Characteristic Analysis of Pole Change Motor by Equivalent Circuit Considering Harmonic Components

Seung-Kyu Jung
Department of Electrical Engineering,
Changwon National University,
Changwon, Korea

Hyuk Nam
Department of Electrical Engineering,
Changwon National University,
Changwon, Korea

Jung-Pyo Hong
Department of Electrical Engineering,
Changwon National University,
Changwon, Korea

Tae-Uk Jung
Digital Appliance Company Research Lab.,
LG Electronics,
Changwon, Korea

Seung-Myun Baek
Digital Appliance Company Research Lab.,
LG Electronics,
Changwon, Korea

***Abstract* —This paper deals with the method of the characteristic analysis of the capacitor-run single-phase induction motor has two poles (4-pole and 2-pole). This motor, which is called 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.**

***Key Words* — harmonic components, magnetic flux density distribution, pole change motor, single-phase induction motor**

I. INTRODUCTION

The capacitor-run single-phase induction motor is widely used in household appliances. The major reason 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 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 constantt orque range using the pole change technique. In addition, it is maintenance-free and cheap in comparison with the motors such as the 3-phase inverter motor and the brushless DC motor, because it uses 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 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.

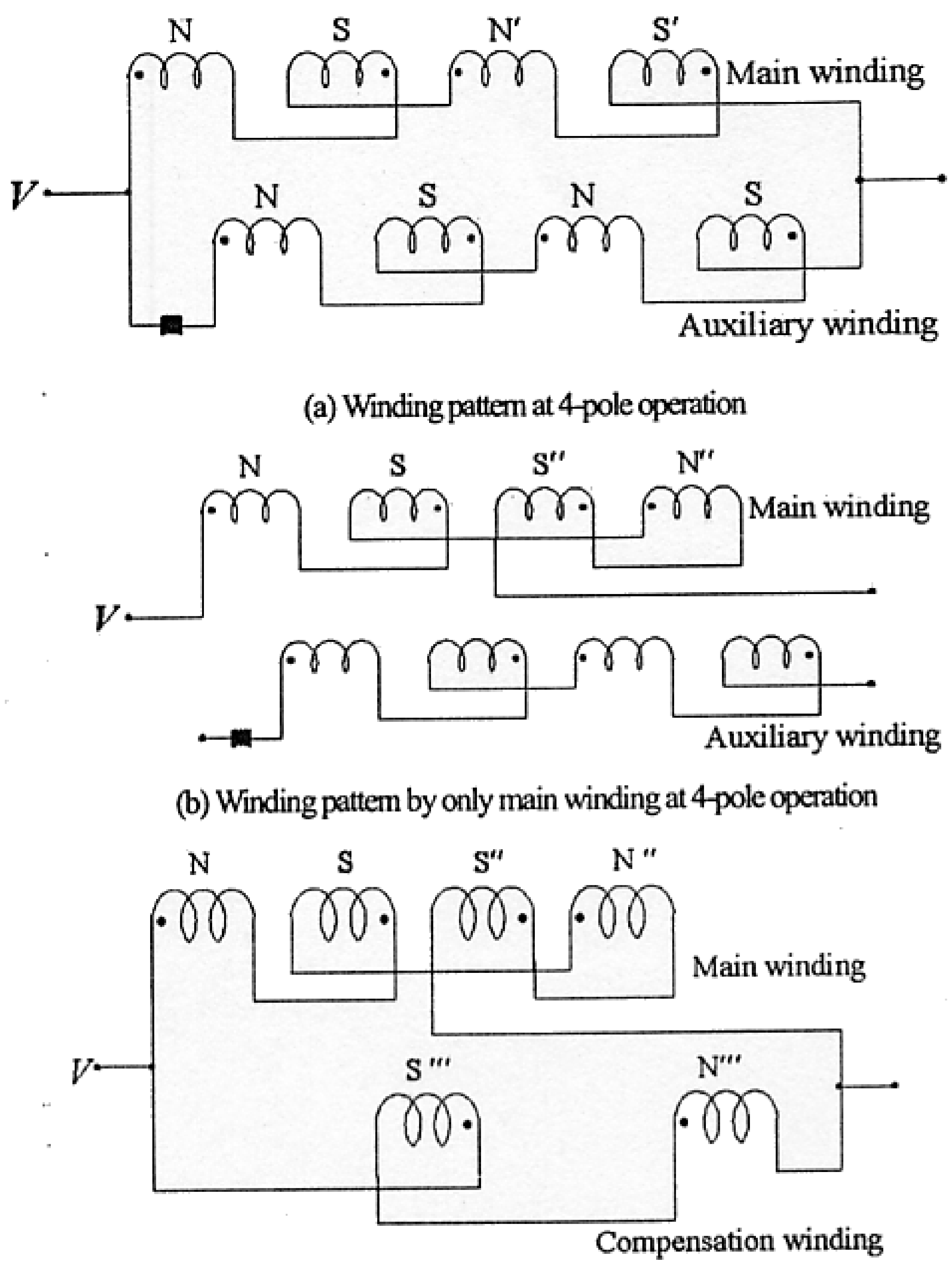
The magnetic flux density distribution by only the main winding can result in severe distortion caused by harmonic components. The existence of harmonics is well known to have a significant detrimental effect on the characteristics of the machine such as crawling [1]. To compensate the magnetic flux density and the 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, speed-torque curve is distorted by the harmonics such as the 3^{rd}, 5^{th} 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 pole change SPIM are analyzed from equivalent circuit considering the harmonic components. The simulation results by the proposed analysis method are compared with the experimental results.

II. POLE CHANGE METHOD

Fig. 1 shows the winding patterns at 4-pole operation and 2-pole operation according to the existence of compensation winding. Pole N′, pole S′ of the main winding in Fig. 1(a) are changed into pole S″, pole N″ in Fig 1(b), respectively. The auxiliary winding is disconnected, as the pole change motor is started at 4-pole. The compensation winding is connected parallel with the main winding instead of auxiliary winding in Fig. 1(c).

Fig. 2 shows the magnetic flux density distribution by Finite Element Method (FEM), 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. The magnetic flux density distributions in Fig. 2(a) are obtained by FEM at no load condition.

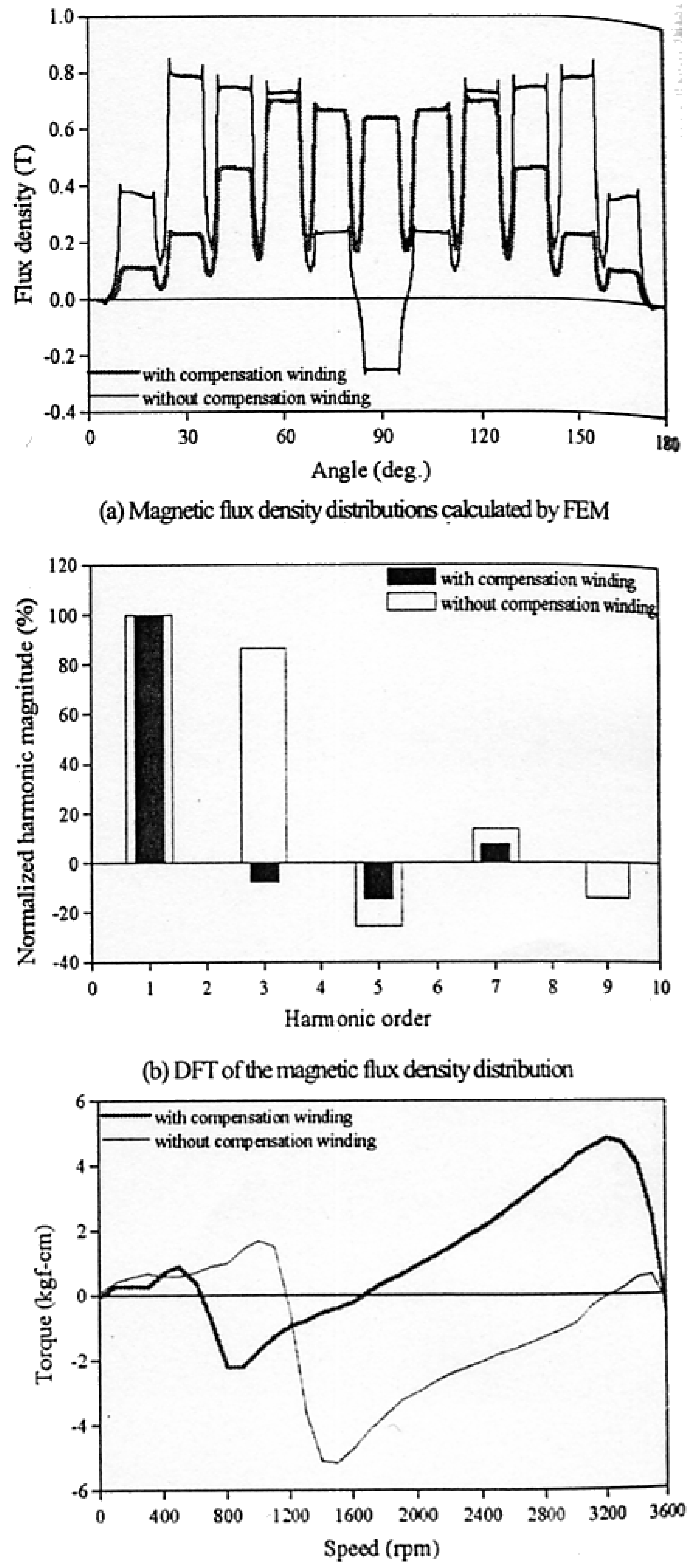


(a) Winding pattern at 4-pole operation

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

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

Fig.1 Winding pattern according to the pole number



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

The unbalanced 6-pole of N-S-N-S-N-S per 1 cycle occurs by harmonic components such as 3^{rd}, 5^{th} order at the 2-pole operation with only main winding in Fig. 1(a), (b). As the results, the speed-torque curve is distorted in Fig. 2(c). In addition, the 3^{rd} order harmonic component synchronizes the speed near 1,200 rpm and generates the negative torque is larger than the positive torque.

Thus, the compensation winding is wound to compensate the magnetic flux density distribution and torque such as negative torque, breakdown torque. In Fig. 2, the magnetic flux density distribution of 6-pole becomes that of 2-pole by the compensation winding and the harmonic components as well as the negative torque are reduced. In spite of the compensation winding, the distortion of the speed-torque curve can 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.

III. CHARACTERISTIC ANALYSIS METHOD

A. Magnetic Flux Density Distribution Calculation

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

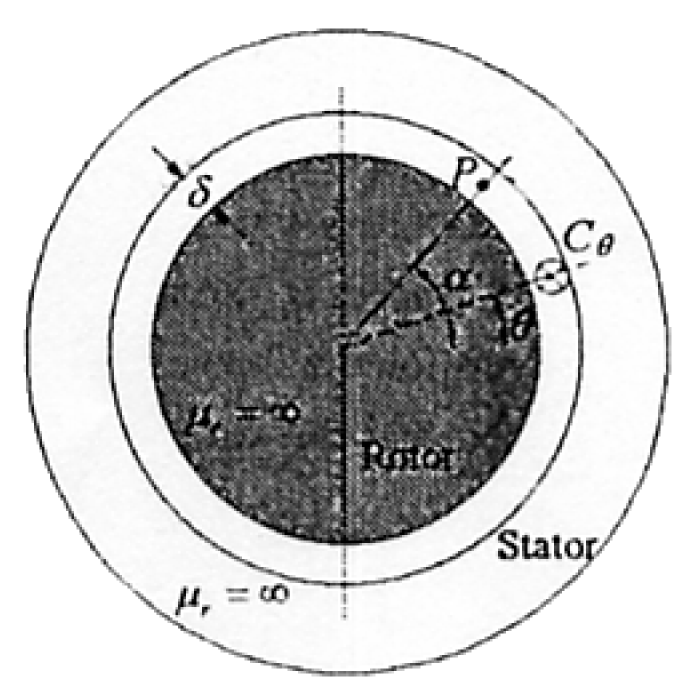


Fig. 3 Illustration relating to the calculation of the field of conductors

complexity, certain simplifying assumption is made. 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 made of a magnetic material and the cylinders are separated by the air gap in Fig. 3. 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.

B. Discrete Fourier Transform

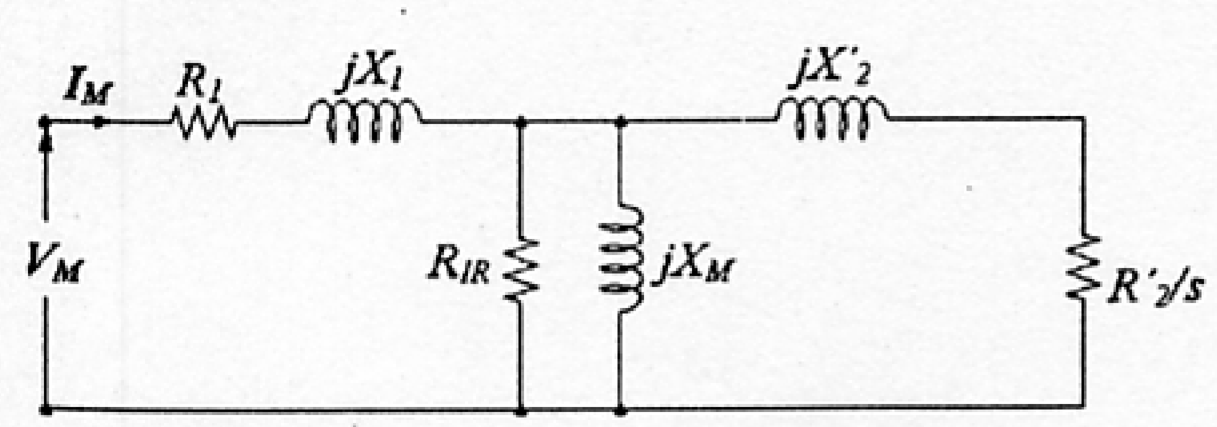
DFT can be expressed as equation (2).

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

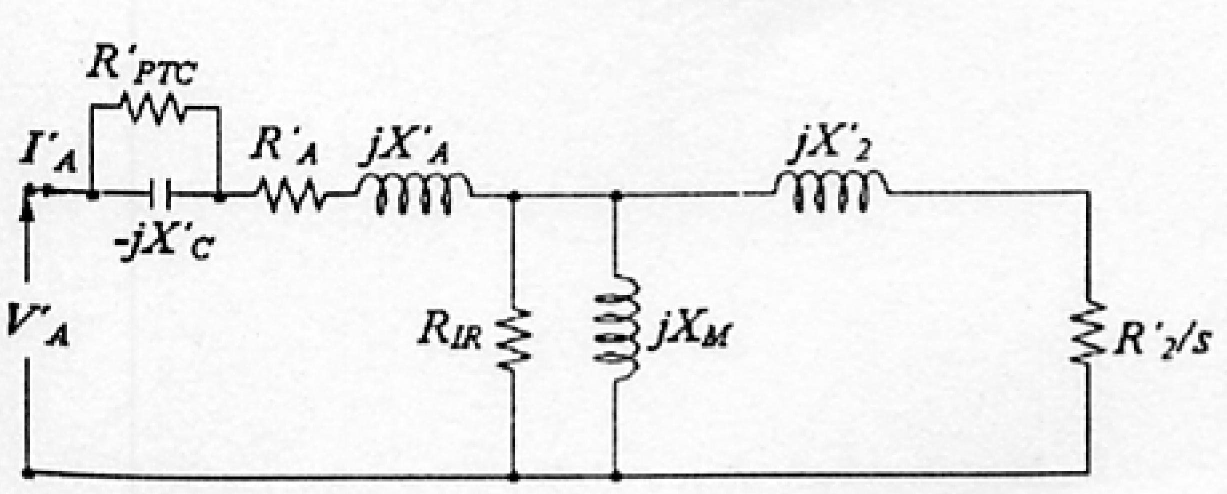
where a_n is the n-th harmonic magnitude of the magnetic flux density , Num is the number of data and b_i is the flux density magnitude at each data. The ratio of the fundamental magnitude to the harmonic magnitude a_n/a_1 is used to obtain magnetizing reactance and secondary parameters of the n-th harmonic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

C. 4-Pole Characteristic Analysis

Fig. 1 shows the equivalent circuit of the pole change motor. After common voltage is separated from the equivalent circuit of the main and auxiliary winding of the motor, auxiliary winding is transformed at the main winding.



(a) Equivalent circuit of main winding



(b) Equivalent circuit of auxiliary winding transformed to main winding

Fig. 4 Equivalent circuit of pole change motor for 4-pole

where R_1, X_1, R_{IR} and X_M are winding resistance, winding leakage reactance, core loss resistance and excited reactance of main winding, respectively. R'_A, X'_A, R_{PTC}' and X_C' are winding resistance, winding leakage reactance of main winding, PTC (Positive Temperature Coefficient) resistance and capacitor reactance, respectively. These values are transformed to the main winding. R'_2/s and X'_2 are secondary resistance and leakage reactance transformed to primary part. V_M and I_M are input voltage and current of main winding. V'_A and I'_A are input voltage and current of auxiliary winding transformed to the main winding.

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

Equation (3) and (4) are the positive and negative voltage by the symmetrical-coordinate method, respectively.

$$V_P=\frac{1}{2}\left(V_M - jV'_A\right) \tag{3}$$

$$V_N=\frac{1}{2}\left(V_M + jV'_A\right) \tag{4}$$

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

$$T=\frac{1}{9.8}\,\frac{60\ \times 10^2}{2\pi\ N_0}\,(P_{2P}-P_{2N}) \quad (\ kgf\cdot cm\ ) \tag{5}$$

where N_0 is the synchronous rotating velocity. P_{2P} and P_{2N} are the secondary output power of the positive and negative phase sequence component, respectively, as shown in equation (6), (7).

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

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

where I_{2P} and I_{2N} are the secondary input currento f the positive and negative phase sequence component, respectively.

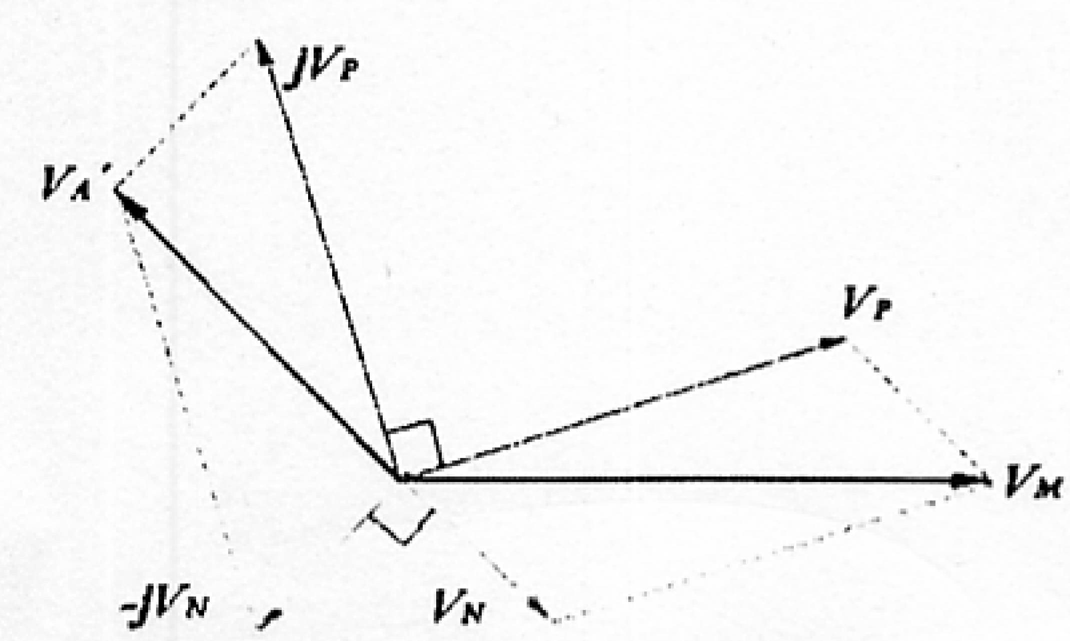


Fig. 5 Symmetrical coordinate method

D. 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 do not contain the harmonics. 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 use 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, shows the equivalent circuit of the main or compensation winding considering the harmonic components for the characteristic analysis at the 2-pole operation. It is a useful concept to visualize the electromagnetic behavior of the various space harmonic as being similar to the behavior of separate motors, with a common stator winding and a common shaft, but with magnetizing reactances 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. 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, such as that shown in Fig. 4(a). The magnetizing reactance of each of the harmonics, such as X_{M5}, is based on the component of air gap flux of that particular harmonic.

In addition, the slip function of $R_{2\text{-}n}$ 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.

Thus the n-th slip function can be expressed as equation (8) if it is a forward rotating field, and can be expressed as equation (9) if it is a backward rotating field [4].

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

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

where n is the order of the harmonic, s is the slip of the fundamental component. Considering the fundamental component as a harmonic of order one, the harmonic order of the pole change SPIM consists of odd terms only [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 compensation windings according to slip.

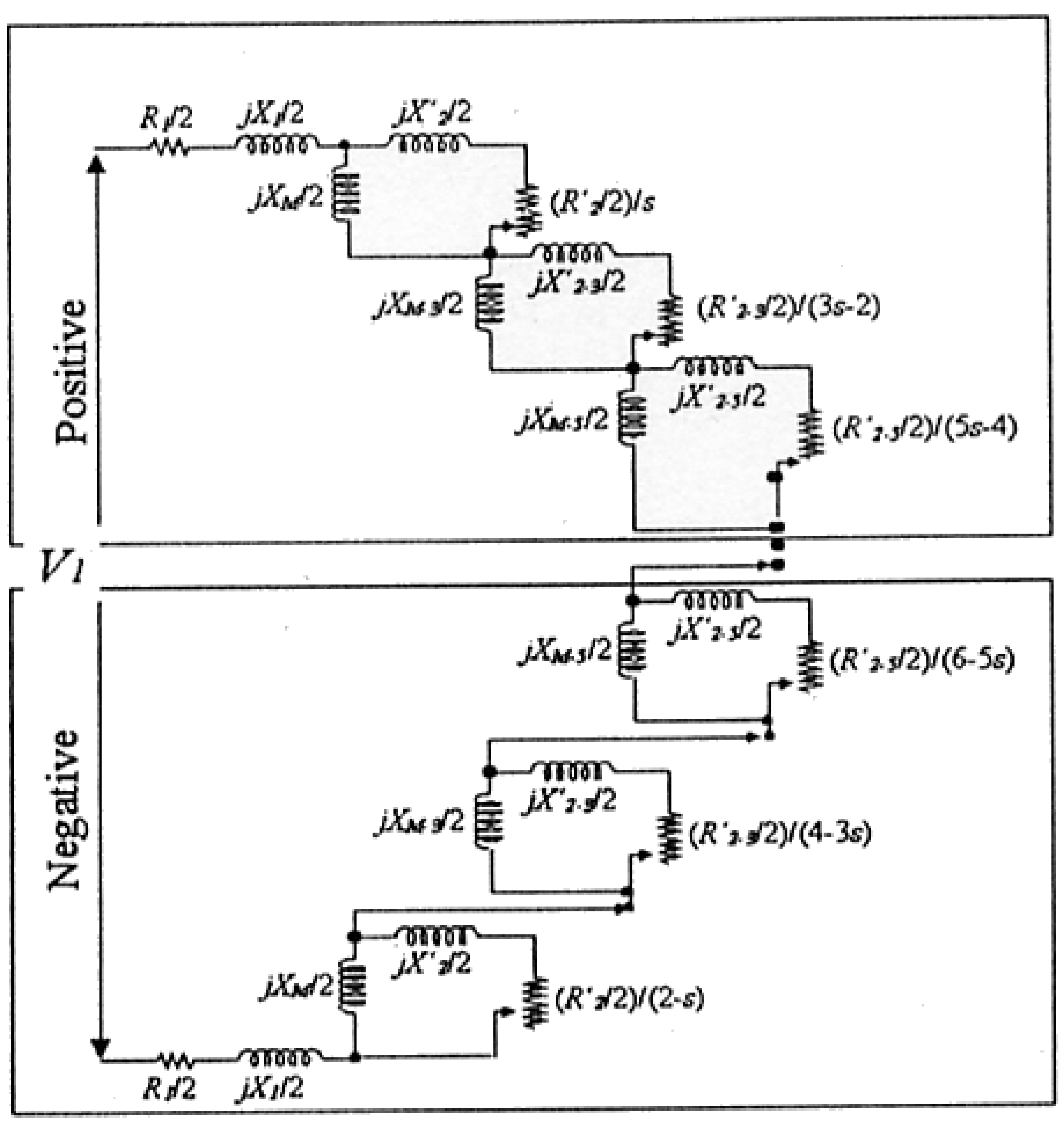


Fig. 6 Equivalent circuit of the main or compensation winding considering harmonic components

IV. ANALYSIS MODEL AND RESULTS

Table I shows the specifications of the pole change SPIM analysis model. Input voltage is 220 V and frequency is 60 Hz. Output power and Synchronous speed are 160 W and 3,600 rpm at 2-pole operation. And, Output power and Synchronous speed at 4-pole operation are 80 W and 1,800 rpm.

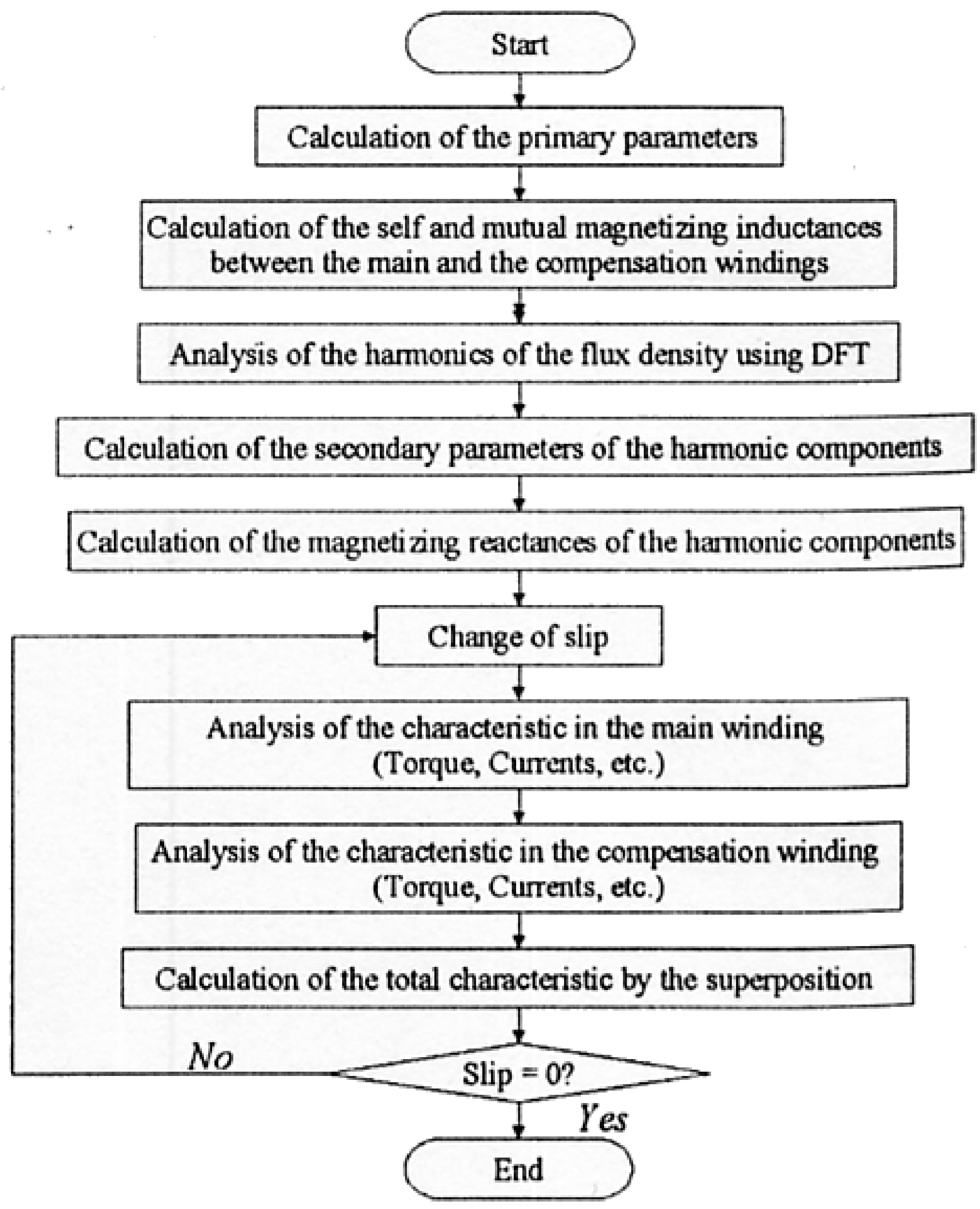


Fig. 7 Flow chart for characteristic analysis at 2-pole operation

Table. 1 Specification of analysis model

Input voltage	220	*V*
Frequency	60	*Hz*
No. of slot (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*

Fig. 8(a) shows the magnetic flux density distribution in the air gap using the analytical method in comparison with the FEM. 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 Fig. 8(b) and Table. 2. These results show that the 3rd order harmonic component is evaluated in large and the 5th order harmonic component is evaluated in small in the analytical method in comparison with the FEM.

Therefore, the speed–torque curve of the analysis model by the experimental result is affected by the 5th order harmonic component, while that of the analysis model by the simulation result is affected by the 3rd order harmonic component than the 5th order harmonic component as shown in Fig 8(d).

Table. 2 The results of the 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
9	2.3	0.4

V. CONCLUSIONS

This paper proposes the characteristic analysis method by equivalentc ircuit considering the harmonic components of pole change SPIM. 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 3rd, the 5th harmonics, especially, affect the characteristico f the pole change (2-/4-pole) SPIM. Therefore, there is need to design the windings in order to reduce the harmonics and obtain torques such as pole change torque, breakdown torque in 2-pole operation.

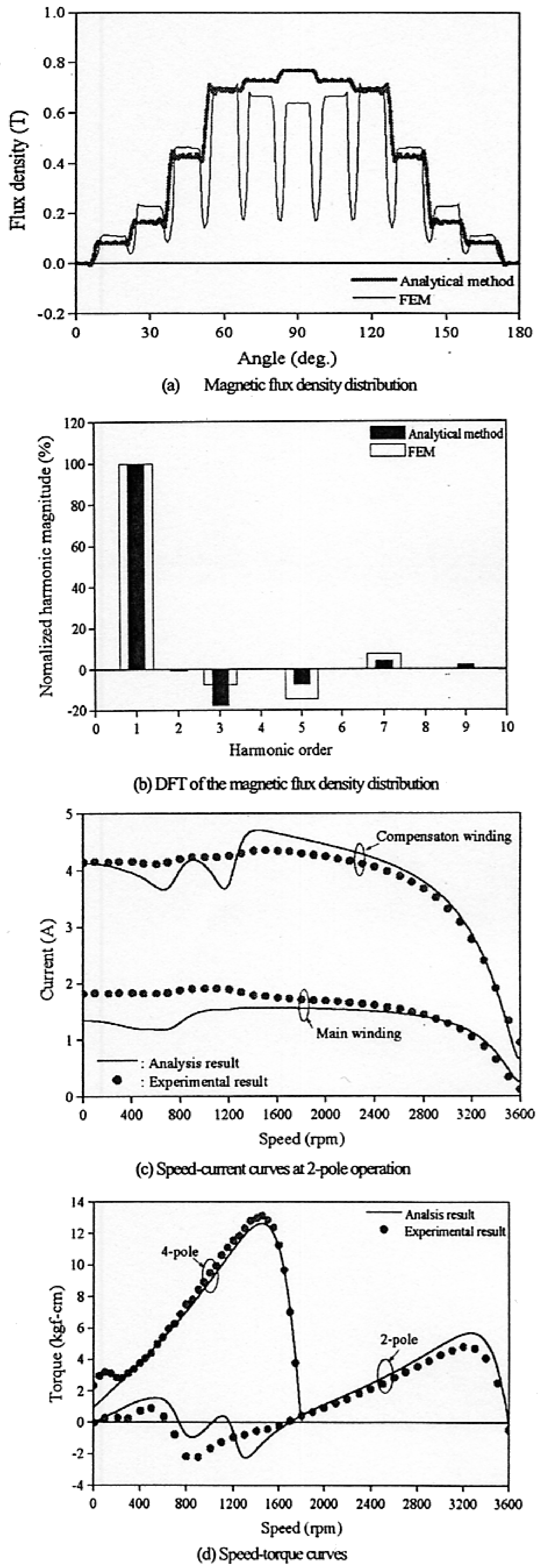
REFERENCE

[1] H.A. Toliyat, and N. Sargolzaei, "A Comprehensive Method for Transient Modeling of Single Phase Induction Motors Including the Space Harmonics", Journal of Electric Machines and Power Systems, Vol. 26, No. 3, pp.221-234, 1998.

[2] B. Heller and V. Hamata, Harmonic Field Effects in Induction Machine, Elsevier Scientific Publishing Company, 1977.

[3] C. G Veinott, Theory and Design of Small Induction Motors, McGRAW HILL, 1959.

[4] P. L. Cochran, Polyphase Induction Motors, Analysis, Design, and Application, Marcel dekker, 1989.



(a) Magnetic flux density distribution

(b) DFT of the magnetic flux density distribution

(c) Speed-current curves at 2-pole operation

(d) Speed-torque curves

Fig. 8 Characteristics of the analysis model