RESEARCH ARTICLE

COMPARISON ANALYSIS OF STATOR RESISTANCE ESTIMATION OF THREE PHASE INDUCTION MACHINE WITH AIR GAP POWER AND REGRESSION METHODS

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ARTICLE INFO	ABSTRACT
	This paper proposes two online algorithms for estimating stator resistance of an induction motor without using rotor resistance. In this research, we use "air gap power" and "linear regression" methods to estimate resistance of stator in different speeds and torques. These methods are tested using simulation and experimental data from a commercial induction motor. Benefits and defaults of each method will be compared with the other method result. Obtained results of both methods show that estimations of stator resistance in low speeds have been well but air gap method has been presented more accurately rather than linear regression.

INTRODUCTION

Today, induction motors are the most applicable ones in industry. The highlight benefits of these motors are: fastening, simple structure, low manufacturing fees, low weight, higher velocities, easier maintenance, velocity controlling accurately and at last low inertial of rotor. The main problem applying these motors is motion controlling. In control methods of the induction motors, field-oriented Control (FOC) and direct torque control(DTC) methods, dynamical model of the motor is used. These control methods are extremely sensitive to value of dynamical model parameters and as we know, values of the parameters of induction motor vary with the time, and their large variations can seriously degrade control performance of the proposed control methods .So it is necessary to estimate the motor parameter accurately. Resistance of stator is an important parameter of dynamical model of induction motor which changes due to temperature variations. The first research about estimating induction motor parameters to improve controlling the FOC was done by Graces in 1980. The method used included an extra function as a setting reactive power and required much calculation. Wang and Birdwell (1982) suggested a method by using extended Kalman filter, since measuring the tourqe is an important principle in this method, it may not be able to perform this method for big machines. In some references of this research such as 4, 5, 6, 7, 8, 9, 10 and 11 expressed in the last section, a few methods are introduced to simultaneous estimate rotor resistance. As a whole, methods to simultaneous estimate stator resistance are similar to methods used to estimate rotor resistance (time constant of rotor) and divided

to four group: spectral analysis techniques – signal injection [13], techniques in terms of observers [14], techniques in terms of model reference adaptive system (MRAS) [15] and other new methods [16 & 18]. This paper consider two methods, air gap power and linear regression to online estimation of stator resistance and compare accurately the result about benefits and defaults of each method.

II. Air Gap Method

By this method, stator resistance(R_s) is obtained from the steady-state power flow between stator and rotor through the air gap. the steady-state power across the air gap is given by:

$$P_{ag} = \frac{\overline{\omega}_e \overline{T}_e}{p} \qquad (1)$$

Where $\overline{T}_e$ is steady-state value of generated torque, $\overline{\omega}_e$ is steady-state value of Angular velocity of *d–q* synchronous reference coordinate frame and *p* is the number of poles. If input power (*P*) and magnitude of stator current vector (*I*) are defined as:

$$P = V_{ds}i_{ds} + V_{qs}i_{qs} \qquad (2)$$

$$I = \sqrt{i_{ds}^2 + i_{qs}^2} \qquad (3)$$

Therefore by using motor dynamical equations, the steady-state input power and the steady-state power dissipated by stator windings are obtained by: [18]

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$$\overline{P}_{in} = \frac{3\overline{P}}{2} \tag{4}$$

$$\overline{P}_{cu} = \frac{3R_S|\overline{I}|^2}{2} \tag{5}$$

Since input power is equal to sum of air gap power and dissipated power in stator windings, we have:

$$\overline{P} = R_s|I|^2 + \frac{2\omega_e T_e}{3p} \tag{6}$$

It is clear that we can use (6) to calculate stator resistance if the steady-state value of the generated torqueis available. It is possible to prove that although sign of $\overline{T}_e$ is not available, but $|\overline{T}_e|^2$ can be expressed in terms of the steady-state values of the reactive power (Q), the stator current magnitude (I) and the angular velocity of the d–q synchronous reference coordinate frame (ω_e) as follows: [18]

$$|\overline{T}_e|^2 = |K_T|^2 (a_0\overline{Q} - \overline{\omega}_e|\overline{I}|^2) \\ \times \{Ma_3\overline{\omega}_e|\overline{I}|^2 - (a_0\overline{Q} - \overline{\omega}_e|\overline{I}|^2) \} / |a_3\overline{\omega}_e|^2 \tag{7}$$

$$K_T = \frac{3pM}{2L_r}, a_0 = \frac{1}{\sigma L_s}, a_3 = \frac{M}{\sigma L_s L_r}$$

So for stator resistance, the following relation is obtained:

$$R_s = [\overline{P} - (2/(3p))\overline{\omega}_e \, \mathrm{sgn}(\overline{T}_e)\sqrt{|\overline{T}|^2} \,]/|\overline{I}|^2 \tag{8}$$

Overally, it seems very difficult to identify directly the sign of $\overline{T}_e$ from the stator variables. But stator resistance is one of the following values in place of appointing sign of $\overline{T}_e$:

$$R_1 = [\overline{P} - (2/3p)\overline{\omega}_e \sqrt{|\overline{T}_e|^2}\,]/|\overline{I}|^2 \tag{9}$$

$$R_2 = [\overline{P} + (2/3p)\overline{\omega}_e \sqrt{|\overline{T}_e|^2}\,]/|\overline{I}|^2 \tag{10}$$

Note that, in this paper, the simulations indicate that only one of tow above values is an acceptable answer and the other is extremely High or extremely low and so it is unacceptable. This method answers well in most of torques and speeds.

III. Linear regression method

This method is on the basis of mathematical law "linear regression" and so we call this to the same name. We should know that this method Use Only Voltage and Current Measurements for Online Estimation of the Stator resistance.

A. Parameter Identifiability

The vector voltage and flux-linkage equations of an induction motor in a fixed reference frame could be written as:

$$0 = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_r \tag{11-a}$$

$$0 = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_r \tag{11-b}$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \tag{11-c}$$

$$\vec{\psi}_r = L_m \vec{i}_s + L_r \vec{i}_r \tag{11-d}$$

We can express the above dynamical model as:

$$\vec{V}_1 + \frac{R_r}{L_r} \int \vec{V}_2 dt = j\omega_r \int \vec{V}_1 dt \tag{12}$$

Which:

$$\vec{V}_1 = \frac{L_m}{L_r} \frac{d\vec{\Psi}_r}{dt} = \vec{V}_S - R_S \vec{i}_s - \sigma L_S \frac{d\vec{i}_s}{dt} \tag{13}$$

$$\vec{V}_2 = \frac{L_m}{L_r}\vec{\Psi}_r + (1-\sigma)L_s i_s = V_S - R_S \vec{i}_s - L_S \frac{d\vec{i}_s}{dt} \tag{14}$$

If rotor flux does not change, it can be written as:

$$\vec{V}_1 = j\omega \int \vec{V}_1 dt \tag{15}$$

According to (12), space vectors $j\int \vec{V}_1 dt$, $\vec{V}_1$ and $\int \vec{V}_2 dt$ are along the same direction regardless of Rr. Thus it is possible to estimate stator resistance by using linear dependence between $j\int \vec{V}_1 dt$ and $\int \vec{V}_2 dt$. Furthermore, if these space vectors are along the same direction, their cross product must be zero. Thus:

$$\mathrm{Re}\left\{\int \vec{v}_1 dt \int \vec{v}_2^* dt\right\} = 0 \tag{16}$$

We obtain the following relation by using (13) to (16): [19]

$$\left|\int \vec{v}_s dt\right|^2 + R_S^2 \left|\int \vec{i}_s dt\right|^2 \\ -2R_S \,\mathrm{Re}\left\{\int \vec{v}_s dt \int \vec{i}_s^* dt\right\} \\ -(1+\sigma)L_S \,\mathrm{Re}\left\{\vec{i}_S^* \int \vec{v}_s dt\right\} + \sigma L_S^2 i_S^2 = 0 \tag{17}$$

Equation (17) needs a state variable filter to calculate derivatives and integrals but the supply frequency (ω) is accessible, we can rewrite this equation as:

$$v_S^2 + (R_S^2 + \sigma L_S^2 \omega^2)i_S^2 - 2R_S \frac{P_E}{3} \\ -(1-\sigma)L_S \omega \frac{Q_E}{3} = 0 \tag{18}$$

We can rewrite equation (17) and (18) by using linear regression as a linear model:

$$Y = U.\theta \tag{19}$$

θ is the parameter to be estimated:

$$Y/U = \theta \tag{20}$$

Defining appropriate parameters U and Y, an equation would be obtained to estimate stator resistance. Ofcourse this direct calculation will be affected by noise, but this noise will be decreased by averaging.

B. Appropriate definition of parameters U and Y

If in Equation (17), L_s and $\sigma L_S = L_{ls}$ are considered constant ,this Equation can be written as

A second-order equation in terms of R_s [see (15)]:

$$aR_s^2 + bR_s + c = 0 \tag{21}$$

Which we have:

$$a = \left| \int \vec{i}_r \, dt \right|^2 \tag{22}$$

$$b = -2\,\mathrm{Re}\left\{ \int \vec{v}_S \, dt \int \vec{i}_S^* \, dt \right\} \tag{23}$$

And

$$c = \left| \int \vec{v}_S \, dt \right|^2 - (1+\sigma)L_S \,\mathrm{Re}\left\{ \vec{i}_S^* \int \vec{v}_S \, dt \right\} \tag{24}$$

$$+ \sigma L_S^{\,2} i_S^{\,2}$$

Which with:

$$y = -b - \sqrt{b^2 - 4ac} \tag{25}$$
$$u = 2a \tag{26}$$

Then, by using Linear regression method R_s can be calculated as follows:

$$R_s = Y/U \tag{27}$$

IV. Computer simulation

Here, The proposed methods are tested on an induction motor that it's properties are given in table(1) using MATLAB-SIMULINK software .the results of the methods of estimating the parameter are illustrated as in the figures 1 to 11 and comparing with each other described in table (2).

Table1. Properties of tested induction motor

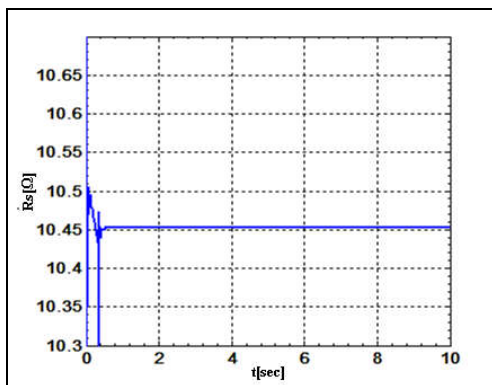|	
$T_l = 2.8$ N.m	$T_r = L_r/R_r = 0.0667$ s
$V_n = 230$ v	$T_{ss} = L_s/R_s = 0.0534$ s
$f_n = 50$ Hz	$J = 0.00688$ kg.m^2
$R_s = 10.5$ Ω	$F = 0.001795$ N.m.s
$L_{ls} = 0.0455$ H	
$R_r = 8.4$ Ω	sig = 1-
$L_{lr} = 0.0455$ H	$((L_m^2)/(L_s*L_r)) = 0.1557$
$L_r = L_{lr} + L_m$	$L_m = 0.515$ H
$= 0.5605$ H	

Fig. 1 Estimation of stator resistance by air gap power method in low speeds (40-120 rpm) and rated torque (2.8 N.m)
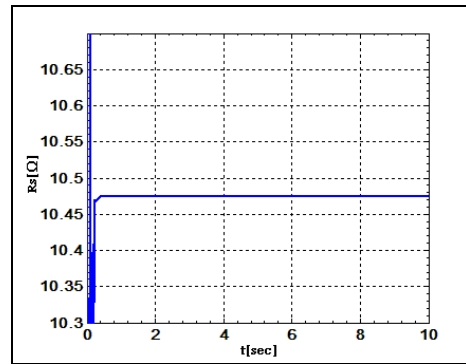

Fig. 2. Estimation of stator resistance by air gap power method in low speeds (40-120 rpm) and a half of rated torque (1.4 N.m)
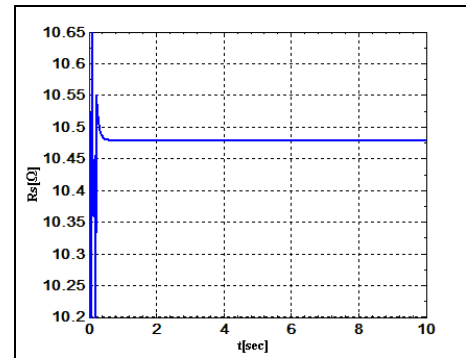

Fig. 3. Estimation of stator resistance by air gap power method in low speeds(40-120 rpm) and one fourth of rated torque (0.7 N.m)
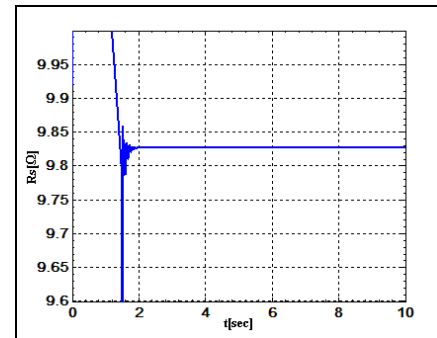

Fig. 4 Estimation of stator resistance by air gap power method in speeds close to the rated one (1400 rpm) and rated torque (2.8 N.m)
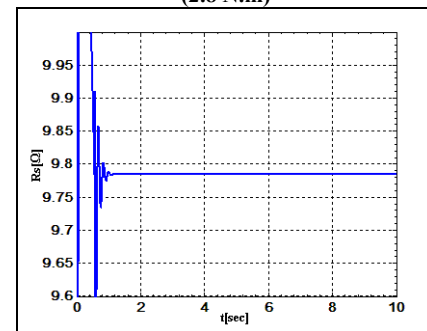

Fig. 5. Estimation of stator resistance by air gap power method in speeds close to the rated one (1400 rpm) and a half of rated torque(1.4 N.m)
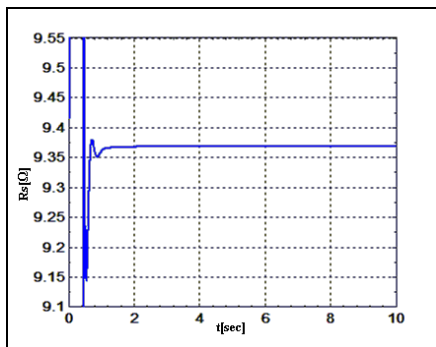
Fig. 6. Estimation of stator resistance by air gap power method in speeds close to the rated one (1400 rpm) and one fourth of rated torque(0.7 N.m)
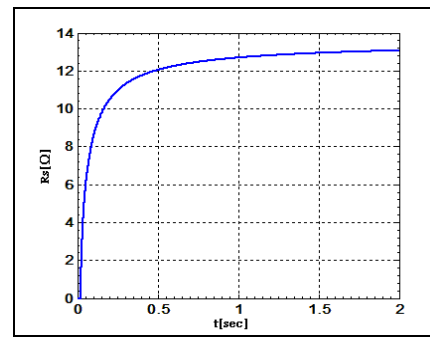

Fig. 7. Estimation of stator resistance by linear regression method in low speeds(40-120 rpm) and rated torque (2.8 N.m)

Fig. 8. Estimation of stator resistance by linear regression method in low speeds(40-120 rpm) and a half of rated torque(1.4N.m)

Fig. 9. Estimation of stator resistance by linear regression method in low speeds(40-120 rpm) and a one fourth of rated torque(0.7 N.m)

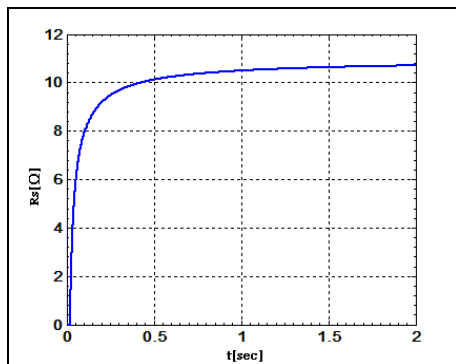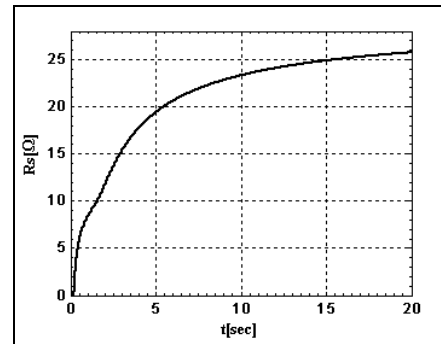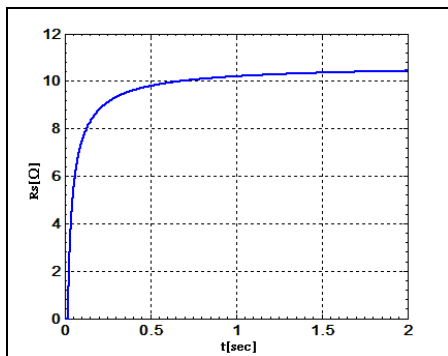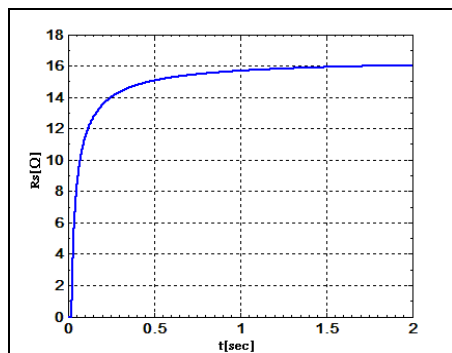**Fig.10. Estimation of stator resistance by linear regression method in medium speeds (500 rpm) and rated torque(2.8N.m)**

Fig.11. Estimation of stator resistance by linear regression method in rated speeds (1500 rpm) and rated torque(2.8N.m)

Table 2. Comparison results of estimation methods of stator resistance

Parameter	Air gap power method				Linear regression method				
	Low speeds		High speeds		Low speeds		Median speeds		High speeds
	Low torque	High torque	Low torque	High torque	Low torque	High torque	Low torque	High torque	Per torque
R_s	10.47	10.47	9.37	9.83	16	10.6	14	13.2	25
Error (%)	0.285	0.285	10	6	52.4	0.95	More than 30%	20	more than %100

Conclusion

We have considered the methods of air gap power and linear regression to estimate the stator resistance and we have obtained the following results by comparing them:

1) The air gap power method estimates the stator resistance better in low speeds (40 – 120 rpm) and torque of the load is not effective on it in these velocities.
2) The air gap power method estimates the stator resistance well in speeds close to the rated one (1400 rpm) from the rated torque to a half of it which has error of less than 5%.
3) The linear regression method estimates the stator resistance better in low speeds(40 – 120 rpm) only to a half of rated torque(1.4 Nm).
4) The linear regression method estimates the stator resistance in medium speeds of 500 rpm with 20% error which has more errors in other torques   and speeds.

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