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Energy properties of double-fed machine.

1. Introduction

A necessary step in the creation, operation and maintenance of electromechanical energy converters involves acceptance tests, confirming successfulness holding of the design performed, manufacture or repair and availability of the electric machine for use with specified technical parameters.

In recent years the requirements for energy efficiency of these tests have sharply increased, forcing the management of enterprises to think of new strategies in the field of energy resources consumption and to seek necessary engineering solutions to reduce them.

At present the engineering solutions to drastically reduce energy expenditure of machine-building enterprises, when conducting acceptance tests of electric machines, lie in the field of creating energy-saving test stands (ETS).

These stands are characterized by two fundamental features:

1. 1. There is a closed energy loop consisting of two electric machines and making it possible to provide energy transmission between them, and in doing so one machine provides direct transmission of energy, and the second transmits energy in the opposite direction [4]. Thereby their mutual loading is achieved.
2. Owing to artificially implemented energy coupling between the two machines, the power from an external source of energy is spent only to compensate for losses and its consumption is minimal. Thus a considerable, 5-10 times, energy saving is achieved that is especially important for high-power electric machines during long-time life tests [4].

2. Functional diagram of the stand for testing asynchronous machine with wound rotor .

The asynchronous machine with a wound rotor (WR) may be connected in the scheme of double-fed machine (DFM). The functional diagram of DFM is shown in Figure 1.

Stator windings in DFM are connected directly to the power supply network (U1 = const, f1 = const), and the rotor windings are connected to a separate controlled power source (active semiconductor converter - ASC).

The active semiconductor converter consists of two semiconductor switches, combined by DC link with a capacitor filter.

The double-fed machine allows adjustment of an external and an internal flows of the active and reactive power at any speed of rotation of the rotor [1, 5, 7].

This DFM property allows to build energy-saving stands for testing the asynchronous machine with a wound rotor without using an additional electric machine.

3. Modes of operation, vector and energy diagrams of the double-fed machine.

Below all DFM modes of operation are considered in detail:

- Motor and generator modes of operation at the speed below the synchronous;
- Motor and generator modes of operation at the speed above the synchronous;

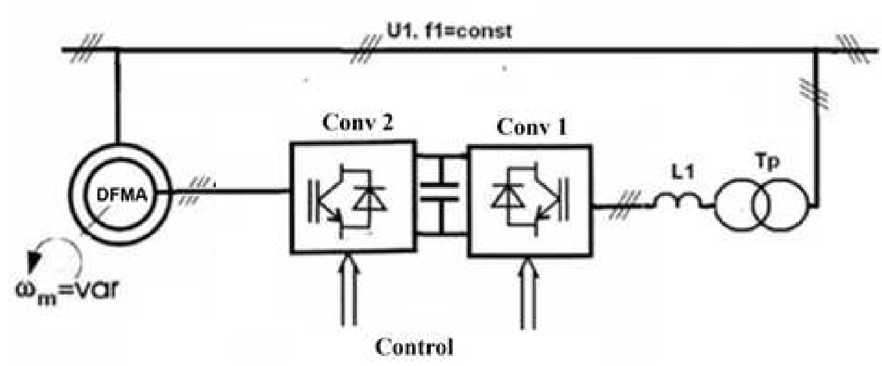


Fig. 1. The scheme of double-fed machine (DFM).

In all the listed modes, the set of equations defining electromagnetic processes of the machine in a steady state, using the method of resultant vector [1, 2, 5] is of the form:

$$\frac{\bar{U}_2}{s} = \bar{U}_1 + R_2\bar{I}_2 + jX_2\bar{I}_2, \qquad (1)$$
$$\bar{U}_1 = jX_{1m}\bar{I}_m,\ \bar{I}_m = \bar{I}_2 + \bar{I}_2.$$

Where $R_2 = R_sC + \frac{R_r}{s}C^2 \approx R_s + \frac{R_r}{s},\ X_2 = X_{ls}C + X_{lr}C^2 \approx X_{ls} + X_{lr},\ X_{1m} = X_{ls} + X_m$ are active resistances and inductive reactances of the G -shaped equivalent circuit.

Voltage $\bar{U}_2$ is generated at the output of a semiconductor converter (Conv 2, Fig. 1). The first harmonic of the resulting voltage vector equals [6]:

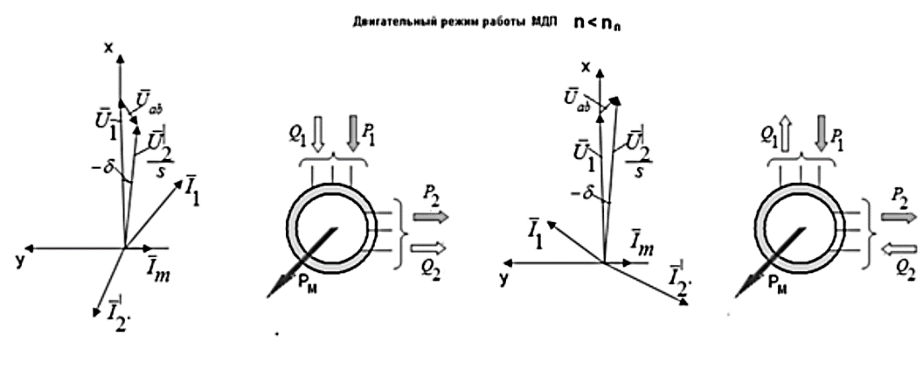
$$\bar{U}_2 = \frac{m}{2}U_d\exp(\delta) = \frac{m}{2}U_d(\cos\delta + j\sin\delta) \qquad (2)$$

Where m is a modulation factor, δ is a modulation phase (phase of voltage $\bar{U}_2$ with respect to voltage $\bar{U}_1$ of the network).

In assessing the energy properties of DFM, one should take into account that:

- active power in the source is positive when the source gives up energy and negative when the source consumes energy;
- reactive power in the source is positive (inductive) when its voltage leads the current and negative (capacitive), when its voltage lags behind the current;
- mechanical shaft power is positive in the motor mode of DFM operation and negative - in the generator mode of DFM operation.

Fig. 2 shows the vector and energy diagrams of DFM operation in the motor modes with positive and negative slips, constructed according to equations (1).



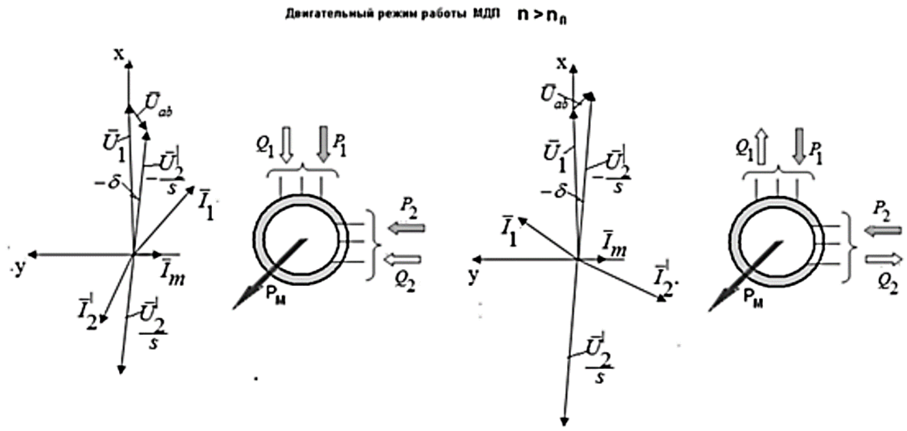


Fig. 2. DFM properties in independent frequency control of AP2 in the motor mode of operation

Fig. 3 shows the vector and energy diagrams of DFM operation in the generator mode with positive and negative slips, constructed according to equations (1).

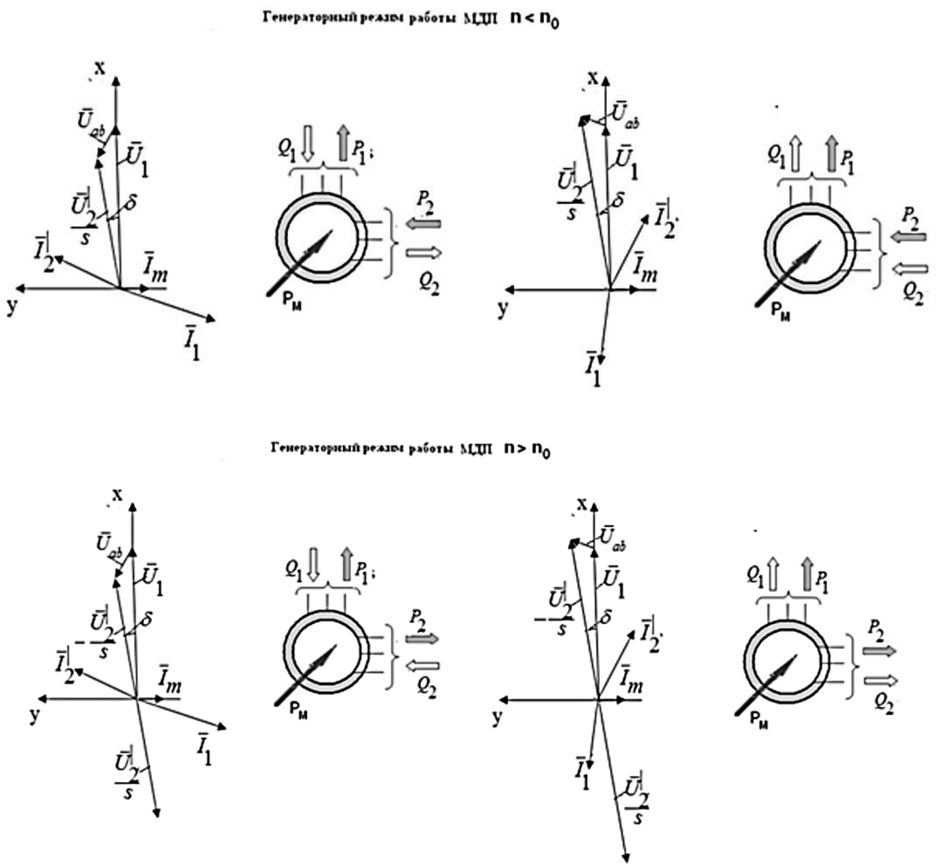


Fig. 3. DFM properties in independent frequency control of AP2 in the generator mode of operation

The main properties of DFM obtained on the basis of qualitative analysis , are as follows:

- direction of active power flows in the stator and rotor circuits testifies that when slips in DFM are positive, a closed energy loop is formed which is the bases for building an energy saving test stand;
- motor mode of DFM occurs with negative δ , generator mode takes place with positive δ ;

• the value of active power , transformed in the machine, is proportional to the value of δ ;

• sign of reactive power in the stator circuit depends on the ratio of $\bar{U}_1$ and $\frac{\bar{U}_2}{s}$. When the value of voltage $\bar{U}_1$ exceeds the value of $\frac{\bar{U}_2}{s}$, the reactive power in the stator circuit is positive (inductive). If value $\frac{\bar{U}_2}{s}$ exceeds voltage $\bar{U}_1$, the reactive power is negative in the stator circuit (capacitive) , i.e. the machine is excited from the rotor side.

Thus, to determine electromagnetic, electromechanical and energy properties of the asynchronous machine with a wound rotor, it is necessary to connect the machine in DFM circuit and conduct a study of DFM at positive slips.

4. Investigation characteristics of the DFM with positive slides.

The rotor winding of DFM is energized from the converter at the output of which the value of voltage, the phase of this voltage with respect to the mains voltage and frequency of the voltage $\omega_2 = \omega_1 - p\omega_m$ change.

The laws of rotor frequency control are similar to the laws of frequency control of the asynchronous machine by the stator circuit, i.e. it is required to maintain a certain relationship between ω_2 and U_2. In what follows we consider DFM properties for the simplest law of frequency control.

$$\frac{U_2}{s} = \frac{\omega_1 U_2}{\omega_2} = U_{2m} = const \tag{3}$$

For quantitative estimation of DFM properties one should solve the set of equations (1, 2). This solution is carried out in a rotating coordinate system *x*(real axis), *y*(imaginary axis). In so doing voltage $\bar{U}_1$ coincides with the real axis x, and for the secondary voltage the ratio $U_{2m} = \frac{\omega_1 U_2}{\omega_2}$ and δ phase are given.

An electromagnetic torque is determined from the equation [5, 8, 9]:

$$T_e = \frac{3}{2} pL_m \cdot (\bar{I}_2 \times \bar{I}_1) = \frac{3}{2} pL_m (I_{2x} I_{1y} - I_{2y} I_{1x}) \tag{4}$$

The energy properties of DFM are determined after calculating currents in accordance with the listed below expressions:

$$\begin{aligned} &P_1 = 1.5 \cdot U_1 \cdot I_{1x}, \;\; Q_1 = -1.5 \cdot U_1 \cdot I_{1y} \\ &Q_2 = 1.5 \cdot (U_{2y} I_{2x} - U_{2x} I_{2y}), \\ &P_m = T_e \cdot \omega_m = T_e \frac{(1-s)\omega_1}{p}, \\ &P_2 = 1.5 \cdot (U_{2x} I_{2x} + U_{2y} I_{2y}) - P_m sign(s). \end{aligned} \tag{5}$$

A further study was carried out for DFM in which the machine 215 HP (160kW), 400 V, 50Hz, 1487 RPM has the following parameters:

$$R_s = 13,79 \cdot 10^{-3}\Omega, L_{ls} = 0.152 \cdot 10^{-3}\ H, R_r = 7.728 \cdot 10^{-3}\ \Omega, L_{lr} = 0.152 \cdot 10^{-3}\ H, L_m = 7.69 \cdot 10^{-3}\ H.$$

All variables of DFM are calculated and constructed using relative (dimensionless) values (pu-per units), which are determined in dividing the calculated variables by basic values. For the machine with the above parameters, the basic values of the variables are calculated from formulas and are equal to:

$$P_b = 160\,kVA,\ \ U_b = 400V,\ \ Z_b = \frac{U_b^2}{P_b} = 1.0\,Ohm, I_b = \frac{U_b}{\sqrt{3}Z_b} = 231.2\ A,$$

$$\omega_b = 2\pi f_n = 314\ 1/s, \qquad T_b = \frac{\sqrt{3}pU_n I_b}{\omega_b} = 1019\ Nm.$$

The results of DFM study in frequency control from the rotor side are shown in Fig. 4.

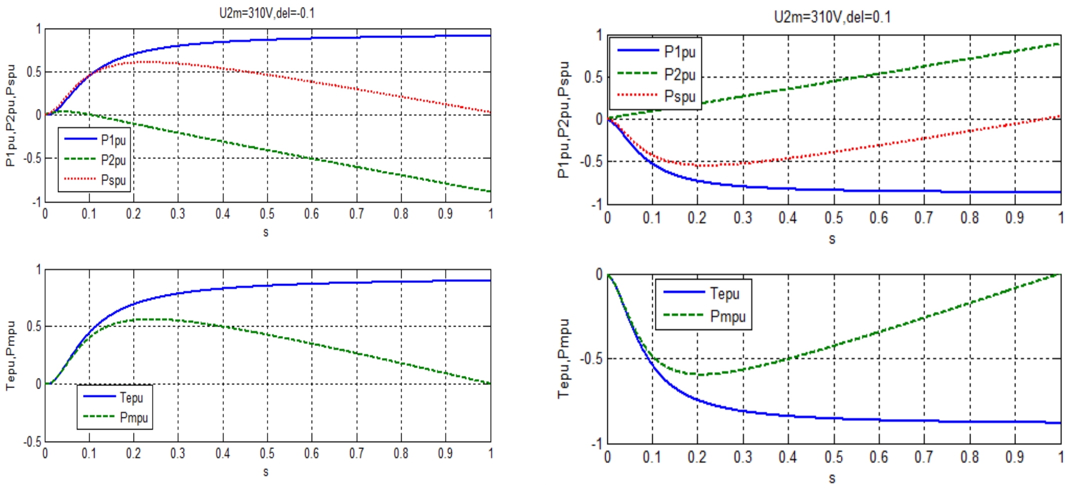


Fig. 4. DFM characteristics in independent frequency control in the motor (a) and generator (b) modes of operation

Fig. 4 a, b shows dependences of the active power in the network, the stator and rotor circuits , electromagnetic torque and power at the machine shaft upon a slip in the motor and generator modes of DFM operation when the slip changes in the range from 0 to 1.

The quantitative estimation of DFM properties permits the following conclusions to be made:
• energy savings in the stand for WR testing is achieved with considerable slips, in this case the most efficient mode is the mode of short circuit (s = 1.0).
• with considerable slips DFM is a source of torque;
• electric power consumed by DFM from the network in the motor mode is determined by difference in the stator and rotor powers;
• similarly the mechanical power, consumed by DFM from the shaft, is also determined by difference in the stator and rotor power.

Therefore, an electromagnetic power, circulating in DFM, can be tens of times greater than the power of an external source (electrical or mechanical).
The adjusting properties of DFM are demonstrated in Fig. 5.
These characteristics are obtained by solving equations (1, 2). They were calculated at a constant slip of $s=1.0$. The power consumed by DFM from external sources at $s=1.0$ in the motor ($\delta < 0$) and generator ($\delta > 0$) modes, is expended only to compensate for losses in the machine.

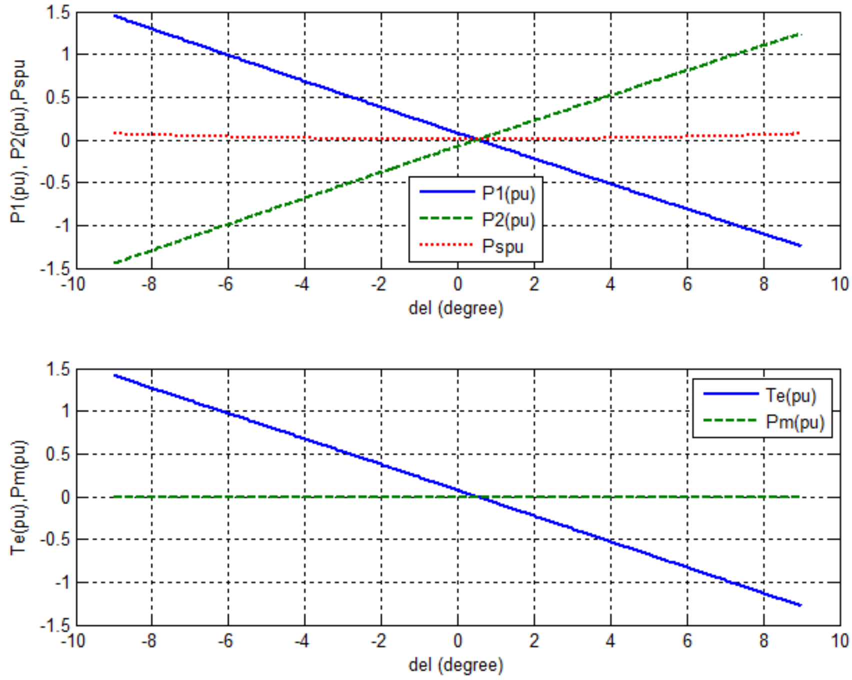


Fig.5. Adjusting properties of DFM at *s=1.0*.

5. Simulation results.

The simulation results of a simulation model of DFM in the package *Simulink* are presented in Fig.6 for a positive slip. The oscillograms of voltages and currents in the stator and rotor circuits were taken in transient conditions. The change from the motor mode of operation to the generator one was carried out by an abrupt angle change from δ -0.05 rad. to +0.05 rad. at the time of t=0.3sec.

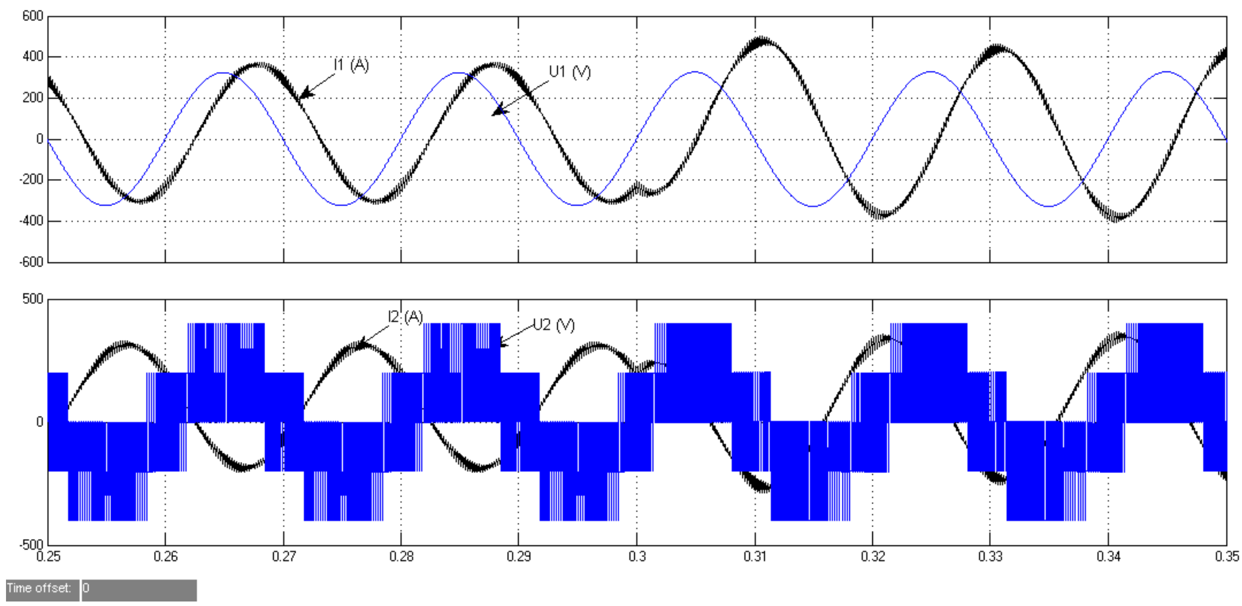


Fig.6. Results of DFM model simulation at s=1.0.

The simulation results show that in transient conditions there are not current (power) overloads both in the stator and the rotor circuits, the time of transient process approximately amounts to one and half cycle of the network frequency.

6. Conclusion.

In the test stands where the main requirement is energy efficiency, one can use some simple algorithms for double-fed machine control. The variation range of DFM slips should be chosen depending upon the purpose of system application.

For the test stands it is more energy efficient to design DFM in the range of positive slips.

7. Literatura

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