Study on Output Voltage Ripple Coefficient of DC Charger Based on Orthogonal Test

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Abstract. DC chargers output high voltage, large current during their charging process, which inevitably produce and carry a lot of ripple. The ripple will not only damage performance of electric vehicle battery, but also cause current distortion at AC side. Therefore, studies on output voltage ripple coefficient of DC charger are important. In this paper, we consider the condition that the structure of DC charger is fully established, and take AC input voltage, DC output voltage and DC output current as the three main parameters. Then orthogonal test method and matrix analysis method are introduced successively, through orthogonal test table, range analysis and matrix calculations, the optimal combination status when DC chargers produce the minimum ripple coefficient is studied. Results show that when AC input voltage, DC output voltage reach up to maximum and DC output current reach up to median, output voltage ripple coefficient of RMS and peak-peak value of DC charger reach to the minimum value simultaneously. Finally, validity and reliability of the analysis results are verified through the traditional test method.

1. Introduction

In recent years, electric vehicles have grown explosively due to their advantages in environmental protection and energy saving, which has become a new trend in the development of automobile industry. As the most important supporting facilities, electric vehicle charging equipments have already got a lot of constructions [1, 2]. Due to its fast and efficient characteristics, DC charging is gradually replacing AC charging and become the mainstream charging way, which undoubtedly lead researches on electric vehicle DC charging into further level [3].

DC charger is mainly composed of rectifier, power conversion unit and controller etc.. So it will inevitably produce and carry a lot of ripple during the charging process with high output voltage and large current. Most existing DC ripple studies are mainly focusing on rectifier of DC power supply [4], suppression of DC ripple [5] etc., but studies directly about output voltage ripple of DC charger are rare. During the charging process, DC ripple will not only damage vehicle battery performance, disturb electric energy measurement [3], but also increase electromagnetic interference and cause current distortion in AC side [6]. It is obvious that studies on output voltage ripple or ripple coefficient of DC charger are becoming more and more important. Thus this paper starts from ripple coefficient test of normal DC charger, then introduces orthogonal test and matrix method to analyze the test results, finally gains weights of all influence factors and reveals the best combination, which provides certain guidance for related producers, inspectors, user, etc.

2. Design of ripple coefficient test

Specific methods and steps of DC charger output voltage ripple coefficient test has been stipulated in relevant standard. Firstly, connect DC charger to resistive load, set DC charger to run in the condition of constant voltage, adjust the setting value of its output voltage, respectively adjust input voltage to 85%, 100%, 115% of its rated value, adjust load current to 0%, 50%, 100% of its rated output current value, then measure its DC output voltage, RMS and peak-peak value of AC component in DC output voltage respectively. Finally, change the setting value of output voltage in its upper and lower range (U_{max}, U_{men}, U_{min}), and repeat the upper measurement. Technical parameters requirements for the measuring oscilloscope in this test is: frequency bandwidth is 20 MHz, horizontal scanning speed is 0.5 s/DIV. Schematic diagram of the output voltage ripple coefficient test platform is designed under related standard requirement, as it's shown in Fig.1.

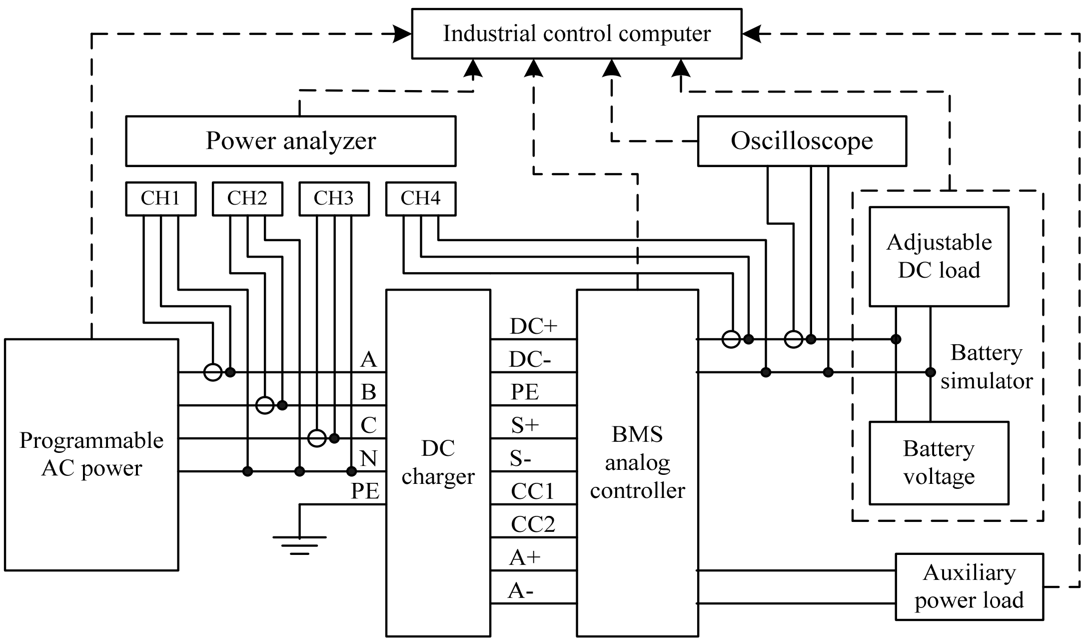


Figure 1. Schematic diagram of ripple coefficient test platform.

In Fig.1, it can be seen that the platform is mainly composed of AC power, BMS analog controller, battery simulator, power analyser, oscilloscope, industrial personal computer, etc. Power analyzer collect input and output voltage, current value etc.; Oscilloscope collect signals such as CC1, output voltage and current, complete RMS and peak-peak value measurement of the ripple and monitor the whole working sequence; Industrial personal computer control all equipments to work under the scheduled process, and complete all data and waveforms acquisition of the test.

3. Orthogonal test

3.1. Design of the orthogonal test

Orthogonal test is an important scientific method in multifactor experimental study. Orthogonal test uses orthogonal test table to select some representative combinations from all combinations, then carry out representative test and not to repeat. Compared with traditional test methods, orthogonal test can reduce test times as much as possible, but gain the optimal combination result from test data based on fewer tests, which guides correct production practice [7, 8]. Due to its unique superiority, orthogonal test has been widely used on kinds of fields such as, electrical engineering [7], mold engineering [9], chemical engineering [10], etc.

Even high frequency switch type chargers with low ripple coefficient also carry with ripple when they work, so ideal and steady DC output is difficult to achieve. The factors influencing output voltage ripple coefficient of DC charger contain rectifier, ripple suppression function unit, AC input voltage, DC output voltage and DC output current, etc. Considering the condition that structure of DC charger is fully established, we take AC input voltage U_{in}, DC output voltage U_{out} and DC output current I_{out} as test factors to study the best state of DC charger in actual use. Take the recommended three test points of all factors at chapter 2 as the three level values, the test factor level table with three factors three levels is got as it's shown in Table 1.

Table 1. Factors and levels of orthogonal test.

Levels	Factors		
	U_{in}/V	U_{out}/V	I_{out}/A
1	85% U_n	U_{min}	0% I_n
2	100% U_n	U_{men}	50% I_n
3	115% U_n	U_{max}	100% I_n

3.2. Test scheme and results

We take ripple coefficient of RMS X_{rms} and peak-peak value X_{pp} as the test index. All combinations for three factors three levels will be expected to carry out 27 times of test, which is quite laborious. If using $L_9\,(3^4)$ orthogonal table is just need 9 tests, which can gain the relationship between the factors and indexes as the 27 times tests do. The combinations of 9 tests and its schedule table obtain from $L_9\,(3^4)$ orthogonal table, as shown in the first 4 columns of Table 2.

Randomly take an DC charger as the research object, whose input parameter is: AC380V, output parameters are: DC300 ~ 750V, 80A, 60kW, we use the above orthogonal experiment table to carry out the test and gain the ripple coefficient X_{rms} and X_{pp}, as shown in the last 2 columns of Table 2. Only 9 incomplete combinations and their test results can't directly come to the conclusion, so test result analysis with mathematical method will be carried out in the following.

Table 2. Design and results of orthogonal test.

Test number	Levels			Test index	
	U_{in}	U_{out}	I_{out}	X_{rms}/%	X_{pp}/%
1	1	1	1	0.0799	0.2409
2	1	2	2	0.0451	0.0927
3	1	3	3	0.0330	0.0715
4	2	1	2	0.0720	0.2138
5	2	2	3	0.0469	0.1245
6	2	3	1	0.0333	0.0633
7	3	1	3	0.0738	0.2289
8	3	2	1	0.0419	0.0908
9	3	3	2	0.0282	0.0609

4. Analysis of test results

For multiple index cases, common methods for test results analysis include variance analysis, effect analysis and so on, but operations of these methods are complex [9]. Therefore, we decided to attempt a simple matrix analysis method, which can find the optimal combination scheme through analysis of the weight of each level of all influence factors. Contents and steps of matrix analysis method are:

Firstly, we find out layer matrix M, factor layer matrix T, horizontal layer matrix S of each test index, and then calculate their product matrix, namely weight matrix W_k.

Index layer matrix *M*: index average value in the *j* level of the *i* factor is K_{ij} (i = 1, 2, …, m; j = 1, 2, …, n). If we expect the weight value is the larger the better, take $K_{ij} = K_{ij}$; and if we expect the value is the smaller the better, take $K_{ij} = 1/K_{ij}$; then establish matrix *M* as follows:

$$M = \begin{Bmatrix} K_{11} & 0 & \cdots & 0 \\ K_{21} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & K_{mn} \end{Bmatrix} \tag{1}$$

Factor layer matrix T: take $T_i = 1 \Big/ \sum_{j=1}^{n} K_{ij}$, and establish matrix T as follows:

$$T = diag(T_1, \quad T_2, \quad \cdots, \quad T_m) \tag{2}$$

Horizontal layer matrix S: if the range is Ri, take $S_i = R_i \Big/ \sum_{i=1}^{m} R_i$ and establish matrix S as follows:

$$S^T = (S_1, \quad S_2, \quad \cdots, \quad S_m) \tag{3}$$

Calculate weight matrixes of each test index as Eq.4 shows:

$$W_k = M_k T_k S_k \ \text{(k = 1, 2, …, z)} \tag{4}$$

Secondly, calculate average value of all weight matrixes and gain the total weight matrix *W*:

$$W = \sum_{k=1}^{z} W_k \Big/ z \tag{5}$$

Finally, we find out the level number *j* corresponding to the extreme value of each factor in the matrix *W*, then take *j* as the optimal level to its factor, and finally determine the optimal level combination of all factors.

Test results are analyzed under this matrix method as follows. Calculate the average value K_i in the same level of each factor and the range value R_i of each factor according to Table 2, and all results it's shown in Table 3.

Table 3. Range analysis.

Index	Levels	K_1	K_2	K_3
	1	0.0527	0.0752	0.0517
X_{rms}	2	0.0507	0.0446	0.0484
(%)	3	0.0480	0.0315	0.0512
	R	0.0047	0.0437	0.0033
	1	0.1350	0.2279	0.1317
X_{pp}	2	0.1339	0.1027	0.1225
(%)	3	0.1269	0.0652	0.1416
	R	0.0082	0.1626	0.0192

Matrix M, T, S of Two indexes Xrms and Xpp are calculated respectively. Here we undoubtedly expect the smaller values of these two indexes are better. Therefore, take $K_{ij} = 1/K_{ij}$, according to steps described above, we gain weight matrixes of the two indexes as they are respectively shown in Eq.6 and Eq.7:

$$W1 = [11.3939, 11.8433, 12.5095, 74.2906, 125.2614, 177.3542, 8.1601, 8.7164, 8.2398]T \quad (6)$$

$$W2 = [0.8077, 0.8143, 0.8593, 9.4874, 21.0533, 33.1622, 1.9386, 2.0842, 1.8031]T \quad (7)$$

Finally, weight matrix which affects the overall index of this test is gain in Eq.8:

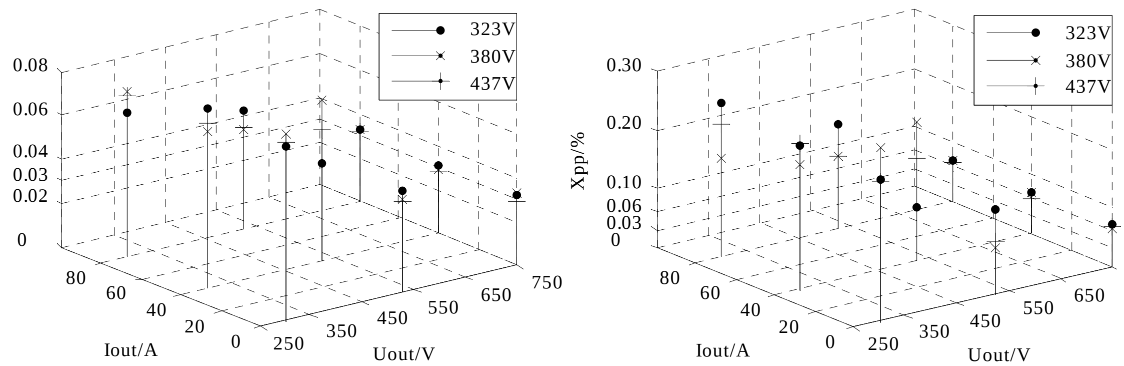
$$W =[6.1008, 6.3288, 6.6844, 41.8890, 73.1573, 105.2582, 5.0493, 5.4003, 5.0214]T \quad (8)$$

$$W = [U_{in}(1), U_{in}(2), U_{in}(3), U_{tou} (1), U_{out}(2), U_{out}(3), I_{out}(1), I_{out}(2), I_{out}(3)]T \quad (9)$$

It can be seen from Eq.8 and Eq.9, weights of the third level are all the maximum for U_{in} and U_{out}, but the maximum of I_{out} is the sceond level. We know that the greater the weight, the smaller the ripple coefficient. As a result, the best combination scheme of this test is $U_{in}(3)U_{out}(3)I_{out}(2)$.

We verify the analysis results with traditional method in the following. That is carrying out ripple coefficient test with all 27 kinds of combinations and collected all the test results as it's shown in Fig.2. It is found that when testing with the best collocation scheme $U_{in}(3)U_{out}(3)I_{out}(2)$, we simultaneously gain the minimum ripple coefficient X_{rms}=0.0282 and X_{pp}=0.0609 comparing with Table 1, which demonstrate validity and reliability of the previous analysis results. It is not an accident, the author carry out tests on DC chargers with different type specifications and almost gain the same results.

Therefore, the above test results tell us that we should try to keep charger output with high voltage and moderate current of its capacity, namely avoid full output, which is helpful to reduce ripple interference, alleviate damage to battery performance and reduce electromagnetic interference etc.



(a) Xrms of all combinations (b) Xpp of all combinations

Figure 2. Test results of all combinations by traditional method.

5. Conclusion

In order to obtain the minimum condition of output voltage ripple coefficient of DC charger. Carry out orthogonal test design on three main parameters of DC charger including AC input voltage, DC output voltage and DC output current, we get three factors and three levels table and orthogonal test table. Then based on a normal DC charger, tests and measurements are carried out according to the designed orthogonal test table, range analysis and matrix computations on the measurements are proceeded. Analysis results show that when AC input voltage, DC output voltage reach up to maximum and DC output current reach up to median, output voltage ripple coefficient of RMS and peak-peak value of DC charger reach to the minimum value at the same time. Finally, compared with the traditional test method, validity and reliability of all the results which gained through orthogonal test method and matrix analysis method are verified. So the charger should avoid keeping in full output status.

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