The Characteristic of Control Algorithms for an Induction Electromotor by the Parameters Change in Stator Winding Voltage

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Abstract—In this paper we study various control algorithms of electromagnetic torque and rotor rotation speed by parameters change in stator voltage for an induction electromotor.

Index Terms—Control Algorithm; Induction Electromotor; Stator Voltage.

I. INTRODUCTION

The induction motors are very common because they are inexpensive and robust, finding use in everything from industrial applications such as pumps, fans and blowers to home appliances. Traditionally, induction motors have been run at a single speed, which was determined by the frequency of the main voltage and the number of poles in the motor. Controlling the speed of an induction motor is far more difficult than controlling the speed of a DC motor since there is no linear relationship between the motor current and the resulting torque as there is for a DC motor [1]. Moreover, in contrast to dc motors, induction motors can be used for a long time without maintenance because of their brushless structures.

The least expensive and most widely spread induction motor is the squirrel cage motor. There is no current supply needed from outside the rotor to create a magnetic field in the rotor. This is the reason why this motor is so robust and inexpensive [2].

The technique called Vector control or Field Oriented Control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973) [3]. In the vector control scheme, a complex current is synthesized from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor.

The field Oriented Control was originally developed for high-performance motor applications that are required to operate smoothly over the full speed range, generate full torque at zero speed, and have high dynamic performance including fast acceleration and deceleration. However, it is becoming increasingly attractive for lower performance applications as well due to FOC’s motor size, cost and power consumption reduction superiority [4].

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents [5]. An induction motor can be modelled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct (id) and quadrature (iq) are responsible for producing flux and torque respectively in the motor. By definition, the iq current is in phase with the stator flux, and Id is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system.

The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control. The second fundamental idea is that of reference frames. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a reference frame, which is rotating at the same frequency. Once a sinusoidal quantity is transformed to a constant value by careful choice of reference frame, it becomes possible to control that quantity with traditional proportional integral (PI) controllers.

II. THE INFLUENCE OF STATOR VOLTAGE PARAMETERS ON MECHANICAL CHARACTERISTIC OF INDUCTION ELECTROMOTOR

The parameters of stator sinusoidal voltage are the active value U1 and the angular frequency ω1. Thus we can control the electromagnetic torque by the change of U1 and (or) ω1.

With the change of stator voltage active value U1 and constant angular frequency ω1, the induction electromotor critical torque Mk varies proportionally to the voltage square U1 with a constant value of critical slip Sk. The variation of angular frequency ω1 with constant voltage value U1 will provoke the variation of critical torque but just a bit influences on the rotor current frequency critical value.

The induction electromotor mechanical characteristics in per-units system with separate variation of active voltage U1 and angular frequency ω1 are represented in figure 1.
The deep regulation of induction electromotor speed by voltage reduction on stator winding will lead to the increase of rotor current frequency. With high rotor current frequency, the power losses will increase. (Figure 2)

The deep regulation of induction electromotor speed by reduction of stator winding voltage frequency will lead to the increase of magnetization current and energy losses in stator windings. Thus, to ensure high energy efficiency of induction electromotor control, with squirrel-cage rotor, it is necessary to have a mutual control of voltage amplitude and frequency on stator winding.

Control Algorithm with Maximal Energy Efficiency
In stationary functioning regime, the total electrical power losses in electromotor stator and rotor winding:

$$\Delta P_E = m(R_1.I_1^2 + R_2.I_2^2) = M[1 + \omega_1^2.(T_{02}^2 + T_o^2)]/(\omega_2.T_o^2)$$

From that equation, the active losses depend on angular rotor currents frequency. They have a minimum value:

$$\Delta P_E_{min} = 2M.\sqrt{T_{02}^2 + T_o^2}/T_o^2 \approx M.2.\sqrt{2}/T_o.$$  \hspace{1cm} (1)

For $$\omega_2 = \omega_{2 min} = 1/\sqrt{T_{02}^2 + T_o^2} \approx 1/(\sqrt{2}.T_o)$$

The maximal factor value of energy efficiency for an induction electromotor with squirrel-cage rotor is expressed as follows:

$$E_{max} = M/\Delta P_E_{min} = L_o/(2.\sqrt{2}.R_1; R_2) = T_o/(2\sqrt{2})$$

It is proved that the maximal possible value of energy efficiency of induction electromotor is:

$$E_0 = T_o/2$$

Thus, the maximal possible value of energy efficiency coefficient is:

$$K_E = E_{max}/E_0 = 1/\sqrt{2}$$

If we consider that the magnetic circuit of the machine is linear, then $$\omega_{2 min}$$ is a constant value, and does not depend on the load. If we consider the non-linearity, then the main time constant value $$T_0$$ is to be studied as a function of magnetization current.

The plot of dependence for power electric losses on rotor frequency current is shown in figure 2.

Finally, the construction algorithm of electromagnetic torque ensuring maximal energy efficiency is as follows:

1. We stabilize angular rotor currents frequency at the level $$\omega_{2 min}$$ by varying the angular frequency of voltage such that $$\omega_1 = \omega + \omega_{2 min}$$;
2. We ensure the given electromagnetic torque by varying the voltage amplitude in stator winding.

We shall express the condition of minimal losses in a different manner:

Magnetization currents are:

$$I_{01} = U_1/Z(\omega_1, \omega_2); I_2 = \sqrt{C}.U_1.\omega_2.T_o/Z(\omega_1, \omega_2)$$

Consequently,

$$I_2 = \sqrt{C}.I_{01}.\omega_2.T_o$$

By replacing the expression $$\omega_2 = \omega_{2 min} = 1/(\sqrt{2}.T_o)$$, we have the second condition:

$$I_2 = I_{01}.\sqrt{C}/2$$

The electromagnetic torque of induction electromotor with stabilization of angular rotor currents frequency at the level $$\omega_{2 min}$$ is defined by the expression:

$$M = m.R_1.U_1^2/2(Z(\omega + \omega_{2 min}, \omega_{2 min}))^2$$  \hspace{1cm} (2)

The set of mechanical characteristics with stabilization of angular rotor currents frequency at level $$\omega_{2 min}$$ will have the aspect represented in figure 3.
The active voltage value that can ensure the given electromagnetic torque is found by using the formula (2):

$$U_1 = \frac{Z(\omega_1 + \omega_{2\min}, \omega_{2\min})}{L_0} \sqrt{\frac{M.R_2}{m.\omega_{2\min}}}$$

Where

$$Z(\omega_1, \omega_2) = R_1\sqrt{(1 - \omega_1.\omega_2.T_e^2)^2 + (\omega_1.T_{01} + \omega_2.T_{02})^2}$$

The plots of stator voltage dependence on angular frequency $\omega_1$ with $\omega_2 = \omega_{2\min}$ and various torque values are shown on figure 4.

![Fig. 4. Stator Voltage dependences on stator currents frequency for fixed rotor currents frequency](image)

Finally, for the realization of control from the power losses point of view it is necessary to maintain the stator voltage less than nominal value $U_N$.

The plot of dependence that characterizes the decrease of energy efficiency of squirrel-cage induction electromotor with reduction of rotor currents frequency from $\omega_{2\min}$ is shown in figure 5.

![Fig. 5. Dependence of Squirrel-cage induction electromotor energy efficiency coefficient on rotor currents frequency](image)

Finally, the use of such control algorithm ensures minimal and constant electrical losses value is possible only for little rotor rotation frequencies or for little values of electromagnetic torque. That is why this control mode is not often applied.

III. THE CONTROL ALGORITHM WITH CONSTANT MAGNETIZATION CURRENT

This control algorithm has received a great expansion:

1) We stabilize the stator magnetization current at the level of nominal value by acting on voltage vector $U_{01}$;

2) We ensure the given torque by acting on angular voltage frequency $\omega_2$.

We study in details this mutual control of amplitude and voltage frequency in stator. For a fixed magnetization current value at $I_{01N}$, the winding stator voltage is $U_1 = I_{01N}.Z(\omega_1, \omega_2)$.

If we replace $Z(\omega_1, \omega_2)$ and $I_{01N}$,

$$U_1^* = \frac{\sqrt{(1-\omega_1.\omega_2.T_e^2)^2 + (\omega_1.T_{01} + \omega_2.T_{02})^2}}{\omega_{01.N}} \approx / \omega_1^* + \omega_2^*/\omega_1/3$$

The plots of voltage $U_1^*$ dependence on angular frequency $\omega_1^*$ for various values of $\omega_2^*$ are shown in figure 6.

![Fig. 6. Dependences of stator active voltage value on stator voltage angular frequency that ensure constant magnetization current](image)

If we maintain a constant magnetization current

$$I_{01}^* = \frac{1}{I_0} \text{ then } I_2^* = j.\omega_2^*, L'_1.I_{01}/R_2^* = j.\omega_2^*/R_2^* \quad (4)$$

From that, magnetization stator current $I_{01}^*$ and rotor current $I_2^*$ are orthogonal.

Thus the electromagnetic torque is proportional to rotor current or to its angular frequency:

$$M^* = I_2^* = \omega_2^*/R_2^* = (\omega_1^* - \omega_2^*)/R_2^* \quad (5)$$

Induction motor mechanical characteristic with squirrel-cage rotor with constant magnetization current will be defined by:

$$\omega^* = \omega_1^* - R_2^* M^*$$

The induction electromotor mechanical characteristics with voltage variation according to (3) are shown in figure 7.

![Fig. 7. Mechanical characteristics for various voltage dependences on frequency](image)
Electrical losses with constant magnetization current are defined by expression:

\[ \Delta P_E^* = R_2^* [I_{01}^2 + (1 + T_{02}/T_0^2).M^*2] \approx R_2^* (I_{01}^2 + 2.M^*2) \]

The energy efficiency coefficient with constant magnetization current \( I_{01}^* = 1/L_{01}^* \) is determined by losses ratio:

\[ K_E = \frac{\Delta P_{Emin}^*}{\Delta P_E^*} = \frac{2.\sqrt{2}.C.M^*}{1/L_{0}^* + 2.L_{0}^*.M^*2} \]

Where \( C = R_1^*/R_2^* \)

The plot of dependence is shown in figure 8.

Fig. 8. Energy efficiency coefficient of squirrel-cage induction electromotor with stabilization (1) of rotor currents frequency and (2) of magnetization current

IV. CONCLUSIONS

For the control of torque, it is necessary to act simultaneously on frequency and amplitude of three-phase symmetrical voltages system of stator windings. There are two possible control modes for squirrel-cage induction electromotor. The first mode is based on ensuring minimal electric losses. For that purpose, the algorithm will maintain the constant value of rotor currents frequency \( \omega_2 = \omega_{2min} \), and the electromagnetic torque regulation is done by stator voltage. The second mode is based on stator magnetization current as constant by acting on voltage amplitude. The electromagnetic torque is regulated through stator voltage frequency.

From figure 8, it is obvious that from the criteria of energy losses, the first control algorithm is more effective than the second. For the torque \( M^* \approx I_{01}^N \), the losses for both algorithms can be comparable. The induction electromotor control algorithm with constant magnetization current ensures the electromagnetic torque regulation in a large diapason.

REFERENCES