REACTIVE POWER SUPPORT FOR OPTIMAL GRID INTEGRATION OF FAST-CHARGING INFRASTRUCTURE IN GERMAN LOW-VOLTAGE NETWORKS

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ABSTRACT

The number of fast-charging electric supply equipment (EVSE) with rated charging power up to 50 kW is rising. As most of the charging systems will be installed in low-voltage networks, the impact on power quality has to be considered. Important criteria for grid access of EVSE are discussed in this study, and reactive power support is identified as advantageous for EVSE installation in remote low-voltage network branches. As reactive power support generates additional grid losses, the effects of different control schemes are compared using a probabilistic load flow simulation.

INTRODUCTION

Public fast charging infrastructure

The majority of Electric Vehicle (EV) trips can be covered by normal power recharging offering an AC connection power from 3,7 kW up to 22 kW. However, to fulfill the requirements of long distance trips and flexible spontaneous route planning, a fast charging infrastructure is necessary. For 2020, a demand for a public charging infrastructure consisting of 173.000 normal power recharging points (22kW, AC charging) und 7.100 high power recharging points (50kW, DC charging) is predicted in Germany [1]. Connecting fast-charging DC electric vehicle supply equipment (EVSE) to a low-voltage (LV) network has a significant impact on power quality.

Standards and technical rules for EVSE network connection

To ensure the standardized voltage characteristics in public distribution networks [2], several standards and technical rules have to be met for grid access of an EVSE in Germany. As demanded in [3], the EVSE operator requests a network connection for a load exceeding 12 kW rated power from the distribution network operator. As the common range of standardization for loads connected to low-voltage networks is limited to currents up to 75 A [4,5], an individual technical assessment of network disturbance has to be done [6].

ASSESSMENT OF NETWORK DISTURBANCE FOR TYPICAL EVSE

For the assessment of network disturbance, the following aspects are considered:

- First, the characteristics of EVSE with passive and active front-end rectifiers are summarized.
- Next, typical LV network characteristics are analyzed, as the network disturbance has to be calculated at the point of common coupling (PCC).
- This is followed by a discussion of the most relevant disturbance types.

Characteristics of EVSE operation

The total efficiency η of a DC-EVSE, measured from the AC power consumption to the DC charging power, can be estimated as 95 %. With a DC charging power of 50 kW, the rated AC power is 53 kVA, resulting in an AC three phase power connection request of at least 3x80 A.

The key component for the impact on power quality in LV-networks is the rectifier topology. Most EVSE interface AC mains with a passive line-commutated rectifier as shown in Figure 1a. This rectifier type draws an inductive power factor λ of 0,96 at rated power operation. The total harmonic distortion of the line currents (THD_I) is limited by technical measures (AC commutating reactor and DC smoothing reactance) in the range of 40 to 70 %.

The EVSE in Figure 1b is equipped with an active front-end. Using IGBTs, this self-commutated rectifier draws a nearly sinusoidal current with a THD_I lower than 10 %. This rectifier topology also features full independent control of the reactive power consumption.

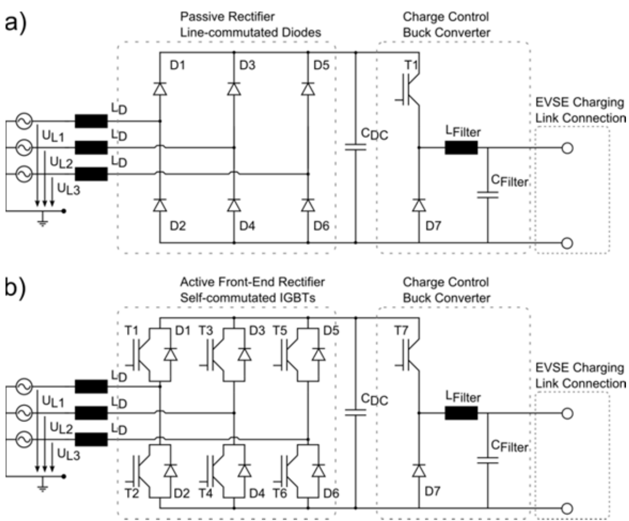

Figure 1: Considered EVSE-Topologies a) standard line-commutated rectifier b) proposed self-controlled rectifier

Network characteristics

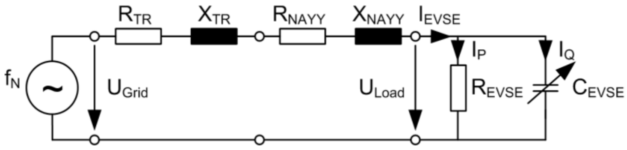

Figure 2: Single-Line Network diagram of LV-network

A key factor for the assessment of network disturbances is the grid impedance at the PCC of the EVSE. The impedance at a PCC can be calculated by using the network diagram shown in figure 2. As it is more convenient for calculations, the grid impedance is usually expressed in the short-circuit power $S_{SC,PCC}$ and the network impedance ratio R/X.
The high-voltage and medium voltage network are modelled in the source resistance R_S and impedance L_S. A standard local substation 20kV/0,4kV transformer with a rated power of 400 kVA feeds a LV cable type NAYY4x150mm², which is the most used standard cable in German LV networks [8]. With the parameters given in table 1, the short-circuit power and R/X ratio is calculated for variable cable length (figure 3).

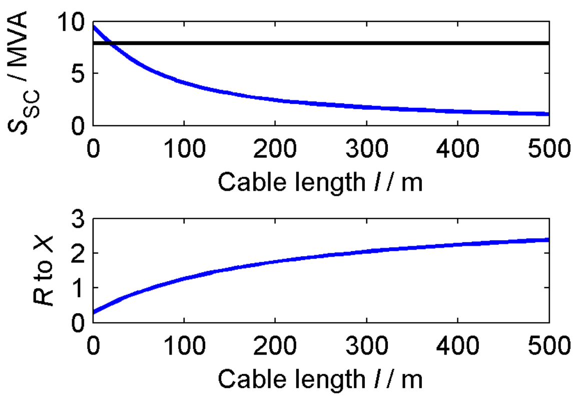

Figure 3:
Upper plot: Short-circuit power (blue), required short-circuit power for uncontrolled rectifier (black).
Lower plot: R/X ratio for variable LV cable length

Table 1: Network parameters used in Figure 2

Parameter	Value	Unit	Description
U_{Grid}	400	V	nominal voltage
f_N	50	Hz	power frequency
R_{TR}	5,7	mΩ	transformer resistance
L_{TR}	70	µH	Transformer inductance
R'_{NAYY}	256	mΩ/km	Resistance per unit length
L'_{NAYY}	255	µH/km	Impedance per unit length
R_S	620	µΩ	Source resistance
L_S	2,6	µH	Source inductance

Assessment of network disturbance for EVSE

Harmonic Voltages

EVSE rectifiers inject harmonics in the power system. Due to the line impedance, harmonic voltages build up.
In case of an EVSE with a 6-pulse *line-commutated rectifier* (figure 1 a), a short-circuit power 150 times higher [6] than EVSE rated power (shown as black curve in figure 3) is required for grid access. The critical line length providing this amount of short-circuit power is 20 m. For longer cable distances, additional measures have to be taken for harmonic current limitation, e.g. use of a 12-pulse rectifier fed by a three-winding transformer.
An EVSE featuring a *self-commutated rectifier* meets harmonic emission requirements with ease. With a THD_I smaller than 10 %, no harmonic assessment has to be done. To suppress interharmonic voltage emission, the IGBT switching frequency has to be locked to an integer ratio synchronous to the grid frequency.

Rapid voltage changes (flicker)

Fast fluctuations in electrical power consumption generate rapid voltage changes. While starting a charging process, EVSE avoid flicker emission with a slow power-on ramp over several seconds. During charging and towards the end of the charging process, power fluctuation are small, so rapid voltage changes are no limiting factor for the installation of EVSE.

Supply voltage variations (slow variations)

The charging time of an EV is estimated to be at least 10 min. Therefore, the change rate r for supply voltage variation is r = 0,1 min^{-1} and the maximum tolerated voltage drop $d_{max,LV}$ due to charging activity is 3 % of nominal network voltage U_{Grid} [6]. This crucial criterion defines the maximal line length between a local substation and an EVSE and is investigated in detail in this study.

Proposed EVSE topology

Offering the feature of independent regulated reactive power and low harmonic voltage emission, an EVSE with a self-commutated active front-end is selected. The active-rectifier is dimensioned for a power factor of 0.9 at rated power, resulting in a total connection power of 60 kVA fed by a three phase AC connection 3x100 A.

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Expansion of maximal line length by reactive power support

Analytical Approach

First, the principle effect on supply voltage variations during EVSE operation and the reactive power support to reduce voltage drop is analytically investigated. The voltage amplitude drop U_Δ during EVSE operation at the

EVSE PCC is expressed in equation 1 by applying the Kapp triangle shown in Figure 4.

$$U_{\Delta} = U_{Grid} - U_{Load} = U_d + U_m \quad (1)$$

$$U_d = R \cdot I \cdot \cos\varphi + X \cdot I \cdot \sin\varphi \quad (2)$$

$$U_q = X \cdot I \cdot \cos\varphi + R \cdot I \cdot \sin\varphi \,. \quad (3)$$

Using the example LV network shown in figure 2, the resistance R and inductance X is given by

$$\begin{aligned} X &= X_S + X_{TR} + X_{NAYY}, \quad X_{NAYY} = X'_{NAYY} \cdot l \\ R &= R_S + R_{TR} + R_{NAYY}, \quad R_{NAYY} = R'_{NAYY} \cdot l \end{aligned}, \quad (4)$$

where l is the cable line length. The current I is calculated from the EVSE active power drawn from the AC mains. The EVSE power factor is calculated by

$$\begin{aligned} I &= \sqrt{I_P^2 + I_Q^2} \\ I_Q &= I_P \cdot \tan\left(\cos^{-1}\varphi\right) \end{aligned}. \quad (5)$$

Using the geometric relations defined in Figure 4, U_m can be defined by the following equation:

$$\left(U_{Grid} - U_m\right)^2 + U_q^2 = U_{Grid}^2 \,. \quad (6)$$

By substituting U_m in (1) using (6), the voltage amplitude drop between U_{Grid} and U_{EVSE} is now defined by

$$U_{\Delta} = U_d + U_{Grid} - \sqrt{U_{Grid}^2 - U_q^2} \,. \quad (7)$$

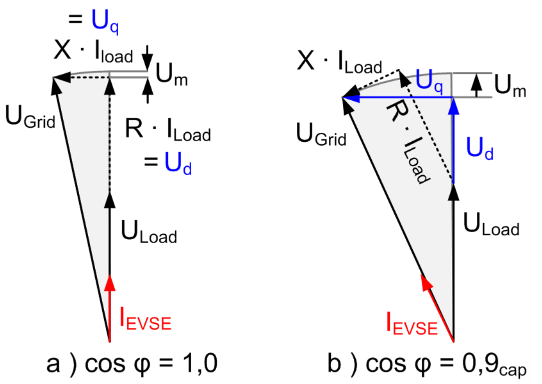


Figure 4.: Kapp triangle for a) unity and b) capacitive-ohmic power factor.

Calculation of maximal line length

The maximal cable length between the local substation and the PCC can be calculated by solving equation (1) for

$$U_{\Delta} = d_{\max} = 3\% \cdot U_{Grid} \,, \quad (8)$$

calculating with the rated current value and unity power factor in (2),(3) and (5):

$$I_P = 80\text{ A} \quad \text{and} \quad \varphi = 0^\circ \,. \quad (9)$$

As we can see in the upper plot of figure 5, the maximal line length is determined as 330 m. For longer distances, a capacitive power factor has to be increased to preserve the d_{max} criterium. With respect to the minimal required power factor of 0.9 [3] for LV connected loads the maximum line length can be increased by 30 % to 429 m (lower plot in figure 5).

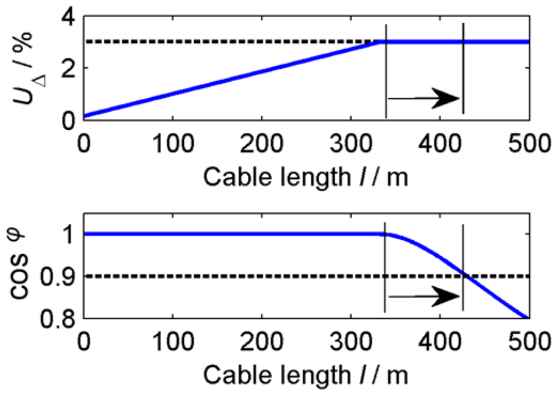


Figure 5:
Upper plot: Voltage drop for variable cable length l
Lower plot: Required cos φ_{EVSE} to ensure d_{max} = 3 %

With increasing reactive power consumption, the EVSE draws an increasing line current I_{EVSE} (figure 6). As higher line currents result in higher network losses, the impact of reactive power compensation is considered using a probabilistic simulation.

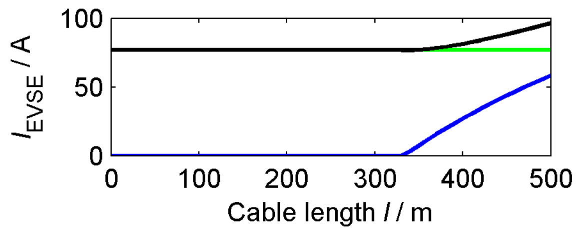


Figure 6: EVSE currents $I_{EVSE,}$ Rated current (black), active current I_P (green) Reactive current I_Q (blue)

Probabilistic Simulation

Scenario definition

For analyzing the performance of different reactive power concepts, a suburban low-voltage network (figure 7) is derived from statistical data [7,8]. The network is dominated by domestic customers (table 2). In addition, a supermarket is connected to the most distant location in the network (cable segment 4). A 400 kVA transformer feeds the low-voltage network and for each segment, NAYY4x150mm² cable is used, as this is the most dominant network equipment in LV-networks.

In this scenario, to improve attraction to the supermarket, a 50 kW EVSE is built at its parking lot. With a line length of 420 m, EVSE operation fulfills voltage stability requirements by reactive power support.

Table 2: Network parameters used in Figure 7

Segment	1	2	3	4	5	6	7
Length / m	225	352	315	420	225	352	315
Customers	9	32	15	70	9	32	15

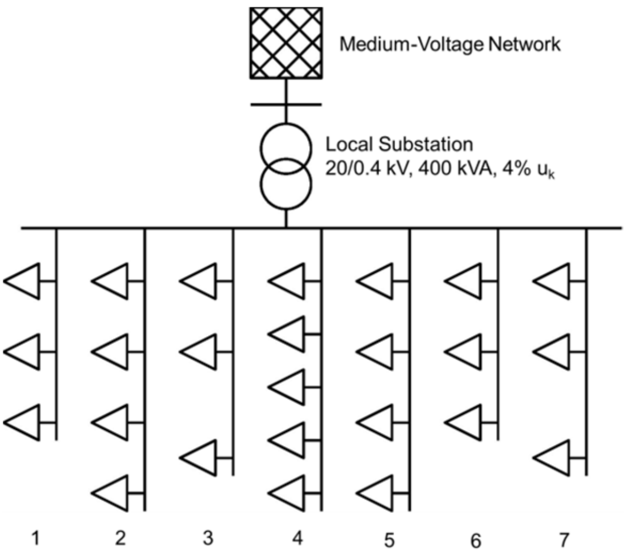


Figure 7: Suburban low-voltage scenario

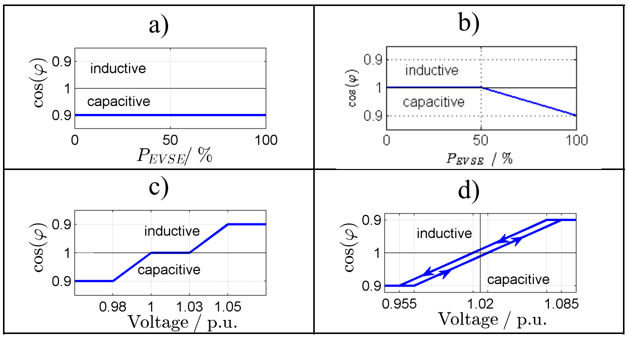
Reactive Power Controllers

Inspired by power factor schemes utilized nowadays for voltage control of distributed generation in low-voltage networks [9,10], four different power factor schemes (table 3) are implemented in the simulation model.

Table 3: Evaluated power factor schemes:

a) fixed $\cos(\varphi) = 0.9_{cap}$ b) $\cos(\varphi(P))$

c) $\cos(\varphi(U))$ d) Hysteresis Control



Simulation Environment and Result Evaluation

The MATLAB® load flow framework MATPOWER [11] is used to model the low-voltage network and for load-flow estimation. For probabilistic domestic customer load profiles, a behavior based load profile generator of the TU Chemnitz [12] generates individual load curves for each simulation run. A typical load flow of the low-voltage network is shown in figure 8.

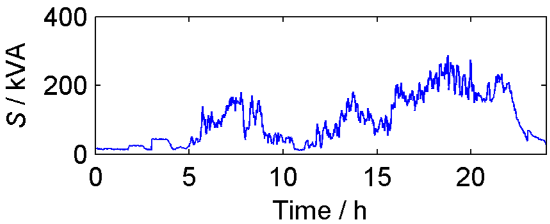


Figure 8: Example LV network power consumption

EV charging behavior is derived from statistical data [13], based on a scenario with 6 millions EV in 2020 in Germany. An exemplary charging curve is shown in figure 9.

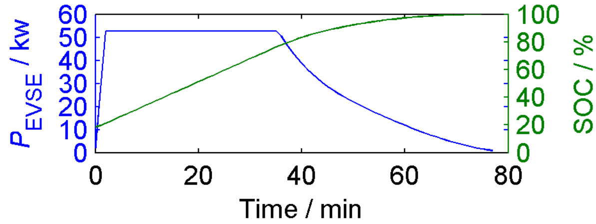


Figure 9: Example electric vehicle load profile

Results

The losses of the different power factor schemes are compared to EVSE operation with unity power factor, evaluating a set of 50 simulations (figure 10). The median values of all considered reactive power schemes are in a similar range between 2 % to 4 %, increasing line losses slightly.

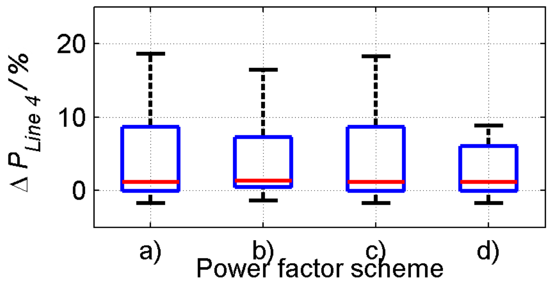


Figure 10: Additional losses of the four evaluated power factor schemes (table 3)

The hysteresis power factor scheme features the least scattering of losses. Offering capacitive power during high power consumption as well as inductive power during high distributed generation, this power scheme can be recommended.

CONCLUSION

The requirements for grid access for passive rectifiers and rectifiers featuring an active front-end have been compared. EVSE close to a local substation can be installed without special requirements. The benefits of active front-end become apparent as soon as line length increases. For distant EVSE locations, the supply voltage limitation is crucial. Reactive power compensations are an effective measure to increase maximal line length.

MISCELLANEOUS

Acknowledgments

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