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Phase-wise enhanced voltage support from electric vehicles in a Danish low-voltage distribution grid

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ABSTRACT

High deployment of electric vehicles (EVs) imposes great challenges for the distribution grids, especially in unbalanced systems with notable voltage variations which detrimentally affect security of supply. On the other hand, with development of Vehicle-to-Grid technology, EVs may be able to provide numerous services for grid support, e.g., voltage control. Implemented electronic equipment will allow them to exchange reactive power for autonomous voltage support without communicating with the distribution system operator or influencing the available active power for primary transportation function. This paper proposes a voltage dependent EV reactive power control and quantifies its impact on a real Danish low-voltage grid. The observed network is a heavily unbalanced three-phase four-wire grid modeled in Matlab SimPowerSystems based on real hourly measurement data. Simulations are performed in order to evaluate phase-to-neutral voltage support benefits as well as to address neutral-to-ground values, active power losses and the unbalances at the same time. The analysis shows that reactive power support both raises minimum phase-to-neutral voltage magnitudes and improves voltage dispersion while the energy losses are not notably increased. Further on, since the control is voltage dependent, provided reactive power is unequal among the phases leading to greater support on heavily loaded phases and decreased unbalances caused by residential consumption. Hence, implementation of such a phase-wise enhanced voltage support could defer the need for grid reinforcement in case of large EV penetration rates, especially in highly unbalanced networks.

1. Introduction

Distribution system operators (DSOs) have historically designed and operated their networks in order to follow a predicted demand with single-direction power flow only. Nowadays, due to increased share of renewable energy resources, DSOs are confronted with changes in the low-voltage grid operation [1]. Additionaly, since the market share of electric vehicles (EVs) is expected to grow significantly in the following years, even greater system complexity is imposed [2,3]. Danish Energy Association predicts 47,000 EVs in Denmark by 2020 in a moderate penetration scenario [4] meaning that distribution networks will have to cope with great increase in consumption and overall voltage degradation, especially in unbalanced systems where voltage quality is already decreased.

Unlike in other European countries, the three-phase connection is not reserved only for industrial consumers in Denmark, but it is also available for residential customers. Distribution system operators experience high unbalances in the semi-urban areas where more loads are eventually connected to phase *a* due to the lack of regulation for per phase load connection [5]. Uncontrolled EV charging in such grids may result in violation of the minimum voltage boundary followed by the need for grid reinforcement. As an economic alternative, different EV charging strategies can be used for supporting the grid as well as providing various flexibility services.

An extensive amount of research has been made on coordinated EV charging proving that such concept can be used for lowering the impact on the power system [6] or providing ancillary services such as frequency control [7]. Most of these strategies require an aggregator to coordinate larger amount of EVs and, if possible, offer their services to the power system operators. However, high local EV concentrations may occur before significant penetration rates occur on the higher level. Taking into account that residential EV charging highly impacts the power profile, voltage magnitudes and voltage unbalances, different approaches are considered in order to alleviate these adverse effects and make the grid compliant with existing standards. In order to integrate electric vehicles in the distribution

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grid, both centralized and decentralized charging strategies have been explored in the literature. Comparison of such two charging strategies has been presented in [8,9]. Centralized algorithm leads to the least cost solution and is easily extended to a hierarchical scheme, but requires great communication infrastructure for information exchange. On the other hand, decentralized control provides similar results to the centralized one, both in terms of cost and robustness against forecast errors. This would seem to favor decentralized control since it is based on local measurements and does not require additional communication infrastructure. However, the drawback is charging simultaneity since all controllers would respond instantaneously to the measurements which could eventually lead to instability in some cases [10].

It is shown across a variety of studies that centralized EV control reduces losses, improves voltage stability and performs peak shaving or congestion control [11–14]. In addition to linear optimization methods, model predictive control is investigated for scheduling EV charging with various network constraints [15]. On the contrary, decentralized voltage dependent charging strategy which requires only local voltage measurement is discussed in [16]. EV charging power can also be modulated in order to compensate for the voltage unbalances [17], but such an autonomous procedure is possible only for three-phase charging since the single-phase charger has solely the voltage measurement of the phase to which the EV is connected and therefore, does not have any information on the voltage unbalances.

The impact of controlled EV charging on voltage profiles and unbalances has been investigated mainly by modulating the active power which influences the time needed for full charge and consequently, the user comfort. On the contrary, reactive power control (RPC) from electric vehicles has scarcely been discussed in the literature. Such reactive power compensation can be used for grid support and mitigating induced voltage issues, both while vehicles are charging, and discharging in Vehicle-to-Grid mode [18]. Balancing the phases by reactive power provision has been discussed in [19] where centralized control is used for scheduling the vehicles located on different phases, but this approach requires additional communication infrastructure. Decentralized approach, more precisely, autonomous reactive power control based on droop control has been investigated in [20–22], but only in the case of a balanced system. The reactive power support in an unbalanced network has been investigated in [23]. Despite showing that capacitive load behavior in EV chargers has beneficial impact on the voltage, this approach assumes a fixed power factor for all vehicles regardless of the their connection phase which may not be good enough for high EV penetration rates in case of highly unbalanced networks.

1.1. Objectives

To the authors' knowledge, phase-wise enhanced voltage support from electric vehicles has not been extensively discussed in the literature so far. Not only does such a control provide voltage support while vehicles are charging, it also provides unequal reactive power on different phases leading to greater support on highly loaded phases and partial mitigation of unbalances caused by other loads. Hence, this paper investigates the impact of voltage dependent EV reactive power control on a residential low-voltage network by conducting unbalanced three-phase load flow, and evaluating voltage deviations and several unbalance factors. The modeled network represents a typical Danish semi-urban feeder with high penetration of photovoltaic installations where hourly consumption and production data are available for individual units. Furthermore, the paper compares the phase-to-neutral along with neutral-to-ground voltage benefits at the expense of potential increased currents and power losses aiming to assess the grid impact as well as the need for including such a control in future grid compliance regulations to allow better EV integration.

This paper is organized as follows. Section 2 presents the unbalance indicators used for evaluating the results, and briefly recalls the standards regarding the voltage power quality as the main motivation for presented voltage support. In Section 3, the applied methodology has been presented, whereas the test case with the description of conducted scenarios is given in Section 4. Finally, the results are discussed in Section 5 followed by the conclusion in Section 6.

2. Unbalance indicators

Contrary to other disturbances in the power system for which the performance is evident for the ordinary customers, unbalance belongs to those disturbances whose perceptible effects are produced in the long run. Unsymmetrical consumption and production lead to voltage and current unbalances which imply greater power losses, interference with the protection systems, components' performance degradation and overheating possibly to the point-of-burnout. To calculate the unbalanced voltages and currents in three-phase systems, symmetrical components are generally employed. The voltage unbalance can be decomposed into a direct sequence voltage, an inverse sequence voltage and a zero sequence voltage, with the relationship between the symmetrical sequence systems and the initial system as follows:

$$\begin{bmatrix} U_{direct} \\ U_{inverse} \\ U_{zero} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (1)$$

where $\alpha = e^{j2\pi/3}$. The same definition can be applied for defining the current direct, inverse and zero component.

For ensuring that electric appliances are operated in a safe manner, the European standard EN50160 [24] defines acceptable limits for several grid parameters. More precisely, the standard defines the limits for rms phase-to-neutral voltage magnitude ($|U_{pn}|$) and the voltage unbalance factor (VUF) as follows:

$$0.9U_{nom} \leq |U_{pn}| \leq 1.1U_{nom} \quad (2)$$

$$VUF \leq 2\%, \quad (3)$$

for >95% of all weekly 10 min intervals, and

$$0.85U_{nom} \leq |U_{pn}| \leq 0.9U_{nom}, \quad (4)$$

for <5% of all weekly 10 min intervals. The inverse sequence VUF is defined as the ratio between the inverse and direct component as follows:

$$VUF_{-}[\%] = \frac{|U_{inverse}|}{|U_{direct}|} \times 100. \quad (5)$$

There are many voltage and current unbalance definitions for three-phase three-wire systems which assume that zero sequence current is negligible since it cannot flow through three-wire systems. However, the zero sequence unbalance has significant impact in the three-phase four-wire systems which are common in the distribution systems, and should be taken into consideration when assessing the unbalances in such cases. So, the zero sequence VUF can be defined as the ratio between the zero and the direct component as follows:

$$VUF_0[\%] = \frac{|U_{zero}|}{|U_{direct}|} \times 100. \quad (6)$$

Current unbalance factors CUF_{-} and CUF_0 are defined analogously to VUF definitions shown in Eqs. (5) and (6). In order to combine the impact of both VUF_{-} as well as VUF_0, i.e. to combine