HARMONIC ANALYSIS OF ELECTRICAL VEHICLE FAST-CHARGING STATION CONSIDERED UNCERTAINTY OF LOAD

Pan HU, Yuchuan HU, Ding Kai, Yimin QIAN
State Grid Hubei Electric Power Research Institute – China
E-mail hupaninwh@whu.edu.cn, huyuchuan91@foxmail.com, 6502169@qq.com, 61893790@qq.com

ABSTRACT

Focusing on the qualitative and quantitative analysis of harmonic issue caused by high integration of electric vehicles, a quick-charging harmonic analysis model considered time series pattern of electrical vehicles station is proposed. By taking charging mode, car type, battery characteristics, and driving habits into consideration, the charge-discharge probability density function (PDF) of electrical in an account of sequence behaviour is put forward. Subsequently, considering the topology of electric vehicles charger, an analytic expression of the electrical vehicles along with the time-series behaviours of load is utilized to establish the harmonic analysis model of electrical vehicles station. The impact of electric vehicles charger on the power harmonic is intensively studied. The results show the topology and number of electric vehicles charger exert a significant impact on harmonic current, and the THD is consistent with the sequence behaviour of load. The typical period and the combination of electric vehicles chargers should be detailed considered at the planning stage to analyze and reduce the harmonic impact of electrical vehicles station.

INTRODUCTION

As with the rapid grown of electrical vehicles (EVs), the harmonic issue inevitably arises as long as the high integration of EVs charging station [1]. The harmonic current injected by the nonlinear of EV charger, especially quick-charging station, significantly influences the long-period safe and stable operation of distribution network. Notably, the charge-discharge habit and behaviour of EV users make the EVs stations show a distinctive uncertainty feature. Consequently, the load demand of EVs shows a typical sequence characteristic resulting in harmonic current varying at different time-series. [2]. Therefore, a harmonic analysis model of EVs fast station considered uncertainty is needed for smart distribution network operation.
The harmonic impact of EVs charger attracts many scholars' attention in recent works. Reference [3] analyses the harmonic characteristic of distribution network under different charging power, periods, and integration capacity. Reference [4] presented a PQ impact assessment methodology for distributed plug-in EVs considering the random operating characteristics of the vehicles. In all, researchers have conducted a few studies of EVs chargers to establish harmonic models. But the uncertainty and topology of EVs load need to be considered together during object modelling.
This paper proposes a quick-charging harmonic analysis model in account of time series pattern of electrical vehicles station. The harmonic model is on a basis of practical industrial database. The article is organized in the manner as follows. Section 3 theoretically presents the harmonic models of EVs fast-charging station. Findings and results are given in section 4. Conclusions and future works are summarized in section 5.

HARMONIC MODEL OF EV FAST-CHARGING STATION CONSIDED UNCERTAINTY

The PDF model of fast charging station based on practical industrial data

The fast charge-discharge behaviour of EVs station often couples with the car type, battery characteristics and driving habits. To better reveal the relationship between charge-discharge power and harmonic current, the PDF of private-EV, e-bus, and e-taxi is given in the following section.

PDF of private-EV fast charging station

Generally, private-EV owners often charge their vehicle at night or at trip for an emergency. This emergency often requires fast charging and lead to charging uncertainty.
The modelling of EVs is often restricted by a lack of quantitative data. Since the behaviour of electric vehicles is usually consistent with the petrol energy vehicle, the PDF of private-EV fast charging station is based on a database of National Household Travel Survey 2009 (NHTS) [5]. According to the survey, the PDF of travel distance follows:

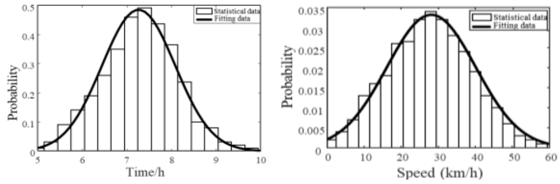
$$f_{\mathrm{D}}(x)=\frac{1}{x\sigma_{\mathrm{D}}\sqrt{2\pi}}\exp\left(-\frac{(\ln x-\mu_{\mathrm{D}})^2}{2\sigma_{\mathrm{D}}^{2}}\right) \quad (1)$$

where μ_{D} =3.2, σ_{D} =0.88; x represents the daily distances of private EVs. According to the database, the departure time and average speed of EVs are in line with the normal distribution, which is expressed as:

$$f_{\mathrm{T}}(y)=\frac{1}{\sigma_{\mathrm{T}}\sqrt{2\pi}}\exp\left(-\frac{(y-\mu_{\mathrm{T}})^2}{2\sigma_{\mathrm{T}}^{2}}\right) \quad (2)$$

$$f_{\mathrm{s}}(z)=\frac{1}{\sigma_{\mathrm{s}}\sqrt{2\pi}}\exp\left(-\frac{(z-\mu_{\mathrm{s}})^2}{2\sigma_{\mathrm{s}}^{2}}\right) \quad (3)$$

where, μ_{T} =7.26, μ_{s} =1.08, σ_{T} =28.3, σ_{s} =11.6. y in (2) represents departure time and z is the average speed in (3). The fitting result based on Hubei industrial database is shown in Fig. 1.



(a) departure time (b) average speed

Figure 1 PDF of departure time and average speed

PDF of e-bus charging station

According to the schedules of transportation routes in Hubei, the e-bus service works from 6:30 a.m. to 8:30 p.m. The transportation routes often run 30 kilometres at a cost of $6t = 60$ min 0 min. In each terminal, the bus leave in about 15 min and the driver has 20 min for rest after each arrival.

Though the transportation routes and time schedules are fixed, the traffic jam and driver habits lead to the uncertainty of charging power. The travel time for each trip is expressed as:

$$T = t\alpha \tag{4}$$

where T is the actual travel time for each trip, $t = 60$ min , α is the converted coefficient, and its value depends on the magnitude of traffic flow and jam.

Considering the traffic jam situation during morning and evening rush-hour, the traffic flow can be divided into three parts. The PDF of each stage is expressed as:

$$f_1(x_1) = \frac{1}{\sigma_1\sqrt{2\pi}}\exp\left(-\frac{(x_1-\mu_1)^2}{2\sigma_1^{\,2}}\right) \tag{5}$$

$$f_2(x_2) = \frac{1}{\sigma_2\sqrt{2\pi}}\exp\left(-\frac{(x_2-\mu_2)^2}{2\sigma_2^{\,2}}\right) \tag{6}$$

$$f_3(x_3) = \frac{1}{\sigma_3\sqrt{2\pi}}\exp\left(-\frac{(x_3-\mu_3)^2}{2\sigma_3^{\,2}}\right) \tag{7}$$

where σ_1 =1.2, u_1 =7.3, σ_2 =1.35, u_2 =18.5, σ_3 =4, u_3 =15.5, x_1 , x_3 and x_2 are the traffic flow state of morning, evening rush-hour and non-peak hour respectively [14]. Assume the 0.1 value represents the most congested state, the PDF model of traffic flow after normalization yields:

$$f_z(t) = \frac{5500 f_1(t)}{0.1} \tag{8}$$

Then, the converted coefficient can be expressed:

$$\alpha = 0.4252 f_z^3(t) - 0.3719 f_z^2(t) + 0.1833 f_z(t) + 1 \tag{9}$$

PDF of e-taxi charging station

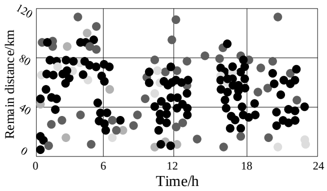
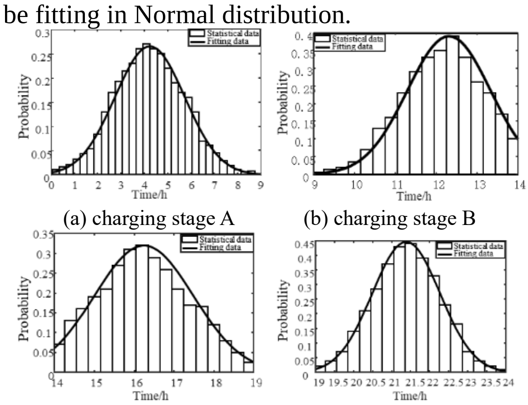


Figure 2 Statistical charging time of e-taxi

In China, the e-taxi company provides service 24 hours a day, two drivers in two shifts. Since the travel route and working period of e-taxi is stochastic, the PDF of e-taxi charging station is better to establish the model by using data fitting method. According to the daily charging data of e-taxi station shown in Fig. 2 which is provided by the website of BYD EV company in China, the charging stage can be fitting in Normal distribution.



(a) charging stage A (b) charging stage B
(c) charging stage C (d) charging stage D

Figure 3 Fitting-figures of charging period under different stages

From Fig. 3, the e-taxi battery needs to be charged for several times a day to satisfy operation requirement. Considering the impact of travel distance, shifting, meal times, and business hours, the charging periods can be divided into four stages, including 0:00 a.m. to 9:00 a.m., 9:00 a.m. to 2 p.m., 2 p.m. to 7 p.m. and 7 p.m. to 12 p.m. The fitting results corresponding to each stage is shown in Fig. 3 after maximum likelihood estimation and normalization of original data provided by BYD company (http://www.bydauto.com.cn/news-id-2557.html).

Fast charging model of EV station

To better establish the fast charging model of EV station, we assume that the departure time, average speed, travel distance of each EV transportation are generally independent. Sine the e-taxi and e-bus provide facilitating travel for the public, the charging behaviors of e-taxi and e-bus can both be summarized as:

a) The state of charge (SOC) of e-taxi and e-bus at the beginning of each trip and the full tank of fuel satisfy evenly distributed U (0.8, 0.95).

b) The battery consuming capacity is proportional to travel distance, then the SOC after travelling is updated by utilizing:

$$S_{\mathrm{ocl}} = S_{\mathrm{ocf}} - \frac{l}{L}\times 100\% \tag{10}$$

where, S_{ocf} and S_{oc1} is the neighboring state of EV, l and L are the actual and maximum travel distance respectively. For private-EV, the SOC is stochastic due to the variety of travelling habits and requirements. Therefore, the initial SOC is assumed to satisfy evenly distributed U (0.1, 0.9). For initial state j, the private-EV needs to decide if the car requires fast-charging by using:

$$S_{\mathrm{oc}j} - \frac{L_j \cdot \sigma_j}{C_j} \le 0.1 \qquad (11)$$

where C_j is the battery capacity of EV j and σ_j is the consume energy per kilometer provided by car producer. If the battery power meets Eq. (11), the private-EV need to fast charge for the next trip. Otherwise, the SOC updates by using:

$$S_{\mathrm{oc}j} = S_{\mathrm{oc}j} - \frac{L_j \cdot \sigma_j}{C_j} \qquad (12)$$

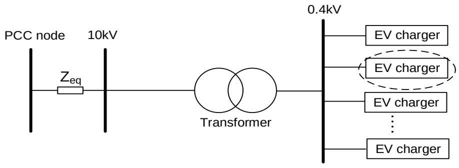
For some private-EV that want to recharge their battery, the SOC updates using:

$$T_j(\xi) = T_{\mathrm{t}j} + \frac{(S_{\mathrm{oc}j} - \xi) C_j}{S_j \sigma_j}, \quad \xi \in \{0.1, 0.4\} \qquad (13)$$

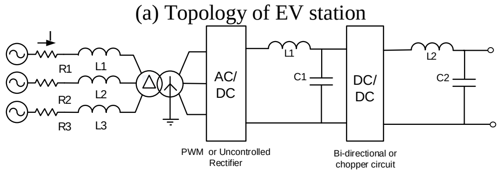
where, $T_{\mathrm{T}j}$ and S_j is the departure time and the average speed in (2) and (3) respectively. According to NTHS survey, people do not tend to recharge when SOC is high than 0.4. Therefore, $\xi \in \{0.1, 0.4\}$ in (13). The averring time of the private-EV satisfy $Ar_j \in U[t_j(0.4), t_j(0.1)]$. Then, the $S_{\mathrm{oc}j}$ can be obtained by (13).

Harmonic model of EV fast charger

The main topology of electric vehicles charger influences harmonic behavior of EV fast charging station. The main structure of EV station is shown in Fig. 3(a). To establish the analytic expression of EV station, two types of charger are considered. The first type is uncontrolled rectifier combined with DC/DC converter. The other type is PWM rectifier combined with DC/DC converter.



(a) Topology of EV station



(b) Topology of EV charger

Figure 4 Common topology of EV station

Due to paper length limitation, the mathematic of EV charger are not given in this paper. According to [6], the harmonic current of first type converter satisfies:

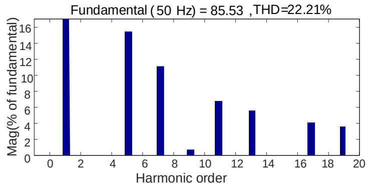
$$I_n = \frac{\sqrt{6}}{n\pi} I_d \,(n = 6k \pm 1, k = 1, 2, 3, \cdots) \qquad (14)$$

where I_n is the inject harmonic current, I_d is the DC charging current which can be calculated by dividing nominal DC voltage. Then, the harmonic current of type 2 converter satisfies:

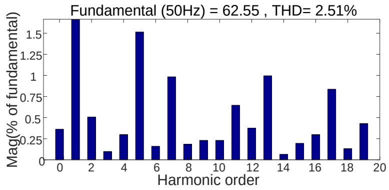
$$U_{\mathrm{h}} = \frac{U_{\mathrm{d}}}{2} \cdot \frac{4}{n\pi} \cdot J_k \cdot \frac{an\pi}{2}, \quad n = 1, 2, 3...... \qquad (15)$$

$$I_{\mathrm{h}}(n) = \frac{U_{\mathrm{h}}(n)}{\omega_n (L_{\mathrm{s}} + L_{\mathrm{z}})} \qquad (16)$$

where, a is the modulation ratio, J_k is the Bessel functions. L_{s} and L_{z} are the inductors both on grid side and converter side.



(a) FFT analysis of type 1 charger



(b) FFT analysis of type 2 charger

Figure 5 FFT analysis of EV charger

The FFT analysis of type 1 and type 2 are given in Fig. 5. From the results, the characteristic harmonic of current in type 1 is 6k±1, and the fifth and seventh harmonics are the main disturbances. The PWM based charger mainly contains odd harmonics and the impact is less severe.

CASE STUDY

Table 1 Typical parameters of EV in Hubei province

Car type	EV capacity /kWh	Maximum range/km	Market share/%	Charging power/kW
Nissan Altra	29.1	130	23.7	60
Nissan Leaf	24	160	21.2	60
BAW E150	22.8	130	33.1	60
BYD e5	43	305	22	60

Table 2 Fitting-parameters of charging time and travel distances of e-taxi

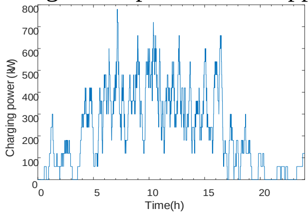
Time stage	μ_s	σ_s	μ_l	σ_l
0:00-9:00	4.23	1.5	154	38
9:00-14:00	12.31	1.02		
14:00-19:00	16.24	1.24	4.03	0.42
19:00-24:00	21.37	0.89		

Table 3 Typical operation parameters of e-bus

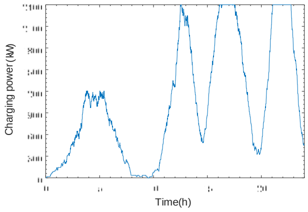
Car type	EV capacity /kW	Maximum range /km	Charging power /kW
BAW BJ6851EVUA	135	120	125

The harmonic analysis model is tested under a typical charging station. The structure of this system is shown in Fig. 4. The practical Industrial data of Hubei is introduced to establish the PDF of private-car, e-taxi, and e-bus charging station (Operation Date comes from one of a fast charging station in Xudong area, Wuhan, China). The main topology of EV charger including type one and two are taken into consideration.

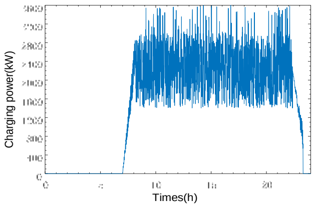
The simulation parameters of private-car, e-taxi and e-bus charging station are given in Table 1 to 3. For private-car, four types of EV are considered and the total number in this area is set to be 1200 while the chargers in station are 20. E-taxi cars in China are based on BYD e6 which is widely utilized in EV market. With an 82-kWh battery, the maximum travel distance is 400 km. According to e-bus operation data, there are 8 bus lines in this area. In each bus station, 35 chargers are provided to supply 20 bus.



(a) Stochastic simulation of private-car charging station

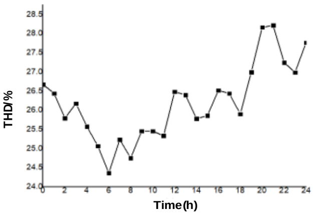


(b) Stochastic simulation of e-taxi charging station

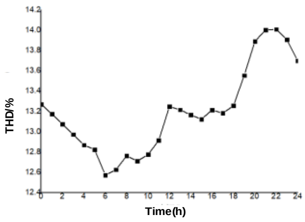


(c) Stochastic simulation of e-bus charging station

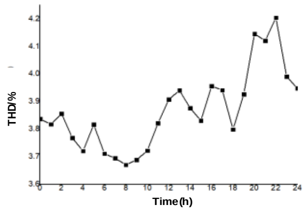
Figure 6 Simulation of private-car, e-taxi, and e-bus charging station



(a) Uncontrolled rectifier

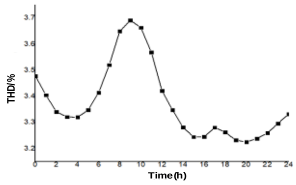


(b) Uncontrolled:PWM=1:1

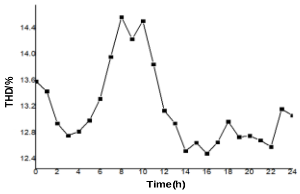


(c) PWM

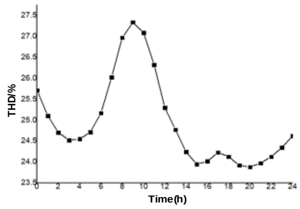
Figure 7 THD of private-car charging station during one day by utilizing different EV charger



(a) Uncontrolled rectifier

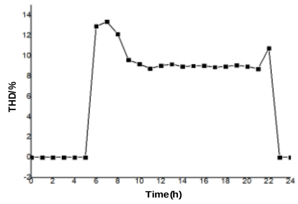


(b) Uncontrolled:PWM=1:1

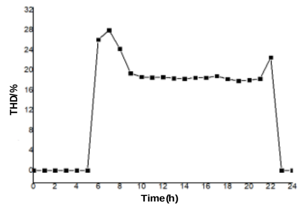


(c) PWM

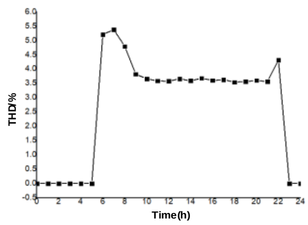
Figure 8 THD of e-taxi charging station during one day by utilizing different EV charger



(a) Uncontrolled rectifier



(b) Uncontrolled :PWM=1:1

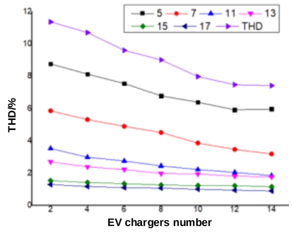


(c) PWM

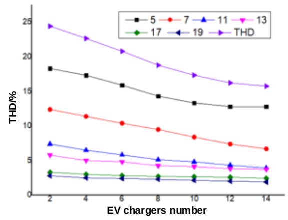
Figure 9 THD of e-bus charging station during one day by utilizing different EV charger

By applying Monte Carlo sampling, the load requirement of different types of EV station is given. According to the EVs' PDF and practical industrial data, the power curves of private-car, e-taxi, and e-bus charging station are drawn in Fig. 6. Based on the power curves of charging station, the sequence harmonic behavior under different topology of EV charger can be analyzed. Three typical charging combination are considered, including uncontrolled rectifier based, PWM-based, and 1:1 capacity between type 1 and type 2. The simulation results of private-car, e-taxi and e-bus charging station are shown Fig. 7 to 9.

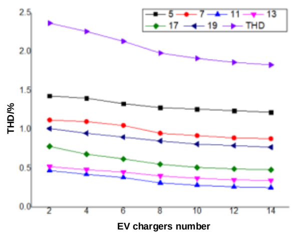
According to the above results, the total harmonic distortion (THD) follows the behavior of EV load showing sequence characteristic. The typical period should be detailed considered at the planning stage. The 95% maximum THD at the minimum operation state is more convinced.



(a) private-car charging station



(b) e-taxi charging station



(c) e-bus charging station

Figure 10 Harmonic analysis of charging station under different charging power

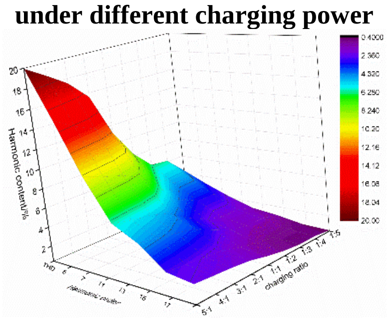


Figure 11 Harmonic analysis of EV charging station under different charging requirement

To better analyze the impact of the combination of EVs chargers, the THD and THDi of each harmonic current are investigated at a different working state. Fig. 10 gives the harmonics of private-car, e-taxi and e-bus charging station respectively.

In regards to the results, the THD and THDi of each harmonic current is gradually counteracting as long as the increasing of EV chargers. But, with the high integration of EV chargers, the counteract effect gradually fades away. To better analyze the harmonic impact of a combination of chargers, Fig. 11 gives the harmonic results at a different combination of type 1 and type 2, including 5:1、4:1、3:1、2:1、1:1、1:2、1:3、1:4、1:5. The results further verify the conclusion above.

CONCLUSION

This paper proposed an advance model of EV fast-charging station to study the harmonic impact of EV integration intensively. On the basis of practical industrial data, some beneficial conclusions can be drawn:

1) The topology of EV charger determines the harmonic characteristics. For type 1, the characteristic harmonic of current is 6k±1, and the fifth and seventh harmonics are the main disturbances. For type 2, charger mainly contains odd harmonics and the impact is less severe.

2) The THD and THDi of each harmonic current is gradually counteract as long as the increasing of EV chargers. But, with the high integration of EV chargers, the counteract effect gradually fades away.

3) The THD is consistent with the sequence behaviour of load. The typical period and the combination of electric vehicles chargers should be detailed considered at the planning stage to reduce the harmonic impact.

REFERENCES

[1] D. Chakravorty, J. Meyer, P. Schegner, et al, 2017, "Impact of modern electronic equipment on the assessment of network har-monic impedance", *IEEE Trans on Smart Grid*, vol. 1, 382-390.

[2] N. Korolko, Z. Sahinoglu, D. Nikovski, 2016, "Modeling and forecasting self-Similar power load due to EV fast chargers", *IEEE Trans on Smart Grid*, vol. 3, 1620-1629.

[3] P. S. Moses, S. Deilami, A. S. Masoum, et al, 2010, "Power quality of smart grids with plug-in electric vehicles considering battery charging profile", *Proceedings, ISGT Europe Conference*, Gothenberg, vol. 1, 1-7.

[4] C. Jiang, R. Torquato, D. Salles and W. Xu, "Method to Assess the Power-Quality Impact of Plug-in Electric Vehicles," in IEEE Transactions on Power Delivery, vol. 29, no. 2, pp. 958-965, April 2014.

[5] NHTS National Household Travel Survey [EB/OL], *http://nhts.ornl.gov*.

[6] D. Tong, H.K. Chen, and B. Wu, 2018, "Harmonic Characteristics Analysis of PWM-Based Electric Vehicle Chargers Considering Control Strategy", *Proceedings, ICHQP 2018*, Ljubljana, vol. 1, 1-5.