Control Aspects in Voltage Dependent Electric Vehicle Charging

Thorsten Schlößer; Eckehard Tröster; Pablo Gambín Belinchón
Energynautics GmbH
Darmstadt, Germany
t.schloesser@energynautics.com

***Abstract*—Controlled vehicle charging has the potential to increase the grid hosting capacity of electric vehicles. In this paper, a control algorithm following a linear P(V)-characteristic with locational dependent parameters is assessed in terms of its dynamic behavior. Locational dependency has been introduced to coordinate the charging of the individual cars in a non-discriminating manner. In the control algorithm, a measured voltage value is translated into a change of charging power. This however bears the risk of overcompensation and thus voltage instabilities if too many vehicles react with a certain delay to the same voltage change. To avoid such effects a PID- control and a PT1-filter have been implemented for comparison. Various simulations using an RMS-Model in DIgSILENT PowerFactory have been carried out to assess the impact of an increasing number of EVs and the influence of additional household loads on system stability. Results show that both PID- control and PT1-filters have a very similar behavior. Due to the higher complexity of the PID-control, the PT1-filter has been chosen for further investigation. With this in place, it can be shown that if the time constant T of the PT1-filter is set to 30 % above the time it takes an electric vehicle to react to a change in voltage, system stability is reached within all simulations. With this relatively easy measure, instabilities at high penetration levels can be avoided.**

I. Introduction

In recent years, various control strategies for electric vehicle (EV) charging have been introduced to avoid grid overloading [1]. Quite often only static stability is shown, without considering instabilities caused by time-related interdependencies. Therefore, the purpose of this paper is to assess dynamic behavior of EV charging on one exemplary control algorithm.

Within the SNOOPI-Project [2] a concept has been developed and tested to control the reactive power in-feed of photovoltaic generators depending on the local voltage level to avoid communication. In this paper the SNOOPI concept is adapted to voltage-dependent active power control for EV charging.

The basic idea is to achieve location-independent adjustment of the vehicle charging power at critical voltage levels. In case of too many vehicles reacting to the same voltage change, the following could occur: Assuming a grid voltage close to the nominal value, the electric vehicles will start charging, resulting in a voltage drop. Due to the decreased voltage however, the electric vehicles reduce their charging power, which will lead to an increase of the voltage back to nominal. Thus, the cycle begins anew. The purpose of this paper is to evaluate the impact of such effects and to propose a method to avoid resulting instabilities.

The paper is structured as follows: In chapter II, the general simulation outline is introduced, followed by the P(U)-characteristic outline. Chapter III is focused on an analysis of the simulation results, while chapter IV gives a brief summary followed by a conclusion and an outlook on future evaluations.

II. Simulation outline

An RMS model is created within DIgSILENT PowerFactory to assess the impact of dynamics of electric vehicle charging. Within this paper the voltage instabilities caused by voltage-dependent active power control (P(U)-control) is assessed. Nevertheless, the results are expected to be transferable to other control mechanisms such as Fuzzy-Control or transformer load-dependent power control. To make sure the voltage stays stable and within its limits, a worst-case scenario of maximum simultaneous charging vehicles is considered. Following the results of Kerber's research of typical German distribution grids [3], a feeder prone to voltage deviations is selected. A maximum number of 60 households is expected to be connected to a single NAYY-4x150 cable with 10 meters distance between each household connector. Assuming each household owns two electric vehicles, which is far above the German average of 1.1 vehicles per household [4], 120 electric vehicles are distributed along the feeder. As described in a previous paper, not all vehicles will be charging simultaneously [5]. It has been shown, that for 11 kW maximum charging power per vehicle with a certainty of 99.99 % at maximum 23 % of the vehicles are drawing power simultaneously. As a consequence, simultaneous charging of 30 vehicles with even distribution along the grid is assumed in this analysis.

A. P(U)-Control curve

As mentioned in the introduction, the SNOOPI concept is adapted to voltage-dependent active power control (P(U)-control). The analyzed algorithm reduces the active power when approaching low voltage levels. Furthermore, it needs to be considered that most electric vehicles require a minimum current of 6 A to start the charging process **??**. As a result, a cut of voltage U_{min} with a sudden drop in charging power contains a high risk for instabilities. To design a smoother transition, a hysteresis is added around the cut-off voltage U_{min}. This way, electric vehicles are only allowed to start charging when the voltage is 20 % above U_{min} in relation to U_{max} following linear Interpolation. (e.g. U_{start} = 0.96 p.u. for U_{min} = 0.95 p.u. & U_{max} = 1p.u.) In addition,

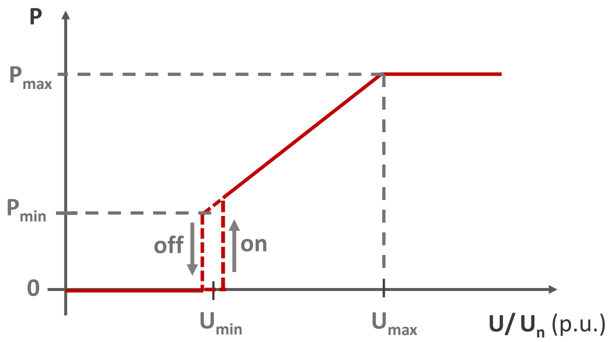

Fig. 1. Basic P(U)-control characteristic including hysteresis at the cut off power corresponding to 6 A current.

The values of the individual start- and end-voltage U_{max} and U_{min} of each electric vehicle are subject to the feeder position to achieve discrimination-free behavior. Otherwise cars at the end of the feeder would be restricted to a greater extent than cars at the beginning. As introduced by Hempel et al. [2] the relative feeder position can be evaluated by analyzing the voltage over a longer period of time. Since only a short period is simulated in this paper, some assumptions have to be made to achieve the same effect. Even
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vehicles gradually start charging. The second scenario is set up to evaluate cases of increased charging correlation and the impact sudden voltage changes caused by external factors can have on stability. Finally, the reaction of the EV charging process to sinus voltage swings is evaluated regarding damping and resonance behavior.

A. *Comparison of PT1- and PID-Control*

To avoid instabilities as described in the introduction, two methods are evaluated. The first method is derived from a requirement of the new German grid code for Q(U)-control of photovoltaic systems at the low voltage level [6], which requires PT1 filter behavior. Secondly, a PID-controller is evaluated since it is a widely adopted control strategy. In case of the PID, the controller output is fed back directly, instead of considering measurement data of the current charging power. This is due to the fact, that it cannot be assumed that an electric vehicle will react to the provided set points, since those only represent the maximum allowed values. For example, the general electric vehicle charging capabilities or the battery health management might limit the actual charging power well below the maximum set-points sent to the EV. In this case the control-error would never be reduced to zero. Furthermore, in order to reduce the set of parameters and to find generally stable settings, the PID was parametrized following Ziegler-Nichols [7]. Still two parameters are necessary instead of one for the PT1 filter. Throughout all simulations it could be shown that the

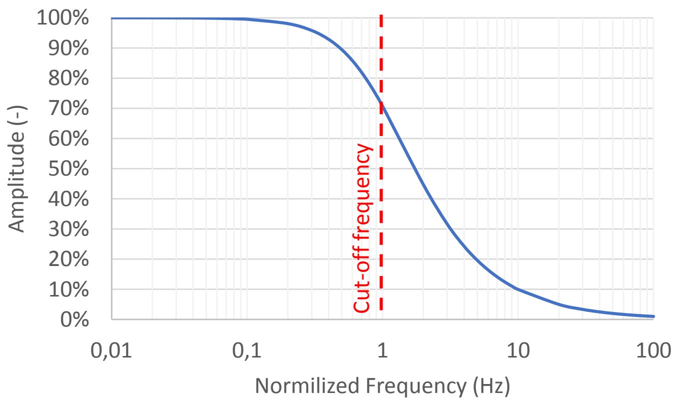


Fig. 3. Bode Diagram of normalized PT1-Filter amplitude reduction.

PT1 filter dynamics are best shown via a uniform step response in the time domain. From figure 4 it can be observed, that the step response dynamics decrease linearly with the PT1 parameter T setting. In order to have a fast response, the parameter should be chosen as small as possible. Therefore, a compromise needs to be found between fast dynamics and sufficient damping.

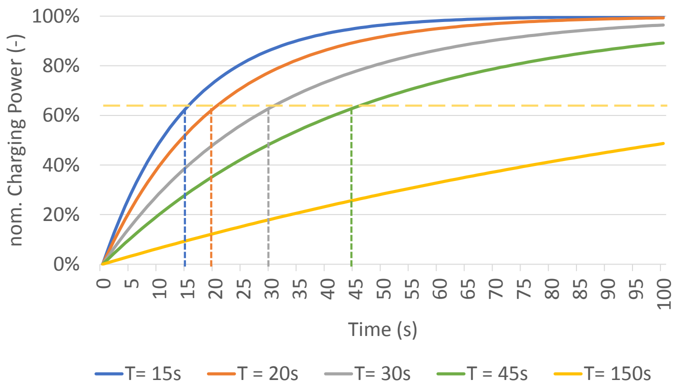


Fig. 4. Step response of a PT1 filter with varying filter settings.

B. Single filter behavior

Before addressing the behavior of multiple EVs charging, the general characteristics of a single PT1 filter element in a single charging start-up process is analyzed. In this case, only one EV and no other loads are connected to the feeder. As the grid will not see any voltage issues, the P(U)-dependency indicates full charging potential of 11 kW at all times. The green line in figure 5 indicates the setpoint of 11 kW, which at the same time equals the PT1 filter input. Normally the PT1 filter output would start at 0 kW, but in order to avoid unnecessary ramp up until the minimal charging power of the EVs is reached, the filter output is set to a starting value of about 4 kW as shown in red in Figure 6. This adaption to accelerate the start-up process, should only be use at initial grid connection of the vehicle and only if the filter input value is above 120 % of the minimal charging power of 4 kW. Once the charging process is started, the PT1 filter should not be further influenced in order to avoid frequent on-off switching.

As shown in figure 6, the output of the filter is continuous, but the electric vehicles react to the provided set-point with a 15 second delay. Although in practical operations, faster

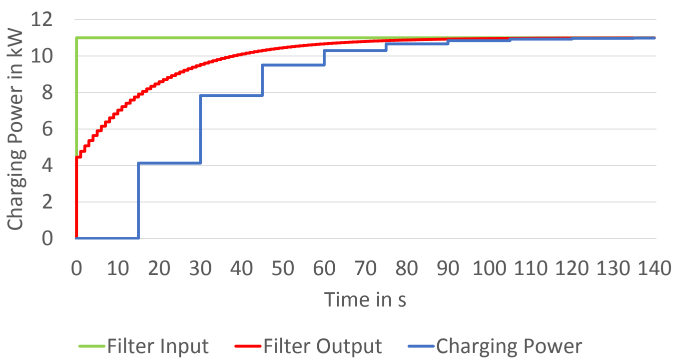
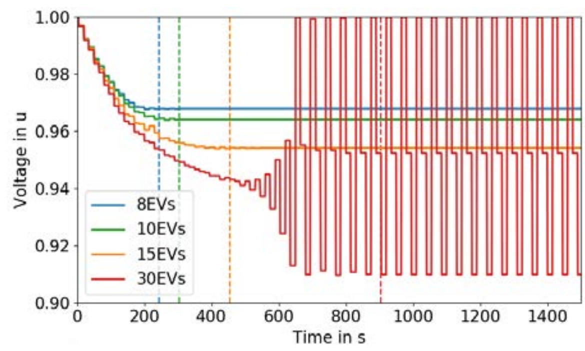


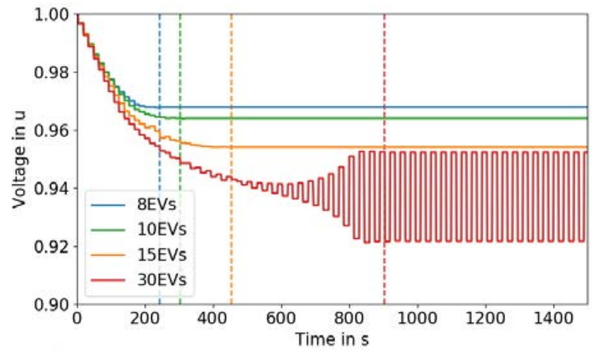
Fig. 5. Individual PT1 behavior at the beginning of a charging session at nominal voltage levels.

C. Increasing number of electric vehicles

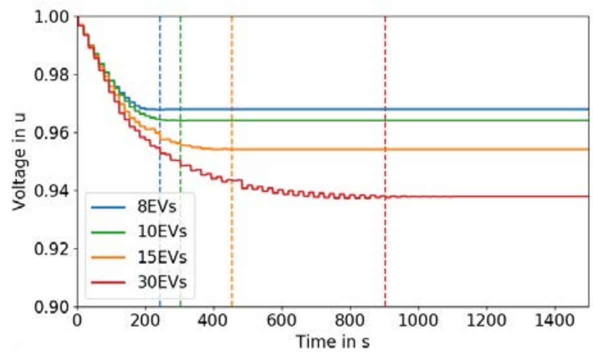
In the next evaluation an increasing number of electric vehicles (8, 10, 15, 30) within the grid are assessed without additional conventional load. For this purpose a scenario without a filter is compared to a PT1 filtering with the parameter T set to 10 and 15 seconds (fig. 6). To reduce initial dynamics, EVs added one by one every 30 seconds. The vertical lines represent the time until all EVs are online, which basically depends on the total number of EVs (e.g. with 30 EVs it takes 30 EVs times 30 s = 15 minutes). When charging up to 15 electric vehicles the slope of the P(U)-control alone is able to avoid voltage swings. However with more than 16 vehicles the system becomes instable. By introducing a PT1 filter with T = 10 s, the stability is improved and by further increasing T to 15 s eventually completely recovered. This shows that the PT1 parameter needs to be at least as large as the EV delay time which has been assumed in the simulation to be 15 seconds. Larger values would increase stability, but hamper system dynamics.



(a) No PT1-filter



(b) T = 10s



(c) T = 15s

Fig. 6. Impact of varying numbers of charging vehicles on the grid voltage at the end of the line under the influence of different PT1-filter settings.

Figure 7 contains information about the position independency of the average charging power along the feeder. It can be related back to the initial assumption of even load distribution for the calibration of the P(U) curve. Notably, the maximum charging power of 11 kW is not reached in any of the scenarios, even though the minimum voltage at the end of the feeder is above 0.93 p.u. in all stable cases (compare with fig. 6)). The linear dependency of the P(U)-characteristic is responsible for this effect. To avoid instabilities, the charging power is reduced starting at the individual U_{max} value. As a consequence, charging power reduction occurs too early in case just a few vehicles are charging. An increased steepness would reduce the effect at the potential cost of stability. The maximum safe slope should be evaluated within field tests and would also depend on fluctuations coming from the medium voltage grid.

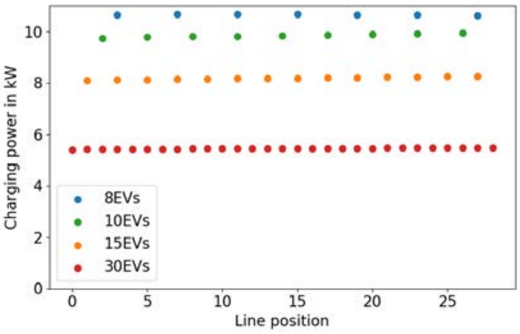


Fig. 7. Individual PT1 behavior at beginning of charging session.

D. *Influence of starting times and voltage drop behavior*

In the following, the influence of the electric vehicles' starting times is assessed and once stable settings are reached, the reaction to an external voltage drop (e.g. due to transformer tap changing) is evaluated. Instead of a new vehicle starting its charging process every 30 seconds as used in the previous simulation, the time until another vehicle starts charging is reduced to 1s, 5s, 10s, 15s and compared to the old settings of 30 seconds. Only the possible maximum number of 30 EVs is added in each case to reduce the number of simulation cases. The PT1 parameter T is set to 20 seconds, since lower values have been unstable in some cases as will be discussed within the voltage drop analysis. The results of the complete simulation are displayed in figure 9.

It can be observed that swinging can be mostly prevented, even when the vehicles are added in a fast consecutive manner. Only for electric vehicles starting their charging process with a one second delay, slight overreaction occurs at the very beginning of the charging process. In this case even the minimal charging power of 6 ampere results in voltage boundary violations. These high correlations can occur after a blackout if all EVs start charging directly once the power comes back online. Rather simple random starting delays, evenly distributed over one minute, can prevent new power failures in combination with a charging power ramp up starting at the minimal charging power.

Within the same simulation, the impact of adding a large conventional load is further analyzed after all the EVs have started their charging process and stable operation is reached.

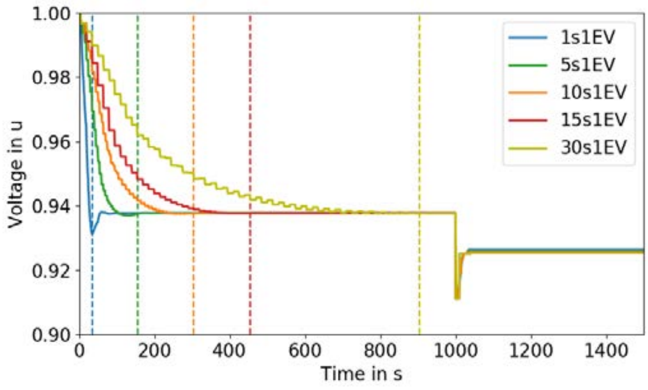


Fig. 8. Start and load drop behavior of charging EV's with PT1 parameter T = 20 s and varying start-up times.

Fig. 9. Impact of varying numbers of charging vehicles on the grid voltage at the end of the line at different EV start frequencies and the reaction to a voltage drop after 1000s with a PT1 parameter setting of T = 20s.

Therefore, after 1000seconds a 1.25-kW-load is added at each of the 60 households. This results in an instantaneous voltage drop to 0.91 p.u. at the end of the feeder, which is below the minimum P(U)-control voltage level of 0.93 p.u. As can be seen in figure **??**, the charging power is reduced without causing instabilities, leading to quick stabilization at a new safe voltage level within 30 seconds.
The PT1 parameter T needs to be larger than the previously evaluated critical T ($T_{crit.}$) value = 15s. Otherwise, the damping magnitude is not high enough when $T_{crit.}$. equals the reaction time of the EVs. Still the parameter T should be chosen as small as possible to keep the filter as dynamic as possible. In these simulations a 33 % increase above the EV reaction time to T = 20s has proven to be the best solution. Since the new voltage level is below Umin, some of the electric vehicles have stopped charging and are prevented from restarting their charging process due to the hysteresis.

E. *Reaction to periodic voltage changes*

In the previous chapters it has been shown that the charging process is kept stable under dynamic starting of the EV charging processes as well as sudden voltage changes if the right PT1 parameter is used. In the real world the grid voltage is constantly fluctuating and stability needs to be proven under these conditions as well. Thus, the impact of more realistic voltage variations represented by sine-waves of different frequency is analyzed.
For this purpose, each of the 60 households contains a conventional load following a load amplitude of 1.25 kW, which results in a voltage amplitude of about 0.03 p.u. at the end of the feeder. The cycle time of the sine-wave is varied between 30 and 1000 seconds in different simulations. The PT1 parameter T is left at 20 seconds as in the previous simulation and the EVs start their charging process one by one every 30 seconds. The resulting behavior of the electric vehicles reacting to the voltage swings is shown in figure 10.

For periods large than 250 seconds the electric vehicle charging scheme follows the voltage fluctuations. The amplitude is reduced to 0.011 p.u. from the undampened voltage amplitude of 0.03 p.u. at the end of the feeder.

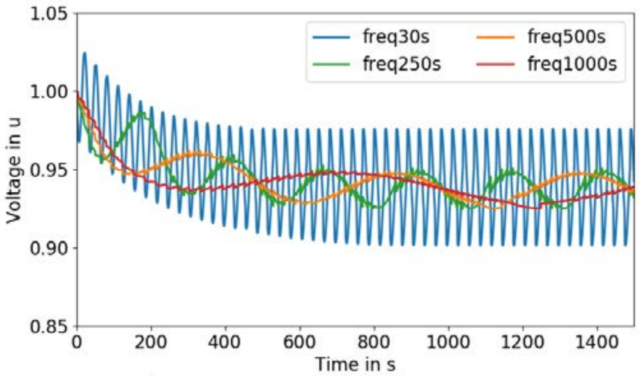


Fig. 10. Reaction of EV-charging on voltage fluctuations following a sinus wave of varying periods and an amplitude of about 0.03 p.u. for a PT1 parameter of T=20s.

Periods smaller than 250 seconds result in an amplitude increase until the resonance point is reached. This resonance period can be easily calculated when considering the EV reaction time of 15s. At a period of 30s of the voltage fluctuations the EV charging power will match the maximum of the conventional load, instead of opposing it. Thus the amplitude increased to a maximum of 0.037 p.u. at the end of the feeder. A PT1 parameter change has confirmed that the resonance amplitude cannot be decreased by the PT1 filter under any reasonable setting. While in theory, a clear resonance frequency exists, it has to be kept in mind that the time for an electric vehicle to react to a given voltage measurement will vary widely depending on the car make, SOC, ambient temperature and other factors. In real world application the reaction time of one EV-make could be 60s while another takes only 5 s to react. Therefore, no clear resonance point is expected in practical applications.

IV. Summary

A comprehensive set of dynamic simulations has been performed to analyze the effect of voltage dependent electric vehicle charging. The concept is based on the SNOOPI controller and coordinates charging processes to avoid discrimination of users at the end of a feeder. It was shown that without additional measures the grid can become unstable once enough electric vehicles simultaneously react to the same voltage change. In principle the results are transferable to other control algorithms as well. The effect occurs when a large number of electric vehicles reacts to the same value, thus influencing this value to such an extent that overreaction leads to unstable swinging. By using either PT1 filters or PID-controllers at each charging station instabilities can be avoided. It was decided to use PT1 filters since less parameters are necessary compared to the PID-controller. PT1 elements belong to the class of low pass filters and therefore dampen frequency signals above the cut-off frequency (f_{cutoff}=1/T). In order to avoid voltage instabilities in all analyzed cases, the PT1 parameter T should be about 30 % above the critical value. The critical value represents the time it takes for an electric vehicle to change its charging power in accordance to the new set-point. Since most electric vehicles are expected to have different reaction times a detection mechanism could be created to dynamically change the PT1 set-point for the fastest stable behavior. It should be noted, however, that the proposed control mechanism is not able to avoid swinging effects caused by hitting the resonance frequency of the control loop.

In real-world applications, constant changes of the charging power might have a negative effect on the car battery health. It might be desirable to allow changes only when a certain voltage change is detected, but this bears the risk of new instabilities since more cars would react simultaneously. Randomization of the voltage change thresholds and inaccuracies within real-world distribution grids could make this concept more stable. Additionally, charging stations should have a random waiting time until restarting the charging process after a power failure to avoid another blackout close after. It can be concluded that regardless of the control scheme (voltage, transformer load, CO2 emissions etc.), simultaneous reaction of a large group of charging electric vehicles has to be avoided. A successful countermeasure is to use PT1 elements, since they are easy to use and a well-established control method. Industry-wide adoption should therefore be possible without major complications.

References

[1] T. Schloesser, *Grid Load Relief by Smart Charging of Electric Vehicles*. Energynautics GmbH, 2018.

[2] Sabrina Hempel et al., *Smart Network Control with Coordinated PV Infeed*. IET Journals, IET Renewable Power Generation, no. 13, pp. 661-667, 2019), 2018.

[3] G. Kerber, *Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen*. Technische Universität München, 2010.

[4] Statisches Bundeamt, “Ausstattung privater haushalte mit fahrzeugen - deutschland,” 2018, last accessed: 21.06.2019. [Online]. Available: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Einkommen-Konsum-Lebensbedingungen/Ausstattung-Gebrauchsgueter/Tabellen/liste-fahrzeuge-d.html

[5] T. Schloesser, *Probabilistic Modelling of Charging Profiles in Low Voltage Networks*. Energynautics GmbH, 2018.

[6] VDE, *VDE-AR-N 4105*. Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE), 2018.

[7] Hochschule Beuth, “Einstellregeln: Faustformelverfahren,” 2012. [Online]. Available: ftp://141.64.72.2/VORLES/RT1/Optimierung/Regelflaeche/Einstellverfahren_empirisch.pdf