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Impact of electric vehicle fast charging on power system voltage stability

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ABSTRACT

The electric vehicle (EV) brings a sustainable future for the next generation of automobiles. Market penetration of EV has been increasing drastically in the recent past. However, EV integration into power grids adds more challenges for power system engineers worldwide. It is essential to evaluate potential grid impacts due to EV integration to guarantee consistent grid operation. Even though a number of power system impact studies have been performed covering several aspects of the problem, the impact on voltage stability has remained almost unattended. The lack of accurate load models to represent EV load for system stability studies is found to be a major gap. Hence, a static load model is developed in this study as an essential base for realistic stability studies. A specific EV load behavior which has not yet been revealed in the literature is identified during the study. Subsequently, the influence of EV load on power system voltage stability is evaluated under different scenarios. The study has discovered that integration of EV fast charging stations may significantly reduce the steady state voltage stability of the power grid.

1. Introduction

Numerous research and development projects are being performed all over the world to identify efficient and economical methods to electrify the transportation sector. Depleting fossil fuel resources, environmental and health problems associated with vehicular emissions and the energy security concerns are factors that have led to the gearing up of electric vehicle (EV) penetration rates. The well-to-wheel studies have proven the EV's improved energy efficiency compared to conventional vehicles, even when charging from fossil fuel generated electricity [1]. It is certain that demand for EV will further increase with the maturity of battery and charging technologies. Therefore, a rapid and significant EV load integration to the power grid is anticipated. Thus, carrying out system studies and taking remedial actions for any discrepancies are essential at the early stages of EV deployment to maintain consistent grid operation.

EV charging will impose a relatively large load demand and EV load characteristics are different from other conventional system loads. The location, time and duration of charging as well as the real and reactive power consumption of the EV load cannot be simply predicted in advance. Hence, EV charging may cause violations to local or regional grid constraints. Many probable grid impacts have already been identified by different system studies. Possible increases in peak demand, regulatory voltage limit violations, harmonic problems, distribution system asset over-loadings and increased power losses are among them. However, only scant attention has been given to the impact of EV charging on system voltage stability [2]. Moreover, proper EV load models have not yet been developed for voltage stability studies. Therefore, the main concern of this study is to develop a load model and to evaluate steady state voltage stability.

2. Literature review

Electric vehicle charging may degrade power systems, though the EV brings one of the most welcomed greener options for transportation. A number of system studies which disclose numerous grid impacts associated with EV charging have been identified [3–11,1,12,13]. Increased system peak demands [3,4], voltage regulatory limit violation [4,8–11], increased power system losses [11,1,12–14], possible overloading of distribution transformers, distribution lines and cables [1,12,13,15–17] are among associated grid impacts. System stability studies are of primary importance as an increased number of power system blackouts have been reported due to system instabilities. However, only a few studies concentrated on the impact of EV load on power system stability [18–22].

Among stability impact studies [18] provides a study on the IEEE 3-bus test system. It has identified that the system with EV load is less stable when considering the system dynamics following a three phase fault. A small signal stability analysis has been carried out in [19] by modeling EV load as a constant power load (P) and constant impedance load (Z). It confirms that the modeling of the EV as a P load provides a lower loading margin than that for

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Nomenclature

C_1	dc link filter capacitance
C_2	buck converter filter capacitance
CC–CV	constant current–constant voltage charging
CPF	continuation power flow
d_d	direct axis duty ratio
d_q	quadrature axis duty ratio
EV	electric vehicle
I	constant current load
i_B	battery charging current
i_d	direct axis current
i_L	current through the buck converter inductor
i_q	quadrature axis current
i_{qref}	quadrature axis reference current
i_o	dc link current
k	duty ratio of buck converter switching
L	input filter inductance
L_{dc}	dc–dc converter inductance
λ_*	loading parameter at bifurcation point
λ_o	loading parameter at base case
ω	angular velocity
P	constant power load
P	real power consumption of the load
PCC	point of common coupling
P_{cp}	constant power consumption of the charger
P_o	power consumption of the charger at base voltage
P.F.	power factor
P_{vd}	supply voltage dependent power consumption of the charger
Q	reactive power consumption of the load
r	parasitic resistance of the buck converter inductor
R	lead resistance
R_S	turn on resistance of the IGBT switches
R_L	input filter inductor parasitic resistance
R_1	combined input resistance ($R_S + R_L$) of ac–dc converter
SOC	state of charge
SVSM	Static Voltage Stability Margin
V2G	vehicle to grid
V_B	battery voltage
V_d	direct axis voltage
V_{dc}	dc link voltage
V_{ref}	dc link reference voltage
V_o	base voltage
V_q	quadature axis voltage
V_s	voltage behind the buck converter switch
Z	constant impedance load

the Z load representation. The influence of V2G practices on short-term voltage stability of the grid was assessed in [20], by representing the EV load as a constant current load (I). Furthermore, the study in [22] evaluates the L-index of an EV smart park by considering EV load as a P load. Providing solutions to the stability problem, a wide area control method is proposed in [21] to damp the oscillations due to sudden charging and discharging of EV, according to real time electricity price signal. It is apparent that the existing studies have been done so with an uncertainty of the EV load behavior, by representing the EV load with different load models (P, I, Z). Hence, it is evident that the derivation of the system load models to represent EV load for accurate stability studies is a primary task.

Power system voltage stability has become a major concern in system planning and operation due to an increasing number of voltage instability incidents reported worldwide [23]. The system load characteristics are found to be among the main factors affecting voltage instability. The negative exponential power-voltage relationship of air conditioning loads has contributed to the 1987 power system failure incident in Tokyo [24]. Therefore, the development of an accurate load model to represent EV load for the power system voltage stability studies is essential to obtain most realistic outcomes and considered in this study.

3. EV Load modeling

3.1. Charger configuration

The EV charging technologies undergo constant researches and developments. The chargers can be categorized mainly into ac or dc and further according to their charging level (1–3). The level 1 charger is basically for home based charging, while level 3 chargers are commercial fast chargers. The fast charger power rating can even exceed 200 kW [25] and charging duration falls into a scale of minutes. Fast charging stations are likely to be comparable to the fuel filling stations. There is a high probability that fast charging will become more popular as it appears to be a more convenient charging option for EV users. Fast charging will place considerable demand on power networks and hence, it is important to assess their impact on power systems.

The well-established EV charger configuration consists of two stages; an ac–dc converter at the front end and a dc–dc converter at the battery end [26–32]. The dc–dc stage is to achieve the required charging current suitable for different state of charge (SOC) conditions and cell temperatures of the battery. Furthermore, it maintains the ripple content of the charging current within a safe operation status of the battery [27,33]. A universal input EV fast charger, which consists of an active rectifier front-end and a dc–dc buck converter at the battery-end is considered here for modeling. It comes with many desirable features like unity power factor operation and the ability of connecting to a wide range of input voltages [34]. It provides a regulated dc voltage output which is independent of the input voltage variations which are within the designed limits. The charger arrangement is shown in Fig. 1.

3.2. Analytical load modeling

Load modeling for power system voltage stability requires identification of load demand variation with respect to the variation in system voltage. This P–V relation is derived analytically for the charger shown in Fig. 1. Analytical expressions for the front end active rectifier (Fig. 2) are derived first.

The conversion from abc reference frame to d_q reference frame is well documented [35,36], and hence not shown here.

$$V_d = L\frac{di_d}{dt} + R_1 i_d - L\omega i_q + d_d V_{dc} \quad (1)$$

$$V_q = L\frac{di_q}{dt} + R_1 i_q + L\omega i_d + d_q V_{dc} \quad (2)$$

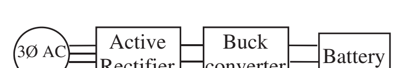

Fig. 1. The EV fast charger arrangement.