Parameter identification of capacitive transfer system based on Fitting Algorithm

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Abstract. At present, in the wireless power transfer (WPT) of electric vehicle (EV), inductive power transfer (IPT) is still the main method. However, capacitive power transfer (CPT) has the advantages of no eddy current loss of coupling mechanism and light weight, which make it become a new research hotspot in the charging application of EV. But CPT system has high working frequency and sensitive parameters, therefore, in practical application, it is necessary to identify important parameters such as coupling capacitance and load. But at present, there are few identification methods for parameters of CPT. In this paper, a multi-parameter identification algorithm is proposed for capacitive wireless charging technology. Based on Vector Fitting algorithm and network synthesis principle, multi-parameter identification is realized. But in order to be widely used in practice, some parameters in circuit model are considered as known constraint. This can ensure that the proposed algorithm can not only realize multi-parameter identification, but also ensure the identification accuracy of system parameters in practical application.

1. Introduction

Environmental pollution and energy shortage are two major problems facing the automobile industry at present. With the rapid growth of the world's automobiles, the impact of traditional fuel vehicles on the environment and dependence on petroleum resources are becoming more and more serious. On the contrary, the advantage of EV is that they are less polluted to the environment, and even can achieve zero pollution. It can not only make the car get rid of dependence on petroleum resources, but also reduce the air pollution of the car.

At present, WPT can be classified IPT [1] [2], CPT [3] [4]. IPT system has been developed for a long time, and scholars at home and abroad have invested a lot of research, so the technology has become more mature. Figure 1 is the system structure of the CPT system. Because the system uses metal plates to couple, the distance between two metal plates is difficult to increase due to the limitation of the coupling capacitance value. This leads to the CPT system has been limited to short-range, low-power application scenarios.

In 2015, researchers such as D.C. Ludois and Lu Fei began to improve the power of CPT system. The designed system can be used to charge electric vehicles, and the system efficiency can reach 2.4kW power is 90.8% [5].

Unlike IPT system, CPT system has lower transmission loss in the environment with metal objects, and it can also resist the interference of magnetic field [6]. In addition, the coupling mechanism of CPT system uses metal plates, which not only makes the cost of system equipment lower, but also makes the weight of the whole system smaller.
When CPT system works, (1) various factors such as the placement of the metal plate of the coupling capacitor and its environment will lead to the system working under different conditions; (2) the system also guarantees that the system can work normally under the load of different parameters. It can be seen that the important parameters such as coupling coefficient and load in the actual system are not constant values, but constantly changing, which brings identification requirements to those parameters. There are some parameter identification methods in IPT system, but there are few parameter identification methods in CPT system [7].

In reference [8], the matching circuit model of IPT system is analyzed, and the relationship between input voltage and current and load resistance is deduced, so that the parameters of load resistance can be identified.

Reference [9] adopts step-by-step operation. Firstly, the standard load resistance is used to identify the coupling inductance, and then the actual load resistance is identified by the value of the previous step. By using this method, the multi-parameter identification of the system is realized.

However, in the field of CPT system, the reason for the lack of parameter identification methods is that the working frequency of capacitive wireless charging system is relatively high, and the resonant peak is relatively narrow, which makes the working state of the system vulnerable to the influence of system parameters.

However, in the field of CPT system, the reason for the lack of parameter identification methods is that the working frequency of capacitive wireless charging system is relatively high, and the resonant peak is relatively narrow, which makes the working state of the system vulnerable to the influence of system parameters. Once the parameters of the circuit model cannot be accurately measured, the identification algorithm of IPT system described above will not get accurate results. Therefore, it is very important to study a more accurate algorithm to identify the parameters of CPT system.

2. Parameter identification method based on spectrum information

Figure 2 is the circuit model of CPT system. When the system load is stable, the system can be used as a single port network, and the components of the system are linear. Therefore, the CPT system can be regarded as a single-port network. By identifying the parameters of the single-port network, the parameters of the CPT system can be obtained. For a linear single-port network, its external characteristics can be determined by the driving point function of the port. Taking admittance function as an example, it is defined as follows:

\[
Y(s) = \frac{I_m(s)}{U_m(s)}
\]

where, \(I_m(s)\) and \(U_m(s)\) are the voltage and current of the input end at different frequencies.

Figure 2. Circuit model of CPT system.
Supplying power to the system shown in figure 2, the corresponding admittance value is obtained according to equation (1) by measuring the corresponding voltage and current signals. We can constantly change the frequency of the inverters, so a series of admittance values are obtained. By fitting these admittance values with the fitting algorithm, the expression of the driving-point function of the circuit can be obtained.

By synthesizing the network parameters and combining the circuit model parameters in figure 2, the unique analytic expression of the system function can be obtained, and then combined with the fitting expression, the unknown parameters of the system can be calculated effectively. Therefore, it is clear to identify the parameters of CPT system, which mainly includes the following contents: (1) the fitting of the driving-point function; (2) the synthesis of network parameters.

2.1. Fitting of driving-point function

For a single-port linear network, the driving-point function can be expressed as a rational fraction:

\[ Y(s) = \frac{N(s)}{D(s)} = \frac{\sum a_i s^i}{\sum b_j s^j} \]  

(2)

where, a and b in the above equation are all real numbers, and the order of the numerator and denominator is determined by the topology and component parameters of the circuit.

2.2. Fitting of driving-point function

In the process of fitting, it is generally assumed that the noise distribution of sampling values obeys the normal distribution rate, then the sum of squares and the minimum of fitting errors can be taken as the index, but the fitting function is a non-linear function, so the non-linear least squares is chosen for fitting:

\[ \text{min} \sum \left\| \Phi(s) - Y(s) \right\|^2 \]  

(3)

where, \( \Phi(s) = \sum \frac{\delta_i}{\delta_i^s} \), \( \delta_i \) and \( \delta_i^s \) are undetermined parameters of functions.

If we directly using the sum of squared errors as an optimization object, the optimization problem is non-convex, there are multiple local optimum of the fitting error in the solution space. Therefore, if we use Levenberg-Marquardt method or the trust region method directly, it is difficult to converge to the optimal value for nonlinear optimization. In order to solve the local optimum problem of the fitting algorithm of the non-linear least squares method in rational fraction fitting, Sanathanan and Korener proposed the S-K iteration method of iterative solution, which transformed the non-linear least squares problem into the iteration process of the linear least squares problem[10], which can convert equation (3) to equation (4).

\[ \text{min} \sum \frac{1}{\delta_i^s} \left\| \sum a_i s^i - Y(s)\sum a_i s^i \right\|^2 \]  

(4)

Taking LC series resonant circuit model as an example, we use S-K iteration method to linearize the objective function in the search space. The value of the objective function is shown in the blue surface in figure 3. Compared with the square sum error represented by the purple surface in the graph, the linearization function of S-K iteration method keeps the value of the objective function of the optimal solution position unchanged, while the value of the objective function outside the optimal point becomes flat and has a unique minimum value, so it can converge to the optimal solution better.

2.3. Fitting of driving-point function

In the fitting objective function expression (3) of the S-K iteration method, when the frequency range of sampling points is very wide, because of the existence of the high order term of s, the order of magnitude of the coefficients is very different in the linear least squares problem. Finally, the number of matrix conditions is very large, and the numerical accuracy is poor when solving the problem. To
solve this problem, Bjørn and Adam proposed Vector Fitting algorithm [11], which reduces the condition number of matrix by transforming the basis of polynomial.

Figure 3. Linearization of objective function by S-K iteration method.

By transforming Equation (2) into zero-pole point through partial fractional expansion, the following fitting expressions can be obtained:

\[ Y(s) = \sum_i \frac{r_i}{s - p_i} = \prod_i \frac{(s - z_i)}{(s - p_i)} \]  \hspace{1cm} (5)

Linearizing equation (3) and multiplying weight \( \sigma(s) = \prod_j \frac{(s - p_j)}{j(s - p_j^1)} \), the linearized least squares problem can be obtained:

\[ \min \sum \left\| \sigma \tilde{Y}(s) - Y(s)\sigma(s) \right\|_2 \]  \hspace{1cm} (6)

Where

\[ (\sigma \tilde{Y})_j = \prod_j \frac{(s - z_j)}{(s - p_j^1)} = \sum_i \frac{r_i^{(1)}}{s - \tilde{p}_j^1} \]  \hspace{1cm} (7)

\[ \sigma(s) = \prod_j \frac{(s - p_j)}{j(s - p_j^1)} = \sum_i \frac{r_i^{(2)}}{s - \tilde{p}_j^1} + 1 \]  \hspace{1cm} (8)

Because there is no higher order term of \( s \) in the expression, the number of conditions of each matrix of the linear least squares problem is smaller, so it can have better numerical accuracy in solving the problem.

The specific algorithm flow is as follows:

(1) Given the initial pole value of iteration \( \tilde{p}_j^1 \);
(2) Using equation (6), we can get \( r_i^{(1)} \), \( r_i^{(2)} \);
(3) By equation (8), \( p_i \) is solved by \( r_i^{(2)} \) and \( \tilde{p}_j^1 \) as new pole.
(4) Then we use equation (6) to get \( r_i^{(1)} \), \( r_i^{(2)} \);
(5) To determine whether the fitting error of the algorithm is greater than the set limit, if it is greater than the set limit, the new solution will be recalculated as a new estimation \( \tilde{p}_j^1 = p_i \), back to (2). Otherwise, the value of \( p_i \), \( r_i^{(1)} \) and \( r_i^{(2)} \) are directly used as fitting results.

2.4. Fitting of driving-point function

After using Vector Fitting algorithm to fit the driving-point function of the system, it is necessary to obtain the actual circuit parameters from the expression of the function, which is the synthesis of the
circuit network. In CPT system, Cauer synthesis method can be used because the topological structure of matching circuit is mostly T-shaped network structure [12].

For double-sided LC-matching CPT system shown in figure 2, the expression of input admittance function is obtained by Cauer synthesis method:

$$Y(s) = \frac{1}{Ls + R_l + \frac{1}{C_s + G_l + \frac{1}{C_a s + R_a + \frac{1}{C_s + G_s + \frac{1}{L_s s + R_s + R_{load}}}}}}$$

(9)

We can know that the highest denominator order of admittance function is 4 after expand the formula obtained above:

$$Y(s) = \frac{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}$$

(10)

Therefore, the input admittance function is fitted by using the fourth-order Vector Fitting algorithm, and the circuit is solved by using equation (10). When network synthesis is used, the impedance of the coupling capacitor is very large in the CPT system, which leads to the loss resistance can not be identified properly. Therefore, we neglect the loss resistance, but there is a degree of freedom in the circuit. Because there is a degree of freedom in the circuit that can not be solved, it is necessary to know a receiver end parameter as a known condition to completely solve the circuit parameters [13]. In this paper, the inductance of matching circuit is taken as the known condition. The identification results shown in this section can be obtained. The result is that the parameter identification of the whole circuit is basically close to the model parameters.

**Table 1.** Noise-free identification results of parameter identification algorithm based on vector fitting.

| Circuit parameters | Vector Fitting identification results | Model parameters |
|--------------------|--------------------------------------|------------------|
| L1(uH)             | 82.24                                | 82.24            |
| R1(Ω)              | 3.4772                               | 3.44             |
| C1(pF)             | 288                                  | 288              |
| Cm(pF)             | 19.998                               | 20               |
| C2(pF)             | 288.01                               | 288              |
| L2(uH)             | 82.24                                | 82.24            |
| R2(Ω)              | 3.3562                               | 3.44             |
| Rload (Ω)          | 33.4222                              | 33.1             |

3. Vector fitting algorithm with constraint

The Vector Fitting algorithm introduced in the second section has no constraints, so we call it the unconstrained Vector Fitting algorithm (Unconstrained-VF algorithm). It can be proved that the algorithm can identify all the parameters in the circuit, however, in order to improve the applicability of the parameter identification, we consider the part of the component parameters in the model circuit which are not easy to change as the known conditions. The purpose of that is:

- In practical use, not all the parameters of components need to be identified, and some of them can be measured in advance.
The Vector Fitting algorithm can be constrained by taking some component parameters as known conditions, which can improve the accuracy of parameter identification in practical use. Some known component parameters divide the double-sided LC matching capacitive system shown in figure 2 into several parts. As shown in figure 4, the whole circuit model is divided into known and unknown parts. We can solve the problem by following steps:

Step 1: give initial values to the elements of the unknown part of the middle part and the rightmost part. Just like the coupling capacitance $C_m$ and the load resistance $R_{\text{load}}$. We can take $C_m$ and $R_{\text{load}}$ as the initial values of $C_m$ and $R_{\text{load}}$.

Step 2: at this time, it is reasonable to assume that the unknown part on the right (the load resistance $R_{\text{load}}$) becomes a known condition. When both sides are known, Vector Fitting algorithm is used to solve the parameters of the unknown part in the middle (the coupling capacitance $C_m$), and the parameters obtained are taken as known conditions. In turn, Vector Fitting algorithm is used to solve the unknown parameters on the right-most part (the load resistance $R_{\text{load}}$).

Step 3: through this continuous iteration method, until the final fitting error is less than the error limit, the final parameters can be used as identification results.

This method is called Vector Fitting algorithm with constraints (Constrained-VF algorithm), if you want to identify more parameters, you can choose to divide the model into more parts, which are either known or unknown, then repeatedly use the Constrained-VF algorithm.

We then use the 2.2 section of the simulation model and the sampling parameters. However, we only identify the coupling capacitance $C_m$ and the load resistance $R_{\text{load}}$. By comparing the simulation results with table 1, we can find that the Constrained-VF algorithm avoids the static error of the model caused by the loss resistance neglected in network synthesis. Table 2 only show the identified parameters $C_m$ and $R_{\text{load}}$, others are all known parameters.

![Figure 4. CPT circuit model segment.](image-url)

**Table 2.** Noise-free identification results of parameter identification algorithm based on constrained-VF algorithm.

| Circuit parameters | Constrained-VF identification results | Model parameters |
|-------------------|--------------------------------------|------------------|
| L1(uH)            | -                                    | 82.24            |
| R1(Ω)             | -                                    | 3.44             |
| C1(pF)            | -                                    | 288              |
| Cm(pF)            | 20                                   | 20               |
| C2(pF)            | -                                    | 288              |
| L2(uH)            | -                                    | 82.24            |
| R2(Ω)             | -                                    | 3.44             |
| R_{\text{load}}(Ω)| 33.121                               | 33.1             |
4. Experimental verification

According to the circuit model of the double-sided LC matching shown in figure 2, we can make an actual circuit shown in figure 5. The inductance of the matching circuit part of the circuit is wound by the Litz wire, and the capacitance of the matching circuit part is formed by connecting a plurality of film capacitors having a capacitance of 1nF in series. The coupling capacitor is a 20pF ceramic capacitor. Since the determinism of the algorithm needs to be compared by the true value of the component, the individual components in the actual circuit are measured as true using the Agilent E4980A LCR meter.

![Figure 5. Double-sided LC matching CPT system circuit physical map.](image)

In the experiment, the inductance, resistance and capacitance of the matching circuit are taken as known conditions, and the identification of coupling capacitance and load resistance is selected. The true value of coupling capacitance and load resistance are 20 pF and 20 Ω, respectively. All the results are recorded in table 3, from which we can know that the identification results of the Unconstrained-VF algorithm and the Constrained-VF algorithm for the coupling capacitance are 19.429 pF and 20.5 pF, respectively, and the identification results of the load resistance are 24.2609 Ω and 20.6463 Ω, respectively. Compared with the results of load resistance identification, the identification accuracy of the constrained model is less than 1 Ω, while that of the unconstrained model is about 4 Ω, its identification error is about four times that of the constrained model.

![Table 3. Parameter identification effect of parameter identification algorithm on model physical circuit.](image)

| Circuit parameters | Unconstrained-VF identification results | Constrained-VF identification results | Component measurement |
|--------------------|----------------------------------------|--------------------------------------|-----------------------|
| L1(uH)             | 79.646                                 | -                                    | 77.1773               |
| r1(Ω)              | 2.8533                                 | -                                    | 3.6928                |
| C1(pF)             | 256.53                                 | 265.7394                             |                       |
| Cm(pF)             | 19.429                                 | 20.5                                 | 20                    |
| C2(pF)             | 250.15                                 | 252.2711                             |                       |
| L2(uH)             | 79.342                                 | -                                    | 78.8456               |
| r2(Ω)              | 2.5634                                 | -                                    | 3.43                  |
| Rload(Ω)           | 24.2609                                | 20.6463                              | 20                    |

The fitting curves of the two algorithms are shown in figure 6. Due to the narrower resonance peak of the CPT system, the fitting results of the two algorithms are quite different from the real curve in the two peaks. If we want to improve the identification accuracy of the algorithm, we can consider adding sampling points in two peaks, but it may be that too many sampling points lead to over-fitting, and the identification accuracy of the algorithm will decrease.

By comparing the two algorithms, it can be found that for the coupled inductor, both algorithms can get accurate conclusions, while the inverse of the load resistance, the results of the two algorithms have large deviations. Therefore, it is necessary to verify the identification range of the load resistance. In the experiment, by changing the resistance of the load resistance, two kinds of algorithms are used to identify the resistance of the load resistor. The result is shown in figure 7. The result shows that if
the load resistance is in the range of 2 Ω to 200 Ω, the identification accuracy of Unconstrained-VF algorithm (calculated using equation (11)) is between 14.78% and 37.45%, but the identification accuracy of Constrained-VF algorithm is between 0.05% and 8.85%.

\[ Y(s) = \frac{a_3 s^3 + a_2 s^2 + a_1 s + a_0}{b_3 s^3 + b_2 s^2 + b_1 s + b_0} \]  

(11)

where, \( \sigma(\%) \) is the identification accuracy, \( V_{\text{fitting}} \) is the resistance value obtained by fitting, \( V_{\text{ground true}} \) is the ground true.

Figure 6. Comparison of fitting results of two kinds of parameter identification.

Figure 7. Relationship between load resistance change and identification accuracy.

5. Conclusion
CPT system have high operating frequencies and narrow resonant peaks, which makes them more sensitive to system frequencies, and system efficiency is also susceptible, which puts higher demands on system parameters. Therefore, we need to improve the parameter identification accuracy of the system to ensure efficient operation of the CPT system under weak coupling. In this paper, a parameter identification algorithm based on Vector Fitting is proposed, and the multi-parameter identification of the system is realized by combining the network parameter synthesis principle, as we called Unconstrained-VF algorithm. However, in order to ensure the applicability of the algorithm, some of the component parameters are selected as known conditions to constrain the Unconstrained-
VF algorithm, which we called it Constrained-VF algorithm. Finally, both of the above algorithm are verified for the doubled-sided LC-matching CPT circuit. The results show that the proposed algorithm can obtain higher-precision parameter identification while multi-parameter identification.

6. References

[1] A J. T. Boys and G. A. Covic, "The Inductive Power Transfer Story at the University of Auckland," IEEE Circuits and Systems Magazine, vol. 15, no. 2, May 2015, pp. 6-27, doi: 10.1109/MCAS.2015.2418972.

[2] L Pugi, A Reatti, and F Corti. "Application of modal analysis methods to the design of wireless power transfer systems," Meccanica. vol. 54, Jan. 2019, pp. 321-331, doi: 10.1007/s11012-018-00940-x.

[3] J. Dai and D. C. Ludois, "A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications," IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6017-6029, Nov. 2015, doi: 10.1109/TPEL.2015.2415253.

[4] C. Li, X. Zhao, C. Liao and L. Wang, "A graphical analysis on compensation designs of large-gap CPT systems for EV charging applications," CES Transactions on Electrical Machines and Systems, vol. 2, no. 2, pp. 232-242, June 2018, doi: 10.30941/CESTEMS.2018.00029.

[5] F. Lu, H. Zhang, H. Hofmann and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6011-6014, Nov. 2015, doi: 10.1109/TPEL.2015.2446891.

[6] C.Y. Xia, C.W. Li and J. Zhang, "Analysis of power transfer characteristic of capacitive power transfer system and inductively coupled power transfer system," 2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC), Jilin, 2011, pp. 1281-1285, doi: 10.1109/MEC.2011.6025703.

[7] H.Y. Zhang. "Load and mutual inductance identification method of ICPT system based on switching capacitors," Chongqing University, 2015. Conference on Mechatronic Science, Electric Engineering and Computer (MEC), Jilin, 2011, pp. 1281-1285, doi: 10.1109/MEC.2011.6025703.

[8] X. Dai, Y. Sun, C. Tang, Z. Wang, Y. Su and Y. Li, "Dynamic parameters identification method for inductively coupled power transfer system," 2010 IEEE International Conference on Sustainable Energy Technologies (ICSET), Kandy, 2010, pp. 1-5, doi: 10.1109/ICSET.2010.5684445.

[9] Z. Wang, Y. Li, Y. Sun, C. Tang and X. Lv, "Load Detection Model of Voltage-Fed Inductive Power Transfer System," IEEE Transactions on Power Electronics, vol. 28, no. 11, pp. 5233-5243, Nov. 2013, doi: 10.1109/TPEL.2013.2243756.

[10] C. Sanathanan and J. Koerner, "Transfer function synthesis as a ratio of two complex polynomials," IEEE Transactions on Automatic Control, vol. 8, no. 1, pp. 56-58, Jan. 1963, doi: 10.1109/TAC.1963.1105517.

[11] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by vector fitting," IEEE Transactions on Power Delivery, vol. 14, no. 3, pp. 1052-1061, July 1999, doi: 10.1109/61.772353.

[12] S.Q. Luo, F. Liu, and Z.G. Han. Principles of Network Synthesis, 2nd ed., Tongji University Press, 2009.

[13] C.H. Li. "Design of Capacitive Power Transfer System for Electric Vehicle Charging." University of Chinese Academy of Sciences, 2018.