CONTROL OF INDUCTION ELECTROMOTOR IN CASCADE CIRCUITS
(ASYNCHRONOUS-RECTIFIER CASCADE)

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ABSTRACT
In this paper, we study the design of control system of asynchronous rectifier cascade. For the presentation of equations in per-units, as basic values, we consider the nominal active values of stator current and voltage.

INTRODUCTION
With the development of power devices, many high-performance full-power devices have emerged [1, 2]. Therefore, PWM technology has been applied to rectifiers in combination with today's full-performance power switches with different performances. Various types of PWM have been developed, such as Asynchronous Rectifier Cascade [3]. However, due to the withstand voltage and power limitation of the currently controlled devices, the power voltage and power they are subjected to are relatively small, so they cannot be used normally in high-voltage and high-power applications, and application development is limited. In order to achieve high-voltage and high-power applications, on the one hand, it is necessary to design power devices with higher withstand voltage levels; on the other hand, it is necessary to improve the topology to improve the withstand voltage level [4, 5].

With regard to improving the topology, the currently accepted view is two methods [6, 7]: one is to adopt a clamped multilevel rectifier; the other is to take the form of an H-bridge cascade. For the first type, there is a problem of capacitance voltage balance control, which affects the power quality. For the second type, there is no problem of capacitance imbalance, and it is easy to realize modularization, and subsequent voltage level increase is also convenient, so the cascading structure to reduce the withstand voltage of the power device becomes an effective method to solve this problem [8].

The slip energy of induction electromotor for deep speed regulation is very high. That is why it is convenient to give back the slip energy to the network. The circuit that will ensure the transfer of slip energy to constant voltage source is shown on figure 1.

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In rotor circuit we include a three-phase bridge rectifier. The endings of direct current rectifier are connected to constant voltage source that is having regulated e.m.f value $E_{d}$, internal resistance $R_s$ and dispersion inductance $L_{ld}$.

In direct current circuit, we can include a reactor with inductance $L_{b}$. This circuit will be called Asynchronous – Rectifier Cascade (ARC).

The control of electromagnetic torque and consequently the rotor rotation speed is done by the change of e.m.f $E_{d}$ in rotor rectified current circuit. Part of alternative current source energy is transformed into mechanical energy with losses in electromotor, while the other part is consumed by direct current circuit. The source of constant e.m.f $E_{d}$ functions in consumed energy regime.

**Dynamic Model of Asynchronous Rectifier Cascade**

For the design of control system ARC, we have the equivalent circuit of rectified current that is a series connection of two e.m.f sources, an inductance and resistance (figure 2).

![Figure 2](image)

The equivalent inductance of rectified current circuit:

$$L_d = L_{in} + L_{rd} + L_{do},$$

With $L_{in} = 2$, $L_{rd}$ – the equivalent inductance carried in rectified current circuit from the rotor side;

$$L_{rd} = L_1 + L_2$$

- total dispersion inductance of stator and rotor windings

The equivalent active resistance of rectified current circuit

$$R_d = R_{rd} + R_{do},$$

With $R_{rd} = 2R_d$ – active resistance carried in rectified current circuit from rotor side;

$$R_d$$ – rotor winding active resistance;

- The commutation resistance of rectified bridge

$$\omega^2, X_d, \omega, L_k$$ – commutation resistance of rectifier bridge and slip $\omega^2 = 1$.

Applying the 2nd Kirchoff law in figure 2,

$$L_d \cdot P_{ld} + \omega^2 \cdot X_d \cdot I_d + R_d \cdot I_d = \omega \cdot E_{2rdo} - E_{1d}$$

With $E_{2rdo}$ – rectifier e.m.f. for slip $\omega^2 = 1$.

The control of rotor current $I_d$ and electromagnetic torque $M$ is done by e.m.f change in rotor current $E_{1d}$. As an e.m.f source $E_{1d}$, we can use any regulated constant voltage source, that is capable of functioning in consumed energy regime. Very often, we can use a thyristor transducer that functions in inverter regime.

We assume that the e.m.f. source $E_{1d}$ is controlled by the voltage $u_0$ so that:

$$E_{1d}(u_0) = E_{2rdo} - E_d(u_0),$$

With $E_d(u_0) = K_{de}u_0$; $K_{de}$ – amplification coefficient of electrical energy transducer.

Let us assume that we settle

$$E_d(u_B) = K_{dr}u_B = E_{2rdo} = K_{de}u_N,$$

With $u_B$ – Basic value of control system signals;

$K_{de}$ – the coefficient of three–phase rectifier bridge;

$u_B$ – nominal active value of stator circuit phase voltage, From those expressions, in per-units:

$$K_{dr} = K_{de},$$

Thus $E_d(u_0) = K_{de}u_0$ and equation (1) becomes:

$$L_d \cdot P_{ld} + \omega^2 \cdot X_d \cdot I_d + R_d \cdot I_d + \omega \cdot K_{de} = E_d(u_0)$$

With $R_d = X_d + R_d$; $\omega^2 = 1 - \omega^2$ – angular rotation speed $u_0 = u_B/U_B$.

Let us assume that the rectified current $I_d$ and active rotor current value $l_d$ are linked by equation

$$K_d = K_{de}l_d = 0.78L_d$$

$$l_d = P_{ld} + \omega \cdot X_d \cdot I_d + R_d \cdot I_d + \omega \cdot K_{de}$$

With $E_d(u_0) = E_d(u_0)/K_d$; $l_d = K_{ld}l_d$; $R_d = K_{rd}R_d$; $X_d = K_{xd}X_d$;

$$X_d = K_{rd}X_d \approx L_1 = L_2$$

$K_{rd}$ – coefficient of parameters calculations.

The linear element of electrical part for the electromotor has aperiodical transfer function:

$$W_d = \frac{1}{T _{iph} + 1},$$

With $T_d = L_{rd}/R_{xd}$ – electric time constant of the electromotor.

The nonlinear electrical part of ARC is due to the presence of commutation resistance $\omega^2 X_{2d}$, that depends on angular rotor rotation speed $\omega^2$.

The electric transducer constructs e.m.f. $E_{2r}(u_0)$ so that $E_{2r} = u_0$; the transducer is represented in figure 3 as an aperiodical element of first order with transfer function:

$$W_{et} = \frac{1}{(T _{iph} + 1)}.$$
That characteristic is verified only if the rectified rotor current is continuous. If the e.m.f. is constructed by a three-phase bridge transducer, then in the domain of little currents values, it appears a zone of interrupted currents.

The limit-continuous rectified rotor current is defined: \( I^*_g = I^*_{ag} \sqrt{1 - (1 - \omega^*)^2} \),

With \( I^*_{ag} = K_e/E_{ag} \cdot (1 - \pi/6. \cot g(\pi/6)) \)

The set of mechanical characteristics in per-units for various \( u^*_0 \) is shown on figure 4.b.

The mechanical characteristic \( M^*(\omega^*) \) has a maximal value \( M^*_m = \frac{1}{4x^2_{2d2}} \) with \( \omega^* = \omega^*_m = 2u^*_0 - \frac{R_{2s}}{x^2_{2d2}} \).

Subordinate Control System of Arc

The differential equation (3) that characterizes the dynamics of electromagnetic processes is nonlinear.

For the design of dynamic processes in structural circuit of figure 3, we fix \( X^2_{2d2} = 0 \).

The subordinate control system ARC with current loop and a speed loop is shown on figure 5.

The current regulator is a proportional-integral element with transfer function:

\[
W_{cr} = K_{r_2} + \frac{1}{T_{r_2}}P,
\]

With \( T_{r_2} = 2K^*/T_e/R_{x_2d2}; K_{r_2} = T_2/T_{r_2}; K = U_b/I_{2max} \).

The speed regulator is proportional with amplification coefficient

\[
K^*_s = K^* \cdot \frac{T_{Mech}}{4T_e}
\]

The statistic electromechanical characteristic of ARC with speed loop is:

\[
\omega^* = x^*_3 - \frac{4T_e}{T_{Mech}}I^*_2.
\]

CONCLUSIONS

The circuit of asynchronous-rectifier cascade (ARC) gives the possibility to transfer the slip energy of induction electromotor rotor to the network. There are various technical variants for that purpose.

The classical circuit of ARC is a frequency transducer with a direct current element, composed of a rectifier and inverter.

The ARC has good regulation properties. The usual inconvenient is the high reactive current value, consumed from the network for rotor rotation speed near to synchronous speed. The energetic properties of ARC are analogue to the properties of squirrel-cage induction motor, controlled by frequency transducer with constant magnetization current.

References