Adjustable Field PM Motor Based on Permeability Modulation Technique Using Zero-Phase Current

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***Abstract*— An adjustable field magnetic flux permanent magnet (PM) motor is proposed in this paper, which is based on a permeability modulation technique. The proposed PM motor has magnetic paths made of soft magnetic metal between the permanent magnet poles in the rotor, and a special coil for the permeability modulation of the soft magnetic metal. The proposed PM motor can control the amount of the leakage flux between the rotor permanent magnet poles by means of magnetic saturation of the soft magnetic metal, where the main magnetic flux interlinking to the stator windings is effectively reduced because the leakage flux between the permanent magnet poles is dominant. However, when the soft magnetic metal is magnetically saturated by the zero-phase magnetic flux, the leakage magnetic flux is reduced, resulting in the enhancement of the main magnetic flux to the stator. This paper demonstrates computer simulation results of the proposed strategy for the adjustable field magnetic flux PM motor.**

Keywords—3D magnetic path, permeability modulation, adjustable field, PM motor, magnetic saturation, zero-phase current

I. INTRODUCTION

Permanent magnet (PM) motors have widely been used for varieties of applications such as automotive and industry equipment. The PM motors have achieved higher power density than any other different types of motors, taking great advantage of high-energy density PM such as NdFeB. It is difficult, however, to design a particular PM motor for low-speed-high-torque applications and high-speed-low-torque applications at the same time because of the constant magnetic field caused by the PM. Therefore, a field weakening technique has been employed by a negative injecting d-axis current to the motor, but the significant copper loss increase due to the d-axis current injection can cause serious degradation of the efficiency.

In order to solve the problems described above, adjustable magnetic field PM motors are intensively discussed in recent years [1]-[5]. The refferences [1]-[4] describe techniques to adjustable operation of an air gap flux by using static magnetic field generated by a field winding. However, there are some problems about power losses of a DC/DC converter for the field windings, and other problems on higher power losses by a field winding also remain. On the other hand, the reference [5] reports a different adjustable magnetic flux technique using inverse magnetic poles generated by a second-order space harmonic component. The technique makes it possible to control the magnetic flux freely particularly in a low speed range. Furthermore, almost all the adjustable magnetic flux PM motors are hard to generate reluctance torque, so they have an essential demerit of low power density, compared with standard interior permanent magnet (IPM) motors.

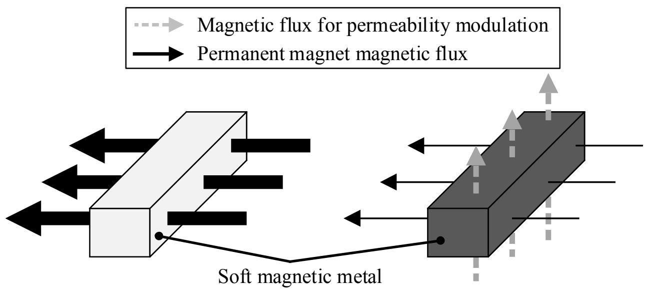
In this paper, a novel technique to achieve electromagnetically the adjustable magnetic flux PM motor is presented, which has inverse saliency to generate the reluctance torque as well as the PM torque. Some computer simulation results are demonstrated to show the performance of the proposed strategy, followed by the basic operation principle and a magnetic circuit design method of the PM motor.

II. ADJUSTABLE MAGNETIC FLUX TECHNIQUE BASED ON PERMEABILITY MODULATION

A. *Adjustable Magnetic Flux Technique of Principle Model*

Fig. 1 shows a basic principle of the permeability modulation used for adjusting the magnetic flux. As can be seen in the figure, the main magnetic flux is horizontally penetrating the soft magnetic metal, which is adjusted by the different magnetic flux for permeability modulation penetrating the soft magnetic metal vertically. By intensifying the magnetic flux for the permeability modulation, the soft magnetic metal is magnetically saturated, and its permeability is lowered, resulting in the decrease of the main magnetic flux horizontally flowing into the soft magnetic metal. Therefore, it is possible to control the main magnetic flux amount by using the different magnetic flux for the permeability modulation.

Fig. 2 illustrates an application of the permeability



(a) Without magnetic saturation. (b) With magnetic saturation.
Fig. 1. Permeability modulation principle.

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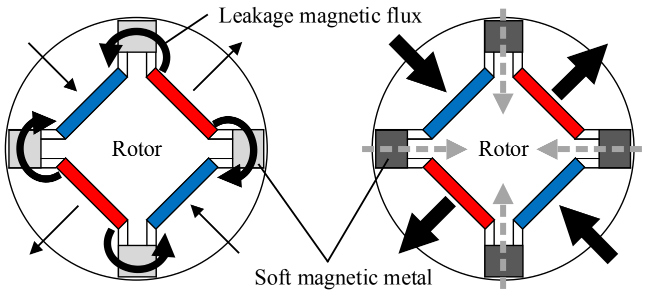
modulation described above, which makes it possible to control the leakage magnetic flux between the PM poles. The figure shows cross sections of the 4-pole IPM rotor, where the soft magnetic metal is inserted between the N poles and the S poles of the embedded PMs in the rotor. As already described, the permeability modulation of the soft magnetic metal is carried out by using the differently allocated special winding in the stator in addition to the standard three-phase windings. As shown in Fig. 2(a), when the soft magnet metal is not magnetically saturated, short circuits are caused between the PM poles of the rotor. Therefore, the main magnetic flux of the PMs hardly interlinks to the stator windings, which is equivalent to the field weakening operation. On the other hand, since the reluctance between the PM poles is increased due to the magnetic saturation of the soft magnetic metal, most part of the PM flux interlinks to the stator windings, which corresponds to the intensified field operation as illustrated in Fig. 2(b). As described above, the proposed strategy achieves the adjustable magnetic flux operation by means of permeability variation caused by the magnetic saturation of the soft magnetic metal placed between the PM poles of the rotor. Many of the adjustable magnetic flux approaches give the motor some kinds of electromagnetic energy to weaken the PM flux of the rotor as presented [1]-[5], but the proposed strategy does not energize the rotor for the field weakening operation, which is completely different from any other approaches in the past. The magnetic saturation of the soft magnetic metal is controlled by a radial direction magnetic flux, which is a DC magnetic flux and is generated by a zero-phase current. Therefore, in order to have a magnetic flux path for the permeability modulation, a three-dimensional magnetic circuit design of the motor is required.

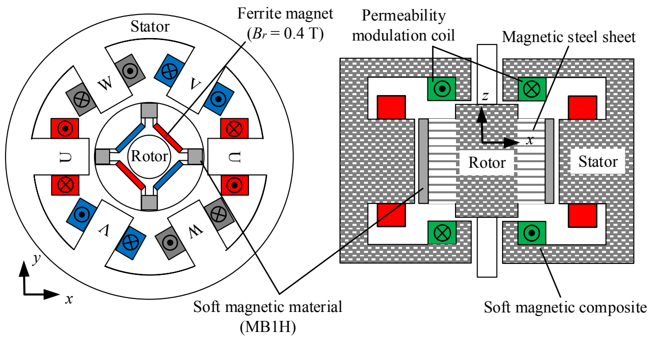
B. *Feasibility Study of Proposed Adjustable Magnetic Flux Operation*

Figure 3 shows a principle model of the adjustable magnetic flux IPM motor, which has a 4-pole and concentrated winding configuration. As can be seen in Fig. 3(b), the special winding for the permeability modulation is placed at the both ends of the stator so as to have a z-axis direction magnetic flux path. All the following electromagnetic analyses are conducted with JMAG-Designer 17.0 ™.

Figure 4 shows magnetic field intensity distribution of the soft magnetic metal when the magnetomotive force of 1800 AT is given to the permeability modulation winding. As can be seen in the figure, it is confirmed that the soft magnetic metal is entirely magnetized around 5000 A/m. Soft ferrite (JFE steel MB1H) is employed as the soft magnetic metal in this investigation. The initial relative permeability of MB1H is 1600, and its saturation magnetic flux density is 0.5 T. When the magnetic field intensity of the MB1H is 5000 A/m, its relative permeability decreases down to 80 dues to the magnetic saturation. Therefore, it is possible to vary the



(a) Without magnetic saturation. (b) With magnetic saturation.
Fig. 2. Principle of proposed motor.



(a) Cross section. (b) Axial cross section.
Fig. 3. Principle motor model.

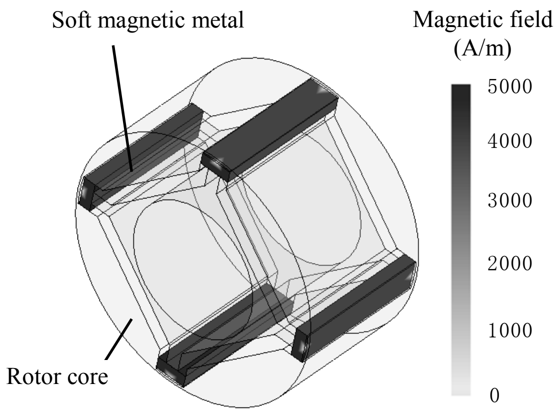
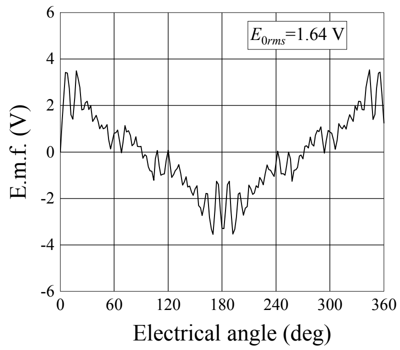
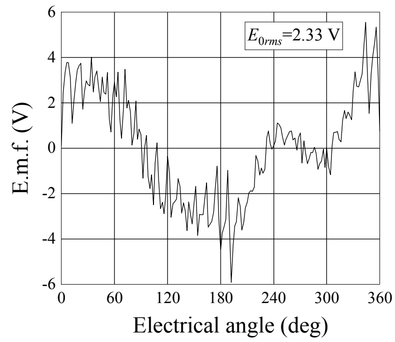


Fig. 4. Magnetic field distribution caused by permeability modulation coil.

permeability of the soft magnetic metal placed between the PM poles by using the magnetomotive force of the permeability modulation winding.

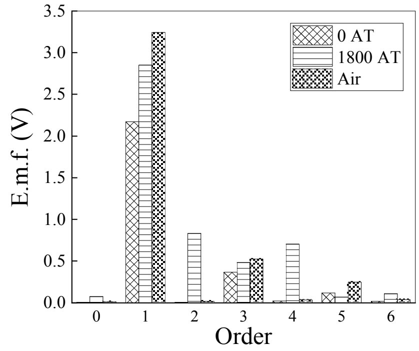


(a) Without magnetomotive force for permeability modulation.

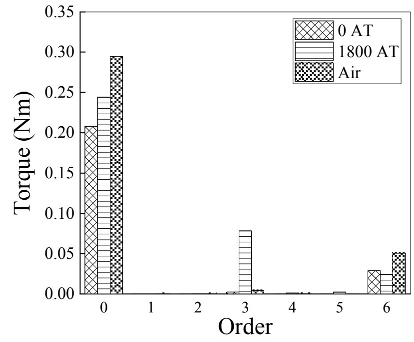


(b) With magnetomotive force for permeability modulation.

Fig. 5. No-load electromotive force waveforms.



(a) Back e.m.f.



(b) PM torque.

Fig. 6. FFT analysis results of back e.m.f. and PM torque of principle motor model.

Figure 5 shows no-load induced electromotive force (e.m.f.) waveforms at the rotating speed of 1800 r/min in the two cases of 0 AT and 1800 AT of the magnetomotive force of the permeability modulation winding. Figure 6 shows the FFT analysis results of the no-load induced e.m.f. and the electromagnetic torque when 600-AT armature magnetomotive force is given to the q-axis winding. According to Fig. 5 and Fig. 6(a), the fundamental component of the induced e.m.f. is increased by 30 % when the magnetomotive force of the permeability modulation winding is 1800 AT, compared with the 0-AT case. In addition, the average torque is also raised by 17 % as can be seen in Fig. 6(b). Hence, it is found that the magnetomotive force of the permeability modulation winding makes it possible to adjust the fundamental component of the induced e.m.f. However, even-number order harmonics are superimposed to the no-load e.m.f. as shown in Fig. 6(a). These harmonic components are caused by the DC magnetic flux used for the permeability modulation. The DC magnetic flux intensifies either N poles or S poles, and weakens the rest of the poles, which causes imbalance of the PMs like consequent pole motors. Figure 7 shows current phase angle and torque characteristics under the condition of 600-AT magnetomotive force in the stator windings. There exists the maximum torque per ampere (MTPA) operating point at the current phase angle around 30 deg., which proves that the proposed motor has the inverse saliency.

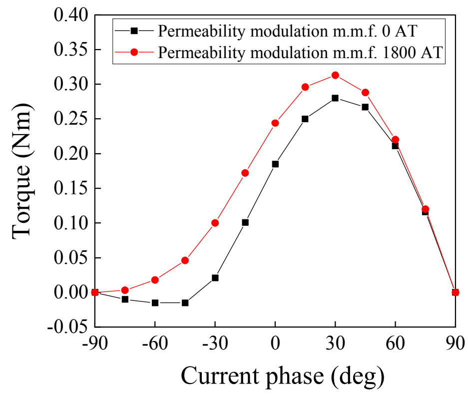


Fig. 7. Current phase-torque characteristics.

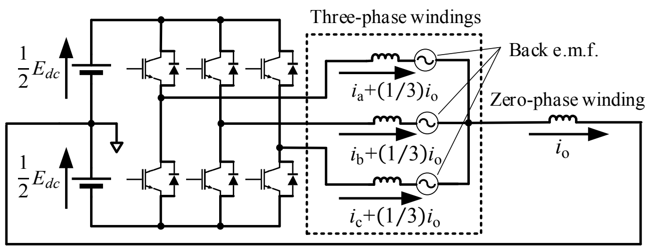
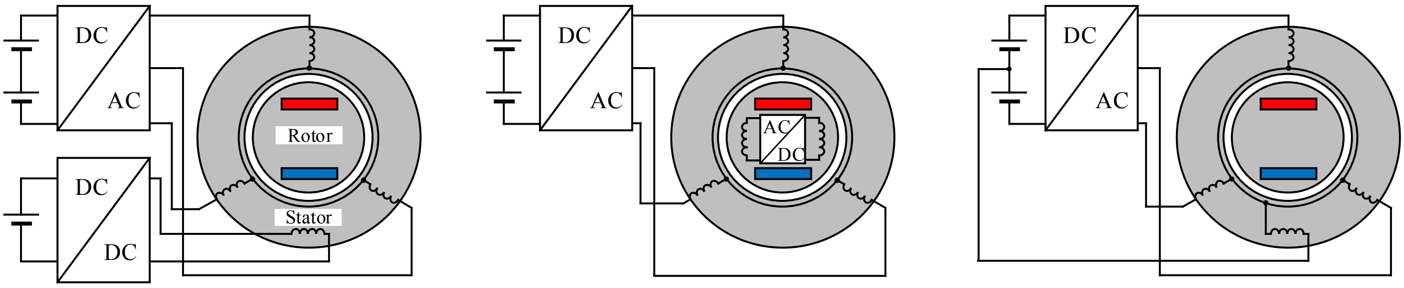


Fig. 8. Circuit configuration of proposed motor drive.



(a) Method using DC/DC converter. (b) Method using time and/or space harmonics. (c) Method using zero-phase current.

Fig. 9. Motor drive circuits.

TABLE Ⅰ. Evaluation of various motor drive circuits.

Motor drive circuits	Switching loss	Controllability	Power supply voltage utility
Method using DC/DC converter	×	○	○
Method using time and/or space harmonics	△	×	○
Method using zero-phase current	○	○	○

III. Generation of Magnetic Flux for Permeability Modularion

A. Proposed Circuit Configuration of Motor Drive

The proposed circuit configuration is depicted in Fig. 8, where the adjustable magnetic flux PM motor is connected to a three-phase full-bridge two-level inverter with 4 wires. Therefore, it is possible to control not only the three-phase currents but also the zero-phase current. Since the proposed configuration gives three-degrees of freedom of the motor current control, the zero-phase current can be controlled independently of the conventional d-axis and the q-axis currents in the vector control algorithm. The zero-phase current is utilized for the permeability modulation of the soft magnetic metal in the rotor. The voltage equation of the adjustable magnetic field PM motor is as follows:

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} (R_a + 3R_0) + 3\mathrm{p}L_0 & 0 & 0 \\ 0 & R_a + \mathrm{p}L_d & -\omega L_q \\ 0 & \omega L_d & R_a + \mathrm{p}L_q \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega \Psi_f \end{bmatrix} , \quad (1)$$

where the variables and the parameters are defined as

v_0, v_d, and v_q: voltages on the 0-d-q reference frame,

i_0, i_d, and i_q: currents on the 0-d-q reference frame,

R_a: three-phase winding resistance,

R_0: zero-phase winding resistance,

L_0, L_d, and L_q: winding inductances on the 0-d-q reference frame,

p: differential operator, and

ω: angular speed.

B. Comparison among Zero-Phase Winding Excitation Methods

Figure 9 and TABLE Ⅰ indicates 3 examples of zero-phase winding excitation methods, which are used to generate the permeability modulation magnetic flux. The table includes qualitative evaluation results from the viewpoints of switching losses, controllability, and power source voltage utility. The method to use a DC/DC converter introduced in (1)-(4) has good controllability because it can control the field magnetic flux independently of the d-axis and the q-axis currents. It also has good performance in terms of the power source voltage utility because the separate DC/DC converter can apply its voltage to the zero-phase winding regardless of the main inverter DC bus voltage. However, additional power semiconductor devices are definitely indispensable for the DC/DC converter circuit, which leads to the extra power losses such as the switching loss and the conduction loss. On the other hand, if the zero-phase winding is self-excited like (4)-(9), it is impossible to control the permeability modulation magnetic flux freely regardless of the operating points of the motor. The method is based on use of space harmonics generated by the concentrated windings of the motor, and it requires diode rectifiers on the rotor to obtain the zero-phase winding excitation. The space harmonic magnetic flux induces the e.m.f. proportional to the rotating speed, so the zero-phase current is almost proportional to the rotating speed, which implies that this method is not applicable to the proposed adjustable magnetic flux PM motor.

The proposed circuit configuration using the three-phase-four-wire system does not require extra power semiconductor devices at all, and makes it possible to control the zero-phase current independently of the d-axis and the q-axis currents. In addition, the potential level at the neutral point of the motor does not vary because the zero-phase current is DC. The zero-phase winding can be wound separately from the three-phase windings, so the number of turns can be determined regardless of the three-phase windings, which implies that the

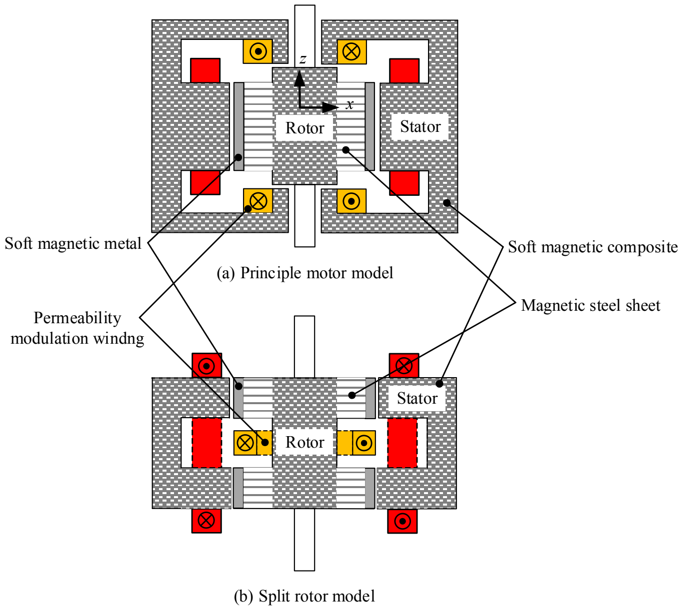
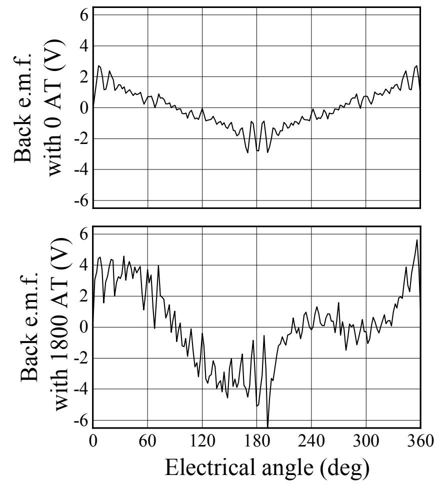
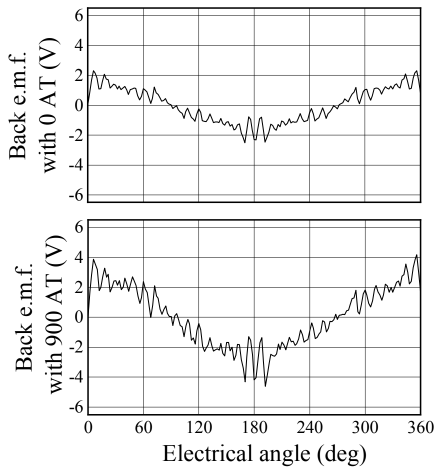


Fig. 10. Cross section of principle and split rotor models.



(a) Principle motor model.



(b) Split rotor model.

Fig. 11. Waveforms of back e.m.f.

superimposed zero-phase current onto the three-phase currents can be reduced without sacrificing the magnetomotive force.

IV. Improved Magnetic Circuit Design to Reduce Harmonics in Electromotive Force.

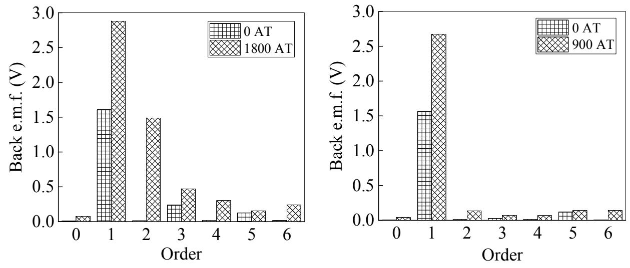
A. Split Rotor Structure and Its Magnetic Circuit Design

The principle model of the adjustable magnetic flux IPM motor has a distorted e.m.f. waveform as shown in Fig. 5, which is caused by the even-order harmonic components. In order to reduce the even-order harmonic e.m.f., the zero-phase winding to generate the permeability modulation magnetic flux is placed in the center of the stator and between the split rotor, surrounding the shaft. Fig. 10(b) illustrates the split rotor model, which has an advantage in simplification of the motor configuration. The most important merit of this approach is significant suppression of the low-order harmonic e.m.f., especially the 2nd and the 4th. For fair comparative evaluation between the principle model and the split rotor model, only the stator shape is changed, but the rotor volume, the used materials, the winding turns, the PM volume, etc. are identical with each other.

B. Performance Evaluation of Adjustable Magnetic Flux Operation

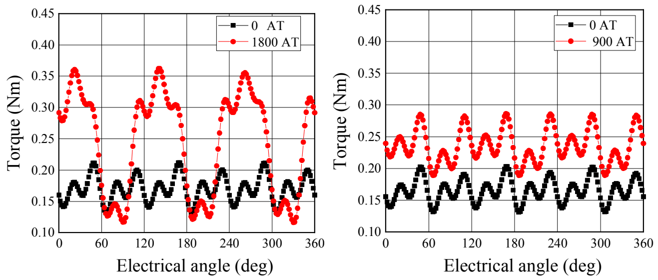
Figure 11(a) shows no-load e.m.f. waveforms of the principle model at the rotation speed of 1800 r/min under the conditions of 0-AT and 1800-AT magnetomotive force of the zero-phase winding. Figure 11(b) also shows no-load e.m.f. waveforms of the split rotor model at the same speed, but the magnetomotive force of the zero-phase winding is 0 AT and 900 AT. Figure 12 is FFT analysis results of the no-load e.m.f. of the two models. As can be seen in these figures, the fundamental components of the no-load e.m.f. have been varied by 40 % depending on the magnetomotive force of the zero-phase winding. The most important different point between the two models is the low-order harmonic components. It is confirmed that the 2nd and the 4th harmonics are effectively suppressed. The split rotor model intensifies either of the N-poles or the S-poles in the upper rotor due to the DC zero-phase magnetic flux, but the other poles are intensified in the lower rotor. Therefore, the total magnetic flux gained by all the N-poles and all the S-poles is balanced, which results in the efficient suppression of the even-order harmonics in the no-lad e.m.f. Moreover, the split rotor model can achieve almost same performance of the magnetic flux adjustment even with 900-AT zero-phase magnetomotive force. This advantage is obtained by a common magnetic circuit of the zero-phase magnetic flux between the two rotors.

Figure 13 shows electromagnetic torque waveforms at 1800 r/min under the condition of 600-AT q-axis magnetomotive force, and their FFT analysis results are indicated in Fig. 14. The average torque is almost same between the two models, but the torque ripple is efficiently reduced by the split rotor model. Particularly, the 3rd harmonic component is dramatically reduced by 87 %. The effective reduction of the even-order components of the no-load e.m.f. contributes great



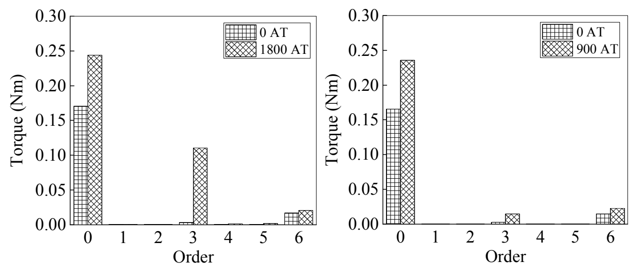
(a) Principle motor model. (b) Split rotor model.

Fig. 12. Comparison of FFT analysis results of back e.m.f.



(a) Principle motor model. (b) Split rotor model.

Fig. 13. Comparison of torque waveforms.



(a) Principle motor model. (b) Split rotor model.

Fig. 14. Comparison of FFT analysis results of torque.

suppression of the 3rd harmonic component of the torque in the split rotor model.

V. Conclusion

A novel strategy to achieve an adjustable magnetic flux operation of the IPM motor has been described in the paper, which is based on a permeability modulation technique. Detail of the magnetic circuit design and performance of the adjustable magnetic flux operation have been discussed, taking up two models of the adjustable magnetic flux IPM motors, i.e., a principle model and a split rotor model. By taking advantage of the permeability modulation technique, the adjustable magnetic flux operation has been achieved by the different approach rather than conventional approaches without sacrificing inverse saliency based reluctance torque. Furthermore, utilization of the zero-phase current of the inverter for the permeability modulation makes it possible to separate the e.m.f. control from the conventional d-axis and q-axis current control. This zero-phase approach has significant advantages from the viewpoint of semiconductor device counts, inverter losses, circuit configuration, and more.

It has been confirmed that the adjustable range of the no-load e.m.f. is 40 % in both of the two motor models even though the both models employ low-residual-flux-density ferrite magnets. Further improvement of the adjustable range of the magnetic flux is expected through the optimization of the magnetic circuit, shape and material modification of the soft magnetic metal, use of higher-grade PM, and so forth.

The proposed strategy gives three-degrees of freedom in the current control of the IPM motor owing to the zero-phase winding separate from the ordinary three-phase windings. This means that the magnetic flux control can be carried out by not only the zero-phase current but also the conventional d-axis current, and that the torque can be controlled by the zero-phase current as well as the conventional q-axis current. Therefore, it is necessary to consider the extended MTPA control and the extended field weakening control, taking the permeability modulation, i.e., zero-phase current control, into account.

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