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EFFECT OF PARAMETER VARIATION ON THE PERFORMANCE OF FIELD ORIENTED INDUCTION MOTOR

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ABSTRACT

In practical applications, the field orientation control technique encounters many serious problems. These problems could indeed undermine the application of induction motors unless they could be solved. The most important problems are to develop an accurate motor model, and that the control algorithm is sensitive to motor parameter variations. Unfortunately, the motor parameters do vary with operating conditions in practice, and any parameter variation or mismatch will degrade the control performance. The effect of parameter variations on the performance characteristics of induction motors with field oriented control is studied in this paper. The variation of induction motor characteristics from starting up to synchronous speed is investigated.

طريقة التحكم بتوجيه المجال المغناطيسى تواجه بعض المشكلات الصعبة فى الواقع التطبيقى و هذه المشكلات يمكن بالفعل أن تقوض عمل المحرك الحثى إذا لم يتم حلها. و أهم مشكلة فى المحرك الحثى هو النموذج الصحيح للمحرك حيث أن طريقة التحكم تتأثر بتغير معاملاته و لسوء الحظ فإن معاملات المحرك تتغير بتغير ظروف التشغيل فى الواقع ووجود أى تغير أو خطأ فى المعاملات فإنها تقلل كفاءة التحكم. لذا فإنه فى هذا البحث تم دراسة تأثير تغير معاملات المحرك على خواصه عند تسييره بطريقة التحكم بتوجيه المجال المغناطيسى. و أيضا تم دراسة تغير خواص المحرك الحثى منذ البدء و حتى سرعة التزامن.

Keywords: Induction motor, Field oriented control, Parameter variation, Self tuning

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1. INTRODUCTION

The parameters of the equivalent circuit of an induction machine (IM) vary according to the operating conditions such as temperature, operating frequency, air gap flux, and the magnitude of the current. Also, the parameters of all electric machines vary very widely according to the rated voltage, speed, and frequency [1].

The rotor resistance varies according to the frequency of the current flowing in the rotor conductors. Usually, the rotor conductors are made of aluminum- or copper-based alloy, and the resistance varies due to the skin effect. The resistance increases as the frequency increases. In addition to the skin effect, the resistance varies according to the temperature of the conductors.

Because the stator conductors are normally made of a stranded wire, the skin effect can be neglected. However, the variation of the resistance due to the temperature rise should be considered.

The rotor leakage inductance is affected by the skin effect, and the inductance decreases as the frequency increases. In addition to the skin effect, the leakage inductance is affected by the magnetic saturation of the leakage flux in the rotor core.

The slot of the stator is normally open and the variation of the leakage inductance due to the magnetic saturation of the leakage flux is not severe compared to that of the rotor leakage inductance of the closed slot rotor.
The magnetizing inductance varies according to the air-gap flux level, by several tens of percentages. If the excitation current is reduced from its rated value, the inductance increases slightly and decreases with further decrease of the current.

The resistance R_m which represents iron loss varies according to the air-gap flux, and the excitation frequency ω_s.

2. PREVIOUS RESEARCH WORK

Early research work on the field oriented control considers all the motor parameters constant neglecting the expense of core loss resistance, variations in stator and rotor resistance, effect of saturation on magnetizing, stator and rotor leakage reactance. This will due to detuned field oriented control (FOC), so some research focused on the effects of these variations. Vas [2] concluded that if incorrect modulus and angle of the flux-linkage space vector are used in a vector control scheme, then flux and torque decoupling is lost and the transient and steady state responses are degraded. Low frequency response, speed oscillations, and loss of input-output torque linearity are major consequences of detuned operation, together with decreased drive efficiency.

The effect of parameter variations on FOC induction motor has been considered at starting and full load at constant flux region and constant power region [3]. In [4] the sensitivity of FOC to the variation in motor parameters is studied. The saturation effect in induction motor is taken into consideration. All of the models of the induction motor are discretized in order that the identification algorithms can be implemented with a digital signal processor. A linear parameter varying system model was proposed and found to be most suitable to describe IM. The procedure described in [5] leads to a set of parameters and parameter variations which represent induction motor performance considerably more accurately than when parameter variations are ignored.

Shiri et al. [6] proved that, the maximum effect on the torque and rotor flux is caused by variations of the rotor resistance (R_r). For a 100% increase in the rotor resistance, the torque and rotor flux increase 1.2% and 66.6% respectively, while for the same percentage of increase in mutual inductance (L_m), the increase of torque and flux are only 0.43% and 8.3%, respectively. It should be mentioned that although the effect of variation of L_m on torque and flux is negligible, it causes oscillations in torque and flux. It can be concluded that variations of rotor resistance in comparison with other parameters cause the maximum deviation in torque and flux from their reference values.

In direct FOC, a constant stator resistance (R_s) is considered which is used for stator flux calculation. In fact, stator resistance is subject to variations which can exceed 50% of its startup value, depending on the operating conditions. These variations do not really affect the calculations precision for normal operation, as the voltage drop on stator resistance is negligible compared to the stator voltage. However, in low speed operating range this voltage drop plays a dominant role to the calculation of the stator flux components. As a result, errors occur in the calculations of the flux, which can lead to imprecision or instability in the vector control algorithm [7]. The compensation for the skin effect in vector controlled induction motor drive has been found in [8]. For test purposes in this paper, a 400

Hz, 1 kW induction motor was used which exhibits the skin effect at low power ratings.

The effects of the variation of the rotor time constant (T_r) and L_m on the behavior of IM under FOC in both steady-state and transient operations has been introduced [9]. The aim of [10] is to compare the influence of parameter uncertainties on the performance of indirect FOC and direct FOC. Reference [11] investigates the effects of iron loss on the direct stator-flux-oriented control system of IM, and proposes a control algorithm considering iron loss. Torque control capability is much improved and the speed estimation error for a speed sensorless drive is reduced. The motor iron loss has been taken into account using a speed dependent shunt resistance [12]. The total losses have been minimized in the stationary reference frame using an effective flux search method independent from all drive parameters. A little disagreement observed between experimental results and corresponding simulations can be explained because of inaccuracies that exist in data accusation system, inaccurate IGBT models employed in the extraction of simulation results as well as motor magnetic saturation that was not taken into account in the system modeling.

A better understanding of induction motor saturation with experimental data from 96 motors of 11–90 kW has been proposed [13]. This paper calculates typical data on stator leakage reactance saturation and magnetizing reactance saturation and gives the average value and the dispersion for the main saturation parameters. A passivity-based controller, which takes into account saturation of the magnetic material in the main flux path of the induction motor, is developed to provide close tracking of time-varying speed and flux trajectories in the high magnetic saturation regions [14].

3. INDIRECT VECTOR CONTROL

In this section, the indirect vector controller is derived from the dynamic equations of the induction machine in the synchronously rotating reference frames. The rotor equations of the induction machine are given by:

$$R_r i_{qr}^e + p\lambda_{qr}^e + \omega_{sl}\lambda_{dr}^e = 0 \qquad (1)$$

$$R_r i_{dr}^e + p\lambda_{dr}^e + \omega_{sl}\lambda_{qr}^e = 0 \qquad (2)$$

Where:

$$\omega_{sl} = \omega_s - \omega_r \qquad (3)$$

$$\lambda_{qr}^e = L_m i_{qs}^e + L_r i_{qr}^e \qquad (4)$$

$$\lambda_{dr}^e = L_m i_{ds}^e + L_r i_{dr}^e \qquad (5)$$

In this equations, R_r, the referred rotor resistance per phase; L_m, the mutual inductance per phase; L_r, the referred rotor self inductance per phase; i_{dr}^e and i_{qr}^e, the referred direct and quadrature axes currents respectively; i_{ds}^e and i_{qs}^e, the stator direct and quadrature axes currents respectively; p, the differential operator; ω_{sl}, ω_s and ω_r, slip speed, synchronous speed and electrical rotor speed in rad/sec, and λ_{dr}^e and λ_{qr}^e are rotor direct and quadrature axis flux linkages. Aligning the d-axis with rotor flux phasor yields:

$$\lambda_r = \lambda_{dr}^e \qquad (6)$$

$$\lambda_{qr}^e = p\lambda_{qr}^e = 0 \qquad (7)$$

Substituting equations (6) and (7) in (1) and (2) and using equations (4) and (5), the followings are obtained:

$$i_f = i_{ds}^e = \frac{\lambda_r}{L_m}(1 + pT_r) \qquad (8)$$

$$i_t = i_{qs}^e = \frac{\lambda_r}{L_m} T_r \omega_{sl} \qquad (9)$$

Where T_r the rotor time constant and equal to:

$$T_r = L_r / R_r \qquad (10)$$

The q- and d-axis currents are labeled as torque and flux producing components of the stator current phasor, respectively. The induction machine torque equation can be obtained as:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda_r i_{qs}) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_r i_t = K_t \lambda_r i_t \qquad (11)$$

Where K_t is torque constant and equal to:

$$K_t = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r} \qquad (12)$$

From previous equation, it can be noted that, the torque is proportional to the product of the rotor flux linkages and the stator q-axis current. This resembles the torque expression of dc motor, which is proportional to the product of the field flux linkages and the armature current. If the rotor flux linkage is kept constant, then the torque is simply proportional to the torque producing component of the stator current (i_t), as in the case of the separately excited dc machine.

4. SIMULATION RESULTS

A matlab program is developed based on the steady state equations of the induction motor in FOC, this program calculates and plots the steady state characteristics of IM for field oriented control before and after varying one parameter only. In all the following figures, only one parameter is varied at a time and all the other parameters are kept constants, after that the next parameter is varied and all the other parameters are constant and so on. All parameters are increased to 150% of their original values except the magnetizing inductance that decreases to 80% of its original value.

The variation of motor parameters is mainly due to temperature change. Since the time constant for this variation is much larger than that for the induction motor, therefore the analysis can be performed based on steady state operation of IM. The characteristics of induction motor have the same shape when the motor is loaded or at no load because these characteristics depend upon the value of speed.

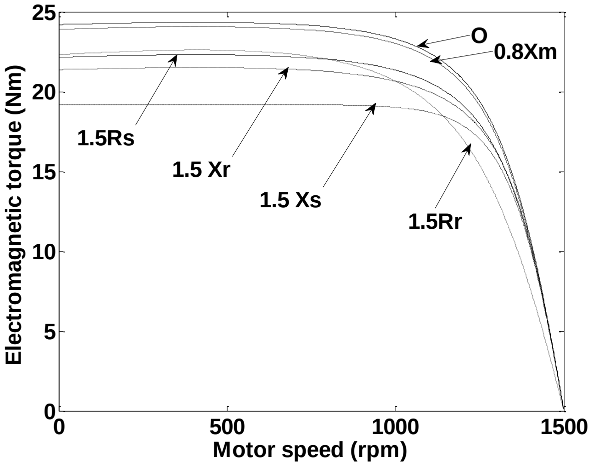

Fig. (1) Variation of electromagnetic torque with speed for motor parameter variations

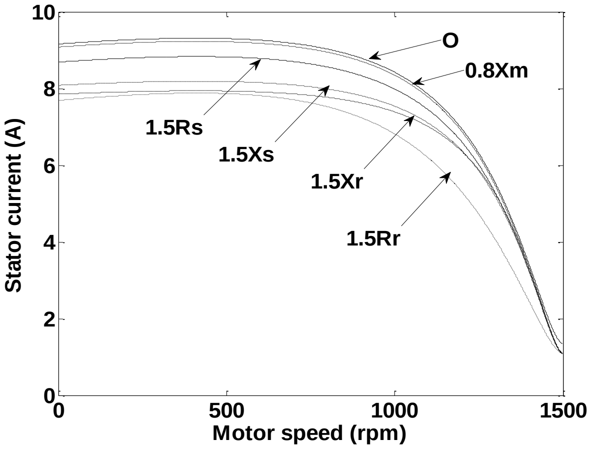

Fig. (2) Variation of stator current with speed for motor parameter variations

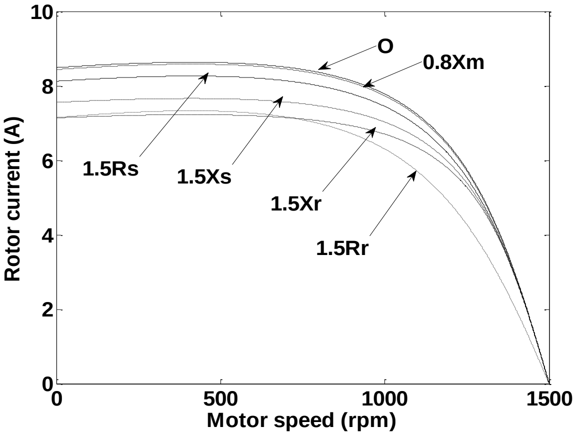

Fig. (3) Variation of rotor current with speed for motor parameter variations

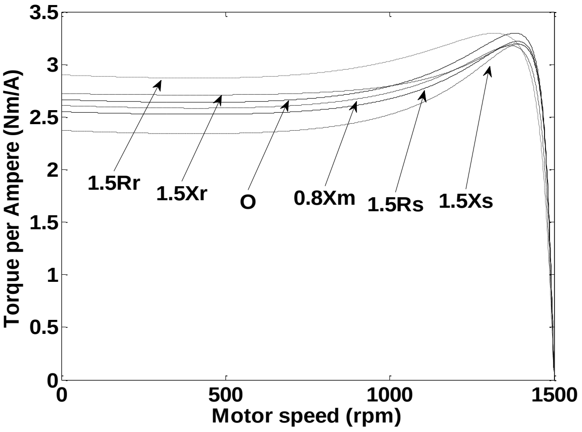

Fig. (4) Variation of torque per ampere with speed for motor parameter variations

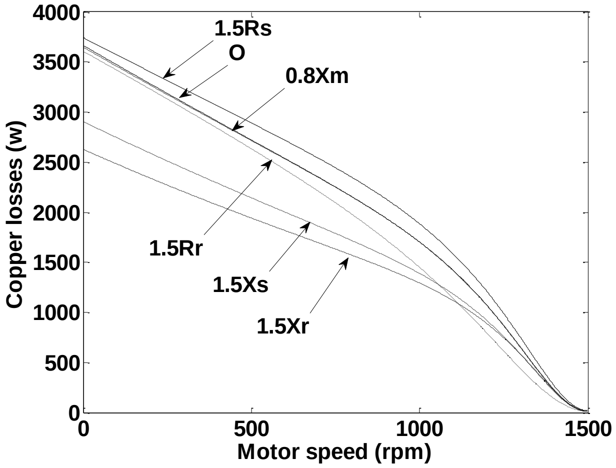

Fig. (5) Variation of copper losses with speed for motor parameter variations

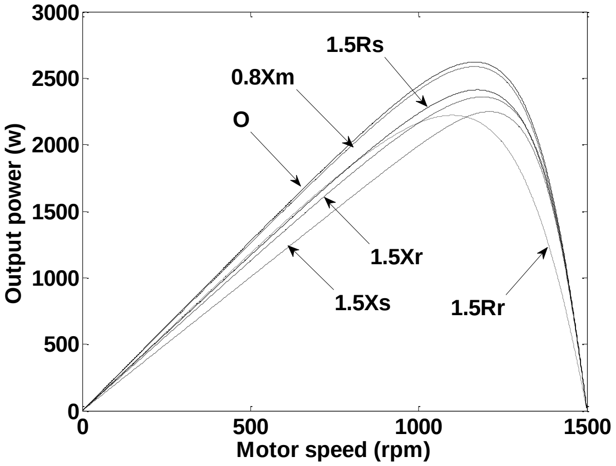

Fig. (8) Variation of output power with speed for motor parameter variations

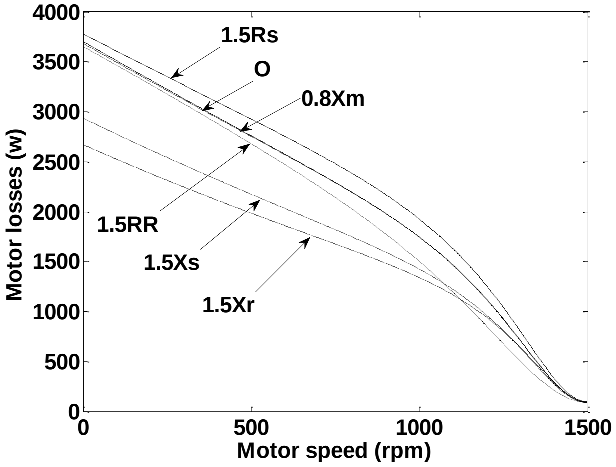

Fig. (6) Variation of motor losses with speed for motor parameter variations

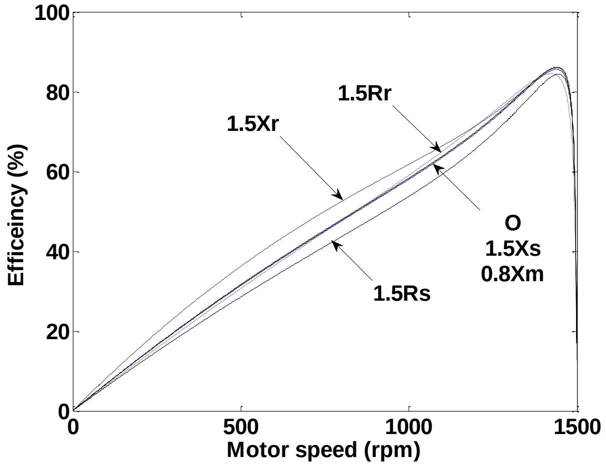

Fig. (9) Variation of motor efficiency with speed for motor parameter variations

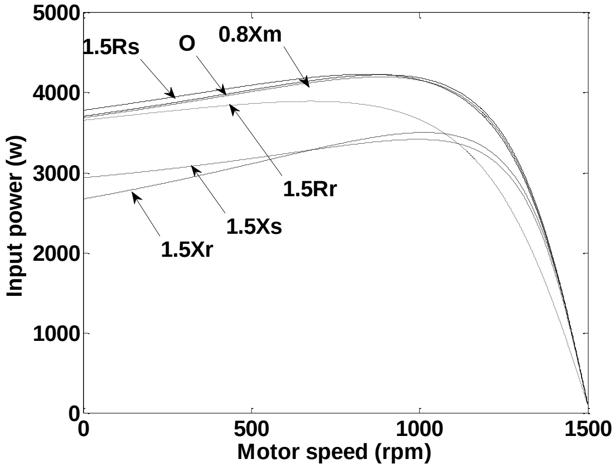

Fig. (7) Variation of input power with speed for motor parameter variations

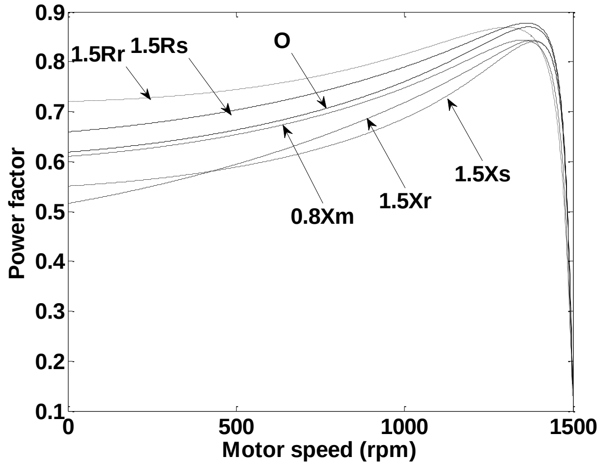

Fig. (10) Variation of input power factor with speed for motor parameter variations

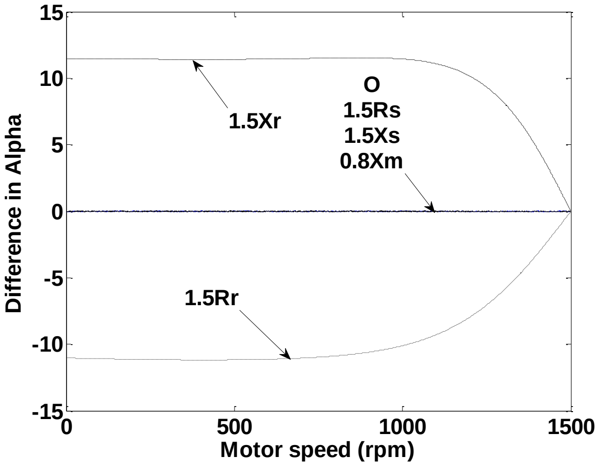

Fig. (11) Variation of difference in actual angle with speed for motor parameter variations

From the above figures O means original FOC with no parameter variation. And that figures show that, for a 50% increase in stator resistance, the starting torque decreases by 8.4%, the starting stator and rotor currents, and starting torque per ampere all decrease by 4.3%, the maximum torque per ampere decrease by 2.4%, copper losses increase by 2.1%, the starting motor losses and starting input power increase by 2%, the maximum input power increase by 0.15%, maximum output power decrease by 8%, maximum efficiency decrease by 2%, finally the starting power factor increase by 6.6%.

For the same percent of increase in rotor resistance the starting torque decrease by 7.8%, the starting stator current decrease by 15.3%, the starting rotor current decrease by 15.8%, the starting torque per ampere increase by 8.8%, the maximum torque per ampere does not change, copper losses decrease by 1.6%, the starting motor losses and starting input power decrease by 1.4%, the maximum input power decrease by 7.9%, the maximum output power decrease by 15.3%, the maximum efficiency decrease by 1.9%, the starting power factor increase by 16.4%, finally the angle between the rotor and magnetizing current increase by 11%.

For the same percent of increase in stator inductance, the starting torque, starting copper losses, starting motor losses and starting input power all decrease by 20.8%, the starting stator and rotor currents, starting torque per ampere and starting power factor all decrease by 11%, the maximum torque per ampere decrease by 3.2%, the maximum input power decrease by 19.1%, the maximum output power decrease by 14.2%, finally the maximum efficiency does not change.

For the same percent of increase in rotor inductance, the starting torque decrease by 11.7%, the starting stator current decrease by 13.5%, the starting rotor current decrease by 15.9%, the starting torque per ampere increase by 2.2%, the maximum torque per ampere decrease by 3%, copper losses decrease by 28.3%, the starting motor losses and starting input power decrease by 28%, the maximum input power decrease by 17%, maximum output power decrease by 10%, maximum efficiency decrease by 0.2%, the starting power factor decrease by 16.6%, finally the angle between the rotor and magnetizing current decrease by 11.5%.

For a 20% decrease in mutual inductance, the starting torque decreases by 1.2%, the starting stator current increase by 1%, the starting rotor current, starting motor losses, maximum input power and maximum efficiency all decrease by 0.6%, the starting torque per ampere decrease by 2.1%, the maximum torque per ampere decrease by 3.7%, starting copper losses and starting input power decrease by 0.5%, the maximum output power decrease by 1.3%, finally the starting power factor decrease by 3%.

5. CONCOLUSION

For the same increase in stator resistance, rotor resistance, stator leakage reactance and rotor leakage reactance, the following can be concluded:

The largest decrease in starting and maximum torques, starting torque per ampere, iron losses and maximum input power is due to variation in stator leakage inductance. The largest decrease in stator current and maximum output power is due to variation in rotor resistance. The largest decrease in rotor current, copper losses motor losses and starting power factor is due to variation in rotor leakage inductance. The largest decrease in maximum efficiency is due to variation in stator resistance. The largest decrease in maximum torque per ampere is due to variation in magnetizing inductance.

The angle between rotor and magnetizing current increase when increasing rotor resistance, whereas it decrease when increasing rotor inductance and remain constant for variation in stator resistance, stator leakage inductance an magnetizing inductance.

The variations in motor characteristics due to variation in magnetizing inductance are very small compared to variations due to the remaining parameters.

Appendix

Induction motor details:

$$2\,Hp, 380\ v, 4-pole, 50\,Hz, R_s = 3.41\ \Omega,$$

$$R_r = 4.5 + 8.57S^2\ \Omega, X_s = 7.37\ \Omega, X_r = 11.77\ \Omega,$$

$$X_m = 195\ \Omega, R_m = 1700\ \Omega$$

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