Improved Characteristic Analysis of a 5-phase Hybrid Stepping Motor Using the Neural Network and Numerical Method

Ki-Chae Lim, Jung-Pyo Hong, Gyu-Tak Kim and Tae-Bin Im

Abstract - This paper presents an improved characteristic analysis methodology for a 5-phase hybrid stepping motor. The basic approach is based on the use of equivalent magnetic circuit taking into account the localized saturation throughout the hybrid stepping motor. The finite element method(FEM) is used to generate the magnetic circuit parameters for the complex stator and rotor teeth and airgap considering the saturation effects in tooth and poles. In addition, the neural network is used to map a change of parameters and predicts their approximation. Therefore, the proposed method efficiently improves the accuracy of analysis by using the parameter characterizing localized saturation effects and reduces the computational time by using the neural network. An improved circuit model of 5-phase hybrid stepping motor is presented and its application is provided to demonstrate the effectiveness of the proposed method.

Key Words - Hybrid stepping motor, saturation, equivalent magnetic circuit, neural network

1. Introduction

Hybrid stepping motors are the most commonly used for servo systems as having the advantages of higher torque and resolution over other types of the stepping motors[1]. Especially, 5-phase hybrid stepping motors have better performance than 2-phase hybrid motors due to the fact that they produce a low torque ripple and have a good low-speed characteristics with high-torque.

The accurate prediction to the performance of electric machines has been a major concern for researchers and it has been dramatically improved by using the numerical method to obtain more precise solution for a problem. The finite element method(FEM) has been one of the most powerful and widely used technique in machine design and analysis. However, it has a disadvantage of excessive demand for computational time and resources. Especially, the application to analysis for hybrid stepping motors is more inefficient task and may generate unreliable results because of small airgap and 3-D nature of motor. Therefore, the equivalent magnetic circuit method with lumped circuit parameters has been widely applied to predict the performance of the hybrid stepping motor.

But, it is difficult to obtain clear equivalent circuit of hybrid stepping motors than that of other type motors because they are actually a 3-D device of which main flux takes both radial and axial paths. And, its circuit parameters cannot be easily calculated because they are designed to operate under highly saturated conditions to achieve a competitive torque per the unit volume[1]. The equivalent circuit method is not always accurate enough but flexible and time-saving for the changes of circuit parameters and its accuracy can be archived by improving the precision of lumped parameters.

To analyze the hybrid stepping motor accurately, two different methods are used ; the equivalent magnetic circuit and the FE analysis. The lumped parameters of each flux path are required to apply the equivalent magnetic circuit. Especially, the tooth or airgap permeance represented by the permeance of both the stator or rotor teeth and airgap region plays a important role in torque characteristics with displacement. In addition, the reluctance of each stator pole should be considered due to the saturation effect, as the exciting current increases over the rated current.

To calculate the airgap permeance, an analytic method has been used; which calculates the space distribution of the permeance by using quasi-flux tubes determined by straight lines and semicircular segments drawn to maximize the permeance of each flux path[2,3].

However, it cannot consider the saturation of iron core and the geometric complexity which significantly affect the machine performance. As an alternative, FEM is introduced to obtain the permeance data reliable enough[4]. And, using the neural network, we calculated the total distribution of permeance considering the saturated characteristics.

The equivalent circuit coupled with FEM is solved by the net matrix which describes the relationship between MMF sources and lumped parameters. Then, the virtual

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work technique is applied to compute the torque.

2. Equivalent magnetic circuit model

Fig. 1. shows the construction of the 5-phase hybrid stepping motor consisting of 50 rotor teeth, 10 stator poles, and 4 teeth per pole in the stator. Fig. 2 shows a side view and represents the flux paths of the motor. From Fig. 1. and Fig. 2, the equivalent magnetic model of the 5-phase hybrid stepping motor can be derived from two orthogonal fields; a radial field produced by stator excitation windings and an axial field produced by the permanent magnet on the rotor[1].

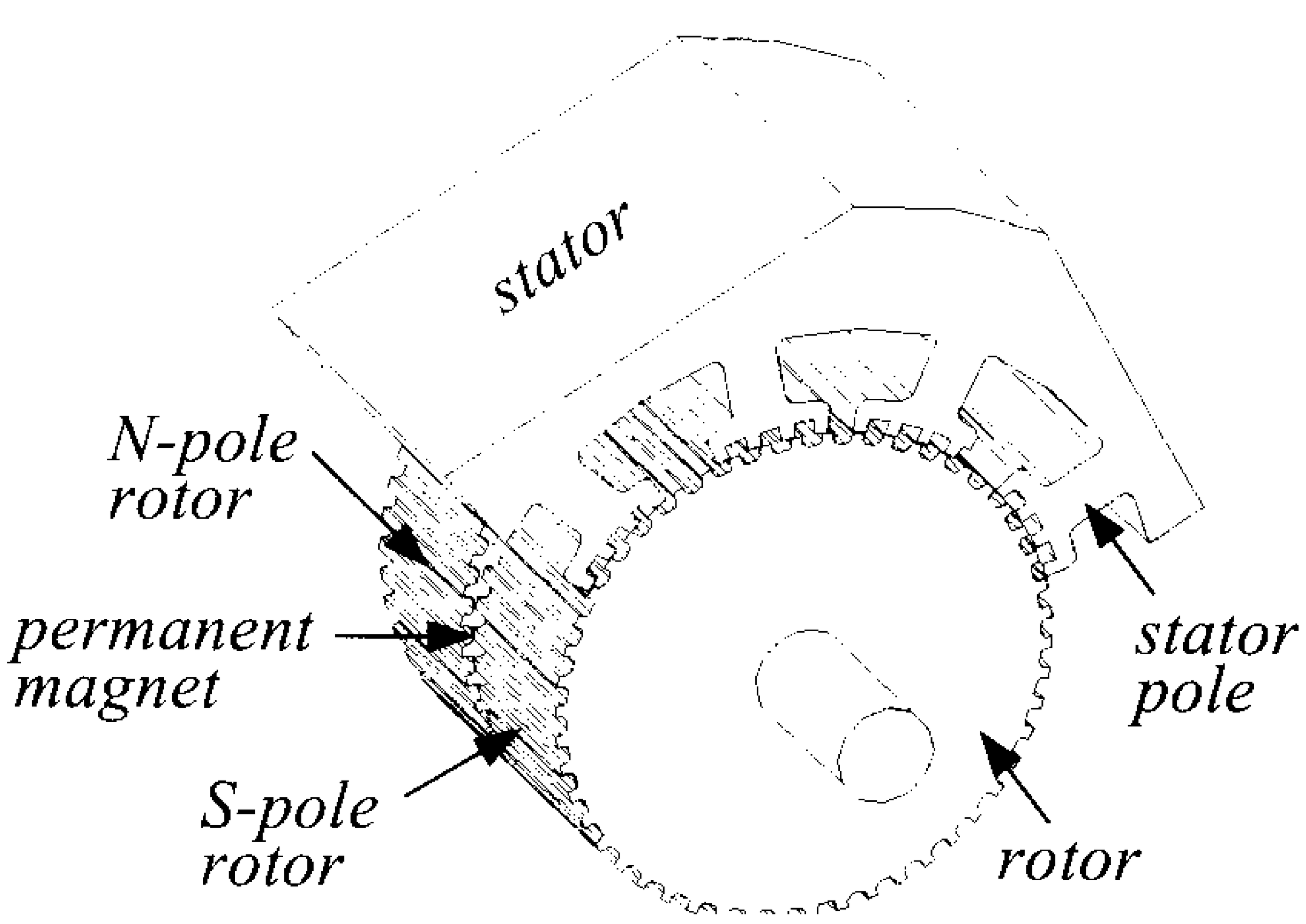


Fig. 1 Basic structure of the hybrid stepping motor

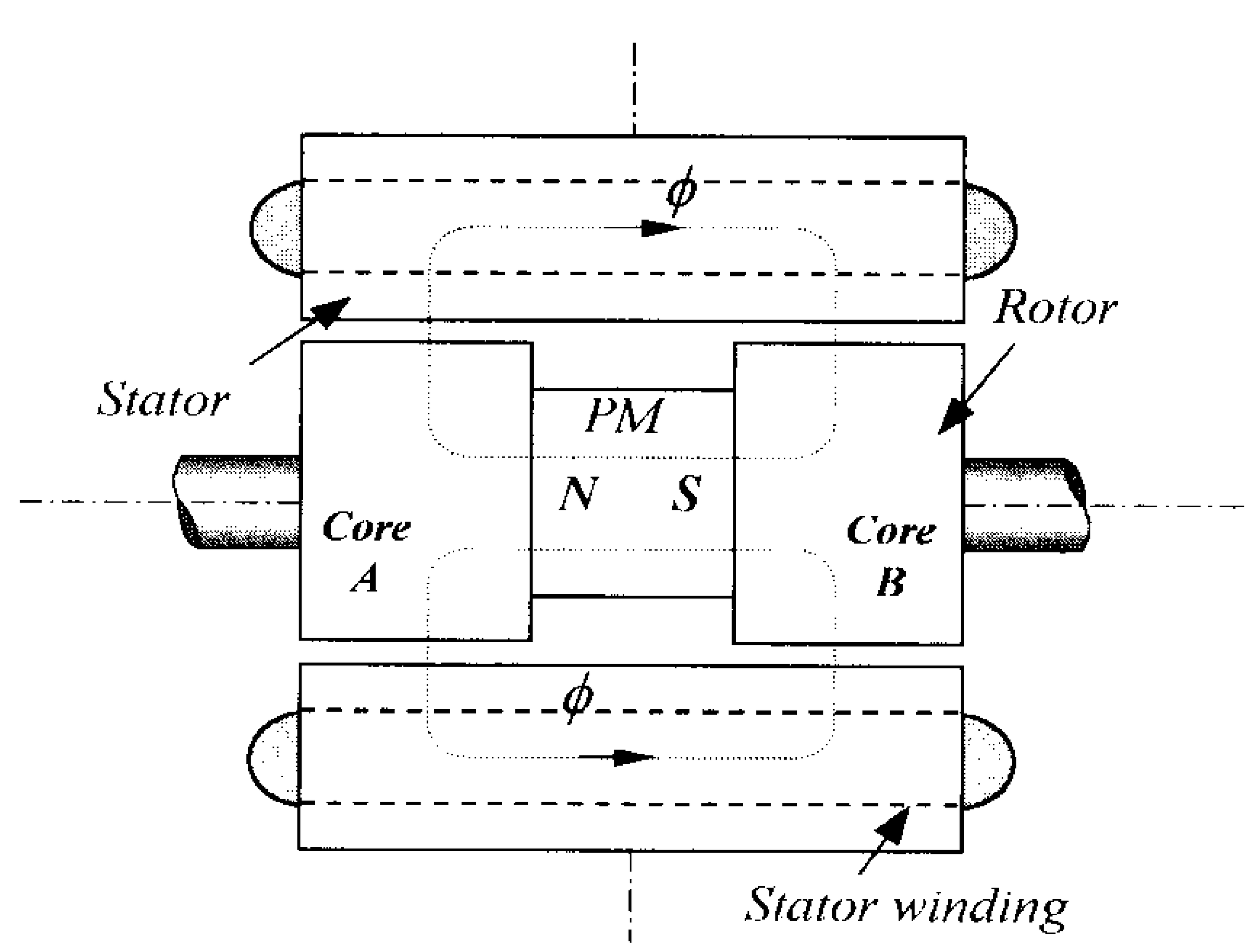


Fig. 2 Flux paths of the hybrid stepping motor

Fig. 3 shows the equivalent magnetic circuit of the 5-phase hybrid stepping motor. The equivalent magnentic circuit model is made up with 5 stator poles due to symmetric construction of the motor. The permeances for the radial flux path between A-phase pole on the stator and N- and S-pole rotors are defined P_{AN} and P_{AS}. And the other symbols expressed as permeance form can be understood easily in the same way. As the rotor and stator are normally made of laminated silicon steel, they have magnetic resistors, expressed by R_r and R_s for the axial flux path due to the permanent magnet.

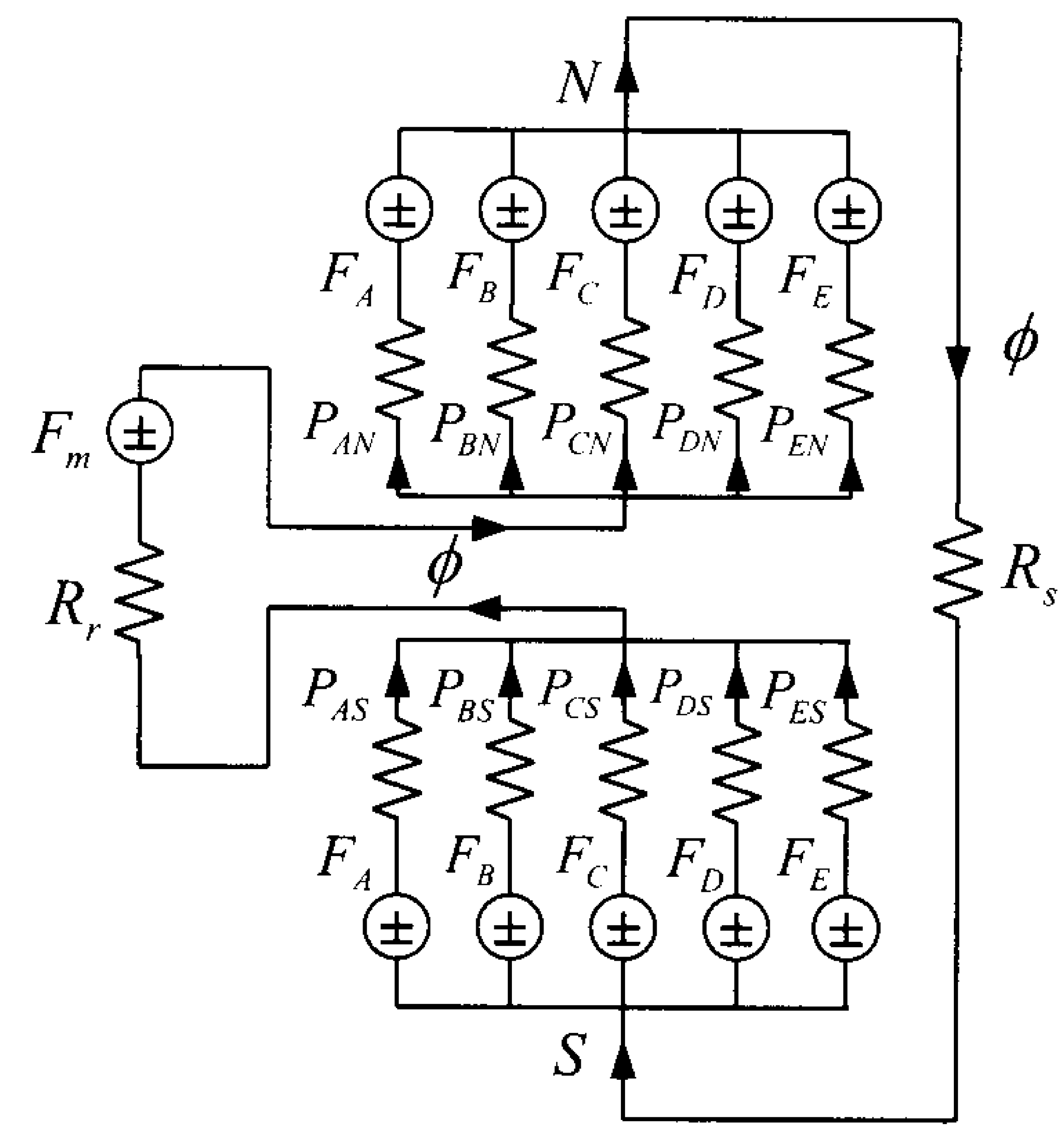


Fig. 3 Equivalent magnetic circuit of the 5-phase hybrid stepping motor

The peranent magent is modeled as ideal magneto-motive force(MMF) having internal reluctance expressed by R_m. The symbol F is a product between the number of turns of stator winding and the excited current of each phase.

3. Calculation of permennce using the finite element method

The equivalent circuit method is a simple and flexible technique for predicting the machine performance. In this paper circuit parameters include non-linear magnetic property and detailed geometry. Thus, the permeance representing the circuit parameters is calculated by usnig the FEM for a given condition and for an accuracy.

The use of FEM in calculation of the circuit parameters provides a significant advance in the degree of accuracy with which the equivalent circuit can be modeled at the price of excessive computing time.

In this paper, the FEM formulated from the magnetic scalar potential is introduced to calculate the permeance. Equation (1) is the governing equation for the magnetic scalar fields.

$$\nabla^2\phi = 0 \tag{1}$$

where ϕ is a scalar magnetic potential.

Generally, the saturation in the hybrid stepping motor is chiefly developed by the stator and rotor teeth. For the purpose of taking the saturation effect of the stator and rotor teeth into account, the tooth and airgap model shown in Fig. 4 is treated in FE analysis. The tooth and airgap model is presented to calculate the permeance of the stator and rotor teeth or airgap. As shown in Fig. 4, the permeance between the stator pole and rotor of each phase is replaced by the permeance calculated by the FE analysis when the reluctance of the stator pole of each phase and rotor is neglected.

Fig. 5 shows the FEM results for the tooth and airgap model when the stator and rotor teeth are aligned or unaligned with each other. By applying the FEM for the single tooth pitch region, the airgap permeance $P_g(\theta_e)$ can be calculated by both the magnetic stored energy W_s and the given MMF F_g in (2).

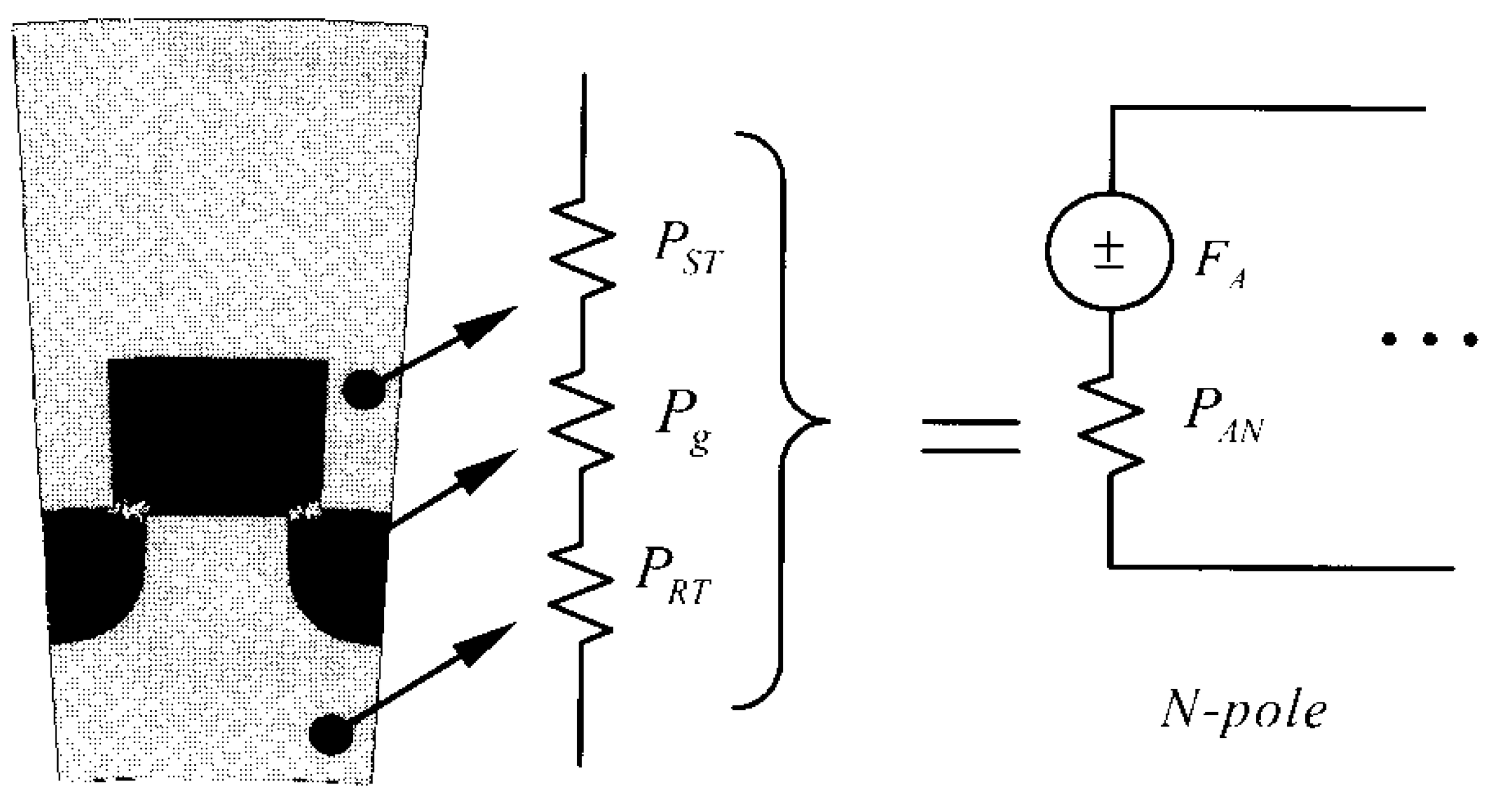
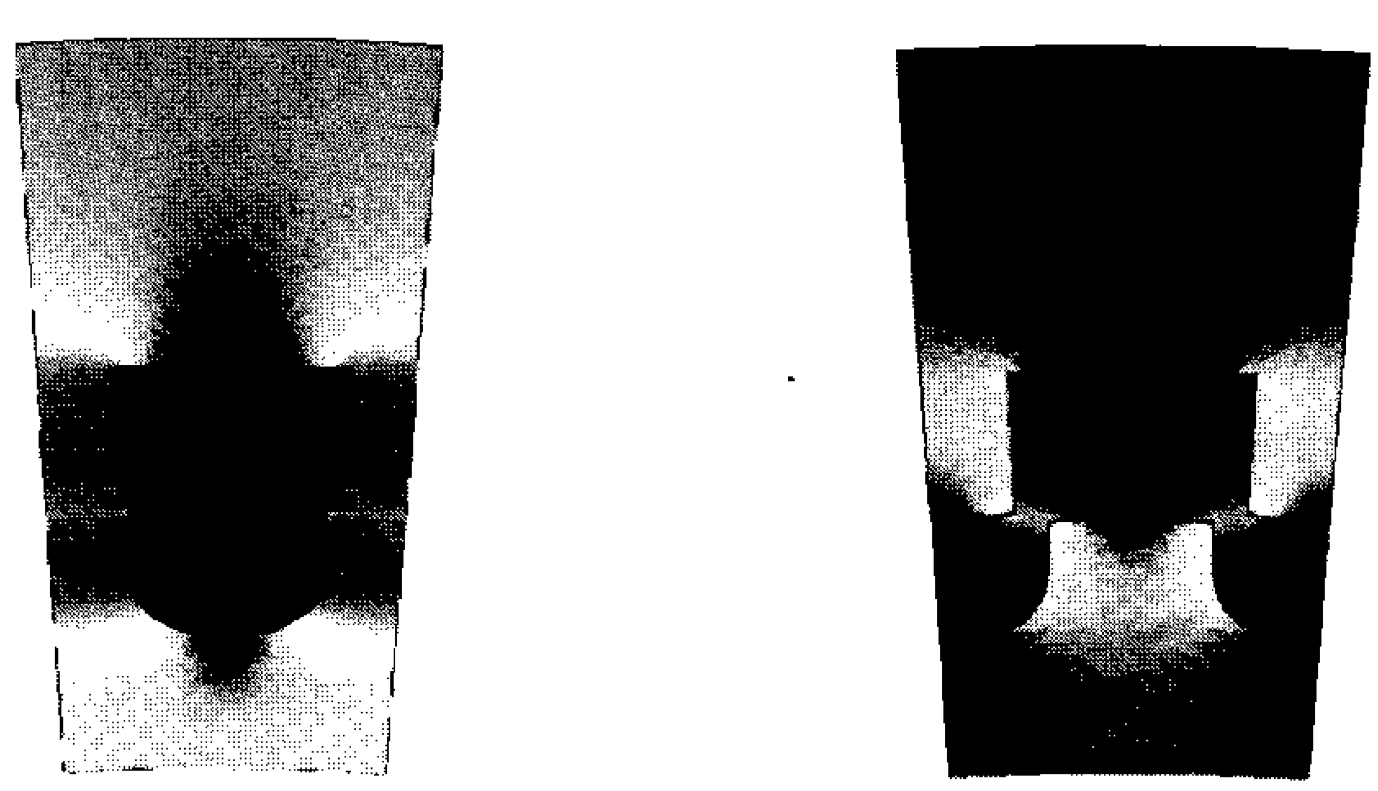


Fig. 4 Tooth and airgap permeance model



(a) Aligned (b) Unaligned

Fig. 5 FE analysis results for tooth and airgap model

$$W_s = \frac{1}{2} F_g^2 P_g(\theta_e) \tag{2}$$

where, θ_e is electrical displacement angle from 0 to 2π, which corresponds to one rotor tooth pitch and is derived by a product of mechanical angle θ_m and the number of teeth of the rotor, N_r.

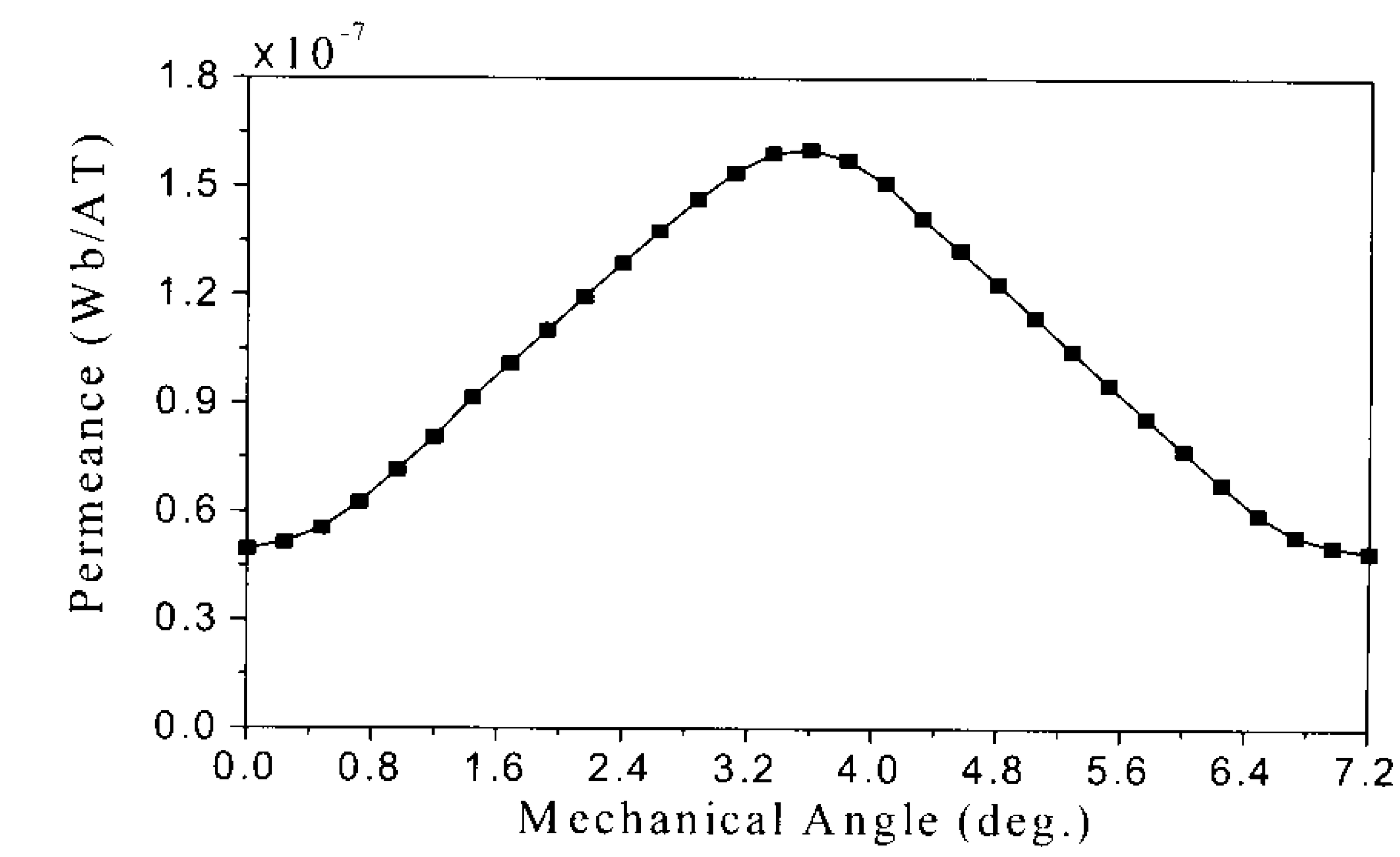
Therefore, the airgap permeance can be expressed as the following Fourier series form for the N-poles of the 5-phase hybrid stepping motor[2].

$$\begin{aligned}
P_{gAN} &= P_0 + \sum_{i=1}^{\infty} P_i \cos(\theta_e) \\
P_{gBN} &= P_0 + \sum_{i=1}^{\infty} P_i \cos(\theta_e + \frac{4}{5}\pi) \\
P_{gCN} &= P_0 + \sum_{i=1}^{\infty} P_i \cos(\theta_e + \frac{8}{5}\pi) \\
P_{gDN} &= P_0 + \sum_{i=1}^{\infty} P_i \cos(\theta_e + \frac{12}{5}\pi) \\
P_{gEN} &= P_0 + \sum_{i=1}^{\infty} P_i \cos(\theta_e + \frac{16}{5}\pi)
\end{aligned} \tag{3}$$

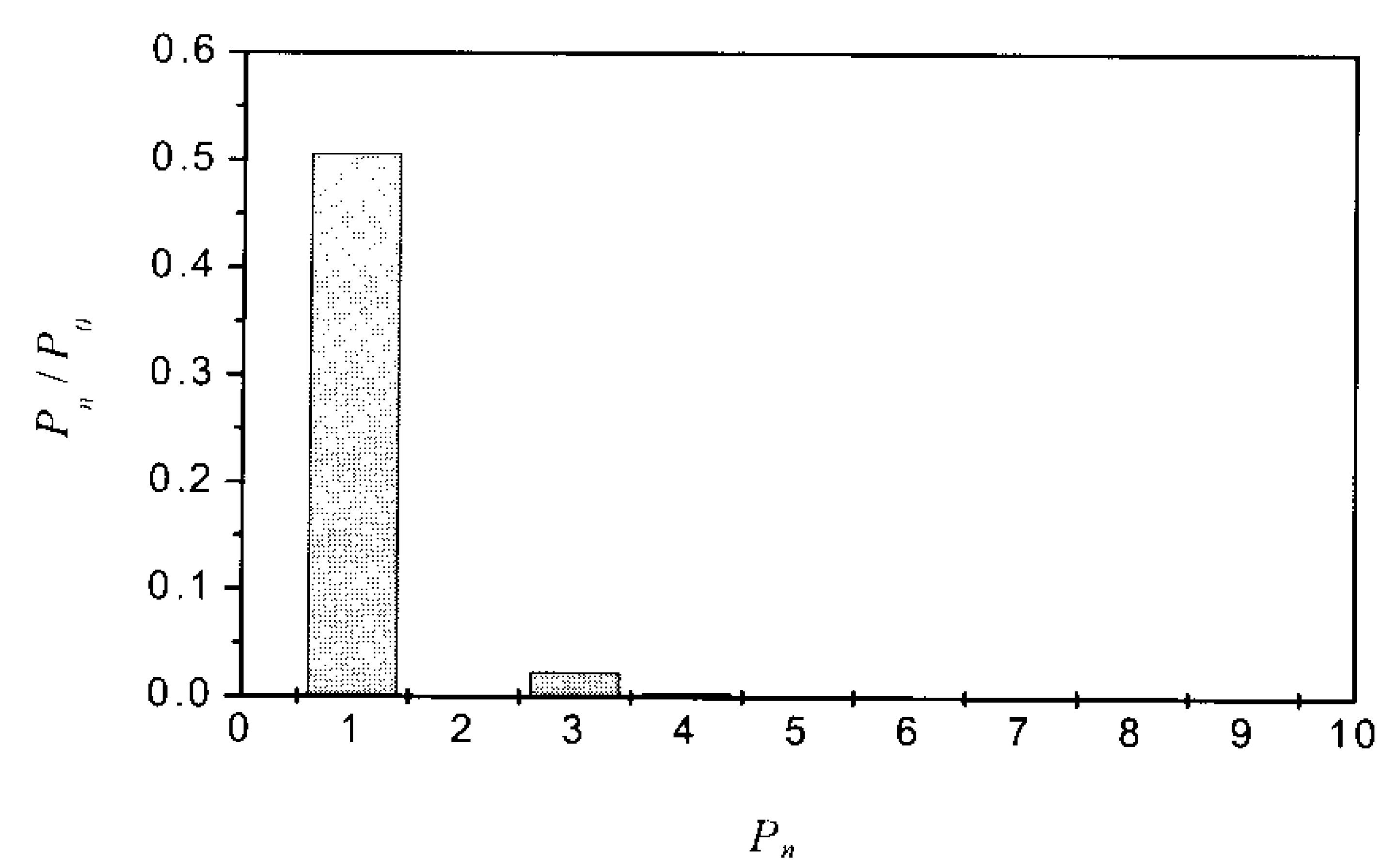
where, P_0 and P_i are permeance coefficients, and i is order of harmonics.

From (3), the airgap permeance for the S-poles is clearly written by replacing θ_e by $\theta_e + \pi$ due to the fact each N- and S-pole is offset by half of rotor tooth pitch corresponding to electrical angle π.

The permeance coefficients actually represent the space harmonic distribution for the permeance curve with respect to the rotor position obtained from the FE analysis. And the permeance variations expressed by (3) are coupled with the equivalent circuit to estimate the performance of the motor.



(a) Airgap permeance curve



(b) Space harmonic distribution

Fig. 6 Airgap permeance characteristic

Fig. 6 shows an airgap permeance curve and its space harmonic distribution on the assumption that the relative permeability of the iron core is infinite and the leakage flux in the axial direction can be neglected. The result of Fig. 6 is taken from the airgap model and not affected by the change of the applied MMF across the airgap.

4. Characteristic analysis

Torque developed by the principle of virtual displacement is

$$T = \frac{\partial W_s}{\partial \theta_m}, \tag{4}$$

where θ_m is mechanical angle and W_s is the magnetic stored energy.

Since the flux is kept constant as the change of rotating angle, the corresponding torque expression can be obtained as

$$T = -\frac{1}{2} N_r F_a^2 \frac{\partial P(\theta_e)}{\partial \theta_e}, \quad (5)$$

where T is the static torque, F_a is the applied MMF, and P is the permeance[5].

Therefore, the static torque with respect to each rotating angle can be calculated by solving the equivalent magnetic circuit with its circuit parameters obtained by the FEM.

The permanent magnet type motors generally have a cogging torque even in the absence of source current because of the flux from the permanent magnet. And the torque formula is identical to (4).

To solve the equivalent magnetic circuit, it is important to predict the accurate permeance value, especially, the permeances between the stator pole and the rotor described by symbol P in the equivalent circuit.

The static torque neglecting the non-linearity and reluctance of the iron core can be easily obtained by using the permeance between the stator pole and rotor which has only a part of the airgap permeance shown in Fig. 4. In this case, the holding torque is estimated about 1.5 or 2 times greater than experimental result according to a different size of the 5-phase hybrid stepping motor.

The hybrid stepping motors, however, are designed to operate under saturated conditions, therefore, it requires the non-linear analysis method in the equivalent circuit. In case of considering the saturation of the stator/rotor teeth, the equivalent circuit cannot be solved at a time because its permeances are the function of the applied MMF drop which is unknown at the start of the problem and represents a degree of the saturation. Therefore, the circuit solution must be determined by an iterative process and keep correcting the permeance by the obtained MMF until it is consistent with the circuit solution.

Fig. 7 illustrates the whole process to treat the nonlinear parameters in the equivalent circuit. Although the permeance data should be re-calculated through the FE analysis when the new local MMFs are determined by solving the equivalent magnetic circuit, it is computationally time expensive. Consequently, the parameter approximation techniques are needed to reduce the computational time in predicting the non-linear permeance while maintaining a good accuracy of parameter estimation.

Fig. 8 shows the permeance distribution of the tooth and airgap model with respect to both the mechanical angle between the rotor and stator tooth and the MMF drop. The permeance coefficients are taken from each permeance distribution for a given MMF drop.

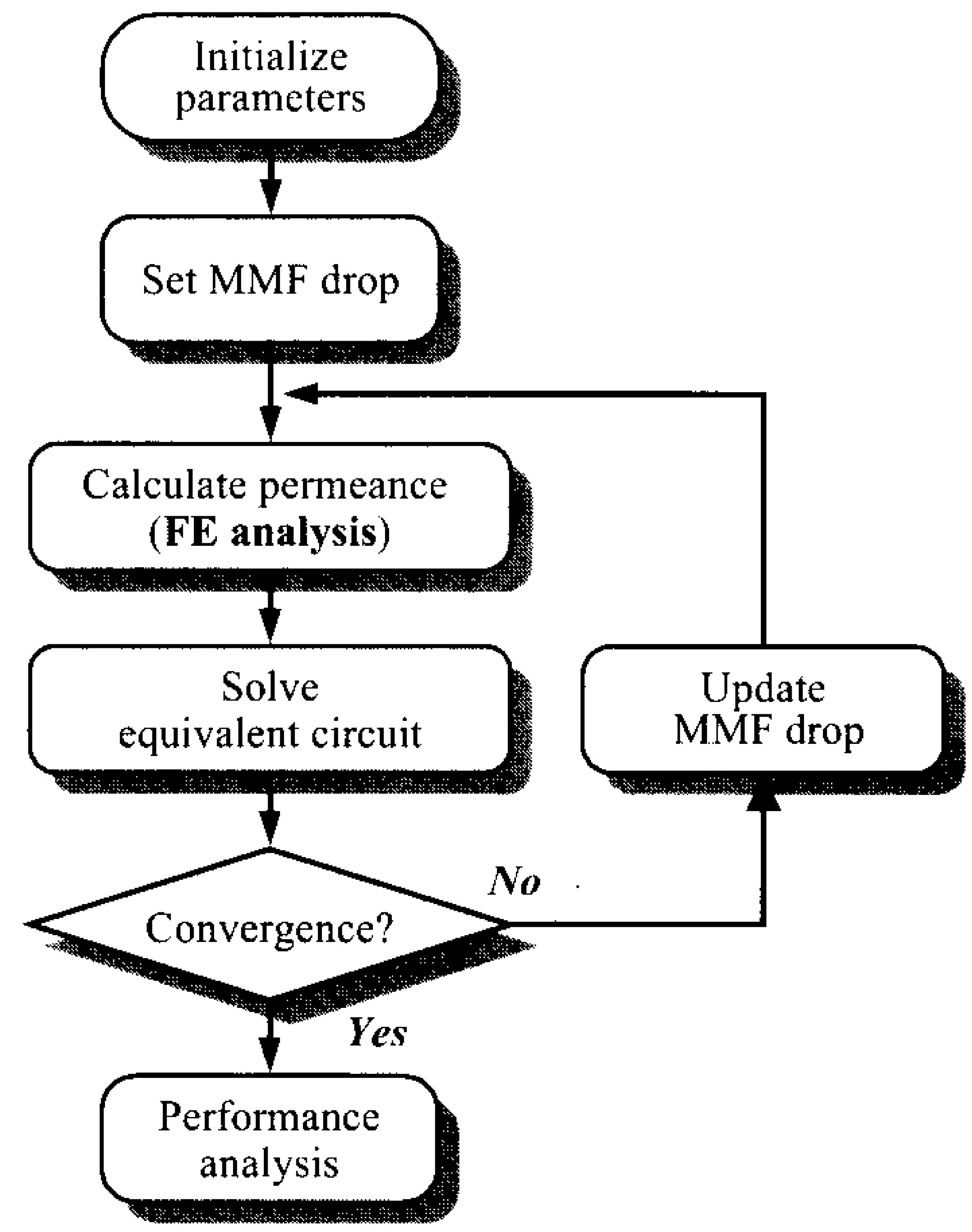


Fig. 7 Flow chart of performance analysis

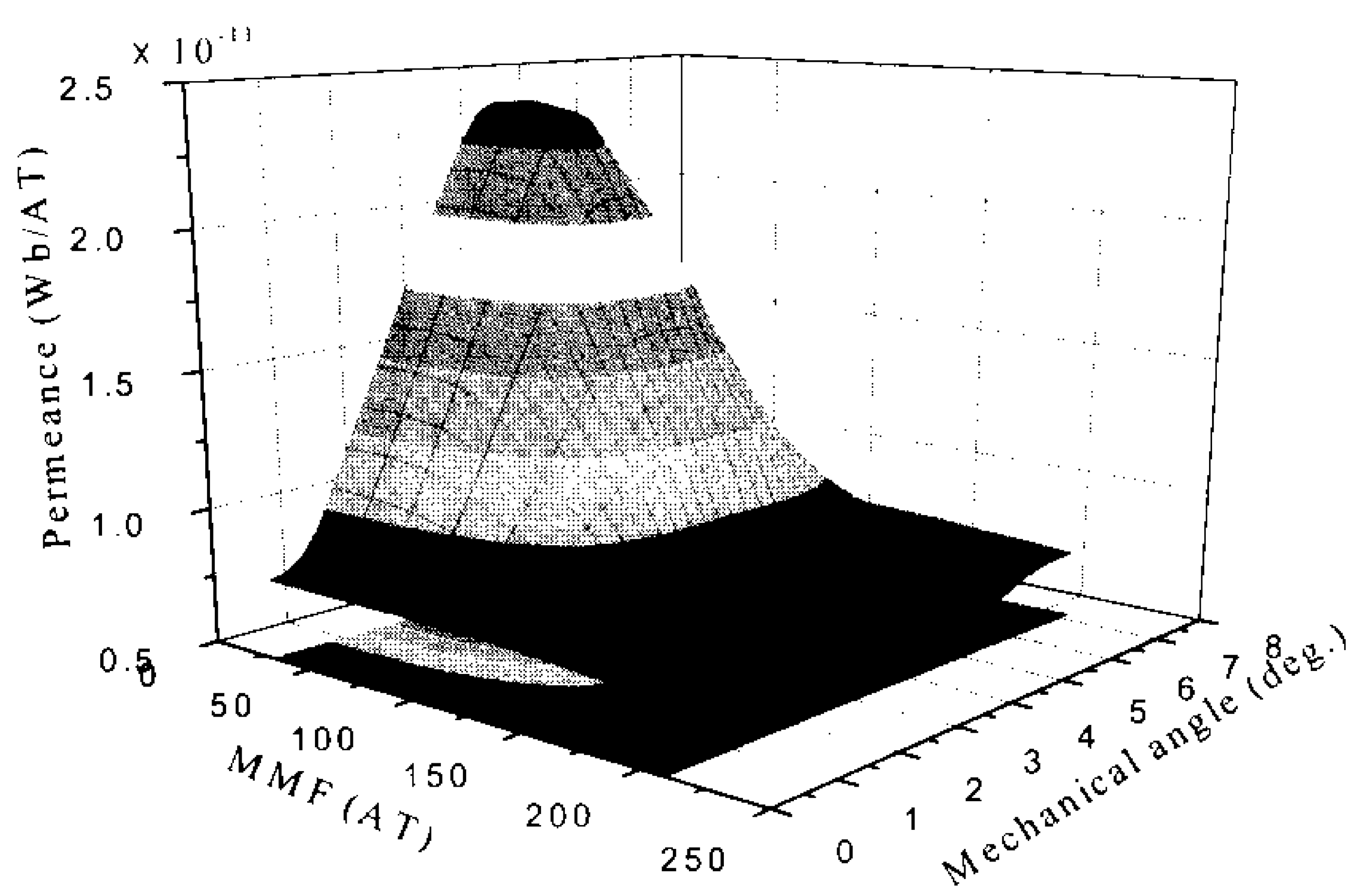


Fig. 8 Permeance characteristics of the tooth and airgap model

When the hybrid stepping motor is used in over-rated current region, the saturation on stator poles cannot be ignored, especially, in condition that fluxes produced by both permanent magnet and exciting current are added on the stator pole. The saturation on the stator pole can be treated in the equivalent circuit by using its geometric dimension and the non-linear permeability computed by B-H characteristic curve.

5. Neural Network Model

Artificial neural networks are composed of simple elements called neuron operating in parallel. As in nature, the neural network is implemented largely by connection between neurons and capable of learning and storing complex information in various fields of application[6].

Fig. 9 shows a multi-layer feed-forward neural network which is generally composed of three different layers. The back-propagation is a very popular network model for most multi-layer feed-forward network and appropriate for

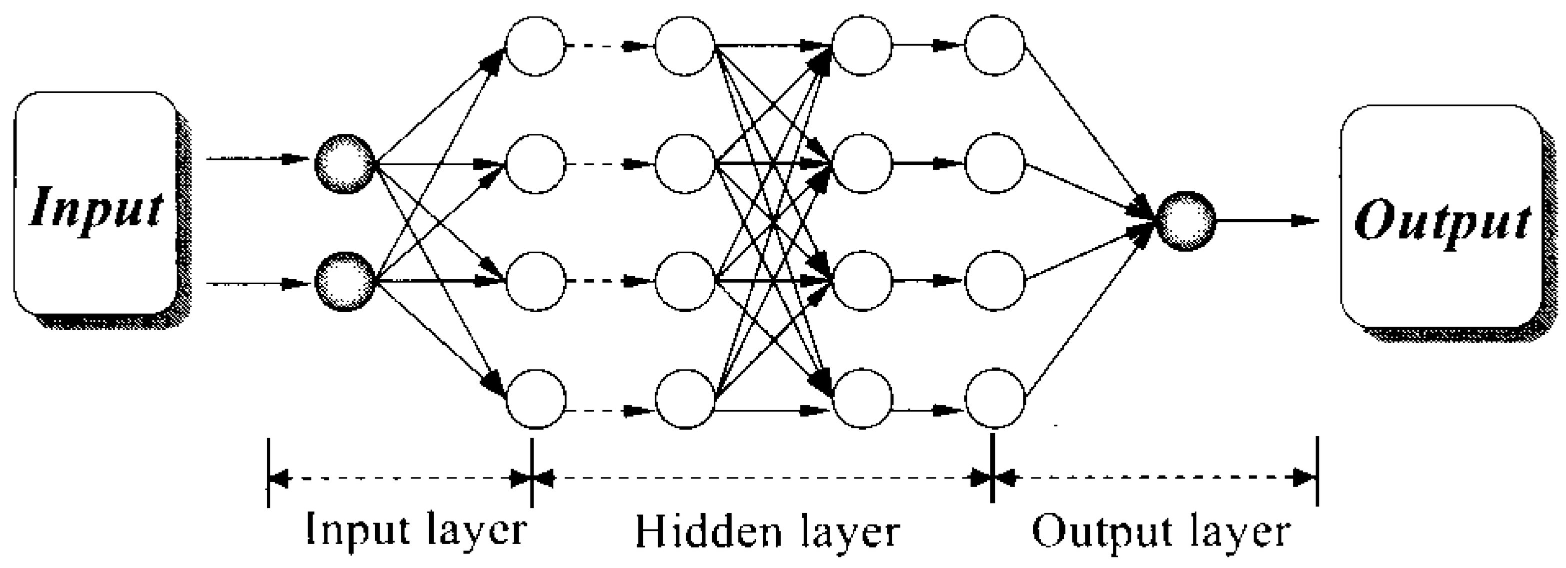


Fig. 9 Multi-layer feed-forward neural network

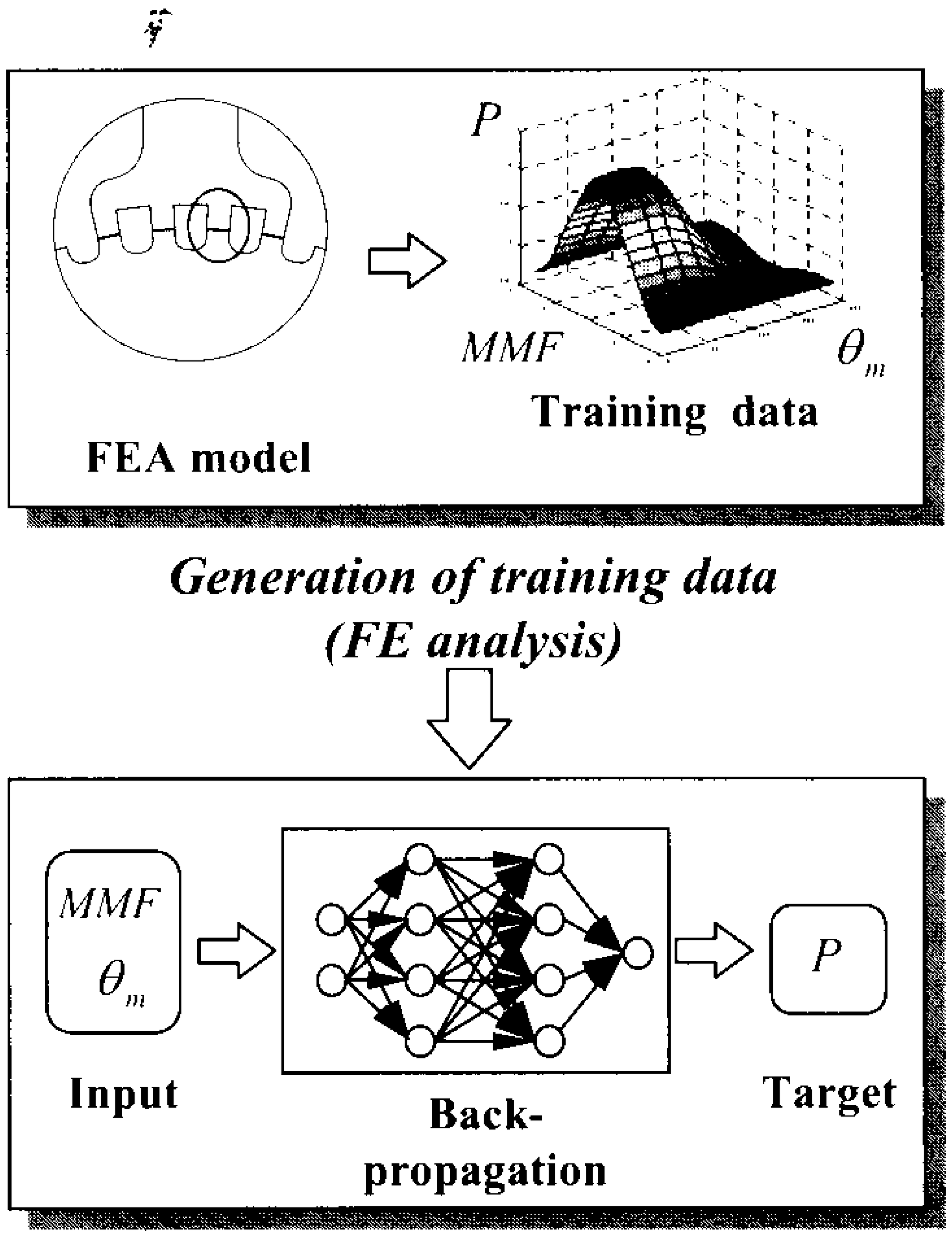


Fig. 10 Off-line neural network training process

the function approximation.

Fig. 10 illustrates the training process of the neural network which is employed to map the relations between MMF drop and rotor position as the input and magnetic circuit parameters as the output. The training process is achieved by using the well-known Levenberg-Marquardt algorithm which reportedly has the fastest convergence[6].

The number of neuron in the input and output layer is determined by the number of the input and output variables but the choice of the number of the hidden layers and neurons are not clearly determined but somewhat experimental work. In this application, the neural network has 4 layers with a 2-10-10-1 structure in which two hidden layers are used.

A series of different permeance data with respect to both MMF drop and rotor position in the feasible region are calculated using FE analysis and used to train the neural network estimator. The permeance data to create the properly-trained neuron network are already shown in Fig. 8.

Fig. 11 shows the flow chart of the characteristic analysis of the 5-phase hybrid stepping motor, in which the neural network is used as the parameter estimator. In this application, the neural network maps the relations between the rotor position and MMF drop as input and the magnetic circuit parameter, permeance, as output.

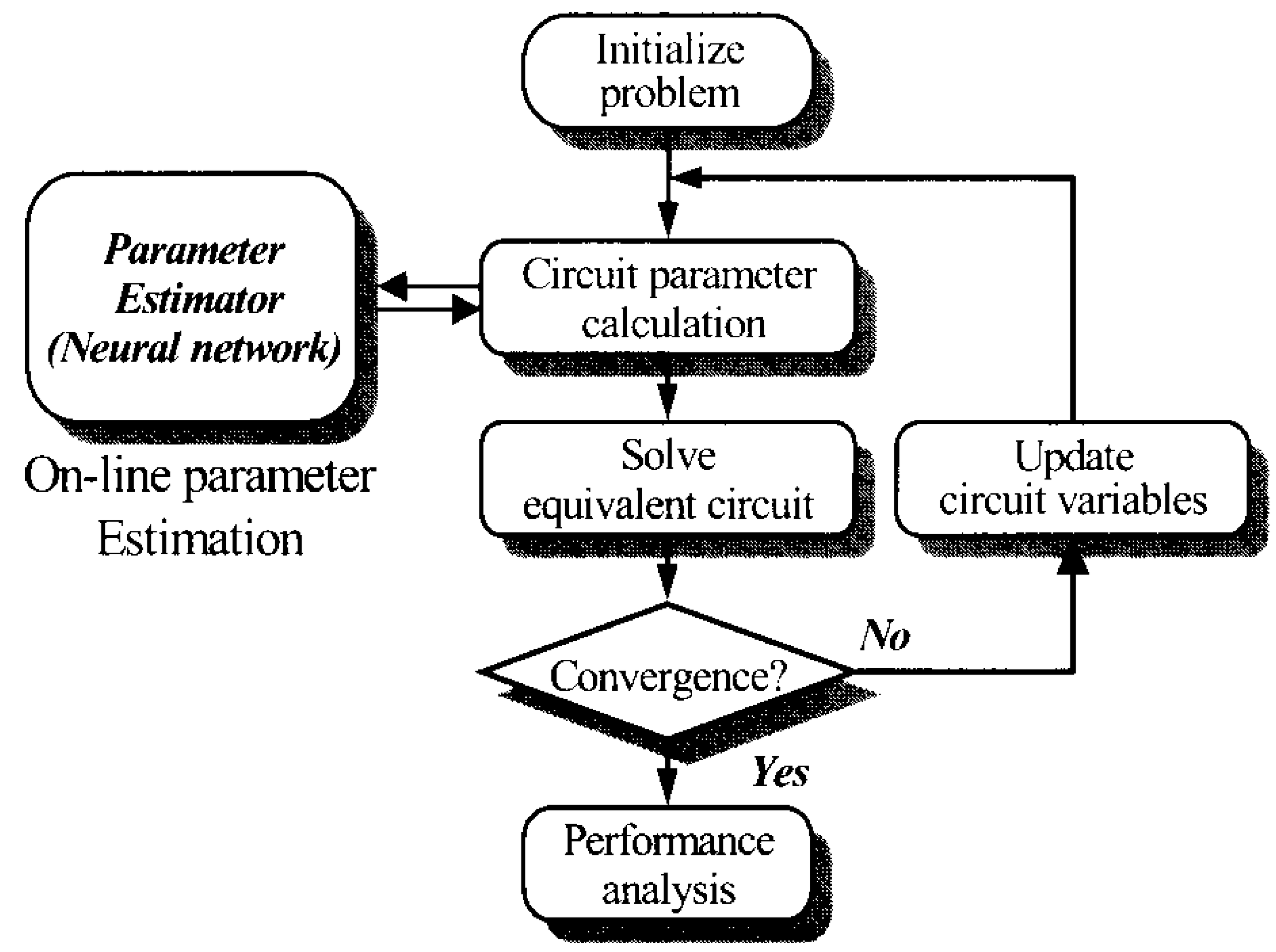


Fig. 11 Improved process of performance analysis

In Fig 11, the invariable circuit parameters including MMF source are initialized and the neural network trained by FEM results predicts the permeance between the stator pole and the rotor. The net flux is obtained by solving the equivalent magnetic circuit so that MMF drop of the permeance can be re-calculated using the net flux. Finally, if each non-linear permeance converges to a desired tolerance, the performance of the motor is analyzed.

6. Simulation and experiment

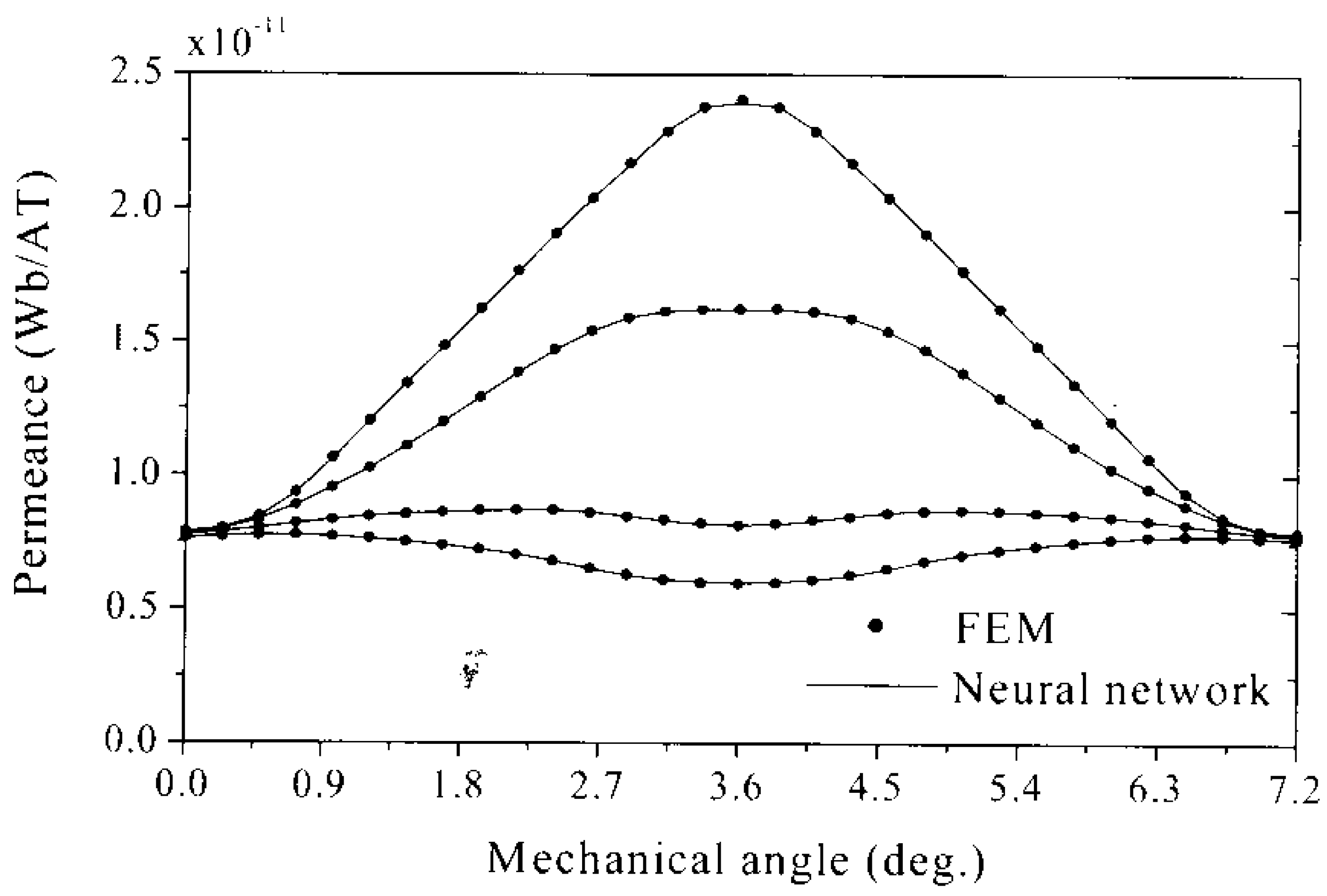
The brief specification of a test motor, which has been widely used in industry applications, is given in Table I.

Fig. 12 shows the permeance distribution calculated by the trained neural network and the FEM. They show a good correlation, however, the difference is still exist and slightly increased around an unaligned tooth position which represents zero mechanical angle. Fig. 12-(a) describes the direct comparison of the FEM results as the desired data and the neural network results as the estimated data. And Fig. 12-(b) shows the calculation results at the center of mechanical angle value in Fig. 12-(a). And the unknown values according to MMF drop are successfully estimated.

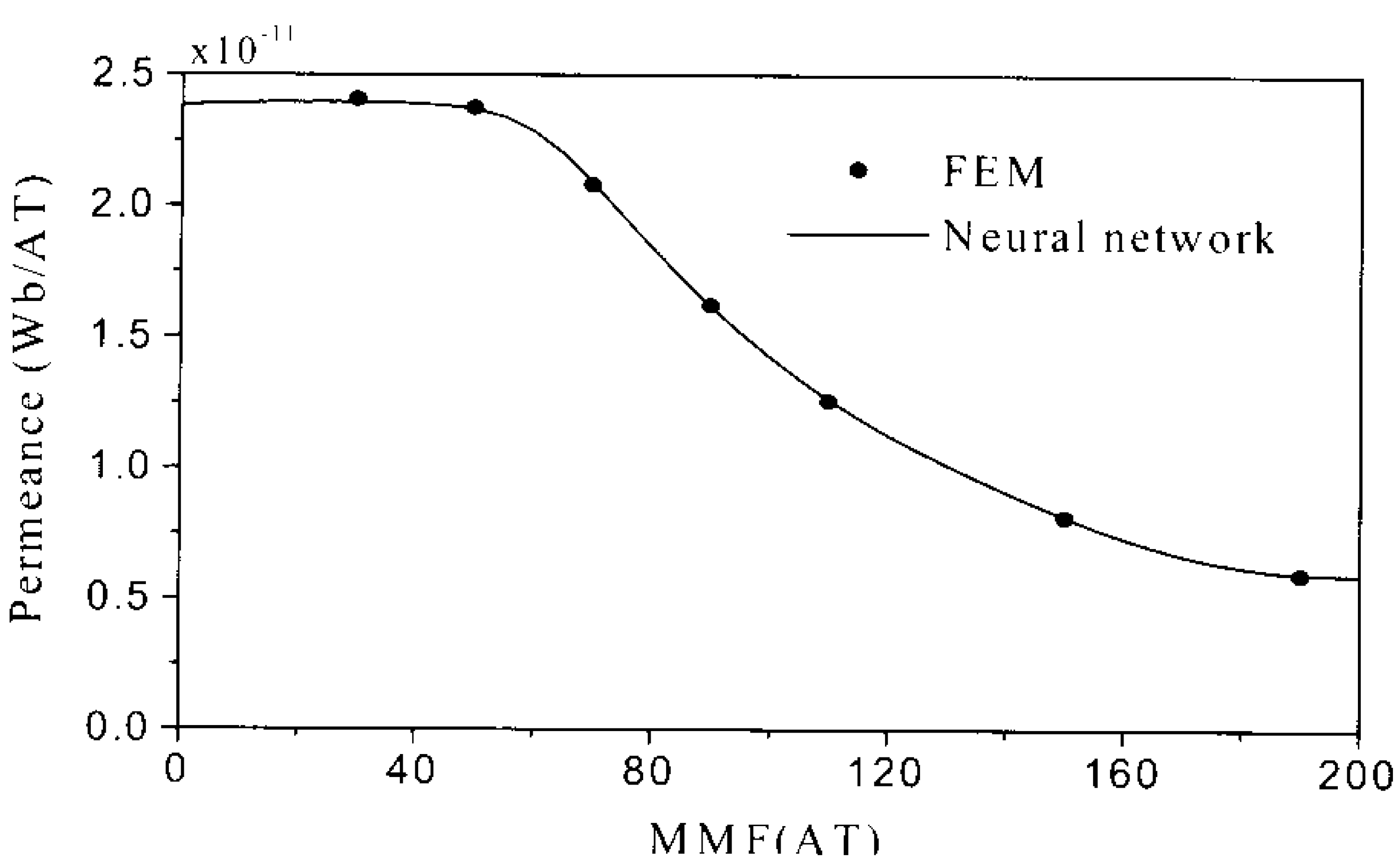
For a given motor specification, the solution time for the calculation of the equivalent circuit parameters by using the properly-trained neural network is by far less

Table 1 Specification of a test motor

Items	Values	Units
Number of phases	5	
Rated current	0.75	(A)
Rated holding torque	0.24	(Nm)
Turns per pole	53	
No. of teeth per stator pole	4	
No. of rotor teeth	50	
Airgap length	0.05	(mm)



(a) Rotor position versus permeance



(b) MMF drop versus tooth airgap permence

Fig. 12 Comparision of FEM and Neural network results

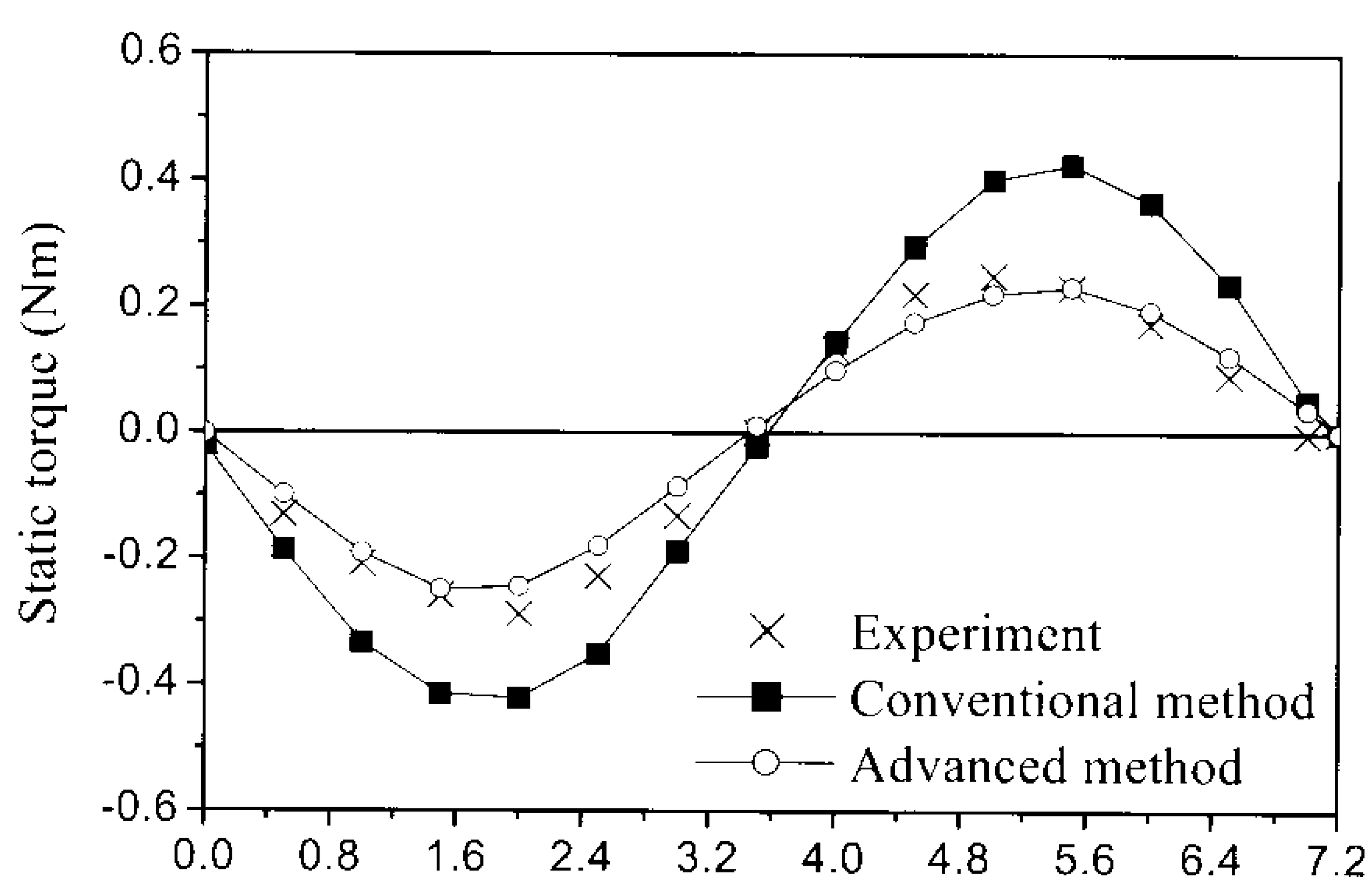


Fig. 13 Static torque characteristics

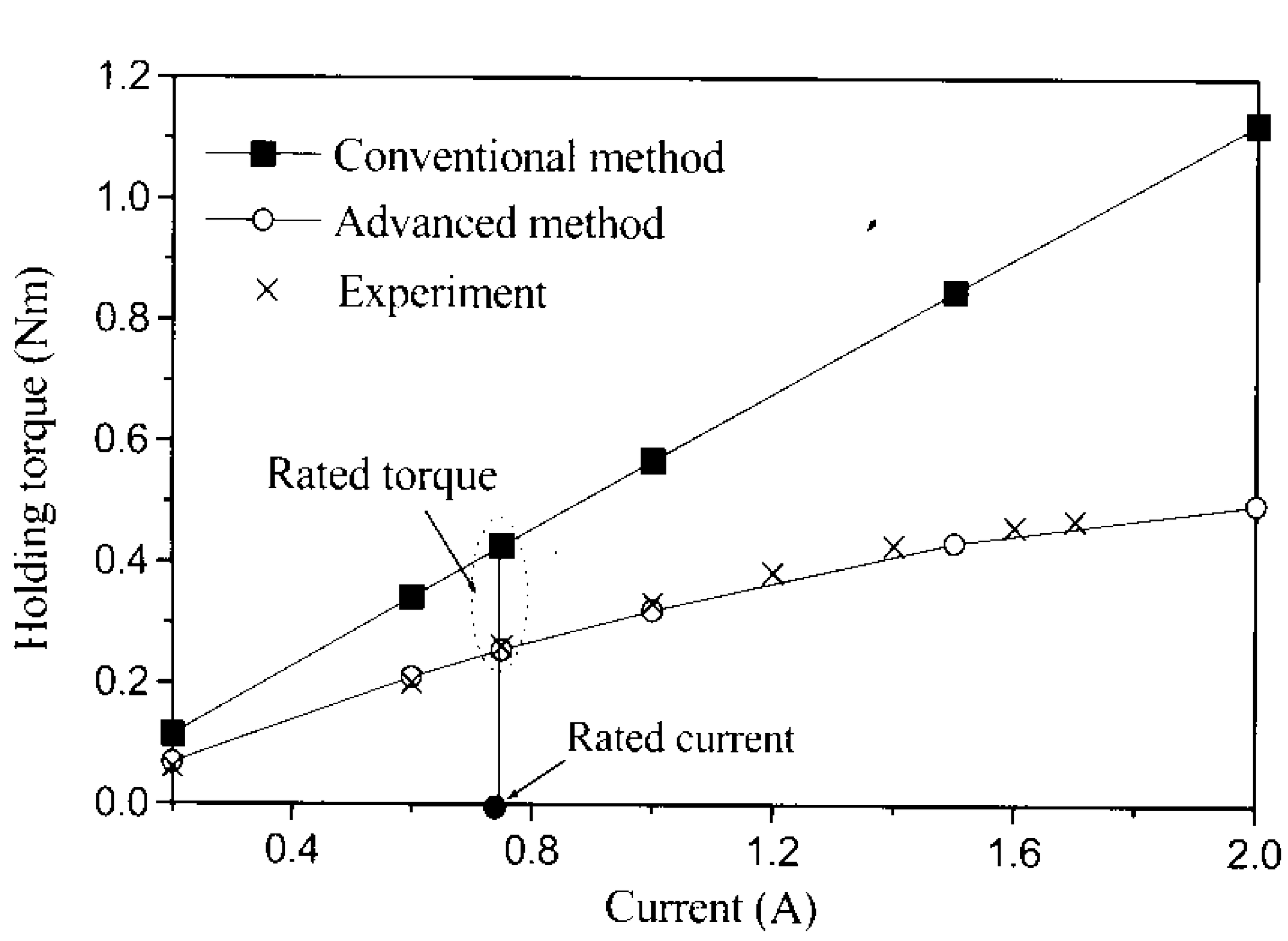


Fig. 14 Holding torque versus exciting current characteristics

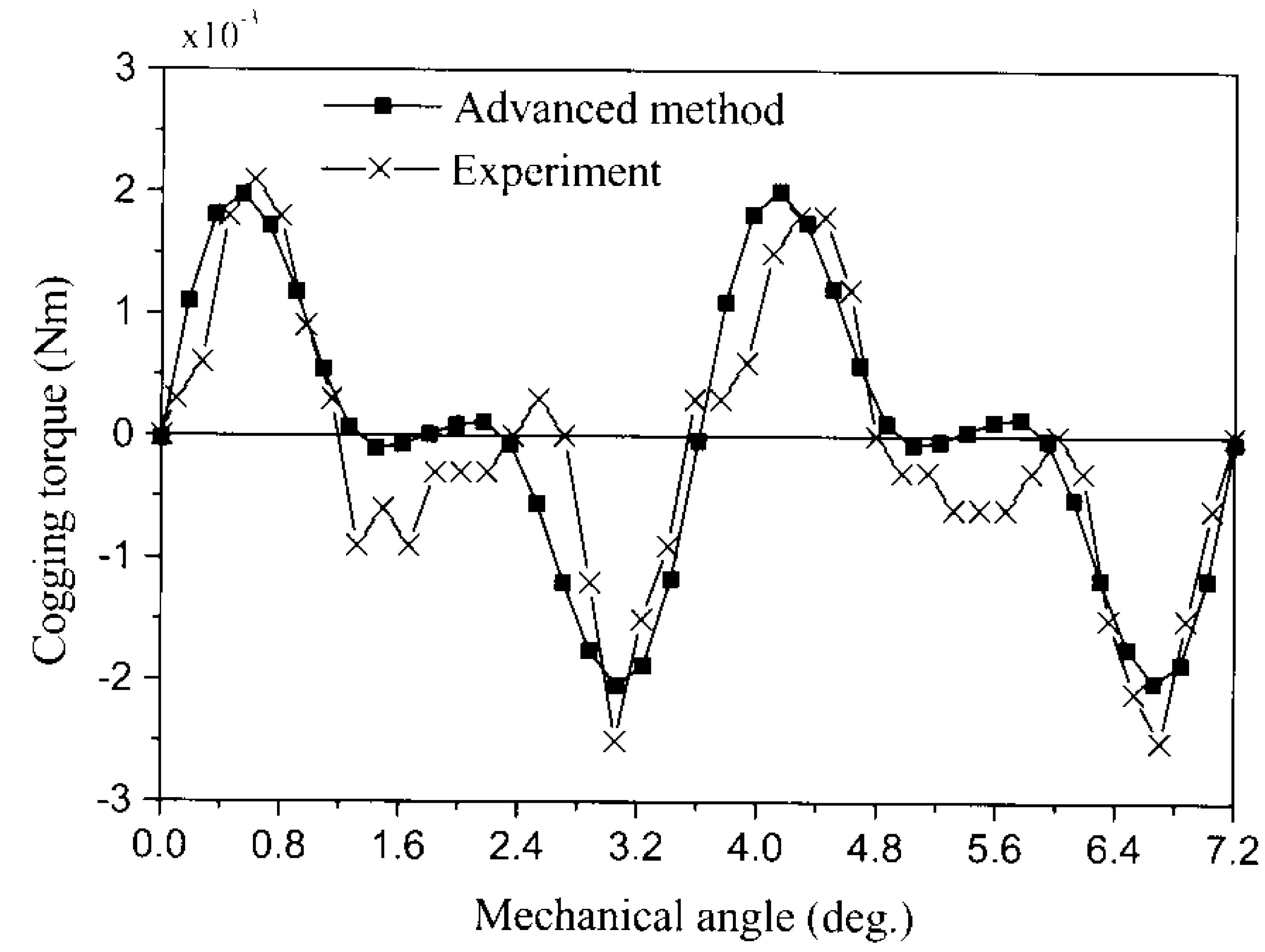


Fig. 15 Cogging torque characteristics

than the calculation time required by the FEM solution.

Fig. 13 shows the static torque characteristics of the test motor at the rated current which are calculated for each incremental rotor position. In Fig. 13, the conventional method describes the case that the permeance between the stator pole and the rotor is considered as the airgap permeance alone. The advanced method is to take the required permeance from the tooth and airgap model illustrated in Fig. 4 and has the sufficient accuracy for the analysis of highly saturated motors.

The conventional method estimates the maximum value of the static torque distribution, which is defined as the holding torque, to be approximately 2 times the experimental one while the advanced method shows the more reasonable result corresponding to the experimental value.

Fig. 14 illustrates the holding torque to the exciting current characteristics. The conventional method shows that the holding torque curve have a linearity in all current region. However in the advanced method, the holding torque has a saturation characteristic which has a good agreement with experimental one.

Fig. 15 shows the cogging torque with respect to the rotor position computed by the advanced method.

In general, the cogging torque is susceptible to the accuracy of the circuit parameters and difficult to measure the reliable results experimently because of relatively small value.

When the exciting current is increased over certain current level, the developed torque is on the decrease due to the saturation of the stator pole as well as the tooth. And, the saturation of the stator pole can be easily considered by adding the non-linear reluctance of the stator pole to the equivalent circuit.

7. Conclusion

This paper proposes the advanced analysis technique by using the equivalent magnetic circuit taking into account the saturation effect of a 5-phase hybrid stepping motor, in which the FEM is used to calculate the accurate magnetic circuit parameters. In addition, the neural network is used in combination with the FEM results to estimate the circuit parameters. As a result, the solution time for calculating the circuit parameters using the neural network estimator is dramatically reduced while a sufficient accuracy is still provided.

The proposed analysis technique can be easily applied to the design process and optimization problem in case that the tooth and airgap geometries are determined in advance.

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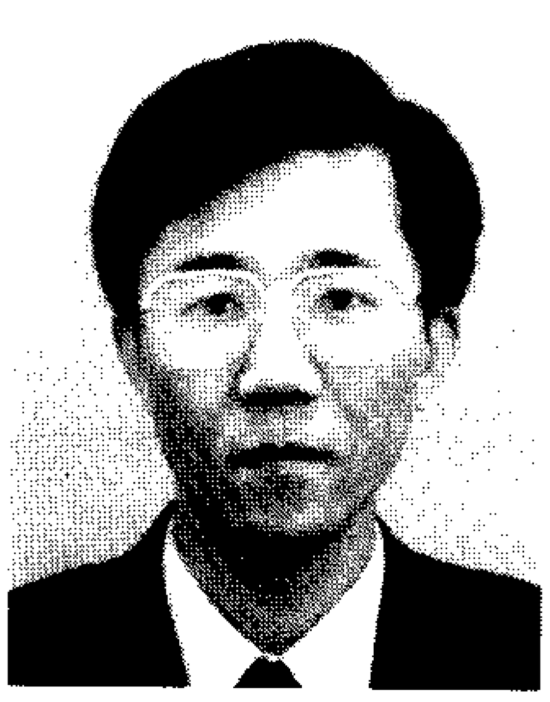

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