# ANALYSIS OF THE EFFECT OF SHANGHAI EXPO ELECTRIC VEHICLE CHARGING STATION ON URBAN GRID POWER QUALITY

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## ABSTRACT

*More than 100 pure electric vehicles (EVs) and super capacitor EVs were employed in 2010 Shanghai World Expo. Ground conductive charging stations have been established for these EVs. Chargers in stations employing the principle of silicon diode converter are typical nonlinear equipments. When running, these equipments will inject a lot of harmonics into power grid which will make the power polluted. In this paper, the charging principles of different types of energy storage equipments such as lithium manganate battery, lithium phosphate battery and super capacitor energy storage were analyzed. The harmonic emission models of chargers were developed with the non-controllable and high-frequency PWM control theory. On this basis, the harmonic synthesis model of multiple chargers was also developed. The harmonic current level injected by charging stations and the harmonic voltage level of the point of common coupling were calculated and analyzed in different operation modes of power grid and different charging modes of chargers. According to relevant China National Standards, the effect of charging station operation on the urban grid power quality was evaluated. Two types of filtering schemes, active filtering and passive filtering were proposed and compared from the point of view of both technical and economical. Some suggestions to improve the power quality of charging stations and minimize the effect on the grid were proposed which have reference value to similar EV charging stations.*

## 0 INTRODUCTION

Chargers in 2010 Shanghai World Expo EV charging stations are typical nonlinear equipments in the power grid. When running, these equipments will inject a lot of harmonics into the power grid which will make the power polluted. With increasing numbers of EVs and charging stations in the future, the power quality problems brought to the power grid by EVs' charging will become more prominent [1].

## 1 CHARGING PRINCIPLE OF EV CHARGERS

Presently, three types of EV chargers with different working principles are mainly used [2].

(1)The first type of chargers consists of power frequency transformer, uncontrolled rectifier and chopper. It is large in size, large current harmonic on the grid side and low conversion efficiency. Thus, it's not discussed in this paper.

(2)The second type of chargers consists of power frequency transformer, three-phase uncontrolled rectifier and DC/DC converter insolated by high-frequency transformer as shown in Figure 1. Its characteristics are small voltage ripple on the DC side, nice dynamic property, high-frequency isolation, small equipment size, large harmonic current on the grid side (about 30%) and low conversion efficiency.

Current waveform of this type of chargers has been greatly improved over the first category. However, total current harmonic distortion is higher and odd order harmonic current is larger, spatially the 5th, 7th, 11th and 13th.

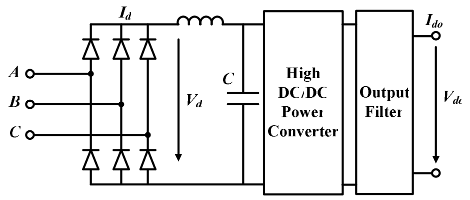


**Figure 1** Structure of chargers with uncontrolled rectifying principle

(3) The third type of chargers consists of three phase PWM rectifier and DC/DC converter insolated by high-frequency transformer as shown in Figure 2. Charger cost increases because of adopting PWM. However, the advantages are reflected in high power factor, small harmonic current on the grid side, total current harmonic distortion injected into grid less than 5%, small corresponding harmonic current, high-frequency isolation, small equipment size, small output ripple, nice dynamic property and high conversion efficiency.

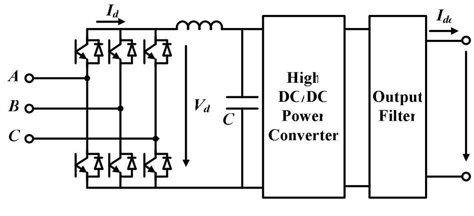


**Figure 2** Structure of chargers with PWM rectifying principle

## 2 HARMONIC CHARACTERISTICS OF EV CHARGERS

### 2.1 Chargers with Uncontrolled Rectifying Principle

Uncontrollable three-phase full-bridge rectifier is employed in this type of chargers. Thus, the theoretical value of uncontrollable three-phase full-bridge rectifier can be chosen as harmonic characteristics of this type of chargers.

When the overlap voltage on the valve side of the rectifier is $\boldsymbol{E}$, transformer capacity is $\boldsymbol{S_T}$, impedance is $\boldsymbol{u_k}$, ignition angle $\boldsymbol{\alpha}=0°$, commutation impedance $\boldsymbol{X_\gamma}$ and no-load DC voltage $\boldsymbol{V_{do}}$ can be expressed as:

$$X_\gamma = \frac{E^2}{S_T} u_k \qquad (1)$$

$$V_{do} = \frac{3\sqrt{2}}{\pi} E \qquad (2)$$

If DC power $\boldsymbol{P_d}$ is given, DC voltage $\boldsymbol{V_d}$ can be calculated from Equation (3):

$$V_d^2 - V_{do} + \frac{3}{\pi} X_\gamma P_d = 0 \qquad (3)$$

And then, DC current $\boldsymbol{I_d}$, stacked arc angle $\boldsymbol{\gamma}$, total power factor of rectifier $\boldsymbol{\cos\varphi}$ and fundamental reactive power of rectifier $\boldsymbol{Q}$ can be calculated from Equation (4)~(7):

$$I_d = \frac{P_d}{V_d} \qquad (4)$$

$$\gamma = \arccos\left(\frac{2V_d}{V_{do}} - 1\right) \qquad (5)$$

$$\cos\varphi \approx \frac{1}{2}(1 + \cos\gamma) \qquad (6)$$

$$Q = V_d I_d \frac{2\gamma - \sin 2\gamma}{1 - \cos 2\gamma} \qquad (7)$$

The $\boldsymbol{n}_{\text{th}}$ characteristic harmonic current $\boldsymbol{I_n}$ on the AC side of converter is:

$$I_n = 2K_2F_2I_1 \qquad (8)$$

where, $\boldsymbol{I_1}$ is virtual value of fundamental current on the AC side of converter.

$$I_1 \approx \frac{\sqrt{6}}{\pi} I_d \qquad (9)$$

$$K_2 = \frac{1}{2n(1-\cos\gamma)} \qquad (10)$$

$$F_2 = \sqrt{\frac{\sin^2\frac{(n-1)\gamma}{2}}{(n-1)^2} + \frac{\sin^2\frac{(n+1)\gamma}{2}}{(n+1)^2} - \frac{2\sin\frac{(n-1)\gamma}{2}\sin\frac{(n+1)\gamma}{2}\cos\gamma}{n^2-1}} \qquad (11)$$

### 2.2 Chargers with PWM Control Principle

Since the PWM output pulse sequence is axisymmetric, it can be expanded into Fourier series with only odd orders:

$$u_{AB}(t) = \sum_{k=1}^{\infty} U_{km} \sin k\omega_1 t \qquad (k=1, 3, 5\ldots) \qquad (12)$$

Where, $\boldsymbol{U_{km}}$ is the voltage amplitude of the $\boldsymbol{k}$th harmonic the voltage amplitude in the $\boldsymbol{k}$th harmonic is:

$$U_{km} = \frac{2}{\pi}\sum_{i=1}^{n}\int_{\theta_i-\frac{1}{2}\delta_i}^{\theta_i+\frac{1}{2}\delta_i} U_d \sin k\omega_1 t\, d\omega_1 t = \frac{4U_d}{k\pi}\sum_{i=1}^{n}[\sin k\theta_1 \sin\frac{k\delta_i}{2}]$$
$$= \frac{4U_d}{k\pi}\sum_{i=1}^{n}[\sin\frac{(2i-1)k\pi}{2n}\sin\frac{k\delta_i}{2}] \qquad (13)$$

Thus, PWM output wave can be expressed as:

$$u_{AB}(t) = \sum_{k=1}^{\infty}\frac{4U_d}{k\pi}\sum_{i=1}^{n}[\sin\frac{(2i-1)k\pi}{2n}\sin\frac{k\delta_i}{2}]\sin k\omega_1 t \qquad (14)$$

Besides fundamental wave with the same frequency of sinusoidal modulation wave, $\boldsymbol{u_{AB}}(t)$ contains high-frequency harmonic components related to carrier frequency, i.e. carrier frequency $\boldsymbol{\omega_c}$ and neighboring harmonic components as well as $2\boldsymbol{\omega_c}$, $3\boldsymbol{\omega_c}$…and neighboring harmonic components. Neighboring harmonic components of $\boldsymbol{\omega_c}$ has the greatest effect. The amplitude of high-frequency harmonic components is inversely proportional to the order of harmonic. In other words, the higher the order of harmonic is, the less the amplitude is.

The power factor of rectifier can reach 0.99 in typical charger adopting PWM technology. Basically, there is no low order harmonic current on grid side. The maximum total harmonic content is not more than 5%. Typical harmonic characteristics of charger with PWM rectifying principle are shown in Table 1.

**Table 1** Typical harmonic characteristic of chargers with PWM rectifying principle

| Harmonic order | $I_n/I_1$(%) | Harmonic order | $I_n/I_1$(%) |
|---|---|---|---|
| 3 | 0.80 | 11 | 0.16 |
| 5 | 0.20 | 13 | 0.13 |
| 7 | 0.13 | 15 | 0.11 |
| 9 | 0.21 | 17 | 0.11 |

In table 1, harmonic current content is presented using the percent of it to fundamental current.

### 2.3 Harmonic Superposition Method of Multi Chargers

When a transformer is supplying power to multi chargers simultaneously, the total harmonic current is the superposition of the harmonics of multi chargers. However, because the powers of multi chargers are different and the phases of the harmonic currents are different, the total harmonic current is always less than the algebraic sum of the harmonic currents of multi chargers. The harmonic superposition method was given in both the IEC Standard 61000-3-6 and Chinese National Standard GB/T 14549-1933. The method in Chinese Standard GB/T 14549-1933 was mainly referred in this paper.

According to GB/T 14549-1933, when harmonic currents in the same order of two harmonic sources are overlaid in the same phase and the phase angle is known, equation (15) is calculated:

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + 2I_{h1}I_{h2}\cos\theta_h} \quad (15)$$

where, $I_{h1}$ is the $h_{th}$ harmonic current of source 1; $I_{h2}$ is the $h_{th}$ harmonic current of source 2; $\theta_h$ is the phase angle between the harmonic currents of source 1 and source 2.

When the phase angle is uncertain, Equation (16) is calculated:

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + K_h I_{h1} I_{h2}} \quad (16)$$

where, the coefficient $K_h$ is chosen according to Table 2.

When more than two harmonic currents are overlaid, two harmonic currents are overlaid firstly, and the result is overlaid with the third harmonic current, and so on.

**Table 2** Specification of $K_h$ Value

| **Harmonic order** | $K_h$ | **Harmonic order** | $K_h$ |
|---|---|---|---|
| 3 | 1.62 | 11 | 0.18 |
| 5 | 1.28 | 13 | 0.08 |
| 7 | 0.72 | 9,>13,even orders | 0 |

The superposition method of harmonic currents of ***N*** chargers in this paper is treated according to the situation of the uncertainty of the phase angle in GB/T 14549/-1933.

## 3. CASE STUDIES

Figure 3 is the diagram of the charging station for EVs in the World Expo, the station is connected to the 10 kV buses of substation D by two independently operated cable.

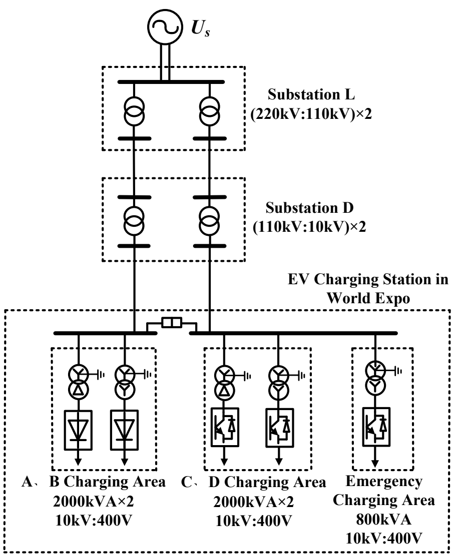


**Figure** 3 Diagram for charging station of EVs in World Expo

A, B charging areas are for buses with the lithium manganese oxide energy storage battery, and chargers with uncontrolled rectifying principle are used. In each charging area, a set of charger is 9kW and 7 sets are set in one charging rack. There are 28 charging racks, and the total is 1764kW.

C, D charging areas are for buses with the lithium phosphate energy storage battery, and chargers with PWM control principle are used. In each charging area, a set of charger is 30kW and 2 sets are set in one charging rack. There are 28 charging racks, and the total is 1680kW.

The emergency charging area is for buses with the super capacitor energy storage battery. There are four sets of 75kW charger with the same electrical characteristic of the 30kW charger in C, D areas.

## 3.1 Power Quality Limits

According to the calculation method of GB/T 14549-1993, the harmonic current limits injected to the PCC(10 kV bus of substation D) is given in Table 3.

**Tab. 3** Harmonic current limits injected to the PCC

| Harmonic order | Harmonic Limit | |
|---|---|---|
| | Line 1 (4000kVA) | Line 2 (4800kVA) |
| 5 | 6.40 | 7.45 |
| 7 | 6.31 | 7.19 |
| 11 | 5.64 | 6.24 |
| 13 | 5.13 | 5.64 |
| 17 | 4.14 | 4.53 |
| 19 | 3.72 | 4.08 |
| 23 | 3.10 | 3.40 |
| 25 | 2.83 | 3.10 |

## 3.2 Calculation Mode

Three different calculation modes are considered as Table 4:

**Table 4** Calculation modes

| Calculation mode | 10kV Bus tie switch | A, B area | C, D area | Emergency area |
|---|---|---|---|---|
| Mode A | Hot Spare | Rated Load | Rated Load | Rated Load |
| Mode B | Hot Spare | Break down in Area A, Normal Operation in Area B | Rated Load | Rated Load |
| Mode C | Operation | Rated Load | Rated Load | Rated Load |

## 3.3 Calculation Result

Under different modes, the calculation results of harmonic current injected into the 10kV bus of the substation D are shown in Table 5.

**Tab. 5** Harmonic current injected to 10kV bus of substation D(A)

| Harmonic order | Mode A | Mode B | Mode C | Limit |
|---|---|---|---|---|
| 5 | 2.66 | 19.33 | 7.84 | 6.40 |
| 7 | 1.77 | 12.77 | 5.22 | 6.31 |
| 11 | 9.02 | 6.37 | 9.57 | 5.64 |
| 13 | 6.46 | 4.56 | 7.01 | 5.13 |
| 17 | 0.29 | 2.31 | 0.99 | 4.14 |
| 19 | 0.14 | 1.63 | 0.66 | 3.72 |
| 23 | 1.32 | 0.95 | 1.94 | 3.10 |
| 25 | 1.22 | 0.87 | 1.82 | 2.83 |

The following brief conclusions can be obtained from the

calculations in Table 5:
(1) For the A, B charging areas adopting uncontrollable rectifier, as the characteristic harmonics, the 11th and 13th harmonics significantly exceed the standard.
(2) Because the situation that one rectifier or transformer breaks down is considered, the 5th, 7th, 17th and 19th harmonic currents of the rectifier transformer on the network side can not offset each other, which causes that the these harmonic currents under the calculation C increase significantly compared with that under other calculation modes, among these, the over-limit situation of the 5th and 7th harmonic currents are obvious.
(3) For the C, D charging areas adopting rectifier with PWM control principle, harmonic current is obviously lower than these in A, B charging area, and there is no over-standard situation.

## 3.4 Harmonic Control Schemes

### 3.4.1 Passive Filtering Scheme

Because the rectifier works under the uncontrollable mode, its power factor is relatively higher, for example, it may reach 0.97 at the rated load.
Under the calculation mode A, when the 2×240kvar capacitors series with 1% reactor are equipped on the 10kV bus in A, B charging areas, the calculation results of the harmonic currents injected into the grid are shown in Table 6.

**Table 6** Harmonic current injected to substation D, in calculation mode A (capacitor equipped)

| Harmonic Order | Harmonic currents injected to 10 kV bus of substation D | Limit |
|---|---|---|
| 5 | 2.87 | 6.40 |
| 7 | 2.10 | 6.31 |
| 11 | 5.32 | 5.64 |
| 13 | 5.05 | 5.13 |
| 17 | 2.04 | 4.14 |
| 19 | 1.46 | 3.72 |
| 23 | 1.22 | 3.10 |
| 25 | 1.13 | 2.83 |

Calculation results show that all order harmonic currents injected to the 10 kV bus of the substation D in A, B charging areas are all under the allowable value. As a result, equipping capacitor bank is effective for inhibiting the harmonic current injected to the grid.

### 3.4.2 Active Filtering Scheme

The characteristics of load change fast and the harmonic, reactive compensation and the requirements of voltage regulation sometimes can not coordinate. At this time, passive filtering measures can not meet requirements well, and the treatment scheme with active power filter technology can be used to control the 5th, 7th and 11th harmonic currents under the condition that the reactive capacity of the fundamental wave is constraint. The choice of the compensation capacity can be referred:

$$S_n = K\eta\xi\sum S_C \qquad (17)$$

where, $\boldsymbol{K}$ is reliability coefficient, 1.05~1.20 can be chosen, $\boldsymbol{\eta}$ is the charging efficiency of the charger, $\boldsymbol{\xi}$ is the harmonic current content of the charger generated at the input terminal of the AC power and $\boldsymbol{S_c}$ is the power of a single charger.
The feasibility of adopting this kind of treatment scheme should be determined after carrying out the accounting of essential investment cost and benefit according to the factors of the frequency and lasting time of this special condition and so on. If the frequency of this kind of working condition and the lasting time is short every time, it’s obvious that because of the low usage rate, the active filter compensation scheme should not be adopted.

## 4. CONCLUSION

(1) The connection of the EVs charging station affects the power quality of the grid. As a result, when the EVs charging station is constructed, the effect on the power quality of the grid should be fully considered in various links of equipment selection, planning design, maintenance.
(2) Under the same working condition, the harmonic current injected into the grid in the charging station adopting uncontrollable rectifier is obviously higher than that in the charging station adopting the rectifier with PWM control principle. As a result, in the condition without considering the installation of the filtering equipments, the filter controlled by the PWM can be used to reduce the pollution on the grid if the budget of the project is allowable.
(3) The harmonic control measures adopting the passive filtering sometimes can not meet the requirements of the reactive compensation and voltage regulation; although adopting the active filtering equipments can filter the harmonic waves, the cost is relatively high. The planning scheme should be determined after checking the investment cost and benefit combined with the concrete situation in the project.

## REFERENCE

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