AC Induction Motor Stator Resistance Estimation Algorithm

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Abstract: Stator resistance identification algorithm for AC induction motor is presented in this paper. It does not require additional external excitation. The algorithm is intended to capture slow variations of stator resistance which are given by the changes in stator windings temperature. Steady state operation with harmonic voltages and currents are located during the operation of the motor and the stator resistance is determined from RMS values of the voltage, current and from actual active power. Simulation experiments have proved the theoretical expectations. The algorithm is not computationally intensive which makes it suitable for real time implementation in reasonable hardware. The experimental results confirm that the proposed method gives acceptable results on a real motor. The disadvantage is the dependency of the stator resistance estimate on the level of magnetic flux excitation. The off line measurement of stator inductance on excitation current is proposed to solve this problem.

Key–Words: AC induction motor, stator resistance, identification, on-line

1 Introduction

The presented article tries to make an important step towards the successful realization of speed sensorless control algorithm on an AC induction motor because it proposes the algorithm for online stator resistance estimation. The value of this parameter is mainly influenced with the stator windings temperature. The changes are slow but unfortunately they can be relatively big. Stator resistance is also influenced with the slip frequency. Other parameters of the equivalent AC induction motor circuit changes too. Motor inductances depend on on magnetic saturation [6]. This is the reason why some on-line method is needed to modify motor model parameters to achieve good control performance [7].

The methods for on-line identification of AC induction motor parameters can be divided to method with or without external excitation. External excitation usually also influences produced level of torque which can be also visible on rotational speed. This situation is usually not demanded or even not allowed which disables the employment of such methods. The methods which do not require external excitation are mostly based on some kind of least squares methods. These methods require high computational power and their employment on some real hardware which usually uses fixed point arithmetics is more or less theoretical.

There are three types of stator resistance estimation. The first one is zero sequence model based R_s estimation by solving least squares minimisation problem [3]. The access to neutral of the stator winding is needed for current injection. The second disadvantage is the heating of the winding. The second one is based on DC model. It comes from the fact that the input impedance of the motor is directly equal to R_s for the DC signal. The DC injection is simply realisable for line-connected AC induction motors [4]. The DC injection is difficult in field oriented scheme since it is usually compensated with the controllers and AC component also appears which disturbs the torque generation. The third group of methods require knowledge of induction machine model. [1] These methods are non-invasive because they do not require any external injection and does not disturb the control process. It is well known that these methods are not very precise since they depend on motor parameters which are nonlinear and they depend on operating conditions [3, 5].

This paper presents practical verification of novel algorithm for stator resistance identification [2] which belongs to the third group of stator identification method as described previously. This algorithm operates online and requires no external excitation. The identification is realized from steady state operation. This partially limits the employment of proposed algorithm for drives which are designed to run time to time in steady state. It means for those drives where the load stays constant or slowly changing for some time. The presented method uses the fact that the inductances are during operation of vector control algorithm constant when the flux is kept constant. Both, the stator and rotor resistances are varying with time due to changes in temperature.

The resulting estimation algorithm is not computationally intensive which makes it suitable for real time implementation in corresponding hardware. Second advantage is the fact that it incorporates no external excitation.

The paper is organised as follows. The second section contains description of AC induction motor model. The third section outlines the proposed algorithm for online stator resistance estimation. The fourth section describes predictive direct stator flux control algorithm and observer for flux and speed estimation. The fifth chapter contains simulation results realized in the environment of Matlab Simulink. The sixth section validates the proposed algorithm on a real motor. The last section concludes the results.

2 AC Induction Motor

The three phase squirrel cage AC induction motor is studied in this paper. Let's assume inverse Γ-form model of this motor. It can be described using voltage equations in stator reference frame

$$\boldsymbol{u}_s = R_s \boldsymbol{i}_s + \frac{d\boldsymbol{\Psi}_s}{dt}, \tag{1}$$

$$0 = R_R \boldsymbol{i}_R + \frac{d\boldsymbol{\Psi}_R}{dt} - \jmath z_p \omega_{mech} \boldsymbol{\Psi}_R. \tag{2}$$

Both stator and rotor fluxes come from the following relations between stator and rotor currents

$$\boldsymbol{\Psi}_s = L_L \boldsymbol{i}_s + \boldsymbol{\Psi}_R, \tag{3}$$

$$\boldsymbol{\Psi}_R = L_M(\boldsymbol{i}_s + \boldsymbol{i}_R). \tag{4}$$

The motor motion is given by equations

$$\frac{d\omega_{mech}}{dt} = \frac{1}{J}(T - T_{load}), \tag{5}$$

$$T = 1.5 z_p \Im(\bar{\boldsymbol{\Psi}}_s \boldsymbol{i}_s). \tag{6}$$

The meaning of variables and parameters used above is as follows. $\boldsymbol{u}_s$ is the stator voltage vector $\boldsymbol{u}_s = u_{s\alpha} + \jmath u_{s\beta}$, $\boldsymbol{i}_s$ is the stator current vector $\boldsymbol{i}_s = i_{s\alpha} + \jmath i_{s\beta}$, $\boldsymbol{i}_R$ is the rotor current vector $\boldsymbol{i}_R = i_{R\alpha} + \jmath i_{R\beta}$, $\boldsymbol{\Psi}_s$ is the stator flux vector $\boldsymbol{\Psi}_s = \Psi_{s\alpha} + \jmath \Psi_{s\beta}$, $\boldsymbol{\Psi}_R$ is the rotor flux vector $\boldsymbol{\Psi}_R = \Psi_{R\alpha} + \jmath \Psi_{R\beta}$, R_s is the stator resistance, R_R is the rotor resistance, L_M is the magnetizing inductance, L_L is the leakage inductance, z_p is the number of pole pairs, ω_{mech} is the actual angular speed of the rotor, T and T_{load} are the motor and load torques, respectively and $\jmath$ is the imaginary unit. It should be noted that all rotor parameters are referred to the stator side.

2.1 Equivalent circuit

There are different models of AC induction motor. Because the T-form model has one redundant parameter it is often transformed into more simple Γ-form or inverse Γ-form. The inverse Γ-form model equivalent circuit is shown in Figure 1. It is valid for steady state operation. The equivalent impedance according to Figure 1 can be expressed as

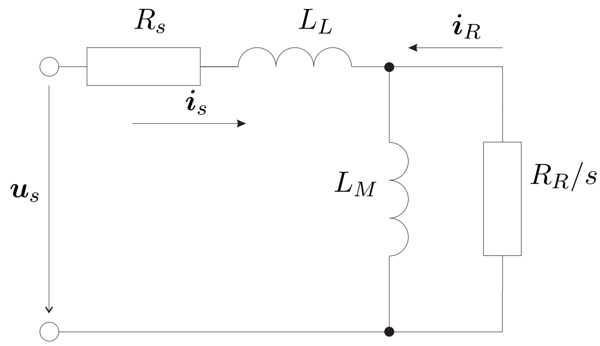

Figure 1: Inverse Γ-model of AC induction motor

$$Z_{eq} = R_{eq} + \jmath X_{eq} = R_s + \jmath X_L + \frac{\jmath X_M R_R/s}{R_R/s + \jmath X_M}, \tag{7}$$

where reactances are $X_L = \omega_{el} L_L$ and $X_M = \omega_{el} L_M$ The slip s can be computed using

$$s = \frac{\omega_{el} - z_p \omega_{mech}}{\omega_{el}}. \tag{8}$$

3 Stator Resistance Identification Algorithm

The voltage and the current are harmonic in steady state. Their RMS values can be easily computed using

$$U = \sqrt{\frac{1}{T_{el}} \int_t^{t+T_{el}} u_s^2(t) dt}, \tag{9}$$

$$I = \sqrt{\frac{1}{T_{el}} \int_t^{t+T_{el}} i_s^2(t) dt}. \tag{10}$$

We can also compute the active power

$$P = \frac{1}{T_{el}} \int_t^{t+T_{el}} u_s(t) i_s(t) dt. \tag{11}$$

These quantities can be used to compute the equivalent impedance. First, we compute $cos\phi = \frac{P}{UI}$ and

$sin\phi = \sqrt{1 - cos^2\phi}$. The real and imaginary part of equivalent impedance are

$$R_{eq} = \frac{U}{I} cos\phi = R_s + \frac{R_R/sX_M^2}{(R_R/s)^2 + X_M^2}, \quad (12)$$

$$X_{eq} = \frac{U}{I} sin\phi = X_L + \frac{X_M(R_R/s)^2}{(R_R/s)^2 + X_M^2}. \quad (13)$$

Let's assume that the inductances L_L and L_M are known a-priori from some off-line test. They are also assumed to be constant during the motor operation. This simplification is conditioned with the fact that the level of flux magnitude is kept constant. The equation (13) depends on rotor resistance divided by slip so we can express it as

$$\frac{R_R}{s} = X_M \sqrt{\frac{X_L - X_{eq}}{X_{eq} - X_L - X_M}}. \quad (14)$$

The resulting equation depends only on reactances which we assume to know.

When the vector control algorithm works with the speed sensor than it is possible to compute the slip and by multiplying both sides of (14) we obtain rotor resistance estimation.

In the case of sensor-less control (which is of our interest), it is not possible to compute rotor resistance by computing the slip. The estimated speed corresponds to the rotor resistance which is used in estimator so the rotor resistance from the estimator would be obtained instead of real rotor resistance value.

Substituting (14) into (12) and expressing stator resistance R_s gives

$$R_s = R_{eq} - \frac{R_R/sX_M^2}{(R_R/s)^2 + X_M^2}. \quad (15)$$

The whole algorithm can be summarised as follows. Zero crossing of voltage is detected. The voltage is selected for detection because it is less influenced with the noise. It starts the integration of squared stator voltage, squared stator current and their product. When the next zero crossing is detected then the electrical period T_{el} is computed. It is used to compute RMS voltage, RMS current and the active power using (9), (10) and (11). These results are used to compute components of equivalent impedance R_{eq} (12) and X_{eq} (13). Finally, the R_R/s is computed using (14) which helps to compute stator resistance estimate R_s using (15).

The decision on steady state operation is realised as follows. The successive values of electrical period T_{el}, RMS voltage U, RMS current I and power P are compared with their previous values. It they differ for less than 5 percent than the motor is assumed to be running in steady state.

3.1 Modified algorithm

In a real application it is necessary to provide some kind of filtering of obtained results to prevent fast unrealistic changes in stator resistance. Simple first order filter can be used for this purpose

$$R_s(k) = R_s(k-1) + k_f[R_s - R_s(k-1)], \quad (16)$$

where the coefficient k_f is in the range $(0; 1\rangle$. It should be set experimentally. The parameter k represents the index of the stator resistance estimate.

The stator resistance estimate can be computed either directly from one of the tree phases voltages u_A, u_B, u_C and currents i_A, i_B, i_C or from transformed voltages $u_{s\alpha}, u_{s\beta}$ and currents $i_{s\alpha}, i_{s\beta}$ in α or β coordinates. At maximum it is possible to obtain six estimates of stator resistance R_s per one electrical period T_{el}.

4 Simulation results

This section shows number of simulation experiments. They are executed with different conditions. They are described and the simulation results are discussed herein. During the simulation we expect AC induction motor with parameters outlined in Table 1.

Motor parameters:	
stator resistance	$R_s = 34\Omega$
rotor resistance	$R_R = 15.2\Omega$
stator leakage inductance	$L_L = 300$mH
magnetizing inductance	$L_M = 1.06$H
pole pairs	$z_p = 2$

Nominal values:	
current	$i_{nom} = 0.85$A
torque	$T_{nom} = 1.7$Nm
speed	$\omega_{nom} = 144.5$rad/s

Table 1: AC induction motor parameters

We assume that the required speed is changed from 0 to 50 rad/s at $t = 0.25$s in all simulations. The torque on the shaft is changed in three steps. The first one occurs in $t = 1$s from 0 to 0.3 Nm. The second one starts in $t = 1.4$s and goes to -0.3Nm. The last one takes place in $t = 1.8$s and changes the torque on shaft to 0Nm. The corresponding progresses can be seen in Figure 2. The individual simulation experiments follow.

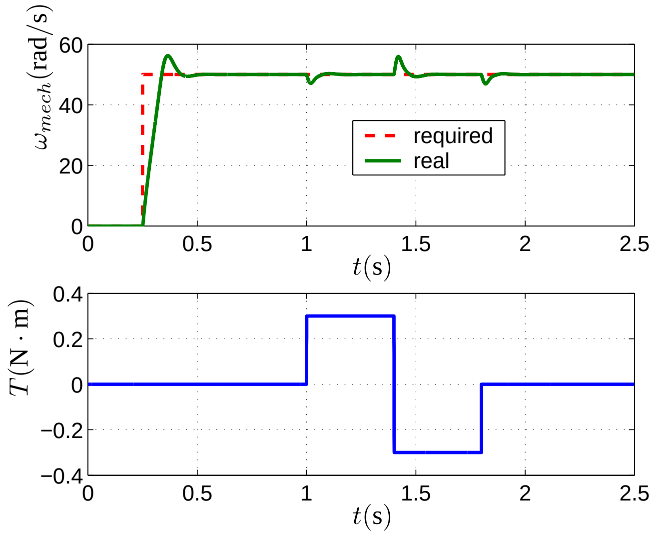

Figure 2: Required speed, real speed and torque on shaft.

First, let's assume that the stator resistance remains constant and that the estimator uses correct value of stator resistance. Identification algorithm gives results as shown in Figure 3. Note that when the stator resistance equal to zero then the motion is not in steady state and therefore the resistance is not estimated.

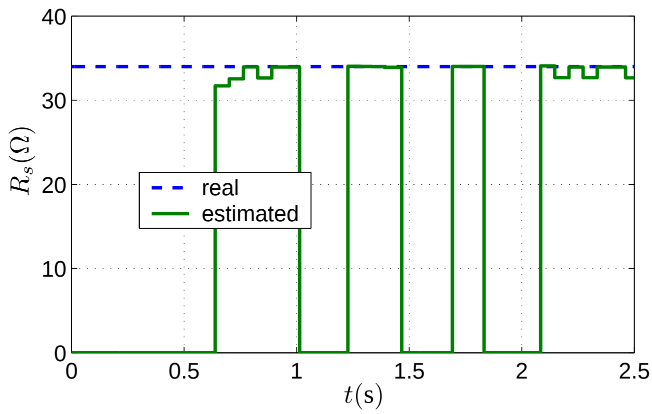

Figure 3: Estimated stator resistance.

Second simulation example shows the situation when there is about 25% error in stator resistance which is used in the estimator $\tilde{R}_s = 42.5\Omega$. The real value stays $R_s = 34\Omega$. The obtained stator resistance estimate can be seen in Figure 4. It can be seen that there is almost no influence on resulting estimate since the progress is almost identical with the one in Figure 3.

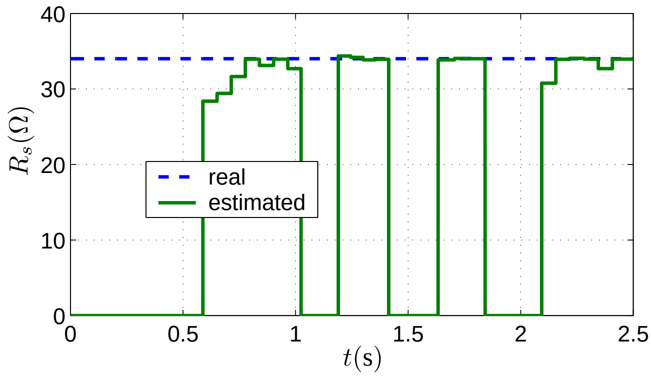

Figure 4: Estimated stator resistance with 25% error in estimated stator resistance in observer.

Next simulation experiment shows the case of changeable stator resistance. Stator resistance is assumed to be varying linearly from $R_s = 34\Omega$ at time $t = 0$s to $R_s = 51\Omega$ at time $t = 2.5$s. This growth is unrealistic but it will show the ability of proposed algorithm to follow the stator resistance changes. The simulation results are displayed in Figure 5.

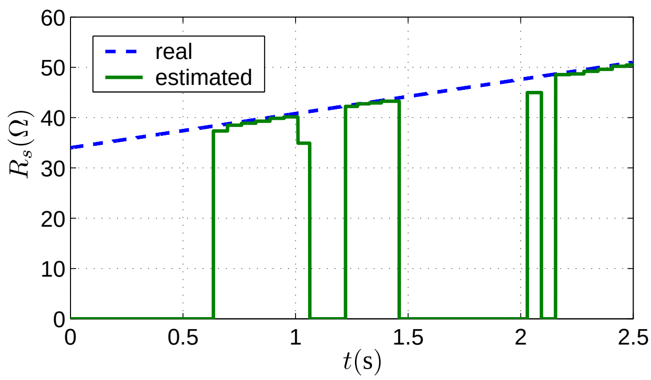

Figure 5: Estimated stator resistance with its linear increase.

The last simulation shows the estimation of both the stator and the rotor resistance in the case when the speed sensor is used to obtain the mechanical speed ω_{mech}. It can be seen in Figure 6. Stator and rotor resistances are assumed to be varying linearly from nominal values $R_s = 34\Omega$ and $R_R = 15.2\Omega$ at time $t = 0$s to $R_s = 51\Omega$ and $R_R = 22.5\Omega$ at time $t = 2.5$s. The rotor resistance estimation gives in some cases bad results. This is in times where the torque on the shaft is equal to zero and therefore the rotor current equals to zero which means that there is no information about rotor resistance.

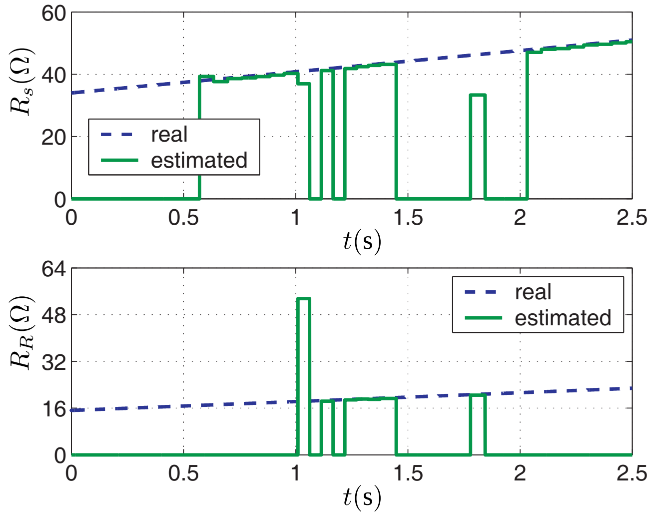

Figure 6: Estimated stator and rotor resistance with speed sensor.

5 Practical experiment

The real experiments were realized on AC induction motor with equal parameters as they were used in simulations. The PDSFC control algorithm was implemented in DSP 56F805 EVM from Freescale Semiconductors. The Freescale AC BLDC power stage was used as a voltage source inverter. The sampling frequency of PWM block was $f = 16$kHz. The motor was loaded with 380W DC motor with permanent magnet which was connected to Statron electronic load with adjustable current.

The voltage and current waves were saved in files using FreeMaster software in real time and than they were treated in the environment of Matlab. The RMS values were computed and the active power as well. These values were than used to compute the estimate of stator resistance according to proposed algorithm. The measurements were realised in temperature range from 26°C to 48°C. The temperature was measured with thermocouple mounted on the AC induction motor body. The measurements were also realised on three different speeds: 250rpm, 500rpm and 750rpm.

Experimental results are displayed in Figure 7. As can be seen, they all show correct tendency of increasing resistance with increasing temperature. The problem is that stator resistance estimates depend on the rotational speed. The reason is probably the wrong assumption that the magnetizing current can be kept constant for any working condition of the motor. The

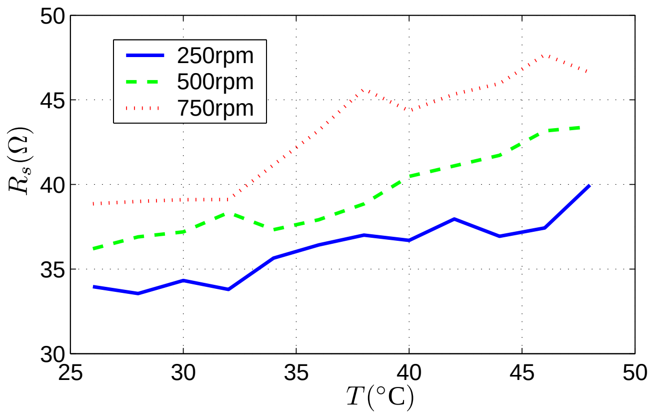

Figure 7: The measured dependency of stator resistance on temperature on a real motor.

magnetic saturation causes the changes in the inductances which are used for the stator resistance estimation. The problem can be partially solved using nonlinear inductances in the motor model. Another reason can be unknown voltage drop on power semiconductor devices which was not compensated in our scheme.

6 Dependency on excitation

The dependency of stator inductance $L_s = L_L + L_M$ on excitation current was measured using no load test. The stator windings were fed by three phase voltage with defined frequency and with changeable amplitude. The mechanical speed was kept equal to the synchronous speed by connected DC motor. The rotor current was equal to zero. The impedance of the motor was measured under these conditions. The obtained reactance corresponds to stator inductance . The resulting characteristics for three different angular speeds can be seen in Figure 8. The significant dependency of stator inductance on the excitation current can be seen there.

7 Conclusion

This paper presents simple algorithm for stator resistance identification in a sensor-less vector control scheme. It is based on measurement of voltage, current and power which is realized in steady state. This algorithm also gives the estimate of rotor resistance when the speed sensor is used. The main advantage of proposed algorithm is its simplicity and low additional computational requirements on targeting hardware. The second advantage is that it does not require additional signal injection which usually causes the fluctuation of the produced torque. In contrast with

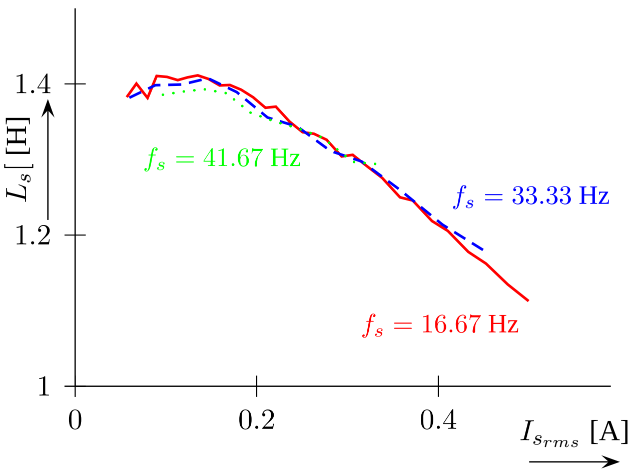

Figure 8: Dependency of stator inductance on excitation current.

very precise simulation results where the only problem is in decision on steady state operation of the motor the experimental results suffer from dependency on actual operation conditions. Nevertheless, the correct tendency of increasing stator resistance with the increase in temperature was obtained.

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