The Control of Squirrel-Cage Induction Electromotor with Constant Magnetization Current

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Abstract—In this paper, we study the control algorithm of electromagnetic torque and rotation speed of squirrel-cage induction electromotor with constant magnetization current. We can ensure the constant magnetization current by acting on stator voltage vector. We distinguish two methods of construction of the given magnetization current. The first method is based on variation of stator voltage amplitude from the information just of rotor rotation speed. The second method is based on the stator voltage frequency and amplitude from the stator current information. The second method permits to influence the characteristic equation roots of the control system and to have magnetization current dynamic properties.

Index Terms—Control, Induction Electromotor, Constant Magnetization Current.

I. INTRODUCTION

Direct torque control (DTC) of induction motors has gained popularity in industrial applications mainly due to its simple control structure from its first introduction in 1986 [1]. An electric motor drive controlled with the DTC technique exhibits performance similar to a field-oriented drive despite a simpler structure [1],[2]. In fact, a DTC scheme achieves the closed-loop control of the motor stator flux and the electromagnetic torque without using any current loop or shaft sensor. Many researchers are interested in this control technique because of its wide area applications used with various ac machine types as induction motor [3], PMSM [4],[5], PM Brushless [6], and reluctance motor [7].

The DTC scheme requires information about the stator currents and the dc-link voltage, which is used with the inverter, switches states, to estimate the values of stator flux and electromagnetic torque. The current feedback for the closed-loop control is usually obtained by sensing instantaneous phase currents by current sensors. In general, galvanically isolated current sensors such as Hall-effect sensors and current transducers are widely used in many applications [8], [9]. They are typically used on, at least, two outputs of the power inverter to provide current feedback signals. Such a kind of sensors performs well, but brings disadvantages to the overall drive system in terms of cost, encumbrance and somehow nonlinearity. Recently, single current sensor operation has been proposed to reconstruct phase currents from the dc-link current sensor [10]. In this way, various approaches have been proposed in the literature. Some methods adjust the pulse-width modulation (PWM) signals to ensure that two-phase currents can be sampled in each control period [11], [12]. Other strategies introduce modifications of the modulation algorithm in order to guarantee the reliability of the measurements from the dc-link current sensors under all the operating conditions [16]-[18]. Other interesting approaches are based on the estimation of the motor phase currents using prediction-correction algorithms, thus introducing additional computational burden to the drive system [19] – [22].

Only a few papers deal with DTC technique for induction motor [23] and PMSM [24].

For the design of three-phase induction electromotor with squirrel-cage rotor, we assume that the stator winding is supplied through the frequency transducer (see Fig. 1).

![Fig.1. Electric drive of induction electromotor with frequency transducer (FT)](image)

We design a three-phase voltages system: \( U_5 = [u_A \ u_B \ u_C] \).

The frequency transducer has a high fast action, that is considerably greater than the speed of electromagnetic processes in induction electromotor.

II. DYNAMICS CONSTRUCTION OF ELECTROMAGNETIC PROCESSES IN INDUCTION ELECTROMOTOR

The electromagnetic processes in the induction electromotor have an oscillating character. To get expected dynamic processes is possible only in closed-loop control system.

Let us create a control loop with proportional regulator (Fig. 2)
Fig. 2. Structural circuit of electromagnetic processes construction in induction electromotor with squirrel-cage rotor

\[
\dot{u}_1 = K_1 \dot{Y}_1 + K_{01} i_{01} + K_2 i_2
\]

(1)

With \( \dot{Y}_1 \) – vector of input action \( K_1 \);

\( K_{01} \) et \( K_2 \) – regulator parameters

After various replacements, we have the following equations:

\[
L_K \ddot{p}_{i2} = (R_1 + j. \omega. L_{01} - K_{01}). i_{01} - (R_2 + j. \omega_1. L_K). i_2 - \dot{u}_1;
\]

And \( L_0.p_i01 = -j. \omega_2. L_0.i_{01} - R_2.i_2, \)

Where \( L_K = \frac{K_{01}.L_{01}}{L_0}; \quad R_2 = \frac{K_{01}.L_{01} + L_0.K_2}{L_0}; \quad \omega = \omega_1 - \omega_2 \)

Thus

\[
p^2. i_{01} + \dot{a}_2.p_{i01} + \dot{a}_0.i_{01} = K_1/(L_K.T_{20}).Y_1
\]

(2)

Where \( \dot{a}_1 = (R_K + K_2)/L_K + j.(\omega_1 + \omega_2); \)

\( \dot{a}_0 = (R_1 - K_{01})/(L_K.T_{20}) - \omega_1 \omega_2 + j.\{p. \omega_2 + [\omega_1. L_{01} + 2.\omega_2. (R_K + K_2)/L_K]; \}

\( T_{20} = L_0/R_2 \)

If we consider \( K_1 = T_{20}/L_K.T^2; \)

\( K_{01} = R_1 + K_1 (T^2.\omega_2^2 - 1) \)

\( + j.K_2.\{T.p.\omega_2 + d. \omega_2\} + \omega L_0]; \)

\( K_2 = K_2 \cdot d.T_k/T - 1 - j.T_k.\\{\omega_1 + \omega_2\}; \)

Then (3) becomes:

\[
T^2.p^2.i_{01} + d.T.p_{i01} + i_{01} = \dot{Y}_1
\]

(4)

where \( T \) – middle geometrical time constant;\n
d – damping parameter \( T_k = L_K/R_2 \)

The time constant \( T \) in the frame of this model can take any value. But little values can lead to unstable control system.

III. EQUATIONS OF INDUCTOR AND ARMATURE IN INDUCTION ELECTROMOTOR

The choice of damping parameter \( d \) depends on control algorithm. If there is necessity of control with minimal energy losses, then we consider \( d = \sqrt{2} \).

If there is necessity to control with stator constant magnetization current, then \( d > 3 \). In that case, electromagnetic processes can be divided into fast and slow. Slow processes will characterize stator magnetization current variation, while fast ones will characterize the rotor current. The equations that characterize the variation of magnetization current are called "equations of inductor" while those that characterize the variation of magnetization current are called "equations of armature".

If \( \dot{Y}_1 = Y_1 \) – real variable, then from equation (4) the stator magnetization current is also a real value \( i_{01} \).

And for \( d > 3 \) (4) can be approximated with

\[
d.T.p_{i01} + i_{01} = Y_1
\]

(5)

Very often in per units \( Y_1^* = 1/L_0^* \). And in established regime, the stator magnetization current is also a constant expression \( i_{01} = Y_1^* = 1/L_0^* \).

When constructing the control system, \( d.T \) should be given a high value but still be less than \( T_{Mech} \).

For example, we could choose \( d.T = T_{Mech}/3 \).

Let us find equations that characterize fast processes. If the imaginary part of magnetization current \( i_{01} = 0 \), and the real part \( i_{01} \) varies slowly, after analysis, \( i_{20} = 0 \) (the real part of rotor current), and \( i_2 = i_{20} = j.\dot{i}_2 \)

From (2) we have

\[
T_2.p_{i2} + i_2 = -L_0.\{T_2.p.\omega_2.\omega_1 + \omega_2.\omega_2\}/R_2
\]

Where \( T_2 = T/d \)

That equation is the armature equation. And it characterizes fast processes in induction electromotor.

The time constants of fast and slow processes are different by \( d^2 \) times.

If we assume that in the feedback coefficient \( K_{01}.p_{a02} = 0 \), then the armature equation is:

\[
T_2.p_{i2} + i_2 = -L_0.\omega_2.i_{01}/R_2 \text{ where } T_2 = T/d \]

(6)

If we consider that \( i_{01} \) is constant and equal to \( 1/L_0^* \) in per units, the rotor current – output signal, and rotor current frequency – input signal, then (6) can be represented in the form of transfer function:

\[
W_2 = \frac{i^*_{20}}{\omega_2^*} \approx \frac{i_2^*}{\omega_2^*/2 + 1}
\]

(7)

IV. CONTROL OF INDUCTION ELECTROMOTOR ELECTROMAGNETIC TORQUE

In per-units, the electromagnetic torque is

\[
M^* = L_0^*.i_{01}^*.i_2^*
\]

If the magnetization current \( i_{01} = 1/L_0^* \), then the electromagnetic torque is proportional to rotor current.

\[
M^* = i_2^* \cdot \text{ The control of rotor current } i_2^* \text{ can be done by variation of rotor current angular frequency } \omega_2^* = \omega_1^* - \omega^*
\]

Where \( \omega_1^* \) - angular stator voltage frequency; \( \omega^* \) - angular rotor rotation speed.

The angular rotor rotation speed is defined by the movement equation:

\[
T_{Mech}.p.\omega^* = M^* - M_r^*
\]

(8)
Where \( T_{Mech} \) - Mechanical time constant
\( M_r^* \) - resistance torque in per-units.

We assume that the frequency transducer that varies the angular stator voltage frequency \( \omega_1^* \) is aperiodical first order element with transfer function

\[
W_E = \frac{1}{T_E p + 1}
\]

\( T_E \) – Small time constant.

The structural control circuit of rotor current constructed from the subordinate principle and considering the relations above is represented in Fig. 3.

The rotor current loop control object is similar to direct current motor armature current control object.

The rotor current loop installed at technical optimum will have expected transfer function:

\[
W_{exp} = \frac{1}{2 T_u^* p^2 + 2 T_\mu p + 1} \approx \frac{1}{2 T_\mu p + 1}, \text{where } T_\mu = T_E
\]

The limitation of induction electromotor rotor current and torque is done by limitation of input-signal, where \( I_{max}^* \) – maximal acceptable rotor current value.

V. CONTROL OF ROTOR ROTATION SPEED FOR AN INDUCTION ELECTROMOTOR

The control of rotor rotation speed is related with the control of electromagnetic torque. We can construct subordinate speed control system. The internal current loop and the external speed loop with proportional speed regulator:

\[
K_{sr}^* = \frac{T_{Mech}}{4 T_\mu}
\]

The structural circuit of subordinate control is shown in Fig. 4.

Let us study the direct control of rotor rotation speed without the rotor current loop.

The transfer function of control object (Fig. 5) for speed loop on input signal is:

\[
W_{01} = \frac{\omega^*/\omega_1^*}{1/(T_M P + 1)},
\]

Where \( T_M = R_\mu^2, T_{Mech} \) – electromechanical time constant;

Let us assume that the expected transfer function of speed loop has the following aspect:

\[
W_{exp}(P) = 1/(2 T_\mu^2 P^2 + 2 T_\mu P + 1)
\]

Thus the speed regulator is:

\[
W_R = \frac{1}{W_{01}, 2, T_\mu P (T_\mu P + 1) = \frac{1}{2 T_M P}}
\]

Where \( T_\mu = T_M \).

Obviously, the integral speed regulator will ensure rigidity of mechanical electric drive characteristics and the start of electromotor in a minimal possible time. Meanwhile in that case, the electromotive torque in dynamics can reach very high values. The Laplace transform of electromagnetic torque in speed loop is:

\[
M^* = T_{Mech} P, W_{exp} x_2^* + (2 T_M P + 1) W_{exp}, M_r^*
\]

The plot of torque transient function, created by the transfer function \( W_M = T_{Mech} P, W_{exp} \) is shown on Fig. 6.

The maximal torque value with \( x_2^* = a \cdot 1(t) \) can be evaluated \( M_{max}^* = a \cdot 0.322/R_\mu^2 + M_r^* \).

For the limitation of dynamic torque values in control system input, we can install the intensity captor start (Fig. 5).

The intensity captor will limit the exceeding torque by the value \( M_{exc} = T_{Mech}/T_0 \).

Finally, the direct rotor rotation speed control (without rotor current loop) can be used in case when it is necessary to start the induction electromotor rotor in a given time.

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VI. CONCLUSION

The control of squirrel-cage induction electromotor assumes the stabilization of magnetization current by action on stator voltage vector. The stabilization of magnetization can be achieved through stator voltages vector as functions of angular stator voltage frequency and rotor rotation speed.

Another way towards magnetization current stabilization assumes the construction of control loop with feedback links on stator magnetization current and rotor current.

For constant magnetization current, the electromagnetic torque is proportional to rotor current angular frequency that is why the stabilization of electromagnetic torque is done by action on rotor current angular frequency. For that purpose, we construct rotor current control loop.

With the presence of rotor current control loop, the control of rotor rotation angular speed can be achieved by the subordinate control. Another way for rotor rotation speed stabilization is direct speed loop without rotor current loop.

In that case, for limitation of rotor current and exceeding torque, it is necessary to install the intensity captor at speed loop input.

REFERENCES


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