A DATA-DRIVEN HARMONIC MODELING METHOD FOR ELECTRIC VEHICLE CHARGING STATION

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ABSTRACT

Electric vehicle (EV) chargers are non-linear loads mainly composed of power electronic devices, which will produce harmonics when connected to distribution networks on a large scale, endangering the safe and stable operation of the power grid and power equipment. When high-power charging stations are connected to the distribution network, the mechanism modeling methods are usually too complex. This paper proposes a data-driven harmonic modeling method for EV charging stations. Firstly, the actual measured data is obtained by the charging monitoring system to analyze the harmonic characteristics of current and voltage in the dynamic process of charging. Then, the overall equivalent modeling strategy is adopted for EV charging stations. The relationship between the amplitude and phase angle of each harmonic current and the fundamental voltage, the state of charge (SOC) of the battery and the type of rectifier circuit is non-linearly mapped by the radial basis function network (RBFN). In order to validate the effectiveness of this modeling method, a battery-SOC-based charging station model of EV is built to simulate the output characteristics of the charging station in a complete charging cycle, and RBFN modeling is conducted with the acquired data. The results show that the method can well reflect the harmonic external characteristics of the parallel points of the charging station, and has the advantages of fast simulation speed and high precision. It is an effective harmonic source modeling method, which can be applied to the harmonic estimation of large-scale grid connection of EV charging stations and power quality management.

INTRODUCTION

With the gradual exhaustion of fossil energy and increasingly serious environmental pollution, electric vehicles, as a form of clean energy consumption, have ushered in a major opportunity for their own development[1]. Electric vehicle charger is a non-linear load mainly composed of power electronic devices, which will inject harmonics into distribution network after large-scale grid connection, endangering the safe and stable operation of power grid and power equipment. Electric vehicle is a typical dynamic harmonic source. The charging load corresponding to different charging stages has significant difference, and the impact on the power grid will also be different[2]. At present, the most commonly used EV charger is the three-phase bridge uncontrolled rectifier with high frequency DC/DC power converter. Most of the research on the charging process of electric vehicle is based on the equivalent model of charging power: the charging process is equivalent to a non-linear resistor, and the change of charging power of the battery is simulated by the variation of the non-linear resistor during the charging period[3-5]. However, in the actual charging process of electric vehicles, the charging power varies greatly with the type and parameters of the charger[6]. Therefore, the nonlinear time-varying resistance model based on charging power needs to be re-modeled according to the different parameters of the charger. State of Charge (SOC) is an important parameter to measure the charging state of battery. In practical application, SOC is easier to obtain than other parameters and has high measurement accuracy[7-8]. Based on this, this paper establishes the equivalent model of electric vehicle based on SOC of battery charging state.

For the nonlinear load in the power system, the existing harmonic source models mainly include the constant-current source model, the model based on cross frequency admittance matrix, Norton equivalent model and the simplified model based on least square method[9]. When a high-power charging station is connected to the distribution network, it is difficult to obtain its mathematical model for harmonic source combination composed of multiple chargers, and the mechanism modeling method is usually too complex, computationally expensive and time consuming[10]. With the increase of the types of harmonic sources and the complexity of topological structure, the neural network modeling method has appeared, which does not need to consider the internal mechanism of the harmonic source[11]. In reference[12], a modeling method based on least squares support vector machine is proposed. The harmonic source is regarded as a black box, and the nonlinear mapping relationship between the amplitude and phase angle of each harmonic current, power supply voltage and load characteristic parameters is established by LS-SVM training. [13] proposes a load harmonic source modeling method based on measured data. The nonlinear load is equivalent to a constant current source, and the constant current source model of load under measured data is established through practical examples.

The research of this paper mainly focuses on the establishment and application of the harmonic modeling of EV charging station. The relationship between the amplitude and phase angle of each harmonic current and fundamental voltage, SOC of the battery and the type of rectifier circuit is non-linearly mapped by the radial basis function network (RBFN). It can dynamically and accurately reflect the harmonic output characteristics of the grid point of the charging station in the charging process of electric vehicles, and lay a mathematical foundation for harmonic analysis of the charging station of electric vehicles. The modeling method can well reflect the external characteristics of PCC (Point of Common Coupling) and has fast simulation speed, which can be applied to the harmonic estimation of large-scale grid-connected EV charging stations and the power quality management.

HARMONIC MODELING BASED ON RADIAL BASIS FUNCTION NEURAL NETWORK

Radial basis function network

Radial Basis Function neural network is a three-layer feedforward network, which has the characteristics of local approximation and fast convergence. It is a local neural network with strong non-linear mapping ability[14]. RBFN not only has the advantages of general neural network, such as multi-dimensional non-linear mapping ability, generalization ability and parallel information processing ability, but also has strong clustering analysis ability, simple and convenient learning algorithm. It can integrate the harmonic dynamic characteristics generated in the charging process of electric vehicles into the network characteristics. Therefore, in this paper RBFN is chosen to map the harmonic characteristics of the charging process of electric vehicles.

RBFN consists of input layer, hidden layer and output layer. The network is a non-linear mapping from input layer to hidden layer and a linear mapping from hidden layer to output layer. In this paper, Gauss function is chosen as the radial basis function of hidden layer neurons. The output of the network can be expressed as follows:

$$f(x)=\sum_{k=1}^{n}\omega_k R_k(x)=\sum_{k=1}^{n}\omega_k\phi(\|x-u_k\|)=\sum_{k=1}^{n}\omega_k e^{-\frac{\|x-u_k\|^2}{\sigma_k^2}} \quad (1)$$

Where x is the n-dimensional input vector; ω_k is the network weight of the k-th neuron; $R_k(x)$ is the radial basis function of the k-th neuron; x_i is the input vector of the first training; u_k is the center of the radial basis function of the k-th neuron of the hidden layer, which is used to define the location of the hidden layer neurons; σ_k is the radial basis function width of the k-th neuron of the hidden layer, and is used to define the sensitivity of the hidden layer neurons. From the Gauss radial basis function expression of the hidden layer neurons, it can be seen that when the input vector is close to the center of the neuron, the output of the hidden layer neurons is larger.

The training of RBFN can adopt both batch learning algorithm and continuous learning algorithm[15][16]. In batch learning algorithm, training samples that meet the requirements of network performance should be collected first and then input into the network to train the neurons. Serial learning algorithm is an online algorithm. After each sample input, the network will train the network or adjust the network weight to adapt to the new data. In practical applications, in order to reflect the dynamic harmonic characteristics in the process of charging, the serial learning algorithm can be used to train the harmonic neural network model of EV charging stations. When the load characteristic parameters of electric vehicle change during the charging process, the harmonic model can be updated dynamically.

Equivalent model of ev based on state of charging

At present, the most commonly used EV charger is the three-phase bridge uncontrolled rectifier with high-frequency DC/DC power conversion device. The main components are a three-phase bridge uncontrolled rectifier circuit, a filter device, a power conversion device, a power conversion circuit and a battery[17]. Using a time-varying resistor R_C to equivalent the input impedance of high frequency power conversion circuit, the equivalent model of EV charger can be obtained as shown in Figure 1.

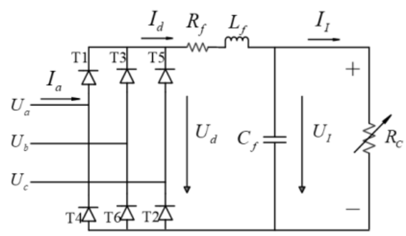

Figure 1 Equivalent model of EV charger

The relationship between the equivalent non-linear resistance R_C and charging power P_O can be expressed as follows:

$$R_C=\frac{U_I}{I_I}=\frac{U_I^2}{U_I I_I}=\frac{U_I^2}{P_I}=\frac{\eta U_I^2}{P_O} \quad (2)$$

Where P_I and P_O are the input power and output power of the power converter; η is the efficiency of the charger, generally 95%;U_I is the output voltage of the rectifier circuit, generally regarded as a constant value. The two-stage charging mode of the charger divides a charging cycle into two stages: constant current and voltage limitation in the first half and constant voltage and current limitation in the second half. In the constant current and voltage limiting stage, the charger charges with a large charging current, and the change of battery voltage is very small. The output power of the charger increases rapidly to the peak, and the SOC of the battery rises rapidly. When SOC increases to 70%-80%, the voltage remains basically constant, and the output power decreases rapidly. At this time, SOC increases slowly to full charge. According to the actual recorded data of battery charging process, the relationship between the output power and time under two-stage charging mode is obtained as follows:

$$P_O(t)=\begin{cases}0.79P_{Omax}t^{0.048}, 0<t\le T_C\\ P_{Omax}e^{-0.021(t-T_C)}, \ T_C\le t\le T\end{cases} \quad (3)$$

Considering that in the charging process the data of SOC can be easily obtained, so SOC is selected to represent the nonlinear resistance for modeling. The relationship between SOC and charging power is as follows:

$$SOC=SOC_0+\frac{\int i_o dt}{C}=SOC_0+\frac{\int P_o dt}{Q} \quad (4)$$

Where SOC_0 is the initial charging state; i_o is the charging current; C and Q are the rated charge and capacity of the battery respectively. In the constant current stage, the relationship between SOC and charging time t is as follows:

$$SOC=0.004872\times t \quad (5)$$

By combining the above equations, the equivalent simulation model of charger based on battery SOC, i. e. the equivalent relationship between non-linear resistance and SOC, can be obtained, as shown in Formula(6). In the constant current charging stage, the non-linear resistance is approximately constant; and in the constant voltage charging stage, it is only related to the SOC of the battery.

$$R=\begin{cases}\frac{\eta U_I^2}{1.048\cdot 0.004872Q}, 0<t\leqslant 150\\ \frac{\eta U_I^2}{P_{omax}-0.021(SOC-SOC_{150})Q}, 150<t\leqslant 270\end{cases} \quad (6)$$

Harmonic model based on RBF network

The harmonic current generated by harmonic sources basically depends only on their working conditions and applied voltage, and has little to do with the impedance of external circuits. Therefore, these harmonic sources can be regarded as constant current sources that can generate harmonic current. The voltage-current nonlinearity of harmonic source can be expressed as

$$\dot{I}_h=F_h(\dot{V}_1,\dot{V}_2,...,\dot{V}_N,C),\ h=1,2,...,N \quad (7)$$

Where F_h is the h-th harmonic current vector absorbed by the load; V_1, V_2, …, V_N are the fundamental and each harmonic voltage of the supply voltage; C is the characteristic parameters of the load. Once the power supply voltage waveform and load characteristic parameter C are given, each harmonic current absorbed by the harmonic source can be accurately calculated through numerical calculation. For different harmonic sources, their parameters C are also different.

In reference[18], the concepts of voltage operation degree S_V (ratio of actual fundamental voltage to rated voltage) and power load degree S_P (ratio of actual fundamental power to rated power) are introduced. S_V and S_P can reflect the commonness of all harmonic sources, and can be used as a subset of characteristic parameters of harmonic loads for all harmonic sources. Thus Equation (7) can be simplified as

$$I_h=F_h(S_V,S_P),\ h=1,2,...,N \quad (8)$$

In summary, the characteristics of harmonic source of electric vehicle charger can be expressed as

$$I_h\angle\theta_h=F_h(U_1,SOC,n),\ h=1,2,...,N \quad (9)$$

Where U_1 is the amplitude of fundamental voltage, SOC is the state of charge of the battery, n is the rectifier circuit type (6 pulses/12 pulses), I_h and θ_h are the amplitude and phase of each harmonic current. For an EV charging station formed by multiple charging units, the amplitude of each harmonic current can be output according to the combination of different SOC and THD_U.

$$I_h\angle\theta_h=F_h(n_1,n_2,\ldots,SOC_1,SOC_2,\ldots,THD_U),\ h=1,2,...,N \quad (10)$$

MAE and RMSE are used to measure the learning accuracy of the network.

$$\varepsilon_{MAE}=\sum_{i=1}^{n}\left|f(x_i)-y_i\right|/n \quad (11)$$

$$\varepsilon_{RMSE}=\sqrt{\sum_{i=1}^{n}\left|f(x_i)-y_i\right|^2/n} \quad (12)$$

Where $f(x_i)$ is the output of the model; y_i is the actual output of the original system, and the closer ε_{MAE} and ε_{RMSE} approach to 0, the better the performance of the model. The specific process of the harmonic modeling method for EV charging stations based on RBF neural network is shown in Fig. 2.

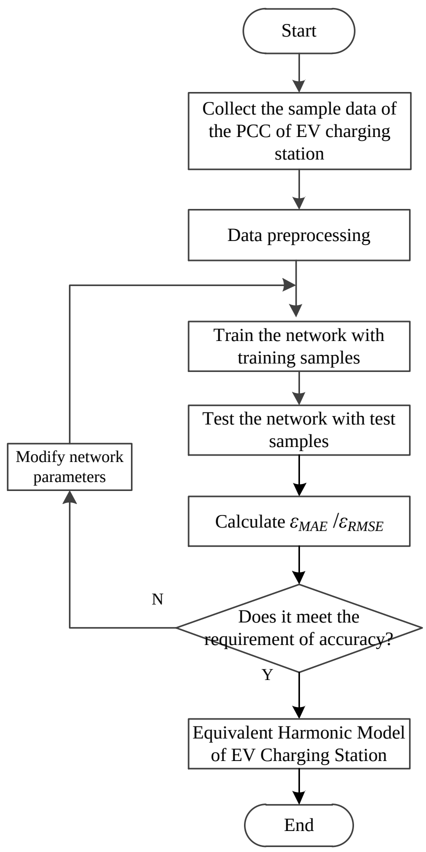

Figure 2 Harmonic Modeling Process of EV Charging Station Based on RBFN

EXAMPLES

In order to obtain training data, this paper uses simulation data as training data to train the harmonic model of EV charging station. According to the basic structure of a typical EV charger and the relationship between the above nonlinear resistance and the SOC, single/multiple EV charger models are built on PSCAD/EMTDC simulation platform.

Single charger

A *SOC*-based charging equivalent model of a single 6-pulse EV charger is established on PSCAD/EMTDC, and a typical example of charging electric vehicles connected to a low-voltage distribution network is established, as shown in Fig. 3. The EV charging power is 9 kW and it is connected to the grid through a 10/0.4 kV transformer, with the connection mode of Dyn11.

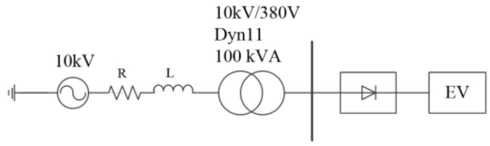

Figure 3 A typical example of low voltage distribution network

(1) Data acquisition. Under the condition of three-phase balance of the system, the harmonic number generated by the 6-pulse charger on the AC side is mainly $6k\pm1(k=1,2,3\cdots)$, and the higher the harmonic number, the smaller the harmonic amplitude. For the harmonic current generated by the charger in a charging period, its amplitude increases slowly in the constant current phase, and decreases gradually in the constant voltage phase, reaching the maximum value at the end of the constant current phase (when *SOC* is about 75 %). Harmonic characteristics such as harmonic content in the dynamic charging process of the charger are analyzed to form the sample data, including fundamental voltage U_1, *SOC* of the battery, rectifier circuit type *n* and the amplitude and phase angle of each harmonic current, where the phase angle of each harmonic current is based on the phase angle of the fundamental voltage on the power supply side.

(2) Data preprocessing. In a charging cycle (270min), a value is taken every 30s to generate a total of 540 sets of data, and the training set and test set are generated randomly. 500 sets of samples are randomly generated as the training set, and the remaining 40 sets are taken as the test set, and the input and target output vectors are normalized.

(3) Construction of RBFN. According to the construction process of RBFN proposed above, the nonlinear mapping relationship is established. The fundamental voltage amplitude U_1, *SOC* and rectifier circuit type *n* are used as the input of the neural network, and the amplitude I_h and phase θ_h of each harmonic current are used as the output.

(4) Result analysis. The training results of the model are shown in Table 1. It can be seen that the precision of the model is high, and the training time is short, which can meet the needs of practical application. Considering the maximum harmonic current in the charging process of EV, that is, when *SOC*=76.67% and *THDu*=1.78%, the results are shown in Table 2 and Fig. 4.

Table 1 Training results

Error	Amplitude	Phase
ε_{MAE}	0.00174	0.00621
ε_{RMSE}	0.00217	0.00767

Table 2 Training output comparison for case: SOC=76.67%, THDu=1.78%

Harm.	Simulation		RBF Neural Network	
	Mag.（p.u.）	Phase (°)	Mag.（p.u.）	Phase (°)
1	1.0102	-0.146	1.0095	-0.1378
5	0.3819	-0.0076	0.3808	-0.0038
7	0.1994	0.8771	0.1998	0.8805
11	0.0854	0.2828	0.082	0.2813
13	0.0558	-0.0402	0.059	-0.0543

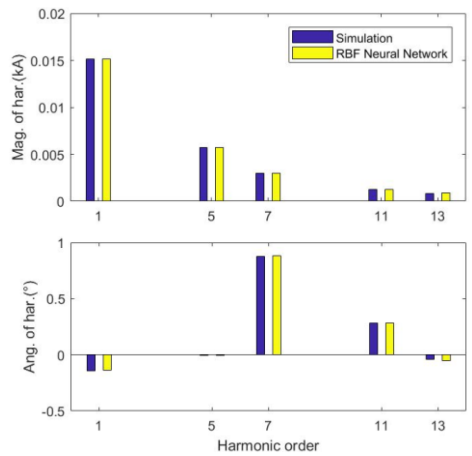

Figure4 Comparison of the model output results

Multiple chargers

Taking two chargers as an example, the harmonic characteristics generated by asynchronous charging process of EV chargers are simulated. The initial state of the two chargers are both 0, and the second charger is put into operation at 30min after the first charger is charged. The training results of the model are shown in Table 3. For the case when SOC_1=76.7%, SOC_2=60.7%, and THDu=3.11%, the results are shown in Table 4and Fig. 5.

Table 3 Training results

Error	Amplitude	Phase
ε_{MAE}	0.00256	0.00152
ε_{RMSE}	0.00527	0.00305

Table 4 Training output comparison for case: SOC1=76.7%, SOC2=60.7%,THDu=3.11%

Harm.	Simulation		RBF Neural Network	
	Mag.（p.u.）	Phase (°)	Mag.（p.u.）	Phase (°)
1	1.0004	-0.1609	0.9884	-0.1645
5	0.3527	-0.0411	0.3511	-0.0526
7	0.1547	0.6618	0.1555	0.6652
11	0.082	-0.0893	0.0805	-0.0749
13	0.046	-0.4919	0.0458	-0.516

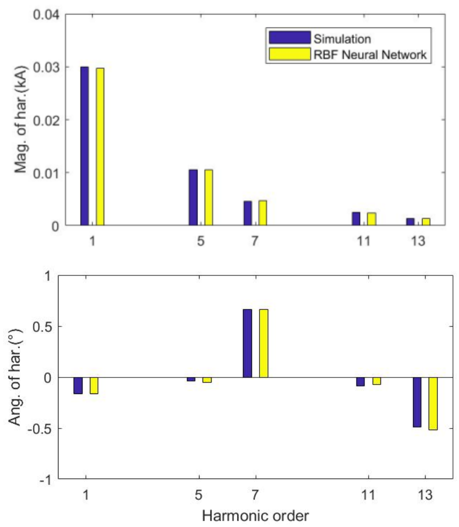

Figure5 Comparison of the model output results

According to the above analysis, we can see that when multiple chargers are charged at the same time, harmonic currents produced by each charger have the cancellation effect, and the superposition value of the same harmonic current cannot be obtained by linear fitting. Therefore, the harmonic modeling method of EV charging station based on neural network proposed in this paper is more practical.

In practical application, the dynamic modeling of harmonic source model can be realized by using serial learning algorithm and update with measured data in real time.

CONCLUSION

In this paper, an equivalent model of electric vehicle charger based on SOC of the battery is established, and a data-driven harmonic modeling method for EV charging station is proposed. The relationship between the amplitude and phase angle of each harmonic current and fundamental voltage, battery SOC and rectifier circuit type is mapped nonlinearly by RBFN. The method only needs to know the measured data of the PCC of EV charging station, and does not need to go into its specific parameters and structure. Once trained and tested, the harmonic model can meet the simulation requirements. In practical applications, the model can be easily established online and update dynamically. The simulation results show that the modeling method can well reflect the external characteristics of PCC and has fast simulation speed and high precision. Since SOC is an important parameter to measure the battery charging status, which can be directly obtained and measured with high accuracy, it has great practical value in engineering.

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