STUDY OF THE INFLUENCE OF SUPPLY VOLTAGE ON THE DYNAMIC BEHAVIOR OF INDUCTION MOTOR LOW VOLTAGE DRIVE

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Abstract: *Paper deals with the dynamic behavior of pump unit electric drive. The electric motor, subject of development, is a new standard efficiency induction motor with squirrel cage rotor, designed to operate in continuous operation. The determination of operating characteristics of induction motor in dynamic modes is necessary to establish the properties of the machine in specific conditions. In some industrial areas can occur very often sags with a depth of between 10% and 15% of the rated voltage as a result of switching electrical loads on systems of users. As a result of simulation studies the influences of the supply voltage and total torque of inertia of the electric drive have been assessed on arising impact torques and currents and electric energy losses of electric drive for pump unit. The results obtained are in addition to experimental studies of the same motor. Some of the study results have been presented graphically. An analysis and conclusions from the results obtained have been done.*

KEYWORDS: *INDUCTION MOTORS, MATHEMATICAL MODEL, MOTOR DRIVES, PUMPS.*

1. Introduction

Electricity represents one-third of all energy consumed around the world. Growing energy prices are causing the industry and consumers to rethink things. Therefore the future belongs to intelligent solutions for low energy consumption in the industrial plants as well as household.

The topic of electricity quality is comprehensive. It covers all aspects of the design of electrical systems, analysis of transmission and distribution levels and problems for end users. Therefore, the quality of electricity is an important issue for electricity distribution companies and end-users as well as for manufacturers. Low power quality can disturb the customer's production process, and this, in turn, leads to loss of revenue. It is in the user's interest that the downtime of the manufacturing process due to power supply problems is minimized. Conversely, customer activity may also affect the quality of electricity and it is in the interest of the electricity distribution company that this effect be limited.

Voltage deflections may include instantaneous low voltage (voltage drop), high voltage (peak) or voltage loss (interruption). Breaks are the most severe in terms of their consequences for end users. But the voltage drops may be more important because they are more common. In case of failure, it is possible to monitor voltage drops in many places in the system without interrupting the end users. This is the case for many electricity transmission failures. Many end-users use equipment that could be sensitive to such changes.

The electric drive is a power-operated device, driven machine or mechanism. The basic component of each electric drive is an electric motor designed to convert electrical energy into mechanical or mechanical energy into electrical. Among the most widely used electric motors are induction, both due to their direct supply of mains voltage and due to their dynamic characteristics, their economical cost and the simple, easy to maintain layout.

Despite the fact that the design of the induction motor has been worked on for decades by many design groups of investigators, work continues on its improvement and modification. The problem of saving materials forced us to look for ways to create a no-waste technology and replace traditional materials used in electric machine manufacturing. On the other hand, it is becoming more and more demanding to reduce energy consumption and losses through optimal design with a view to the ubiquitous orientation towards energy-efficient technical solutions. In addition, it is known that to boost overall system efficiency, it is necessary to improve the efficiency in each constituent circuit. The focus is now placing on energy efficiency. In view of the rising cost of energy, it is obvious that a reduction in consumption should be part of the plan for the future. So the challenge is to the engineering community to develop a wide spectrum of energy-efficient solutions and wasting energy must be avoided.

Losses in electrical machines are converted into heat and cause heating of individual parts. For work safety and for a certain life, the heating of the parts must be limited.

As induction motors became more popular, then consumer expectations increase, leading to greater chalenges for designers. Efficiency is a key concern of many consumers, driven by rising energy costs worldwide and by the increase regulations strictness. Designers also have to be concerned with safety and reliability, ensuring that a product does not fail. A significant percentage of the induction motors used have a power output of up to 2.2 kW. Modern electric drives are developed dynamically and are characterized by a wide range of technical solutions. Studies done have shown that the number of produced electric motors worldwide is huge and the share of electricity consumed by them is considerable.

One of the major applications where electric motors are used is where motors are connected to the grid and are operated at a fixed rotor speed. Examples of fixed frequency grid driven applications are pumps or fans that move medium without the need to adjust the medium’s speed. In these cases driven motors always deliver full power and a significant portion of power is converted into heat. At the same time, there is a widespread use of induction motors for pump drives with different applications.

2. Theoretical considerations

Despite the many important documents, articles and books on the quality of electricity, there is no unambiguous definition of this term. Almost everyone, however, is of the opinion that this issue is of paramount importance for electrical systems and electrical equipment and has a direct bearing on the efficiency, safety and reliability of systems. The term "electrical power quality" is used both for reliability of power supply, service quality, voltage quality, power quality and consumption quality. Considering the different definitions, the quality of the energy is generally used to express the quality of the voltage and / or the quality of the electricity.

First of all, it is important to understand what deflections in the quality of electricity can cause problems. Sustained-state deflections include normal variations in RMS voltage and harmonic distortion. In fact, there is no sustained state in the electrical system. The loads are constantly changing and the system constantly adapts to these changes. All these changes and the corresponding reactions lead to deflections in voltage. This can be reduced or increased voltages, depending on the specific conditions in the circuit.

Most of the end-user equipment is not particularly sensitive to these voltage deflections, provided they are within certain limits. It is assumed that the changes are long-term when they go beyond these set limits within more than one minute.

Consumers whose equipment is of high power and critical to not stopping work need constant voltage power supply with sinusoidal waveform at nominal frequency and current strength. Therefore, a electricity supply problem occurs when there is a voltage violation.

There are two main approaches to solving problems with the quality of electricity. One is a load stabilization consisting of a selection of technological equipment that is less susceptible to disturbances in the power supply and, when it is occurring, it suffers them without damage. The other approach involves installing power stabilization devices that suppress interruptions. To ensure that the production process will not be interrupted during such downtimes, a dynamic voltage regulator (DVR) can be installed. The DVR must be able to react quickly and be equipped with a power source and a voltage transformer.

Technical progress and competition are the driving forces behind the development of systems with higher productivity and a degree of automation. In this respect, the requirements for electric drives in terms of parameters such as the range of speed control, overload capability, etc., are constantly increasing. Another direction is to prevent overheating of the motors.

The development of the technique is constantly leads to simplification of driven mechanisms kinematics, reducing the application of mechanical brakes and heavy gears, as more flexible, responsive and reliable electric drives takes over all complicated acceleration and deceleration modes, speed control and speeds coordination.

During the transient processes in the electromechanical system arise considerable impact currents that cause impact torques and loads of the motor and the components of the drive mechanism [6]. With direct-on-line start of the motor and low drive inertia, the motor speed quickly reaches a set value and the starting current also fast decreases without causing overheating of the stator windings. But such a significant current shock in power supply can cause a remarkable voltage drop. In applications characterized by a low-power mains supply, powerful induction motors with a squirrel cage rotor are started up by starting current and starting torque limitations. Technically, the lower voltage supplied by the stator to the motor is made through three basic solutions - the inclusion of additional resistors, reactors or autotransformers in the machine's start-up process.

The need to limit the current of the motor is dictated by electrical and mechanical reasons. Electrical reasons for limiting peaks of current may be the following:

- Reducing the shocks of the currents in the network;
- Reducing electrodynamic forces in motor windings.

Mechanical reasons for limiting motor torque peaks may be varied, for example, prevention of:

- Breakage or rapid wear of gears;
- Greater acceleration or deceleration, unacceptable for equipment.

In all cases where the operating conditions do not require forced accelerations or decelerations, it is desirable to calculate the modes for the minimum current peaks, and hence the torque, thereby preserving the gears, the motor and the equipment. It is necessary to pay attention to the fact that the limitation of the current and torque of the motors is obtained due to the complication of the control circuits and the cost of the installation, and therefore should only be used where it is justified.

Primary voltage deflections at constant mains frequency and at near-nominal loads cause deterioration in the operating conditions of induction motors. For this reason, primary voltage deflections should be limited.

If the primary voltage drops significantly, the maximum torque may be less than the torque applied to the motor shaft. This causes the motor to stop completely and it is in a short-circuit state.

The aim of the research was to evaluate the influence of the deflection in voltage on the performance of specific induction motor as part of the electric drive. In the studies the approach is to adopt more different intervals and the tolerances of the voltage (+ 10% ÷ -20%) as defined in EN 50160:2010, in order to obtain general regularities.

3. Mathematical model

Transient processes when starting electric drive of pump unit are considered. Speed variations depends on the total torque of inertia of the rotating masses [1]. The electric motor, the object of development, is a new induction motor with squirrel cage rotor, produced by Caproni JSC, Bulgaria whose technical data and parameters 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*. 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 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 [2]. 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 [3].

The total torque 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 [4].

We introduced the term *multiplicity of supply voltage* as [4]

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

where

V current value of supply voltage;

V_{rated} nominal value of the supply voltage.

The electrical losses in the windings of the stator and the rotor are variable losses as their magnitude depends on the values of the currents in these windings.

The amount of electrical losses in the stator and rotor can be expressed so [5]:

$$\Delta P_1 + \Delta P_2 \approx 3I_2^{'2} r_1 + 3I_2^{'2} r_2^{'} \tag{3}$$

where

$\Delta P_1 = 3I_1^2 r_1$ – electrical power losses associated with stator windings heating when current flows thereon.

$\Delta P_2 = 3I_2^2 r_2^{'}$ – electrical power losses in the rotor windings.

Since

$$I_2' = \sqrt{\frac{T\omega_0 s}{3r_2'}} \tag{4}$$

therefore overall electrical losses can be represented as

$$\Delta P_1 + \Delta P_2 = T\omega_0 s + T\omega_0 \frac{r_1}{r_2'} s = T\omega_0 s\left(1+\frac{r_1}{r_2'}\right). \tag{5}$$

On the other hand, the electrical losses in the rotor can be represented as follows:

$$\Delta P_2 = P_{EM} - P_{MECH} = T(\omega_1 - \omega_2) =$$

$$= T\omega_1 \frac{\omega_1 - \omega_2}{\omega_1} = T\omega_1 s = P_{EM}\, s \tag{6}$$

$$\Rightarrow T = \Delta P_2 / (\omega_1 s) \tag{7}$$

The electrical losses in the rotor are directly proportional to motor slip, induction motor operation is more economical for small slips, since as the slip increases the electrical losses in the rotor increase.

4. Results obtained

For solving 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.

Using the proposed mathematical model, the electrical power losses and energy losses have been calculated in case of different values of supply voltage and factor of inertia. Some of the results obtained are presented tabular and graphically.

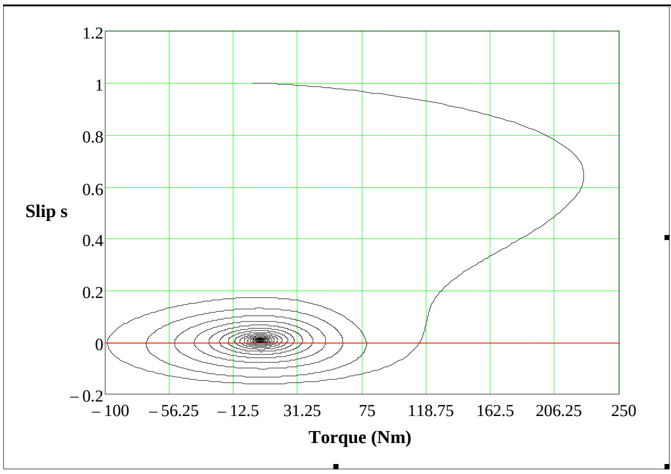

Fig. 1 Torque-slip dynamic characteristic for K_V=0.90 and FI=3.5

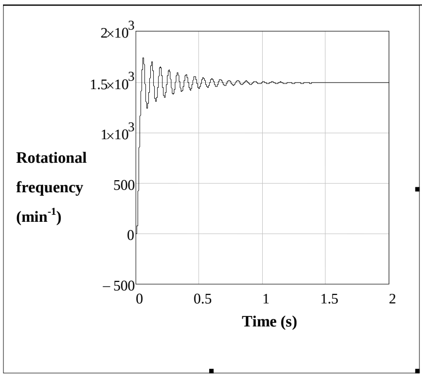

Fig. 2 Speed characteristic for K_V=0.90 and FI=3.5

Table 1: Influence of supply voltage and factor of inertia FI

K_V	FI	T_{imp}, Nm	i_{imp} *	t_{st}, s	Electrical power losses – steady state regime $\Delta P_1 + \Delta P_2$, W	Energy losses – starting regime W_{START}, kWh
1.00	1.5	57.854	14.430	0.768	47.327	0.066
	2.5	141.734	14.523	2.146		0.317
	3.5	272.075	14.566	2.516		0.515
	4.5	293.130	14.591	1.847		0.475
	5.5	212.990	14.607	1.354		0.420
0.95	1.5	47.235	13.730	1.137	52.361	0.101
	2.5	166.142	13.811	2.965		0.453
	3.5	262.321	13.849	2.809		0.583
	4.5	233.231	13.870	1.927		0.499
	5.5	119.452	13.884	1.350		0.421
0.90	1.5	44.883	13.027	1.096	58.239	0.098
	2.5	182.356	13.098	2.411		0.366
	3.5	225.443	13.130	1.863		0.382
	4.5	161.935	13.148	1.252		0.322
	5.5	78.166	13.160	0.854		0.266
1.05	1.5	71.425	15.127	0.780	42.983	0.067
	2.5	117.219	15.233	2.019		0.295
	3.5	267.909	15.283	2.997		0.614
	4.5	326.866	15.311	2.503		0.647
	5.5	290.984	15.330	1.787		0.555
1.10	1.5	85.160	15.822	0.589	39.209	0.050
	2.5	97.848	15.941	1.443		0.206
	3.5	253.091	15.997	2.529		0.511
	4.5	354.361	16.030	2.420		0.621
	5.5	358.458	16051	1.847		0.572
1.15	1.5	96.837	16.514	0.739	35.909	0.063
	2.5	86.090	16.647	1.694		0.242
	3.5	226.316	16.710	3.325		0.676
	4.5	354.549	16.747	3.656		0.948
	5.5	400.670	16.771	2.959		0.924
1.20	1.5	105.170	17.203	0.503	33.009	0.042
	2.5	83.006	17.350	1.083		0.152
	3.5	195.628	17.421	2.223		0.442
	4.5	350.045	17.462	2.860		0.731
	5.5	433.191	17.490	2.535		0.784

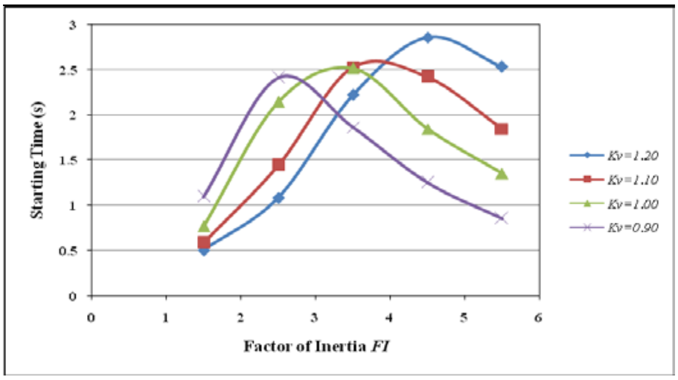

Fig. 3 Starting time versus Factor of Inertia FI.

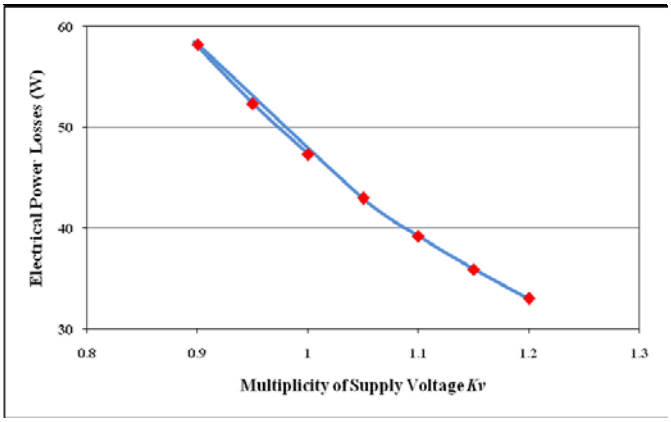

Fig. 4 Electrical Power Losses versus Multiplicity of Supply Voltage.

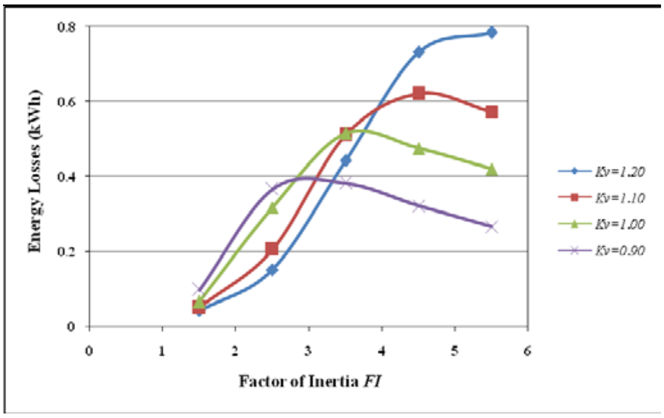

Fig. 5 *Energy Losses versus Factor of Inertia FI*

5. Conclusions

As a result of simulation studies the influences of the supply voltage and total torque of inertia of the electric drive have been assessed on arising impact torques and currents and electric energy losses of electric drive for pump unit.

The voltage deflections of the supply line voltage related to its nominal value are accompanied not only by torque changes but also by variations in the rotor speed. By reducing the supply line voltage, rotor speed decreases (slip increases). Mains voltage affects the maximum torque value and also the motor overload capacity.

When starting induction motors to increase the starting torque, it is necessary to increase r_2' and in the nominal mode to increase the efficiency and the power factor and to reduce electrical losses r_2' must be less to be slip in the 1-4% range.

Given the low slip value at nominal load, it follows that with a deflection of the primary (feed) voltage the rotational speed changes slightly.

The stator current of the engine $I_1 = I_\mu - I_2'$ also changes. Its magnetizing component I_μ is practically equal to the reactive component of the magnetizing current $I_{\mu r}$. It depends non-linearly on the magnetic flux of the motor. As the primary voltage drops, the magnetic flux also decreases. When the primary voltage drops, the stator current I_1 increases with a dominant rotor current I_2' (working at a load close to nominal) or decreases with a dominant reactant of the magnetizing current $I_{\mu r}$ (low-load operation). In this case, the electrical losses in the rotor winding increase. Electrical losses in stator winding as well as primary current increase at significant load or decrease in small motor loads. Generally, with a significant motor load, lowering of the primary voltage causes an increase in the total loss in the machine.

Some technology solutions to reduce total losses in order to increase the efficiency of induction motors are:

- Use of suitable steel for housings with elongated structures and thinner walls to reduce eddy current losses (losses in the metal part);
- Using more copper as well as thicker wires to increase the cross-section of stator windings, reduce their resistance and reduce electrical stator losses;
- Use of larger rotor grids to increase cross-section, reduce their resistance and reduce electrical losses in the rotor;
- Use an efficient fan to reduce friction losses.

In many applications, like pumps, a large percentage of the electric energy is wasted because these uncontrolled motors are not operated at their optimum speed and torque which is determined by the load ot work required to be delivered.

The results obtained could be of great practical importance when considering to start and possibly control the speed of induction motors.

Appendix

INDUCTION MOTOR DATA AND ELECTRIC EQUIVALENT CIRCUIT PARAMETERS

Description	Data
Type, Designation	ATM 100L4
Rated power (P_{rated})	2.2 kW
Rated stator voltage (V_{rated})	400 V
Operating frequency (*f*)	50 Hz
Line stator current (I_1)	4.95 A
Rated torque (T_{rated})	14 Nm
Pole pair number	2
Rotor speed (N_r)	1435 rpm
Power factor	0.80
Efficiency	80.1%
Stator resistance r_1	2.400 Ω
Rotor resistance r_2’	2.206 Ω
Stator leakage reactance x_1	3.040 Ω
Rotor leakage reactance x_2’	3.243 Ω
Magnetizing reactance x_m	76.831 Ω

References

1. H. Merz, *Electrical Machines and Drives*. Berlin, Germany: VDE VERLAG GMBH, 2002, pp. 348-355.
2. R. Crowder, *Electric Drives and Electromechanical Systems*. Oxford, U.K.: Elsevier, 2006, pp. 35-42.
3. A. Hughes, *Electric Motors and Drives*. Oxford, U.K.: Elsevier, 2006, pp. 369-375.
4. Rachev S. R., and Koeva, D. Y. (eds), (2016), Electromechanical Model and Operating Modes of High-voltage Induction Motor Electric Drive – Part I: Impact Torque and Currents, Proceedings of 2016 International Symposium on Fundamentals of Electrical Engineering (ISFEE), 30 June-2 July 2016, University Politehnica of Bucharest, Romania – sponsored by IEEE (published in IEEE *Xplore* https://www.ieee.org/conferences_events/conferences/xplore_conference_proceedings.html INSPEC Accession Number: 16563023, DOI: 10.1109/ISFEE.2016.7803188, Part Number: CFP1693Y-POD, Xplore PU Number: 7786011). ISBN 978-1-4673-9576-2.
5. Rachev S. R., and Koeva, D. Y. (eds), (2016), Electromechanical Model and Operating Modes of High-voltage Induction Motor Electric Drive – Part II: Power Losses, Proceedings of 2016 International Symposium on Fundamentals of Electrical Engineering (ISFEE), 30 June-2 July 2016, University Politehnica of Bucharest, Romania – sponsored by IEEE (published in IEEE *Xplore* https://www.ieee.org/conferences_events/conferences/xplore_conference_proceedings.html INSPEC Accession Number: 16563051, DOI: 10.1109/ISFEE.2016.7803189, Part Number: CFP1693Y-POD, Xplore PU Number: 7786011). ISBN 978-1-4673-9576-2.
6. Stoyanov I, T. Iliev, G. Mihaylov, E. Ivanova “Synthesis and Design of Virtual Measurement System for Investigation on Photovoltaic Modules”, 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE), pp. 915 – 918, 2017 (published in IEEE Xplore http://ieeexplore.ieee.org/document/7905070).