STUDY OF RESISTING MOMENT INFLUENCE ON OPERATION OF HIGH-VOLTAGE INDUCTION MOTOR PUMP ELECTRIC DRIVE

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Abstract: *Paper deals with dynamic behavior of powerful electric drive for pump unit. The practical application of these electric drives is diverse. In industry they drive a wide range of mechanisms connected to them. Some of them are pumps with varying degrees of security for thermal or nuclear power plants. The nature of the flow of transient processes in the electrical machine often determines the behavior of the entire system, an element of which is the machine. As a result the values of the energy losses components in the induction motor have been obtained according to different values of initial resisting moment. 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

Electricity represents one-third of all energy consumed aroud the world. Growing energy prices are causing the industry and consumers to rethink things. Therefore the future belongs to solutions for low energy consumption in the sector of industrial plant. So the challenge is to develop a wide spectrum of energy-efficient solutions [1].

Induction motors with squirrel-cage rotor are the most common type motors. They are cheap, with the most simple and reliable construction and easy maintenance. The absence of collectors and brushes eliminates largely the conditions of arcing and makes them suitable also for fire and explosive environments.

The shape of the torque-speed characteristics makes induction motors with squirrel-cage rotor particularly suitable for drive centrifugal pumps with a quadratic dependence of resisting torque versus angular speed align naturally with the mechanical characteristics of the electric motors. The shape of mechanical characteristic varies depending on the structure of the rotor. Double-cage motors have a higher starting torque, which makes them more suitable for loads with a relatively large initial resisting torque and a relatively larger mass.

If the initial resisting torque of the load is significant, or that its mass is so large that time for acceleration is unacceptably high, the outcome is either to use a more powerful motor with cage rotor, which is oversizing, or use another type of motor.

In assessing the economy of an electric drive in the first place should take into account the loss of power and energy that occur when operating the mechanism driven.

2. Features of medium voltage electric drives for pump units

Broadly speaking, the drive of medium voltage (MV) is used in high power driven load. For units with high power has a margin of capacity in the range 500-10000 kW and more.

Currently it is well known widespread shift towards more efficient technical solutions for reducing consumption of energy and the losses during operation.

Subject of research is calculating the parameters of movement and dynamic loads of widespread mechanism - a centrifugal pump.

There are several hundred identifiable types of pump design tailored for varying volume throughputs and delivery heads, and including many specialized designs for specific fluid applications. The most common type, accounting for perhaps 80 per cent of fluid transfer applications, is the broad ‘centrifugal pump’ category [2].

Hydraulic machines as appearing pumps have been significant development and application in all areas of life. Working hydraulic machines convert mechanical energy into potential and kinetic energy of certain quantities of a fluid. Most often they are powered by electric motors.

Usually this type of electric motors are running under constant load indefinitely, reaching a thermal steady-state condition, i.e. continuous duty S1 [3].

Resisting torque of each turbo-mechanism is derived from the aerodynamic (or hydraulic) torque and resistance torque determined by mechanical resistance (friction in the bearings, gears and in others.).

With some approximation it can be considered that between the shaft torque and the rotational speed of centrifugal pumps a correlation exists $T \sim \omega^2$. Practically speed exponent varies between 2-6 for different structures and working conditions that need to be considered when selecting electric drive. Specified limits are determined at the pumps by the presence of static head. In general, the mechanical characteristic feature is the significant reduction in resisting torque in reducing angular speed. It should be borne in mind and even landed turbo mechanism has a significant aerodynamic drag and consequently the shaft torque constitutes at a rated speed of about 40% of the nominal. When calculating the starting characteristics of such electric drives is not recommended initial resisting torque be taken for less than 25% nominal static resisting torque of turbo mechanism. For most pumps the power, and hence the starting torque is less than 50% of the nominal value.

The pumps usually are started at closed throttle valve in the pressure line, i.e. while placing flow is 0. This method of starting in most cases is to eliminate bumps and pressure pulsations in the hydraulic system. Starting at closed throttle valve in the pressure pipe as a rule eases and conditions of employment of the drive motor.

Once the pump is put into operation, it should not work in a closed valve more than one to a few minutes, because liquid is heated, and the individual parts, thereby reducing clearances and risk of seizure arise. There is also the danger of damage to the shaft seal.

The correct clearances and fits are a basic but important part of a pump’s fitness for purpose. The importance of obtaining the accurate dimensions, particularly on bore diameters, increases with pump size [2].

In the cases of non-compliance for placing pumps in operation, receiving an overload of electrical motors, which drive them, and very often they are burned.

The power of the motor which drives the pump is usually chosen slightly larger (by 10-20%) of the power to drive the turbo machine at its nominal operation. The need for such stockpiling having the kind of characteristic of her that turbo machines are often used for work in modes other than the nominal.

Losses in turbo machines are three types: hydraulic, volumetric and mechanical. The hydraulic losses are obtained by fluid flow through the machine. Volume losses represent the amount of any omission of flow from the machine outside and flow that returns from the pressure to the suction side of the machine. The mechanical losses are the result of mechanical friction between stationary and rotating parts of the machine, such as friction bearings and sealing box. All these losses have an impact on the pumps efficiency.

It's necessary coordination of the operating point of the motor for normal operation of electric drives. It consists in that the operating point of the motor, i.e., the intersection of the characteristics of the torque of the motor and load to be located near or slightly below the point with coordinates 'rated torque - rated speed'. In this way it is ensured motor cooling - on the one hand, the losses emitted in the form of heat are within the design, on the other - the speed of rotation of the cooling impeller mounted on the shaft of each standard induction motor, it is sufficient to provide design flow of air.

Important is the motor type - with induction motors with squirrel-cage rotor heat is released completely in the machine itself.

It is also taking into account mechanical shocks during start and ripple of the load. Any abrupt change in torque, either from the motor or from the side of the load, leading to mechanical stresses and fatigue in the shafts. Also, for pumps abrupt changes in torque can lead to hydraulic shocks in the system. This is one of the factors, along with thermal overload and increased energy losses in frequent releases to prefer methods with soft start, such as placing a soft starter or frequency converter. The last one provides an additional advantage - it can cover changed in resistive load during operation and also allows quick passage through any resonant frequencies at start and avoid work at these frequencies.

By the way in industry 80% of operated machines have no requirements for maintaining accurate torque and speed, but only a fraction of the drives require work at very low speeds or high performance regulation.

The need for speed control is evident when itself technological process requires it. But there are other cases where such adjustment is appropriate. For example in circulating centrifugal pumps in systems with small static head, reducing the speed, respectively, flow rate by 20% results in a reduction of power consumption by up to 50%.

The greater is the static head in the system, the smaller the economy, but still have it. Therefore, where the technological process enables a reduction in productivity using frequency regulation can be implemented very large energy savings. Additional savings, including by increasing the lifetime of the equipment come from a change in the cycle of work – less frequent starts and stops at a lower flow rate.

Methods for starting and control the rotational frequency [4]

Direct starting is undoubtedly the simplest and cheapest method, as long as the power system and the characteristic of the load to allow it.

In the starting methods using start with reduced voltage is achieved reducing starting current, but also an even greater reduction in starting torque. Thus these methods are applicable to loads with low initial resisting torque.

Applicable are also and non-electrical means for regulation of the resisting torque of the load. One possibility is the starting of centrifugal pumps with closed pressure pipe-line and gradually opening after acceleration the motor. The method is applicable to both synchronous and induction motors, provided that the technological process allows it. It must be selected suitable plumbing fittings or used pumps with controllable steering system, which is appropriate only for large capacities. Regulation of the pumps performance in a continuous duty in this way is inadvisable because it is accompanied by losses and wear of the hydraulic equipment.

Another possibility is to use a hydraulic clutch. It allows to modify the speed of the mechanism driven, not amended the rotational speed of the motor. When it is typical that in the initial moment of acceleration motor is loaded only with internal resistance of the clutch. With the rise in motor speed increases the amount of hydraulic fluid pumped to the clutch impeller and thereby increasing motor torque applied to the load. The selection of characteristics of the hydraulic clutch so as to fit the mechanical characteristics of the load is a complex engineering task. In operating mode after accelerating the motor to the rated speed, clutch remaining work, as has its own slip, causing heat in it and respectively – energy losses. The hydraulic clutch is capricious device that requires maintenance. All these shortcomings make its use more rarely.

Frequency converter control still remains relatively expensive method for induction motors with squirrel-cage rotor MV, but with significant advantages over other methods of starting and especially to regulate the speed in operation:

- Frequency converters provide start, stop and speed control ranging from 0 to over-synchronous speed; occupy relatively little space and have small losses.
- Hold most flexible starting characteristics suitable for all loads.
- Completely missing abrupt changes of current and torque typical for moments of switching to other starting methods.
- Even with drives where technology does not require a speed change during operation in some cases frequency converters can implement substantial energy savings by reducing operating speed.
- They are not sensitive to the parameters of the scheme as other starting devices, so that the selection of apparatus is not so complicated task and tolerate future changes in the pattern, including the replacement of the motor.

A specific problem of frequency drives are high-voltage peaks fed to the motor. These peaks arise from the trapezoidal shape of the output voltage pulses of inverters with PWM, which have very steep front (high dv/dt).

High frequency surges increase the risk of disruptive voltages and vagabond currents in the shaft and breakthroughs in motor bearings. These phenomena lead to overheating and arcing occurs and an electric arc, disrupting the bearings.

3. Mathematical model

Transient processes when starting a powerful electric drive of pump unit are considered. Speed variations depends on the total torque of inertia of the rotating masses [5].

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 to slip $s = 1$.

The electric motor, the object of development, is induction motor with double-cage rotor, produced by IHB Electric JSC, Bulgaria. whose technical data and parameters at slip $s = 1$ are given in the Appendix.

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 [6]. It includes torque developed by the electric motor and resisting torque of the pump unit. Engineering accuracy requirements in studying the dynamics of the pump unit driven by induction motor, fully able to meet with using one-mass dynamic model. 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 [7].

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 moment of inertia.

We use system relative units participating in the equations values. In this system voltages, currents, power and parameters are expressed in parts of the underlying values of those variables. As basic values are nominal values of current, voltage, power, torque, speed, resistances. Amending the scale of time using relatively time $\tau = \omega_b t$ – e.g. time in relative units.

Below are outlined the various components of energy and energy losses during starting and steady-state regime of the induction motor.

Adopted energy from the grid in starting mode is:

$$W_{ST} = \sum_{k=0}^{a_{n-1}} \left[\left(P_{a_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{b_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{c_k} \right) t_n \right] \tag{2}$$

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.

Adopted energy from the grid at steady state mode is:

$$W_{SS} = \sum_{k=a_{n-1}}^{n-1} \left[\left(P_{a_k} + P_{b_k} + P_{c_k} \right) \right] \left[(n-1)\delta t - t_n \right] \tag{3}$$

δt – a discrete of time axis in seconds;

t_n – duration of the transient process in seconds.

The energy losses in butts (frontal connections) in starting mode are:

$$W_{1ST} = 0.5 r_1 \sum_{k=0}^{a_{n-1}} \left[\left(I_{a_k} \right)^2 + \left(I_{b_k} \right)^2 + \left(I_{c_k} \right)^2 \right] \delta t \tag{4}$$

r_1 – resistance of one phase of the stator winding;

I_a, I_b, I_c – phase stator currents.

The energy losses in butts (frontal connections) in steady state mode are:

$$W_{1SS} = 0.5 r_1 \sum_{k=a_{n-1}}^{n-1} \left[\left(I_{a_k} \right)^2 + \left(I_{b_k} \right)^2 + \left(I_{c_k} \right)^2 \right] \delta t \tag{5}$$

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

$$W_{MMST} = 0.5 J \omega_b^2 + T_L \omega_b t_{a_{n-1}} \tag{6}$$

J – total inertia moment of the electric drive;

ω_b – rated circular frequency; T_L – resisting torque, Nm

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

$$W_{MMSS} = \sum_{k=a_{n-1}}^{n-1} \left[T_k \omega_k \delta t \right] \tag{7}$$

Heat released in motor in starting mode:

$$W_{HST} = W_{ST} - W_{MMST} \tag{8}$$

Heat released in motor in steady state mode:

$$W_{HSS} = W_{SS} - W_{MMSS} \tag{9}$$

4. Results obtained

Solving of differential equations system which describes the dynamic behavior of pump electric drives is a complicated task. Because of this reason there is a need of applying of numerical methods for integrating in combination with micro-processor devices.

To solve the differential equations system the software MathCad® of Parametric Technology Corporation (PTC®) has been used and specifically laid down therein functional method "Rkadapt" - method for solving differential equations with adaptive size of approximating step.

The format of the function in method mentioned is:

Rkadapt(y,x_1,x_2,npoints,D)

y - vector of initial conditions;

x_1,x_2 - points defining the boundaries of the range, which will seek a solution of differential equations. The initial conditions set out in y concern at point x_1;

npoints - number of points in the given interval, which will be carried approximation;

D - vector of the right side of the system differential equations containing the first derivatives of the unknown variables /functions/.

Using the proposed mathematical model, the components of energy losses have been calculated in case of different values of initial resisting torque and factor of inertia. Some of the results obtained are presented in the paper – Table 1, Figure 1 and Figure 2.

Table 1: *Influence of initial torque and factor of inertia FI*

T_{INIT}*	*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
0.2	2.0	4.755	3.401	4.017	2.275	0.903	6.811	8.820	3.400	4.016
	2.5	3.693	2.825	4.893	2.632	0.997	6.575	9.735	2.825	4.892
	3.5	3.376	3.008	5.171	3.188	1.025	7.659	10.010	3.007	5.170
	4.5	3.341	3.351	5.202	3.647	1.028	8.985	10.040	3.350	5.201
	5.5	3.424	3.788	5.129	4.053	1.021	10.410	9.968	3.786	5.128
0.25	2.0	4.850	3.509	3.942	2.294	0.895	6.894	8.739	3.508	3.941
	2.5	3.702	2.851	4.885	2.650	0.996	6.583	9.727	2.850	4.884
	3.5	3.385	3.037	5.162	3.210	1.024	7.667	10.000	3.036	5.161
	4.5	3.350	3.383	5.194	3.672	1.027	8.994	10.030	3.382	5.193
	5.5	3.435	3.826	5.119	4.082	1.020	10.420	9.959	3.825	5.118
0.3	2.0	4.943	3.614	3.871	2.312	0.887	6.973	8.660	3.613	3.870
	2.5	3.710	2.875	4.878	2.668	0.996	6.590	9.721	2.874	4.877
	3.5	3.396	3.067	5.153	3.233	1.023	7.676	9.991	3.066	5.152
	4.5	3.361	3.417	5.184	3.698	1.026	9.003	10.020	3.416	5.183
	5.5	3.447	3.867	5.107	4.112	1.019	10.430	9.948	3.866	5.106
0.4	2.0	4.954	3.664	3.862	2.344	0.886	6.983	8.651	3.663	3.861
	2.5	3.726	2.924	4.864	2.706	0.994	6.603	9.708	2.923	4.863
	3.5	3.419	3.128	5.133	3.278	1.021	7.696	9.973	3.127	5.132
	4.5	3.384	3.487	5.164	3.752	1.024	9.023	10.000	3.486	5.163
	5.5	3.473	3.950	5.085	4.172	1.016	10.460	9.928	3.949	5.084
0.5	2.0	4.887	3.644	3.914	2.378	0.892	6.925	8.710	3.643	3.913
	2.5	3.839	3.065	4.767	2.744	0.984	6.701	9.612	3.064	4.766
	3.5	3.438	3.187	5.116	3.325	1.020	7.712	9.958	3.187	5.115
	4.5	3.525	3.700	5.039	3.808	1.012	9.145	9.883	3.699	5.038
	5.5	3.498	4.035	5.062	4.233	1.014	10.480	9.907	4.034	5.061

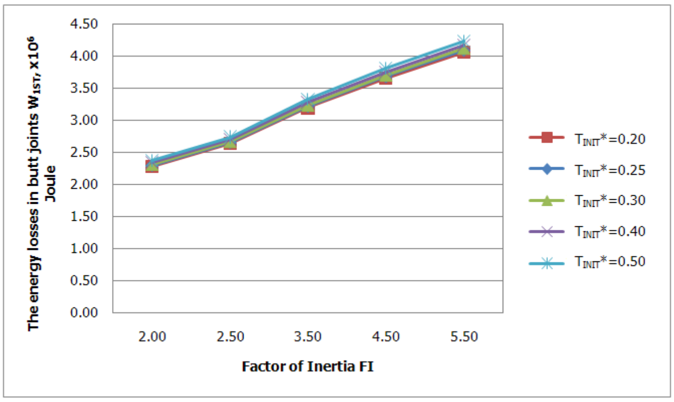

Fig. 1 *Heat released in motor* W_{1ST} *in starting mode versus factor of inertia FI.*

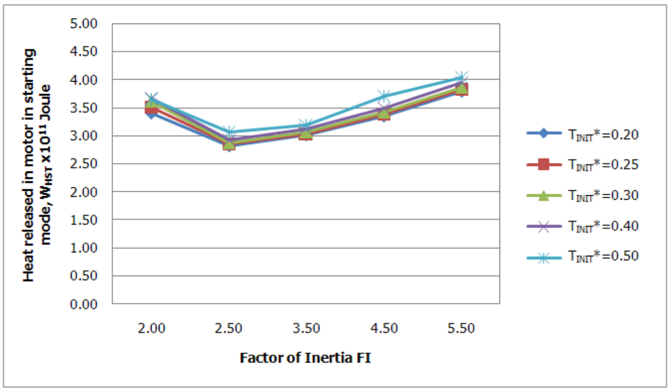

Fig. 2 *The energy losses in butt joints* W_{HST} *in starting mode versus factor of inertia FI.*

5. Conclusions

The operation of the complex system of production unit – motor has been studied. Following work on the model of the mechanical system - pump in coordination with the rated mechanical characteristic of induction motor is obtained function $\omega=f(t)$, it appears slip of an induction motor $s=f(t)$, which determines the nature of its dynamic load. All values are presented in the time domain.

Dynamic changes are determined by the balance of torques, i.e. when the load increases on the motor shaft slip increases, which decreases the reduced active rotor resistance, which increases the current in the rotor, and hence the torque of the shaft, i.e. all variables related to the features of an induction motor follow the dynamic changes of slip.

Confirmed the assertion that the selection and sizing of the drive system is influenced by the range of variation of static torque, which is the ratio of static torques at minimum and maximum loading of mechanism (usually calculated at nominal speed).

The mathematical model developed in the paper helps to examine the transient processes when starting a powerful electric drive for pump unit. The mathematical model developed makes it possible to determine the proper design and selection of mechanical parameters in order to achieve customized requirements.

The energy losses in butt joints in starting mode нарастват с нарастването на Factor of Inertia *FI*.

The heat released in motor during starting е най-малка при Factor of Inertia *FI*=2.5, което се явява оптимален вариант.

Acceleration time depends to a greater extent from the value of the inertia moment of the electric drive as a whole and, to a lesser extent by the value of the initial resisting torque of the pump unit driven.

The acceleration time is directly proportional to the load inertia moment, including the rotor of the motor and the inversely proportional to motor torque. If the motor can not provide a big enough motor torque and acceleration time becomes too large, it can lead to motor overheating due to overcurrent.

The detailed study of electromagnetic and electromechanical transient processes makes possible the most rational design of induction electric drives.

Appendix

INDUCTION MOTOR DATA AND ELECTRIC 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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