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ELECTRIC DRIVE WITH DOUBLE FED MACHINE AND IT'S MATHEMATICAL DESCRIPTION

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ABSTRACT:
Double fed machine has the big advantage for electric drives with high rated power and with the close range of working speed. Pumped storage power plant (rated power e.g. 330MW) with speed range from 90% to 110% of the synchronous speed (i.e. the range of the slip is ±10%) is typical example. Double fed generator reduces the required power of the supplying converter (for the power plant of 330MW we need converter with rated power "only" 33 MW). We have to apply a special control algorithms based on the mathematical description for using the double fed machine.
KEYWORDS:
Double Fed Machine, Control Algorithm, Mathematical Model, Physical Model

1. BASIC IDEA OF THE DOUBLE FED MACHINE

The typical connections of the drive with double fed machines are shown in figure 1 and figure 2. The induction motor with wounded rotor is main component. The stator winding is connected to power grid (directly or via supply transformer etc.). The rotor winding is supplied from special "rotor converter". In each time (working regime) the output rotor frequency set by converter has to be the same as a slip frequency f_R (see equation (1.1c)). Rotor converter can be realised as indirect frequency converter or as a direct converter. Solution for the highest rated power is shown in figure 1 (rotor converter is realised as a SCR direct converter so called cycloconverter – see for example figure 12 or [7]).

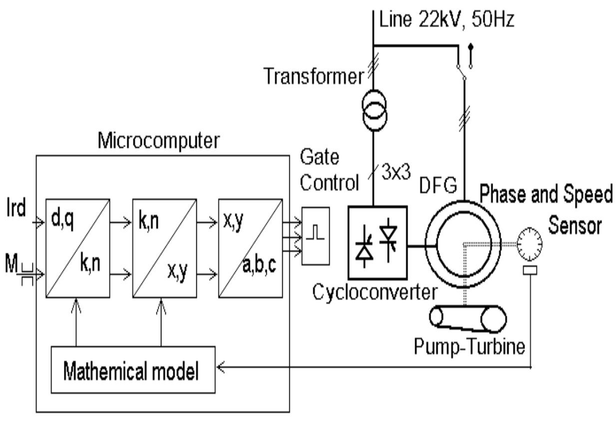

FIGURE 1. Double fed machine for high power applications (for example for pumped storage power plants, nominal power 330 MW).

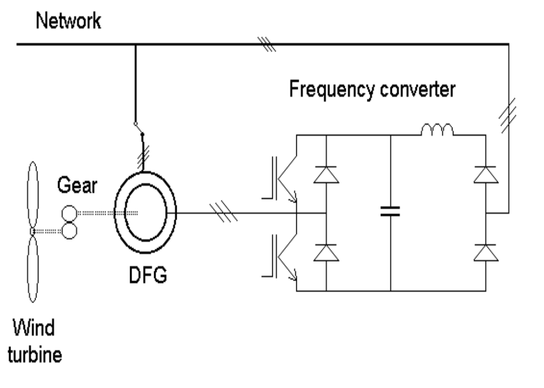

FIGURE 2. Double fed machine for "low" power applications (for example wind power plants – see [3] or [11])

The machine with the number of pole pairs p_P, which is supplied into stator winding with the frequency f_S (in Europe usually f_S =50 Hz) is the mechanical synchronous speed:

$$\omega_{Smech} = \omega_S / p_P = 2\pi \cdot f_S / p_P \tag{1.1a}$$

An actual value of mechanical speed of this machine ω_{mech} means the slip of this induction machine:

$$s= (\omega_{Smech} - \omega_{mech})/ \omega_{Smech} \tag{1.1b}$$

Consequently the rotor frequency f_R (so called slip frequency) has the value:

$$f_R=s \cdot f_S=(2\pi \cdot f_S / p_p - \omega_{mech}) \cdot f_S/ \omega_{Smech} = f_S - p_p \cdot \omega_{mech}/(2\pi) \tag{1.1c}$$

The drive is reversible in speed and torque using commands based on a "field oriented" control. The machine can be operated at subsynchronous or supersynchronous speed by exciting the rotor winding (the alternating current of the frequency corresponding to the difference between power system frequency and the rotating speed of a machine – see equation (1.1c)). At synchronous speed this machine works as synchronous machine. In this regime the power flow through converter is minimal (only for supplying the losses in rotor winding). This is why in this regime the disturbances produced by the converter are minimal too.

In each of this speed (subsynchronous, synchronous or supersynchronous) this drive can operate with arbitrary power factor (lagging or leading). Via the rotor current Ir (see figure 3) we can control the magnitude and phase angle of the stator current Is and therefore the active and reactive power of the double fed wound-rotor induction machine and set to any required values in all four quadrants (if there is used direct converter or bidirectional indirect converter – see for example [6]).

2. DOUBLE FED MACHINE IN STEADY STATE

Control algorithm for the double fed machine is based on the mathematical model. The Park's transformation is used for the description of the three phase system. This mathematical transformation has many advantages – for example the actual working regime is very illuminated (figure 3 presents this transformation but figure 4 shows the phase current and voltage without this transformation).

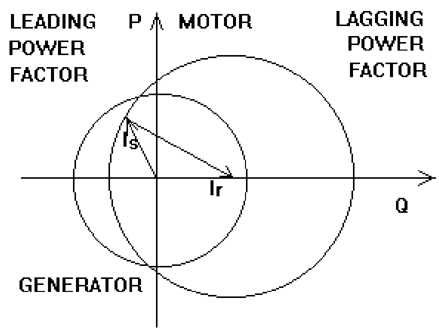

FIGURE 3. The area of maximal values of the currents of stator and rotor, and the area of maximal power of drive and the basic idea of control algorithm

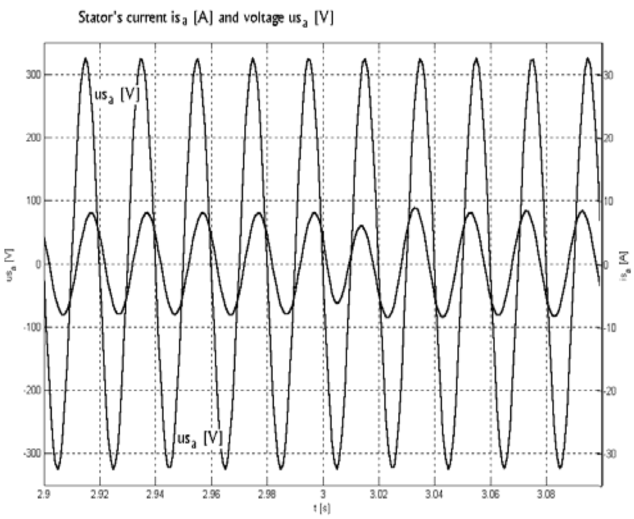

FIGURE 4. The value of stator's current and stator's voltage for changing value of the stator's power factor from lagging to leading power factor)

The definition of the Park's transformation of actual current values of stator phases $I_A(t)$, $I_B(t)$, $I_C(t)$:

$$I_x(t) = 2/3 \cdot [\, I_A(t) \cdot\cos(\beta) + I_B(t) \cdot\cos(\beta - 2\pi/3) + I_C(t) \cdot\cos(\beta + 2\pi/3)] \tag{2.1a}$$

$$I_Y(t)= -2/3\cdot [\, I_A(t) \cdot\sin(\beta) + I_B(t) \cdot\sin(\beta - 2\pi/3) + I_C(t) \cdot\sin(\beta + 2\pi/3)] \tag{2.1b}$$

$$I_0(t) = 1/3 \cdot [\, I_A(t) + I_B(t) + I_C(t)] \tag{2.1c}$$

The third component $I_0(t)$ is not important to consider, because it usually takes zero value in the practical situation (symmetrical connection without neutral wire). First and second component can been assumed as a one complex number:

$\underline{I}(t)= I_x(t) + j \cdot I_Y(t)$ (2.1d)

The same definition is used for voltages $\underline{U}$ and for magnetic fluxes $\underline{\Psi}$ and for these values in rotor as well. In system of coordinate axes with synchronous speed of rotation (it means that $d\beta/dt=\omega_S=2\pi \cdot f_S$) the transformation (1.1) changes the three phase symmetrical system with harmonic values into system with constant values (in steady state).

For the conversion between two systems of coordinate axes (for example from the not rotating system with zero angle into system with the actual value of angle ϑ) we can use following equations:

$V_x^{\{\vartheta\}}= V_x^{\{0\}} \cdot \cos(-\vartheta) - V_Y^{\{0\}} \cdot \sin(-\vartheta)$ (2.1e)

$V_Y^{\{\vartheta\}}=V_x^{\{0\}} \cdot \sin(-\vartheta) + V_Y^{\{0\}} \cdot \cos(-\vartheta)$ (2.1f)

Following equation represents general way of conversion (see figure 6):

$\underline{V}^{\{\vartheta\}} = \underline{V}^{\{0\}} \cdot e^{-j \cdot \vartheta}$ (2.1g)

Typical input values into control circuits can be assumed as the request value of active and reactive power (P_S and Q_S). The value of active power (P_S) determinates the type of regime, double fed generator should operate as a motor or as a generator (see figure 1). For concrete value of speed the request active power means concrete value of torque. The value of reactive power (Q_S) determinate, if power factor can be lagging or leading.

For the description of these regimes we can use the voltage equation for the stator circuit of the machine (in steady state) and in the system of coordinate axes with synchronous speed of rotation ($\omega_S=2\pi \cdot f_S$):

$\underline{U}_S = R_S \cdot \underline{I}_S + j \cdot \omega_S \cdot \underline{\Psi}_S = R_S \cdot \underline{I}_S + j \cdot \omega_S \cdot (L_S \cdot \underline{I}_S + L_H \cdot \underline{I}_R)$ (2.2)

The equation (2.2) can be used for computing the rotor currents:

$\underline{I}_R = (\underline{U}_S - R_S \cdot \underline{I}_S - j \cdot \omega_S \cdot L_S \cdot \underline{I}_S) / (j \cdot \omega_S \cdot L_H)$ (2.3)

From the equation (2.3) we can distribute the value of rotor currents into “real” active component I_{Rq} (so called “torque-compose” component) and “imaginary” reactive component I_{Rd} (so called “flux-compose” component):

$I_{Rd} = (U_{sq} - \omega_S \cdot L_S \cdot I_{sd} - R_S \cdot I_{sq}) / \omega_S \cdot L_H \cong (U_s - \omega_S \cdot L_S \cdot I_{sd}) / \omega_S \cdot L_H$ (2.4a)

$I_{Rq} = (0 - \omega_S \cdot L_S \cdot I_{sq} + R_S \cdot I_{sd}) / \omega_S \cdot L_H \cong (- \omega_S \cdot L_S \cdot I_{sq}) / \omega_S \cdot L_H$ (2.4b)

In this equation the resistors were neglected. The final explications can be multiplied by the parameter ($k_P \cdot U_S$). This parameter can convert the values of currents into correspondent values of power (i.e. active power P_S and reactive power Q_S flow from the stator winding):

$k_P \cdot U_S \cdot I_{Rd} = (k_P \cdot U_S{}^2 - k_P \cdot U_S \cdot I_{sd} \cdot \omega_S \cdot L_S) / \omega_S \cdot L_H = (Q_{ZR} - Q_S) \cdot L_S / L_H$ (2.5)

$k_P \cdot U_S \cdot I_{Rq} = (- k_P \cdot U_S \cdot I_{sq} \cdot \omega_S \cdot L_S) / \omega_S \cdot L_H = - P_S \cdot L_S / L_H$ (2.6)

3. CONTROL ALGORITHM OF DOUBLE FED MACHINE

Equations (2.5) and (2.6) explain the relationship between active and reactive power and active component I_{Rq} and reactive component I_{Rd} of rotors currents. These equations present the basic idea of the drive control with double fed machine - see the first block on the left side in figure 5. The next block shows controllers, witch should keep the real values of rotor currents of the requested values (computed in accordance with equations (2.5) and (2.6)). For the better function of these regulators we can use the approximate values of rotor voltages (computed in mathematical model of double fed machine – see chapter 4). The third block converts values of rotor voltages from system of coordinate axes with synchronous speed of rotation to system with zero speed of coordinate axes. This block needs the angle of magnetic flux of the machine (computed in mathematical model of double fed machine). The fourth block converts values of rotor voltages from system of coordinate axes with zero speed of rotation to system which is synchronised with the rotor. This block takes the angle of the rotor position (figure presumes the machine with the sensor for actual position of rotor). The fifth block converts the request values of voltages to the real values for each phase of rotor winding.

The control algorithm shown in figure 5 is illuminating, but for realisation in low-cost one-chip control processor is too complicated, because the conversions of the values of rotor voltages between various systems of coordinates axes needs to use more calculations with trigonometric functions (sinus and cosine) etc.

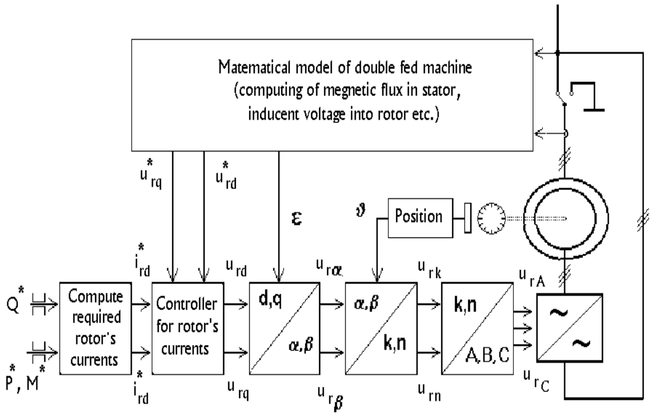

FIGURE 5. The control algorithm of the double fed machine (basic idea)

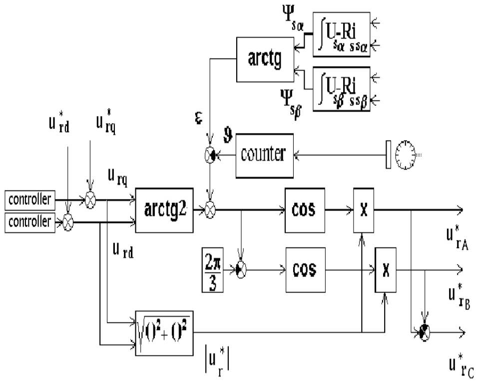

FIGURE 6. The control algorithm (realization).

This is the reason for modification of the control idea. For example the figure 6 presents the one possibility of simple realisation the algorithm (shown in figure 5). This algorithm can be realised on microcontroller with a low capacity of complicated mathematical operations (which are used in equations from (2.1a) to (2.1f)).

4. THE COMPUTING OF VALUES OF ROTOR'S VOLTAGES

In figure 5 and figure 6 there are used the approximate values of rotor voltages (computed in mathematical model of double-fed machine). These values are used for the better function of rotor current controllers. These values are very important – namely in the range of high values of the slip **s** of the machine. Therefore we show the calculation of these values in the following.

Voltage equation for the rotor circuit in system of coordinate axes with synchronous speed of rotation:

$$\underline{U}_R = R_R \cdot \underline{I}_R + j\cdot\omega_R(L_{ER}\cdot\underline{I}_R + \underline{\Psi}_H) = j\cdot\omega_R\cdot\underline{\Psi}_S + (j\cdot\omega_R\cdot L_{ER} + R_R)\cdot\underline{I}_R - j\cdot\omega_R\cdot L_{ES}\cdot\underline{I}_S \qquad (4.1)$$

Equation (2.2) yields the equation (4.2) and equation (4.3) without the influence of stator resistance:

$$\underline{U}_S = j\cdot\omega_S(L_S\cdot\underline{I}_S + L_H\cdot\underline{I}_R) \qquad (4.2)$$

$$\underline{\mathbf{I}}_{\mathbf{R}} = \frac{\underline{\mathbf{U}}_S - j\cdot\omega_S\cdot L_S\underline{\mathbf{I}}_S}{j\cdot\omega_S\cdot L_H} \qquad (4.3)$$

Equations (2.2), (4.1) and (4.3) yield next term (4.4):

$$\underline{\mathbf{U}}_{\mathbf{R}} = \underline{\mathbf{U}}_{\mathbf{S}}\cdot\frac{\omega_R}{\omega_S} + [R_R + j\cdot\omega_R\cdot L_{ER}]\cdot\frac{L_S}{L_H}\cdot\left[\frac{\underline{\mathbf{U}}_S}{j\cdot\omega_S\cdot L_S} - \underline{\mathbf{I}}_S\right] - j\cdot\omega_R\cdot L_{ES}\cdot\underline{\mathbf{I}}_S \qquad (4.4)$$

$$\underline{\mathbf{U}}_{\mathbf{R}} = \underline{\mathbf{U}}_{\mathbf{S}}\cdot s - \left[R_R + j\cdot\omega_R\cdot\left(L_{ER} + \frac{L_H\cdot L_{ES}}{L_S}\right)\right]\cdot\frac{L_S}{L_H}\cdot\left[\underline{\mathbf{I}}_S - \frac{\underline{\mathbf{U}}_S}{j\cdot\omega_S\cdot L_S}\cdot\frac{R_R + j\omega_R L_{ER}}{R_R + j\omega_R\left(L_{ER} + \frac{L_H\cdot L_{ES}}{L_S}\right)}\right] \qquad (4.5)$$

Let us to define next complex functions $\underline{I}_U(s)$ and $\underline{K}_U(s)$:

$$\frac{\underline{\mathbf{U}}_S}{j\cdot\omega_S\cdot L_S}\cdot\frac{R_R + j\omega_R L_{ER}}{R_R + j\omega_R\left(L_{ER} + \frac{L_H\cdot L_{ES}}{L_S}\right)} = \underline{\mathbf{I}}_U = I_{UM}\cdot e^{j\cdot\varphi_{IU}} \qquad (4.6)$$

$$\left[R_R + j\cdot\omega_R\left(L_{ER} + \frac{L_H\cdot L_{ES}}{L_S}\right)\right]\cdot\frac{L_S}{L_H} = \underline{\mathbf{K}}_U = K_{UM}\cdot e^{j\cdot\varphi_{KU}} \qquad (4.7)$$

The values of these complex functions $\underline{\mathbf{I}}_U(s)$ and $\underline{\mathbf{K}}_U(s)$ are shown in the figure 7 (phases of these coefficients) and in figure 8 (magnitudes of these coefficients) for the practical values of the slip $s = \omega_R / \omega_S$.

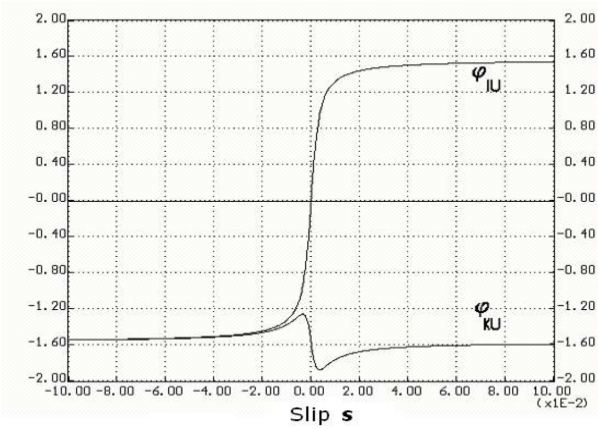

FIGURE 7. The phase of the complex coefficients (versus value of the slip s).

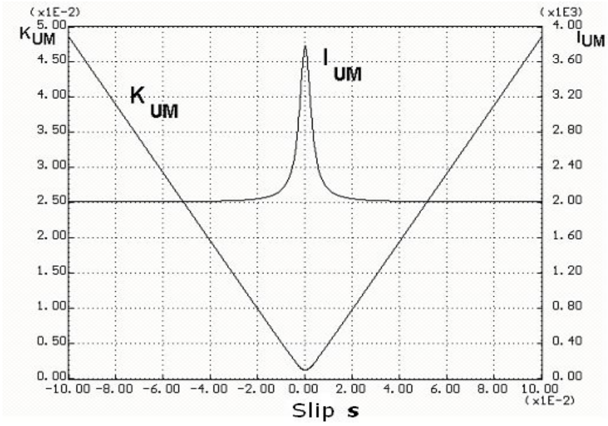

FIGURE 8. The magnitude of the complex coefficients (versus value of the slip s).

The equation (4.5) can be simplified using the coefficient defined in (4.6) and (4.7). It yields equation (4.8):

$$\underline{U}_R=\underline{U}_S \cdot s - \underline{K}_U \cdot [\, \underline{I}_S - \underline{I}_U \,] \tag{4.8}$$

Equation (4.8) defines mathematical operation which shows how to change the working area which represents the stator and rotor currents (shown in figure 3) into according working area representing the rotor voltage.

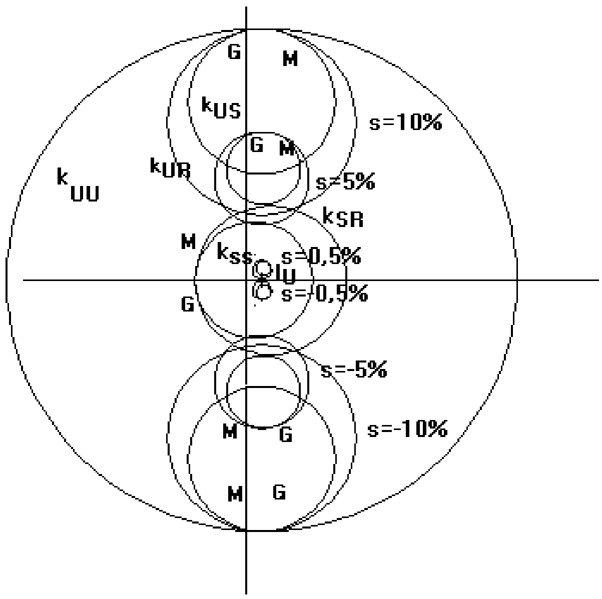

FIGURE 9. The area of the limitation of the currents and rotor's voltage

Figure 9 shows the representation of the following coefficients: the circle k_{UU} - the limitation of maximal value of rotor voltages, the circle k_{SS} - the limitation of maximal value of stator currents, the circle k_{SR} - the limitation of maximal value of rotor currents (see chapter 2 and figure 3).

Other circles show the value of rotor voltage for defined slip values (we consider following slips: s= ±10%, s= ±5% and s= ±0.5%). For each of these slip values the circle k_{SS} is changed into circle k_{US} (and circle k_{SR} is changed into circle k_{UR}).

The figure 9 shows the limitation of the maximal rotor voltage (it means the maximal output voltage from the rotor converter) which is important for the highest value of the slip and for working regime with leading power factor.

5. OTHER ALGORITHMS FOR THE DOUBLE FED MACHINE

For some types of converters (namely for the current-source converters) we can use the simplest algorithm for control of the drive with the double fed machine. The output of the algorithm represents required rotor currents (usually it is used for drives with high rated power - about a hundred of MW– see [7]). Figure 10 shows the control algorithm without the sensor of rotor position - in this control algorithm the rotor position is calculated from the value of magnetic flux position (computed in mathematical model of machine) and from values of stator and rotor currents (measured by current sensors).

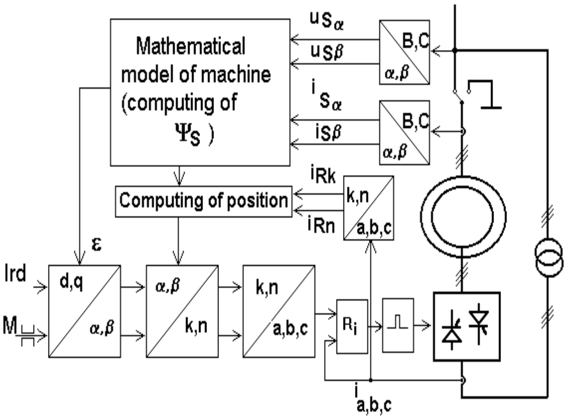

FIGURE10. Control algorithm which can operate without sensor of rotor position

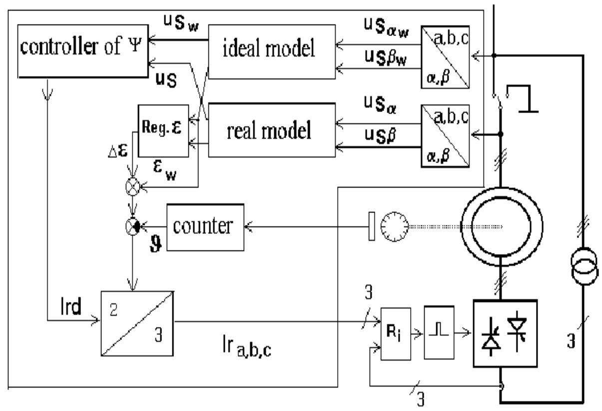

FIGURE 11. Algorithm for automatic connection of stator winding to the power distribution network

Drive with double-fed machine can be automatically connected to the power distribution network without the shock of phase currents. The principle of this method is shown in figure 11 - controller computes two models of magnetic flux of machine. First model calculates ideal flux of machine (it means the case, that the machine is connected to the power distribution network). Second model computes real magnetic flux of machine. The differences between values and angles of these magnetic fluxes are corrected by two controllers. The first controller controls the value of magnitude of magnetic flux of machine (using value of rotor currents). The second controller controls the value of angle of magnetic flux.

6. POWER OF THE ROTOR CONVERTER

Low rated power is the main advantage of using of the double fed machine, for supplying the rotor winding (i.e. low rated power of rotor converter). It means low cost solutions and the minimization of the negative influence of the converter (see for example [8] or [5]).

We can approximately qualify (for example see [6]) the value of input power P_S into stator winding (without losses etc.) using the synchronous speed ω_S (recomputed for 2-poles machine), main inductance L_H (inductance between stator and rotor winding), torque T (recomputed for 2-poles machine) and actual values of currents:

$$P_S = k_P \cdot \omega_S \cdot L_H \cdot (i_{SY} \cdot i_{RX} - i_{SX} \cdot i_{RY}) = \omega_S \cdot T \tag{6.1}$$

Input power P_R into rotor winding (so called “slip power” – this power flows via the frequency converter) can be approximately calculated (without losses and the value ω means the speed recomputed for the 2-poles machine):

$$P_R = k_P \cdot (\omega_S - \omega) \cdot L_H \cdot (i_{RY} \cdot i_{SX} - i_{RX} \cdot i_{SY}) = (\omega - \omega_S) \cdot T = \omega_R \cdot T = s \cdot \omega_S \cdot T \tag{6.2}$$

This equation presents the main idea of the topology with DFG – close range of working speed fundamentally decreases the power of the supplying converter of the rotor winding. Typical applications are high rated power pumped storage stations.

In classical realisation we use synchronous generator only for constant working speed. Topology with double fed generator (DFG) brings some advantage (for example speed adjustable working regime, higher efficiency according standard synchronous machine etc). Standard solutions (which are used in common industry and traffic application – i.e. squired cage induction machine supplied by converter into stator winding) need the converter for full rated power of these drives (see equation (6.1)).

The applications with DFG need only “low-power” converter – with the approximate maximal power according to equation (6.2). You can emagine following example – for the maximal slip of the drive with DFG s= ±10% we can expect the maximal value of converter approximately s= ±10% too. This close range area of speed (applications as fans, centrifugal pumps and storage pump power plant etc.) enables controlling of the output power in the range from 45% to 100% of full rated drive power.

7. SOLUTIONS OF THE MATHEMATICAL AND PHYSICAL MODELS

Mathematical model of the drive with double fed machine has been realized as simulation on PC. This mathematical model has been compared with laboratory prototype of small rated power of 30 kVA.

The laboratory prototype has been realized in laboratory as the same topology as assumed practical device (i.e. double fed machine with the cycloconverter – see figure 1 or figure 12). Only the rated power of the prototype (total power of our physical model is 30kVA but the power of the assumed real drive for the storage pump power plant was considered 330MW) is the main difference between laboratory prototype and practical device.

The connection of the physical model is shown in the figure 12. The switch Sw1 is used only for the start-up of the drive (in the start-up regime we supply only the rotor winding via converter and the stator winding is short circuited). The auxiliary switch Sw2 has been opened ever more (in real machine there are only 3 rings to connect the converter to rotor winding).

Figure 13 and figure 14 have been measured on the laboratory prototype. Figure 15 presents simulation on the mathematical model on the PC (transient phenomena of practical model shown in figure 13 in comparison with simulated results shown in the figure 15).

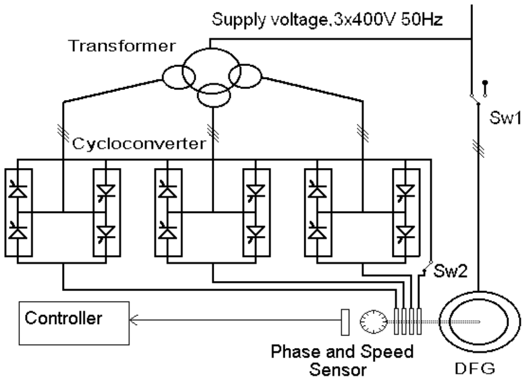

FIGURE 12. The schema of the laboratory prototype realized in the laboratory

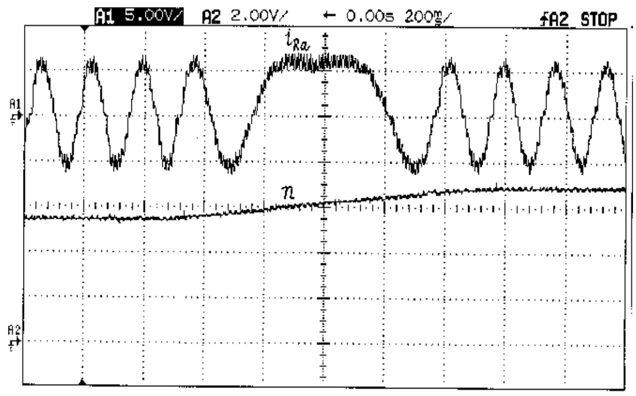

FIGURE 13. The value of rotor current of the speed change from sub-synchronous to super-synchronous value (physical model)

Figure 14 shows the phase voltage on the stator winding before, during and after automatic connecting to the power distribution network (the control algorithm is shown in figure 11). This connection has been realized in the sub-synchronous speed and without the shock of the currents or the torque.

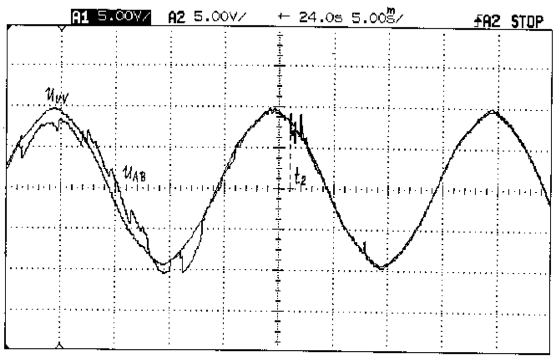

FIGURE 14. Automatic connecting of stator winding to the power network (measured results on the laboratory prototype shown in figure 12).

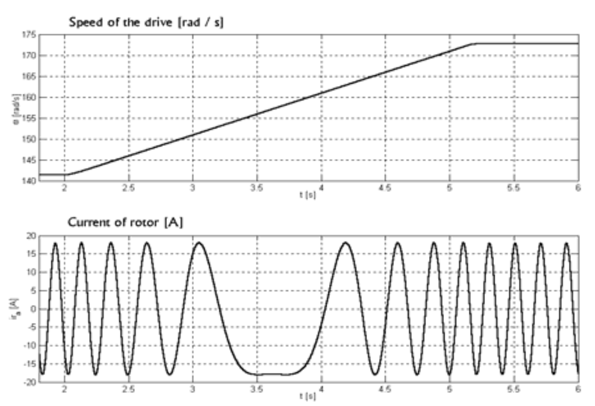

FIGURE 15. Rotor current during the speed change from sub-synchronous to super-synchronous value (simulation results of the mathematical model on the PC).

8. CONCLUSION

The main goal of this research was to design the special drive topology using DFG and its control strategy motivated by industrial demand for considered 300 MVA storage pump power plant. Mathematical model, main idea for the control strategy of DFG and its possibility for the practical realization have been discussed in detail. The presented simulation and experimental results confirm proper function of designed drive topology with DFG.

The application of DFG fundamentally reduces the required power of the supplying converter and brings new trends to high power drives applications.

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