On the Impact of PEV Charging on Transmission System: Static and Dynamic Limits

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***Abstract*—The number of Plug-in Electric Vehicles (PEVs) is increasing worldwide, as well as are the rates with which vehicles can be charged. This poses the question regarding how many PEVs may ultimately be connected simultaneously for charging, and how quickly the load of PEVs can increase, before the existing power grids show stability issues. In particular, we denote the first as a static limit, and has mainly an impact in terms of node voltages, while the second is a dynamic limit, which mainly affects the frequency of the system. In this paper, we shall use a transient stability model of power systems to assess both limits for a realistic power transmission system, and conclude that the static limit is actually the most critical one.**

***Index Terms*—Plug-in electric vehicles, power systems, power systems simulators.**

I. Introduction

The market of Plug-in Electric Vehicles (PEVs) is increasing year by year, and estimates are that PEVs will make up 57% of passenger car sales globally by 2040 [1]. Motivations behind this mobility revolution are many: environmental reasons, tight emissions regulations in cities, decreasing prices of batteries, and the possibility to use PEVs for other reasons than as simple means of transportation, and exploit their energy storage capabilities, for instance to provide ancillary services to the power grid. The experience of countries where the penetration level of PEVs has reached significant levels has shown that so far PEVs have been smoothly accommodated in the existing power systems. However, as batteries are increasing in sizes to extend the range of PEVs, and as faster and faster charging infrastructure is becoming available, there is a need to assess what are the physical static and dynamic limits of the power grid, or in other words, whether increasing numbers of PEVs and increasing charging rates may ultimately threaten the nominal functioning of power grids.

A. Literature Review

The increasing electrification of the mobility sector is posing novel challenges in terms of the economic, environmental and electrical impact of PEVs [1], [2]. For what concerns the power grid, [2] concludes that the performance and the efficiency of the power grid could be affected by PEVs charging, especially if vehicle charging is unconstrained and uncontrolled, with consequent need of extra investments in generation and transmission capacity. Alternatively, adoption of smart charging programs would be the low-cost most reasonable solution to prevent such investments from becoming unavoidable. Ontario's grid potential for charging PEVs during off-peak periods is instead analyzed in [3], concluding that 6% of the total vehicle fleet in Ontario can be charged without any additional power system investments. Another interesting analysis of the PEVs penetration impact on composite power systems is described in [4], where both local and aggregated effects on the entire power grid are studied, including the generation and the transmission components of the electricity network. In this case, reliability of modern power systems was evaluated using Monte Carlo simulation algorithms.

As aforementioned, in addition to representing a considerable load to the power system, PEVs may be also seen as a virtual storage device and as an opportunity for the power grid to receive ancillary services, exploiting Vehicle-To-Grid (V2G) power flows. In this context, [5] proposes an aggregate model of PEVs for the Primary Frequency Control (PFC), where distribution network characteristics are included for a realistic analysis. A conceptual framework where PEVs are successfully integrated into power systems is presented in [6], considering both technical and electricity market aspects; a deep study about the maximum number of PEVs to be integrated in the grid is conducted using the PSS/E software tool, concluding that the adoption of advanced centralized EV charging control strategies reduces the negative impacts of PEVs, and possibly increases their potential benefits, as for instance to deliver frequency control services.

B. Contributions

In this work, we want to assess the limits of the power grid from the perspective of the transmission system, in terms of the maximum capability to charge connected PEVs. As the number of PEVs, as well as the charge rates for PEVs are constantly increasing, it is important to assess, in an accurate way, what is the maximum number of PEVs, or the maximum load, that may be tolerated by existing infrastructures. For this purpose, we employ the power grid simulator DOME (as described in the more detail in Section II-B), to simulate the power system behaviour and provide practical and accurate assessments.

In particular, we focus on two different aspects related with the PEV charging problem, i.e., the static limit and the dynamic limit. The first one, refers to the maximum capacity of PEVs that can be charged simultaneously by the power grid. On the other hand, the dynamic limit refers to the rate with which PEVs connect to the grid for charging. In principle, while the power grid may easily simultaneously charge a large number of PEVs (up to the static limit), still it might occur that a smaller number of PEVs may also give rise to stability

[1] BloombergNEF, *Electric Vehcicle Outlook 2019*

issues, if they connect to the grid practically at the same time (i.e., giving rise to a stiff load ramp). From this perspective, concerns regarding the dynamic limit are motivated by a number of statistical analyses that have shown that a significant number of PEVs are charged in a domestic scenario ([7], [8]), as soon as the drivers come back home after work ([6], [9]). This behaviour is expected to give rise to an evening peak consisting in a large power demand requested to the power system in a relatively short time interval. Investigation of such a dynamic behaviour is thus also of interest in this case study. Accordingly, this paper responds to the general problem of whether static or dynamic limits are more relevant, and up to what threshold, for the PEV charging problem.

The paper is organized as follows: Section II describes the research problem, with more details regarding the used software, the considered case study of interest, and the modeling of the PEVs charging problem. Then, in Section III, our main simulation results are presented and discussed, and in Section IV we conclude our paper and outline our current lines of research.

II. Problem Set-up

A. The load ramp problem

Uncontrolled charging of PEVs pose significant challenges to current power grids. In particular, two kinds of challenges are examined in this paper. The first one regards the maximum number of vehicles that may simultaneously connect to the grid for charging, and we denote this as the static limit of the grid. The second one considers that most PEVs may be connected around the same time, e.g., in the evening in domestic scenarios, when drivers come back home from work. In this last case, the number of connected PEVs may quickly increase in a short time, and we refer to this as a dynamic scenario. In principle, the two limits may have a different impact on the power grid, as one may expect that the static limit should have a greater impact on the reactive power, thus requiring voltage regulation, while the dynamic limit should mainly affect the frequency of the power system.

In this paper, we evaluate the *static limit* in a simulation case study, by *slowly* increasing the total number of connected PEVs, until a maximum number is achieved, after which a grid collapse occurs. On the other hand, we evaluate the *dynamic limit* as the maximum rate of PEVs arrivals that the grid can support. With this aim, in both cases, we assume that the load increases in a ramp fashion (i.e., constant rate, adding some noise to simulate the stochasticity of the charging event).

B. Simulation set-up

In this work, we consider as the set-up of our simulations the well-known IEEE 39-bus, which corresponds to the 10-machine New England Power System [10], and consists of 10 synchronous machines. Synchronous machines are equipped with turbine governors, automatic voltage regulators and power system stabilizers. In our case study, we have slightly modified the original network by replacing two generators with wind farms with detailed dynamic models of the doubly-fed induction generator, wind turbine and MPPT and voltage controllers of the power electronic converters, to mimic modern power systems with significant penetration of power generated from renewable sources.

Overall, the power system model is formulated as a set of hybrid differential-algebraic equations with inclusion of stochastic processes that represent wind speed variations and noise on the loads, as follows [11]:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z},\dot{\boldsymbol{\eta}}), \\ \boldsymbol{0} &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z},\boldsymbol{\eta}), \\ \dot{\boldsymbol{\eta}} &= \boldsymbol{a}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\eta}) + \boldsymbol{b}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\eta})\,\boldsymbol{\xi}\ , \end{aligned} \tag{1}$$

where $\boldsymbol{f}$, $\boldsymbol{g}$ are the differential and algebraic equations, respectively; $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ are the state, algebraic, and discrete variables, respectively; $\boldsymbol{u}$ are the inputs, e.g. active power schedules and reference voltage of the AVRs; $\boldsymbol{\eta}$ represents stochastic perturbations, e.g. wind speed and load variations, which are modeled through the last term in (1); $\boldsymbol{a}$ and $\boldsymbol{b}$ represent the *drift* and *diffusion* of the stochastic differential equations, respectively; and $\boldsymbol{\xi}$ represents the white noise vector. The set of SDAEs (1) is implemented and simulated using Dome, a Python-based power system software tool [12].

The evening peak of domestic charging is simulated by aggregating PEVs into load ramps, connected to 19 buses of the original network, in correspondence of the original loads. In particular, the amount of PEVs connected to each bus is proportional to the original node's energy demand, which is formed by both industrial and residential loads. The rate of the considered domestic chargers is 3.3 kW, the typical nominal capacity of the household charging point [13]. The model of the loads where EV are assumed to be connected is as follows:

$$\begin{aligned} p &= p_0 v^{\gamma} + R_{\mathrm{EV}}(t - t_0) + \eta_p, \\ \dot{\eta}_p &= -a\eta_p + b\xi_p, \end{aligned} \tag{2}$$

where p_0 is the aggregated voltage-dependent pre-existing load at the bus, R_{EV} is the ramp rate of the electric vehicles and η is a Gaussian mean-reverted stochastic process that represent load random fluctuations [11].

III. Results

A. Static Limit

We first evaluate the static limit. For this purpose, we assume that the number of connected PEVs increases in a linear fashion (with a *low* rate R_{EV}) until the maximum number of PEVs is connected to the grid. In particular, we consider the case where 125000, 250000 and 500000 PEVs, respectively, connect for charging (in total, taking all buses of the system into account). Figs. 1-3 show what happens at bus 18 of the system, and similar results are obtained at all other load buses. Fig. 1 shows the load ramps of the three scenarios, respectively: the rate of arrival of PEVs is constant and equal to 125000 vehicles every 15 minutes in total in the whole system (which corresponds to about 139 new PEVs that connect for charging to the grid every second).

Figs. 2 and 3 indicate that the maximum load of electric vehicles that can be accommodated by the power grid is

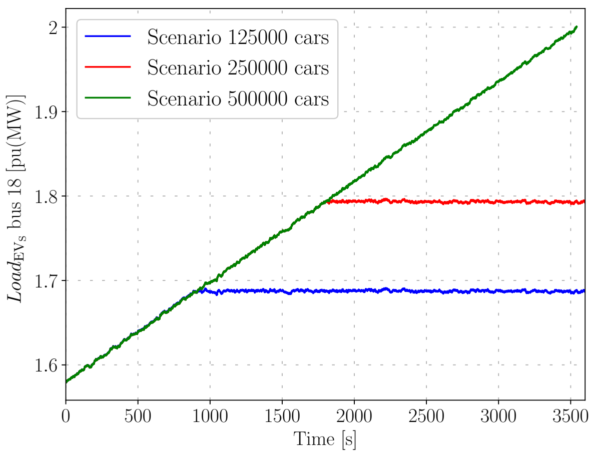

Fig. 1. Bus 18: load ramp at bus 18, in the three different scenarios, where a total number of 125000, 250000, and 375000 PEVs (among all power system buses) arrive and charge gradually in a time window of 15, 30 and 60 minutes respectively. The rate of cars arrivals is constant for all the three scenarios.

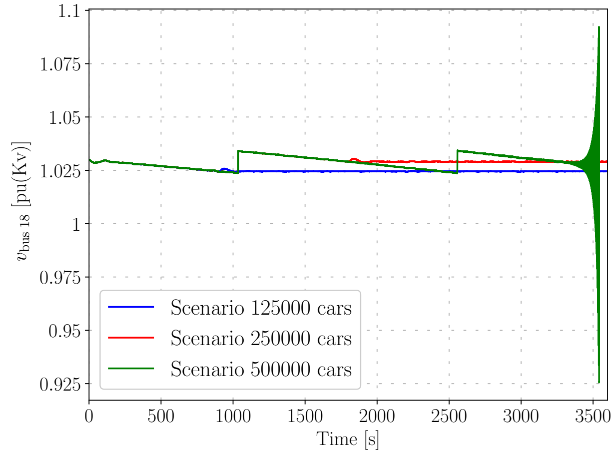

Fig. 2. Bus 18: voltage behaviour at bus 18, in the three different scenarios, where a total number of 125000, 250000, and 375000 PEVs (among all power system buses) arrive and charge gradually in a time window of 15, 30 and 60 minutes respectively. The rate of cars arrivals is constant for all the three scenarios.

14.2 pu, that corresponds to approximately 430300 vehicles. Moreover, in Fig. 3 it is possible to observe that frequency drops occur at the beginning of the charging process; then, the signal stands at about 0.9977 pu, but primary and secondary frequency regulation of the system manage to bring back the frequency to nominal values as soon as new vehicles stop connecting for charging. On the other hand, as shown in Fig. 2, the voltage tends to decrease, but Under Load Tap Changer (ULTC) transformers (which feed the distribution buses where the loads are connected) start compensating the voltage drops after a few minutes, bringing back the voltage to a safe range.

The static limit corresponds to a long-term voltage stability problem, as the generators fail to provide the reactive power required to balance the reactive power losses occurring in the transmission lines.

B. Dynamic Limit

In this section, we study the grid when PEVs connect in a relatively short time, i.e. the arrival rate of PEVs is steep. With this aim, we consider 5 scenarios, with increasing rates of arrival of vehicles per second. In the first scenario, about 58300 PEVs ask for charging within a time interval of 700 s. The arrival rate of PEVs then keeps increasing, up to the fifth case study, corresponding to the highest rate of arrival (about 830 vehicles per second). For the highest ramp rate, the system collapses slightly before $t = 700$ s shown in Fig. 4.

These results indicate that the dynamic limit is less binding than the static one. This is due to two combined effects of the system controllers, as follows.

On one hand, ULTC transformers are slower than the fastest ramps considered in Scenario 5. This means that tap ratio variations cannot properly follow the increase of the load. This is known to be an unintuitive but positive effect of ULTC controllers, i.e., the fact that a slow control of the ULTCs do

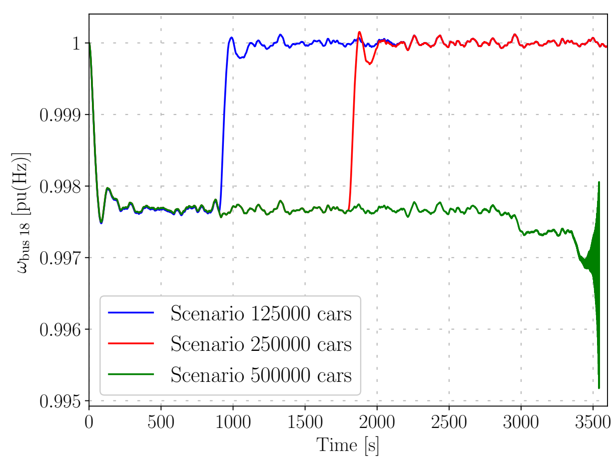

Fig. 3. Bus 18: frequency behaviour at bus 18, in the three different scenarios, where a total number of 125000, 250000, and 375000 PEVs (among all power system buses) arrive and charge gradually in a time window of 15, 30 and 60 minutes respectively. The rate of cars arrivals is constant for all the three scenarios.

not contribute to the load restoration of the voltage dependent part of the loads [14]. In fact, Fig. 5 shows that the collapse for Scenario 5 happens far way from the last variations of the tap ratio of the ULTCs. Were the ULTC controllers faster, the collapse would occur earlier, i.e., at the value determined for the static limit of the grid.

On the other hand, the higher the ramp of vehicles, the higher the frequency variations of the system (see Fig. 6). However, such variations are not too severe in magnitude, and they remain within a safe interval of $[0.98, 1.02]$ pu. The control of conventional turbine governor, thus, can properly follow the ramp of EVs. This implies that frequency instability

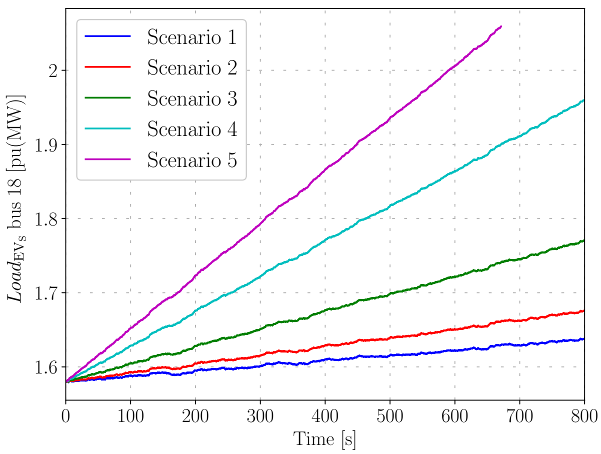

Fig. 4. Bus 18: load ramp at bus 18, in the 5 different scenarios, where the total number of PEVs (among all power system buses) gradually increases, from the scenario 1 to the scenario 5. In the last scenario, the curve stops before the end of the simulation because a grid collapse happens.

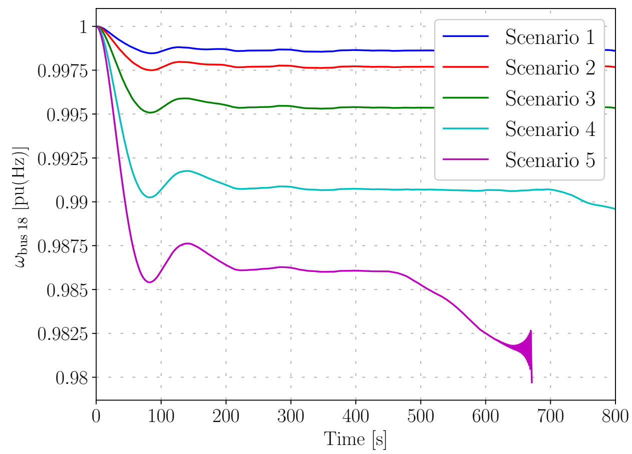

Fig. 6. Bus 18: frequency behaviour at bus 18, in the 5 different scenarios, where the total number of PEVs (among all power system buses) gradually increases, from the scenario 1 to the scenario 5. In all scenarios, the frequency oscillations remain in a safe range of $[0.98, 1.02]$ pu.

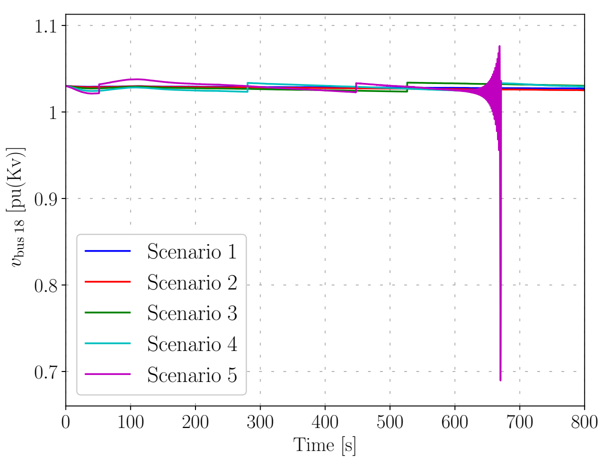

Fig. 5. Bus 18: voltage behaviour at bus 18, in the 5 different scenarios, where the total number of PEVs (among all power system buses) gradually increases, from the scenario 1 to the scenario 5. In the last scenario, the curve stops before the end of the simulation because a grid collapse happens.

is not to be expected to be an issue. Ultimately, thus, even in the scenarios with very steep EV ramps, the instability is caused by a reactive power shortage in the system and is, in turn, due to a voltage collapse phenomenon.

C. Aggregated Control

Since increasing EVs impact mainly on the voltage stability of the system, simple control strategies can be implemented to prevent grid collapses from occurring. The simplest strategy is that, obviously, no more vehicles are charged once the maximum value is connected. Then, when a vehicle is fully charged, a new one can start charging. This approach, however, requires a detailed coordination of the chargers and the need to send differnet signals to different chargers, which might not be feasible.

Assuming that charging stations (CS's) have the possibility to modulate the charge rates, a more feasible strategy consists in decrease the charging rates of *all* chargers of a given area when the number of charging vehicles exceeds a given threshold. In this way, the overall power consumption of the charging PEVs remains constant even if the number of EVs keeps increasing.

The outcome of such a simple control strategy is shown in Figs. 7 and 8 where 500000 vehicles connect for charging, for two extreme values of rates of arrivals. If the final number of vehicles exceeds the static limit for the New England Power System, the charge rates are decreased to never exceed the maximum power consumption, and this makes the charging of all vehicles feasible for the power grid.

IV. Conclusions

As the number of PEVs is increasing worldwide, and as their batteries are increasing in size to provide ever longer range autonomy, and as faster and faster charging stations are being built, there is an interest in keep estimating the maximum number of vehicles that can be accommodated by the existing power infrastructures. Taking into account that charging peaks may occur as well, for instance at evening time in domestic charging, also the rate at which PEVs connect for charging may be of concern for grid operators. In this paper we try to estimate both such static and the dynamic limits, using accurate and realistic power system simulations. In particular, we found that static limits may be actually more critical than dynamic limits. While simple methodologies for reactive power compensation may be easily taken to prevent such voltage collapses from occurring, still this may take a

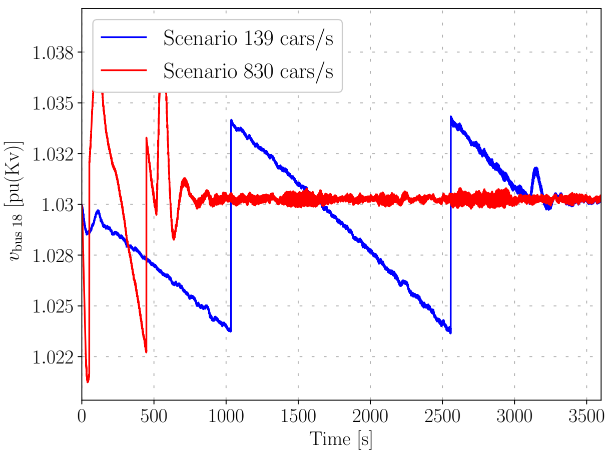

Fig. 7. Bus 18: evolution of voltage response in controlled cases.

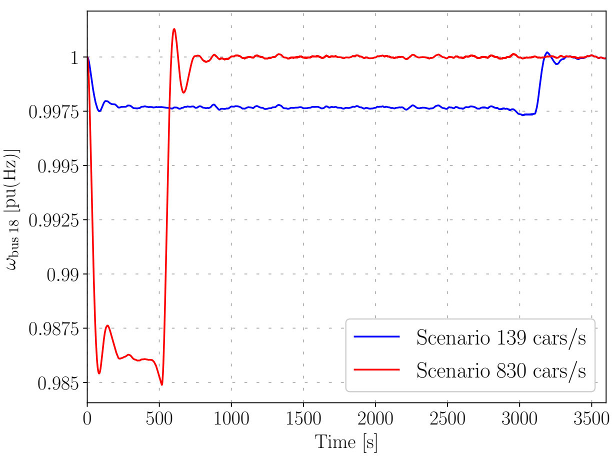

Fig. 8. Bus 18: frequency behaviour at bus 18, for the controlled cases, for two different values of arrival rates.

price in terms of required electrical equipment (e.g., to instal banks of capacitors at relevant nodes).

Another viable solution is to design appropriate controlled charging strategies to keep the PEV load within safe values. Here, we only showed a simple solution that actually has a number of shortcomings, as it assumes the ability to estimate the number of connected vehicles. This may be actually hard to be easily available, both due to the communication burden required to exchange such information, but also for privacy preserving issues as PEV owners may be reluctant to communicate their charging and traveling patterns. Accordingly, it is of our interest now to design decentralized charging solutions that constrain the load consumption to remain below the static limit, without requiring exchanging relevant private information.

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