

Characteristics of an Axial-flux Permanent Magnet Synchronous Machine with Contra-rotating Rotors under Unbalanced Load Condition from 3-D Finite Element Analysis

Yichang Zhong, Shoudao Huang, *Senior Member, IEEE*, Derong Luo, Xuan Wu

Abstract— During recent years, the axial-flux PMSM with contra-rotating rotors has become a hot topic in academic research due to its high efficiency and simple structure. However, its back-EMF may be distorted under the condition of different angular positions. This paper investigates characteristics of the novel motor used for contra-propeller driving. Considering the torque ripple and current oscillation under unbalanced load condition, this paper analyzes the distorted back-EMF of the machine when its two rotors get different angular positions during rotating. The analysis results are validated by transient-magnetic 3-D FEA method, which the 3-D FEA software is used to model this motor and transient simulations are carried out to obtain its magnetic characteristic and main performances. A main focus is put on the back-EMF characteristic with different angular positions between the two rotors. Furthermore, the characteristic of torque production under unbalanced load is investigated. Finally, a prototype motor is fabricated to validate the analyses of this paper.

Index Terms— 3-D finite element analysis (FEM), back electromagnetic force (back-EMF), contra-rotating rotors, permanent magnet machines.

I. INTRODUCTION

CONTRA-ROTATING propellers (CRP) comprise two propellers settled coaxially and operated in an opposite direction. When used for ship propulsion, the CRP can recover energy from the circumferential flow of its main propeller. It has been demonstrated that the efficiency of the system can be raised up 15% [1] when a CRP is installed. Moreover, the CRP

allows canceling of rotational torque produced by a single propeller, thus can also be applied to torpedoes, among other under water vehicles, to prevent spinning and keep stability. A novel axial-flux permanent magnet synchronous machine (PMSM) with contra-rotating rotors is proposed in [1]-[2], which is designed exclusively for direct driving of a CRP. Also, a radial-flux PMSM with contra-rotating rotors is presented in [3]-[7], which is the same as the former in principle. The most salient feature of such a machine is the only one set of three phase windings and a single inverter. However, it is exactly this feature that poses a challenge for control of it due to its different characteristics from conventional PMSM. With regard to the control of a PMSM with contra-rotating rotors, few literatures can be found to the present. In the research of these novel motors [8]-[13], Zhao et al. discussed the significant performance of higher torque (power) density and efficiency via sample quasi-2D or 3-D FEM (finite element analysis) method. Unfortunately, there are no discussion and analysis of the effect of the two rotor positions on the back EMF and torque production. Given the great advantages in term of cost, weight and efficiency of this type of machine, Cheng et al. [14] designed a small-scale axial-flux prototype machine and implemented its control using a dynamic master-slave control strategy. It was found that the torque ripple and current oscillation would rise during the tests under unbalanced load condition, and it was also found that the main reason accounted for the problem was that the back-EMF (back electromagnetic force) superimposed by the two rotors was distorted not only in amplitude but also in phase angle, due to misalign of the two rotors under unbalanced load in [14]. Hence, this paper presents an investigation into the characteristics of the back-EMF and torque production of the axial-flux PMSM with contra-rotating rotors under unbalanced load. Related research can only be found in [15]-[16], which investigated a radial-flux PMSM with contra-rotating rotors and analyzed the mutual effects of the two rotors through the common stator based on 2-D FEA (finite element analysis). The results suggested that the peak value of the back-EMF in the stator winding is related to the relative position of the two rotors.

As the limited test equipment, the total back-EMF superimposed by the two rotors, between which a certain

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position difference is kept during rotating, can't be obtained as expected. Since the 3-D FEA method is an effective tool to simulate the characteristics of a machine precisely and thoroughly, the analysis of this paper is based on it.

In this paper, section II will analyze how the distorted back-EMF affects three phase currents of an axial-flux PMSM with contra-rotating rotors under unbalanced load condition. Section III will present a 3-D FEA model and a transient magnetic analysis will be carried out to simulate the unbalanced load operation. In this section, the characteristic of back-EMF in the stator winding and torque production of the two rotors will be obtained. Section IV will draw a conclusion of this paper.

II. MACHINE AND ANALYSIS

A. Machine Principle

The machine investigated in this paper is characterized by that two permanent magnet (PM) rotors shares a common single stator, which employs a special toroidal winding and allows an anti-rotational electromagnetic field to be formed at the both sides of it. A 1/16 3-D model of the machine and a winding diagram of one pole are represented in Fig. 1(a) and (b). As can be seen, the winding is wounded toroidally on the stator core in such manner that a pair of rotating field in opposite direction can be formed at dual annular air gaps of the stator when a symmetric current is commanded in the stator winding. The detailed description regarding the machine's principle can refer to [1]. When the three-phase symmetrical currents are supplied to the toroidal stator windings, the opposite rotating magnetic fields can be generated at the both sides of the stator. The two rotating fields separately interact with respective rotor flux to develop the opposite electromagnetic torques which drive the both rotors rotate. In order to keep two rotors synchronous, a master-slave motor control method is adopted to control the motor[14]. That is to say, the rotor with large load should be selected as the main rotor, and the other rotor with lighter load should rotate and follow the main rotor to ensure the synchronization of the two rotors. Two machine prototypes have been fabricated, as shown in Fig. 1(c) and (d). One can see that two rotor axes in Fig. 1(c) protrude from the same side of the machine in a concentric way, whereas the rotor axes protrude from corresponding side of each rotor in Fig. 1(d). The prototype in Fig. 1(c) is similar to the machine presented in [1], which is designed here to simulate a real CRP system. The prototype in Fig. 1(d) has the same characteristic with in Fig. 1(c). It is built because that its structure is convenient for load testing.

B. Analysis for back-EMF Distortion

Under the unbalanced load torque, the two rotors get different angular position, which leads to a different phase angle of the back-EMF produced by each rotor. The back-EMF in the stator winding is a superposition of back-EMF produced by the two rotors, as the studied machine can be treated as two conventional PMSM connected in series[14]-[15]. Assuming that a waveform of the back-EMF produced by one rotor is

sinusoidal, the total back-EMF can be expressed as

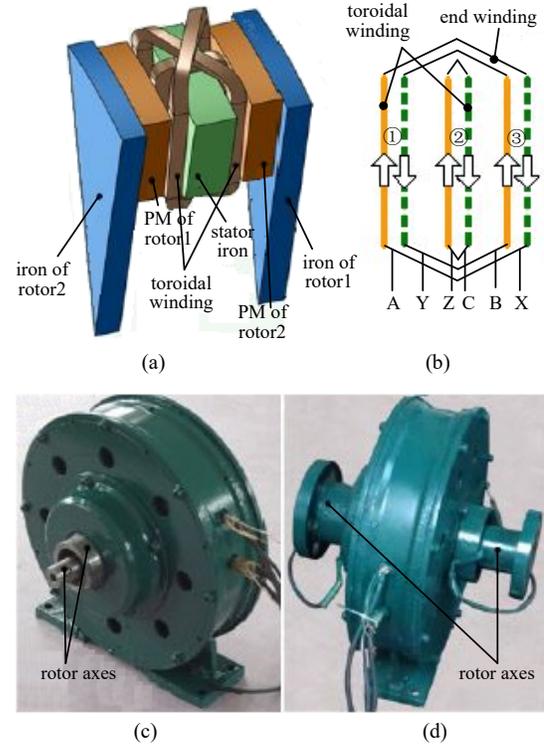


Fig. 1 Machine model and prototype machine.(a) 1/16 3-D model of the machine. (b) winding diagram of one pole. (c) prototype machine1. (d) prototype machine2.

$$e_{tot} = e_{rot1} + e_{rot2} = k_{e1} \cos(\omega t + \varphi_1) + k_{e2} \cos(\omega t + \varphi_2) \quad (1)$$

where e_{tot} is the total back-EMF in the stator winding; e_{rot1} and e_{rot2} are the back-EMF produced by the rotor1 and rotor2, respectively; Likewise, k_{e1} and k_{e2} are the back-EMF constants, and φ_1 and φ_2 are the phase angles; ω is angular speed of the rotors, which is regarded the same for the two rotors in steady state. Given that the phase angle of e_{rot2} leads that of e_{rot1} by 90° , then the correlation among e_{tot} , e_{rot1} , and e_{rot2} is represented in Fig. 2. It can be seen that, with different rotor angular positions, i.e., different phase angles, the total back-EMF e'_{tot} is not in accordance with the total back-EMF e_{tot} obtained with equal angular positions. The differences are both in phase angle and in amplitude. The total back-EMF can then be expressed as

$$e_{tot} = k_e \cos(\omega t + \varphi) \quad (2)$$

where the back-EMF constant k_e and phase angle vary with the difference of angular position between the two rotors.

In [14], an Id=0 vector control strategy is adopted. Assuming that the material of the stator core is linear, in dq-axes reference frame (d-axes is aligned with rotor flux), the model of the machine with contra-rotating rotors takes same forms as the conventional Permanent Magnet Synchronous Machine (PMSM). The voltage equations in dq-axis reference frame can be given by

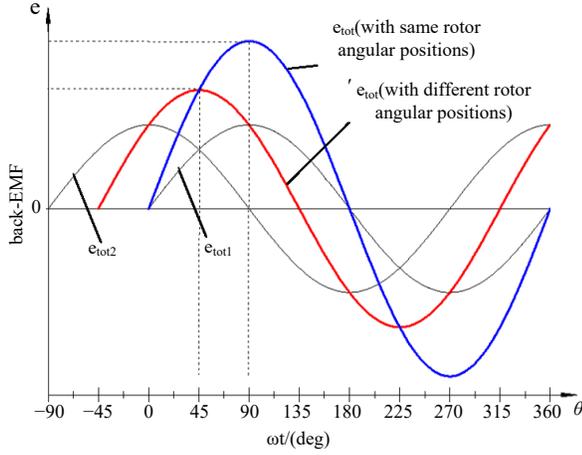


Fig. 2. Comparison of sinusoidal back-EMF with different angular positions of the two rotors.

$$u_d = 2R_s i_d + 2L \frac{di_d}{dt} - Li_q (\omega_1 + \omega_2) \quad (3)$$

$$u_q = 2R_s i_q + 2L \frac{di_q}{dt} + Li_d (\omega_1 + \omega_2) + k_e (\omega_1 + \omega_2) \quad (4)$$

where u_d and u_q are the dq-axis voltages, i_d and i_q are the dq-axis currents, respectively. The subscript 1 or 2 indicates whether the quantify corresponds to dq1 reference frame (for the rotor 1) or dq2 reference frame (for the rotor 2). where k_e is the PM flux linkage, ω_1 and ω_2 are the rotating angle speeds of the two rotors. R_s is the stator winding resistance, and L is the stator inductance. It can be seen from (3) that the d-axis component of the back-EMF, which contributes to the u_d , is zero and the back-EMF constant is changeless. Obviously, the variation in back-EMF discussed above had not been taken into consideration in (3). By considering the variation in back-EMF, the voltage equations above are replaced by

$$\begin{cases} u_d = 2R_s i_d + 2L \frac{di_d}{dt} - Li_q (\omega_1 + \omega_2) \\ \quad + k_e (\omega_1 + \omega_2) \cos(90^\circ - \delta) \\ u_q = 2R_s i_q + 2L \frac{di_q}{dt} + Li_d (\omega_1 + \omega_2) \\ \quad + k_e (\omega_1 + \omega_2) \cos(\delta) \end{cases} \quad (5)$$

where δ is an angle by which one back-EMF leads the other. Equation (5) reveals that the back-EMF has contributed to both the u_d and u_q because of the variation. Therefore, variation in the back-EMF would lead to the incomplete decoupling of the three-phase currents, thereby distorting the current and affecting the torque performance. It is a key reason for the detriment of control.

III. 3-D FEA VALIDATION

A load test bench for the machine investigated in this paper had been built during the control experiments in [14], which is shown in Fig. 3. The test bench employs two generators settled at two sides of the machine to simulate the loads. Each

generator is standalone and the load torque is exerted via manipulating consoles of the generators manually. Obviously, it is impossible to drive the two rotors of the prototype machine synchronously via the generators, to obtain the total back-EMF. Fortunately, the transient-magnetic 3-D FEA method provides a good solution to this problem.

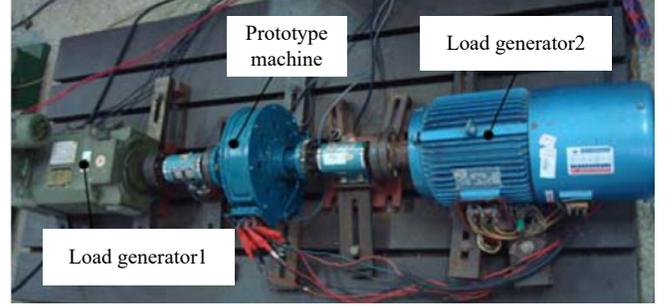


Fig. 3. Load test bench for the prototype machine.

A 3-D FEA model of the axial-flux PMSM with the same specification of the prototype machine is established. The parameters of the prototype machine are listed in Table 1. To the author's knowledge, it is the first experience to analyze a PMSM with contra-rotors using a 3-D FEA method. The key problem here is that there are two motional parts with opposite direction during the transient-magnetic analysis. Hence, it is important to consider a competent electromagnetic FEM software package to perform such an analysis. Considering the periodicity and symmetry, only a 1/16 part of the machine needs to be modeled and analyzed. To achieve a good precision, 600000 or more 2nd order elements may be needed.

TABLE I
CHARACTERISTICS OF THE AXIAL-FLUX PMSM
WITH CONTRA-ROTATING ROTORS

Parameter	Quantity
specified speed (r/min)	500
nominal frequency (Hz)	80
nominal torque (Nm)	21
peak of Back-EMF (V)	100
number of poles	16
air gap flux density (T)	0.5
inner diameter of stator core (mm)	156
outer diameter of stator core (mm)	240
thickness of stator core (mm)	12
thickness of permanent magnet (mm)	8
turns-in-series per-phase	480
number of coils	48

A. Comparison of 3-D FEA and Experiment

To obtain the characteristics of the total back-EMF in the stator winding, the FEA model is first set to a generator, in which the speeds of the two rotors are fixed at the rated value and no current flow in the winding due to an infinite series resistor in each phase. Fig. 4(a) and (b) represent the flux vector distribution of a quarter of the machine model on two occasions during the transient-magnetic analysis. Therein, Fig. 4(a) represents an occasion when the flux path of the two rotors is in parallel through the common stator core. On the contrary, in Fig. 4(b), the flux path on the stator core is in series.

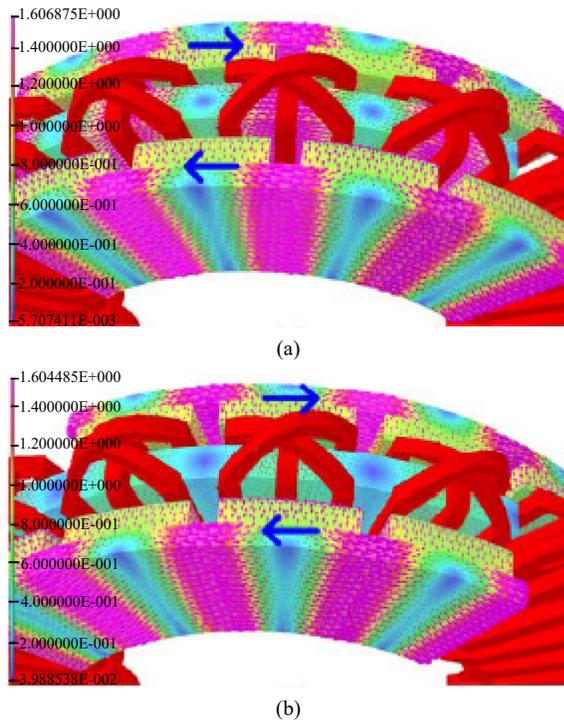


Fig. 4. Flux vector distribution on two occasions. (a) parallel flux path of the two rotors. (b) series flux path of the two rotors

Fig. 5(a) represents a waveform of three-phase back-EMF, which is obtained when the two rotors keep the same angular position all the time during rotating. As is shown in Fig. 5(a), the peak values of the three-phase back-EMF are unequal. Among them, the phase A's gets the maximum (101V) and the phase C's minimum (99V). The difference is caused by the different end length of the three-phase windings.

To verify the correctness of the FEA results, the half back-EMF of the prototype machine has been obtained via setting one of the load generators to rotate at the rated speed, as shown in Fig. 3. Fig. 5(b) shows its waveform. It can be seen that the waveform in Fig. 5(a) is in accordance with the one shown in Fig. 5(b) except its amplitude. The amplitude in Fig. 5(a) is about the twice of the one in Fig. 5(b). Also, the difference in the peak value caused by the different end winding can be observed in the experimental result.

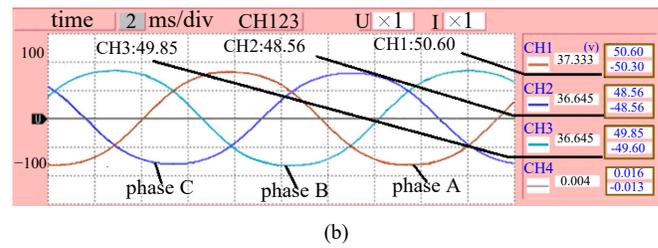
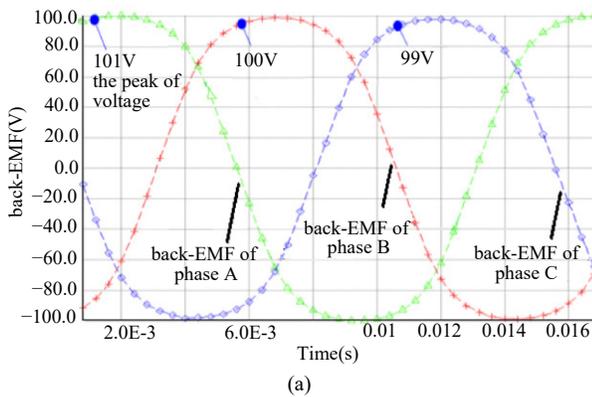
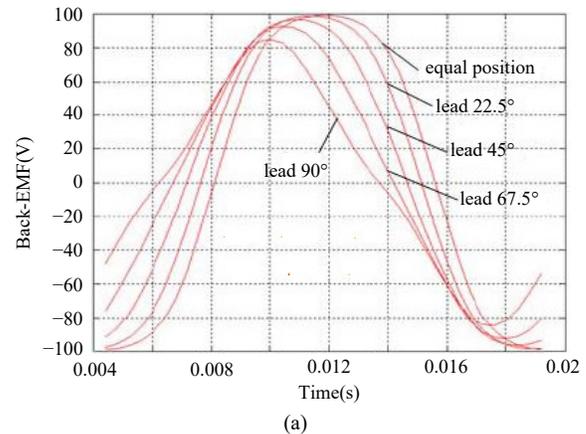


Fig. 5 Comparison of back-EMF between FEA and experiment. (a) total back-EMF from FEA at rated speed. (b) half back-EMF from experiment at rated speed.

B. Characteristic of back-EMF

As described in section II, the back-EMF constant and the phase angle of the total back-EMF vary with position difference between the two rotors. To acquire the relationship of the amplitude and phase angle vs. rotor position difference, the transient-magnetic analyses of the 3-D FEA model with different rotor position arrangement are performed here. Fig.6(a) represents the total back-EMF waveforms with one rotor position leading the other by 0° , 22.5° , 45° , 67.5° and 90° in electric angle, respectively. As can be seen, the waveform is distorted under different rotor positions, especially in 90° electric angle. To clarify the variation of the back-EMF in each case, a FFT analysis for each waveform is performed, as shown in Fig. 6(b) and Fig. 6(c). Fig. 6(b) compared the fundamental component of each back-EMF and Fig. 6(c) gave out the harmonic comparison. From the results, one can find that the amplitude of fundamental waveform decreases with an increasing leading angle. Whereas, phase angle of the fundamental waveform advances following the leading rotor. There is significant 3rd order harmonic with maximum value 10V or so in the back-EMF in each case. The big 3rd order harmonic found in the case of one rotor leading the other 0° is caused by the non-sinusoidal back-EMF produced by a rotor. Fig. 6(d) further illustrates the relationship of the amplitude and phase angle vs. position difference. Through the results obtained, the EMF constant k_e and δ angle in (4) can be taken into account. Thereby, a better control performance of the machine can be expected.



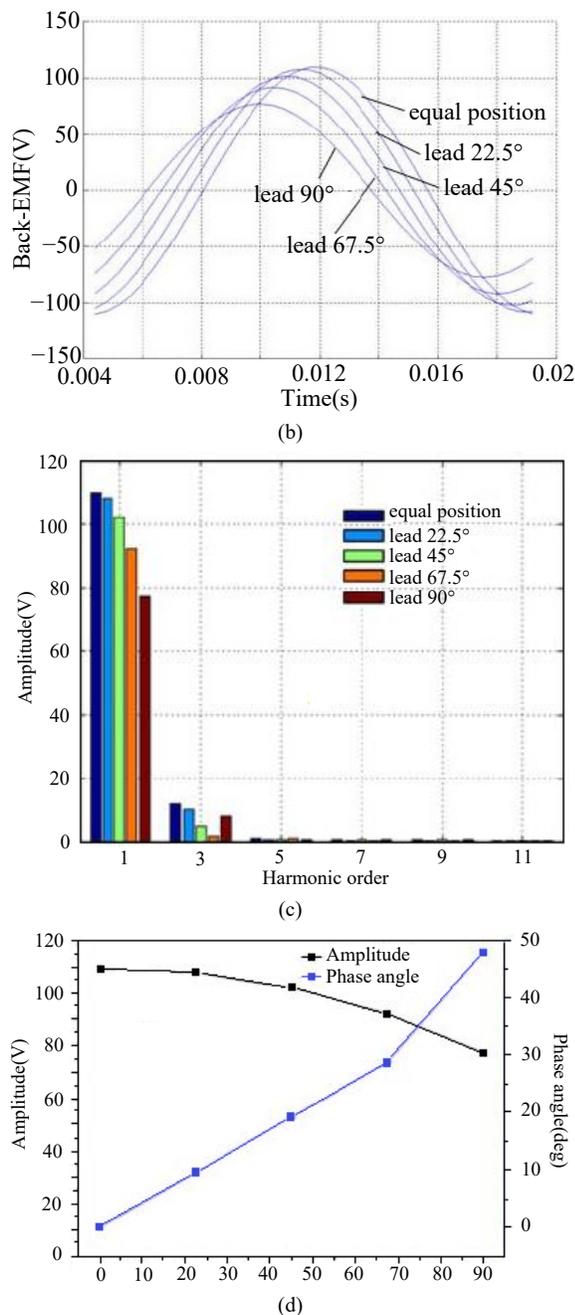


Fig. 6. Characteristic of back-EMF from FEA with different arrangements of rotor positions. (a) back-EMF waveforms. (b) fundamental component of the back-EMF waveforms. (c) comparison of harmonics. (d) relationship of the amplitude and phase angle vs. rotor position difference.

C. Characteristic of Torque Production

To obtain the characteristic of torque production on the two rotors, three-phase sinusoidal currents are assigned to the stator windings of the FEA model. The electromagnetic torque produced on the two rotors in the cases as above, i.e., one rotor position leading the other by 0, 22.5, 45, 67.5 and 90 deg, respectively, is investigated through the transient-magnetic 3-D FEA. In these cases, the phase angle of the currents is set to such a value that the rotor with lagging position produces a maximum torque. As is shown in Fig. 7, the torque on the leading rotor decreases as the leading angle gets bigger and its value approaches to zero when the leading angle approaches to

90 deg. This conforms to the principle of torque production, i.e., the torque changes with value of angle between rotor flux linkage and current vector sinusoidally. As shown in the lower part of Fig. 7, the torques of the lagging rotors are almost the same in each case.

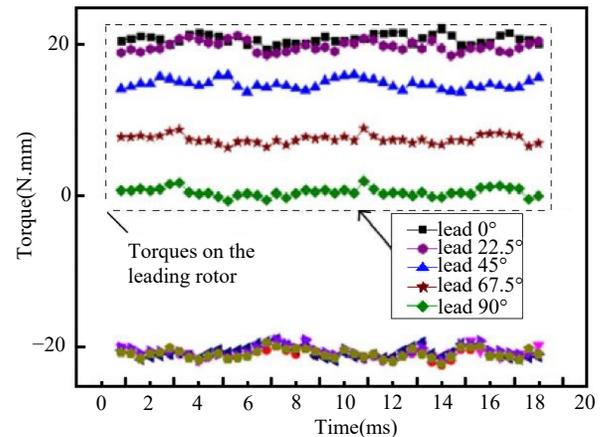


Fig.7. Characteristic of torque production from transient-magnetic 3-D FEA.

IV. CONCLUSION

Axial-flux PMSM with contra-rotating rotors is a novel and special machine, for which, the test and control are complex and cumbersome. Aiming at the current oscillation and torque ripple, this paper utilizes a 3-D FEA tool to obtain the characteristics of the back-EMF and torque production of such a machine. From the 3-D FEA, the theoretical analyses are validated and the relationship of the amplitude and phase angle vs. position difference regarding the total back-EMF produced by the two rotors is obtained. From those analyses, it can be drawn a conclusion that the difference of two permanent magnet rotors' position, amplitude and phase of motor back EMF waveforms are distorted, amplitude with position difference increases with phase difference increases gradually. The offset of the total back-EMF phase is one of the results of the torque ripple of the motor, so the results of this paper provide a reference for the improvement of the torque ripple of the motor. The work done in this paper lays a foundation for better control of this kind of machine.

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