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Algorithmic structure of control system of mine winder electric drive with a doubly-fed motor

V Yu Ostrovlyanchik and I Yu Popolzin

Siberian State Industrial University, 42 Kirova str., Novokuznetsk, 654007, Russia

E-mail: eidoline@yandex.ru

Abstract. Usage of doubly-fed electric machine is a promising means to modernize asynchronous electric drives of mine winders based on wound rotor induction motor. To ensure a wide range of speed regulation, typical of mine winders, while maintaining the critical torque of the machine and its overload capacity, it is necessary to control amplitude, frequency and phase shift of the auxiliary voltage on the rotor. Since the frequency and phase shift determine the additional voltage argument, and the amplitude determines its modulus, then the speed control by changing the module and the argument is a non-trivial task requiring a special structure of control system of mine winder electric drive, as well as special regulators, and the system is non-linear. This article discusses the construction of a functional structural diagram of electric drive control system based on a doubly-fed motor, which allows the indicated features of controlling the speed of a doubly-fed machine to be taken into account by changing the parameters of the auxiliary voltage on the rotor.

1. Introduction

The use of existing a wound rotor induction motor in the circuit of a doubly-fed machine (DFM) is a promising means to modernize asynchronous electric drives of mine winders [1]. The main problem of using a doubly-fed machine in the winder electric drive is the limited range of machine speed control due to a change in the amplitude of the additional voltage in the rotor circuit. With an increase in the amplitude of the additional voltage and a corresponding decrease in the speed of rotation of the machine rotor, the critical torque also decreases, as well as the rigidity of the working section of the mechanical characteristics. For this reason, the range of regulation of DFM speed is often estimated as 2-2.5:1 [2]. However, for mine winders a speed control range of at least 30:1 is required, as well as the implementation of the brake release mode characteristic for winders [3].

In [4] and [5] the so-called synchronous mode of DFM operation is described, in which the mechanical characteristics of DFM are similar to the mechanical characteristics of a synchronous motor. However, the implementation of such regime, especially for powerful induction motors, is fraught with technical difficulties. In [1], the condition was obtained for maximizing of the critical torque of the machine in asynchronous mode by the phase shift of the additional voltage on the rotor in the form:

$$\delta = \arctg\left(\frac{s}{s_{Cn}}\right), \quad (1)$$

where δ is the phase shift of the additional voltage on the rotor relative to the voltage on the stator, s is the current slip, s_{Cn} is the critical slip on the natural mechanical characteristic. Nevertheless, the



fulfillment of condition (1) does not allow reaching the control range of 30:1, since the critical torque of the machine and the rigidity of the working sections of its mechanical characteristics decrease with decreasing speed.

2. DFM mathematical description

The authors also proposed a way to increase the range of regulation of DFM speed by simultaneous change in the amplitude and frequency of the additional voltage on the rotor for correction of machine mechanical characteristics, increase in the rigidity of its working section and increase in the critical torque of the machine. The additional voltage on the DFM rotor changes according to the law:

$$u_R(t) = U_R \sin(\omega_R t + \delta), \quad (2)$$

where U_R is the amplitude of the additional voltage, ω_R is the electric frequency of the additional voltage, u_R is the instantaneous value of the additional voltage. With the change in frequency of the additional voltage on rotor by a value $\Delta\omega_k$, expression (2) takes the form:

$$u_R(t) = U_R \sin((\omega_R + \Delta\omega_k)t + \delta). \quad (3)$$

When additional voltage is applied to the rotor in the rotor circuit, the intrinsic EMF of the rotor and the additional voltage are totaled (3). A linear summation operation is possible if the arguments are equal. Otherwise, it is necessary to consider nonlinear functions and the analysis and synthesis of control systems is much more complicated. For the possibility of analysis and synthesis of systems by the linear method, it is necessary to linearize; in this case, linearization is possible with small deviations, if $\Delta\omega_k$ not enough. Based on the studies conducted in [1], [3], [6-8] an equivalent DFM circuit was obtained with a change in the amplitude and frequency of the auxiliary voltage on the rotor, shown in figure 1.

In figure 1 the following notations are used: z_p – the number of pole pairs of the machine, $\Delta\omega$ is the magnitude of the change in the frequency of the additional voltage on the rotor, ω_0 – the speed of the ideal idle speed of the machine; ω is rotational speed of the machine rotor; C_{em} – coefficient of electromagnetic coupling of the engine, M_{Cn} is the critical torque of the machine on the natural mechanical characteristic, M_s – the static torque of the load; J is the total torque of mechanism inertia reduced to the rotor, u_s – is the voltage at the machine stator, φ_s – the phase shift between the voltage at the stator and the stator current, u_R – the additional voltage at the rotor, i_{Ra} – the active current component of the DFM rotor, $L\mu$ – the mutual inductance of the stator and the rotor of the machine, R_s – the active resistance of the machine stator, k_E – the internal feedback coefficient of the machine EMF, R_R – the active resistance of the rotor, T_R – the electromagnetic time constant of the rotor, M_a – the asynchronous component of the DFM torque, M_ω – the component of DFM torque due to a change in the frequency of the additional voltage on the rotor.

According to the scheme shown in figure 1, it is seen that the DFM torque depends on the amplitude and frequency of the additional voltage. In this case, the speed control of the machine is carried out by changing the amplitude of the additional voltage on the rotor, and changing the frequency allows the correction of mechanical characteristics (the rigidity of the working section and the critical torque to be increased) with increasing amplitude of the additional voltage to be performed. When the frequency of the additional voltage on the rotor increases by the value $\Delta\omega_k$, the speed of the machine increases as well.

Thus, by changing $\Delta\omega_k$, the type of mechanical characteristics of the DFM can be adjusted. Therefore, the correction of the DFM characteristics with the structure shown in figure 1 is carried out by changing the phase shift according to condition (1) and changing the frequency of the additional voltage, the speed and torque are directly controlled by changing the amplitude of the additional

voltage. In this case, technically, the introduction of additional voltage into the rotor circuit and the change of its parameters is carried out using a controlled voltage converter (CVC) in the rotor circuit.

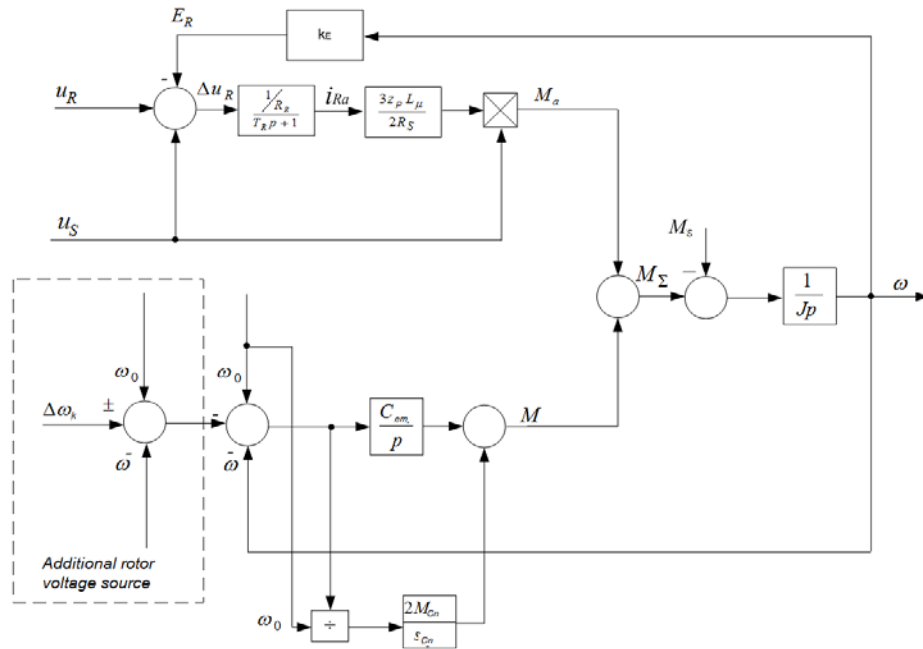


Figure 1. Equivalent structure of an double-fed induction motor with a change in the amplitude and frequency of the additional voltage.

3. The mathematical description of the controlled voltage converter

The formation of the voltage amplitude at the output of CVC in accordance with [9] is carried out according to the law:

$$U_R = \frac{k_C}{T_C p + 1} U_{aU}, \quad (4)$$

where U_{aU} is the voltage of the set amplitude; U_R – the specified amplitude of the additional voltage on the rotor.

The change in frequency at the CVC output is proportional to the set voltage:

$$\Delta \omega_k = U_{a\omega} k_\omega, \quad (5)$$

where $U_{a\omega}$ is the voltage of the frequency setting, k_ω is the proportionality coefficient.

In this case, the frequency ω_R is defined as:

$$\omega_R = \omega + \Delta \omega_k. \quad (6)$$

In accordance with the scheme shown in figure 1:

$$\Delta \omega = \pm \Delta \omega_k - \omega + \omega_0, \quad (7)$$

whence it follows that $\Delta \omega_R$ is determined by the expression obtained from expressions (3-7):

$$\begin{cases} U_R = \frac{k_C}{T_C p + 1} U_{aU}, \\ \Delta\omega_k = U_{a\omega} k_\omega, \\ \omega_R = \omega + \Delta\omega_k, \\ \Delta\omega = \pm \Delta\omega_k - \omega + \omega_0, \\ u_R(t) = U_R \sin(\omega_R t). \end{cases} \quad (8)$$

The system of equations (8) can be associated with the structural diagram shown in figure 2.

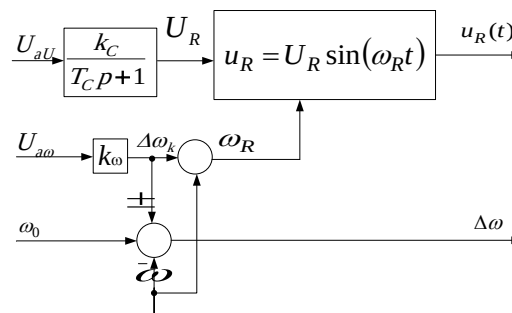


Figure 2. CVC block diagram.

4. Functional relationship of rotor torque and current

As mentioned above, changing the frequency of the additional voltage on the rotor allows the rigidity of the working section of the DFM mechanical characteristics to be increased. The change in frequency, providing the stiffness of the characteristic is not lower than natural, can be determined by the expression obtained by the authors:

$$\Delta\omega = \frac{M_n s_{Cn} \omega_0 - 0,5(\omega_0 - \omega) M_{Cn}}{2M_{Cn}}. \quad (9)$$

During the operation of the DFM in the winder electric drive, it is necessary to control not only the speed of the machine, but also its torque. However, direct identification of the torque of the machine is difficult to implement. The torque can be calculated based on the measured value of the active component of the current. In [3] it is shown that the torque and current of the rotor are related by the relation:

$$M = \frac{3}{2} L_\mu i_{Ri} i_s, \quad (10)$$

where i_s – the stator current of the machine, i_{Ri} – the active component of the rotor current in the coordinate system described in [9]. Given that this coordinate system is associated with the stator current vector, and the additional voltage on the rotor is shifted relative to the voltage on the stator by angle δ (1), then i_{Ri} can be defined as:

$$i_{Ri} = i_R \cos(\delta - \varphi_s + \varphi_R) = i_R \cos\left(\arctg \frac{s}{s_{Cn}} - \arctg\left(\frac{X_s}{R_s}\right) + \arctg\left(\frac{X_R}{sR_R}\right)\right), \quad (11)$$

where i_R – the rotor current; X_s , X_R – reactance of the stator and rotor, respectively; R_s , R_R are the stator and rotor pure resistances, respectively.

The stator current value included in (10) can be measured directly or calculated using the stator voltage value u_s :

$$i_s = \frac{u_s}{\sqrt{R_s^2 + X_s^2}}. \quad (12)$$

Taking into account (10) and (11), expression (10), which determines the functional relationship of the rotor current and torque, can be written as:

$$M = f(i_r) = \frac{3}{2} L_\mu \frac{u_s i_r \cos \left[\arctg \frac{s}{s_{cn}} - \arctg \left(\frac{X_s}{R_s} \right) + \arctg \left(\frac{X_r}{s R_r} \right) \right]}{\sqrt{R_s^2 + X_s^2}}. \quad (13)$$

The torque is calculated in accordance with expression (13) using a nonlinear functional unit, the structure of which is shown in figure 3.

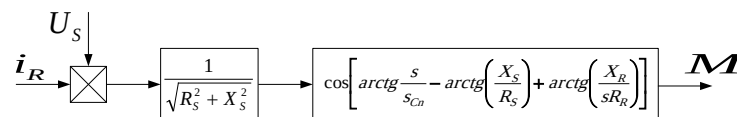


Figure 3. The structure of the functional unit for calculating the torque.

5. Algorithmic structure of control system of mine winder electric drive with a doubly-fed motor

Taking into account the diagrams shown in figures 1 and 2, as well as those described in [1], [3], [6-8], [12], it is possible to compose the algorithmic structure of a winder electric drive control system based on DFM shown in figure 4.

The following notations are used in the diagram: SG – speed controller, CG – current controller, u_ω – feedback voltage by speed, u_i – feedback voltage by rotor current, $k_{\omega\omega}$ – feedback coefficient by speed, k_i – feedback coefficient by rotor current. In the circuit shown in figure 4, two control loops can be distinguished — the speed control loop and the torque control loop. The speed controller SG carries out the formation of a task for changing the frequency of the additional voltage in accordance with (5) to correct the machine mechanical characteristics, as well as setting the amplitude of the additional voltage on the rotor. The current regulator CG performs phase correction according to (1) to maximize the torque developed by the machine. The task for generating additional voltage on the rotor is supplied to a controlled voltage converter, the control system of which generates additional voltage with the given amplitude u_R and frequency $\omega_R = \omega + \Delta\omega_R$ in accordance with this task.

The circuit of a controlled current transducer (CCT) in the rotor circuit described in [3] can also be integrated into the circuit shown in figure 4. Its integration into the shown control system should be accompanied by a change in the functionality of the speed and torque controllers, taking into account the properties of CCT and the peculiarities of the electromechanical energy conversion of DFM with CCT in the rotor.

6. Conclusion

Thus, the circuit diagram of the electric drive control system of a winder based on a double-fed machine, shown in figure 2, allows controlling the torque and speed of the machine with correction of its static and dynamic properties. The use of phase correction in combination with the mode of changing the frequency of the additional voltage on the rotor makes it possible to expand the range of speed control of the machine while maintaining the required critical torque, and the possibility of integration into the CCT circuit allows the modes of braking release and operation of the machine at low speed to be implemented; also CCP can be used as an emergency mode. In this case, speed and

torque controllers in the circuit generate signals for setting phase correction and changing the frequency of the additional voltage on the rotor.

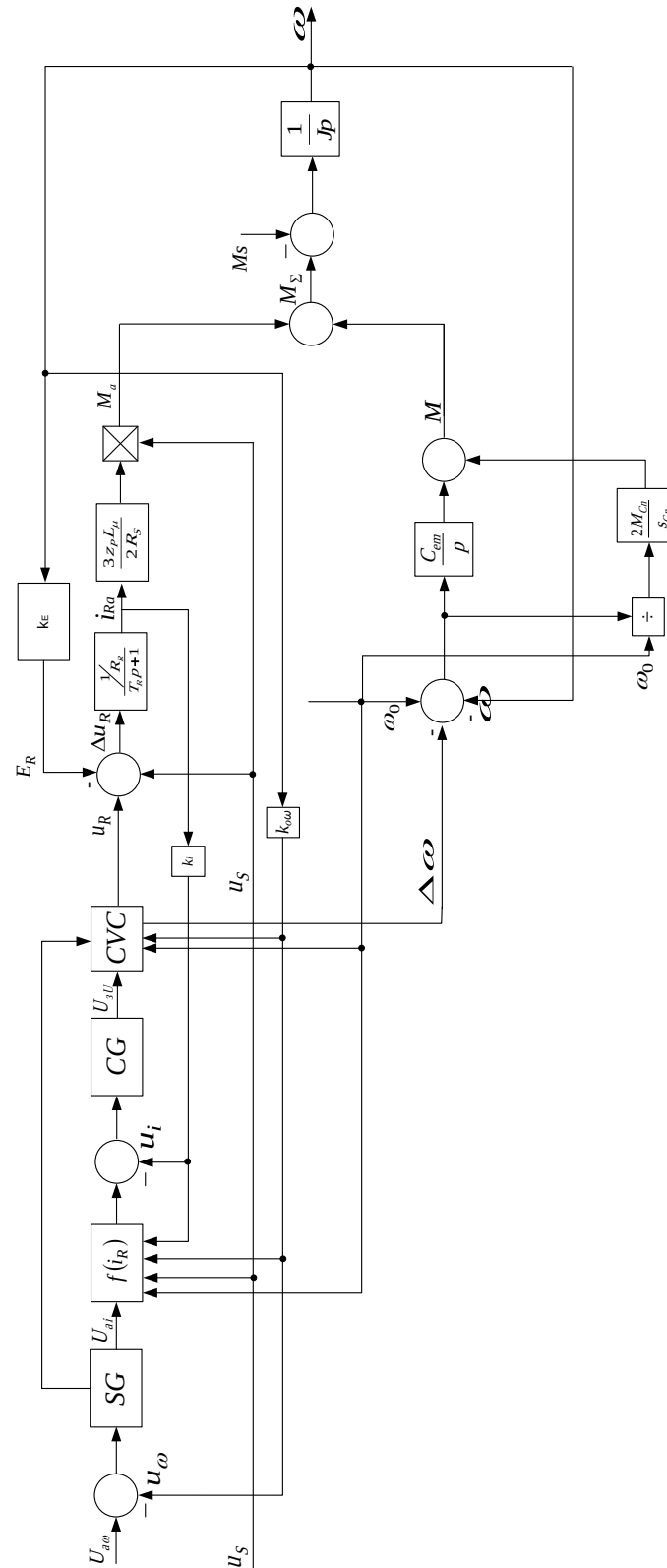


Figure 4. Algorithmic structure of the control system of winder electric drive based on DFM.

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