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Elucidation of the Cause of Positive and Negative Asymmetric Torque Generation of Self-Excited Wound-Field Synchronous Motor Utilizing Space Harmonics

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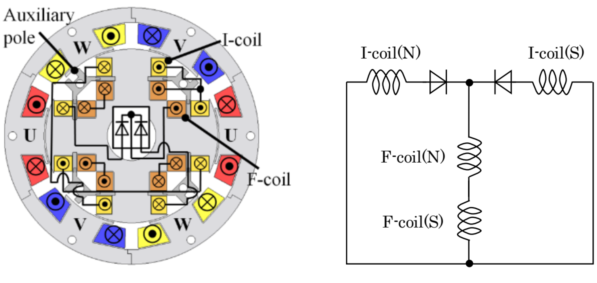
***Abstract*—This paper describes the cause of the asymmetric torque at powering and regeneration of self-excited wound-field synchronous motor in which space harmonic flux is utilized to induce the rotor field current instead of the flux by the permanent magnets. The principle of induction motor torque generation which is considered as cause of asymmetrical torque, and the experimental method to identify the cause of the induction motor torque generation is discussed. In addition, Experimental results using prototype motor revealed that the cause of the asymmetric torque at powering and regeneration is the induction motor torque.**

Keywords*— synchronous motor; field-oriented control; voltage equation; self-excited; space harmonics; rare-earth free.

I. Introduction

An Interior permanent magnet synchronous motor (IPMSM) with high efficiency and high-power density characteristics contributes greatly to high performance of HEV· EV and further demand is expected in the future. Neodymium is used as a material for the permanent magnet which in the IPMSM, and costly rare-earth metals such as Dysprosium and Terbium are added to permanent magnet for mitigating demagnetization caused by the temperature rise.

The self-excited winding field synchronous motor (SE-WFSM) which utilizes the secondary space harmonic generated by the concentrated winding stator as an electromotive power source to induce the field current has been proposed as one of the rare-earth-free motor [1]-[9].



(a) Structure of stator and rotor. (b) Rotor circuit diagram.

Fig. 1. Structure of the SE-WFSM.

SE-WFSM has a structure as shown in Fig. 1. The electromotive force is induced in the rotor induction winding (I-coil) by the space harmonic magnetic flux generated from the concentrated winding stator. Generated AC current due to electromotive force is full-wave rectified through the diode, DC current is passed through the field winding (F-coil) and the field magnetic flux is established in the rotor. Torque is generated by a combination of the field flux torque due to the field magnetic flux and the reluctance torque caused by the salient pole structure of the rotor.

The essential consideration on motor control is not sufficient for SE-WFSM. The authors propose the mathematical model in which the voltage equation of a general synchronous motor is extended based on the operation principle of SE-WFSM from the viewpoint of torque control as a fundamental study of motor control. Moreover, the authors have proposed the experimentally method of identifying motor parameters in the mathematical model and confirmed its effectiveness by actual system verification using a prototype motor, and have advanced modeling necessary for control [10]-[11].

The torque output of the SE-WFSM, an asymmetric torque at power regeneration was recognized, which cannot be explained by the proposed mathematical model so far.

In this paper, we explain the principle of generating induction motor torque inevitably occurring in SE-WFSM considered to be a factor of asymmetric torque, and then show the verification method by experiment. Finally, by verifying by experiment using the prototype motor, to clarify that the cause of the positive and negative asymmetric torque is the induction motor torque.

II. Motor Mathematical Model and Torque Estimation Method

The voltage equation of SE-WFSM expressed on d-q coordinates is shown in (1). Since only the static state is considered in parameter identification, the time derivative term is ignored and only the fundamental flux wave is considered.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R & -\omega_r \cdot L_q(\omega_r, i_m) \\ \omega_r \cdot L_d(\omega_r, i_m) & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_r \cdot \Psi_f(\omega_r, i_d, i_q) \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1)$$

$$\Psi_f(\omega_r, i_d, i_q) = k_s(I_f) \cdot M_m \cdot I_f(\omega_r, i_d, i_q) \quad (2)$$

$$i_m = \sqrt{i_d^2 + i_q^2} \quad (3)$$

Here, L_d and L_q are the d-q axis inductance, Ψ_f is the flux linkage due to the field, and Im is the magnitude of the stator winding current, which are defined by (2) and (3). Also, $k_s(I_f)$ is saturation coefficient, M_m is mutual inductance between the field winding and the stator winding, $I_f\ (\omega_r, i_d, i_q)$ is field winding current. Representative parameters are shown in Table 1. Each parameter is experimentally acquired according to [10].

The torque in the voltage equation model expressed by (1) is shown in (4).

$$\tau_m = P_n\{\Psi_f(\omega_r, i_d, i_q) + (L_d(\omega_r, i_m) - L_q(\omega_r, i_m)) \cdot i_d\} \cdot i_q \quad (4)$$

Fig. 2 shows the results of torque estimation using (4) and the measured torque using a torque sensor. When comparing the estimated value with the measured value by the model, In the regeneration region with the current phase angle of 180 to 360 [degrees] with reference to the d-axis direction, the measured value and the measured value are in agreement. However, in the powering region with the current phase angle 0 to 180 [degrees] with reference to the d-axis direction, the measured value and the measured value are divergent.

Focusing on the measured values, the maximum regenerative torque is about 12% larger than the maximum powering torque. Furthermore, when the current phase angle 0 [degrees], no magnet torque is generated in the theoretical torque equation and reluctance torque should not be output, however when looking at the measured torque, the torque in the negative direction is generated. From the above results, it is shown that the SE-WFSM prototype motor outputs powering and regenerative asymmetric torque characteristics which cannot be explained by the voltage equation so far.

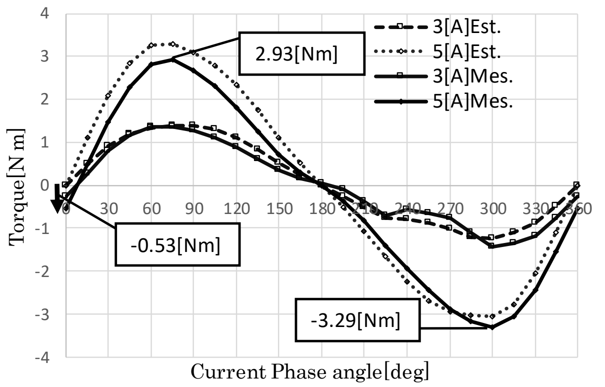


Fig. 2. estimated torque and measured torque.

TABLE I. TYPICAL VALUES OF PROTOTYPE MOTOR.

L_d	38.6[mH] (2000rpm, 5A)
L_q	28.6[mH] (2000rpm, 5A)
Ψ_f	0.318[V/rad/s] (2000rpm, 5A)
M_m	175[mH]

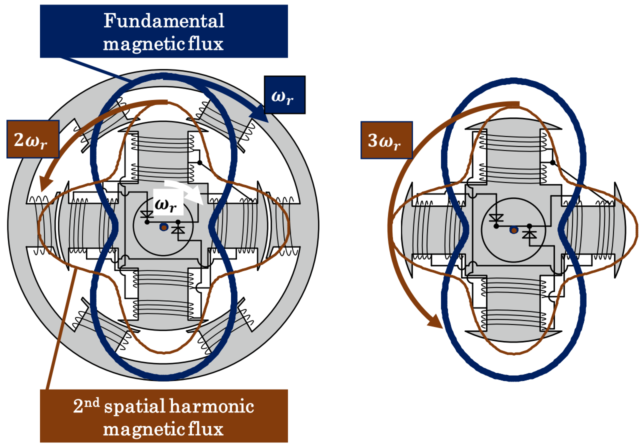
III. GENERATION PRINCIPLE OF INDUCTION MOTOR TORQUE AND VERIFICATION METHOD

A. Position Relationship of Spatial Harmonic Magnetic Field

Considering the magnetic flux space distribution generated from the concentrated winding stator, it can be approximated to the spatial fundamental magnetic flux shown by the bold line and the second spatial harmonic magnetic flux shown by the solid line as shown in Fig. 3 (a). The magnitude of the secondary space harmonic flux is 50% of the spatial fundamental magnetic flux.

Since field-oriented control is performed, when the rotor rotates at the angular velocity of ω_r, the spatial fundamental flux also rotates at the angular velocity of ω_r in synchronization with the rotor. On the other hand, the secondary spatial harmonic magnetic flux is reversely rotated at an angular velocity of $2\omega_r$ asynchronously with the rotor.

When looking at the above phenomenon in the rotor coordinate system, the spatial fundamental magnetic flux is kept at a constant current phase angle with the electromagnet magnetic flux as shown in Fig. 3 (b), and the second spatial harmonic flux is asynchronously rotating at the angular velocity of $-3\omega_r$.



(a) Observed in fixed system of coordinates.

(b) Observed in rotating system of coordinates.

Fig. 3. Structure of the SE-WFSM.

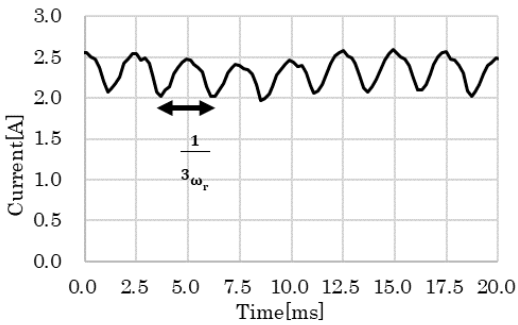


Fig. 4. Pulsating current waveform of rotor coil.

B. *Principle of Induction Motor Torque Generation*

Spatial harmonic fluxes interlink with the rotor windings, electromotive force is generated, and the AC current is full-wave rectified by the diode to become a DC current. As shown in Fig. 4, this full-wave rectified DC current contains a pulsation with the angular frequency $3\omega_r$. The regenerative torque is generated by the vector product of this pulsating current and the space harmonic magnetic flux. Considering in the coordinate system synchronized with the pulsating current of angular frequency $3\omega_r$, it can be seen that slip is always operating as an induction machine of -1. This phenomenon is called induction machine torque in SE-WFSM in this paper.

C. *Verification Method of Induction Motor Torque by Experiment*

In order to verify experimentally that the induction motor torque is generated, consider a method of extracting induction motor torque during field-oriented control.

First, in order to eliminate the electromagnet torque, both ends of the diode winding of the rotor winding are short-circuited so that only the pulsating current flows through the rotor winding. At this time, the SE-WFSM is operated at a constant speed by using a load motor while performing field-oriented control. By the above operation, it is possible to generate the same spatial harmonic flux distribution as in SE-WFSM operation, so the induction motor torque in the SE-WFSM and the reluctance torque due to the salient pole structure of the rotor iron core can be measured. Since the reluctance torque can be measured by the reluctance torque separately by measuring the torque while the rotor winding is open-circuited, the generation of the induction motor torque is confirmed by calculating the difference between them.

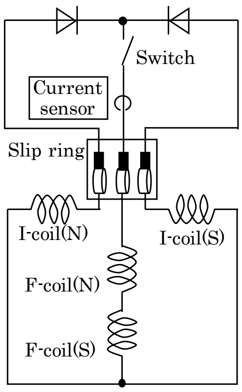


Fig. 5. Modified rotor circuit diagram.

TABLE II. SPECIFICATIONS OF PROTOTYPE MOTOR.

Number of slots/poles	6/4
Motor size	ϕ125[mm]×80[mm]
Maximum speed	2000[rpm]
Maximum stator current	5[A]
Stator winding resistance	2.0[Ω/phase]
Induction-coil resistance	1.1[Ω/coil]
Field-coil resistance	1.1[Ω/coil]

Furthermore, by measuring the magnitude of the ripple of the rotor current when operating with the original connection of the SE-WFSM motor and the torque at the current phase angle 0 [degrees], by showing the correlation between the ripple current and the negative direction torque, verify that the pulsation with angular frequency $3\omega_r$ contributes to the generation of asymmetric torque.

IV. EXPERIMENTAL VERIFICATION

A. *Experiment Configuration*

The parameters of the prototype motor are shown in Table 2, and the structure is shown in Fig. 1 (a). In order to measure the current flowing through the rotor circuit, the prototype motor draws the diode originally included as shown in Fig. 5 outside the motor through the slip ring. The connection diagram when the winding field circuit is short-circuited is shown in Table 3 state A, the connection diagram in circuit open state is shown in Table 3 state B, and the original connection diagram of SE-WFSM is shown in Table 3 state C. Regarding the parameters, the values experimentally acquired in [10] were used. Typical values are shown in Table 1.

The prototype motor is connected to a load motor (2.2 [kW] induction motor) via a torque meter (UNIPULSE UTM II). For the control, the digital control system (Myway Plus PE-Expert 4) is used, prototype motor is field-oriented controlled using the

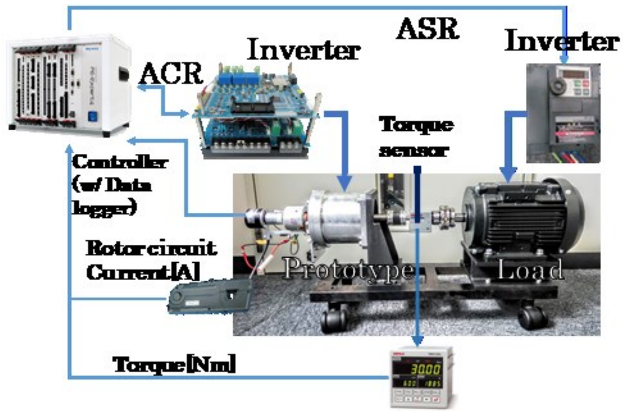


Fig. 6. Experimental system.

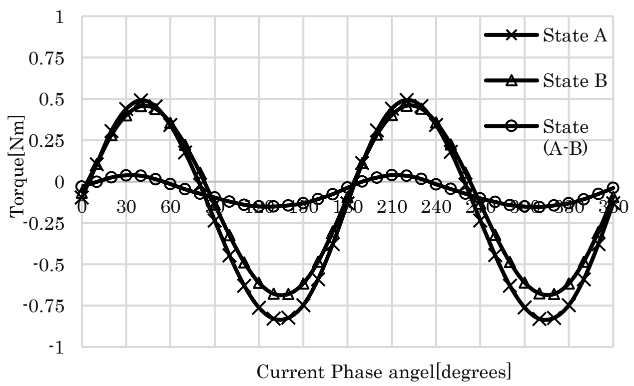
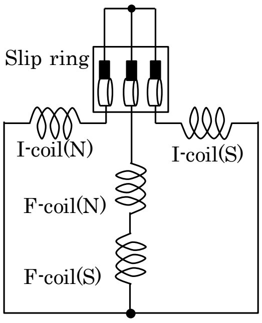
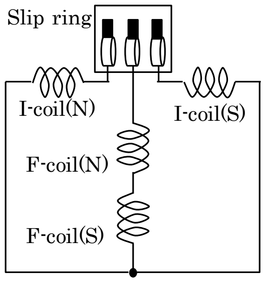
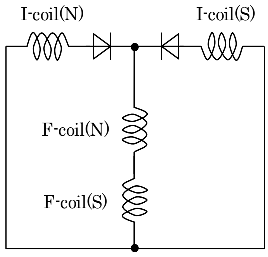
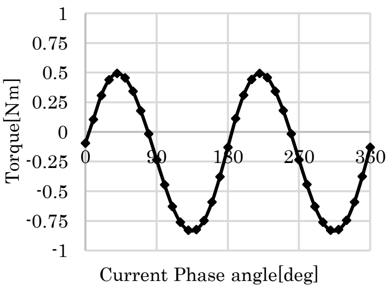
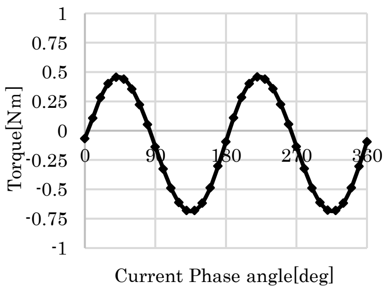
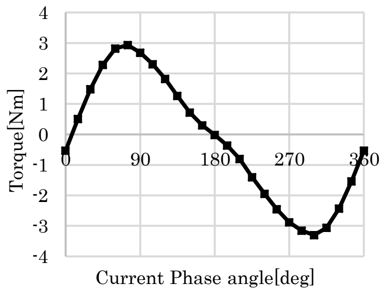


Fig. 7. Result of subtraction of induction motor torque.

TABLE III. ROTOR CIRCUIT CONNECTION DIAGRAM AND EXPERIMENTAL RESULTS.

State.	A. short-circuited state.	B. open-circuited state.	C. SE-WFSM state.
Circuit diagram.			
Types of torque.	・Reluctance torque ・Induction motor torque	・Reluctance torque	・Electromagnet torque ・Reluctance torque ・Induction motor torque
Measured torque.			

inverter (Myway MWINV-5R022) and the angle sensor, the load motor is a general-purpose inverter (Toshiba VF- S15) and speed control by slip frequency control using the rotation speed sensor.

B. Experimental Results and Discussion

Table 3 shows the measured torque in the short-circuited state, the open-circuited state, and the SE-WFSM state. The

rotation speed is constant at 2000 [rpm], the stator winding current command value is constant at 5 [A], and the horizontal axis is the current phase angle with reference to the d-axis direction.

Fig. 7 shows the result of subtracting the torque in the open-circuited state from the short-circuited torque. As shown in the figure, each torques output different torques, and this difference is the induction motor torque.

Fig. 8 shows the relationship between the magnitude of the pulsation of the current flowing through the rotor winding and the number of revolutions measured by the SE-WFSM state. It is understood that the pulsation increases as the rotation speed increases.

Fig. 9 shows the result of comparing the magnitude of the pulsating current of the rotor winding in the SE-WFSM state with the magnitude of the torque at the current phase angle of 0[degrees] based on the d-axis. There is the negative correlation

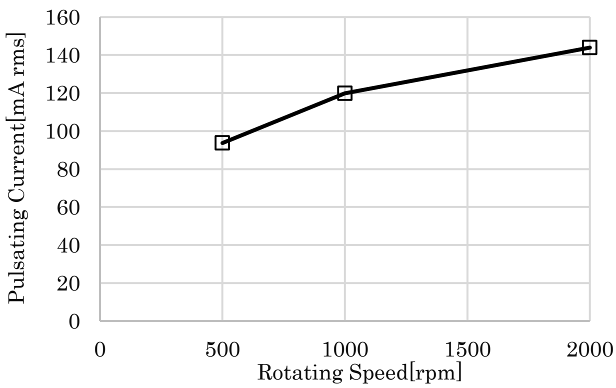


Fig. 8. Relationship between pulsating current and rotational speed.

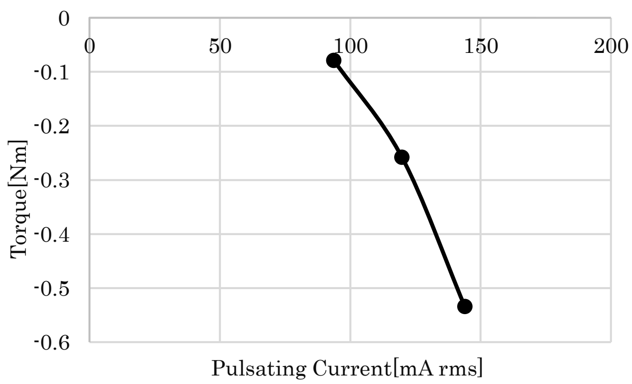


Fig. 9. Relationship between pulsating current and negative direction torque.

between the pulsating current of the rotor winding and the negative direction torque. This indicates that the current pulsation of the rotor winding is responsible for the generation of the induction torque.

V. Conclusion

This paper presented the experimental method to identify the cause of the asymmetric torque at powering and regeneration of SE-WFSM, which cannot be explained by the proposed mathematical model so far. Experimental results using prototype motor revealed that the cause of the asymmetric torque at powering and regeneration is the induction motor torque.

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