EVALUATION OF GRID RELIEVING MEASURES FOR INTEGRATING ELECTRIC VEHICLES IN A SUBURBAN LOW-VOLTAGE GRID

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ABSTRACT

Within this study the impacts of future electric vehicle penetrations on the low-voltage level are analyzed. Therefore, the need for grid expansions is prematurely identified based on a suburban grid, operated by the Austrian distribution system operator Energienetze Steiermark GmbH. The future development of electromobility-induced grid effects is demonstrated by simulating several electric vehicle penetration rates. Additionally, grid restrictions are counteracted by analyzing grid- and user-controlled measures.

The investigated suburban low-voltage grid could face inadmissible voltage range deviations per EN 50160 at an EV-penetration of only 10 %. Moreover, an increased share of electric vehicles leads to critical voltage unbalances (around 40 % EV) and thermal overloads (around 20 % EV). This study shows in addition, that voltage deviations are reduced significantly by several measures. Furthermore, grid expansions can be avoided by a charging infrastructure equipped with voltage-dependent active power control, or switching to three-phase charging with reduced power. These measures prevent inadmissible voltage range deviations and voltage unbalances as well as critical thermal conditions even at an 80 % electromobility penetration.

INTRODUCTION

The amount of traffic-related greenhouse gases in Austria increased by 67% between 1990 and 2016, triggered by higher mileage of passenger cars and trucks [1]. As a countermeasure, Austria’s climate and energy strategy for 2030 aims for a carbon-free traffic sector by 2050, and accordingly, for an expansion of electric mobility in the upcoming years [2]. The rapid development of electric vehicles (EV) in Norway [3], a role model with respect to the implementation of electromobility, demonstrates the potential of how EV-incentives can help to increase the share of electrified vehicles. Austria’s plan to increase the number of EV by monetary (funding for purchasing an EV, taxation benefits) and non-monetary (parking benefits) incentives [4, 5] should promote electromobility in a similar way. According to the Austrian Federal Environment Agency, the number of battery electric vehicles will reach 210,000 in 2020, when providing ideal political and environmental framework conditions [6].

The last years illustrated, that most charging processes take place at household charging stations [7]. As a result of little private charging possibilities in urban areas combined with a lacking implementation of public and semi-public charging infrastructure, the future change to electrified vehicles will specially take place in suburban and rural areas [8]. Consequently, distribution system operators (DSO) will be faced with new challenges due to rising numbers of electric vehicles in the upcoming years [5], especially in suburban and rural low-voltage (LV) grids. Despite Austria’s early stage of e-mobility (0.39 % battery electric vehicle penetration rate in 2018 [2]), these upcoming challenges should be identified prematurely. The integration of future EV-penetrations in existing distribution grids can of course be established by classic grid expansion measures. Due to high costs for excavation, new grid lines and new substations, DSOs are interested in more cost-efficient alternatives [5]. For this reason, this study analyzes future impacts of private charged electric vehicles on a suburban low-voltage grid with respect to voltage range deviations, voltage unbalance and thermal conditions. Based on the identification of critical grid elements, the potentials of several grid relieving measures are also analyzed. This paper provides the methodology behind the executed simulations, the results for a range of EV-penetrations from 10 % to 100 % and a conclusion with key-insights.

METHODOLOGY

Simulations are performed as co-simulations in MATLAB and NEPLAN in order to determine the effects of projected EV numbers on a suburban low-voltage grid. Scenario-dependent grid impacts are analyzed by long-term load flow simulations in NEPLAN. The modelling of the analyzed grid, the modelling of consumer- and EV load profiles and considered control strategies for grid relieving measures are described in the following chapters.

Grid specifications and -modelling

The potentials of grid-oriented measures that may reduce

EV-caused grid restrictions are demonstrated on the basis of a suburban low-voltage grid operated by Energienetze Steiermark GmbH. The grid topology is characterised by a 250 kVA-substation, supplying radially located feeders via cable (91 %) and overhead lines (9 %). Real grid data enables highly accurate grid modelling (NEPLAN) and thereby the identification of grid impacts with a high level of detail. In the grid model, the upper voltage side of the LV substation is connected to a constant voltage source (slack), which means that voltage deviations in the medium-voltage level won't be considered. The permitted voltage range of ± 10 % of the nominal value in accordance with EN 50160 [9] is shared by the medium- and low-voltage level conjunctly. However, only 6.5 % are available for voltage drops at the substation and the LV grid pursuant to the voltage range partitioning in [10]. Therefore, the nominal voltage on the upper voltage side of the LV substation is set to 0.965 pu. This takes the maximal voltage drop caused by medium-voltage loads into account.

Modelling of consumer load profiles

Modelling of consumer loads is separated into a two-step procedure: In the first step, industrial and agricultural consumers are modelled by phase-symmetrical standard load profiles in accordance with [11]. The behavior-based load profile generator by Pflugradt [12] is used in the second step to create highly resolved long-term power profiles for various household structures. This provides phase-asymmetrical synthetic household load profiles, which enables unbalanced load conditions to be considered. All types of consumer load profiles (symmetrical industrial- and agricultural loads as well as asymmetrical household loads) are scaled by the specific customer's annual energy consumption, provided by Energienetze Steiermark GmbH, and aggregated for each grid connection node. Finally, this aggregated load profiles are calibrated by real data. Therefore, long-term active- and reactive power profiles are measured at the LV substation.

Modelling of EV load profiles

EV-caused grid impacts are evaluated by means of an EV reference scenario, considering state of the art charging technology and -distribution: single- and multi-phase charging with 3.7 kW - 22 kW charging power (Figure 1). EV load profiles are modeled for several EV-penetrations (10 % - 100 %) by the use of measured charging data of 21 different EV-models [13] including active- and reactive power profiles. A time resolution of one minute allows the consideration of short-term peak loads. In addition, realistic charging behavior of EV users charging at private charging stations is taken into account. Therefore, the following parameters are determined by statistical data and random numbers for each vehicle, according to the probabilistic approach from Razee et al [14]: driving type (EV or ICE), EV-model (battery capacity, electric consumption, technically feasible charging power), installed charging power as well as the required amount of energy and time of charging based on traffic analyses. While the described probabilistic approach enables the modelling of realistic charging patterns, it also risks excluding critical grid conditions. Consequently, this modelling approach was done for a number of iterations. Finally, the iteration which includes the highest number of charging processes is selected for each EV-user and prepared for load flow simulations. Based on this methodology, charging processes with 3.7 kW (40.6 %) and 11 kW (39.2 %) are represented with a high share within the simulated period (Figure 1). Charging with 7.4 kW and 22 kW is considered with a share of 16.3 % and 3.9 % respectively, which results in an average charging power of 7.9 kW within the reference scenario. All the single-phase charging EV are connected to the same grid phase in order to consider the most critical case with respect to power unbalance.

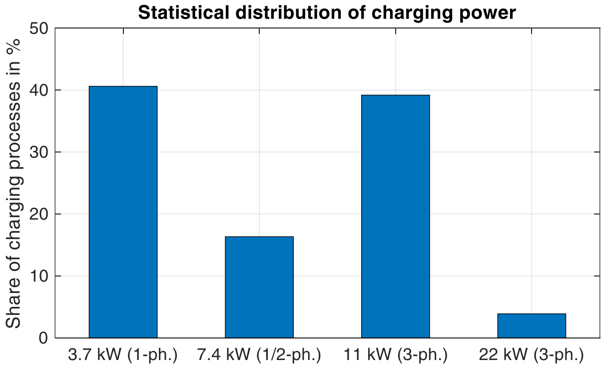

Figure 1: Statistical distribution of charging power for an EV-penetration of 40 %

Control strategies

On the basis of identified grid restrictions provided by the reference scenario, measures for reducing, or rather avoiding the future need for grid expansions, should be examined. Therefore, a range of grid- (A-E) and user-controlled (F) strategies (listed in Table 1) are investigated. Grid controlled measures are characterized by voltage measurements at defined grid nodes. The regulation of scenario-dependent parameters (active power, phase connection between grid and charging station, tap changer) is executed with a time interval of five minutes corresponding to the lowest phase voltage value.

Table 1: List of analyzed grid relieving measures

Scen.	Measure
A	Remote control at distribution substation (RC)
B	Local control at distribution substation (LC)
C	Remote control at critical feeders
D	Voltage-controlled phase selection
E	Voltage-controlled active power regulation - P(V)
F	Three-phase charging with reduced power (3.7kW)

For analyzing grid-controlled measures (A-E), the EV-user behavior and thereby EV load profiles of the reference scenario are considered. Existing technological- (voltage measurement, power control, communication system) and legal frameworks, required for grid control strategies are assumed. The following chapters provide a detailed description of the considered control strategy for each measure.

Voltage-controlled tap changer at the substation (A, B) or rather at critical feeders (C)

Within these scenarios (A-C), EV-caused voltage deviations should be limited to admissible limits according to EN 50160 [9] by the implementation of transformers equipped with on-load tap changers. Voltage-controlled tap changer adjustment at the distribution substation is analyzed by means of two control strategies: remote control based on voltage measurements at defined grid connection nodes in critical feeders (scen. A) and local control based on the voltage measurement at the lower-voltage side of the substation (scen. B). If the measured voltage exceeds the defined voltage control bandwidth (± 0.05 pu for scenario A and ± 0.02 pu for scenario B), the tap changer is adjusted within nine taps ([-2, 6]) with a tap range of 0.01 pu. Scenario C is defined by the installation of variable transformers (voltage-dependent remote control analogically to scenario A) not at the substation but in critical feeders.

Voltage-controlled phase selection (D)

Each charging station in scenario D is equipped with a voltage-controlled phase-switch. The application of this feature enables load-balancing of asymmetrical loads, for example single-phase charging EV. Therefore, grid phases with minimal and maximal voltage values are detected for each grid connection node with a time interval of five minutes. Finally, phase connections between grid and EV-load are switched accordingly in the grid model in case of voltage values lower than 0.95 pu.

Voltage-controlled active power regulation (E)

In contrast to uncontrolled charging of electric vehicles (reference scenario and scenario F), a voltage-controlled regulation of available charging power is analyzed within this scenario. Therefore, each charging station is equipped with an active current/voltage regulation in accordance with the characteristic in Figure 2 in order to avoid critical voltage deviations. Regarding higher charging power, an adaptation of the control characteristic may be necessary.

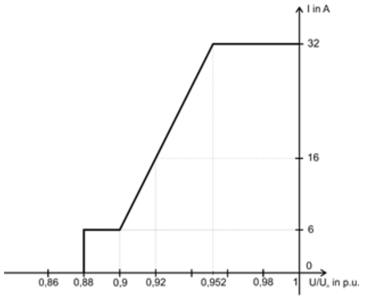

Figure 2: I-u-characteristic of active power control [5]

Three-phase charging with reduced power (F)

This scenario covers a change to three-phase charging with a reduced charging power of 3.7 kW, which can be considered as the optimal charging scenario concerning the prevention of peak loads and power unbalances. Furthermore, this scenario considers area-wide phase-balancing of several single-phase chargers. EV load profiles for scenario F are modelled analogously to the described approach in the reference scenario, considering a charging power of 3.7 kW.

RESULTS

Evaluation of critical grid elements

The need for grid extension measures on the low-voltage level caused by increasing EV numbers is derived by the number of critical grid elements for a certain penetration rate of electric vehicles. Therefore, the following criteria are considered for contrasting with the simulated results of grid nodes and grid lines:

1) Permissible voltage deviation per EN 50160 [9]: 95 % of all 10-minute mean values of one week have to be within ± 10 % of the nominal voltage
2) Permissible voltage unbalance per EN 50160 [9]: Within one week, 95 % of all 10-minute mean values of the relation between negative and positive sequence voltage must be lower than 2 %
3) Thermal line utilization within the line-specification

The examination of voltage range compliance (criteria 1) is based on the determination of the 5 %- and the 100 %-quantiles of all 10-minute mean values within one week for each grid node. Criteria 2 is verified by means of the 95 %-quantile of the relation between negative and positive sequence voltages (10-minute mean values). Critical grid lines are identified accordingly to the maximal thermal utilization within the simulated period.

Identification of grid expansion needs (reference scenario)

The future development of EV-induced grid impacts on the low-voltage level is derived by the simulation of several electromobility penetration rates (10 – 100 %). However, an EV-penetration of 10 % already can result in inadmissible voltage range deviations according to EN 50160 [9] in a number of grid nodes. Figure 3 illustrates the 5 %- and 100 %-quantiles of all 10-minute mean voltage values of each grid node for a 10 %-penetration. The nominal voltage of 0.965 pu as well as the lower voltage limit of 0.9 pu (EN 50160) is marked by a red line. Temporal aggregations of household- and EV-loads, trigger inadmissible voltage decreases in 19 grid nodes. These are located at the end of long feeders, which are characteristic for radially arranged low-voltage grids in suburban and rural areas. In contrast, the considered grid shows no inadmissible voltage unbalance or thermal overload at an EV-penetration of 10 % (Figure 3).

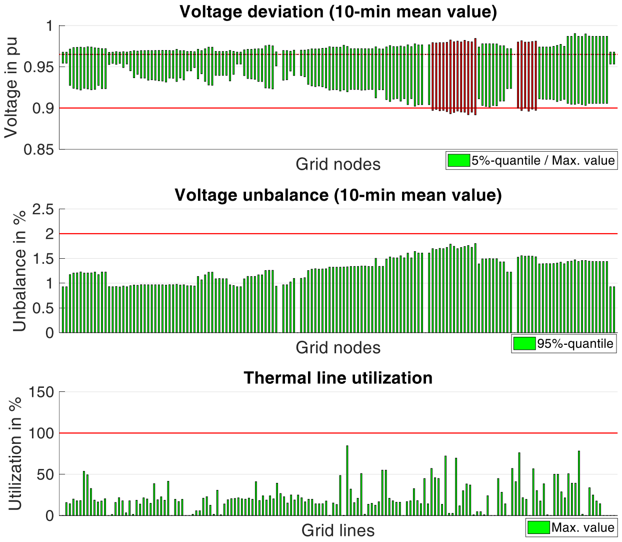

Figure 3:Voltage range deviations, unbalances and thermal utilizations for a 10 %-EV-penetration (reference scenario)

Nevertheless, the described charging pattern (Figure 1) with a high share of single-phase chargers can lead to critical voltage unbalances at future penetrations of around 40 %. Thermal overloads on the other hand are caused by simultaneously charging electric vehicles with high charging power, connected on the same feeder. Therefore, such overloads can occur already at low EV-penetrations (around 20 %). Based on the probabilistic modelling of EV-load profiles, the proportion of critical grid elements does not increase necessarily with higher penetration rates (Figure 4). Therefore, the fitted expectation values of critical grid elements (reference scenario) with respect to voltage deviations, unbalance and thermal overload are added to Figure 4. In other words, a certain share of electrified vehicles (e.g. 40 %, Figure 4) triggers critical voltage characteristics without showing thermal overloads. The reason for that is the probabilistic selection and spatial distribution of single- and multi-phase chargers (with various charging power) by the use of random numbers and statistical data which result in the charging-pattern shown in Figure 1. The further increase of electric vehicles (up to 80 % EV-penetration) raises the share of endangered grid elements for the considered grid and charging-pattern to 41 % (voltage deviation), 39 % (unbalance) and 3 % (thermal overload). These results clarify, that critical voltage characteristics represent the limiting factor for integrating future EV into the analyzed LV grid.

Potentials of grid relieving measures (scen. A-F)

The verified grid relieving measures aim especially for a decrease of inadmissible voltage range deviations and voltage unbalance according to EN 50160. The proportions of endangered grid nodes and grid lines (Figure 4) are therefore illustrated for each strategy (scenario A-F) and contrasted to the reference scenario. Voltage-controlled tap changer adaptations at transformers in dependence of critical grid nodes (remote control) can reduce inadmissible voltage drops even at high EV-penetrations. The use of remote control at the substation (scen. A) or rather the use at critical feeders (scen. C) can reduce the share of voltage range deviations to 0 % or rather 1 %, considering an 80% penetration (Figure 4). In case of critical voltage characteristics in isolated feeders, these two measures (scen. A and C) must be compared with respect to cost-efficiency. Implementing local voltage control at the lower voltage side of distribution substations (scen. B) has lower influence on critical grid nodes compared to remote control: critical voltage conditions will occur continuously with higher EV-penetrations (40-80 %). These results clarify the relevance of the chosen control strategy using a variable distribution substation.

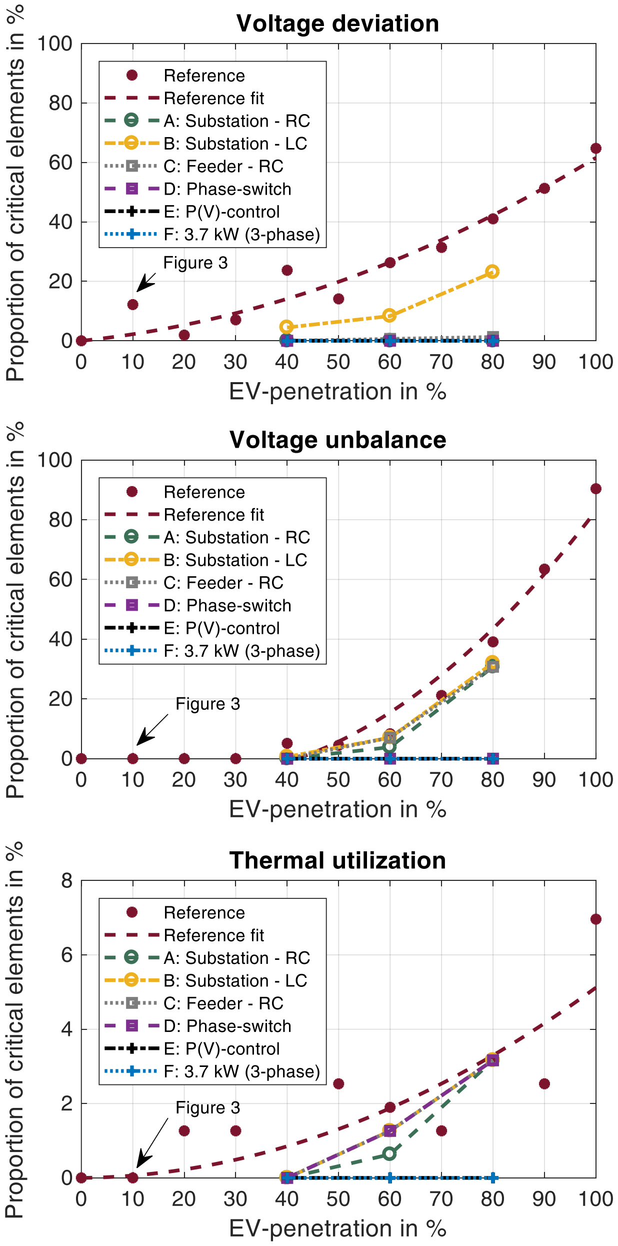

Figure 4: Potential of analyzed strategies with respect to voltage deviations, voltage unbalance and thermal utilization

Beside the reduction of voltage range deviations, scenario A, B and C show little potential for avoiding thermal overload and unbalanced voltage conditions. In contrast, the voltage-controlled allocation of EVs on grid-phases (scen. D) even allows the implementation of EV penetrations up to 80 % without critical voltage characteristics (Figure 4). Similar to the scenarios A-C, the impact on thermal utilization is low: an EV-penetration of 80 % triggers critical conditions in 3 % of all grid lines. Within analyzed grid relieving measures (scen. A-E), the voltage-controlled regulation of available active charging power (scen. E) represents the most effective strategy that integrates high numbers of EV in the considered LV grid. Even at an EV-penetration of 80 %, impermissible voltage range deviations, critical voltage unbalance and thermal overload are avoided (Figure 4) by an extended implementation of P(V)-control. Additionally, EV-induced grid-impacts can as well be prevented by an area-wide adaptation of charging parameters. The limitation of available charging power to 3.7 kW (uniformly phase-distributed) allows for large EV installation capacity and avoids critical voltage- and thermal conditions at high EV-penetrations. This scenario demonstrates, that even poorly developed low-voltage grids are capable of supplying future electromobility, if vehicles are charged three-phase with reduced power. Due to low charging demand in daily life [6] and high duration of parking at home, the comfort of EV-users wouldn't be affected by this measure.

CONCLUSION

Regarding state of the art charging technology (charging with up to 22 kW), the investigated LV grid shows limited capacity for integrating electric vehicles. EV-penetrations of 10 - 20 % could already result in inadmissible voltage range deviations and thermal overload. Furthermore, the local accumulation of single-phase charging EV could lead to critical grid conditions with respect to voltage unbalance at a 40 % penetration. In addition, these grid restrictions are counteracted by the simulation of several grid relieving measures. The relevance of the selected control strategy using a variable distribution transformer is illustrated by the comparison between remote and local control. The tap changer adjustment based on local voltage control shows little potential for avoiding critical voltage deviations at high EV-penetrations. In contrast, EV-induced voltage drops can be reduced by remote control at the substation, and by variable transformers installed in endangered feeders using remote control. Moreover, the implementation of charging infrastructure equipped with voltage-dependent phase-switches represents an effective measure that avoids inadmissible voltage conditions. Beside positive effects on voltage characteristics, the mentioned measures are not capable of adequately reducing the thermal utilization of grid elements. Nevertheless, thermal overload and inadmissible voltage characteristics can be avoided by voltage-controlled active power regulation as well as an area-wide change to three-phase charging with reduced charging power even for an 80 % EV-penetration. Consequently, charging at home during night enables the use of low charging power and provides thereby high potential for reducing the need for grid expansions without any loss of EV-user comfort.

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