Adoption of capacitors to mitigate voltage issues in low voltage networks with photovoltaic systems

ADOPTION OF CAPACITORS IN LV NETWORKS WITH PV SYSTEMS

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ABSTRACT

The penetration of residential-scale photovoltaic (PV) systems in LV networks is expected to increase over the next decades. However, clusters already exist and are resulting in voltage rise issues. This paper presents the adoption of capacitors to manage voltages when lower voltages at the busbar (required to cope with voltage rise in feeders with PV systems) result in even lower voltages in other feeders. The capacitors are placed in the more loaded LV feeders and are operated in a decentralised voltage-based control mode. Monte Carlo-based time-series (1-minute resolution) power flow analyses are carried out considering one capacitor bank or multiple capacitor banks connected in a real UK LV network. Results demonstrate that it is possible to effectively manage voltages by adopting the highest off-load tap position (lowest busbar voltage) and the coordinated control of capacitor banks. In the context of PV systems, this represents a much lower cost solution than LV OLTC-fitted transformers.

INTRODUCTION

The penetration of residential-scale photovoltaic (PV) systems in low voltage (LV) networks is expected to increase over the next decades. However, clusters already exist and are resulting in voltage rise issues. A potential solution to this particular problem is to provide a lower voltage at the busbar (i.e., head of the LV feeders) by adequately adjusting the tap position of the off-load tap changer. While this method performs well in a network where all feeders behave similarly due to an even distribution of PV systems and/or load among them, it would not be able to effectively manage voltages when feeders have contrasting voltage issues.

To achieve an effective voltage management for all feeders, many methods can be used, such as using on-load tap changer (OLTC)-fitted transformers, shunt reactors, and capacitor banks. The latter is the cheapest technology among them.

Capacitor banks are widely used around the world, predominantly in medium voltage (MV) networks. As discussed in [1], there are several reasons that justify their adoption, including: to increase voltage where the load is highly inductive; to improve voltage regulation by adequately switching capacitors; to reduce losses due to reduced active and reactive currents/power flows; and to release kVA capacity of the substation and, hence, defer reinforcements. However, in the UK, they are mainly used by industrial customers for power factor correction.

As for LV networks, worldwide, capacitors are not typically used because voltage management or power factor issues are commonly solved at MV networks. Nonetheless, given the future adoption of low-carbon technologies, primarily residential-scale PV systems, voltage management of LV circuits becomes more important. In this context, due to the different characteristics of feeders within the same LV networks, the benefits from using OLTC-fitted transformers can be limited [2].

This work proposes the use of capacitors to provide extra flexibility when lower voltages at the busbar (required to cope with voltage rise in feeders with PV systems) result in even lower voltages in more loaded feeders. Time-series (1-minute resolution) power flow analyses are carried out to assess the performance of the proposed decentralised control of capacitor banks. Two cases have been considered: one-cap and multiple-cap cases. The uncertainties surrounding the characteristics of residential PV generation and demand (i.e., location, size, and variability) are considered adopting a Monte Carlo approach. In addition, the particular characteristics of UK LV networks (i.e., three-phase four-wire feeders with single-phase connected loads), as well as detailed operational aspects of the capacitor banks, such as delays, switch-on and switch-off voltages are also modelled.

The proposed methodology has been applied to a real LV network as part of the UK Low Carbon Networks Fund Project "Low Voltage Integrated Automation (LoVIA)" [3]. In the context of residential-scale PV systems, this work explores the use of capacitors to manage voltage in LV networks. It is shown that this could be a much lower cost solution than LV OLTC-fitted transformers.

NETWORK MODELLING

Real UK LV Distribution Network

To implement the proposed methodology, a real UK LV residential distribution network is used. The 11kV/400V
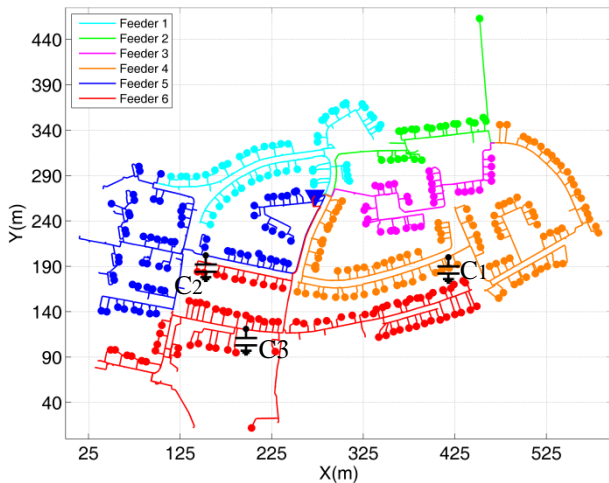
Figure 1. Real UK LV distribution network

network is comprised of six radial feeders (three-phase four-wire underground cables). The rated capacity of the distribution transformer is 500kVA. The topology of the network is shown in Fig. 1, where the triangle represents the transformer. Different feeders are shown in different colours and each solid dot represents a house/customer. There are 49, 21, 30, 100, 68 and 83 customers, respectively, in the six feeders (i.e., 351 in total), all with single-phase connections. As the latter three feeders have more customers than the former three, the mid points at the feeders 4, 5 and 6 are considered as the feasible locations for capacitors to be connected. C_1, C_2 and C_3 in Fig. 1 represent the corresponding three capacitor banks.

Load and Photovoltaic Profiles

The tool developed by the Centre for Renewable Energy Systems Technology (CREST) [4] is used for modelling the load profiles given its high time-granularity (1-minute). The load for each household is realistically modelled considering type of day, seasonality, occupancy and the associated use of electrical appliances [4].

For the network, the adopted number of occupants per household follows UK statistics, i.e., the percentage of houses with 1, 2, 3 and more than 4 persons are 29, 35, 16 and 20%, respectively. Once the occupant number for a household is determined, the load profiles are created adopting a particular day of the year. For PV systems, the same day is adopted and the corresponding generation is produced also using the CREST tool. Due to the area of LV networks, for a given day, all PV systems are considered to have the same generation profile. The nominal capacity of the PV systems is randomly selected from a range of 2.0 to 3.5 kWp.

Distribution Transformer

In the UK, the distribution transformer ratio is typically 11kV (or 6.6kV) to 433V. The off-load tap changer capability range is ±5% (5 tap positions, 2.5% per step) and is commonly set to the nominal tap position (position 3, ~250V line-to-neutral). To assess the benefits brought

by capacitors, tap positions 4 and 5, which will result in even lower voltage (~244V and ~238V, respectively) at the busbar, are considered in this paper.

METHODOLOGY

Voltage Boost Provided by Capacitor Banks

Feeders in distribution networks are typically operated in a radial fashion, and the LV feeders are normally constructed in a tree-like topology rooted at the distribution transformer. When capacitors are placed somewhere in an LV feeder, the capacitors will reduce the reactive power consumption or even inject reactive power to the feeder (depending on the capacitor size and how inductive loads are). This will reduce the voltage drop along the LV feeder, and hence increase the corresponding customer voltages. In this context, capacitors are used in feeders having low voltage problems, i.e., these feeders do not have PV systems or there is no PV generation.

Similarly, considering the secondary substation as a load point in the MV network, the integration of capacitors in LV feeders will also gain voltage at the primary side of the secondary substation. When an off-load tap changer-fitted transformer is used, which is common practice around the world, the voltage at the LV busbar will also increase. The busbar voltage gain will then result in the increase of the customer voltages at the adjacent feeders where no capacitors are placed.

In this paper, the voltage boost at node *i* provided by the *n*th capacitor, C_n, will be defined by the term $\Delta V_i^{C_n}$.

Voltage-Based Control of Capacitor Banks

Capacitor banks can be controlled by different control mode, including current-based control, voltage-based control, kVAr-based control, power factor-based control, and time-based control.

In this paper, the local voltage-based control is used. The curve in Fig. 2 shows the voltage at the capacitor connection point. The capacitor is switched ON when the voltage is lower than the pre-set "switch-on" value for a certain delay of T_{d-on}, and is switched OFF when the voltage is higher than the pre-set "switch-off" value for a time delay of T_{d-off}. The values of T_{d-on} and T_{d-off} can be tuned according to the characteristics of the capacitor.

These switch-on/switch-off voltage values have to be set properly to avoid frequent switching operation or hunting effects. For this purpose, ε is defined as the deadband, as shown in (1).

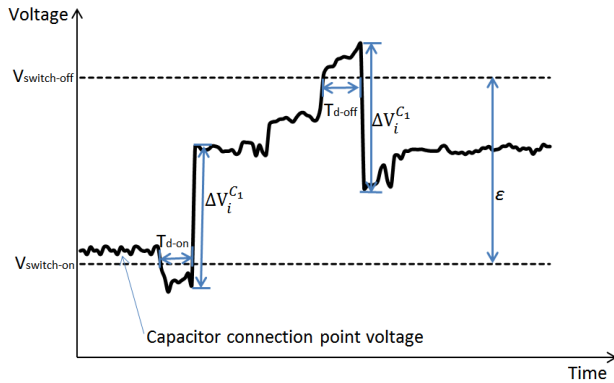$$\varepsilon = V_{switch-off} - V_{switch-on}, (\varepsilon > 0) \qquad (1)$$

Figure 2. Voltage-based control of the capacitor banks

One-Cap Case

When a network has only one capacitor bank connected, the deadband (ε) has to be larger than the corresponding voltage boost at the connection point (CP). This constraint is shown in (2).

$$\varepsilon > \Delta V_{CP_1}^{C_1} \qquad (2)$$

Multiple-Cap Case

When a network has multiple capacitor banks connected, to allow all capacitors being able to switch ON simultaneously, the set deadband for each capacitor bank has to be larger than the sum of all the voltage boosts, at the corresponding capacitor connection point. This constraint is shown in (3), assuming there are N capacitor banks connected to the network.

$$\varepsilon_n > \sum_{k=1}^{N} \Delta V_{CP_n}^{C_k} \qquad (3)$$

where n is the nth capacitor bank in the network.

Voltage Constraints

The voltage at each node of the LV network must be maintained within the statutory limits, as shown in (4).

$$V_{min} \leq V_i \leq V_{max} \qquad (4)$$

The voltage limits in UK LV networks are $+10/−6\%$ of nominal, i.e., 253V (1.10 p.u.) and 216V (0.94 p.u.) line-to-neutral. Compliance with these limits is checked according to the BS EN50160 standard [5], by which 95% of voltages (10-min average rms values) within a week must be between 1.10 and 0.90 p.u., and never outside 1.10 and 0.85 p.u.

Implementation of the Methodology

Monte Carlo-based three-phase power flow analyses are carried out to assess the maximum PV penetration a network can host without causing any voltage or thermal issues with different off-load tap positions and scenarios with and without capacitors.

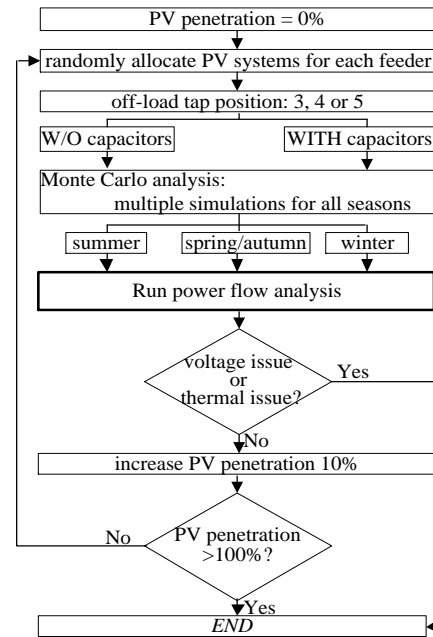The flow chart in Fig. 3 shows the implementation procedure. For each case (tap position 3, 4 or 5,

Figure 3. Flow chart to implement the proposed methodology

with/without capacitors), the PV penetration increases from 0 to 100%. The PV penetration is defined as the percentage of houses with PV systems from the total number of houses in the network. When a voltage or thermal issue occurs, the procedure for that particular case will be terminated and the previous penetration is considered as the maximum hosting PV capacity of the network. For a certain penetration, PV systems are randomly allocated assuming all feeders have the same penetration level. Multiple simulations for the three seasonal categories (50 per season) are carried out.

CASE STUDY

The proposed methodology is applied to the residential, UK LV network presented in Fig. 1. The distribution system analysis software package OpenDSS [6] and MATLAB are used to run the power flow simulations.

Voltage Boost Provided by the Capacitors

The three capacitors (C_1, C_2 and C_3) considered in this work are three-phase with a rating of 50 kVAr (16.7 kVAr per phase). Fig. 4 and Fig. 5 show the voltage snapshots for the 6 feeders at 12:48 of a day (weekday, October) without and with a capacitor in feeder 5 (C_2). It can be seen that this capacitor brought voltage gains at feeder 5 as well as at the busbar and the remaining feeders.

To adequately set the switch-on and switch-off voltages of single or multiple capacitor installations, the voltage boosts provided need to be quantified. Voltages at the busbar and mid and end points of all feeders were examined for different 50 kVAr capacitor installations.
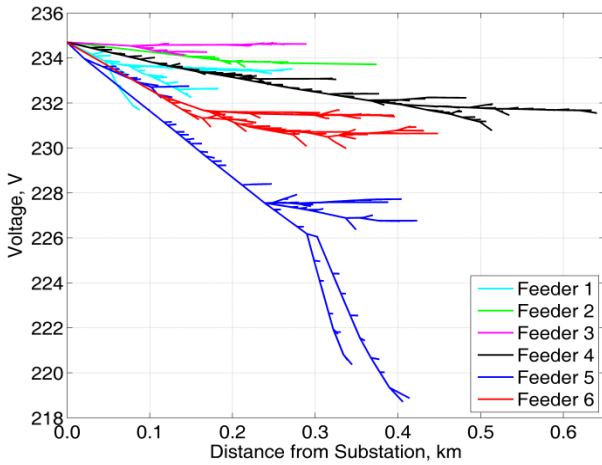
Figure 4. Voltage snapshot (12:48, weekday, October) for the 6 feeders, without capacitors, off-load tap position 5
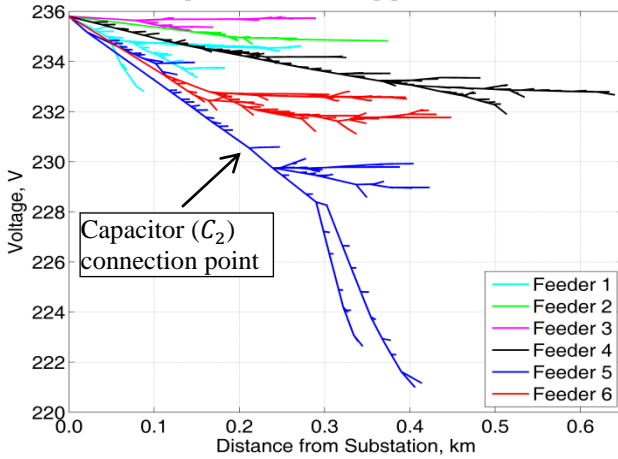

Figure 5. Voltage snapshot (12:48, weekday, July) for the 6 feeders, with capacitors (C_2), off-load tap position 5

The voltage gains were found by comparing these voltages with and without the capacitors. Table 1 shows the daily average voltage gain at the busbar as well as mid and end points of all LV feeders (voltages at each time step are the average of the three phases) considering the installation of single, pairs and three capacitors. For the purpose of quantifying the voltage gain, in each case the capacitor banks were assumed to be connected all the time without any control.

Capacitor Settings

Switch-on Voltage: It is assumed that the use of capacitors could keep voltages at the feeder far ends higher than 0.96 p.u. (2% headroom compared to the lower statutory limit), i.e., L-N 221.7V. Consequently, if the capacitor is placed at the end point of the feeder, a suitable switch-on voltage would be 0.96 p.u.

In the studied LV network, the capacitors are placed approximately in the mid-point of the feeders. Given that there is an assumed 6% voltage drop along an LV feeder during peak load, it can be considered that for an end-point voltage of 0.96 p.u., the mid-point voltage would be 0.99 p.u. Therefore the switch-on voltage can be calculated as shown in (5).

Table 1 Voltage boost brought by the 50 kVAr capacitors

Capacitor	Busbar	F1		F2		F3		F4		F5		F6	
		M	E	M	E	M	E	M	E	M	E	M	E
$\Delta V_i^{C_1}$ (V)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	2.7	2.7	1.2	1.2	1.2	1.2
$\Delta V_i^{C_2}$ (V)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	2.3	2.4	1.2	1.2
$\Delta V_i^{C_3}$ (V)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	2.3	2.3
$\Delta V_i^{C_1} + \Delta V_i^{C_2}$ (V)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.7	3.9	3.5	3.6	2.0	2.0
$\Delta V_i^{C_1} + \Delta V_i^{C_3}$ (V)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.6	3.6	2.0	2.0	3.5	3.5
$\Delta V_i^{C_2} + \Delta V_i^{C_3}$ (V)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.1	3.1	3.1	3.1
$\Delta V_i^{C_1} + \Delta V_i^{C_2} + \Delta V_i^{C_3}$ (V)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	4.7	4.7	4.3	4.3	4.3	4.3

Table 2 Settings for capacitor banks

Capacitor	voltage (V)		delays (s)	
	switch-on	switch-off	switch-on	switch-off
C_1	228.6	235	60	100
C_2	228.6	235	80	80
C_3	228.6	235	100	60

$$(0.96 + 0.03) * 230.94V = 228.6V \qquad (5)$$

One-cap case

Switch-off Voltage: According to (2) and the voltage boost provided by one capacitor, the suitable switch-off voltage for the one-cap case would be 232.6V.

Multiple-cap case

Switch-off Voltage: To allow all the three capacitor banks being able to switch ON simultaneously, according to (3), the difference between switch-off and switch-on voltages has to be larger than 4.7V.

Delays: A specific switch-on/switch-off sequence of these capacitor banks is considered based on the loading of the feeders.

For the studied network, the proposed settings for the three capacitors are shown in Table 2. These capacitors are operated in a decentralized voltage-based control.

Capacitor Operation and Simulation Results

Fig. 6 shows a daily (weekday, October) active power consumption of the 6 feeders and the whole network. Fig. 7 and Fig. 8 present the voltage profiles of the capacitor connection points and the corresponding daily operation of the capacitors. It can be seen that capacitor C_1 was switched ON at 08:00, and capacitor C_3 was then switched ON at approximately 16:30. The capacitor bank C_2 was switched ON around 19:00. The three capacitors were switched OFF at similar times close to midnight. This demonstrates that the proposed deadbands and delays are providing the required coordination among the three capacitor banks.
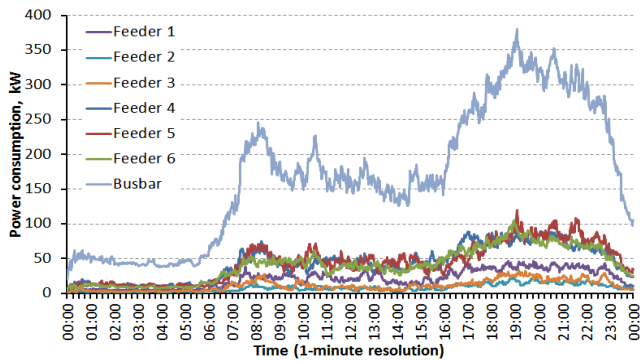
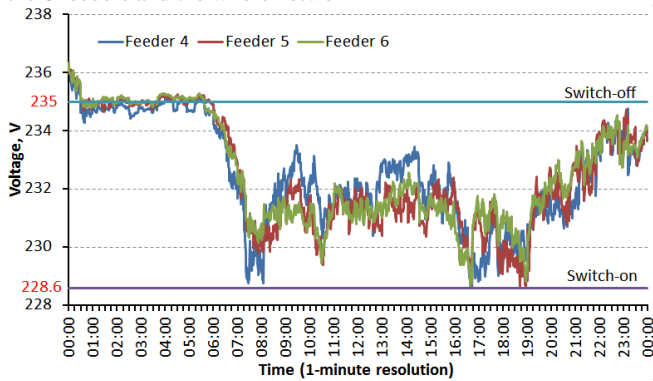**Figure 6.** Daily (weekday, October) active power consumption in the 6 feeders and the whole network

Figure 7. Daily (weekday, October) voltage at the capacitor connection points with the proposed settings for the capacitors and off-load tap position 5
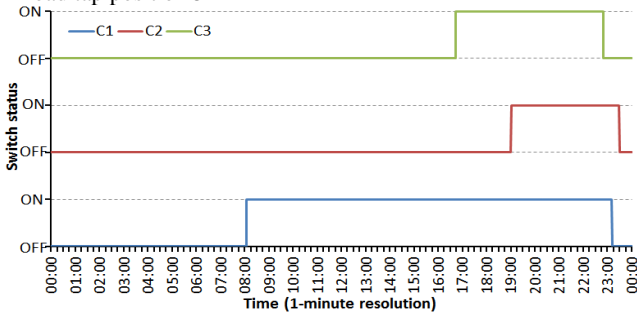

Figure 8. Daily (weekday, October) capacitor operation

Table 3 Maximum PV penetration

Off-load tap changer tap position	Capacitor banks	Max PV penetration, %
3	No	30
	Yes	30
4	No	40
	Yes	40
5	No	50
	Yes	60

Table 3 presents the maximum PV penetration when adopting different off-load tap positions and with/without three capacitors. It is shown that by increasing the off-load tap position from the business-as-usual case of position 3 to positions 4 or 5, the maximum PV penetration can be increased from 30 to 40% or even 50%. This number can be further increased to 60% when the capacitors are used to solve the low voltage problems.

Discussion

The LoVIA project adopted for the trial much larger capacitors (150 kVAr three-phase bank). Simulations and the trial both showed that these 150 kVAr capacitors resulted in voltage gains around 17V. This suggested that smaller devices could be used as smaller gains would still be suitable for LV networks. Consequently, 50 kVAr capacitors were adopted in the analysis carried out in this paper.

Nonetheless, in terms of the capital expenditure, even with three 150 kVAr capacitor banks, the device and installation costs (£6,400 per bank) would still be cheaper than the use of OLTC (approximately £36,500; device and installation without remote monitoring).

It is important to highlight that the analysis did not consider significantly low voltages that may occur at the primary side of the distribution transformer. In those cases, the capacitors may bring benefits even earlier. Similarly, the adoption of new loads, such as electric heat pumps and electric vehicles, are potential scenarios where the use of capacitors may also prove cost effective.

CONCLUSIONS

This work presents the investigation into the use of three-phase capacitor banks to mitigate voltage problems in residential, underground UK LV networks resulting from high penetrations of domestic-scale PV systems. The analysis carried out on a real UK LV network shows that its hosting PV capacity can be increase from 30 to 60% by adequately adopting the highest off-load tap position and the coordinated (yet decentralised) control of capacitor banks. In the context of PV systems, this represents a much more cost-effective solution than the adoption of LV OLTC-fitted transformers.

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