Modeling of Residential EV Loads Applicable to Power Sytem Long-term Voltage Stability Analysis

Yingle Fan[1, *], Rizhao Wang[1, a] and Bin Yan[2, b]

[1]State Grid Xuzhou Power Supply Company, Jiangsu Xuzhou, China
[2]State Grid Chongqing Bishan Power Supply Company, Chongqing, China

*Corresponding author e-mail: fanyingle@sina.cn, [a]490098606@qq.com, [b]342954331@qq.com

Abstract. With the increasing concern over the environmental and energy problems, electric vehicles (EVs) develop rapidly. This paper proposes a deterministic modeling methodology of electric vehicle loads. The modelling of one single EV load is conducted from the dc and the ac side separately, in which the time-varying and voltage dependent load characteristics are considered. The daily loads of aggregate EVs are modelled based on the electricity tariff structure and the initial state of charge distribution. Four types of private EVs are taken as the example to confirm the effectiveness of the proposed methodology. The impact of EV loads on power system voltage stability is analysed. The model developed by the proposed methodology provides accurate EV load characteristics with proper model complexity and it is suitable for long-term large scale power system numerical simulation.

1. Introduction

With the growing concerns over the greenhouse effect and environmental pollution, clean and sustainable energy consumption forms are greatly advocated nowadays. Because of the environment friendly nature of electric vehicles (EVs) and government incentive policies, the quantity of EVs increases rapidly in recent years, which will bring great impact and challenges to the grid [1, 2]. Charging EVs have specific characteristics compared to traditional power loads. The analysis and control of the impact of charging EVs are urgently needed in the development of the smart grid, which are based on the realistic and accurate modeling of EV loads.

Power system numerical simulations are important assistant measures for power system planning, operation and control. A valid simulation process can be used to improve the security, reliability and economy of power systems. Currently series of research works have been reported to analysis the load characteristics of EVs [3-10], and evaluate the impact on the grid. In [3-7], the randomness of the temporal and spatial distribution of EV loads is emphasized. However, in these researches the single EV load is taken as the constant power (CP) model without considering its distinct characteristics such as the voltage dependent and time-varying characteristics. By analyzing the component of the EV charger and the battery, a static load model of a single fast charging EV is derived analytically in [8]. The dynamics of the EV charger and the battery is considered further in [9]. However, the time-varying and random characteristics of EV loads in long time-scale are not covered in [8] and [9]. The dynamic load model in [9] may be too complex to obtain high computational efficiency. A simplified single phase slow charging EV load model is used in [10], with analytical modeling of the EV charger and the battery, while the impact of the grid parameters on the EV load is not considered in [10].

The randomness of the daily EV load and the distinct load characteristics of the single charging EV are analyzed separately in current researches. The main attention has been paid to the randomness of the load with less consideration of the impact of the EV charger and the battery.

This paper establish the numerical EV load model, which is time-varying and grid parameters dependent. Firstly, the time domain calculation of the single EV charging process is conducted to obtain the time-varying load characteristics. Then the power-voltage relationship of the single charging EV is fitted. The randomness of EV loads is represented by the initial SOC distribution and the start charging time distribution. Finally, the load models of four types of private EV with different features are developed by the proposed methodology, and the effect of EV loads on power system voltage stability is analyzed.

2. Components of EV Loads and Modeling Method

The charging EV load mainly consists of the battery, the EV charger and its control units. The charging characteristics of the battery have profound effect on the load. The EV charger is the interface between the battery and the grid.

EV chargers are designed to meet the various demands, which control the battery charging process with their control units following the industrial standards. From the point of view of the load modeling, the EV charger mainly affects the charging efficiency and further the charging load, despite of their different topologies, power levels and components. The EV charger is the source of the grid parameters dependent characteristics of the EV load and should be considered in the modeling process.

The single EV load model can be obtained by combining the battery characteristics and the impact of the charger. Loads of aggregate EVs consist of many single EV loads, which are determined by the start charging time, charging periods and charging power levels of the single EV load. Based on the single EV load model, loads of aggregate EVs can be calculated by summing up the charging power of EVs with different SOC levels at the same time points. The overall load modeling process is shown in Fig. 1, which will be explained in detail in the subsequent sections.

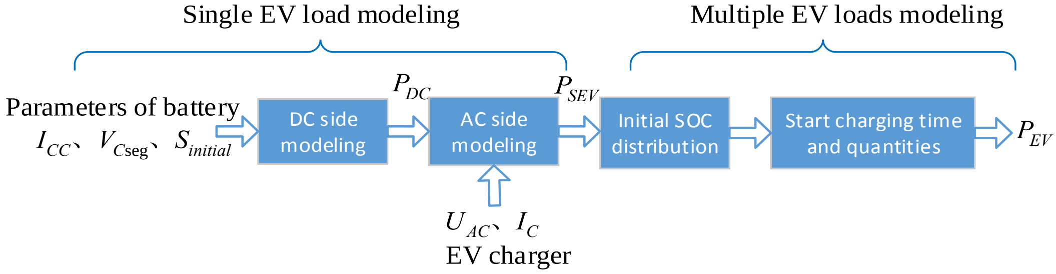

Figure 1. Modeling process of EV loads.

3. Single EV load modeling

The EV charging power is divided into the ac side power and the dc side power by the EV charger. The charging power of the two sides can be modeled separately to combine various battery models and EV chargers. The dc side load model can be represented by the battery charging power, while the ac side load model is the single EV load model. The methodology of the single EV load modeling is expounded in this section, taking the single phase slow charger as an example, which is widely used in the residential side. The EV load with other types of chargers can be modeled in similar way.

The single phase EV charger used in this paper is shown in Fig. 2 [11]. The simulation is performed in MATLAB SIMULINK software whose lithium-ion battery model dynamic behavior is validated experimentally and shows high accuracy [12]. The dynamic battery model parameters can be extracted simply from the manufacturers' battery datasheets [12]. The constant current (CC) charging process can be applied in 20%-90% SOC range, followed by the constant voltage (CV) charging process before the battery is fully charged [3].

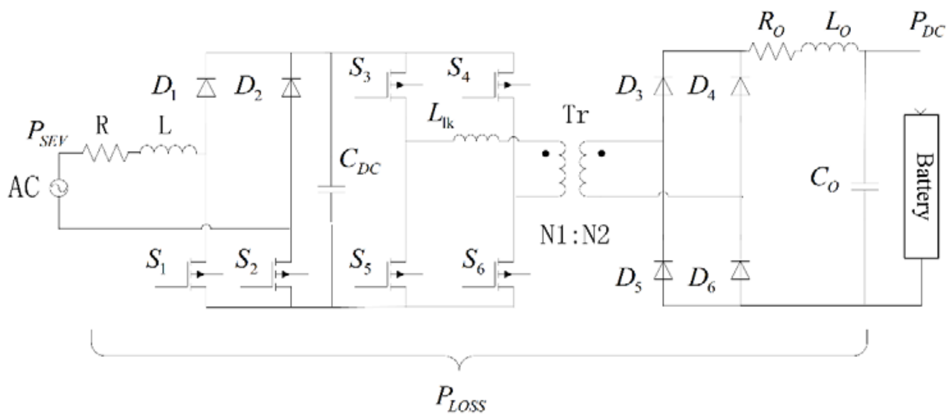

Figure 2. Configuration of single phase EV charger.

3.1. Dc side load modeling

The dc side charging power in the charging process is as in

$$P_{DC} = I_C \cdot V_C \tag{1}$$

Where I_C and V_C is the charging current and the terminal voltage of the battery.

In this period, the terminal voltage of the lithium-ion battery varies with the charging current and the SOC level. In the CV charging period, the charging current decreases with the increase of the charging time.

In the CC charging period, the SOC satisfies (2), where $S_{initial}$ is the initial SOC, I_{CC} is the CC charging current, C is the rated capacity of the battery (A·h) and t is the charging time of duration (h).

$$S = S_{initial} + \frac{I_{CC}}{C} t \tag{2}$$

Based on simulation or actual measurements, the relationship of the battery voltage and the SOC in the CC charging period with charging current I_{CC} , can be numerically fitted as

$$V_C = f_1(S) = \sum_{i=0}^{4} a_i S^i \tag{3}$$

Where a_i is the coefficient. Fourth order polynomial can represent the relationship with good accuracy.

Using (1), (2), (3), the dc side load model in the CC charging period can be obtained as follows:

$$P_{DC} = I_{CC} \cdot f_1(S) = f_2(S_{initial}, I_{CC}, t) \tag{4}$$

As shown in (4), for a certain EV battery model, the time varying dc side charging power in the CC period can be calculated based on the initial SOC and the charging current.

The CV charging period begins from the end of the CC charging period. The battery voltage of the end of the CC charging period is used as the CV charging voltage and kept constant during this period, while the charging current decreases with time. The start time of the CV charging period is as in (5).

$$t_{seg} = C\frac{S_{seg} - S_{initial}}{I_{CC}} \tag{5}$$

Where t_{seg} is the time period from the start charging point to the charging periods change point. S_{seg} Is the SOC level at t_{seg}. The battery voltage at this time is

$$V_{Cseg} = f_1\left(S_{seg}\right) \tag{6}$$

Where V_{Cseg} is the constant charging voltage in CV period.

The relationship of the charging current and the charging time in the CV period can be fitted as

$$I_C = f_3(t, I_{CC}) = I_{CC}\sum_{i=0}^{4} b_i\left(t - t_{seg}\right)^i \tag{7}$$

Where b_i is the constant coefficient. Fourth order polynomial is used in (7).

Using (1), (5), (6), (7), the dc side load model in the CV charging period can be obtained as follows:

$$P_{DC} = I_C \cdot V_{Cseg} = f_4\left(S_{initial}, S_{seg}, I_{CC}, t\right) \tag{8}$$

Based on (4) and (8), the dc side EV load model is

$$P_{DC} = \begin{cases} f_2\left(S_{initial}, I_{CC}, t\right) & 0<t<t_{seg} \\ f_4\left(S_{initial}, S_{seg}, I_{CC}, t\right) & t_{seg}<t<t_{seg}+t_{CV} \end{cases} \tag{9}$$

Where t_{CV} is the duration of the CV charging period, which can be obtained based on the manufacturers' battery datasheets or the practical charging record. The dc side charging power depends on the CC charging current, the initial SOC level, the SOC level (or the battery voltage) at the time when the charging periods change, and the charging time.

3.2. Ac side load modeling

The EV charger links the dc side load model to the ac side load model by the charging efficiency and the charging power factor. The single phase EV charger can keep the power factor unity. The charging efficiency is independent from the changes of the power frequency and the battery voltage. However, the charging efficiency changes obviously when the ac side charging voltage and dc side charging current change. The conclusions above are further confirmed by the simulation results.

In the CC period, the charging current is kept constant and the charging efficiency is mainly affected by the grid voltage. After fitting the simulation data in 1 s step size, the relationship between the charging efficiency and the grid voltage can be represented in quadratic function as in (10).

$$\eta_C = f_5\left(U_{AC}\right) = c_2U_{AC}^2 + c_1U_{AC} + c_0 \tag{10}$$

Where η_C is the charging efficiency; U_{AC} is the ac voltage of the grid where the EV charger is connected; c_0, c_1, c_2 are the undetermined constant coefficients.

The simulation data and the fitted curve based on (10) are shown in Fig. 3, where the x axis is the standardized ac charging voltage and the y axis is the corresponding standardized charging efficiency.

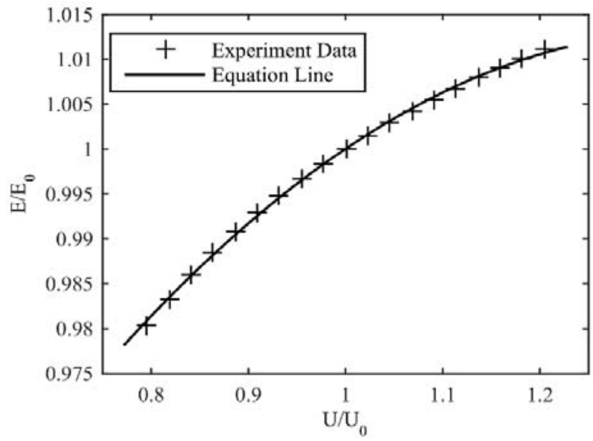

Figure 3. Effect of charging voltage on charging efficiency.

In the CV period, the charging efficiency is affected by the dc side charging current besides the grid voltage. The charging efficiency and the charging current are approximately in linear relationship in the CV period. Considering both the grid voltage and the charging current, the charging efficiency in the CV period can be expressed as

$$\begin{aligned}\eta_C &= f_6\left(U_{AC}, I_C, t\right) = \\ &c_2^1 U_{AC}^2 + c_1^1 U_{AC} + c_0^1 + d\left[f_3(t, I_{CC}) - I_{CC}\right]\end{aligned} \tag{11}$$

Where c_2^1, c_1^1, c_0^1 is the efficiency–voltage relationship coefficients when the charging current is I_{CC}, and d is the undetermined constant coefficient to represent the effect of the charging current on the efficiency.

3.3. Single EV load model

Combining (9), (10) and (11), the single EV load model considering both the battery characteristics and the effect of the EV charger can be obtained as follows:

$$P_{SEV} = \begin{cases} \dfrac{f_2\left(S_{initial}, I_{CC}, t\right)}{f_6\left(U_{AC}, I_C, t\right)} & 0 < t < t_{seg} \\ \dfrac{f_4\left(S_{initial}, S_{seg}, I_{CC}, t\right)}{f_6\left(U_{AC}, I_C, t\right)} & t_{seg} < t < t_{seg} + t_{CV} \end{cases} \tag{12}$$

Where P_{SEV} is the single EV charging power absorbed from the ac grid. The time varying charging power in the dc and ac side with initial SOC 0.2 are shown in Fig. 4 based on (12). As shown in Fig. 4, the change processes of the dc and ac side charging power are similar and the ac side charging power is greater than the dc side one. The effect of the ac charging voltage on the charging power is also shown in Fig. 4 as in the black area, where the ac charging voltage is in the range of 0.85-1.15 times the quantity of the rated value and the change of the charging power is inside $\pm 1\%$ of the rated value.

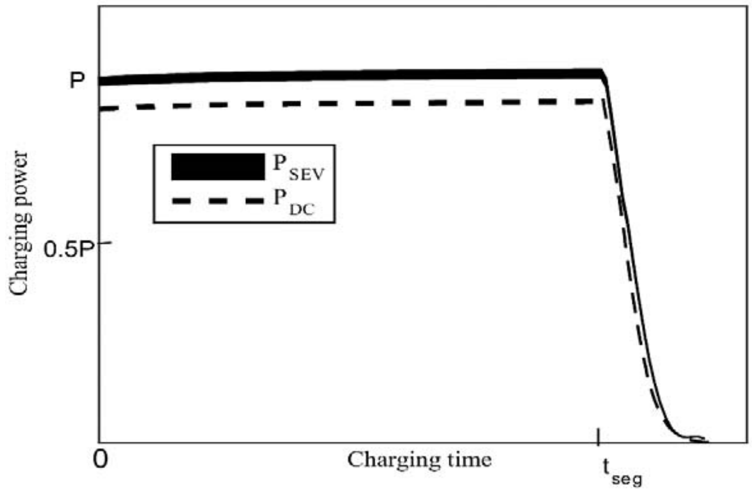

Figure 4. Single EV charging process in the dc and the ac sides

4. Aggregate EV Loads Modeling

The initial SOC distribution of aggregate EVs should be considered. At the same time, the temporal distribution of aggregate EV loads is mainly affected by the start charging time. To model the aggregate EV loads in a daily time period, the start charging time of different EVs should be determined first.

4.1. Initial SOC distribution model

The distribution of the initial SOC is mainly affected by the users' driving habits, battery capacities and range anxiety. According to the law of large numbers and the central limit theorem, when EVs are widely applied, it is reasonable to take the initial SOC distribution as truncated normal distribution with zero probability of occurrence of all negative initial SOC [13].

In (13) and (14), $S_{\text{initial, i}}$ is the obtained charging initial SOC, N is the number of the obtained initial SOC, $\overline{S}_{\text{initial}}$ and $\hat{\sigma}^2$ are the sample mean value and sample variance, while the real distribution of the initial SOC is $N(\mu,\sigma^2)$.

$$\overline{S}_{\text{initial}} = \frac{1}{N}\sum_{\text{i}=1}^{N} S_{\text{initial, i}} \tag{13}$$

$$\hat{\sigma}^2 = \frac{1}{N}\sum_{\text{i}=1}^{N} (S_{\text{initial, i}} - \overline{S}_{\text{initial}})^2 \tag{14}$$

When the statistical data of charging EVs is inadequate, considering the practical EV battery usage range and the users' charging habits, the mean value of the initial SOC distribution can be evaluated based on the mean daily driving distance of EV users and the variance can be estimated properly based on the empirical rule of the normal distribution.

Once the distribution of the initial SOC is determined, all of the EVs can be divided into a number of groups based on a certain SOC interval (e.g. 0.05 or less). The proportion of quantity of each group is determined by the probability of each group interval based on the distribution. The EVs in the same group use the same initial SOC to calculate the charging power with (12). The charging load of each group can be obtained by multiplying the single EV load with the quantity of the group.

4.2. Start charging time model

With the deployment of smart charging facilities in the near future, the charging behavior of EV users can be guided by the charging policies (e.g. real time electricity price), and the randomness of the start charging time can be reduced. The time-of-use (TOU) tariff model is considered in this paper. The EV users are assumed rational enough to meet the scheduled charging demand with the least charging cost in the low price period as shown in (15). The fast charging behavior of EV users influenced by uncertain travel are not included in this paper.

$$\begin{cases} \min \ C = \int_{t_0}^{t_0+t_{seg}+t_{CV}} P_{SEV} \times t \times p(t)dt \\ \text{constraints:} \ E_{demand} = \int_{t_0}^{t_0+t_{seg}+t_{CV}} P_{SEV} \times tdt \end{cases} \tag{15}$$

In (15), C is the charging cost, t_0 is the start charging time needed to be determined, $p(t)$ is the charging price at time t, E_{demand} is the charging energy demand.

Fig. 5 shows the seasonal typical daily load of a certain province in China (standardized by the load values of 14:00) and the optimal EV load distribution to balance the peak and the valley base load when EV load is big enough. The recommended TOU price curve for guiding the charging behavior is also shown in Fig. 5. With the guidance of TOU price, the start charging time is determined to meet the scheduled charging demand with the least charging cost using (15). For example, if an EV needs 7 hours CC charging and 1 hour CV charging and will be used at 8:00 in the next day, the smart charging facility will control the charging process to start from 22:36. EVs with different initial SOC levels need different charging periods, and have different start charging time. In addition, this paper assumes that the EV will not leave halfway in the charging period.

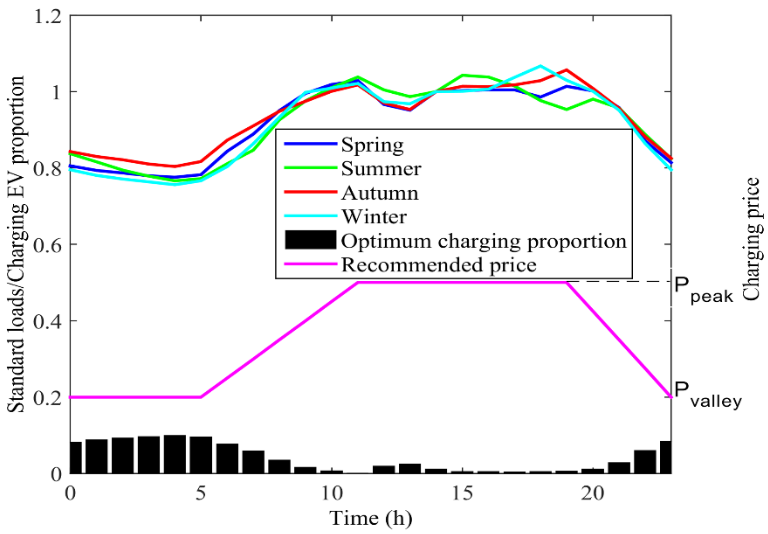

Figure 5. Loads of power system and charging price curve

4.3. Aggregate EV loads model

The procedure used to get the aggregate EV loads is shown in Fig. 6.The daily aggregate EV loads can be obtained by combining the EV loads of different initial SOC groups and the corresponding start charging time. The daily loads of 1000 EVs with 360V nominal battery voltage, 20A (dc) CC charging current and 222.2Ah rated capacity are shown in Fig. 7, using the methodology developed before. The colored areas of Fig. 7 is the change areas of EV loads when the ac charging voltage is in the range of 0.85-1.15 times the quantity of the rated value. The EV loads with different initial SOC distribution are shown in different colors. As shown in Fig. 7, the smaller the variance of the distribution is, the more similar the multiply EV loads and the single EV load are; the bigger the variance of the distribution is, the gentler the decline process of aggregate EV loads is. It is easy to understand that the smaller the mean of the distribution is, the longer the stable CC charging process is.

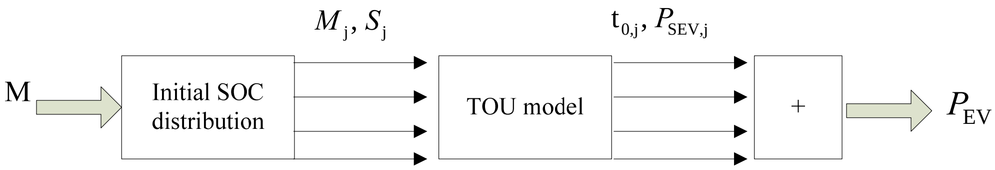

Figure 6. Procedure used to get the aggregate EV loads

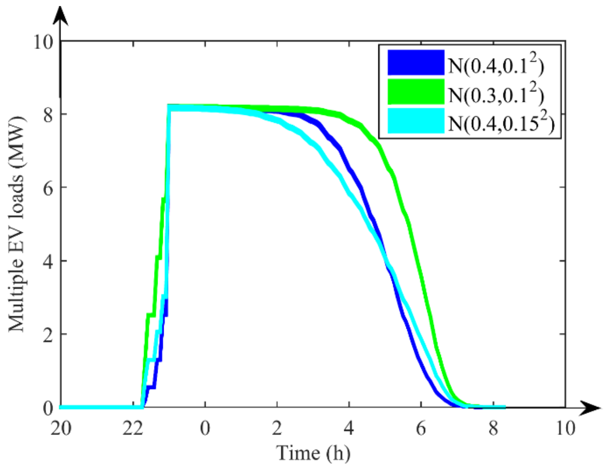

Figure 7. Daily loads of 1000 a certain type of EVs

5. Case Study

5.1. Load models of four types of EVs

Based on the current status and development trends of EV market, four types of private EVs are used to represent the residential EV loads accurately, as shown in Table 1. The fourth type of the EV models represents the low-speed EVs. According the charging power levels published by the manufacturer of EVs, the CC charging current of the four types of EVs is chosen as 10A, 10A, 20A, and 25A separately.

Table 1. Parameters of Four Types of EV Models.

Number	Nominal Voltage (V)	Capacity (Ah)	Driven Distance (km)	Charging time (h)
1	325	73.8	150-200	5-6
2	345.6	92.8	200-250	8-9
3	360	222.2	About 400	About 10
4	83	241	Below 150	6-8

Using the modeling methodology developed in the former sections, taking a large or medium size city in the near future as the case, assume that the mean daily driven distance of the EVs in the city is 35km, and the energy consumption of the EVs is from 14 kWh/100 km to 18 kWh/100 km. The charging EV quantity in a typical day is determined based on the sales of the EVs. According to the aforementioned assumption, the mean value of the distribution of the initial SOC for the first type of EV is taken as 0.33 and the charging EV quantity in a typical day is chosen as 800. In a similar way, the mean values of the initial SOC distribution for the second, third and fourth types of EVs are taken as 0.33, 0.4, and 0.45, and the quantities are chosen as 1600, 1000, and 1600. The standard deviation of the four types is all taken as 0.1. Based on the methodology developed in chapter IV, the daily aggregate EV loads of every type of EVs and the total daily EV loads of the four types are shown in Fig. 8 and Fig. 9.

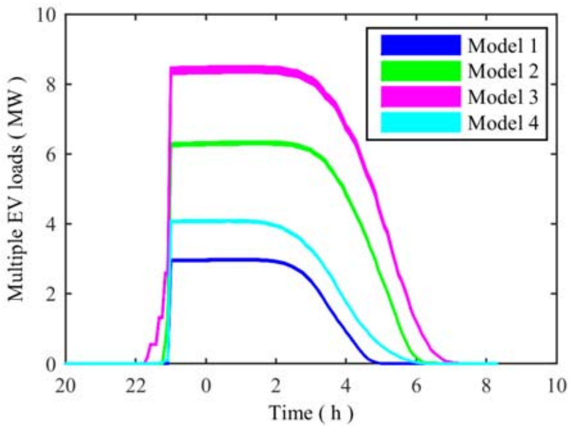

Figure 8. Daily loads of every type of EVs

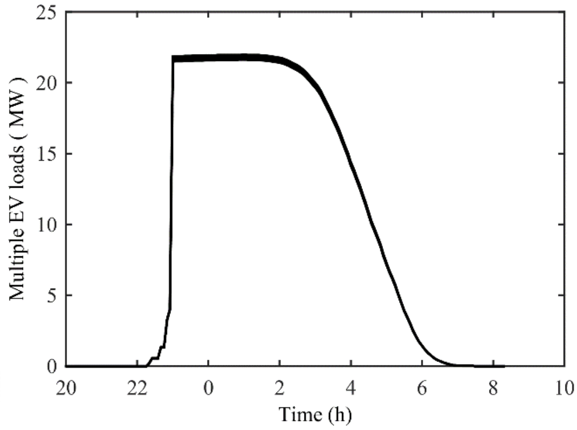

Figure 9. Total daily loads of four types of EVs

5.2. Effects of EV loads

The effect of EV loads on power system voltage stability is analysed in this section using the EV load developed in the last section. The IEEE 14-bus test system [14], which represents a typical medium or low voltage primary distribution system as shown in Fig. 10, is used to analyse the effect. The loading margin or the static voltage stability margin (SVM) in [8] is taken as the evaluation index.

The EV load shown in Fig. 9 is integrated at bus 14 and the loads of the other buses are kept constant during the numerical simulation. The active loading margin of bus 9 is used to show the impact of the EV load. The continuation of power flow (CPF) method tool in PSASP software is incorporated to determine the loading margin. The simulation results are shown in Fig. 11, which includes the result of the developed voltage dependent (VD) EV load model and the result of the traditional simplified CP EV load model. As shown in Fig. 11, the integration of EV loads in power system reduces the voltage stability margin, and using the simplified constant power EV load model will lead to optimistic results, which is more obvious when the EV load is large.

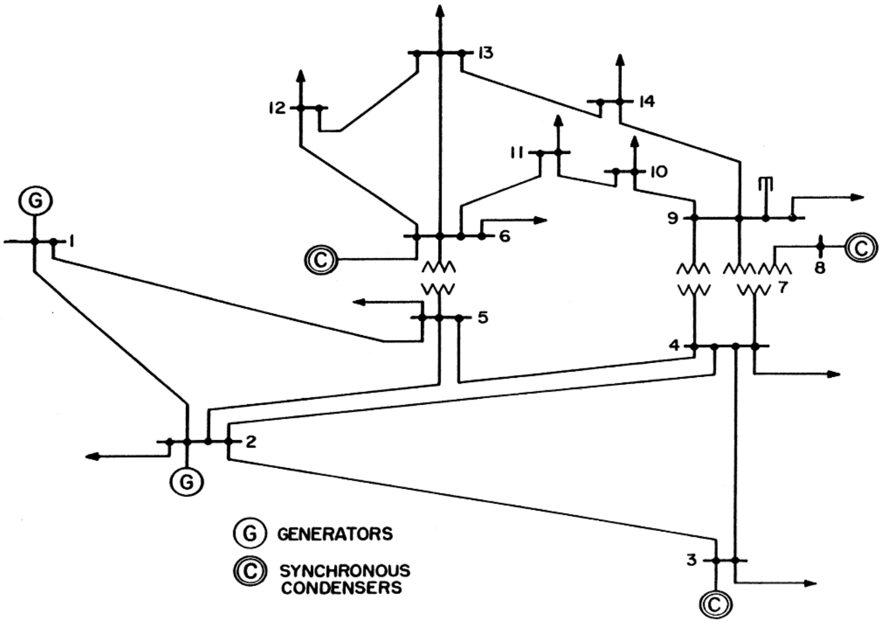

Figure 10. IEEE 14-bus test system

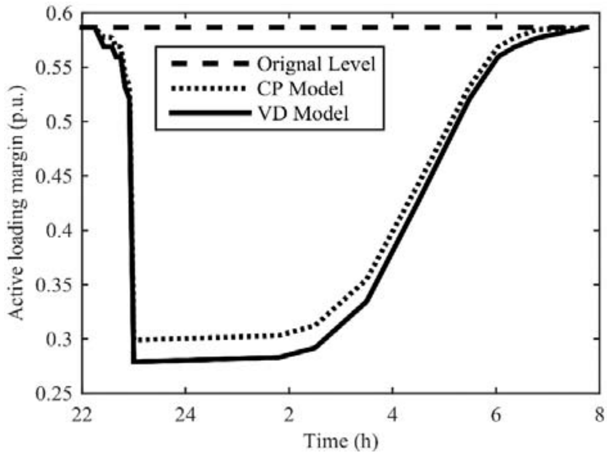

Figure 11. Changes of the active loading margin

6. Conclusion

This paper proposes a modeling methodology of EV loads, which is suitable for long-term large scale power system numerical simulation. The factors needed to be considered in the single and aggregate EV load modeling processes are expounded in detail. Based on the actual charging process and the theoretical analysis, the single EV load can be modeled from the dc and the ac sides. In the dc side modeling, the time varying battery charging power in the CC and CV periods is the main concern. In the ac side modeling, the effect of grid voltage and the charging current on the charging efficiency should be introduced. In the aggregate EV load modeling process, the distributions of the initial SOC and the start charging time are crucial to combine a certain number of single EV loads. In case study, four types of EV load models are established using the proposed methodology. The calculated EV load is further used to analyze its effect on power system voltage stability, and the developed methodology is confirmed to be effective.

The proposed methodology has the characteristics of modularization and hierarchy. The modeling methodology can combine different EV chargers with various EV batteries easily, and it can be adjusted to suit different initial SOC distributions and electricity tariff models. In addition, the effect of battery management systems and battery aging on the EV load can be included by modifying the single EV load model.

References

[1] R. A. Verzijlbergh, M. O. W. Grond, Z. Lukszo, et al., Network Impacts and Cost Savings of Controlled EV Charging, IEEE Trans. Smart Grid, vol. 3, no. 3, 2012, pp. 1203-1212.
[2] N. Leemput, F. Geth, J. Van Roy, et al., Impact of Electric Vehicle On-Board Single-Phase Charging Strategies on a Flemish Residential Grid, IEEE Trans. Smart Grid, vol. 5, no. 4, 2014, pp. 1815 - 1822.
[3] K. Qian, C. Zhou, M. Allan, et al., Modeling of Load Demand Due to EV Battery Charging in Distribution Systems, IEEE Trans. Power Syst., vol. 26, no. 2, 2011, pp. 802 - 810.
[4] M. F. Shaaban, Y. M. Atwa, and E. F. El-Saadany, PEVs model-ing and impacts mitigation in distribution networks, IEEE Trans. Power Syst., vol. 28, no. 2, 2013, pp. 1122-1131.
[5] A. Ashtari, E. Bibeau, S. Shahidinejad, et al., PEV Charging Profile Prediction and Analysis Based on Vehicle Usage Data, IEEE Trans. Smart Grid, vol. 3, no. 1, 2012, pp. 341-350.
[6] H. Zhang, W. Tang, Z. Hu, et al., A method for forecasting the spatial and temporal distribution of PEV charg-ing load, in Proc. IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1 - 5.
[7] M. Ban and J. Yu., Procedural simulation method for aggregating charging load model of private electric vehicle cluster. J. Mod. Power Sys. Clean Energy, 3 (2), 2015, pp. 170 - 179.
[8] C. H. Dharmakeerthi, N. Mithulananthan, and T. K. Saha, Mod-eling and planning of EV fast charging station in power grid, in Proc. IEEE Power Energy Soc. General Meeting, San Diego, CA, 2012, pp. 1 - 8.
[9] C. H. Dharmakeerthi, S. L. Ceylon Electr. Board, N. Mithulanan-than, et al., Development of dynamic EV load model for power system oscillatory stability studies, in Proc. Aus. Universities Power Engineering Conf., Perth, WA, 2014, pp. 1 - 6.
[10] J. Meng, Y. Mu, J. Wu, et al., Dynamic frequency response from electric vehicles in the Great Britain power system. J. Mod. Power Sys. Clean Energy, 3 (2), 2015, pp. 203 - 211.
[11] B. Whitaker, A. Barkley, Z. Cole, B. Passmore, et al., A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices, IEEE Trans. Power Electron., vol. 29, no. 5, 2014, pp. 2606 - 2617.
[12] O. Tremblay and L.-A. Dessaint, Experimental Val-idation of a Battery Dynamic Model for EV Applications. World Electric Vehicle Journal, 3 (2), 2009, pp. 289 - 298.
[13] C. Ahn, C.-T. Li, and H. Peng, Optimal decentralized charging control algorithm for electrified vehicles connected to smart grid, Journal of Power Sources, vol. 196, no. 23, 2011, pp. 10369 - 10379.
[14] Milano F (2005, Jul.) . Power system analysis toolbox documenta-tion for PSAT version 1.3.4.