Permanent Magnet Motors Capable of Pole Changing and Three-Torque-Production Mode using Magnetization

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Energy saving in electrical appliances and electric vehicles can be realized by reducing the power consumption of their motors, which operate at variable speeds. In order to reduce reducing the energy consumption of electrical appliances, flux-weakening currents are used to reduce the voltage at high speeds, which leads to significant copper and core losses. To counter this problem, we developed a new technique that changes the number of poles and components of torque production in a permanent magnet (PM) motor based on rotational speed. In this study, we propose a novel motor that changes the poles and torque components, and also explain its principles and basic characteristics. The results of our study show that a PM motor can vary the induced voltage from 53% to 100%, operate a three-torque-production mode through magnetization, and reduce core loss by 21%. Thus, the results of our analysis prove that the proposed motor can change the poles and torque components, and can be utilized to achieve high performance and efficiency in variable speed drive systems.

Keywords: permanent magnet motor, electric machines, variable speed, pole change, high efficiency, vehicle

1. Introduction

Motors used in electric vehicles (EVs) operate over a wide range of speeds, as shown in Fig. 1. Permanent magnet (PM) motors suitable for variable speed applications that use new methods for varying the magnetic flux have been proposed in (13–15). A. Westa proposed a PM motor that can vary the magnetic flux by demagnetizing the PM in order to reduce the induced voltage at high speeds (13). L.R. Herman developed the Roesel Generator, which produces a constant frequency output at any speed by remagnetizing the PM in the rotor (14). V. Ostovic proposed the concept of a device (memory motor) that varies the magnetic flux and change poles. The memory motor is a squeezed-flux-type interior PM (IPM) that uses a ferrite magnet or an AlNiCo magnet (15) (16). H. Liu et al. performed a magnetic analysis of the memory motor (17). Sakai et al. proposed variable magnetic force motors that vary the magnetic flux by the demagnetization and remagnetization of a PM (18–20). By using analysis results and performing experiments with a model of the motor, they proved that the motor can vary the magnetic flux on load (20–22). One method commonly used to realize variable speed motors is pole changing, which is applied to an induction motor. Because a pole-changing motor can vary the number of poles depending on speed, the motor lets EVs operate with lower power consumption. Induction motors can be operated by the pole changing of variable speed drives. However, induction motors have a lower efficiency than PM motors. If a PM motor could change poles, we could realize an excellent variable speed drive motor with energy saving. In this study, we propose a novel PM motor called a three-torque-mode pole-changing PM motor (3M-PC PM motor) that can change the number of poles and produce three different types of torque (13–15). As shown in Figure 1, when the motor operates with 8 poles, it produces a PM torque in a low-speed area. When the motor operates with 4 poles, it produces a PM torque and a reluctance torque at medium speed. At top speed, the motor produces only a reluctance torque.

2. Pole Changing Principle and Torque Mode

Figure 2 shows the basic configuration of a 3M-PC PM motor. The rotor of the 3M-PC PM motor has a salient core and PMs with low coercive force (variably magnetized magnets) embedded in the iron core. In this section, we discuss...
pole changes and torque modes. First, we describe the 8-pole mode. When all the variably magnetized magnets have the same direction of magnetization, magnetic poles (image poles) with a reverse polarity to the magnets are formed in the rotor core among the magnets. Thus, the rotor forms 8 poles (Figure 3(a)). The motor generates PM torque by using the PM and q-axis current. Subsequently, the motor changes the rotor from 8 to 4 poles, and the connections of the armature winding switch from 8-pole winding to 4-pole winding. When the d-axis pulse current of the 4-pole armature winding flows, the variably magnetized magnets in the rotor are magnetized by the magnetic field of the pulse current. The flow time of the pulse current is 10 ms. The adjacent magnets reverse their polarity to each other and form 4 poles (Figure 3(b)). The motor generates a PM torque and reluctance torque because of the PM as well as the d-axis, and q-axis currents in the IPM mode. Next, the motor changes the rotor to 4 poles in the reluctance motor (RM) mode, producing only the reluctance torque from the 4-pole-IPM mode. When a negative d-axis pulse current is applied to the 4-pole armature winding, the variably magnetized magnets are demagnetized (Figure 3(c)). Conversely, the rotor of the 4-pole-RM mode changes to 8-pole-PM mode. When the connections of the armature winding switch from 4 to 8 poles, an 8-pole magnetic field is generated in the rotor because of the pulse current. The variably magnetized magnets are magnetized to the 8-pole mode.

3. Model of Analysis

A magnetic field analysis with finite element method (FEM) was performed to ascertain the basic pole-changing
characteristics and verify the feasibility of a 3M-PC PM motor. Figure 4 shows the analytical 3M-PC PM motor model. PMs are arranged in V-shape and embedded in the rotor core. Table 1 shows the motor specifications of the analytical model, and Figure 5 shows the winding connections for pole changing of the stator. Figure 6 shows the magnetic properties of the PMs for magnetization.

4. Magnetization Characteristics for Pole Changing and Torque Mode

Magnetization of the PM allows the rotor to change the number of poles. To verify whether this magnetization can change and reverse the polarity, magnetic field analysis is performed. After the magnetizing current flows through the armature winding of the motor, we analyze the magnetization of the PM in the motor. The magnetizing current creates the magnetic field of the pole, which magnetizes the PMs in the rotor. Therefore, the magnetizing current is the d-axis current in the new pole after pole changing. Here, 1 pu is defined as a continuous rated current. Also, the experimental results in a previous paper (7) have confirmed that the PM in the motor obtained using the magnetic analysis can be demagnetized and magnetized. First, we discuss magnetization to change the 8-pole-PM mode to 4-pole-IPM mode. Figure 7 illustrates the magnetization behavior in the motor. Figure 7(a) shows the distribution of the magnetic flux density in the 8-pole state, and Figure 7(b) shows the magnetic flux density when a 4-pole magnetic field magnetizes the PMs. Figure 8 shows the distribution of the magnetization vector in the PM before and during magnetization by the magnetizing current. The magnetization vector shows that the polarity in the PM reverses. Figure 9 shows the magnetization characteristics of the PM when the rotor changes from 8 to 4 poles. For a change from 8 to 4 poles, the magnetization in the PMs varies from 100% to −80% because of the magnetizing current of 4 pu; as a result, the PMs show reverse polarity.

Next, we discuss the magnetization to change the 4-pole-IPM mode to 4-pole-RM mode. Figure 10 illustrates the behavior of demagnetization in the motor. Figure 10(a) shows the distribution of the magnetic flux density during the 4-pole-IPM mode, and Figure 10(b) shows the magnetic flux density when a 4-pole magnetic field demagnetizes the PMs. Figure 11 shows the distribution of the magnetization vector in the PM before and during demagnetization by the magnetizing current. This distribution indicated that the PM is demagnetized. Figure 12 shows the magnetization characteristics of the PM when the rotor changes from the 4-pole-IPM mode to 4-pole-RM mode. For this change, the magnetization of the PMs varies from −100% to 0% because of the magnetizing current of 2 pu; as a result, the PMs show complete demagnetization. In addition, the magnetizing current of 4 pu allows 4-pole-RM mode to 4-pole-IPM mode switching. In this case, the function as a motor can change that as a generator for regenerative braking. Next, we discuss the magnetization to change the 4-pole-IPM mode to the 8-pole-PM mode. Figure 13 shows the behavior of magnetization in the motor. Figure 13(a) shows the distribution of the magnetic flux density in 4-pole-IPM mode, and Figure 13(b) shows the magnetic flux density when an 8-pole magnetic field magnetizes the PMs. Figure 9 shows the magnetization characteristics of a variably magnetized magnet in a 3M-PC PM motor.

![Fig. 7. Change from 8-pole-PM to 4-pole-IPM](image1)

![Fig. 8. Magnetization vector in a PM before and during magnetization for pole changing](image2)

![Fig. 9. Magnetization characteristics of a variably magnetized magnet in a 3M-PC PM motor](image3)
Characteristics of a PM when the rotor changes from 4 to 8 poles. For a change from 4 to 8 poles, the magnetization of the PMs varies from −100% to 80% because of the magnetizing current of 6 pu, and the PMs show reverse polarity.

These results indicate that the PMs in the rotor core can be magnetized (to reverse their polarity) or demagnetized or remagnetized. Therefore, the proposed motor can change the number of poles and torque components by magnetizing the PMs in the rotor.

We discussed the large magnetizing current to magnetize the PMs of this model. This model is a natural cooled type because of a principle model. Motors with a forced cooling operate using an inverter with larger power because of allowance of higher current density. For example, there are motors with a forced cooling which are applied to hybrid electric vehicle, electric vehicle and electric train. Therefore, the inverter with larger power can flow the large magnetizing current. Next, we indicate the solutions to reduce the magnetizing current. One solution is optimization of the coercive force and thickness of the variably magnetized magnet. These parameters of the variably magnetized magnet are defined to minimize the magnetizing current. The other solution is optimization of the shape of stator core and rotor core in order to concentrate the magnetization field on the PMs.

5. Characteristics of Motor

5.1 Pole-changing and Variable Flux Linkage

We verified pole changing of the rotor by magnetic field analysis. Figure 14 shows the distribution of the magnetic flux density in the motor for varying pole configurations.

When all the PMs are magnetized with the same polarity, the magnetic flux forms an 8-pole distribution, as shown in Figure 14(a). When the PMs are magnetized in the polarity opposite to their adjacent poles, the magnetic flux forms a 4-pole distribution, as shown in Figure 14(b). When all PMs are
demagnetized, the magnetic flux resulting from the excitation current forms a 4-pole distribution, as shown in Figure 14(c). Variable magnetization in the PM enables the pole changing of the PM motor. Figure 15 shows the variable characteristics of the induced voltage. Figure 16 shows each harmonic component of the induced voltage. When the motor changes from 8 to 4 poles, the induced voltage can vary from 100% to 53%. Furthermore, the induced voltage can be reduced to 0 V by the demagnetization of the PM (by switching to 4-pole-RM mode). Therefore, the induced voltage of the motor can vary from 0% to 100%.

5.2 Torque Characteristics In this section, we discuss the different torque modes. The torque components of the motor vary according to the number of poles in the rotor. Torque analysis is performed using FEM as a function of the current phase to determine the torque components. Figure 17 shows the torque–current phase characteristics. The current is at a rated value of 3.7 A. When the motor is in the 8-pole mode, a current phase of 98° provides the maximum torque. This result indicates that the torque component is PM torque in the 8-pole-PM mode. When the motor is in the
4-pole mode, a current phase of 119° provides the maximum torque. This result indicates that the torque components are PM torque and reluctance torque in the 4-pole-IPM mode. When all the PMs are demagnetized in the motor, a current phase of 139° provides the maximum torque. This result indicates that the torque component is reluctance torque in the 4-pole-RM mode.

Next, we discuss the motor’s basic performance. A magnetic field analysis of the torque is performed when the rotor is rotating at the rated current. The torque analysis considers irreversible demagnetization characteristics on the demagnetization curve in a PM. Figure 18 shows the torque characteristics during rotation. Because the torque value after one cycle is equal to the value at the starting point, the PMs can maintain magnetization without irreversible demagnetization. Therefore, the PMs can withstand demagnetization fields due to the armature current on the load.

The average torque values in the 8-pole-PM, 4-pole-IPM, and 4-pole-RM modes are 2.96, 1.93, and 0.68 Nm, respectively. The torque in the 4-pole-IPM mode is 0.65 times of that in the 8-pole-PM mode. Because the induced voltage and impedance in the 4-pole-IPM mode are about 0.5 times of that in the 8-pole-PM mode, these results imply that the variable speed drive has a constant power.

5.3 Core Loss We analyzed the loss reduction in the motor resulting from pole changing. Because the core loss is significant at high speeds, the efficiency of the motor is low. If the number of poles in the motor is reduced, the low frequency in the motor reduces the core loss. Figure 19 shows the core loss of stator in each pole mode, as calculated using FEM analysis. The analysis is performed in case of no-load at 9000 rpm. The results indicate that the core loss in the 4-pole mode decreases by 21% of that in the 8-pole mode. Therefore, pole changing provides high efficiency in the motor. Figure 20 and Figure 21 show the harmonic components of the eddy-current loss in each pole mode, as the fundamental harmonic component is 100% in the 8-pole-PM mode. In the 8-pole-PM mode, the third-harmonic component is 17% and the fifth-harmonic component is 5%. In the 4-pole-IPM mode, the third-harmonic component is 35% and the seventh-harmonic component is 19%. Therefore, reductions in the third-harmonic and seventh-harmonic components of the air-gap flux density in the 4-pole-IPM mode will lead to a significant reduction in the core loss by pole changing.

6. Conclusion In this study, we proposed a novel PM motor that changes poles and torque components, and discussed the basic configurations and principles of the motor. The results of our motor analysis have confirmed that the proposed PM motor can change poles as a result of the magnetization of the PMs,
vary the induced voltage from 53% to 100%, operate three different torque components, and reduce core loss by 21%. Therefore, the proposed motor can be utilized in a variable-speed drive system for high performance and efficiency.

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References