

Preliminary Study on Adjustable Field NdFeB Permanent Magnet Motor Based on Permeability Modulation Technique

Toshihiko Noguchi¹, Kiyohiro Iwama² and Masahiro Aoyama³
^{1,2,3} Shizuoka University, Hamamatsu, Japan

E-mail: iwama.kiyohiro.14@shizuoka.ac.jp

Abstract. This paper describes an adjustable field permanent magnet (PM) motor based on a permeability modulation technique. The proposed motor has leakage magnetic flux paths between the rotor magnetic poles. The permeability modulation is a technique for controlling the amount of the leakage magnetic flux by manipulating the permeability of the magnetic paths. This paper proposes two adjustable field PM motor models based on the permeability modulation technique. One is a model using electromagnetic steel sheets and different kind of metal materials in the rotor, and the other is a model using only the electromagnetic steel sheets in the rotor. The paper presents some computer simulation results and makes a comparison between the two models.

1. Introduction

Generally, the permanent magnet (PM) motors have achieved higher power density than any other different types of motors, taking a 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]-[4]. The references [1] and [3] 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 [4] 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.

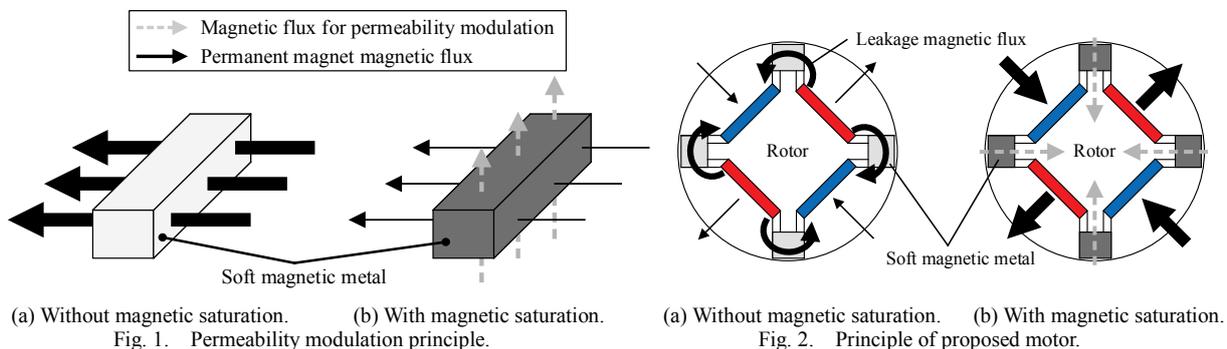
For the above, the writers have proposed the adjustable field PM motor based on permeability modulation technique by using the magnetic saturation of the soft magnetic material positively. The motor is the model inserted the soft magnet material which is dissimilar metal between the rotor magnetic poles of the institute of Electrical Engineers of Japan D-model. This model makes it possible to realizes

the adjustable field PM motor with the inverse saliency. However, this model has problem that output density is low because this model uses the ferrite magnet having low energy density. Two motor models are proposed in this paper as the adjustable field PM motor based on the permeability modulation using NdFeB. One is the motor model using different kind of metal and the other is the motor model using only the electromagnetic steel sheets. The point using the permeability modulation in both motor models is common. This paper describes the magnetic circuit design, the performance evaluation of adjustable field and the fundamental driving characteristics.

2. Principle of adjustable field based on permeability modulation

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 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]-[4], 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.



3. Magnetic circuit design of proposed motor

3.1. Magnetic circuit of model using different kind of metal materials

All the following electromagnetic analyses are conducted with JMAG-Designer 18.0 TM. Fig. 3 shows a quarter motor model using different kind of metal materials. And Table 1 shows the main motor specifications in this model. A soft ferrite core is inserted between the magnetic poles in this model. The

saturation magnetic flux density of this soft ferrite core is 0.5 T. As shown in Fig. 3(b), the rotors of the proposed motor is divided into 2 parts and has special winding to make magnetic flux 3-dimensionally. The proposed motor makes it possible to realize adjustable field with low magnetomotive force (m.m.f.) for the permeability modulation and reduce harmonics by dividing the rotor. In addition, the change of the inductance decreases, and the winding coefficients increase by adopting distributed winding.

3.2. Magnetic circuit of model using only electromagnetic steel sheets

Fig. 4 shows the quarter motor model using only the electromagnetic steel sheets. The main motor specifications in this model is the same in Table 1. This model is consisted of the electromagnetic steel sheets only. This motor configuration can widen adjustable field control width and increase machine strength because the saturation magnetic flux density of leakage magnetic paths is higher than model using different kind of metal materials. And the leakage magnetic paths of the V-shape make it easy to penetrate the magnetic flux for the permeability modulation and decrease m.m.f. for permeability modulation.

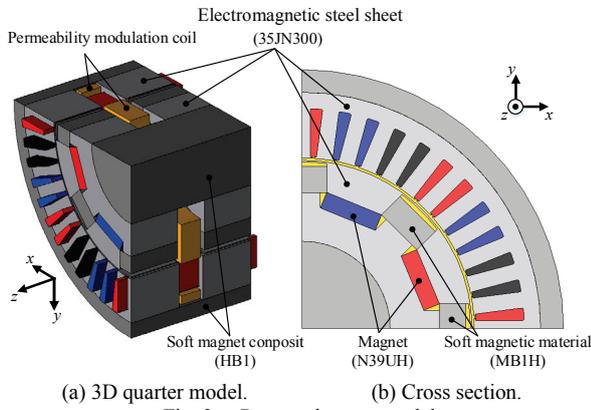


Fig. 3. Proposed motor model using different kind of metal materials.

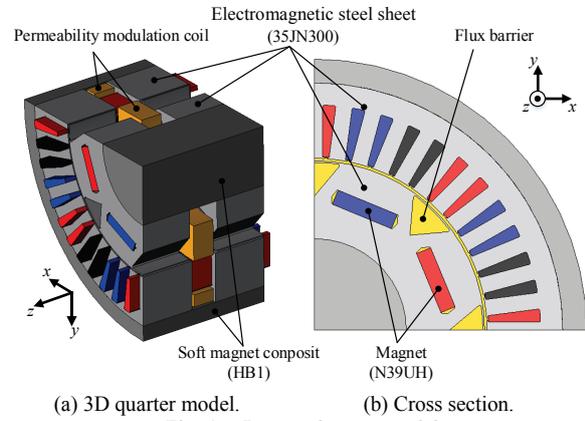


Fig. 4. Proposed motor model using only electromagnetic steel sheet.

Table 1. Specifications of proposed motor.

DC Voltage	270 V
Phase current	50 A _{rms}
Number of poles and slots	8 poles, 48 slots
Number of turns	8
Stator diameter	φ160 mm
Rotor diameter	φ100 mm
Stack length	62 mm
Max m.m.f. for permeability modulation	1500 AT
Armature winding resistance	25 mΩ

4. Magnetomotive force source for permeability modulation

Fig. 5 shows 3 motor drive circuits as system for realizing adjustable field PM motor based on permeability modulation. The characteristics of those circuits is written below down.

4.1. Method using DC/DC converter

Fig. 5(a) shows the method using DC/DC converter. This method introduced in [1] and [3] 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.

4.2. Method using time and/or space harmonics

Fig. 5(b) shows the method using time and/or space harmonics. This method introduced in [4] has good power supply voltage utility. However, it is impossible to control the m.m.f. for the permeability modulation 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.

4.3. Method using zero-phase current

Fig. 5(c) shows the method using zero-phase current. This motor drive 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 superimposed zero-phase current onto the three-phase currents can be reduced without sacrificing the m.m.f.

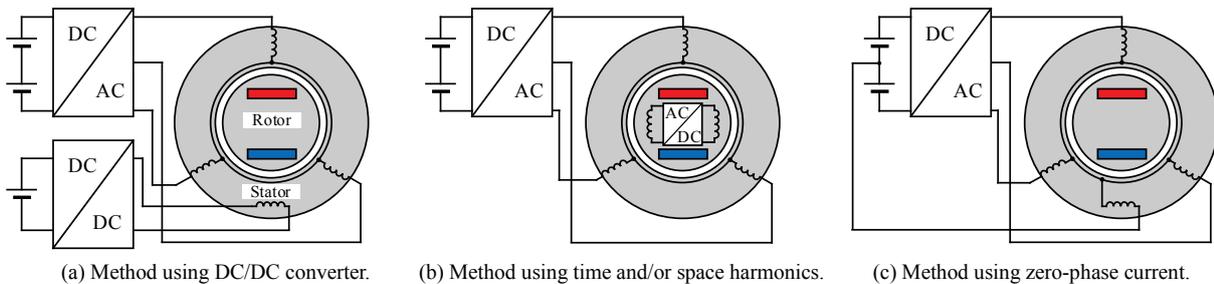


Fig. 5. Motor drive circuits.

5. Comparison of performance evaluation of adjustable field in two motor models

5.1. Relative permeability distribution in leakage magnetic paths

Fig. 6 shows the relative permeability distributions when the m.m.f. of 1500 AT is given to the permeability modulation winding. The motor model in Fig. 6(a) is used the soft ferrite and the model in Fig. 6(b) is used the electromagnetic steel sheet in the leakage magnetic paths. The initial relative permeability of the soft ferrite is 1600 and the maximum relative permeability of the electromagnetic steel sheet is 18000. As can be seen in Fig. 6, it is confirmed that relative permeability in leakage magnetic paths decreases by the m.m.f. for the permeability modulation. Therefore, it is possible to vary the permeability of the soft magnetic metal placed between the PM poles by using the m.m.f. of the permeability modulation winding.

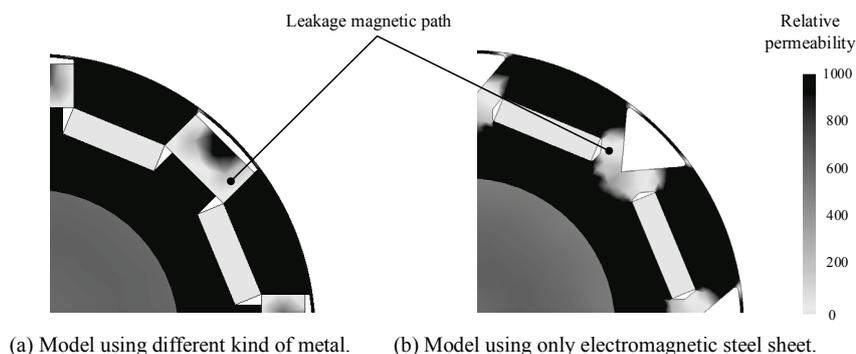


Fig. 6. Relative permeability distributions.

5.2. No-load electromotive force

Fig. 7(a) shows no-load e.m.f. waveforms of the model using different kind of magnetic metals at the rotating speed of 3000 r/min under the conditions of 0 AT and 1500 AT m.m.f. of permeability modulation winding. And Fig. 7(b) shows FFT result of the no-load e.m.f. As can be seen in the Fig. 7, it is confirmed that this model makes it possible to control 26.9% of the fundamental component of the no-load e.m.f. Fig. 8 shows no-load e.m.f. waveforms and FFT result of the model using only the electromagnetic steel sheets on the same condition as Fig. 7. As can be seen in the Fig. 8, it is confirmed that this model makes it possible to control 61.9 % of the fundamental component of the no-load e.m.f. Therefore, the model using only the electromagnetic steel sheets has better performance of the adjustable field than the model using different kind of metal materials. The saturation magnetic flux density of the electromagnetic steel sheet which 3 times has bigger than the soft ferrite contribute great performance of the adjustable field. This paper describes basic characteristics of the model using only the electromagnetic steel sheets after this, because this model has superiority as the adjustable field PM motor.

5.3. Electromagnetic torque

Fig. 9(a) shows electromagnetic torque waveforms under the condition of the armature current 50 Arms, and their FFT analysis results are indicated in Fig. 9(b). As can be seen in these figures, it is confirmed that the model using only the electromagnetic steel sheet can control 43.2 % of the average electromagnetic torque. However, the ratio of the controllable average electromagnetic torque is lower than the ratio of the controllable fundamental component of the no-load e.m.f. because of the magnetic saturation in the leakage magnetic paths by the magnetic flux in the q-axis.

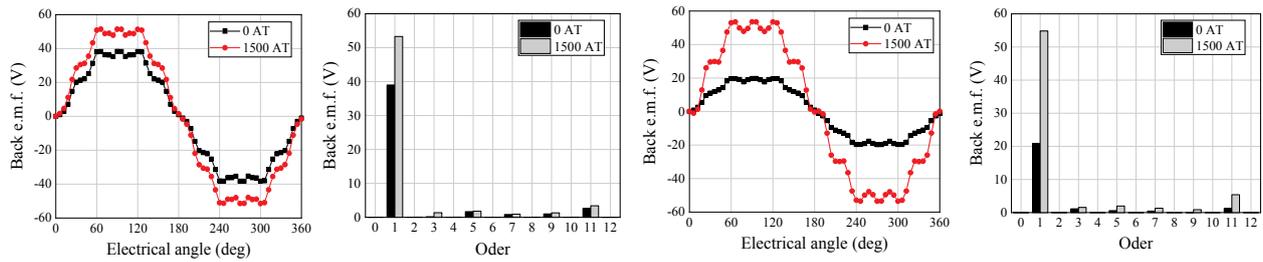


Fig. 7. No-load e.m.f. of model using different kind of metal materials.

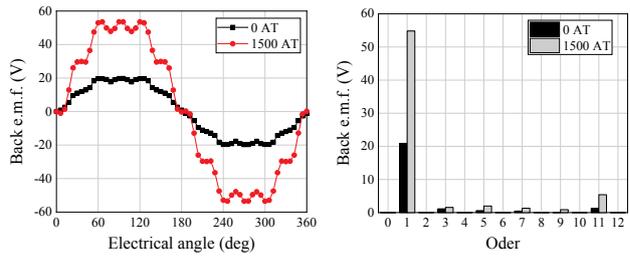


Fig. 8. No-load e.m.f. of model only electromagnetic steel sheets.

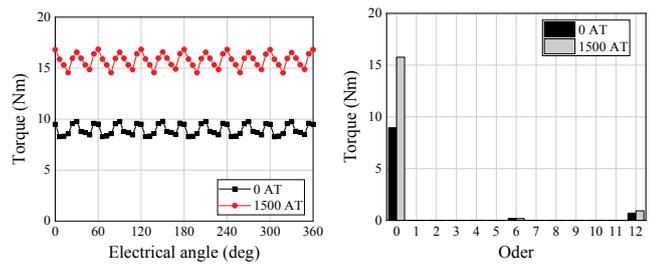


Fig. 9. Magnet torque with 50 A_{rms} armature current in q-axis.

5.4. N-T characteristics with q-axis current

Fig. 10 shows the rotating speed and torque characteristics (N-T characteristics) with maximum armature current of 50 A_{rms} in q-axis only. The motor drive circuit introduced in Fig. 5(a) is used in this analysis to predict the performance only for the motor hardware. As can be seen in this figure, the model using only the electromagnetic steel sheet makes it possible to realize high-torque and low-rotating speed when the m.m.f. of 1500 AT is given to permeability modulation winding and low-torque and high-rotating speed when the m.m.f. of 0 AT is given to permeability modulation winding.

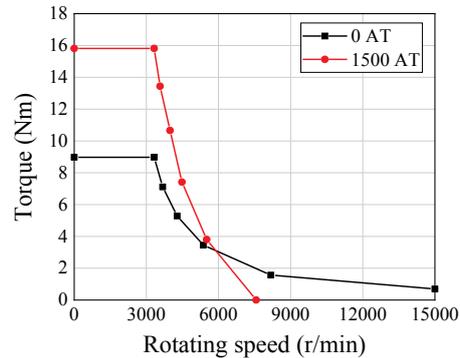


Fig. 10. N-T characteristic with q-axis current only.

6. Conclusion

Two adjustable field neodymium PM motor based on the permeability modulation technique were compared in this paper. One is the model using different kind of metal materials inserted the soft ferrite core between the magnetic poles. The other is the model using only the electromagnetic steel sheet that composes the rotor core of only the magnetic steel sheet. It was shown from the result of the no-load e.m.f. that the model using only the electromagnetic steel sheet can control 61.9 % of the field magnetic flux whereas the model using different kind of metal materials the dissimilar metal can control 26.9 %. And it is confirmed from the N-T characteristics that the proposed motor makes it possible to balance high-torque-low-speed and low-torque-high-speed.

The comparison of adjustable field based on permeability modulation technique and field weakening control, and verification experiment are our future work.

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