A High-frequency Motor Model Constructed Based on Vector Fitting Method

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Abstract—**Electric drive system is a key indicator that distinguishes the electric vehicles from traditional vehicles, and it is a technical innovation of energy generation and distribution. Compared to the traditional mechanical drive system, high-voltage components such as inverter, drive-motor, battery pack are equipped in the electric drive system. During the driving, the switching behavior of power components will produce high amplitude and wide band electromagnetic interference. It is necessary to construct a system-level EMC model to predict the electromagnetic interference, and thus help the EMC engineer to optimize the system EMC design. This paper proposes a high-frequency motor modeling method, which firstly uses the vector fitting method to fit the motor impedance characteristic to a rational expression with series of pole-residue pairs, and then transfers it to a circuit model. In this paper, the high-frequency modeling of a 140kW permanent magnet synchronous motor is carried out by the above method. The accuracy of the model is verified by comparison with the test data.**

Keywords-Electric drive system; Vector fitting method;Motor modeling method;Vehcile EMC

I. INTRODUCTION

With the development of high-power drive technology, the electromagnetic compatibility problems caused by this have been exposed and attracted widespread attraction. The nonlinear characteristics of switch unit and the dynamic impedance mismatch of high-power motor load will produce transient strong EMI，harmonic interference, and surge effects. The EMI will propagate and radiate to the internal and external vehicle EM environment through harness. Conducted EMI may damage the power quality and cause malfunction, failure of the electrical equipment. Radiated EMI will badly influence the signals of onboard communication system and low-voltage control system, and affect the normal cooperative work of those systems. Due to the mechanism complexity of the EMI generation and transmission, the traditional post-test methods based on the experience and experiment could not accurately find and solve the compatible issues induced by the drive system, it is necessary to predict the EMI with the help of system-level simulation, and optimize the EMC design as early as possible in the production design cycle.

Some research groups have achieved many fruitful results of system-level simulation and EMI prediction. The Chingchi Chen team at the Ford Research Laboratory in the United State has established the equivalent circuit of switching converters, passive components, and connectors. The circuit parameters are derived from the component physical characteristics, and the parasitic circuit parameters are obtained based on the reflection measurements. Compared with the EMI test results, their circuit model has a high accuracy before 10MHz, but has a large error at frequency of 10MHz~30MHz [1]. Francois Costa team established a common mode conducted EMI model of the drive system, each unit in the drive system is presented with an S-parameter matrix and could simulate the common mode current and voltage at each unit port [2]. Idir. N team establishes a conducted electromagnetic interference model of the drive system. Each module in the system uses impedance measurement and circuit equivalent to establish its high-frequency circuit model, and combines it into a system prediction EMI model [3]. The EMC Lab of China North Vehicle Research Institute presented a novel combined simulation methods for drive system EMI prediction and achieved a good consistent with the test results [4].

In this paper, the modelling method based on the vector fitting technique will be briefly introduced at first, the common mode impedance measurement method for the permanent magnet synchronous motor will be given in the following. Then, a 140kW motor will be used as an example, whose port common mode impedance will be fitted to a circuit model using the proposed method. At last, the validity and accuracy of the circuit model will be verified by comparison with the test results.

II. HIGH-FREQUENCY CIRCUIT MODELLING BASED ON VECTOR FITTING METHOD

The frequency dependent curves of impedance coefficients can be approximated to the models with series of partial fractions in terms of real or complex conjugate pole-residue pairs by vector fitting technique [5], the rational expression is presented as follows.

$$f(s) = \sum_{n=1}^{N}\left(\frac{c_n}{s - a_n}\right) + d + sh \qquad (1)$$

The values of residue c_n and poles a_n could be real or pairs of complex conjugate. The values of d and h are constant. f(s) could be vector or scalar function.

When the above rational expression is obtained, the establishing process of corresponding basic circuit model could be divided into three parts, as shown in figure 1: 1) circuit segment for the constant term d and first term sh; 2) circuit segment when the poles and residues are real; 3) Circuit segment when the poles and residues are pairs of complex conjugate.

The values of each element shown in Figure 1 are given as follows: For the segment with constant and first term, we have

$$R = d, L = e \tag{2}$$

For the segment with real poles, we have

$$R = -\frac{r_n}{p_n}, C = \frac{1}{r_n} \tag{3}$$

For the segment with poles of complex conjugate, we have

$$\begin{aligned} C &= \frac{1}{r_n + r_{n+1}} \\ L &= \frac{1}{(p_n p_{n+1})C + (r_n p_{n+1} + r_{n+1} p_n)^2 C^3 - (p_n + p_{n+1})(r_n p_{n+1} + r_{n+1} p_n)C^2} \\ R_1 &= -(r_n p_{n+1} + r_{n+1} p_n)CL \\ R_2 &= \frac{R_1}{(p_n p_{n+1})CL - 1} \end{aligned} \tag{4}$$

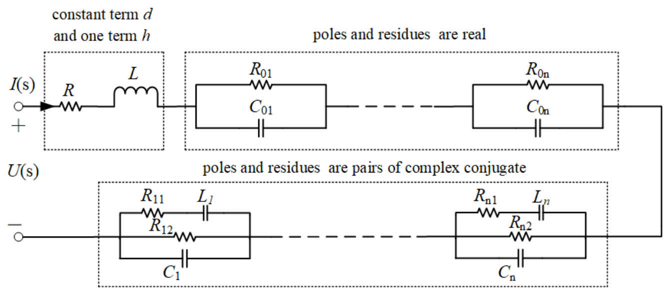


Figure 1. Basic circuit model of impedance rational function *f*(*s*)

Each sub-circuit could thus be obtained by using the above method, and will be cascaded in series to get the whole circuit model.

III. COMMON-MODE IMPEDANCE MEASUREMENT FOR PERMANENT MAGNET SYNCHRONOUS MOTOR

High-frequency modeling method considers the motor as a "black box", and only needs to measure the common-mode impedance characteristics of the motor at the three-phase AC terminals but without knowing the detailed internal structure of the motor.

It is well known that common mode interference is the main form of interference in electric drive systems, so it is necessary to establish a high-frequency common mode equivalent circuit for the motor. Before constructing the circuit, the common-mode S-parameters of the motor should be measured. Here we use network analyzer to do the test. Measurement configuration is shown in figure 2, which includes a 140kW permanent magnet synchronous motor, a network analyzer, a 15cm coaxial cable. The shield and the core wire of the coaxial cable are connected to the motor frame and the three-phase terminal parallel joint, respectively, as shown in the figure 3.

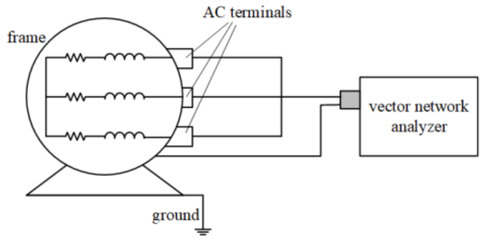


Figure 2. Test schematic of motor AC terminal S-parmameter measurement

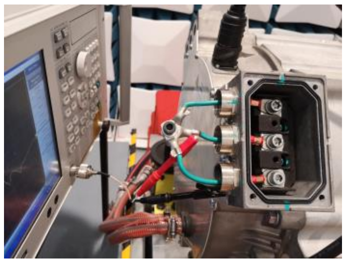


Figure 3. Test picture of motor AC terminal S-parmameter measurement

To ensure the continuity and accuracy of the sampled data, the entire sampling frequency band (100kHz~120MHz) is divided into three sub-bands 100kHz~1MHz, 1MHz~10MHz and10MHz~120MHz, there are1600 points sampled for each sub-band. The measured magnitude and angle of S-parameters are given in Figure 4.

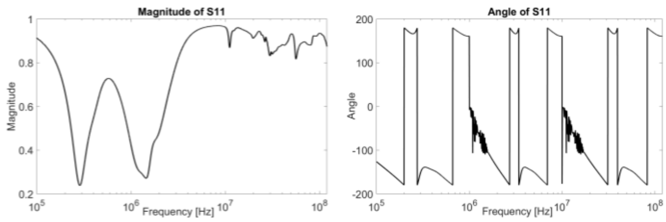


Figure 4. Magnitude (left) and angle (right) of S-parameters

The S-parameters then can be transferred to Z-parameter by using the expression below, where z_0 is 50 ohm standard load impedance. The magnitude and phase of Z-parameters are given in Figure 5.

$$Z_{in} = Z_0 \times (1 + s)/(1 - s) \tag{5}$$

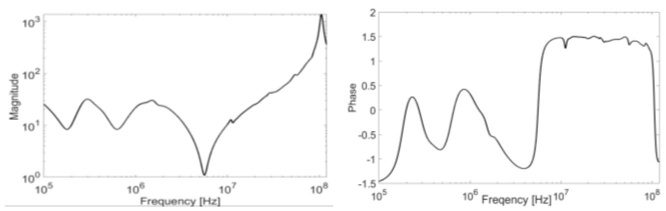


Figure 5. Magnitude (left) and angle (right) of Z-parameters

Using the vector fitting method, the common mode impedance data can be vector-fitted to the rational expression, as Eq. (1) gives. The parameter values are listed in Table 1.

TABLE I. EXTRACTED VALUES OF POLES (p_n) ,RESIDUES (r_n) , CONSTANT D AND E FOR Z-PARAMETER

n	p_n	r_n	D	E
1	-1.3326×10^4	1.9501×10^7	0	5.5575×10^{-8}
2	$-4.7878\times10^5+1.7944\times10^6 i$	$1.2878\times10^7+3.4680\times10^6 i$		

3	$-4.7878\times10^5-1.7944\times10^6i$	$1.2878\times10^7-3.4680\times10^6i$		
4	$-3.5463\times10^6+8.3762\times10^6i$	$1.0531\times10^8+3.6436\times10^7i$		
5	$-3.5463\times10^6-8.3762\times10^6i$	$1.0531\times10^8-3.6436\times10^7i$		
6	$-2.5025\times10^7+6.6675\times10^8i$	$3.3057\times10^{10}+1.1123\times10^9i$		
7	$-2.5025\times10^7-6.6675\times10^8i$	$3.3057\times10^{10}-1.1123\times10^9i$		

According to the rational parameters in Table 1, the corresponding motor circuit can be derived by the method introduced in Part II and can be presented as below:

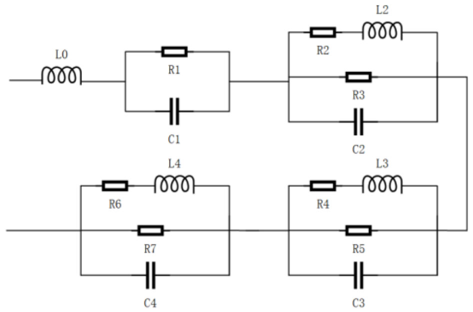


Figure 6. Ciruit model of motor fitted by vector fitting method

The parameter values for each circuit element are listed in Table 2.

TABLE II. CIRCUIT VALUES OF MOTOR MODEL

element values of constant and first terms	L_0 (H)			
	5.5575×10^{-8}			
element values of real poles terms	R_1 (Ω)		C_1 (F)	
	1.4634×10^3		5.1278×10^{-8}	
element values of complex conjugate terms	$R_{2\text{-}4}$ (Ω)	$R_{5\text{-}7}$ (Ω)	$L_{2,3,4}$ (H)	$C_{2,3,4}$(F)
	-0.0332	32.6838	7.4582×10^{-6}	3.8825×10^{-8}
	26.7736	0.3847	2.6811×10^{-6}	4.7478×10^{-9}
	1.7380	1393	1.4855×10^{-7}	1.5125×10^{-11}

IV. SIMULATION RESULT AND DISCUSSION

The amplitude and phase of the motor high-frequency impedance characteristic measurement and the fitting curve are shown in the figure below. The solid blue line represents the measured value and the red dotted line represents the fitted value. It can be seen that the measured and fitting values of the equivalent circuit agree well at each frequency point. It should be noted that some circuit parameters in Table II have negative values, which is impossible for a real circuit. In fact, the parameters of the components in the equivalent circuit calculated by the vector fitting method have no specific meaning and need to be regarded as a whole. The negative value in the simulation circuit can be performed by adding a corresponding controlled source or directly set negative values for the elements.

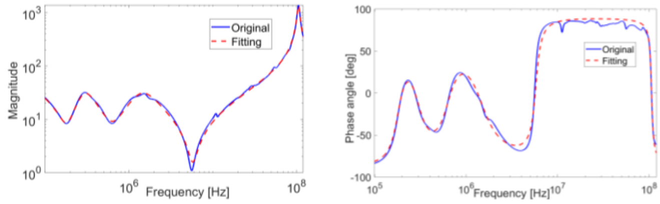


Figure 7. Comparsion between measured and fitting results

The equivalent circuit (see Figure 8) was also simulated to verify the accuracy and convergence of the proposed model. Two sets of sources were used as inputs. One is an 1A AC source, it can be seen that the impedance characteristics of the circuit are consistent with the motor characteristics, as shown in Figure 9. The other is the time domain common mode interference source (see Figure 10), which is measured from a real electric drive system by oscilloscope. This source is used to verify the convergence of the circuit (See Figure 11).

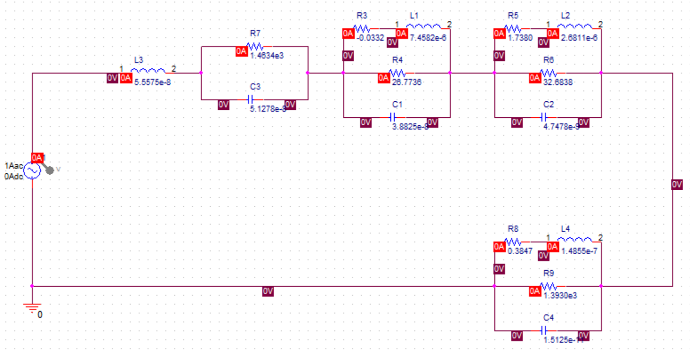


Figure 8. Screenshot of the simualtion model

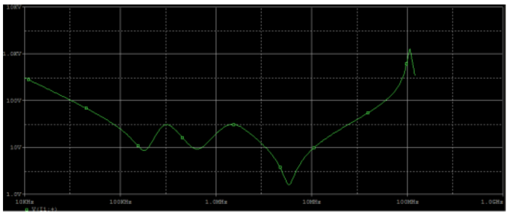


Figure 9. Simulated voltage characteristic when excited by 1A input

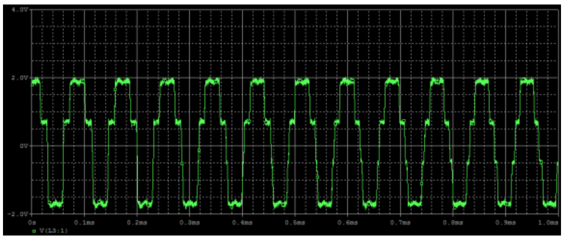


Figure 10. the common mode EMI voltage as circuit input

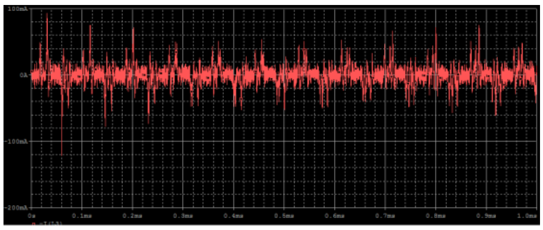
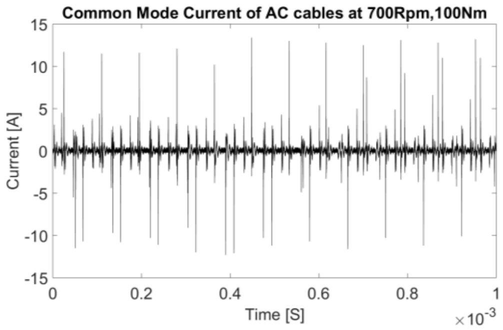
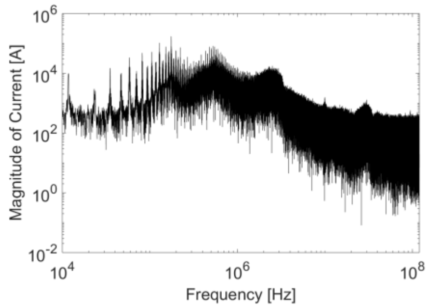


Figure 11. convergence of the circuit validation

The motor impedance characteristic during operation was also measured for comparison. The measured currents in time and frequency domain are given in Figure 12(a) and (b), respectively, and the voltages in time and frequency domain are in Figure 13(a) and (b). Then the load impedance during dynamic operation could be calculated by dividing the voltage by the current, which can be seen in Figure 14. Compared the dynamic impedance with the stable one, below 400kHz, the static motor impedance is about 10 times lower than the dynamic motor impedance.

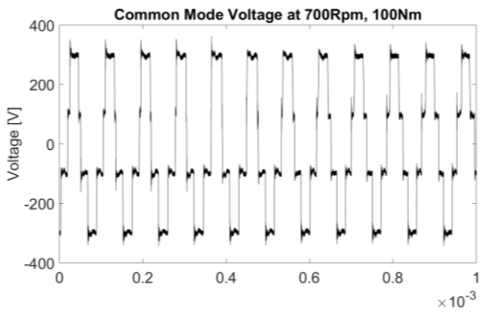


(a)

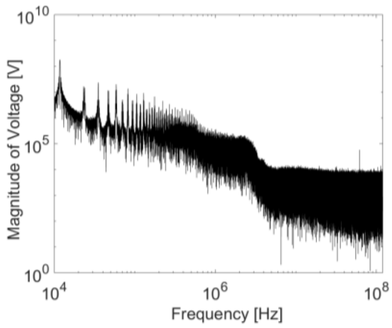


(b)

Figure 12. measured current results: (a) time domain; (b) frequency domain



(a)



(b)

Figure 13. measured voltage results: (a) time domain; (b) frequency domain

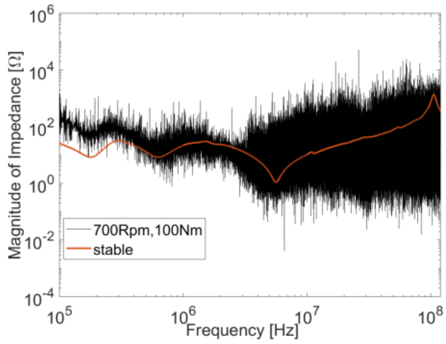


Figure 13. comparison of static and dynamic motor impedance

V. CONCLUSIONS

This paper proposes a motor modeling method based on vector fitting method, and tests and analyzes the difference between static impedance and dynamic impedance of the motor. By using this method to mathematically model a 140kW motor, the effectiveness and accuracy of the method are verified. The method does not need to know the detailed internal structural characteristics of the motor, and can help the electromagnetic compatibility engineer to quickly establish the whole electric drive system model by cascading the motor model with other module circuits of the high-power electric drive system, and help to effectively predict the electromagnetic interference of the system.

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