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Voltage Control in LV Networks Using Electric Springs With Coordination

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***Abstract*—The increasing use of distributed generation like rooftop solar panels and charging of large fleets of electric vehicles will result in over- and under- voltage problems in the low voltage (LV) distribution networks. Distributed electric springs have been proposed as an effective way of controlling these voltage problems. However, when multiple distributed electric springs are activated in a system, each electric spring tries to correct the local voltage problem. As a result, two groups of electric springs located in two different sections of the same radial network can be competing against each other at any given time. In the past, droop control has been suggested as a solution to avoid this conflict. This paper highlights the problem with simple drop control of electric springs in a radial distribution network and presents coordination between electric springs as an alternative. A comparison between the droop control and the coordinated droop control option is presented in terms of their voltage control capability, and required compensator capacity. It is established by means of a case study on a typical European LV network with stochastic demand profile for different types of residential customers.**

***Index Terms*—Coordinated droop control, droop control, distributed voltage control, electric spring, electric spring coordination, LV networks**

I. INTRODUCTION

The increasing use of distributed generation (DG) like rooftop photovoltaic (PV) generation would cause over-voltage problem in low-voltage and/or medium voltage (LV/MV) distribution networks [1], [2]. Managing the distribution system voltage is essential for economical, efficient and safe transfer of active power in distribution networks. There are reverse (active) power flows in the radial distribution networks when PV generation is close to its peak. As a result, the terminal voltages at the far end of a radial distribution feeder can be higher than the maximum allowed voltage limit.

On the other hand, charging the growing fleet of electric vehicles (EV) during the night could lead to under-voltage problem even during otherwise off-peak hours [3]. The power consumption by an EV charger is much higher than the total load of an average domestic customer. It results in very high currents (and hence higher voltage drops) in the system when EVs are being charged. These voltage problems could potentially become unacceptable with increasing penetration of PVs/EVs.

Control of node voltages though reactive power is very efficient in power transmission systems. However, reactive shunt compensators on their own are not very effective in controlling the voltage at the LV network level. LV distribution networks typically have a high R/X ratio. It means that the reactive power control devices require to inject very high values of reactive power in the LV system in order to change the system voltages. If voltages are to be controlled using reactive power compensation only, the required ratings of reactive compensation devices turn out to be very high.

Control of active power flow is possible through either use of distributed energy storage [4], [5] and/or control of active power consumption of the loads. While the former could be quite expensive, the latter could be effectively used with certain types of loads without noticeable impact for the customers. Recently electric spring (ES) has been proposed an alternative approach to employ continuous control over the power consumption of a load by decoupling it from the supply mains using a series compensator (converter) [6]. Distributed ESs are found to be very effective in controlling the distribution system voltages [7], [8].

However, one problem with distributed ESs is that they can be competing against each other as each ES tries to solve a local voltage problem. In the past, droop control has been proposed as a solution [9]. In this paper, it is shown that simple droop control will not be useful in preventing distributed ESs from working against each other. Coordination between ESs is proposed for the first time. It is shown that with coordination, the rating requirements of the ESs will reduce massively. Although, coordination will require some sort of communication infrastructure which comes at an extra cost. However, the cost of communication can be justified by the massive savings that are observed in the converter ratings as a results of coordination to achieve a similar or a better voltage control compared with ESs with uncoordinated droop control.

II. ELECTRIC SPRING CONCEPT

Loads can be divided into two categories; critical loads that require a tightly regulated supply voltage for normal operation and non-critical (NC) loads which can tolerate a larger variation in supply voltage without causing perceivable change in their performance. Some of these non-critical loads

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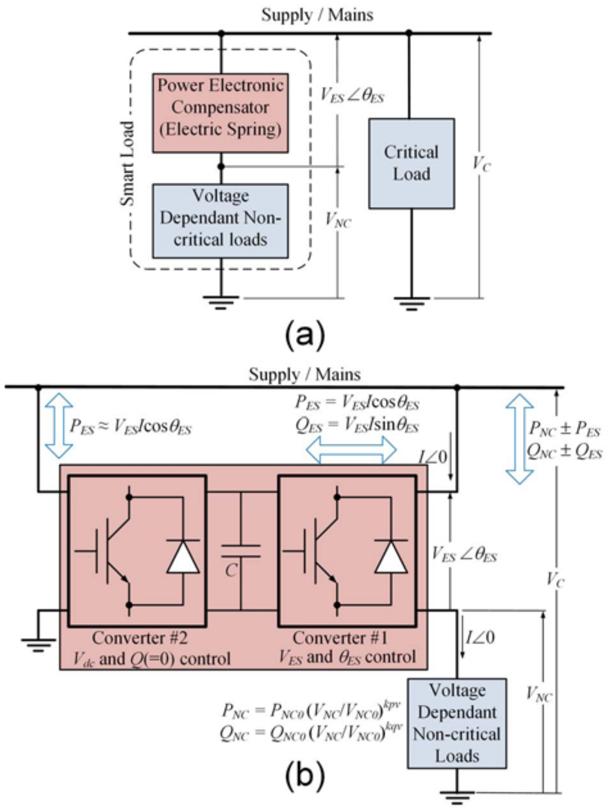


Fig. 1. (a) Smart load concept and (b) Smart load with back-to-back converters (SLBC)

consume constant power over a wide range of supply voltage variation (e.g. air-conditioners), while for others, the power consumption is dependant on the supply voltage (e.g. heaters, lighting systems). The voltage dependant NC loads can be converted into smart loads by inserting a voltage compensator (or ES) in series between the supply/mains and the NC load as shown in Fig. 1.

ES is a power electronic compensator that injects a voltage with controllable magnitude (V_{ES}) in series with the NC load. The voltage (V_{NC}) across the NC load is thus controlled (within allowable bounds) and the power consumed by it is modulated. If the injected voltage is maintained in quadrature with the current flowing though the electric spring (ES), there is no active power contribution from the ES. This type of smart load is called smart load with reactive compensation (SLQ).

If there is no restriction on the angle of the ES voltage, both active and reactive powers of a smart load can be controlled simultaneously. However, this active power exchange is only possible by a back-to-back converter arrangement where a bi-directional AC-to-DC converter facilitates the active power exchange of the series converter. This type of smart load is called a smart load with back-to-back converters (SLBC) and is shown in Fig. 1(b). In this arrangement, converter 1 can inject any voltage in series with the NC load while converter 2 facilitates the active power exchange of the converter 1 by maintaining the dc link voltage. As SLBCs are shown to be more effective than SLQs in voltage control in LV networks with high R/X ratio [8], we will only consider SLBCs in this paper. The 'controller' block for converter 1 is described later in Section. III.

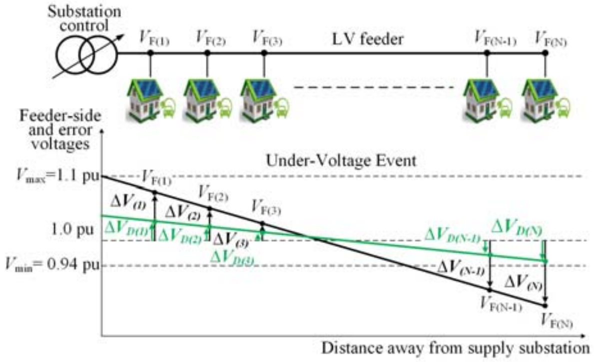
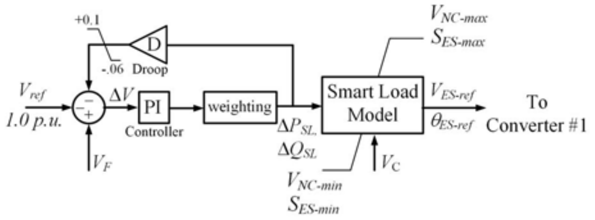


Fig. 2. Typical voltage profile across the LV feeder and modification in voltage profile with SLBCs with droop control

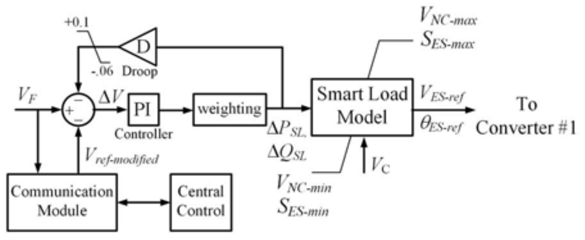
III. DROOP CONTROL VS COORDINATED DROOP CONTROL

Typical voltage profile of a radial LV feeder is shown in Fig. 2. It can be seen that there is an under-voltage at the far end of the feeder (black trace). In order to tackle the under-voltage problem, the distribution substation voltage is set at 1.10 p.u. If voltage control devices are distributed along the feeder, the control devices close to the start of the feeder will see an over-voltage problem (positive values for ΔV) while the devices at the far end of the feeder will see an under-voltage problem (negative values for ΔV). This can result in two groups of control devices to compete against each other. In the past, droop control was presented as a solution to overcome this problem [9]. If all voltage control devices have a droop control, the new voltage profile of the system will look like the green trace in Fig. 2. It has a smaller slope and all voltages are closer to 1.0 p.u. However, there is still a competition between the control devices at the start of the feeder and the devices at the far end of the feeder. Although, the overall voltage profile is improved by using droop control, but there is an unnecessarily high control effort needed to counter the opposing actions of two groups of voltage control devices. This problem can be avoided if the reference voltages for droop control for the voltage control devices at the start of the feeder are modified such that they do not try to reduce the feeder voltage. It can enable us to achieve better voltage profile with relatively smaller number of voltage control devices or a smaller rating of these devices. A similar case can be setup for the over-voltage scenario. The details of simple droop control and coordinated droop control are presented in this section.

The control objective is to vary the active and reactive power consumption of a smart load by varying the voltage across the voltage dependent non-critical loads in order to regulate the feeder voltage. The control loops for an SLBC with droop control and an SLBC with coordinated droop control are shown in Fig. 3(a) and (b), respectively.



(a) SLBC Droop Control



(b) SLBC Co-ordinated Droop Control

Fig. 3. Control loop for voltage control using (a) droop control and (b) using coordinated droop control for an SLBC

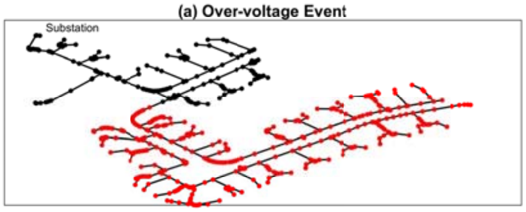
For an SLBC with droop control, difference between the reference voltage (V_{ref}) and the measured feeder voltage (V_F) i.e. ΔV is fed to a PI controller to calculate the required ΔQ_{SL} and ΔQ_{SL}, based on a weighting factor that is shown according to the system R/X ratio. These values are then fed to a smart load model along with supply voltage (V_C), the limits for variation in non-critical load voltage (V_{NC-min}, V_{NC-max}) and the converter/ES reactive power limits (Q_{ES-min}, Q_{ES-max}). The smart load model calculates the required electric spring voltage magnitude (V_{ES-ref}) and angle (θ_{ES-ref}) for convertor no. 1 of an SLBC. A droop gain (D) modifies the reference voltage (V_{ref}) within allowed limits of $+0.1$ and $-.06$ p.u. The control diagram for coordinated droop control is a little different as it involves communication of the feeder voltage value to a central controller. The central controller can send back the modified reference value so that the SLBCs can be stopped from working against each other. This reference voltage can be modified every 1 or 2 minutes.

IV. CASE STUDY

A. Study Network

For this study, the IEEE European Low Voltage (LV) test feeder [10] shown in Fig. 4 was considered. It is a three phase radial network rated at 416 V with 55 single phase residential customers (loads) connected across the three phases. As studying unbalance was not the focus here, only one particular phase with 21 residential customer was considered for the study. The LV network is fed by a distribution transformer with an on-load tap-changer connected at the substation. Using a fast online tap-changer on at a distribution sublation is not a standard practice in 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 medium voltage (MV) side of the transformer is considered to be connected through an impedance to an infinite bus held at 1.0 p.u. to represents the upstream network.

(a) Over-voltage Event



(b) Under-voltage Event

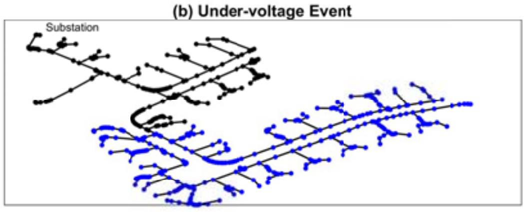


Fig. 4. Nodes of the LV feeder experiencing (a) over- and (b) under-voltages at any time during the summer day.

B. Customer/Load Model

In order to consider real loads along with their dependance on terminal voltage, stochastic demand profiles for the residential customers in the UK were generated using the tool developed by the Centre for Renewable Energy Systems Technology (CREST) [11] based at the University of Loughborough. Power consumption of each residential customer was obtained with one minute resolution by randomizing the occupancy level and the appliances used. 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 and that non-critical loads are available all the time. These two assumptions were made in the previous studies published on electric spring type compensators. Roughly half of the domestic loads were chosen to be non-critical loads. A voltage tolerance of ± 20 % was considered for all non-critical loads.

C. Photovoltaic Generation and Electric Vehicle Charging

To simulate the over- and under-voltage conditions, photovoltaic (PV) panels with a peak power of 3.5 kW are considered to be connected to each residential customer, while an electric vehicle (EV) charging facility of 4.0 kW is considered at every alternate customer. A typical daily PV generation profile is obtained using an average solar irradiation data with a resolution of 1 minute.

The PV generation, EV charging the load variations for a typical summer week day in the UK are shown in Fig. 5. Overvoltage occurs during the day time when the PV generation is close to its peak value while EV charging causes undervoltage during the night. To simulate worst over- and under-

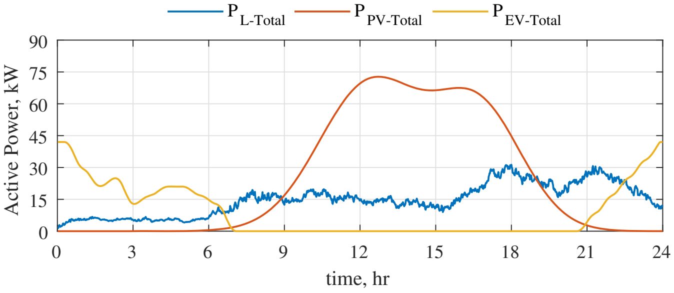


Fig. 5. Variation in total demand, total PV generation and total EV charging power over 24 hours of a typical summer weekday

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) as shown in Fig. 6(a).

V. SIMULATION RESULTS: VOLTAGE CONTROL

The test system described in the previous section is simulated in MATLAB. The results of the simulation studies are discussed in this section.

The steady-state voltages in the LV feeder should be maintained within 0.94 to 1.10 p.u. [12]. The tap positions of the distribution transformer are continuously adjusted according to the power flow which caused the substation voltage to vary as shown by the blue trace in Fig. 6(b). The red trace in Fig. 6(b) 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 and under-voltages (blue zone) for about four hours during the day, which is unacceptable. In fact, several other nodes of the LV feeder would also experience similar voltage problems. Fig. 4 shows all the nodes of the LV system that experience an over-voltage (Fig. 4(a)) and an under-voltage (Fig. 4(b)) during the course of the summer day considered for the study. It can be seen that well over half of the feeder is affected despite the OLTC action.

Fig. 7 shows that both droop control and coordinated droop controlled SLBCs are able to bring back the voltage at node 906 within the allowed limits. However, it can be seen that the droop control results in a tighter bound of voltage around 1.0 p.u compared to the coordinated droop control. This is due the phenomenon discusses in Section. III. This results in a higher compensator ratting requirement.

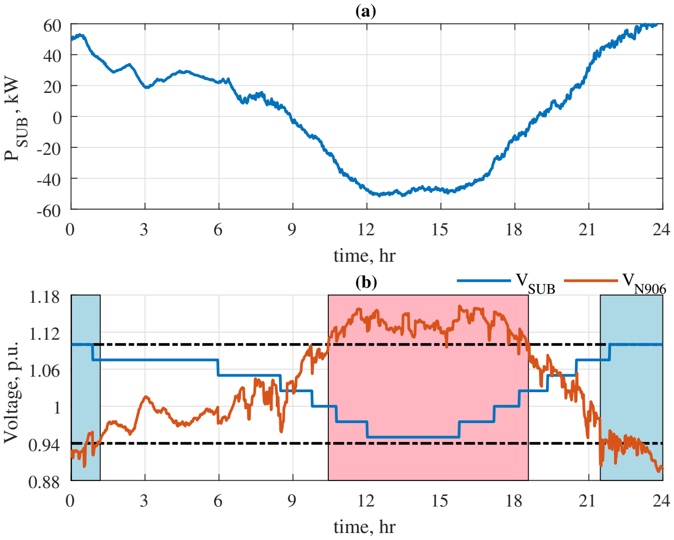


Fig. 6. (a) Power flow through the substation, and (b) Voltages at substation with OLTC, and at node 906 at the far end of the feeder

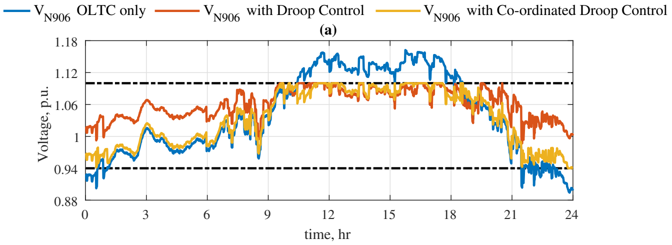
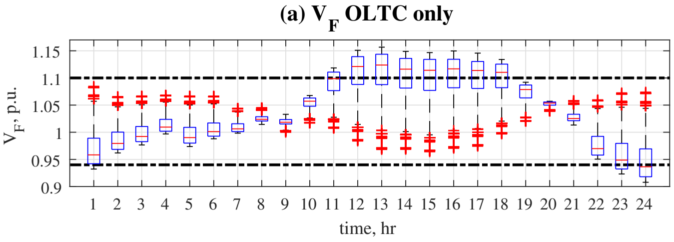


Fig. 7. Feeder voltage at Node 906 with OLTC only, with SLBCs with droop control activated, and with SLBCs with coordinated droop control activated

After observing the variation of voltage at one node (N906) with respect to time, the overall performance of all system nodes can be shown using box plots. The box plots cover all the node voltages over 24 hours and gives an idea about the minimum, maximum, mean values and the deviation from the mean values. It is evident from Fig. 8(a) that under no control condition, when all the SLBCs are deactivated, most system voltages are outside the allowed voltage range after mid day, despite the fact that the voltages at the start of the feeder are held close to 0.94 p.u. The height of the box plots show the range over which different node voltages are scattered. Clearly, there are voltages under than 1.0 p.u. when we have over-voltages at the far end of the feeder. Similarly, there are voltage higher than 1.0 p.u. near the start of the feeder in case of under-voltages at the far end of the feeder.

Fig. 8(b) shows that when SLBCs with droop control are activated, all node voltage remain within the allowed limits. It may also be noted that length of these box plots significantly reduces which shows that now all voltages are more tightly regulated close to 1.0 p.u. When the far end of the feeder is subjected to under-voltages, the SLBCs near the substation are trying to reduce the feeder voltages while the SLBCs near the far end of the feeder are trying to increase it. A similar opposing trend is observed when the far end of the feeder is experiencing an over-voltage. As a result, the voltages are less scattered and the average voltages (red lines inside the box plots) are closer to 1 p.u. This comes with an addition cost in terms of compensator converter rating.

The box plots in Fig. 9 show the statistical variation of all the node voltage over 24 hours. It can be seen that coordinated droop control can maintain the voltages with the stipulated limits. However, the mean values are not close



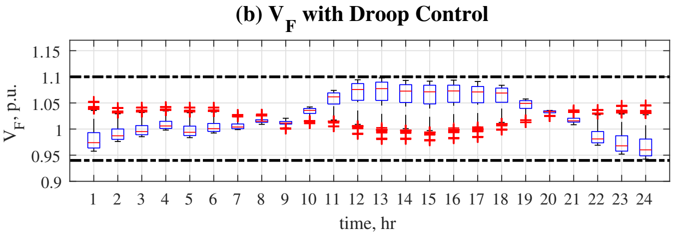


Fig. 8. Box plots showing distribution of (a) feeder voltages with OLTC only, and (b) with SLBCs with droop control over the period of 24 hrs

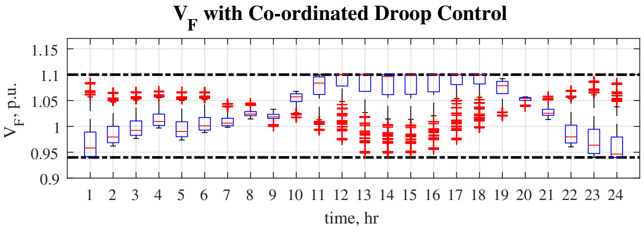


Fig. 9. Box plots showing distribution of feeder voltages with SLBCs with coordinated droop control over the period of 24 hrs

to 1.0 p.u. unlike the case of simple droop control. When far end of the distribution feeder is experiencing an under-voltage, the SLBCs near the substation receive a modified reference such that they do not try to reduce the system voltage when the SLBCs at the far end are trying to increase it. This coordination or communication can stop the SLBCs from working against each other and hence it requires less compensator effort and hence a smaller ratting. A similar trend is observed in the case of over-voltages at the far end. Coordination ensures that the SLBC ratting is optimised and there are no conflicting efforts by one or more SLBCs.

Fig. 10 shows that SLBCs with droop control requires a total compensator ratting of 12.3 kVA for controlling the voltages in this system, which is more than 37% higher than the compensator ratings required if there is coordination between the SLBCs (7.7 kVA required). As, this communication does not have to be very fast, and the reference voltages can be updated after 1 or two minutes, the cost of communication is not very significant compared to the massive savings in the compensator ratings. In case of a loss in communication, the system can still work as a droop controlled system until the communication is restored.

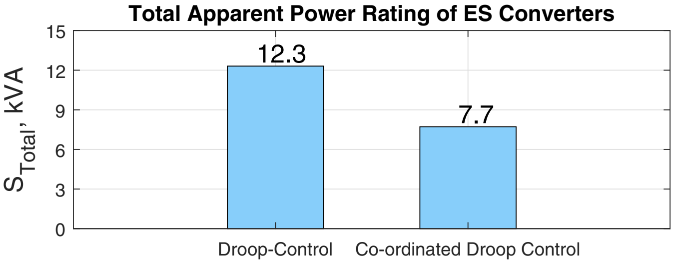


Fig. 10. Total power capacity of power electronic compensators required under different control strategies

VI. CONCLUSION

This paper highlights the problem with simple drop control of ESs in a radial distribution networks by describing how it can make SLBCs work against each other. It presents coordination between ESs as an alternative which is presented for the first time. A comparison between the droop control and the coordinated droop option is shown in terms of their voltage control capability, and required compensator capacity, to build a case for the use of coordination between electric springs. The cost of communication can be justified in terms of the savings in the required compensator ratings to achieve voltage control.

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