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Equivalent structure of a double-fed induction motor with a change in frequency of additional voltage for electric drive systems of mine winders

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Abstract. Using a double-fed machine (DFM) circuit is a promising means of upgrading asynchronous electric drives in mine winders. However, the control range of the DFM speed is limited by an excessive drop in the critical torque and decrease in the rigidity of the mechanical characteristics at a speed reduction. Usage of synchronous mode of DFM operation for high-powered winders is fraught with considerable difficulties, in particular, with the instability of machine operation in this mode. The paper proposes a method for determining and evaluating the effect of the corrective action on the frequency of the rotor additional voltage on the critical torque and the rigidity of the DFM mechanical characteristics; the equivalent structure of a double-fed induction motor with a change in the of the additional voltage frequency on the rotor additional voltage and the results of experimental studies suggesting the possibility and necessity of implementing the method for using the DFM in electric drives of winders are given.

1. Introduction

The construction of a DFM circuit based on existing wound rotor induction motor is a promising means to upgrade mine hoisting systems [1]. However, the use of such scheme in the electric drive of winders is limited due to the problem of implementing a range of speed control of at least 30:1 while maintaining the overload capacity of the machine. In [1] and [2] it was shown that such range of speed control can be realized with a combination of the so-called asynchronous and synchronous operation modes of a DFM. In [3] the condition was obtained for maximizing the critical torque of the machine in asynchronous mode by the phase shift of the additional voltage on the rotor in the form:

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

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} – 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 speed reduction.

When controlling a machine within a speed range, it is possible to realize the mechanical characteristics of a DFM, similar to the mechanical characteristics of a synchronous motor. This can be achieved in two ways:

1) By applying voltage to the DFM rotor with a frequency $\omega_R = 0$, that is, by supplying it with direct current.

2) Realizing the condition $\omega_0 - \omega_R = const$ [4], where, ω_0, ω_R are the angular frequencies of the stator and rotor fields, respectively [4].

2. The operation of the machine when the frequency of the additional voltage on the rotor changes

The additional voltage on the DFM rotor U_R is variable and can be represented as:

$$U_R = U_{R\max}\sin\left(\omega_R t + \delta\right), \tag{2}$$

where U_{Rmax} is the amplitude of the additional voltage. When the frequency of the additional voltage on the rotor changes by a value $\Delta\omega_e$, expression (2) takes the form:

$$U_R = U_{R\max}\sin\left[\left(\omega_R + \Delta\omega\right)t + \delta\right]. \tag{3}$$

From (3) it follows that a change in the frequency of the additional rotor voltage by an amount $\Delta\omega$ leads to a change in the argument of the function. The implementation of the additional voltage on the rotor is associated with the algebraic summation of the intrinsic EMF of the rotor and the additional voltage (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 $\Delta\omega$ is small and the condition is satisfied:

$$\sin\left(\Delta\omega\right) \approx \Delta\omega. \tag{4}$$

In [5] the principle of EMF balancing implemented in [6] was proposed, which allows the description of the mathematical model to be significantly simplified. In this case, the working section of the mechanical characteristic is considered, within which $\frac{dM}{d\omega} \approx const$.

In [4] it was shown that the dynamic properties of DFM in the synchronous mode (subject to the condition $\omega_0 - \omega_R = const$) are similar to the properties of a synchronous motor. Let us use the expression for the electromechanical characteristics of a synchronous motor:

$$M = \left(\frac{C_{em}}{p} + \beta\right)\left(\omega_0 - \omega\right), \tag{5}$$

where ω_0 – is the ideal idle speed of the machine; ω – rotational speed of the machine rotor; C_{em} – coefficient of electromagnetic coupling of the engine; $\beta = \frac{2M_{Cn}}{\omega_0 s_{Cn}}$ – the rigidity of the working section of the mechanical characteristics of the machine in asynchronous mode, M_{Cn} – the critical torque of the machine on the natural mechanical characteristic.

Expression (5) has two components. The first is due to elastic electromagnetic coupling with a coefficient C_{em} and depends on the internal angle of the machine load; the second is due to the damping properties of the rotor winding.

Combining the expression (5) with the basic equation of motion of the electric drive, we obtain:

$$\begin{cases} M = \left(\dfrac{C_{em}}{p} + \beta\right)(\omega_0 - \omega), \\ \omega = \dfrac{M - M_S}{Jp}, \end{cases} \tag{6}$$

where M_S – the static load torque; J – the total torque of inertia of the mechanism reduced to the rotor. The system of equations (6) can be associated with the structural diagram shown in figure 1.

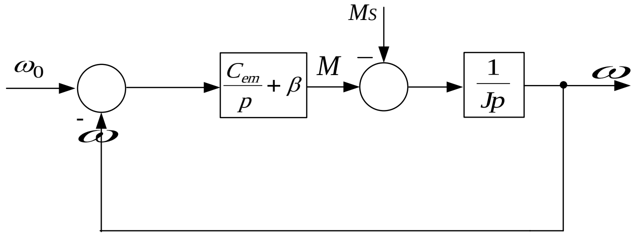

Figure 1. Block diagram of a synchronous motor.

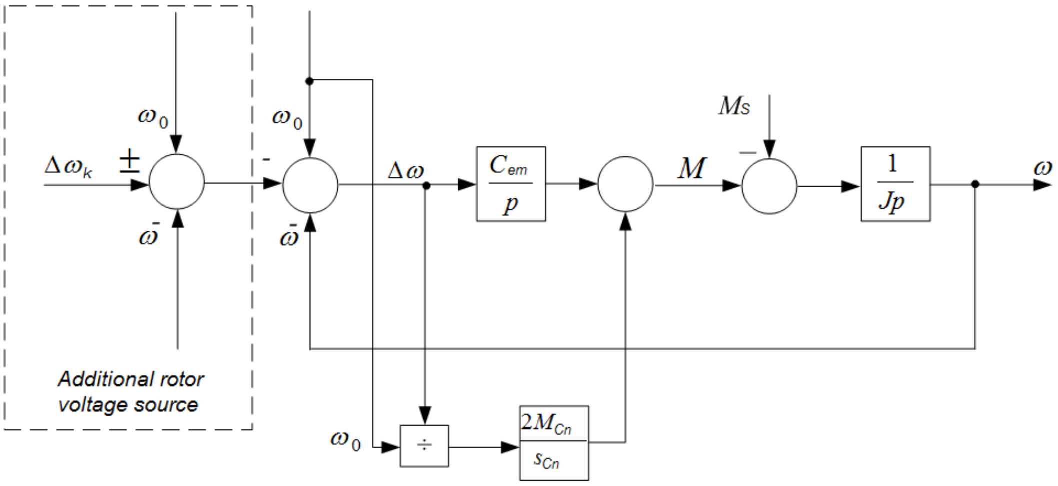

Figure 2. The DFM structural diagram when changing the frequency of the additional voltage on the rotor.

The block diagram shown in figure 1 is for a synchronous motor. For DFMs in accordance with [4], the implementation of a characteristic similar to that of a synchronous motor is possible if the condition $\omega_{0e} - \omega_R = const$ is satisfied for the rotor circuit, i.e. to apply to the input of the circuit shown in figure 1, the difference, where ω_R is the required rotor frequency.

In this case, a synchronized mode of DFM operation, i.e. the mechanical characteristic of DFM is absolutely rigid, and the condition is satisfied at the input:

$$(\omega_{0e} - \omega_R) - (\omega_0 - \omega) = \Delta\omega. \tag{7}$$

In general, the difference $\omega_{0e} - \omega_R$ should be set based on the conditions of technical implementation. When implementing the families of characteristics in the range of variation of speed, we can assume that the condition $\omega_R = \omega \pm \Delta\omega_k$ is satisfied, and the frequency of the additional voltage on the rotor for the formation of (7) changes by $\Delta\omega_k$ In this case (7) will take the form:

$$(\omega_{0э} - \omega) \pm \Delta\omega_k - (\omega_0 - \omega) = \Delta\omega . \tag{8}$$

The scheme shown in figure 1, taking into account (8), will take the form shown in figure 2. It describes the properties of DFM at small increments $\Delta\omega$.

3. Equivalent structure of a double-fed induction motor.

In [5], an equivalent structural diagram of DFM in an asynchronous mode is given in the coordinate system associated with the depicting current vector of the machine stator (discussed in detail in [7]). This scheme can be described by the following system of equations:

$$\begin{cases} e_R = -k_E\omega + u_S, \\ \Delta u_R = u_R + e_R, \\ i_{Ra} = \Delta u_R \cdot \dfrac{1/R_R}{T_R p + 1}, \\ M = \dfrac{3z_P L_\mu}{2R_S} i_{Ra} u_S, \\ \omega = \dfrac{M - M_C}{Jp}, \end{cases} \tag{9}$$

The system of equations (9) corresponds to the structural diagram shown in figure 3.

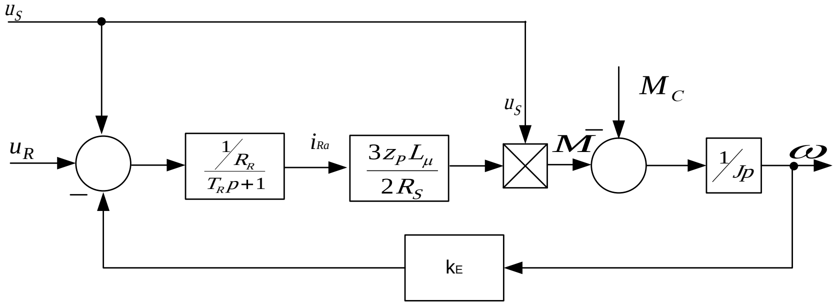

Figure 3. Equivalent block diagram of a DFM in asynchronous mode.

The following notations are used in the system of equations (9) and in figure 3: u_S – the voltage on the stator of the machine, φ_S – the phase shift between the voltage on the stator and the stator current, u_R – the additional voltage on the rotor, i_{Ra} – the active component of the current of the DFM rotor, z_P – the number of pairs of poles of the machine, $L\mu$ – the mutual inductance of the stator and rotor of the machine, R_S – the active resistance of the machine stator, k_E – the internal feedback coefficient of the EMF of the machine, R_R – the active resistance of the rotor, T_R – the electromagnetic time constant of the rotor.

Combining equations (6), (8) and (9), we obtain a system of equations describing the DFM when the frequency of the additional voltage on the rotor changes:

$$\begin{cases} (\omega_0-\omega)\pm\Delta\omega_k-(\omega_0-\omega)=\Delta\omega, \\ M=\left(\dfrac{C_{em}}{p}+\beta\right)(\omega_0-\omega), \\ E_R=-k_E\omega+u_S, \\ \Delta u_R=u_R+E_R, \\ i_{Ra}=\Delta u_R\cdot\dfrac{1/R_R}{T_Rp+1}, \\ M_a=\dfrac{3z_PL_\mu}{2R_S}i_{Ra}u_S, \\ M_\Sigma=M_a+M, \\ \omega=\dfrac{M-M_S}{Jp}, \end{cases} \tag{10}$$

where M_a – the asynchronous component of the DFM torque, M – the torque component due to a change in the frequency of the additional voltage.

The system of equations (10) can be associated with the equivalent structure of a double-fed asynchronous motor with a change in the frequency of the additional voltage shown in figure 4. This diagram allows all the possible modes of DFM operation to be described. If $u_{Ri}=0$ and $\Delta\omega=0$ the circuit describes a wound rotor induction motor without a source of additional voltage on the rotor; if $u_{Ri}\neq 0$ and $\Delta\omega=0$ the circuit describes the asynchronous mode of DFM operation; if $u_{Ri}\neq 0$ and $\Delta\omega\neq 0$ the circuit describes the DFM when changing the frequency of the additional voltage. With the corresponding modification described in [1] and [2], the circuit will also describe the mode of operation of the DFM with a controlled current converter in the rotor.

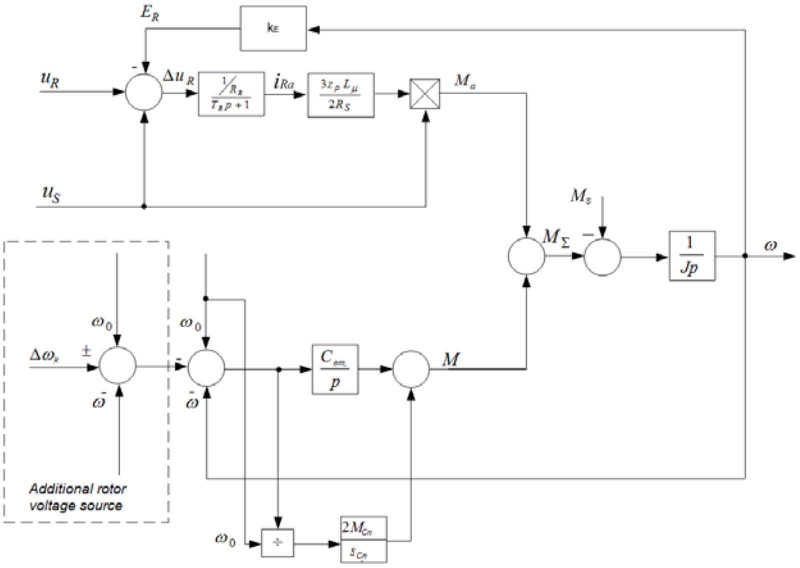

Figure 4. Equivalent structure of a double-fed induction motor with a change in the amplitude and frequency of the additional voltage.

4. Studies of the proposed model

Static characteristics corresponding to the equivalent circuit obtained for a DFM based on the MTF-111 H6 engine are shown in figure 5. It can be seen that an increase in the amplitude of the additional voltage on the rotor of the machine in asynchronous mode, as was shown in [1] and [3], leads to reduction in the rigidity of the working section of the mechanical characteristics. When the frequency of the additional voltage changes, the rigidity of the mechanical characteristics and the critical torque increase; the rigidity depends on Δω. Thus, by changing the voltage on the rotor and its frequency, it is possible to expand the regulation range of the DFM speed while maintaining the critical torque for the use of DFM in the winder electric drive.

The figure also shows the natural mechanical characteristic of MTF-111 H6 model engine, and the working section of the natural mechanical characteristic obtained from diagram 4. It can be seen that the above diagram accurately describes the working section of the mechanical characteristics of the machine.

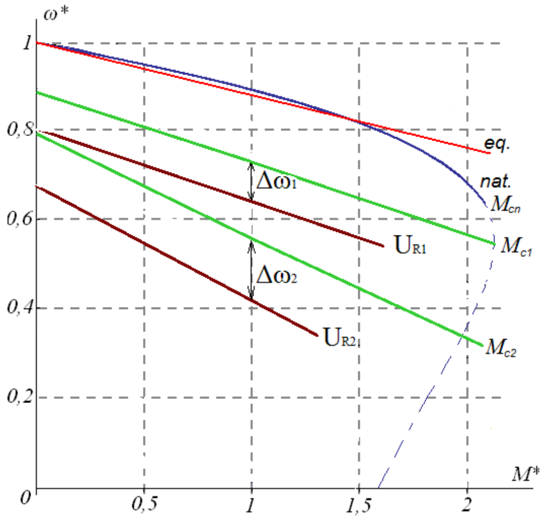

Figure 5. Static DFM characteristics obtained from the block diagram shown in figure 4; $U_{R2} > U_{R1}$; $\Delta\omega_{R2} < \Delta\omega_{R1}$.

The graphs of transients occurring in DFM with a change in the frequency of the additional voltage are shown in figure 6.

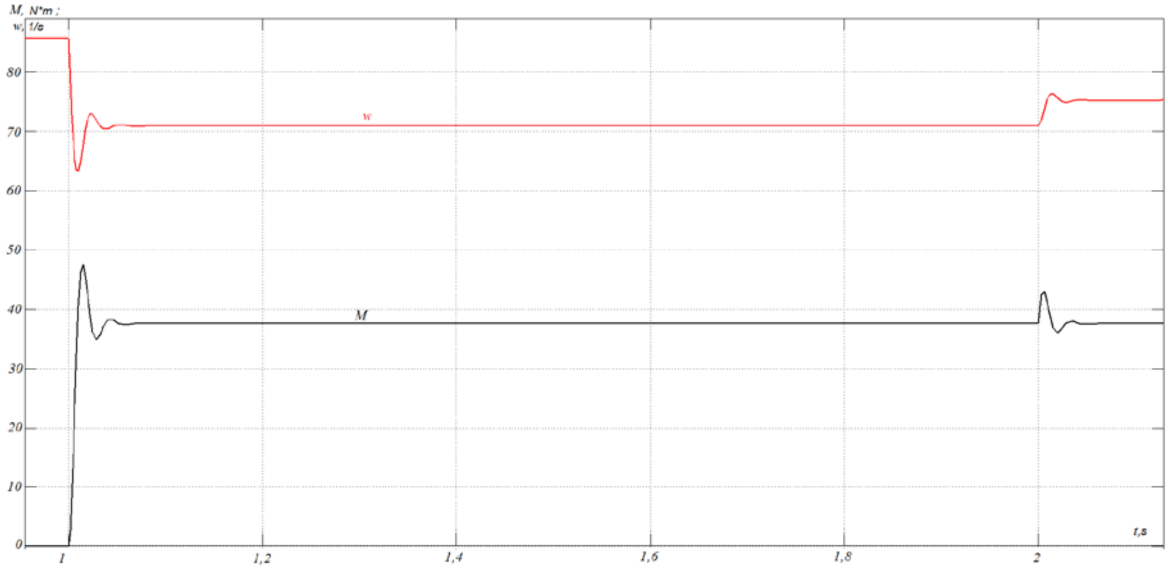

Figure 6. Transient processes of DFM speed and torque based on the MTF-111N6 engine with frequency correction.

After applying the load, the speed reduction was 17.5%. After increasing the frequency of the additional voltage equivalent to 1 Hz (2% of the nominal frequency of the voltage at the stator), the speed reduction was 11.5% at a constant load torque. Thus, an increase in the frequency of the additional voltage by 2% leads to an increase in the rotational speed of the rotor by 6%.

At the same time, it was also experimentally determined that with an increment $\Delta\omega$ of more than 9.4% of the nominal frequency of the voltage on the stator, oscillatory transient processes of speed and torque occur in the machine, i.e. the damping properties of the rotor winding of the machine with this frequency increment is not enough to damp the vibrations.

5. The rigidity of the DFM mechanical characteristics when changing the frequency and amplitude of the additional voltage on the rotor

The equation of the linear section of the machine mechanical characteristics can be written as

$$\omega = \omega_0 - \beta M, \tag{11}$$

where β is the rigidity of the working section of the characteristic.

Taking into account (7), (11) can be written as:

$$\omega = \omega_0 + \Delta\omega - \beta M, \tag{12}$$

The expression for stiffness, with regard to the change in frequency $\Delta\omega$, can be written as:

$$\beta = \frac{M}{\omega_0 s + \Delta\omega}, \tag{13}$$

where $s = \frac{\omega_0 - \omega}{\omega_0}$ is sliding.

The task of changing the frequency of the additional voltage on the rotor is the increase in the rigidity of the natural mechanical characteristics. The stiffness of the natural mechanical characteristics can be found as:

$$\beta_n = \frac{M_{Cn}}{2\omega_0 s_{Cn}}. \tag{14}$$

In order the condition $\beta = \beta_n$ to be fulfilled, the magnitude of the change in the additional voltage on the rotor must be equal to:

$$\Delta\omega = \frac{M_n s_{Cn}\omega_0 - 0.5(\omega_0 - \omega)M_{Cn}}{2M_{Cn}}. \tag{15}$$

According to expression (15), the limiting range of DFM control can be estimated with a change in the frequency of the additional voltage on the rotor while maintaining the rigidity of the working sections of the mechanical characteristic equal to natural. The maximum speed at which $\Delta\omega$ does not exceed the limit defined above in for the model engine MTF-111 H6 is 5.2 rad/s ($0{,}049\omega_0$); wherein the range of speed control is 20.2:1. If we allow a decrease in the stiffness of the mechanical characteristics of the DFM in the low-speed range below the stiffness of natural characteristic, the control range can be expanded to 30-32:1.

To determine the critical torque when changing the frequency of the additional voltage on the rotor and correcting its phase, we use the equation of the DFM mechanical characteristic and the expression (1) given in [1]. Having determined the value $\Delta\omega$ at which the mechanical characteristic of the machine has a maximum (volumetric trivial transformations are not given due to the limited volume of the article), and substituting it into the equation of the mechanical characteristic, we obtain the expression for the critical torque of the machine when correcting the phase and frequency of the additional voltage on the rotor:

$$M_{\Delta\omega} = \frac{M_{Cn}\left(U_R^*\omega_0 s_{Cn}\cos\left(arctg\left(\frac{s}{s_{Cn}}\right)\right) + \sqrt{\omega_0^2 s_{Cn}^2\left(U_R^* + s_{Cn}^2 - 2U_R^* s_{Cn}\sin\left(arctg\left(\frac{s}{s_{Cn}}\right)\right)\right)}\right)}{\omega_0^2 s_{Cn}}. \qquad (16)$$

6. Conclusions

Thus, according to the results of the research, the following conclusions can be drawn:

1) The method is proposed for determining and evaluating the effect of corrective action on the frequency of the additional voltage on the rotor at the critical torque and the rigidity of DFM mechanical characteristics;

2) An equivalent structure of a double-fed asynchronous motor with a change in the frequency of the additional voltage was developed, which describes the operation of the asynchronous motor with and without an additional voltage source in the rotor.

The feasibility of changing the frequency of the additional voltage for DFM is experimentally substantiated, the coefficient and the law of changing the frequency of the additional voltage on the DFM rotor are obtained, which allows the critical torque of the machine and the rigidity of its mechanical characteristics to be kept at an acceptable level.

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