Proposal and Operation Characteristics of Novel Consequent-Pole Permanent Magnet Motor

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Abstract. A novel consequent-pole permanent magnet (PM) motor is proposed in the paper, which has an image pole pair for every pole pair of N and S. The three-phase synchronous impedances of the motor are balanced owing to the rotor configuration. In addition, it is possible to carry out field weakening with less d-axis current, which leads to a highly efficient operation in a high-speed range. This paper describes a basic principle and its operation characteristics of the newly proposed consequent-pole PM motor.

1. Introduction

Research and development aiming at operation range enlargement of the permanent magnet (PM) motor are intensively promoted in recent years. The PM motor can be designed to generate a higher torque in a low-speed range by increasing the electromotive force (e.m.f.) with high-energy-density PMs such as NdFeB and SmCo. In principle, however, it is impossible to design the PM motor to achieve both the high-speed operation and the high-torque generation at low-speeds at the same time; hence field weakening techniques are widely introduced to suppress the e.m.f. in the high-speed operation range[1][2][3][4][5]. Field weakening techniques are carried out by flowing a negative d-axis current to counteract the PM magnetic flux and suppress the e.m.f. generation. The copper loss is produced by the negative d-axis current lead to degrade efficiency of the PM motors. Therefore, it is desired that a novel configuration of the PM motor is capable of operating field weakening techniques with less d-axis currents. In order to make it possible to reduce the d-axis current, a novel geometry of the PM motor that can increase the d-axis inductance is indispensable because more counter magnetic flux against the PM magnetic flux can be easily generated with the less d-axis current.

(a) Proposed motor.   (b) Winding connection of proposed motor.
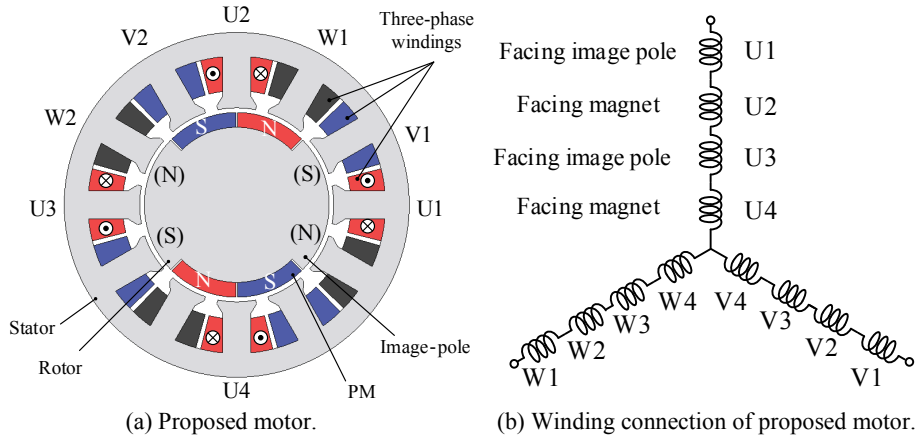
Fig. 1. Proposed motor model.

In this paper, a novel consequent pole PM motor is proposed, which form a unique alignment of the PMs rather different from a conventional consequent-pole PM motor. The proposed motor has an image pole pair per one pair of N and S PM poles on the rotor. There are three important features about the proposed motor. The first, three-phase synchronous impedance is balanced. The second, the e.m.f. of the winding on the real PM pole sides offset the e.m.f. of the winding on the image pole sides in field weakening operation. The third, the d-axis inductance is increased. Therefore, the field weakening operation is efficiently carried out with the less d-axis current. The above advantages make it possible to expand the whole operation range and to improve the operation efficiency. In the paper, basic operation characteristics of the proposed consequent pole PM motor are discussed, compared with a standard surface PM (SPM) motor and a conventional consequent pole PM motor.

2. Configuration and Operating Principle

Figure 1 shows the proposed consequent pole PM motor model. The proposed motor is composed of equivalent eight-pole (four real PM poles and four image poles) and 12 slot concentrated winging structure, which make it possible to downsize the motor. The real PM pole pairs are mounted on the rotor and the image pole pairs are formed between the real PM pole pairs. This configuration is rather different from conventional consequent pole PM motors, and this unique configuration gives the following advantages. Focusing on the U-phase winding , for example, two tooth of the twelve are always facing with the real PM pole pairs, while the other two tooth are always on the image pole pairs, i.e., iron core parts. This feature is same in the V-phase and the W-phase, which cannot be expected in the conventional consequent pole PM motors. Therefore, the magnetic circuit of the rotor iron core is necessarily imbalance, but the impedance of the stator windings can be balanced if the two windings on the real PM pole sides and the other two windings on the image pole sides are connected in series. The three-phase balanced windings do not affect on the motor current control in spite of the imbalance rotor magnetic circuit and give the freedom of magnetic circuit design of the image pole pair parts on the rotor.

Field weakening operation of the proposed motor is different from a conventional PM motor, which decreases the PM magnetic flux by producing a demagnetizing field for the PM. Field weakening operation of the proposed motor is performed by offsetting the e.m.f. of the winding on the real PM pole sides and the winding on the image pole sides.

The proposed motor has a high inductance value because it has lower magnetic flux due to the half amount of the PM and the higher amount of the rotor iron than standard SPM motors. The e.m.f. of the motor is expressed as (1)

$$V_0 = \omega\sqrt{\left(\Psi_a + L_d i_d\right)^2 + \left(L_q i_q\right)^2}$$

(1)

Therefore, the electromagnetic torque of the motor is lower in a low-speed range, but the efficient high-speed operation can be expected because it requires reduced negative d-axis current owing to the lower magnetic flux of the field PM and the higher inductance value of the stator windings.

3. Operation Characteristics of Proposed Motor

3.1. Comparison of No-Load Electromotive Force

The proposed motor compared with a standard surface PM (SPM) motor and a conventional consequent pole PM motor by using an electromagnetic analysis software JMAG-Designer 18.0™. Fig. 1 shows the proposed motor model, Fig. 2 shows SPM motor and a conventional consequent pole PM motor model, of which detailed specifications are listed in TABLE I. As for these motors, the motor size is equivalent, but the rotor structure is different. The proposed motor and the conventional consequent pole PM motor is composed of equivalent eight-pole (four real PM poles and four image poles), but the SPM motor is composed of eight real PM pole. Thus the PM of the SPM motor is double of the consequent pole PM motors.
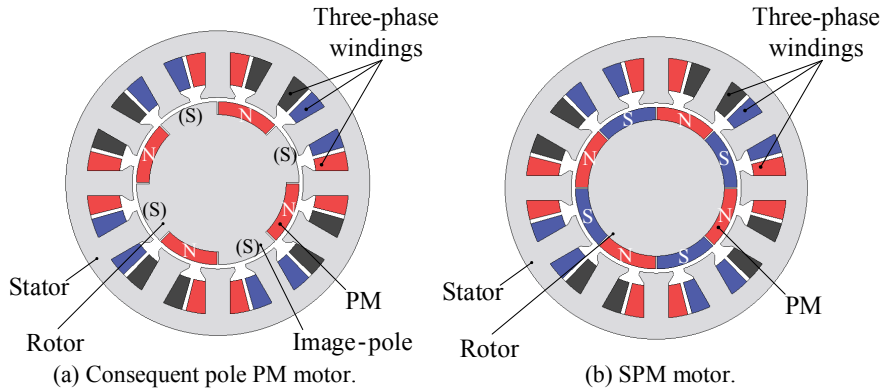

(a) Consequent pole PM motor.　　　　　　(b) SPM motor.

Fig. 2. Comparison motor models.

TABLE I. Motor specifications.

	Proposed PM motor	Consequent pole PM motor	SPM motor
Stator diameter	80 mm	←	←
Rotor diameter	42.85 mm	←	←
Stack length	37 mm	←	←
Air gap length	1.045 mm	←	←
Number of poles	8 (PM:4, Image pole:4)	8 (PM:4, Imagepole:4)	8
Number of slots	12	←	←
Number of turns	16	←	←
PM volume	7.672 cc	7.672 cc	15.344 cc
Armature winding connection	4-series star connection	←	←
PM type	NMX-43SH	←	←

Figure 3 shows the no-load e.m.f. waveforms of the U-phase and their FFT analysis results when the three models rotated at 600 r/min. The e.m.f. amplitude of the proposed motor is half of the SPM motor because the PM volume is 50 % of the SPM motor's. Therefore, the proposed motor can extend the high-speed operation range. The proposed motor is lower e.m.f. amplitude and has a lot of fundamental component in the e.m.f. waveform, compared with the conventional consequent pole PM motor. The proposed motor is suitable for the high-speed operation with field weakening control.

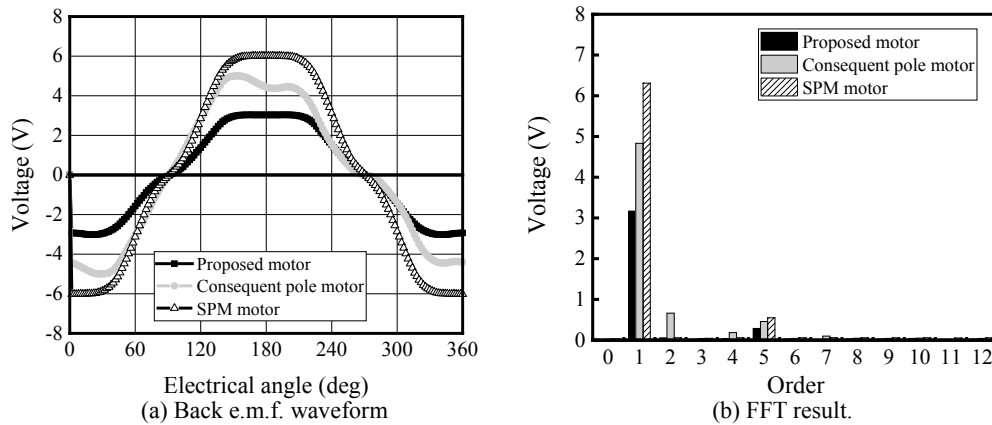(a) Back e.m.f. waveform   (b) FFT result.

Fig. 3. Comparison of back e.m.f. and FFT analysis results.

3.2. Comparison of Inductance

Figure 4 shows variations of the d-axis and the q-axis inductances of the three models when the current phase angle β is changed under the constant current amplitude (20 A). As the current phase angle β increase, the d-axis and q-axis inductance is increased because the amounts of both axis magnetic flux are reduced.

The d-axis inductance of the proposed motor is highest among these motors, and it is larger than the SPM motor by approximately 45 %. The q-axis inductance of the conventional consequent pole PM motor is highest among these motors. The minimum d-axis and q-axis inductance is SPM motor. Any types of the consequent pole PM motor have high inductance value because they are a high proportion of iron in the rotor cores and the reluctance of the magnetic circuit is small. Since the proposed motor has the largest d-axis inductance, the back e.m.f. can be reduced with less negative d-axis current during field weakening control.

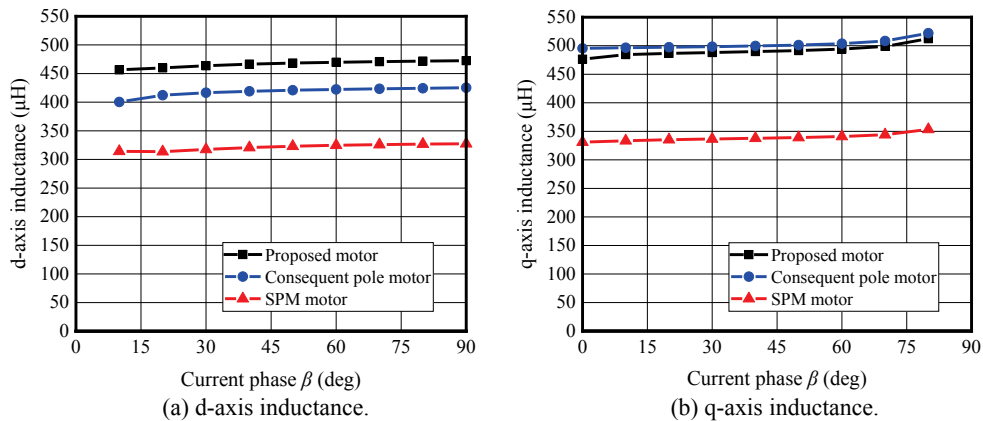(a) d-axis inductance.   (b) q-axis inductance.

Fig. 4. Comparison of inductance.

3.3. Harmonics Comparison of Magnetic Flux

Harmonic components of the magnetic flux has been compared among the three motors. Only the d-axis current is supplied to the motor, and the current amplitude is 20 A . The electromagnetic analysis has been conducted under an assumption of the ideal iron rotor using the PMs replaced with air. Figure 5 shows the magnetic flux linkages of the U-phase and their FFT analysis results of the three motors. The FFT result of the SPM motor includes only the fundamental component, because the permeance variation is hardly caused. In the conventional consequent pole PM motor, the permeance variations is caused by the image poles and PMs on the rotor surface: thus resulting in the even-order harmonic components of the magnetic flux linkage. However, the proposed motor is not affected by the permeance variation because one U-phase winding is facing with the real PM pole while the other U-phase winding is on the image pole side: hence the even-order harmonic components are not seen in the magnetic flux linkage to the U-phase winding.

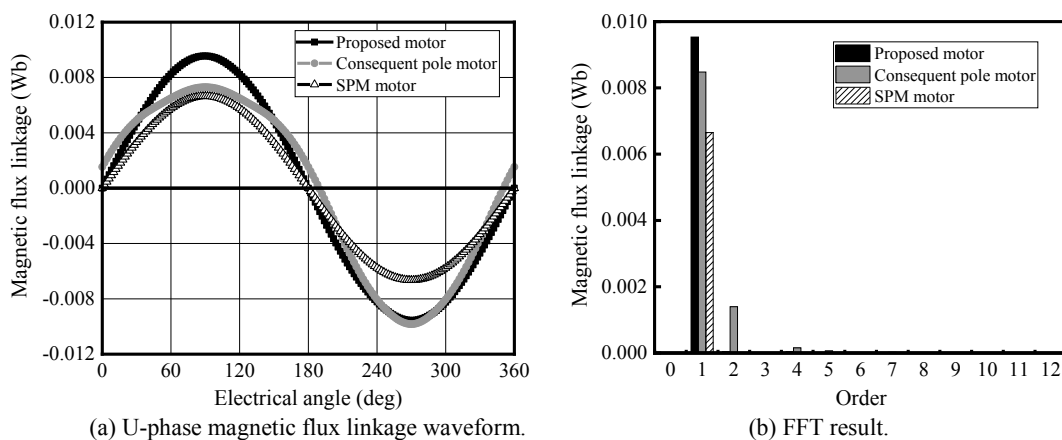(a) U-phase magnetic flux linkage waveform. (b) FFT result.

Fig. 5. Comparison of U-phase magnetic flux linkage.

3.4. Comparison of N-T Characteristics

The N-T characteristics of the three motors at maximum output power are indicated in Fig. 6. The test conditions are 12-V DC bus voltage, the maximum current amplitude of 20 A, and the maximum magnetomotive force (m.m.f.) of 1280 AT.

The SPM motor can deliver high torque in low-speed range due to the no-load e.m.f. is highest among these motors. On the other hand, the proposed motor can operate widely in high-speed range. The proposed motor can expand the high-speed range by field weakening control due to the motor has a low-coefficient of the e.m.f. and the large d-axis inductance of the proposed motor cause the counter e.m.f., which is high enough to cancel the PMs' e.m.f. The N-T characteristic of the conventional consequent pole PM motor is equivalent to that of the SPM motor in high-speed range. This is because the e.m.f. includes even-order harmonic components when the field weakening control is applied to the conventional consequent pole PM motor.

As described above, it has been found that the proposed motor has the largest high-speed operation range with the least negative d-axis current; thus the field weakening operation can efficiently be achieved among the three motors.

4. Conclusion

A novel consequent pole PM motor has been proposed, and its operating characteristics have also been investigated in the paper. The proposed motor has a unique rotor configuration where the real PM pole pairs and the image pole pairs are placed every other pole pair. The image pole pairs are constituted on the iron core parts next to the real surface PMs on the rotor. One of the most important features of the proposed motor is high-speed operation capability with less field weakening current

(negative d-axis current); thus efficient expansion of the high-speed operation range is possible without increasing copper loss.

In the future work, the magnetic circuit of the proposed motor must be investigated because the amount of effective magnetic flux is low, which causes a lower torque in a low-speed range. In order to increase the amount of effective magnetic flux, it is required to investigate the proposed motor with flux barrier.
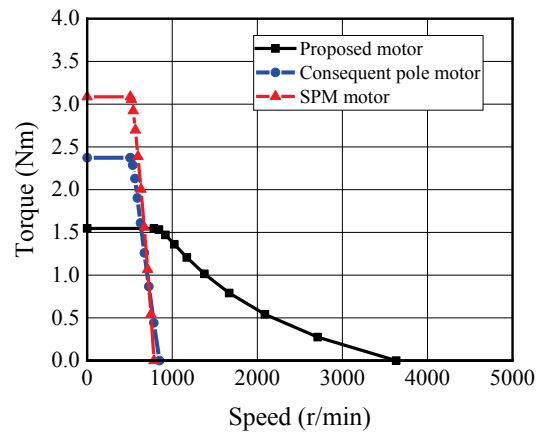

Fig. 6. Comparison of N-T Characteristics.

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