Analysis Method Using Equivalent Circuit Considering Harmonic Components of the Pole Change Motor

Hyuk Nam†, Tae-Uk Jung*, Young-Kyoun Kim, Seung-Kyu Jung** and Jung-Pyo Hong****

Abstract - This paper deals with the method of characteristic analysis of the capacitor-run single-phase induction motor having two poles (4-pole and 2-pole). This motor, which is referred to as a pole change motor in this paper, is capable of variable speed operation without inverters or drives. However, speed-torque curve can be distorted by the harmonic components contained in the magnetic flux density distribution. Therefore, the characteristics of this motor are analyzed using equivalent circuit considering harmonic components and the simulation results are compared with the experimental results.

Keywords: Capacitor-run single-phase induction motor, two poles, pole change motor, harmonic, equivalent circuit.

1. Introduction

The capacitor-run single-phase induction motor is widely used in household appliances. The major reason for this is that the operation of the motor is fed directly from the commercial single-phase voltage source without any type of control strategy. The pole change motor is the capacitor-run single-phase induction motor that has two poles (4-pole and 2-pole). Therefore, this motor is capable of variable speed operation and can expand the constant torque range using the pole change technique. In addition, it is maintenance-free and economical in comparison with other motors such as the 3-phase inverter motor and the brushless DC motor, because it utilizes a pole change switch for changing the speed without inverters or drives.

This paper deals with the pole change motor composed of the main winding, the auxiliary winding and the compensation winding. The main and the auxiliary windings are used for the 4-pole, because this motor is started at 4-pole. When the 4-pole is changed into the 2-pole for the 2-pole operation, the auxiliary winding is disconnected and the winding pattern of the main winding is changed.

The magnetic flux density distribution by only the main winding can result in severe distortion caused by the harmonic components. The existence of harmonics is well known to have a significant detrimental effect on the characteristics of the machine such as crawling [1].

To compensate for the magnetic flux density and the various torque such as negative torque, the compensation winding is connected parallel with the main winding at the 2-pole operation. In spite of the compensation winding, the speed-torque curve is distorted by the harmonics such as the third and the fifth order. Therefore, it is very important to calculate the accurate magnetic flux density and harmonics.

The magnetic flux density distribution in the air gap and the harmonic components are calculated by analytical methods in this paper.

Discrete Fourier Transform (DFT) is used to analyze the harmonics. The characteristics of the pole change motor are analyzed from the equivalent circuit considering the harmonic components. The simulation results by the proposed analysis method are then compared with the experimental results.

2. Pole Change Method

Fig. 1 presents the cross section of the pole change motor. The total number of slots of the stator is 24, and two type windings are inserted in each slot. The symbols, M, A, and C represent the main, the auxiliary and the compensation windings, respectively. The pole center at 2-pole is between slot number 6 and 7.

Fig. 2 shows the winding patterns at 4-pole operation and 2-pole operation according to the existence of compensation winding. Pole N′ and pole S′ of the main winding in Fig. 2(a) are changed into pole S″ and pole N″

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in Fig 2(b), respectively. The auxiliary winding is disconnected, as the pole change motor is initiated at 4-pole. The compensation winding is connected parallel with the main winding instead of the auxiliary winding in Fig. 2(c).

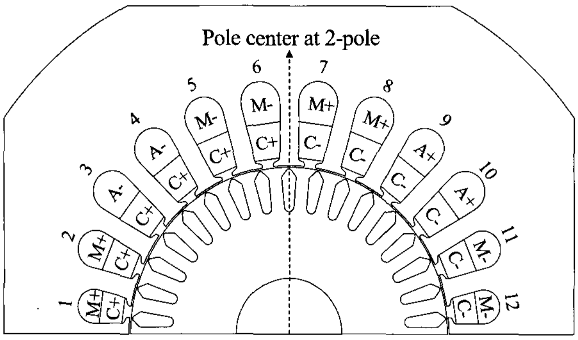
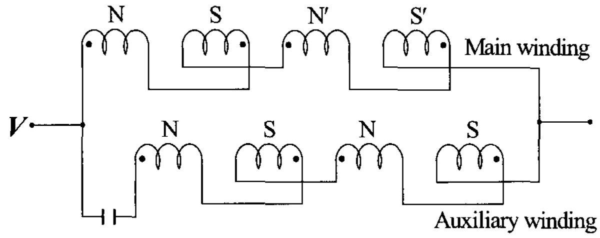
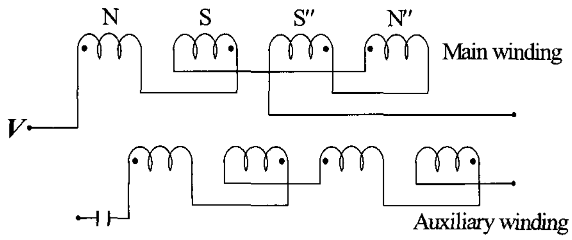


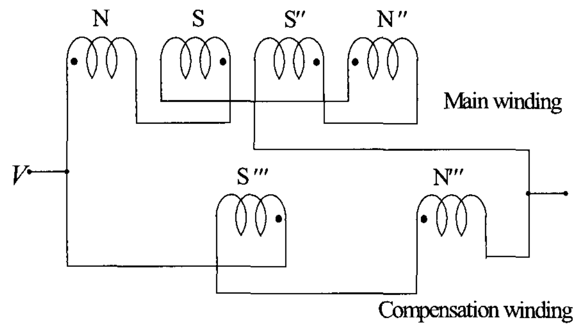
Fig. 1 Cross section of the pole change motor.



(a) Winding pattern at 4-pole operation.



(b) Winding pattern by main winding alone at 4-pole operation.



(b) Winding pattern by main and compensation windings at 4-pole operation.

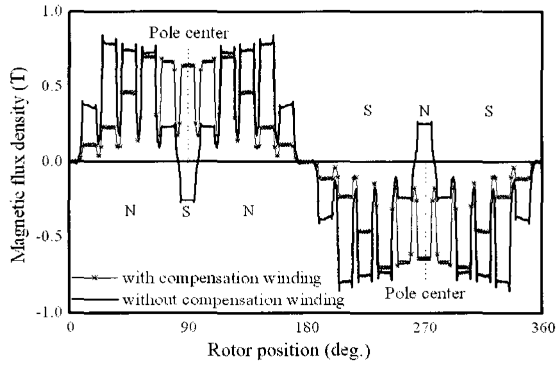
Fig. 2 Winding pattern according to the pole number.

Fig. 3 indicates the magnetic flux density distribution by the Finite Element Method (FEM) at no load condition, Discrete Fourier Transformation (DFT) of the magnetic flux density distribution and the speed-torque curves obtained from the experimental results according to the existence of compensation winding. In this paper, 90 deg. of rotor position in Fig. 3(a) corresponds to the pole center at 2-pole in Fig. 2.

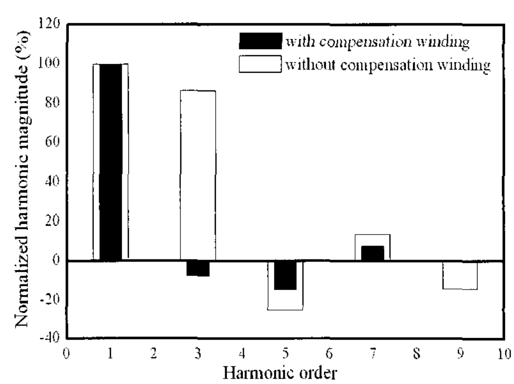
In Fig. 3(a) and (b), the unbalanced 6-pole of N-S-N-S-N-S per 1 cycle occurs due to the harmonic components such as the third and the fifth order at the 2-pole operation with only main winding. As a result, the speed-torque curve is distorted as shown in Fig. 3(c). The third harmonic component synchronizes the speed near 1,200 rpm, and generates negative torque, which is larger than positive torque. Thus, the compensation winding is wound to compensate both the magnetic flux density distribution and torques such as negative torque and breakdown torque at 2-pole.

In Fig. 3, the magnetic flux density distribution of 6-pole is changed into that of 2-pole by the compensation winding, and the harmonic components as well as the negative torque are reduced. However, in spite of the compensation winding, the distortion of the speed-torque curve can still be produced.

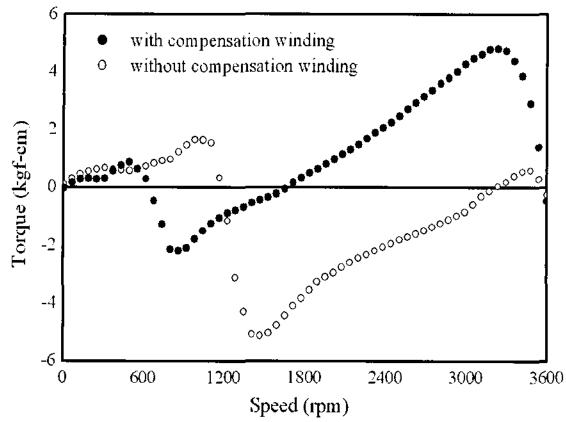
Therefore, it is very important to calculate the magnetic flux density distribution in the air gap and analyze the characteristics of the pole change motor considering harmonic components.



(a) Magnetic flux density distributions calculated by FEM.



(b) DFT of the magnetic flux density distribution.



(c) The experimental results of the speed-torque curves.

Fig. 3 The characteristic according to the existence of the compensation winding at 2-pole operation.

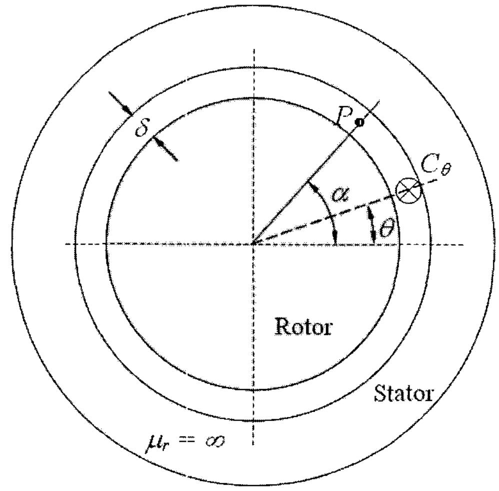


Fig. 4 Illustration relating to the calculation of the field of conductors.

3. Characteristic Analysis Method

3.1 Magnetic Flux Density Distribution Calculation

The flux density distribution in this paper is calculated by analytical method, not FEM.

To avoid unnecessary mathematical complexity, a certain simplifying assumption is made. Primarily, the main simplifying condition is the assumption of the infinite relative permeability of iron ($\mu_r=\infty$). It is assumed that the motor consists of two smooth coaxial cylinders comprised of a magnetic material and that the cylinders are separated by the air gap in Fig. 4.

The magnetic flux density produced by an arbitrary system of conductors in the air gap is obtained by the superposition of the field densities of the individual conductors. The magnetic flux density $B(\alpha)$ of the individual turns at any point P having the coordinate α is obtained by using equation (1) [2].

$$B(\alpha)=\frac{\mu_0 C_\theta i}{\pi\delta}\sum_{n=1}^{\infty}\frac{1}{n}\sin n(\alpha-\theta) \quad (T) \tag{1}$$

where n is the harmonic order, C_θ is the number of conductors that are placed at the position θ and δ is the magnetic air gap.

3.2 Discrete Fourier Transformation

DFT for the harmonic analysis of the magnetic flux density distribution can be expressed as equation (2).

$$a_n=\frac{2}{Num}\sum_{i=0}^{Num} b_i \sin\left(\frac{2\pi ni}{Num}\right) \tag{2}$$

where a_n is the n-th harmonic magnitude of the magnetic flux density , Num is the number of data and b_i is the flux density magnitude at each data. The ratio of the fundamental magnitude to the harmonic magnitude a_n/a_1 is used to obtain magnetizing reactance and secondary parameters of the n-th harmonic [3].

3.3 4-pole Characteristic Analysis

In order to analyze the characteristics of the capacitor-run SPIM by equivalent circuit, a symmetrical-coordinate system considering unbalanced state is introduced as shown in Fig. 5.

Equations (3) and (4) are the positive and the negative voltages by the symmetrical-coordinate system, respectively.

$$V_P=\left(V_M - jV'_A\right)/2 \tag{3}$$

$$V_N=\left(V_M + jV'_A\right)/2 \tag{4}$$

where V_P and V_N are the positive voltage and the negative voltage, respectively. The overall torque in equation (5) is calculated by the difference between the positive and the negative component torques and this equation is expressed as the synchronous watt.

$$T=\frac{60}{2\pi N_0}\,(P_{2P}-P_{2N}) \tag{5}$$

where N_0 is the synchronous rotating velocity. P_{2P} and P_{2N} are the secondary output powers of the positive and the negative components, respectively, as shown in equations

(6) and (7).

$$P_{2P} = \frac{R_2'}{s} \cdot |I_{2P}|^2 \tag{6}$$

$$P_{2N} = \frac{R_2'}{2-s} \cdot |I_{2N}|^2 \tag{7}$$

where I_{2P} and I_{2N} are the secondary input currents of the positive and the negative components, respectively.

3.4 2-pole Characteristic Analysis

The pole change motor at the 4-pole operation is analyzed from the equivalent circuit by the symmetrical-component theory in order to consider the elliptical magnetic field [4]. The main and auxiliary windings are designed for the 4-pole, and the magnetic flux density distributions almost do not contain the harmonics.

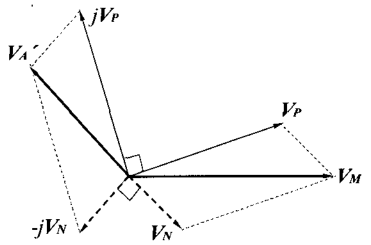


Fig. 5 Symmetrical-coordinate system.

Thus, the equivalent circuit is composed of the fundamental component. The overall torque is calculated by the difference of the positive and negative phase sequence torque. On the other hand, the main winding for the 4-pole operation is also used at the 2-pole operation. Therefore, the magnetic flux density distribution with only the main winding can become severely distorted by harmonic components.

Fig. 6, as suggested by Alger and others, presents the equivalent circuit of the main or compensation winding considering the harmonic components for the characteristic analysis at the 2-pole operation [4].

It is a useful concept to visualize the electromagnetic behavior of the various space harmonics as being similar to the behavior of separate motors, with a common stator winding and a common shaft, but with magnetizing reactance and secondary impedances corresponding respectively to the air gap flux wave of each specific harmonic. Therefore, the effect of the various harmonic torques on the fundamental speed-torque curves can be evaluated from the equivalent circuit.

Thus, the n-th slip function can be expressed as equation (8) if it is a forward rotating field and it can be expressed as equation (9) if it is a backward rotating field [5].

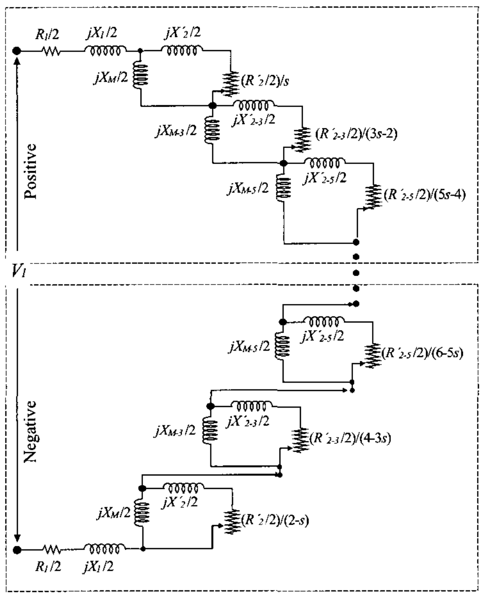


Fig. 6 Equivalent circuit of the main or the compensation winding considering harmonic components.

$$s_{pn} = 1 - n(1-s) \tag{8}$$

$$s_{nn} = 1 + n(1-s) \tag{9}$$

where n is the order of the harmonic and s is the slip of the fundamental component. Considering the fundamental component as a harmonic of the first order, the harmonic order of the pole change SPIM consists of odd terms only.

The phase quantities V_1, R_1, R_2, X_2, and X_M of the circuit are identical to those of the standard equivalent circuit. The magnetizing reactance of each of the harmonics, such as X_{M-5}, is based on the component of air gap flux of that particular harmonic.

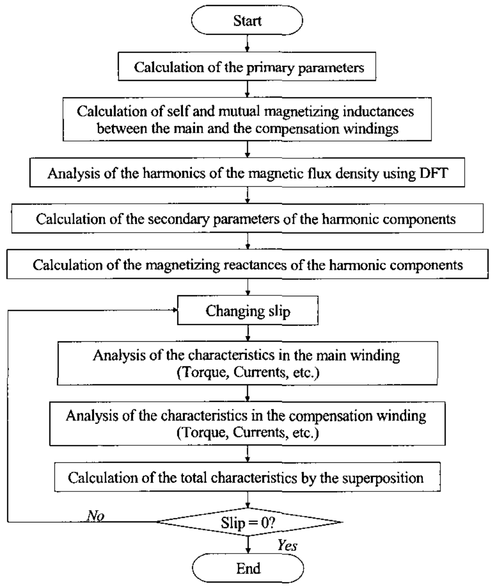


Fig. 7 Flow chart for characteristic analysis at 2-pole

In addition, the slip function of R_{2-n} for each harmonic is set up for the rotor slip for that particular harmonic and is dependent on the order of the harmonic and on whether the harmonic field is positive (or forward) rotating or negative (or backward) rotating [4].

Fig. 7 shows the flow chart for the characteristic analysis at 2-pole operation. The phase of the main and the compensation windings is the same. Therefore, the mutual effect on the two windings must be considered. The total torque can be obtained from superposition of the torques of the main and the compensation windings according to slip.

4. Analysis Model and Results

4.1 Specifications of Analysis Model

To verify the presented analysis method in this paper, the characteristics are analyzed using the prototype model that has the brief specifications of the pole change SPIM as shown in Table I. Input voltage is 220 V and frequency is 60 Hz. While output power and synchronous speed are 160 W and 3,600 rpm at 2-pole operation, those of 4-pole operation are 80 W and 1,800 rpm, respectively.

Table 1 Brief Specifications of Analysis Model

Item	Value	Unit
Input voltage	220	V
Frequency	60	Hz
No. of slots (stator/rotor)	24/34	
Air gap length	0.3	mm
Stack length	48.0	mm
Outer diameter of rotor	60.0	mm
Rated torque	4.4	kgf-cm
Output power (2-/4-pole)	160/80	W

4.2 Harmonic Analysis Results

Fig. 8 indicates the magnetic flux density distribution in the air gap using the analytical method in comparison with the FEM.

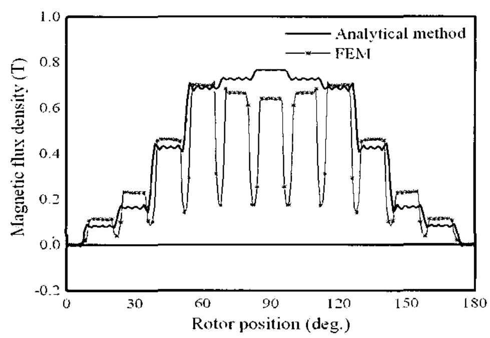


Fig. 8 Magnetic flux density distribution.

Table 2 Harmonic Analysis Results

Harmonic order	Analytical method (%)	FEM (%)
1	100.0	100.0
3	-17.6	-7.5
5	-7.3	-14.5
7	4.0	7.5

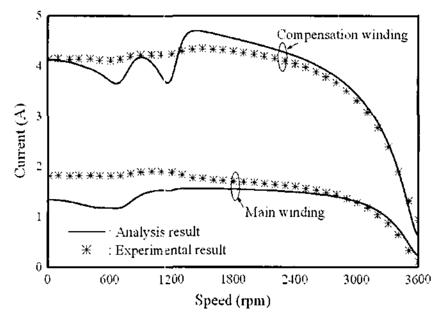
The effect on the saturation can be considered by the FEM, but not by the analytical method. Therefore, the difference of the harmonic analysis result by two methods occurs as shown in Table II. These results demonstrate that the third order harmonic component is evaluated in large and the fifth order harmonic component is evaluated in small in the analytical method in comparison with the FEM

4.3 Characteristic Analysis Results

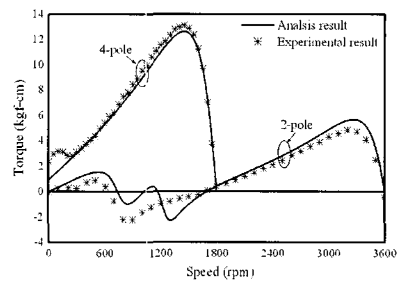
Fig. 9 displays the characteristic analysis results.

The speed–torque curve of the analysis model by the experimental result is affected by the fifth order harmonic component, while that of the analysis model by the simulation result is affected by the third order harmonic component rather than the fifth order harmonic component.

Even though the speed-torque curve of the analysis result differs from that of the experimental result, the analysis results by the presented analytical method show that the effect of the harmonics and the important torques such as the pole change torque and the maximum torque at 2-pole can be estimated.



(a) Speed-current curves at 2-pole operation.



(b) Speed-torque curves.

Fig. 9 Characteristic analysis results.

5. Conclusions

This paper proposes the characteristic analysis method by equivalent circuit considering the harmonic components of the pole change motor. The harmonic analysis results of the magnetic flux density distribution calculated by analytical method in the air gap are used to calculate the parameters of the harmonic equivalent circuit. From the characteristic analysis results, it is confirmed that the speed-torque curve is distorted by the harmonic components contained in the magnetic flux density distribution and the 3^{rd}, the 5^{th} harmonics, in particular, affect the characteristic of the pole change motor. Therefore, there is a need to design the windings in order to reduce the harmonics and obtain torques such as pole change torque, or breakdown torque during 2-pole operation.

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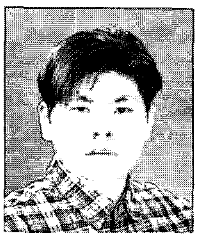

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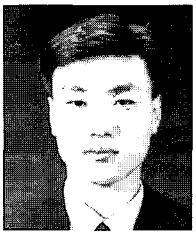

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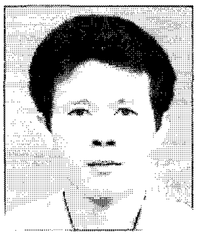

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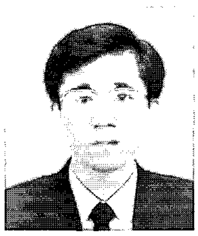

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