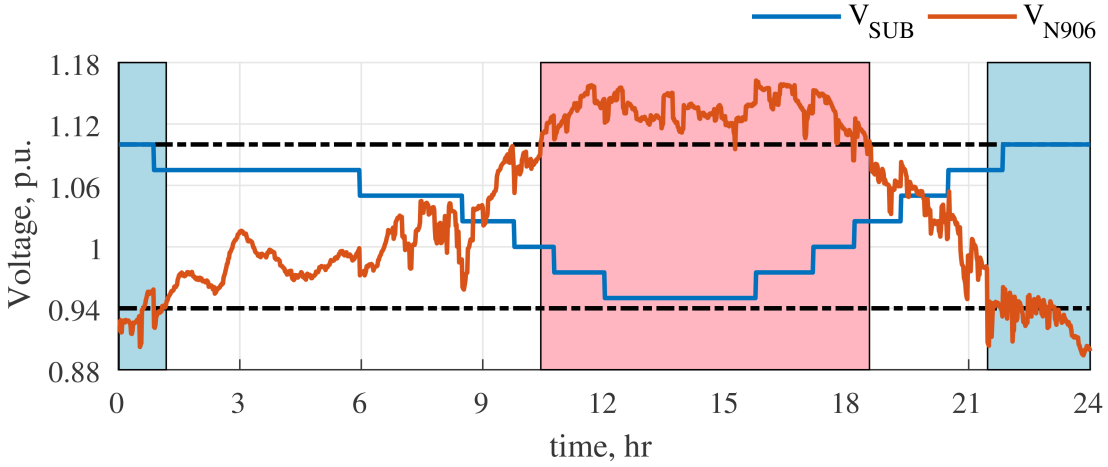


Fig. 6 *System parameters at the substation*
(a) Power flow through the substation, and ***(b)*** Voltages at substation with OLTC, and at Node 906 at the far end of the feeder

alone and demonstrate and compare the effectiveness of PoLC and MFC. This is described in the following subsections.

6.1 With OLTC only

Using a fast online tap-changer on at a distribution sublation is not a standard practice in the UK. However, such an arrangement is considered to highlight the fact that the voltage problems will exist at the far end of the feeder despite the use of an OLTC. The benefit of using MFC and PoLC is shown here in the presence of the OLTC action. It may be noted that without an OLTC, the voltage violation will be worse and it will make a case for MFC and PoLC stronger.

According to EN 50160, the steady-state voltages in the LV feeder should be maintained within 0.94–1.10 p.u. [15]. The tap positions of the distribution transformer could be adjusted according to the power flow to compensate for the line drop [6] and thereby, maintain the feeder voltages within the stipulated limits. The tap positions were adjusted according to this power flow which caused the substation voltage to vary as shown by the blue trace in Fig. 6. The red trace in Fig. 6 shows the voltage at Node 906 at the far end of the LV feeder. It is clear that this node voltage violates the stipulated limits (marked by the black dotted lines). Node 906 is seen to experience over-voltage (red zone) for almost seven hours during the day and under-voltages (blue zone) for about four hours which is unacceptable.

In fact, several other nodes of the LV feeder would also experience similar voltage problem to a different extent and over the different duration. To be precise, 17 out of the 21 residential customers in each of the 9 LV feeders experience voltage violation.

6.2 With PoLC

Activation of PoLC in the zone of voltage violation is expected to mitigate the voltage problems. The load and feeder-side voltages at Node 906 at the far end of the LV feeder under no control, PoLC and MFC are shown in Fig. 7. The zone in which PECs for PoLC are to be installed is calculated based on the worst-case scenarios discussed in Section 4 using the equations provided in Section 3.

It can be seen that PoLC can regulate the load voltage at 1.0 p.u. for most of the time during the day. Load voltage slightly deviates from 1.0 p.u. occurs when the voltage V_C injected by the PEC (Fig. 7*b*) is limited by the converter capacity, which is 5% of the peak load power. With PoLC, although the load voltages (Fig. 7*a* – red trace) are regulated close to 1.0 p.u., the feeder-side voltages (yellow trace) are slightly worse than the nominal case (with OLTC only – blue trace).

A similar trend is observed for other nodes across the feeder which is captured through the box plots in Fig. 8. The box plots cover all the node voltages over 24 h and give an idea about the minimum, maximum, mean values and the deviation from the mean values. It is clear that PoLC regulates most of the load voltages to 1.0 p.u. as indicated by the boxes with zero width (flat red lines in Fig. 8*b*) implying that the load voltages were held at 1.0 during this time. Some of the load voltages (e.g. at Node 906 in Fig. 7) cannot be maintained at 1.0 p.u. mainly during the over-voltage condition due to capacity constraint of the PECs. Nonetheless, Fig. 8*b* shows that even those load voltages are maintained within 1.05 p.u. Also Fig. 8*c* shows that the feeder-side voltages with PoLC are only slightly worse than the nominal case (Fig. 8*a*).

6.3 With MFC

The location where PEC is to be installed for MFC is calculated based on the worst-case scenarios discussed in Section 4. Fig. 7*a* shows that the MFC is able to maintain the voltage at Node 906 at the far end of the feeder within the stipulated limits which was not possible with OLTC only (blue trace). However, it not possible to regulate the node voltages close to 1.0 p.u. throughout the day as in the case of PoLC. The series voltage V_C inserted by the PEC used for MFC (shown in Fig. 7*c*) is determined based on the active (and the reactive) power flow through the MFC (Fig. 7*d*). The voltage at the input (substation side) of the PEC is shown in Fig. 7*e*.

The box plots in Fig. 9*b* show the statistical variation of all the node voltages over 24 h. It can be seen that MFC can maintain the voltages with the stipulated limits. However, the mean values are not close to 1.0 p.u. unlike the case of PoLC.

The above results with PoLC and MFC show that PoLC achieves better load voltage regulation but is not necessarily capable of maintaining all the feeder-side voltages within the stipulated limits for the over-voltage condition. Such violations could occur in general, in case of MFC as well on the substation side of the PEC which was not prominent in this study.

6.4 Comparison

A quantitative comparison between PoLC and MFC was presented in Section 4. Here it is substantiated by considering the specific test case. The total apparent power capacity of the PECs required for PoLC was compared against that of MFC as a percentage of the system rating. Fig. 10*a* shows the PoLC (16.3%) requires more than twice PEC capacity required for the MFC (7.1%) which could be mainly attributed to the load diversity factor which is close to 2.5. The ratings of PECs for PoLC can be significantly reduced, if they are designed to give up compensation action near the peak domestic load as in most cases it occurs only for a few minutes during the day. However, in order to keep the comparison fair, it was not considered in this study.

As both MFC and PoLC control the load voltage and hence the load power consumption in different ways, it is important to consider the overall PV throughput in terms of the PV power flowing back to the grid through the substation and compare against the option of voltage control using PV curtailment/spilling. As PoLC can maintain the load voltages close to 1.0 p.u., it produces slightly higher PV throughput than MFC as shown in

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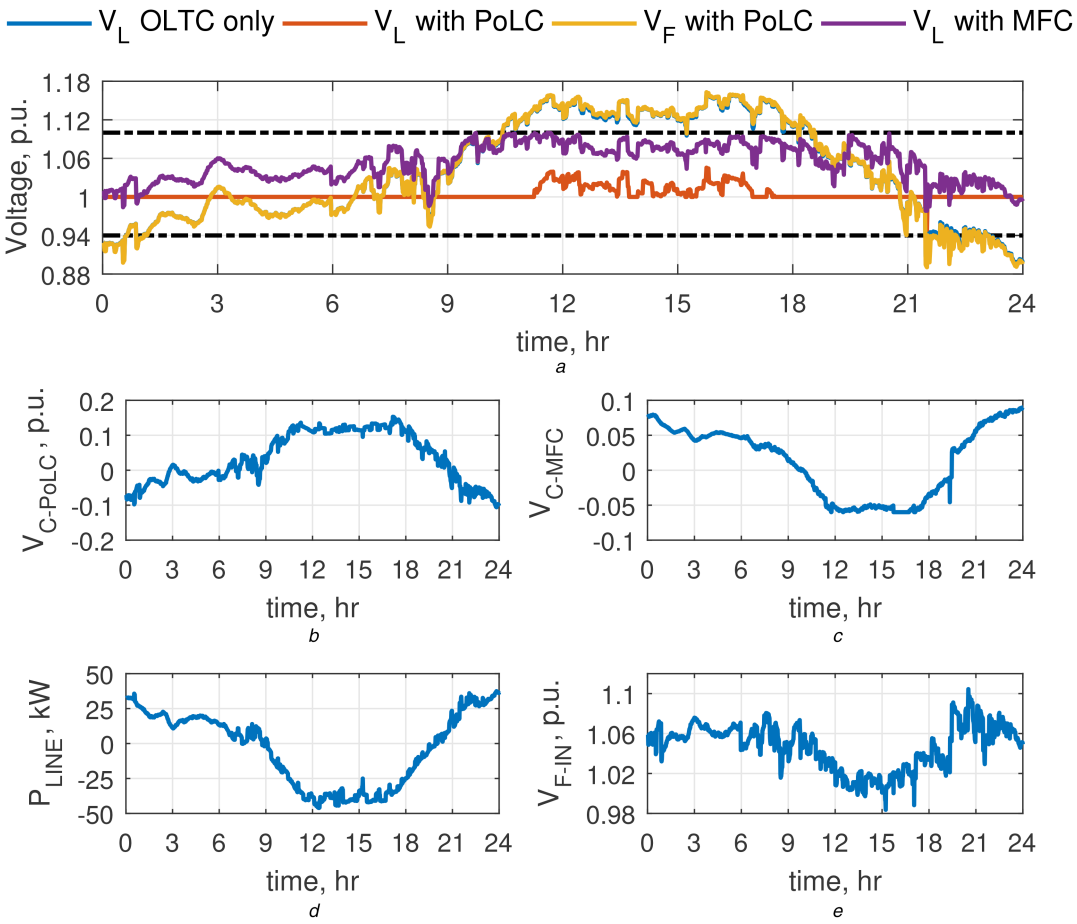


Fig. 7 *System parameters at Node 906 located at the far end of the LV feeder*
(a) Load and feeder-side voltages at Node 906 with OLTC only, with PoLC activated, and with MFC activated, ***(b)*** PEC voltage for PoLC at Node 906, ***(c)*** Compensator voltage for MFC, ***(d)*** Active power flowing through MFC, and ***(e)*** Input voltage to the MFC

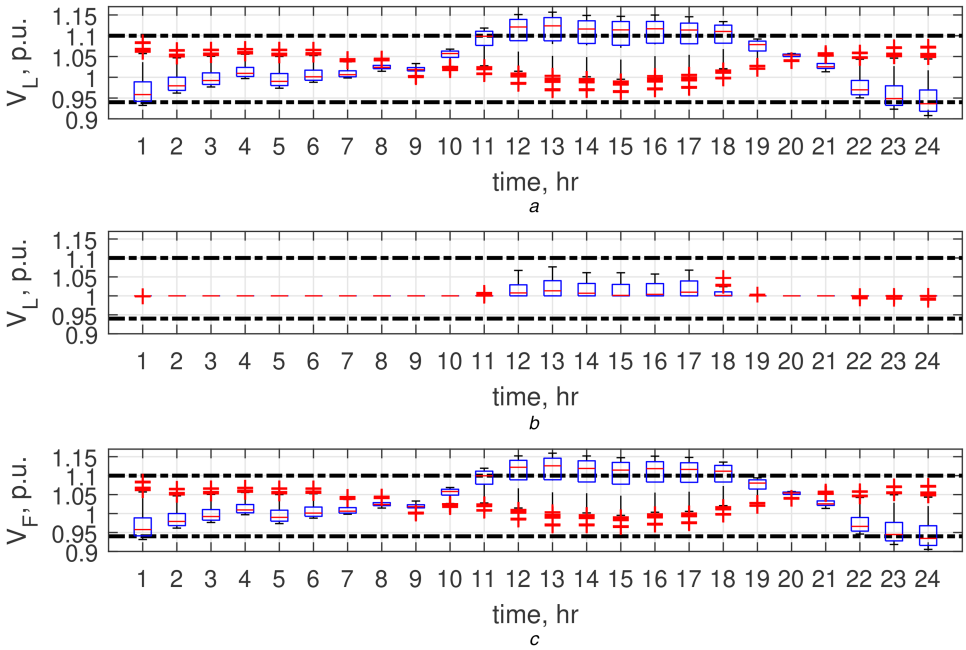


Fig. 8 *Box plots showing the distribution of*
(a) Feeder voltages with OLTC only, and ***(b)*** Load voltages and, ***(c)*** Feeder voltages throughout 24 h with PoLC activated

Fig. 10*b*. To show the effectiveness of PoLC/MFC, the option of controlling (curtailing) PV power using smart inverters to maintain the voltages within the stipulated over-voltage (1.10 p.u.) was studied. As expected, the PV throughput reduced drastically, which illustrates the need for using PoLC and/or MFC. PV curtailment will have a large economic impact. It may also be noted that such PV curtailment was only considered here for a comparison. It may not be possible to curtail large amounts of PV generation in a real-distribution system.

The PV throughput would include the losses in PECs and the feeder which are different for MFC and PoLC as shown in Fig. 10*c*. The total losses in the nominal case (with OLTC only) were 5.94%, which is typical in LV feeders [27]. For PoLC, the losses in the feeder are higher (6.11%) than the nominal case as the

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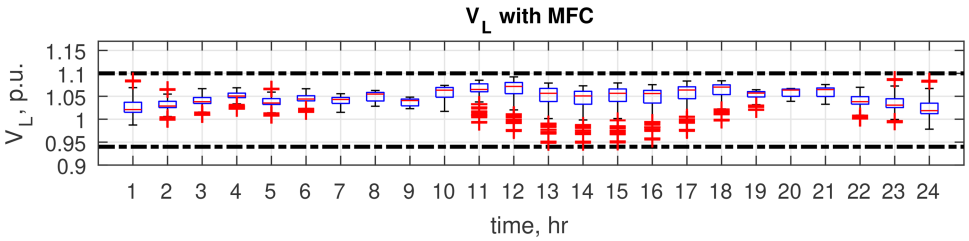


Fig. 9 *Box plots showing the distribution of feeder voltages throughout 24 h with MFC activated*

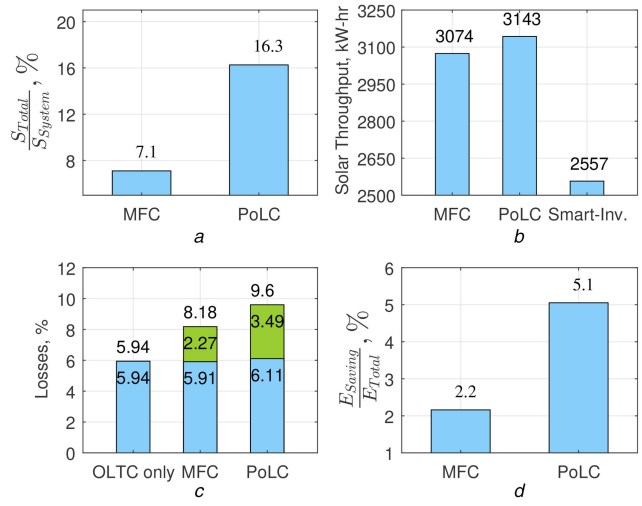


Fig. 10 *Comparison between different types of PECs*
(a) Total power capacity of PECs as a percentage of the system rating, ***(b)*** Total PV throughput, ***(c)*** Total losses–PEC losses, and ***(d)*** Percentage energy savings

reduction in load voltages result in larger current injection from PVs. Although the opposite is true for EV charging, the duration of PV generation is larger for the summer day considered here, which results in this slight increase in feeder losses. The semiconductor losses (green part) incurred in the PECs are higher for PoLC than MFC as more power in processed by the former with slightly larger percentage losses [25]. These losses include both the switching losses, which are proportional to the ratings of the converters, and conduction losses which are proportional power processed by these converters. Both MFC and PoLC can be bypassed with a mechanical switched when not in use to reduce the losses.

For PoLC, when voltage violations are not expected, the PECs could be controlled to maintain all the load voltages (where PECs are installed) at the minimum permissible level (i.e. 0.94 p.u.) to save energy by minimising the power consumption of voltage-dependent loads. Higher energy savings could be achieved with PoLC (5.1%) compared to the MFC (2.2%) as shown in Fig. 10*d*. This is because less reduction in load voltages is possible with MFC without violating the voltage limit at the far end. Typically, 2–3% energy saving is obtained with conservation voltage reduction [6] measures deployed at the substation level which highlights the effectiveness of PoLC.

High number of MFC/PoLCs (or any other fact switching device) will result in additional harmonics in the system. This is a well-known problem with the use of such compensators. It will especially be a problem when the converters are devised to respond to over- and under-voltage problems. PoLC can be designed to contribute in power quality improvement by providing a better voltage waveform to the loads than the input feeder voltage waveform. But it will result in further distortion of the feeder voltage.

7 Reserve for voltage-driven demand response

One way to exercise demand response is to control the voltage across the voltage-dependent loads and thereby, change their power consumption. Such voltage-driven demand response could be exercised by changing the feeder voltage [6]. However, for large voltage drops across the feeders (e.g. during high power injection from roof-top PV panels and/or charging of EV fleet) the depth of voltage change would be limited to maintain the voltages at the far end within the stipulated limits. This could be overcome to some extent using MFC and to a much greater extent using PoLC as illustrated here.

The amount by which the power consumption could be reduced through voltage control is henceforth referred to as ‘reserve’. The reserve available at any time depends on the amount and nature of voltage-dependent loads present and the nominal supply voltage across them. Such reserve would especially be needed under low demand condition when the overall system inertia is low (due to the high penetration of renewable with merit order priority) which makes grid frequency control very challenging [7, 8].

Typically under low demand condition (night hours) less proportion of voltage-dependent loads are connected. However, in the future, low demand conditions as seen from the grid supply points (GSPs) would occur during daytime when the output of distributed generation such as roof-top PV is significant [7]. As shown later, reasonable amount of reserve from voltage-driven demand response is available during the daytime, which could be utilised for grid frequency control.

The available reserve was determined considering two different under voltage limits. Alongside, the normal limit of 0.94 p.u., 0.8 p.u. was considered as most voltage-dependent loads (e.g. heaters etc.) are able to withstand this voltage for short duration (timescale of primary frequency control which is tens of seconds) without any disruptive impact. Same converter capacity as in Section 6 was considered for the PECs here which limits the capability to reduce the load voltages down to the minimum permissible level even with PoLC.

The reserve available with PolC and MFC on a typical summer weekday (considered in Section 6) is shown in Fig. 11. Figs. 11*a* and *b* show the total generation/load and net power flow at the substation. The reserve provided by PoLC (Fig. 11*c*) is significantly higher than that with MFC (Fig. 11*d*) for both voltage limits due to the reasons discussed in Section 4.3. For the normal under-voltage limit of 0.94 p.u. the reserve provided by MFC is zero during a large part of the daytime. This is due to the fact that the output voltage of PECs for MFC had to be controlled near 0.94 p.u. to maintain the voltages at the far end within 1.10 p.u. This shows MFC is not necessarily effective in providing reserve during the daytime which is exactly when it would be needed most as explained earlier. During the early hours of the day, the reserve available is very low due to lack of adequate amount of voltage-dependent loads.

To investigate the effect of seasonal variations in PV generation and loads, similar reserve calculation was done for a typical winter weekend. The results are shown in Fig. 12. It can be seen that the total demand is higher (Fig. 12*a*) than the previous case (Fig. 11*a*) largely due to higher occupancy level during the weekend and greater incidence of heating and lighting loads in winter. The PV generation is available for a shorter duration due to reduced hours of daylight. Due to the larger penetration of voltage-dependent loads and lesser violation of converter capacity during peak PV generation, the reserve is generally higher (Figs. 12*c* and *d*) than the summer weekday. The results presented in section confirm that PoLC is more effective than MFC towards exercising voltage-driven demand response.

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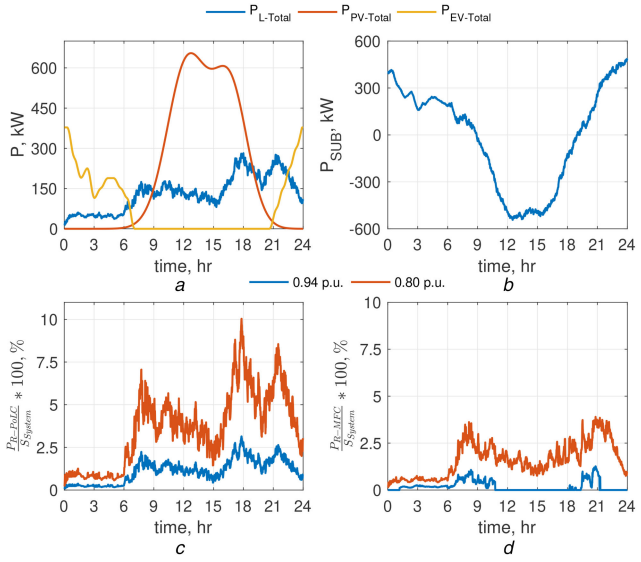


Fig. 11 *Reserve available with PolC and MFC on a typical summer weekday*

(a) Total active power consumption, total EV charging power and total PV generation, ***(b)*** Net power flow through the substation, ***(c)*** Reserve available with PoLC, and ***(d)*** Reserve available with MFC as a percentage of system capacity over 24 h of a typical summer weekday

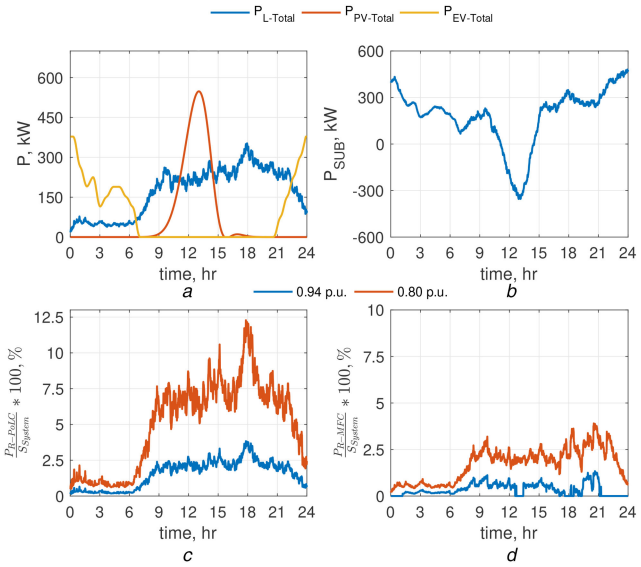


Fig. 12 *Reserve available with PolC and MFC on a typical winter weekend*

(a) Total active power consumption, total EV charging power and total PV generation, ***(b)*** Net power flow through the substation, ***(c)*** Reserve available with PoLC, and ***(d)*** Reserve available with MFC over 24 h of a typical winter weekend

8 Conclusions

The zone in which voltage violation occurs under compensation can be larger than the nominal case (under no compensation). Worst case scenarios should be considered while selecting the optimal location for PECs for both PoLC and MFC. Calculating the optimal location for MFC will allow much smaller PEC rating compared to the previously proposed method. Both PoLC and MFC are shown to be effective in controlling under- and over-voltage problems in LV distribution feeders. Although, PoLC requires overall higher converter capacity than MFC, it can produce better voltage regulation at the load terminals and also provides higher power reserve for voltage-driven demand response when it is required. With PoLC, larger PV throughput in achieved despite higher losses in the feeder and the PECs. Although, PoLC can regulate the load voltages around 1.0 p.u., the feeder-side voltages could still be outside the stipulated limits. PoLC is simpler to implement without requiring any communication, coordination or adjustments based on system condition. On the other hand, MFC either has to rely on remote communication or line drop compensation method to calculate the voltage at the far end. The latter is prone to some error. Both PoLC and MFC are highly effective in accommodating higher PV generation and EV charging than what is possible with OLTC action alone.

PoLC provides nearly 5–10% change in the active power of the loads at the time of peak PV generation which is the time when the overall demand in the system will be lower. It can contribute to the enhanced frequency response, especially considering that it will be a big problem under low demand conditions. This reserve is provided without violating the load voltage limits. The total converter ratings required are a fraction of system ratings. Hence, an effective simultaneous voltage and frequency control can be achieved. MFC is effective in voltage control with a smaller rating than PoLC, but it can provide a limited contribution in demand response for enhanced frequency control.

9 References

[1] Bollen, M.H.J.: '*Understanding power quality problems: voltage sags and interruptions*' (IEEE Press, New York, 2000)

[2] Westacott, P., Candelise, C.: 'Assessing the impacts of photovoltaic penetration across an entire low-voltage distribution network containing 1.5 million customers', *IET Renew. Power Gener.*, 2016, **10**, (4), pp. 460–466

[3] Quirós-Tortós, J., Ochoa, L.F., Alnaser, S.W., *et al.*: 'Control of EV charging points for thermal and voltage management of LV networks', *IEEE Trans. Power Syst.*, 2016, **31**, (4), pp. 3028–3039

[4] Frost, T., Mitcheson, P.D., Green, T.C.: 'Power electronic voltage regulation in LV distribution networks'. 2015 IEEE 6th Int. Symp. on Power Electronics for Distributed Generation Systems (PEDG), Aachen, Germany, 2015, pp. 1–7

[5] Silversides, R., Green, T., Merlin, M.M.C.: 'A high density converter for mid feeder voltage regulation of low voltage distribution feeders'. 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, USA, 2014, pp. 1972–1978

[6] Schneider, K.P., Tuffner, F.K., Fuller, J.C., *et al.*: 'Evaluation of conservation voltage reduction (CVR) on a national level'. Available at http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19596.pdf

[7] 'National Grid System Operability Framework 2015'. Available at http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/

[8] 'National Grid Enhanced Frequency Response 2016'. Available at http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx

[9] McKenna, E., Thomson, M.: 'High-resolution stochastic integrated thermal–electrical domestic demand model', *Appl. Energy*, 2016, **165**, pp. 445–461. Available at http://www.sciencedirect.com/science/article/pii/S0306261915016621

[10] Ghosh, A., Ledwich, G.: '*Power quality enhancement using custom power devices*' (Kluwer Academic, Boston, London, 2002)

[11] Hui, S.Y.R., Lee, C.K., Wu, F.F.: 'Electric springs – a new smart grid technology', *IEEE Trans. Smart Grid*, 2012, **3**, (3), pp. 1552–1561

[12] Chaudhuri, N.R., Lee, C.K., Chaudhuri, B., *et al.*: 'Dynamic modeling of electric springs', *IEEE Trans. Smart Grid*, 2014, **5**, (5), pp. 2450–2458

[13] Lee, C.K., Chaudhuri, N.R., Chaudhuri, B., *et al.*: 'Droop control of distributed electric springs for stabilizing future power grid', *IEEE Trans. Smart Grid*, 2013, **4**, (3), pp. 1558–1566

[14] Luo, X., Akhtar, Z., Lee, C.K., *et al.*: 'Distributed voltage control with electric springs: comparison with STATCOM', *IEEE Trans. Smart Grid*, 2015, **6**, (1), pp. 209–219

[15] Start, D.J.: 'A review of the new CENELEC standard EN 50160'. IEE Colloquium on Issues in Power Quality, Coventry, UK, 1995, pp. 4/1–4/7

[16] Chen, X., Hou, Y., Tan, S.C., *et al.*: 'Mitigating voltage and frequency fluctuation in microgrids using electric springs', *IEEE Trans. Smart Grid*, 2015, **6**, (2), pp. 508–515

[17] Akhtar, Z., Chaudhuri, B., Hui, S.Y.R.: 'Smart loads for voltage control in distribution networks', *IEEE Trans. Smart Grid*, 2016, **PP**, (99), pp. 1–10

[18] Sensarma, P.S., Padiyar, K.R., Ramanarayanan, V.: 'Analysis and performance evaluation of a distribution STATCOM for compensating voltage fluctuations', *IEEE Trans. Power Deliv.*, 2001, **16**, (2), pp. 259–264

[19] Akagi, H., Inoue, S., Yoshii, T.: 'Control and performance of a transformerless cascade PWM STATCOM with star configuration', *IEEE Trans. Ind. Appl.*, 2007, **43**, (4), pp. 1041–1049

[20] Mishra, M.K., Ghosh, A., Joshi, A.: 'Operation of a DSTATCOM in voltage control mode', *IEEE Trans. Power Deliv.*, 2003, **18**, (1), pp. 258–264

[21] Ainsworth, J.D., Davies, M., Fitz, P.J., *et al.*: 'Static VAr compensator (STATCOM) based on single-phase chain circuit converters', *IEE Proc., Gener. Transm. Distrib.*, 1998, **145**, (4), pp. 381–386

[22] Wang, S., Chen, S., Ge, L., *et al.*: 'Distributed generation hosting capacity evaluation for distribution systems considering the robust optimal operation of OLTC and SVC', *IEEE Trans. Sustain. Energy*, 2016, **7**, (3), pp. 1111–1123

[23] Daratha, N., Das, B., Sharma, J.: 'Coordination between OLTC and SVC for voltage regulation in unbalanced distribution system distributed generation', *IEEE Trans. Power Syst.*, 2014, **29**, (1), pp. 289–299

[24] Kejun, Q., Chengke, Z., Allan, M., *et al.*: 'Modeling of load demand due to EV battery charging in distribution systems', *IEEE Trans. Power Syst.*, 2011, **26**, (2), pp. 802–810

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[25] Schwingal, N., Bernet, S.: 'Power semiconductor loss comparison of low-voltage, high-power two-level and three-level voltage source converters'. Proc. of PCIM Europe 2015; Int. Exhibition and Conf. for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2015, pp. 1–9

[26] 'The IEEE European Low Voltage Test Feeder'. Available at http://ewh.ieee.org/soc/pes/dsacom/testfeeders/

[27] Limited, S.A.: 'Electricity distribution systems losses non-technical overview', Ofgem, 2009. Available at https://www.ofgem.gov.uk/sites/default/files/docs/2009/05/sohn-overview-of-losses-final-internet-version.pdf

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