유한요소법을 이용한 3상 유도전동기 등가회로에서의 파라미터 계산

장전해, 렌지얀, 고창섭
충북대학교 전기공학과

Estimation of Equivalent Circuit Parameters of Three-Phase Induction Motor Utilizing Finite Element Method

Dianhai Zhang, Ziyan Ren, Chang Seop Koh
Chungbuk National University

Abstract - An effective estimation method of equivalent circuit parameters of three-phase induction motor by using FEM is presented in this paper. Arbitrary three torque-speed points at asynchronous speed on the torque-speed curve are required by using time-stepping FEM, then the equivalent circuit parameters of IM can be calculated rapidly with presented method. After obtaining the equivalent circuit parameters, the general analysis method based on equivalent circuit can be used to get entire torque-speed curve very quickly. Although the purely numerical method such as FEM also can estimate torque-speed curve directly and accurately, however ,usually this process is time consuming.

1. Introduction

In recent years, the three phase squirrel cage induction motors are increasingly used in different applications, such as chemical industry, electrical power plant, gas, steel and ship building fields due to simple structure and mature technology. [1]

In order to design and analyze the induction machine, most motor manufacturers and factory representatives still favor representing their induction motor as an equivalent circuit, though the purely numerical method such FEM or BEM method also can be used in analyzing the performance of the motor and design the motor. The characteristics of an induction motor, for almost a century, are studied with the help of equivalent circuits. One of the main problems to be solved after an induction machine electromagnetic design is the determination of the motor behavior in terms of torque and current characteristics. The fastest approach is to use the equivalent circuit theory. Usually, the equivalent circuit parameters such as stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance and magnetizing reactance can be obtained by using some approximate analytical expressions, however the parameters calculated by these methods exists relatively greater error, because the geometry of the motor is complex and the property of the material of the motor is nonlinear.[2][3]

Thanks to the use of FEM, the characteristics of the induction motor can be accurately estimated, but the disadvantage of this method is relatively longer computing time. It is better to combine the equivalent circuit method and FEM to analyze the performance of the induction motor. Some works have been published to predict the equivalent circuit parameters by using BEM, however, the required parameters are peak torque, frequency at peak torque, and induced stator voltage at peak torque.[4] It is difficult to determine the position of peak torque at torque-speed curve. So it is difficult to calculate the equivalent circuit parameters by using previous work. In this method, only three arbitrary torque values at asynchronous speed required from time-step FEM, and then the equivalent circuit parameters of the motor can be determined from this three points.

2. Parameter Estimation Approach

The classical equivalent circuit of three phase induction machine is shown in Fig. 1. Here, V_1 is phase voltage, R_1, X_1 X_m, $R_2{}'$, $X_2{}'$ and s is stator resistance, stator reactance, magnetizing reactance, rotor resistance, rotor reactance and slip of the rotor respectively.

From the classical equivalent circuit theory, the expression of mechanical torque can be written as follows:

$$T_{mech} = \frac{1}{\omega_s}\left\{\frac{3\,V_{1,eq}^2 (R_2{}'/s)}{(R_{1,eq} + (R_2{}'/s))^2 + (X_{1,eq} + X_2{}')^2}\right\} \quad (1)$$

Here, ω_s is the synchronous speed, $V_{1,eq}$ and $Z_{1,eq}$ can be calculated as follows:

$$V_{1,eq} = \frac{jX_m V_1}{R_1 + j(X_1 + X_m)} \quad (2)$$

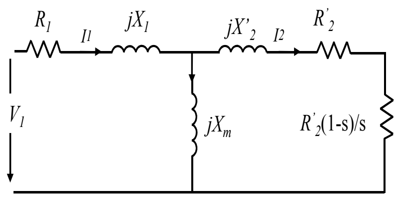
$$Z_{1,eq} = \frac{jX_m (R_1 + jX_1)}{R_1 + j(X_1 + X_m)} \quad (3)$$

Substituting (2) and (3) into (1), the mechanical torque can be expressed as [5]:

$$T_{mech} = 1/(As + Bs^{-1} + C) \quad (4)$$

Here the coefficients A, B and C can be expressed as follows:

$$A = \frac{(X_1 + X_2{}')^2 + R_1^2}{3R_2{}' V_1^2} + \frac{2X_2{}'(X_1^2 + R_1^2 + X_1 X_2{}')}{3R_2{}' V_1^2 X_m} + \frac{X_2{}'^2 (X_1^2 + R_1^2)}{3R_2{}' V_1^2 X_m^2} \quad (5)$$



<Fig. 1> Equivalent circuit of induction motor

$$B = \frac{R_2{}'}{3V_1^2} + \frac{2R_1 X_1}{3V_1^2 X_m} + \frac{R_2{}'(X_1^2 + R_1^2)}{3V_1^2 X_m^2} \quad (6)$$

$$C = \frac{2R_1}{3V_1^2} \quad (7)$$

Rearrange the expression (4), the reciprocal of mechanical torque can be expressed as follows:

$$\tau = \frac{1}{T_{mech}} = As + Bs^{-1} + C \quad (8)$$

If three different torque speed points are given such as s_1, s_2, s_3 and τ_1, τ_2, τ_3 respectively, then the three torque expressions can be expressed as the form of matrix shown as follows:

$$\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\end{bmatrix}=\begin{bmatrix}s_1\, s_1^{-1}\, 1\\ s_2\, s_2^{-1}\, 1\\ s_3\, s_3^{-1}\, 1\end{bmatrix}\begin{bmatrix}A\\ B\\ C\end{bmatrix} \tag{9}$$

Now the coefficients A, B and C can be rewritten by using three slip and torque values shown as follows:

$$A=\frac{\tau_1 s_1(s_3-s_2)+\tau_2 s_2(s_1-s_3)+\tau_3 s_3(s_2-s_1)}{(s_1-s_2)(s_2-s_3)(s_3-s_1)} \tag{10}$$

$$B=\frac{s_1 s_2 s_3[\tau_1(s_3-s_2)+\tau_2(s_1-s_3)+\tau_3(s_2-s_1)]}{(s_1-s_2)(s_2-s_3)(s_3-s_1)}$$

(11)

$$C=\frac{\tau_1 s_1(s_3^2-s_2^2)+\tau_2 s_2(s_1^2-s_3^2)+\tau_3 s_3(s_2^2-s_1^2)}{(s_1-s_2)(s_2-s_3)(s_3-s_1)} \tag{12}$$

The expressions (10) – (12) can be used to determine the coefficients from three different torque-speed points. the determinant of the coefficient matrix in (9) can be calculated as follows:

$$\begin{vmatrix}s_1\, s_1^{-1}\, 1\\ s_2\, s_2^{-1}\, 1\\ s_3\, s_3^{-1}\, 1\end{vmatrix}=\frac{(s_1-s_2)(s_2-s_3)(s_3-s_1)}{s_1 s_2 s_3} \tag{13}$$

From the expression (13) the value of determinant is non-zero and finite only when the slip locate three different asynchronous speeds. Therefore, three different torque-speed points, which located at asynchronous speed can guarantee unique torque-speed curve.

Generally speaking, the magnetizing reactance Xm in induction machine has a larger value compared with other parameters, so this value can be removed from the expression (5) – (7) to simply the equations. Then the simplified expressions can be rewritten as follows:

$$A=\frac{(X_1+X_2{}')^2+R_1^2}{3R_2{}'\,V_1^2} \tag{14}$$

$$B=\frac{R_2{}'}{3\,V_1^2} \tag{15}$$

$$C=\frac{2R_1}{3\,V_1^2} \tag{16}$$

Expression (14) – (16) shows the relation between coefficient A, B and C obtained from three different torque-speed points and equivalent circuit parameters. From expression (14) – (16) the equivalent circuit parameters of induction motor can be derived shown as follows:

$$R_1=\frac{3CV_1^2}{2} \tag{17}$$

$$R_2{}'\approx 3BV_1^2 \tag{18}$$

$$X_1+X_2{}'\approx\frac{3}{2}V_1^2\sqrt{4AB-C^2} \tag{19}$$

The above three expressions can be used to estimate the equivalent circuit parameters of induction motor. Although the magnetizing reactance has to be ignored in the expressions, the expressions can be largely simplified without remarkable error.

3. Verification and Analysis Example

The specifications of the simulation example induction motor are: 380V, 3.7kW, 8 pole, delta connected squirrel cage rotor. The torque at slip=0.067, 0.2 and 0.467 are calculated by using FEM and the torque is 135 Nm, 220Nm and 196Nm respectively. By using the three given points the equivalent circuit parameters can be estimated and then the torque-speed curve can be calculated from these parameters. Fig. 2 shows the torque-speed curve from equivalent circuit method and FEM respectively.

4. Conclusion

This paper presents a method to estimate equivalent circuit parameters of three-phase induction motor. In order to estimate the parameters three different torque-speed points at asynchronous speed by using FEM are required. A practical example is given and guaranteed that the accuracy of the estimation of parameters is reasonably good.

[References]

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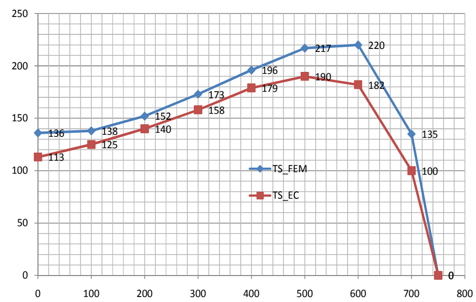

<Fig. 2> Torque-speed curve from FEM and equivalent circuit method