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Study of Energy Losses in High-Voltage Induction Motor Electric Drive

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The dynamic behavior during operation of the high-voltage induction motor electric drive has been studied by means of mathematical model developed. The purpose is to draw out more clearly picture of operation of high-voltage induction motor drives. The system of differential equations has been transformed and solved using suitable software. As a result the values of the energy losses components in the induction motor have been obtained according to different values of supply voltage and factor of inertia. Some of the study results have been presented graphically. An analysis has been made and conclusions from the results obtained have been done.

Keywords*: high-voltage techniques, induction motor drives, electric machines, modeling, energy conversion*

1. Introduction

Induction motors form the basis of modern electric drives. The drive of a number of industrial units require electric motors with high power - 500, 800, 1000 kW and more. Usually induction motors with such power are high voltage - 6,000 or 10,000 V.

In order to have more clearly picture on operation of induction motors it is necessary to study the mechanical and electrical phenomena of dynamic behavior arisen. Important characteristics of induction motors are the starting torque, the maximum torque, and the torque-speed curve [Rizzoni, 1993].

Very often in transient processes there are large currents. They usually subside very quickly, but their maximum values are very large. Current amplitude in the transient process called *impact current*. Serving as a given that the mechanical forces within the windings are proportional to the square of the current, it becomes clear need to determine the currents during transient processes and hence knowledge of the process itself. Given that the impact current is much larger than rated one, it is clear that there will be forces that have large values and acting mostly on the butt joints.

Paper deals with performance of pump high-voltage electric drive as application of induction motor in manufacturing processes of technological cycles from energy efficiency point of view. The emphasis is on working together on the production mechanism and drive electric motor by examining the overall electromechanical system.

2. Mathematical model

Mathematical model is proposed for the study of transient processes and steady-state operation of pumps electric drive. The equations for the voltages of the stator and rotor windings of the induction motor are presented in a coordinate system which rotates at a synchronous speed and they are expressed in relative units. In studies we use the parameters of the T-shaped equivalent circuit of the motor which are determined by calculation methodology of the manufacturing company for value of *slip* s = 1. Parameters of the electric equivalent circuit are active and inductive resistances of one phase of the electric motor.

The driven mechanism is presented by means of a single-mass dynamic model.

We transform the three-phase system into a two-coordinate system. The equations for the voltages of the windings of the induction machine are represented in a coordinate system rotating at the synchronous rotational speed. Using this coordinate system provides the convenience that the system of differential equations attend important parameter of the induction machine *slip* s.

The complete system of differential equations representing mathematical model of electromechanical system of electric drive for pump unit consists of five equations. After converting equations for voltages of windings and presenting expressions received in the form of *Cauchy*, for ease of solving them, we get four equations to model stator currents. Fifth equation is fundamental relationship between torques, so called equation of motion [Crowder, 2006]. It includes torque developed by the electric motor and resisting torque of the pump unit.

The torque-speed characteristics of pumps are often approximately represented by assuming that the torque required is proportional to the square of the speed, giving rise to the terms 'square-law' load [Hughes, 2006].

The total moment of inertia of the electric drive I_{TOT} is set by means of factor of inertia *FI* as

$$I_{TOT} = FI \times I_r \, , \tag{1}$$

where

I_r rotor torque of inertia.

We introduced the name of *multiplicity of supply voltage* as

$$K_V = V / V_{rated} , \tag{2}$$

where

V current value of supply voltage,

V_{rated} nominal value of supply voltage.

The analysis of the transient processes in the induction motor is carried out with the generally accepted assumptions [Rachev, 2004].

In studies we accept the following assumptions and simplifications: it is assumed that the motor operates with a unsaturated magnetic system and there is proportionality between the current and the magnetic flux; currents, e.m.f. and magnetic flux are sinusoidal; the parameters accepted are permanent; the stator and rotor windings are symmetrical, while the air gap is uniform.

Furthermore, it is assumed that the induction motor is connected to a symmetrical, three-phase power supply source. The limiting factor is normally the allowable temperature rise of the windings [Rachev S., K. Karakoulidis, 2014].

It should be understood that different design groups and different authors have different ways of handling losses in induction machines which have proved satisfactory in their own work [McPherson, 1990].

The same author points out and the following: 'Do not assume in any porblem in the practice of engineering that the device you are studying is operating at the rated values given on the nameplate' [McPherson, 1990].

We analyze the behaviour of the machine both from the stator and rotor position. Induction motor transforms electrical energy loaded from power supply mains to the stator into mechanical energy received at the rotor shaft. Moreover this energy conversion is accompanied by losses. The equation of the active power balance can be written as [Sukmanov, 2001; McPherson, 1990; Merz, 2002]

$$P_1 = \Delta P_{e1} + \Delta P_{M1} + \Delta P_{e2} + \Delta P_{MECH} + \Delta P_{ADD} + P_2 , \tag{3}$$

where

$$P_1 = m_1 V_1 I_1 \cos \varphi_1 \tag{4}$$

– electrical power received from power supply mains to the stator,

$$\Delta P_{e1} = m_1 I_1^2 r_1 \tag{5}$$

– electrical (copper) losses of power related to the heating of the windings of the stator, wherein the current flows in them,

$$\Delta P_{M1} = V_1^2 f^{1,3} \tag{6}$$

– magnetic losses of power related to steel core of the stator remagnetization (hysteresis losses) and its heating by eddy currents,

$$\Delta P_{e2} = m_2 I_2^2 r_2^{'} \tag{7}$$

– electrical (copper) losses of power in rotor windings,

$$\Delta P_{MECH} \tag{8}$$

– mechanical losses of power due to friction in the bearings and rotating parts of air (windage losses),

$$\Delta P_{ADD} \tag{9}$$

– additional difficult accounted power losses from eddy currents, determined by the magnetic stray field, by the magnetic flux pulses, by the presence of harmonics (additional losses are $\Delta P_{ADD} \approx 0{,}005 P_{1NOM}$),

P_2 – mechanical power on the motor shaft.

The electrical losses in the rotor are directly proportional to the slip s [Katsman, 2001]:

$$\Delta P_{e2} = sP_{EM}, \tag{10}$$

where P_{EM} – electromagnetic power of the motor

$$P_{EM} = P_1 - (\Delta P_{M1} + \Delta P_{e1}). \tag{11}$$

According to magnetic ΔP_{M1} and mechanical ΔP_{MECH} losses of power, they are essentially not dependable on the load [Katsman, 2001]. The sum of these losses is roughly constant [McPherson, 1990].

Mechanical losses of power for motors with high power (with outer diameter of the stator D_a>0.5 m) are [Kopilov, 1988]

$$\Delta P_{MECH} = K_T (10 D_a)^3, \tag{12}$$

$K_T = 0.7$ for motors with pole number 2p=6.

Bearing-friction and windage losses are small as a rule, and may be neglected for rough calculation [Merz, 2002].

The selection of the point of maximum efficiency depends on the designer, efficiency has a maximum in the area where fixed losses (ΔP_{M1} and ΔP_{MECH}) are equal to the variable losses – electrical (ΔP_{e1} и ΔP_{e2}). The electrical losses in rotor windings are proportional to the slip and thus induction motors are economical in small slips – 1÷4% [Kopilov, 1988].

It should be noted that with the increase of load useful power increased in proportion to the current, and electrical losses grow in proportion to the square of the current. The efficiency is maximum when permanent losses are equal to variable ones. These are magnetic and mechanical losses. Roughly it can be considered that mechanical losses are proportional to the square of the rotational frequency. Variable electrical losses are losses that are proportional to the square of the current. When designing electrical machines aim is to get maximum efficiency at 60-80% of the rated load, because electrical machinery continued work with underloading 15-25%. In order to move the peak efficiency in the area of the nominal load or in the overloading area must be increased cross-section of the windings and to reduce the electrical losses in the machine.

The determination of the components of the energy losses is represented below [Karakulidis, 2015].

Energy taken from the mains in starting mode is

$$W_{ST} = \sum_{k=0}^{a_{n-1}} \left[\left(P_{a_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{b_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{c_k} \right) t_n \right], \tag{13}$$

a_{n-1} – number of point of the time axis, which lasts until the transient process,

P_{a_k}, P_{a_k}, P_{a_k} – power consumed respectively by phase A, phase B and phase C.

Energy taken from the mains at steady-state mode is

$$W_{SS} = \sum_{k=a_{n-1}}^{n-1} \left[\left(P_{a_k} + P_{b_k} + P_{c_k} \right) \right] \left[(n-1)\delta t - t_n \right], \tag{14}$$

δt – a discrete of time axis in seconds,

t_n – duration of the transient process in seconds.

The energy losses in butt joints (frontal connections) in starting mode are

$$W_{1ST} = 0.5 r_1 \sum_{k=0}^{a_{n-1}} \left[\left(I_{a_k} \right)^2 + \left(I_{b_k} \right)^2 + \left(I_{c_k} \right)^2 \right] \delta t, \tag{15}$$

r_1 – resistance of one phase of the stator winding,

I_a, I_b, I_c – phase stator currents.

The energy losses in butt joints (frontal connections) in steady-state mode are

$$W_{1SS} = 0.5 r_1 \sum_{k=a_{n-1}}^{n-1} \left[\left(I_{a_k}\right)^2 + \left(I_{b_k}\right)^2 + \left(I_{c_k}\right)^2 \right] \delta t \, . \tag{16}$$

The energy of moving parts and effective work in starting mode is

$$W_{MMST} = 0.5 I_{TOT} \omega_b^2 + T_L \omega_b t_{a_{n-1}} \, , \tag{17}$$

ω_b – rated circular frequency, T_L – resisting moment of the load, Nm.

The energy of moving parts and effective work in steady-state mode is

$$W_{MMSS} = \sum_{k=a_{n-1}}^{n-1} \left[T_k \omega_k \delta t \right]. \tag{18}$$

Heat released in motor in starting mode is

$$W_{HST} = W_{ST} - W_{MMST} \, . \tag{20}$$

Heat released in motor in steady-state mode

$$W_{HSS} = W_{SS} - W_{MMSS} \, . \tag{21}$$

3. Results.

Solving of differential equations system which describes the dynamic behavior of pump high-voltage electric drive is a complicated task. Induction motor type AO 710 L-66 is used to drive, whose technical data and parameters at slip *s = 1* are given in the Appendix.

The software MathCad® of Parametric Technology Corporation (PTC®) and specifically laid down therein functional method "Rkadapt" - method for solving differential equations with adaptive size of approximating step has been used for solving the system of differential equations. Using the proposed mathematical model, the components of energy losses have been calculated in case of different values of power supply and the factor of inertia, i.e. total moment of inertia. Some of the results obtained are presented below in Table 1 and graphically in Figure 1 and Figure 2.

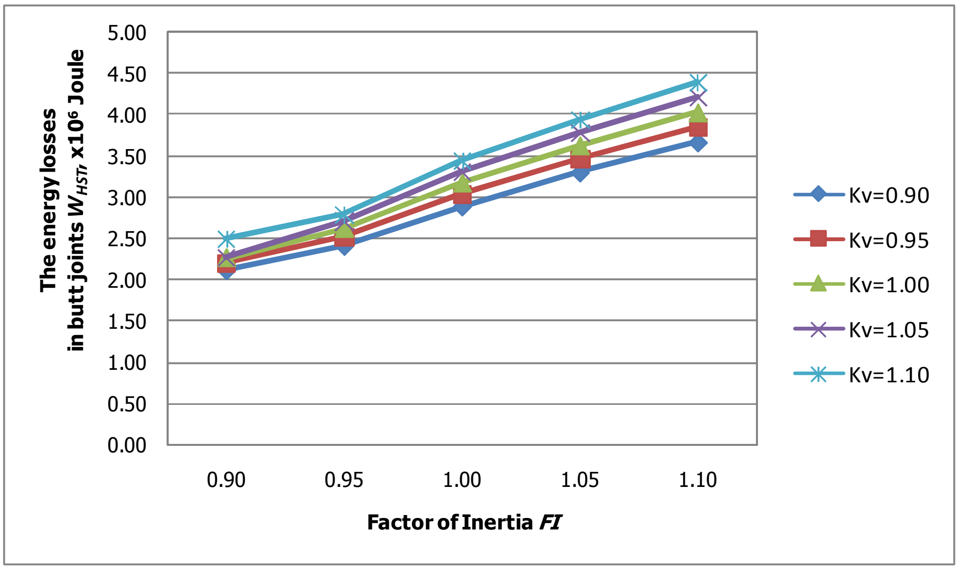

Figure 1. The energy losses in butt joints W_{1ST} in starting mode versus factor of inertia *FI*.

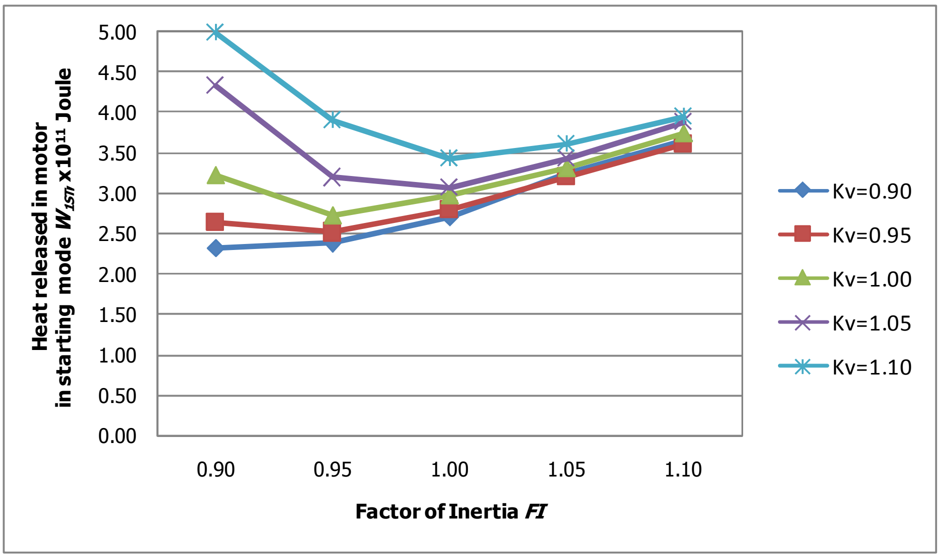

Figure 2. Heat released in motor W_{HST} in starting mode versus factor of inertia *FI*.

Table 1. Influence of multiplicity of supply voltage and factor of inertia

K_V	FI	t_{ST}, s	W_{ST}, x10^{11} Joule	W_{SS}, x10^{11} Joule	W_{1ST}, x10^{6} Joule	W_{1SS}, x10^{5} Joule	W_{MMST}, x10^{7} Joule	W_{MMSS}, x10^{7} Joule	W_{HST}, x10^{11} Joule	W_{HSS}, x10^{11} Joule
0.90	2.0	3.764	2.325	3.915	2.114	0.814	5.958	9.669	2.324	3.914
	2.5	3.486	2.377	4.112	2.408	0.834	6.396	9.909	2.376	4.111
	3.5	3.396	2.710	4.176	2.888	0.840	7.676	9.986	2.709	4.175
	4.5	3.576	3.234	4.048	3.298	0.827	9.189	9.831	3.233	4.047
	5.5	3.664	3.654	3.986	3.665	0.821	10.620	9.756	3.653	3.985
0.95	2.0	4.011	2.632	4.172	2.194	0.880	6.170	9.458	2.632	4.171
	2.5	3.494	2.510	4.574	2.514	0.921	6.403	9.904	2.509	4.573
	3.5	3.323	2.790	4.710	3.028	0.935	7.613	10.050	2.790	4.709
	4.5	3.384	3.208	4.662	3.459	0.930	9.023	9.999	3.207	4.661
	5.5	3.459	3.615	4.602	3.844	0.924	10.440	9.935	3.614	4.601
1.00	2.0	4.573	3.217	4.160	2.254	0.919	6.655	8.976	3.216	4.159
	2.5	3.592	2.719	4.980	2.613	1.006	6.488	9.821	2.719	4.979
	3.5	3.366	2.980	5.179	3.166	1.026	7.650	10.020	2.979	5.178
	4.5	3.330	3.317	5.212	3.621	1.029	8.976	10.050	3.316	5.211
	5.5	3.412	3.750	5.138	4.025	1.022	10.040	9.977	3.749	5.137
1.05	2.0	5.656	4.333	3.683	2.272	0.904	7.588	8.045	4.332	3.682
	2.5	3.957	3.188	5.144	2.706	1.069	6.802	9.508	3.188	5.143
	3.5	3.307	3.065	5.767	3.300	1.131	7.600	10.070	3.064	5.766
	4.5	3.282	3.428	5.792	3.782	1.134	8.935	10.090	3.427	5.791
	5.5	3.369	3.884	5.706	4.205	1.125	10.370	10.020	3.882	5.705
1.10	2.0	5.869	4.991	3.859	2.494	0.966	8.043	7.861	4.990	3.858
	2.5	4.518	3.896	5.086	2.782	1.109	7.285	9.024	3.896	5.085
	3.5	3.503	3.429	6.118	3.432	1.216	7.768	9.897	3.428	6.117
	4.5	3.299	3.615	6.337	3.941	1.238	8.950	10.070	3.614	6.336
	5.5	3.279	3.948	6.360	4.385	1.240	10.290	10.090	3.947	6.539

$*$ t_{ST} is staring time in seconds.

4. Conclusion

The mathematical model developed helps to study processes during start and steady-state operation of the pump mechanism driven by means of high-voltage motor and further define the components of the energy losses.

As a result of simulation studies we evaluate the influence of the supply voltage and the electric drive total moment of inertia on starting time and the components of the energy losses of a powerful electric motor to pump unit. It is necessary to bear in mind that the electric motors operation at higher heating temperature of stator winding leads to a decrease in their reliability and durability.

The change of total moment of inertia I_{TOT} has a significant impact not only on the duration of transient processes but also the energy losses. At invariably supply voltage with increasing of FI starting time decreases and the energy losses in butts and the heat released in motor increase. As optimal value for this motor proves that for total moment of inertia on $FI = 3.5$.

As an overall assessment of the impact of the supply voltage on the characteristics of induction motor can be concluded that both increase and decrease with respect to the rated value affect adversely. Dependencies of the energy losses as a function of the supply voltage also have great practical significance when considering the issues of starting and possibly control the speed of high-voltage induction motors.

5. Appendix

Induction motor data and equivalent circuit parameters

Description	Data
Rated power (P_{rated})	2850 kW
Rated stator voltage (V_{rated})	6000 V
Operating frequency (f)	50 Hz
Line stator current (I_1)	335.841 A
Rated torque (T_{rated})	27442 Nm
Pole pair number	3
Rotor speed (N_r)	992.263 rpm
Power factor	0.845
Rotor torque of inertia (I_r)	275 kgm^2
Stator resistance r_1	0.05 Ω
Rotor resistance $r_2^{'}$	0.062 Ω
Stator leakage reactance x_1	0.957 Ω
Rotor leakage reactance $x_2^{'}$	2.237 Ω
Magnetizing reactance x_m	34.826 Ω

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