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Analytical assessment of voltage support via reactive power from new electric vehicles supply equipment in radial distribution grids with voltage-dependent loads

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ABSTRACT

Grid operators have to cope with secure electric vehicles integration in the power system, which may lead to violations of the allowed voltage band. This work intends to provide an analytical assessment and guidelines for distribution system operators when evaluating new electric vehicle supply equipment installations with fast charging capability in existing low voltage distribution feeders. The aim is to prevent the voltage to exceed the permitted values when charging at high power, by exploiting the effect of reactive power. The contribution of each power component in distribution grids is analyzed, including the loads' voltage-dependency, which influences the effectiveness of reactive power control. The proposed guidelines indicate the amount of capacitive reactive power that an individual electric vehicle supply equipment is expected to provide, in order to effectively manage the voltage rise. The proposed method is validated on the Cigrè benchmark low voltage distribution network as well as on a real Danish low voltage grid.

1. Introduction

The increasing success of electric vehicles (EVs) is bringing new challenges to power system operators. On the one hand, great research effort is made on smart integration solutions of large amount of EVs in the power system, such as aggregation strategies for smart EV charging aim at making EVs a reliable source of system-wide ancillary services [1–3]. On the other hand, to evaluate the practical feasibility of such solutions, the technical capabilities of series-produced EVs in performing smart charging are of high interest too [4,5]. However, since mostly connected at a low voltage (LV) level, one of the most challenging aspects of the integration of EVs in the power system is the impact on distribution grids [6,7].

Distribution system operators (DSOs) should be always able to operate their distribution networks assuring standard-compliant levels of power quality, according to the European technical standard EN 50160 [8]. When connected to electric vehicles supply equipment (EVSE), EVs behave as large concentrated loads. Thus, they may cause technical issues on the electrical infrastructure, such as overloading conditions both in distribution transformers and feeders and drastic power quality worsening. Unless opting for grid reinforcement solutions, a massive penetration of EVs in distribution networks may force DSOs to rely on smart EV charging.

In general, reactive power provision can – to a certain extent – mitigate local voltage issues in distribution networks [9]. In case of small distributed generation plants connected at low voltage levels such as photovoltaics (PVs), grid technical standards require reactive power capability to the inverter-interfaced units [10–12]. Many studies have proved the effectiveness of such capabilities in voltage support in active distribution networks [13,14]. Similarly, it is expected that there might by a need for DSOs to require voltage support capability also to the new EVSEs.

Under a technical feasibility point of view, many studies propose new on-board chargers design and investigate the barriers within the power electronics in applying reactive power solutions [15–17]. Among others, [17] presents an analysis of the technical performance of a conventional unidirectional on-board charger during bidirectional four-quadrant operation, showing how reactive power exchange could be achieved without any considerable changes in the converter type and size. Furthermore, many other studies deal with the development of off-board chargers capable of reactive power operation, showing possible designs and layouts of such technologies [18,19]. Hence, given the mentioned concrete technical feasibility, it is of paramount interest to perform assessment studies upon the effective contribution of such reactive power voltage regulation strategies by charging EVs.

Among other possible control techniques, many reactive power

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Nomenclature

List of symbols

$\overline{E_1}$	phase-neutral voltage phasor at the starting terminal of the line
$\overline{E_2}$	phase-neutral voltage phasor at the ending terminal of the line
E_1	phase-neutral voltage magnitude at the starting terminal of the line
E_2	phase-neutral voltage magnitude at the ending terminal of the line
$\overline{\Delta E}$	complex voltage drop along the generic distribution line
R_l	resistance of the generic distribution line
X_l	reactance of the generic distribution line
P	total active power absorbed by the customer
Q	total reactive power absorbed by the customer
$\overline{I}$	phasor current flowing along the line
I_r	real component of the current flowing along the line
I_i	imaginary component of the current flowing along the line
a_0, a_1, a_2, b_0, b_1, b_2	load voltage dependence modelling coefficients
P_{EV}	electric vehicle active power
Q_{EV}	electric vehicle reactive power
P_{load}	load active power
Q_{load}	load reactive power
P_{load0}	load active power at nominal voltage condition
Q_{load0}	load reactive power at nominal voltage condition
$\cos\varphi_{EV}$	power factor of the charging electric vehicle
$\cos\varphi_{load}$	power factor of the load
S_{scgrid}	external grid short-circuit power
	external grid resistance referred to the low voltage level
X_{grid}	external grid reactance referred to the low voltage level
R/X_{grid}	resistance over reactance ratio of the transformer
$S_{n.trafo}$	transformer nominal power
$S_{sc.trafo}$	transformer short-circuit power
$Z_{sc.trafo}$	transformer short-circuit impedance
$v_{sc\%.trafo}$	transformer short-circuit voltage
R_{trafo}	transformer resistance referred to the low voltage level
X_{trafo}	transformer reactance referred to the low voltage level
R/X_{trafo}	resistance over reactance ratio of the transformer
$R_{LVfeeder}$	low voltage feeder resistance
$X_{LVfeeder}$	low voltage feeder reactance
$RX_{LVfeeder}$	resistance over reactance ratio of the low voltage feeder

control strategies based on solution of optimization problems are proposed in the literature, both with centralized and decentralized control structure. In general, centralized control approaches for this kind of voltage regulation at LV distribution level [20,21] may result in huge amount of data that need to be transported from smart meters to a centralized control room for the elaboration of the proper control signal to be dispatched back to the units. Therefore, in many volt-VAR optimization works it is preferred to rely on decentralized logics, avoiding the need for complex data management [22–25].

Independently on the control logic applied, many other studies have been conducted with the aim to demonstrate the potentials of distributed EV chargers control to solve local voltage issues and allowing high EV penetration to be technically acceptable, deferring the need for grid reinforcement [26–30]. In [26] and [27] the positive effects of reactive power support by EVs applying voltage-dependent reactive power strategies is analyzed. An implementation of a bi-directional EVSE controller is developed in [28], which proposes a control logic able to regulate the bus voltage by exchanging reactive power, while maintaining a given DC-link voltage for the designed charging station. In [29] an example of the impact in the power grid is evaluated by implementing different reactive power control logics such as fixed power factor, power factor as function of either active power or local voltage, and an hysteresis control. An innovative reactive power capability curve as function of both active power and local voltage is proposed in [30], where EVs are considered to be single-phase connected, thus unbalance conditions are evaluated.

The above-listed works do present the positive effects on local voltage by reactive power provision from EVs; however, all these study cases are validated in single distribution grids. As the effectiveness of such controllers depends on the electrical characteristics of the power system, it is of high interest to evaluate their influence in different grid cases. In this respect, in [31] the effectiveness of reactive power control from PV inverters is evaluated with respect to different R/X grid characteristic, and it is shown how, depending on the grid characteristics, over-voltages can be reduced.

Similarly, it is expected that for installations of new commercial EVSEs with fast charging capability in existing LV distribution feeders, the reactive power needed to prevent undesired under-voltages depends on the grid characteristic. Within this context, in [32] we have investigated the influence of the single distribution grid components on the reactive power effect. Specifically, the proposed analysis demonstrates that both the MV/LV transformer and the MV grid (unless extremely weak) have marginal influence on the effects of reactive power on the voltage. Moreover, it is also found that the R/X ratio of the LV feeder does not significantly influence the results, whereas an important role is played by the absolute values of R and X, i.e., the LV feeder length. In this work we aim at extending and enhancing the investigation proposed in [32], by including the voltage-dependency of the loads in the analytical formulation, as well as carrying out a validation on different grids. The reactive power effects on the local voltage are evaluated in case of different load models in terms of inductive power factor as well as voltage-dependent behaviour.

So, the identified research questions we are trying to answer with these contributions are: *how much is it possible to exploit the potential flexibility of EV fast chargers in providing reactive power for voltage control in LV distribution grids? Which guidelines can be given to DSOs in terms of the amount of reactive power that an individual EV must be able to provide?*

The novelty lies on the provision of such guidelines for DSOs, applicable to different types of customers, e.g., residential, commercial, and industrial. The proposed method is to be seen as an assessment criterion when DSOs have to evaluate requests for installation of new EV fast chargers in LV networks. The proposed analytical formulation has been validated by implementing equations in MATLAB. The further validation has been carried out by running load flow calculations in the power system simulation tool DIgSILENT PowerFactory on the LV Cigrè residential radial benchmark [33], as well as on a real Danish LV distribution network previously utilized for other EV integration-related studies [30].

The paper is structured as follows. Section 2 presents the analytical formulation for assessing reactive power effects in distribution grids. Section 3 outlines the methodology to evaluate the contribution of the single power system components. In Section 4 a detailed sensitivity analysis including the load models is presented. Section 5 reports the validation of the proposed methodology. Conclusions are reported in Section 6.

2. Voltage drop assessment in distribution grids

Although reactive power management for voltage support has major effects at HV/MV levels due to low R/X ratios (0.1–0.2), in LV distribution networks (average R/X ratio of 0.5–5) it is anyway seen as a feasible mean to maintain voltages within the allowed limits of ± 10%