STRATEGIES FOR VOLTAGE OSCILLATION MITIGATION IN LV DISTRIBUTION NETWORKS WITH EV SMART CHARGING CONTROL

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ABSTRACT

The increasing penetration of EVs on LV Distribution networks can potentially cause voltage quality issues. Smart decentralized charging controls for EVs that aim to mitigate under-voltages and voltage unbalance, rely only on local voltage measurements. Due to this situation, the simultaneous reaction of all EV charging controls can induce voltage oscillations in the network, which leads to an unstable operation of the system. Three mitigation strategies have been applied to the most relevant decentralized charging controls to eliminate voltage oscillation. Results show that most of the strategies are able to diminish and eliminate voltage oscillations when implementing an EV decentralized charging control in a LV network. The most suitable mitigation strategy depends on the selected charging control, and on the topology of the network.

INTRODUCTION

Electric vehicles (EVs) are becoming a real alternative to traditional combustion engine vehicles. In recent years, several European countries have set national electric car deployment targets as a key measure for diminish pollutant and greenhouse gas emissions in urban areas [1]. Financial incentives and availability of charging infrastructure are decisive factors for the expected growth of electric vehicle market shares in the following years [2].

This predicted change in transportation markets is likely to become a challenge for distribution system operators (DSOs), since it can lead to power quality issues. Typical topology for European LV distribution network is three-phase four-wire network, where phases are not necessarily balanced. EVs charging power demand together with household loads highly contributes to the unbalanced operation of the network, which results in voltage quality problems such as under-voltage conditions and voltage unbalance [3].

EVs smart charging impact on LV networks power quality has been widely studied. Smart charging controls can be divided into centralized and decentralized controls, whose advantages and disadvantages have been discussed in [4]. Centralized smart charging needs for a central aggregator that optimizes the EVs charging load profiles based on a specific control algorithm. In order to do so, it requires a huge interconnected communication network. The centralized architecture allows smoothing the aggregated electric load profile and improves voltage and power quality in a region, but its main drawback is that it may cause individual vehicles to have peaks in their charging profiles.

On the other hand, the decentralized architecture manages the EVs charging process locally. Decentralized controls present several advantages such as scalability and reduced communication requirements [5]. The decentralized control tends to be considered a more practical architecture, since it is based on local measurements and does not need additional communication infrastructure [6]. However, decentralized controls that rely on local voltage measurements may not be the optimal solution for the region, since there could be instabilities when all controllers react simultaneously to the measurements. Namely, since each control acts at the same time and there is no communication between controls, the correction action of each control is unable to reach a stable behaviour because the set point of the control is constantly changing. Consequently, the network suffers from voltage oscillations that should be diminished and eliminated for a reliable operation.

This paper aims to study, analyse and compare different strategies to mitigate the voltage oscillations that the most relevant EVs decentralized smart charging controls introduce in LV networks.

Modulating the active power consumed by the EVs through a droop control [7] is one of the most popular decentralized controls, although this control highly influences the time needed for a full charge. Besides, reactive power provision of EV chargers have been studied in [8]. In case there is a possibility of three-phase connection, is possible to achieve substantial improvement in voltage unbalance by balancing the LV network loads

with the EV charger [9].
The paper is organized as follows: Section 2 presents the test LV network, together with the household consumptions and EV charging power demand. Section 3 introduces the EV smart charging controls selected for the analysis, while section 4 describes the strategies to mitigate voltage oscillations. Finally, results are discussed in Section 5, while conclusion is given in Section 6.

TEST CASE

Test Network

The analysed 400V and 50Hz test network is the Residential subnetwork of the European Low Voltage Distribution Network Benchmark developed by CIGRE Task Force C6.04 [10]. As shown in Fig. 1, the test network is connected to a 20kV Medium Voltage (MV) network. This MV network has a short-circuit power of 100MVA and X/R ratio equal to 1 and is the only feeding point. Besides, the test network is connected to the MV network through a Dyn1 transformer, whose rated power is 500kVA. The transformers' secondary star point winding is grounded through a 3 Ohm impedance.

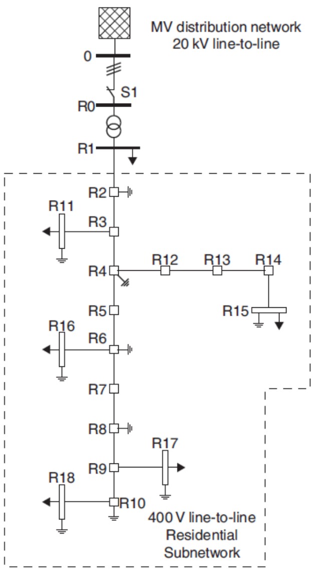

Fig. 1. CIGRE European Low Voltage Distribution Test Network

Test network's consumptions are aggregated in 6 different supply points. Moreover, the test network has its neutral wire grounded every 30 m through a 40 Ohm impedance. Besides, it is composed by 17 line segments of type NA2XY 4x240 mm^2 for the main line, and NA2XY 4x50 mm^2 for the ramifications.

Household Consumptions

[10] proposes standard daily power profiles for the test network at transformer level but lacks information per individual household. This approach does not allow for implementing individual household consumption profiles and individual controls, so authors have disaggregated the supply points based on a previous version of the test network [11].
Therefore, the test network has 12 three-phase consumptions and 14 single-phase consumptions, all with a power factor equal to 0.95. Apparent power of each supply point is stated in [10], and it is divided equally among each node's consumption, so the maximum power consumed by each supply point does not exceed the indicated apparent power. Lastly, feeder located in R1 is represented as a single aggregated household, and it is characterized by the standard power profile proposed in [10].
Household daily individual consumptions for the are obtained with the software LoadProfileGenerator. Power profiles for individual households are randomly generated and are all different. The 14 single-phase consumptions of the network are divided between phases: 4 consumptions connected in phase-a, 5 in phase-b and 5 in phase-c. In this manner, daily power profile at transformer level is calculated by adding up the power profile of each individual consumption.
Power profiles have been obtained at 0.1 seconds basis for 24 hours. Nevertheless, for the purposes of this paper, it is adequate to select a time period of one hour to perform simulations. Worst case scenario is selected, which corresponds to the time period between 21:00 and 22:00. During that hour household consumptions are close to their peak value, and EVs are likely to have arrived home by 21:00 [12] so their charging power consumption can be controlled.

Electric Vehicles

Each household is equipped with an EV. The EV charging power profile corresponds to the "dumb-charging" pattern published in [13]. Namely, the charging starts immediately after the vehicle is connected and consumes 3.68 kW. Nevertheless, smart charging controls described in the following section vary the EVs charging power according to their correcting action.

EV SMART CHARGING CONTROLS

The most relevant EV decentralized charging controls to correct voltage quality problems (i.e. under-voltage conditions and voltage unbalance) are described in this section. All controls rely on local voltage measurements.

Active Power Droop Control

Active power droop control has been widely investigated for being implemented in single-phase EV chargers. Among the different active power droop controls published in the literature, the one proposed in [7] has been selected for this analysis.
This charging control keeps the power consumption at 3.68 kW when the voltage at the phase of connection is above 0.95 p.u. and decreases it linearly until EV stops charging when the voltage diminishes to 0.9 p.u. Namely, it allows for a simple and straightforward under-voltage regulation. The main drawback of the active power droop

control is that the time needed for a full charge is hugely increased, which could be a potential inconvenience to the EV owner.

Reactive Power Droop Control

The reactive droop control selected for this analysis is the one published in [8]. It is designed for being implemented in single-phase EV chargers. With respect to the active power droop control, the reactive power droop control main advantage is that it provides under-voltage and over-voltage regulation without compromising the EV full charge.

The reactive power droop control is a function of the active power consumed by the EV and the voltage at the EV connection point, and it can provide reactive power when the phase-voltage is below 1 p.u., as well as absorb reactive power when it is above 1 p.u.

It is important to properly size the inverter when designing this charging control, so it is capable of provide or absorb the desired reactive power without affecting the consumed active power. The reactive power limits are assumed to be 1 p.u. which equals to 3.68 kvar.

Load Balancing Control

Control proposed in [9] has been implemented in this paper. This charging control is designed for being implemented in a three-phase charger and consists of dividing the EV charging power between the phases based on the phase-to-neutral voltage differences between them, being U_a, U_b, U_c the phase-to-neutral voltages:

$$P_a = \frac{P_{EV} + k(U_a - U_b) + k(U_a - U_c)}{3}$$

$$P_b = P_a - k(U_a - U_b)$$

$$P_c = P_a - k(U_a - U_c)$$

P_{EV} is the EV charging power, and k is a parameter that controls the inter-phase power delivery. For this paper, a constant value of 100 W/V has been selected for this parameter. Besides, the following equations must be accomplished:

$$P_{EV} = P_a + P_b + P_c$$

$$-P_{EV,max} \leq P_a + P_b + P_c \leq P_{EV,max}$$

where $P_{EV,max} = 3.68\ kW$.

STRATEGIES FOR VOLTAGE OSCILLATION MITIGATION

The three strategies described in this section have been selected to reduce and eliminate the voltage oscillations that the previously described EV decentralized charging controls introduce on the network when they react simultaneously.

Random Delay

The random delay strategy consists on implementing a delay to the voltage level that each control is measuring. This delay should be different for each EV charging control, so a random number should be given to each delay. By doing this, EVs charging controls act simultaneously but their correcting action is based on different voltage measurements. Thus, the controls are decoupled and voltage oscillations can be reduced or, depending on the charging control and the network structure, eliminated.

Hysteresis comparison

Hysteresis comparison strategy works in a similar way as a Schmitt trigger. Fig. 2 illustrates this behaviour when applied to the active power droop control. If voltage decreases from values above 0.91 p.u. the droop control follows the blue line, and if voltage grows from values below 0.93 p.u., it follows the red line. Voltage limits of 0.91 and 0.93 be set to a different value for other applications or controls.

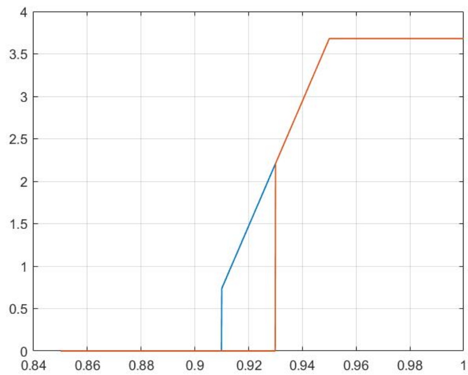

Fig. 2 Hysteresis comparison behavior

This strategy keeps the charging power at the minimum value until voltage reaches the higher voltage threshold of 0.93 p.u. Hence, it can eliminate voltage oscillations, preventing for charging power regulation when voltages are within the dead band (0.91 p.u. - 0.93 p.u.).

Sample Time

The sample time strategy consists on sampling the voltage with a different step time for each control. In this way, each control sets its correcting action based on a fixed voltage until the voltage is sampled again.

The sample time strategy, as happened with random delay strategy, decouples the controls. The difference is that with sample time strategy the controls do not react simultaneously, but each one of them change their set point on a different time instant.

SIMULATIONS RESULTS AND DISCUSSION

In order to analyse the different strategies when mitigating voltage oscillation, simulations have been carried out for the described charging controls. Three scenarios are defined, one with each EV charging control, where they are implemented in each household of the test network. Besides, strategies are as well implemented together with the controls in each scenario, so different cases are compared in each scenario. Hysteresis comparison strategy is only considered for active power droop control scenario since it cannot be applied to the rest of scenarios. Simulations have been carried out in the environment of MATLAB Simulink SimPowerSystems, and voltage levels have been registered at 0.1 seconds over a time span of 1 hour. Results show phase-a voltage evolution during the simulation time for node R15. Voltages for other phases and nodes present different levels than phase-a voltage at node R15, but the amplitude of voltage oscillations is similar for every phase and node. Hence, it is sufficient to present the results for one phase at one node in order to compare and analyse the different strategies for mitigating voltage oscillation.

Active Power Droop Control Scenario

The three strategies for mitigating voltage oscillations are compared in this scenario, together with the active power droop control. As seen in Fig. 3, all three strategies manage to diminish the amplitude of voltage oscillations, although only the sample time strategy eliminates it completely.
Random delay strategy is unable to eliminate the voltage oscillation because the amplitude is higher than its dead band (Fig. 2). On the other hand, hysteresis comparation strategy improves the random delay performance during the first half of the simulation, but the amplitude of the oscillations increases at the end of the simulation.

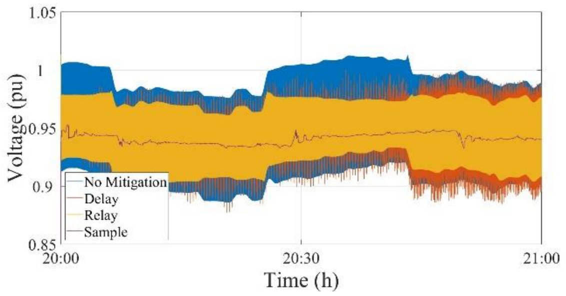

Fig. 3 Active power droop control results

Reactive Power Droop Control Scenario

Fig. 4 shows the random delay and sample time strategies behaviour for the second scenario, where reactive power droop control is implemented. Results show that both strategies are able to eliminate entirely the voltage oscillations. As it can be seen in Fig. 4, voltage profiles for random delay and sample time strategies are considerably different, i.e., the voltage difference between the two profiles reach values close to 0.25 p.u. during the simulation. The control action of the sample time strategy is based on a sampled voltage measurement, which may be distant from the real voltage value during the period between two samples. When the EVs penetration is high the voltage difference may vary significantly, as happen in this scenario. Hence, it is important to set a short step time between two samples, so the control is able to react fast to voltage quality events while reducing voltage oscillations.

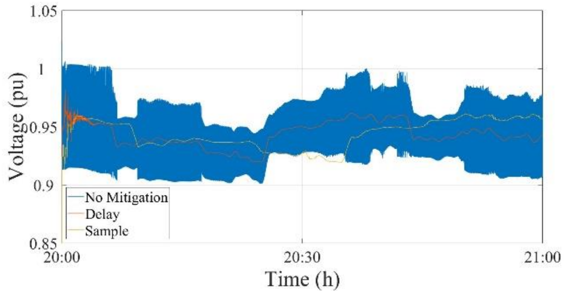

Fig. 4 Reactive power droop control results

Load Balancing Control Scenario

Fig. 5 shows the random delay and sample time strategies behaviour for the third scenario, where load balancing control is implemented. Results show that both strategies are able to diminish considerably the amplitude of voltage oscillations, and sample time strategy is able to eliminate it entirely.
As happened in the first scenario, random delay strategy has a good behaviour at the beginning of the simulation but loses reliability at the end. In this scenario, the difference between both strategies' voltage profiles is less noticeable than in the second scenario, although it is difficult to make a comparison between both voltages due to the oscillations in the voltage profile of the random delay strategy.

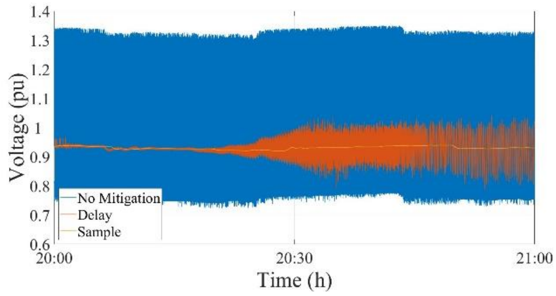

Fig. 5 Load Balancing control results

CONCLUSION

EVs increased penetration in low-voltage (LV) distribution networks is likely to have a significant impact, since it leads to power and voltage quality issues. Decentralized smart charging controls are considered as the best solution for contributing to solve under-voltage conditions and voltage unbalance. However, this type of controls induce voltage oscillations in the network when they react simultaneously, so strategies for mitigating voltage oscillations have been proposed in this paper. Three strategies have been selected: random delay, hysteresis comparison, and sample time strategy. These strategies have been applied to the most relevant decentralized charging controls, proving that even the simplest strategy can diminish the amplitude of voltage oscillations. Moreover, sample time strategy is able to eliminate entire the voltage oscillations. According to the rest of strategies, their effectiveness depends on the charging control and the LV network where they are implemented.

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