Study on behaviour of centrifugal pump driven by medium-voltage induction motor during operation control

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Abstract. When studying electric drives, it is necessary to jointly analyze the processes in the electric power and control circuits of the electric motor as the main component determining the overall performance and in the mechanical executive part. The paper deals with the variation of the occurring torques, the currents flowing in the individual phases and the electrical power losses in the operation of a medium voltage electric drive of a pump unit from the point of view of energy efficiency. Emphasis is placed on the joint operation of the pump as a mechanism and the driving electric motor, studying the complete electromechanical system. During the studies, significant attention has been paid to the mathematical description and modeling with subsequent computer simulation of the ongoing electromagnetic and electromechanical processes. Different ways of controlling the motor have been applied - by softstarter and by frequency control. Also values for the duration of the start-up process have been obtained. Relevant conclusions have been drawn.

1 Introduction

Electric motors (EMs) are a dominant class of electrical energy users in the world. Therefore, research in the field of minimization of the energy consumption of electric drives is always relevant.

Considering the position of EMs as one of the largest consumers of electricity, even small improvements in their efficiency can lead to significant energy savings, which will also contribute to increasing sustainability worldwide.

When designing EMs, the goal is to achieve maximum efficiency at 60÷80% of the rated load, since they usually operate with an under-load of 15÷25%. To move the maximum efficiency in the rated load area or in the overload area, the cross-section of the windings should be increased and the electrical losses in the EM should be reduced.

The induction motor (IM) with a squirrel-cage rotor is the most commonly used rotating electric machine. The reason for this is the simple design of this type of EM, which leads to:

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- low price of the rotating machine.
- cheap service (no need to check and replace brushes, nor clean the dust compartments of the brushes.
- high reliability.

The large starting current is a major disadvantage of the IM in direct on line starting (DOL starting). The quadratic dependence of the IM torque on the supply voltage is its other main disadvantage. Short-term dips in supply voltage can reduce the motor's torque to such an extent that it stops rotating altogether. Voltage dips represent a short-term but significant reduction in the effective value of the voltage in one or more phases. There are two main causes of voltage dips in the power system – commutations in the electrical energy system and poor connections, mostly between aluminium cables and copper cable lugs, leading to a potential contact difference.

It is known that pumps are working machines that serve to suck a liquid standing at a lower level and push it to the desired height to a higher level. To carry out this process, work is expended, produced in other machines, called *power machines*, such as water and steam turbines, EMs, and the like. Pumps are responsible for about 8-9% of the global consumption of electric energy. Large electric motors with more than 375 kW nominal output power are usually high-voltage AC motors and they account for about 23% of all electric energy consumption by motors. [1].

A certain number of pumping stations with pumping units operating in them are always provided for each populated place with a view to drinking water supply. Very often 1, 2 or more pump units are in operation, and even more are available as spares, and these are most often repaired with rewound coils. In most cases, the drive IMs are powered at medium voltage (MV), most often 6 kV and not at low voltage (LV) 400 V.

The higher the voltage level, the higher the installation costs; although the current as the voltage increases becomes smaller, the wire and cable can be selected with smaller sections, but the cost of other medium-voltage circuit breakers, transformers, switchgear and other equipment still increases. The initial investment is large, so small businesses are ready to use LV equipment when they are newly registered, i.e. startups.

The higher the voltage level, the lower the total operating costs; the small current leads to a reduction in power losses, which is suitable in the long run. The cumulative effect is incredible, as many large enterprises replace LV motors with MV motors during technical transformations.

Based on economic calculations, the main costs at pumping stations are for electricity. With the continuous increase in the price, it turns out that about 40% of the energy consumed is practically wasted. Therefore, as an energy-efficient solution with a great economic effect, control of EMs for pump units can be used.

The traditional water supply system, without regulation of the IM drive, can only provide a constant pressure regardless of consumption or momentary loads. The addition of a frequency regulator enables the water supply system to adjust the water pressure as required. When there is no demand for water, the frequency control goes into "sleep" mode until water is needed again and then immediately provides constant water flow. The effect of this control method is to reduce the electrical energy costs of pumping units by 10 to 30%. This results in significant water and electricity savings, which is particularly noticeable in environments with inconsistent water flow. The frequency electric drive reduces the average operating speed of the pumping unit to extend the life cycle and adjusts the output speed according to the needs.

Very often, large currents are obtained during transient processes. They usually decay very quickly, but their maximum values are very large. The amplitude of the current through the transient process is called the *impact current*. It can exceed as a value the starting current declared by the manufacturer as a multiplicity of the rated one. It is necessary to mention that modern electronic static electricity meters (without rotating parts) are very precise and take into account the large consumption of electrical energy when starting powerful electric drives.

Another consideration must be kept in mind. When large MV motors or combinations of MV motors are started, large instantaneous amounts of reactive power are required. This depletion of reactive power from the distribution system can cause objectionable disturbances on the system. Starting a motor with full voltage imposes a high reactive power requirement, with a low, lagging power factor, for a short period of time, during its acceleration period. [2]

The mechanical effort in the windings is proportional to the current squared, and therefore the need to determine the currents during the transient processes, and hence the knowledge of the process itself, is clear. Since the impact current is many times greater than the rated one, it is clear that there will be forces acting mostly on the butt joints of the windings, which have large values.

Large values of torques can also be obtained during transient processes. In this case, the maximum value of the torque can exceed the rated one several times. This maximum torque acts as a shock on the EM and on its shaft, i.e. on the entire kinematic scheme of the electric drive, questioning its reliable operation – hence the name *impact torque*.

Transient processes in many cases are the cause of deterioration of the quality of electrical energy. The main voltage parameters and their permissible deviation ranges are regulated in [3]. In general, voltage dips are a problem affecting the electrical qualities [4].

All of the above substantiates the need to search for technical solutions ensuring the normal operation of pumping units, while at the same time the focus is on the universal orientation towards energy efficiency. Only the technical side of the issue is considered without analyzing the economic benefits of the implementation of energy saving methods.

In brief, the paper deals with the determination of the torques occurring, the stator currents flowing and the electrical power losses in the operation of a medium voltage electric drive of a pump unit from the point of view of energy efficiency, applying two different control methods - a soft starter and a frequency inverter.

2 Methodology

Starting, stopping, maintaining and changing the speed of EMs are basic tasks of industrial automation. All starting and control methods available for MV induction motors are considered successively in [2]. In terms of means of control, EMs can be classified into several categories – schemes without control and those with control.

Schemes without control. Typical connection schemes provide start, stop, short circuit protection, thermal protection, zero protection. Thermal protection also indirectly protects the EM from two-phase operation and under-voltage operation, but in some cases special protections can be added to prevent these modes. Zero protection is self-start protection – if the supply voltage fails during operation, the EM will stop, and when the power is restored, the circuit will not allow the EM to self-start and will wait for an operator to give a start signal.

The self-starting of the EMs is dangerous both from a mechanical (for the safety of the people working with the mechanism) and from an electrical point of view – if a large number of EMs are connected to the same busbars, in the event of a self-starting, they will start spinning at the same time, their large starting currents flow, which can cause a serious voltage dip in the direction of falling well below the rated level. Low voltage will aggravate the already difficult starting process and may lead to starting problems or unacceptably long running of high starting currents, and therefore overheating of the EMs.

In DOL starting, the EM is connected to rated voltage at rated frequency. At the first moment of time after launch, the rotor will still be stationary due to its inertia. By analogy with a transformer, if we are considering a squirrel-cage rotor IM, the secondary winding will be short-circuited. This explains the large starting current that flows then – up to 7 times the rated current of the EM. DOL starting is simple and inexpensive to implement and is used whenever the drive mechanism, thermal considerations and the influence of the inrush current on adjacent loads permit. DOL starting is used when providing stable power to a EM that is hardwired to the drive, such as a pump. The main considerations that limit the application of DOL starting are:

- The large starting current causes intense heating of the EM. The large starting current causes significant thermal overloads on the winding, which can lead to accelerated aging of the insulation, damage to it and, as a result, a short circuit between windings. In addition, it is accompanied by large electro-dynamic forces acting on the EM windings. Due to the uneven distribution of resistances, the large starting current can also cause over-voltages between the windings of the stator coil.
- The starting current of powerful EMs or when starting many EMs at the same time causes a strong voltage dip on the supply busbars, which affects other consumers and the EMs themselves, further complicating the starting process [1]. The power supply transformers are also overloaded.
- Another disadvantage is the fluctuating damping nature of the motor's starting torque. Significant fluctuations in the EM torque in the initial stage of start-up, which can exceed the rated torque many times over, create unfavourable conditions for the operation of the mechanics.

It is possible in rare but not unusual modes to experience a torque deficiency in some mechanisms, i.e. the starting torque is less than the resisting moment of the mechanism and the EM does not spin at all. This is effectively short-circuiting the EM. Because of the listed factors, in more specific applications it is necessary to control the starting process and avoid DOL starting.

Schemes with process control. Various schemes are applied to reduce the large impact current and limit the impact torque, for example, in mechanisms with a fan static resistance characteristic, in which during rotation, i.e. at low rotational frequencies, the resisting moment is small and increases with the second (or greater) power of the rotational frequencies. A possible technical solution is the use of softstarters, providing smooth starting of the EMs, which can also provide some protections.

In softstarters, digital control is integrated with electromechanical starters, which enables smooth acceleration of the EM both to prevent damage to transmissions and to avoid pressure on the power distribution company when starting medium and large EMs at full voltage. Under the general name softstarters, there are many technical developments that differ from each other in terms of their capabilities, connection schemes, need for additional devices.

The power circuit of commercially available softstarters is built as a thyristor (some sources use SCR as a synonym – silicon controlled rectifier) regulator with phase control. By adjusting the opening angle of the thyristors, the effective value of the voltage applied to the EM is controlled. Since they are built with thyristors, which are among the most reliable semiconductor switches, softstarters are characterized by simple construction and operational reliability.

A significant proportion of softstarters could be divided into the following four categories:

- torque limiters.
- regulators without feedback.
- regulators with feedback and current limiting.

- regulators with feedback and current control.

Softstarters provide smooth cranking up to full speed and are used when starting (and stopping if equipped). Soft start is achieved by gradually applying the voltage to the EM using thyristor switches connected in series in the supply line of the EM or in series on each of the windings connected in a delta.

They are often used in pumps to eliminate sudden pressure rises in pipes when the fluid flow rapidly changes direction. In some hydraulic systems with centrifugal pumps, a sudden stop of the pump can cause hydraulic shock. In these cases, softstarters can be used to smoothly reduce the supply voltage and hence the EM torque.

The voltage supplied to the EM is reduced by changing the opening angle of the thyristors – symmetrically for the positive and negative half-waves of the voltage. There are simplified circuits with a single thyristor and reverse diode, but these are not recommended because they are unbalanced and generate even harmonics. The thyristors operate during ramp-up, and after reaching rated speed they are shunted by bypass switches. This significantly reduces EM heating.

Softstarters are usually the cheaper choice in cases where speed and torque are required only when EM starts. In addition, they are very suitable for limited spaces, as they usually take up less space than frequency regulators. Softstarters can reach efficiency up to 99.5÷99.9%. Typically, the voltage drop across the thyristor is less than 1 V. The efficiency depends on the size of the softstarter and the supplied three-phase voltage. After the start-up process is complete, the softstarter turns on the built-in bypass contactors. Thus, the thyristors are shunted and all the current flows through the contactors.

The following electronic element base is used: thyristors – the widely used ones can switch up to 1200 V (leading developments up to 8000 V) and 4000 A. Modern modified variants of thyristors are those with disconnection from the control electrode GTO (gate turn off), GCT (gate commutated thyristor) and SGCT (symmetrical gate commutated thyristor), IGCT (integrated gate commutated thyristor) – GCT with a built-in control circuit. They can switch up to 4500 V (leading developments up to 6500 V).

Medium voltage softstarters usually use two or more thyristors connected in series in each arm, so that the mains voltage is distributed between them and cheaper thyristors with a lower voltage rating can be used.

Advantages of using softstarters for pump units:

- reduced hydraulic shocks in pipes during start and stop.
- the mechanical stress on the EM shaft is minimized.
- reduced starting current.
- low current protection prevents damage due to blocked pipe or low water level.
- automatic restart function ensures uninterrupted operation of a stand-alone pumping station.
- phase reversal protection prevents damage due to reverse pump rotation.
- instantaneous overload protection prevents damage due to garbage entering the pump.

Softstarters are load dependent and the start and stop settings are programmed. An algorithm adjusts the voltage so that the current and torque increase and the EM starts. Based on the reverse electromotive force of the EM, the softstarter determines whether it has reached the required rotation speed. If the softstarter detects that the EM has reached this speed before the scheduled start time, it supplies full voltage and turns on a normal operating status indicator. If the EM does not spin up to the required speed within the set time, the softstarter supplies the full voltage or part of it depending on the load.

For the longer cables/wires used to connect the softstarters, no special measures need to be taken, except that they should be sized correctly to compensate for the voltage drop. With softstarters, special measures and means of electromagnetic compatibility (suppression of the effects of electromagnetic influences) are usually not necessary, so as to satisfy the harmonics requirements according to International Electrotechnical Commission (IEC) standards.

As for any non-linear distortion, the softstarters generate a moderate amount of it – with the 5th harmonic being the biggest contributor. The percentage content of harmonics strongly depends on the degree of voltage reduction, i.e. is largest at the initial launch torque and decreases in the rollout process. The applicable standards tolerate short-term generation of harmonics, so no special measures are required in this regard. As for disturbances in the operation of surrounding facilities, in almost all cases the use of additional filtering devices is not required, but measures such as:

- moving the softstarter electrically further away from the power supply, respectively – closer to the EM.
- if possible – laying the power cables to and from the softstarter along separate routes from those of other power and control cables.
- use of shielded cables.

When choosing a softstarter, it should be taken into account that there are models with the additional possibility of directly connecting the EMs to the full mains voltage (DOL starting), which expands the applications.

The purpose of controlling EMs is to ensure the rotation of the rotor at a precisely defined speed, or to ensure its rotation at a precisely defined angle. The latter is called position control and is a more complex task. In speed control, the task is to apply such control effects to the EM that it maintains the set speed as accurately as possible with a resisting moment varying from zero to rated one. At the same time, it is known that if the powerful EMs work without load in an steady state mode, this means working with poor energy indicators – low efficiency and power factor.

In electrical engineering, the concept of frequency control is widespread. By itself, the term is correct, but not unambiguous. There are two major classes of approaches in the control of frequency inverters. The greatest opportunities are offered by the so-called *vector control*, in which very high accuracy is obtained. Vector control of IMs is truly an innovative method in energy saving. However, in order to implement it, a very good knowledge of the parameters of the specific EM is required. The second major class of approaches is called *scalar control*. With it, the inverter is controlled so that when the frequency changes, the voltage amplitude changes according to a predetermined law. The accuracy provided is significantly less, but the settings of the electronics-motor system are significantly easier. Furthermore, most industrial mechanisms do not require the vast capabilities that vector control offers.

In vector control, by means of mathematical transformations, a separation of the components of the supply three-phase quantities (voltage and currents) is achieved in such a way as to provide an analogy with DC motors – separate components are responsible for the magnetic flux and separate ones for the flowing current, and their product determines the shaft torque. There also appears the possibility of making current and flux perpendicular to each other. The torque is maximized when the flux linkage and current vectors are perpendicular [5]. The ideal scenario, in which field and current vectors are controlled to be orthogonal, is called *field orientation*. Field orientation, creates an ideal dynamic behavior just like the DC commutator machine [6].

The mathematical transformations allowing the separation of the components are based on the space vector theory, which by the way also gave the name of vector control. A necessary condition for achieving maximum efficiency. is the optimal choice of magnetizing current. Improper control of the magnetizing current can cause the consumption of a frequency-controlled EM to be more than that of a direct supply.

Since the basis of the drive's operation is to vary the frequency to the EM in order to vary the speed, the best-suited name for the system is the variable frequency drive (VFD).

However, other names used to reference this type of drive include adjustable speed drive (ASD), adjustable frequency drive (AFD), variable-speed drive (VSD), and frequency converter (FC) [7].

In speed control by changing the frequency of the power supply, the EM is connected to the mains via a frequency converter. Using this method, the important relationship of three parameters must be taken into account: phase voltage, mains frequency and basic magnetic flux. Determining here is the value of the magnetic flux, a significant change of which is undesirable: for example, with an increase in the flux, the saturation of the magnetic circuit increases and the magnetizing current increases sharply, and with a decrease in the flux, the rotor current can increase and it will overheat. Therefore, in most cases, magnetic flux Φ = const. should be maintained. It follows that simultaneously with the change in the frequency of the power supply, the voltage must also change proportionally. On the other hand, it should be noted that the law of voltage change depends on the characteristics of the working mechanism connected to the EM shaft.

When controlling an IM by varying the frequency and amplitude of the supply voltage, in order to keep the maximum torque constant, it is necessary to maintain U2/f = const. It can be considered that the slip remains unchanged if the resisting moment remains unchanged. Then the frequency of rotation of the rotor will be proportional to the frequency of the supply voltage. If the dependence of the inductive resistances of the windings on the frequency of the supply network is taken into account, in order to keep the maximum torque constant, it is necessary to maintain U/f = const.

If the active resistance of the stator winding is neglected, then the condition for a constant ratio of voltage and frequency would also mean an unchanged magnetic flux in the air gap, which is a condition for a constant torque. The latter law is the most applied governing law, because suggests a linear relationship between voltage and frequency.

It is important to mention that the bulk of IMs are produced with self-ventilation – fan blades are mounted on the end of the fan shaft opposite the end for connecting a mechanism or gear. Thus, when the EM rotates, it is blown, and therefore cooled, by its own fan. When the EM speed is reduced, the speed of the own fan also decreases, i.e. cooling worsens. For this reason, even with a current lower than the rated one, the EM may overheat. Therefore, where possible, the voltage is further reduced in order to reduce the current at low rotation frequencies, thereby reducing the heating of the EM. Therefore, when controlling centrifugal pumps and fans, the law U/f^2 = const. is sometimes used, in which the torque decreases strongly with a decrease in revolutions.

It is possible to increase the frequency of the supply voltage above the rated, but then the voltage cannot increase in proportion to the frequency, because the insulation of the EM windings will not withstand the increased voltage. So for over-synchronous speeds, only the frequency increases and the voltage remains equal to the rated one. Of course, this leads to a reduction in EM torque.

Operation at increased frequency is not so dangerous for the EM from an electrical point of view – there are increased losses in the steel and in the windings due to the skin effect. The high speed, however, places increased demands from a mechanical point of view. The higher the speed, the greater the centrifugal forces. Therefore, at over-synchronous speeds, special attention must be paid to the balancing of the rotor and the mechanisms connected to it. Eccentricities (in the sense of unbalanced masses) will result in strong knocking which can damage the bearings. Therefore, it must be certain that the selected EM will mechanically withstand the work at increased revolutions.

The main application area of scalar control of IMs is the drives of pumps, fans and work machines, where a variable speed is required to regulate the performance, but not very accurate job execution is required. Typical accuracy in open coupling systems is around 5% and improves when feedback is included, and can reach 0.5%.

Depending on the settings of the frequency converter, when low voltage is applied, a given pump may run at low speed. With low water consumption, running the pump at reduced power saves energy and increases EM life. But the most important thing is that at the moment of starting the pump, the EM starts to work at the smallest frequency, gradually accelerating to the set speed, which eliminates hydraulic shocks.

Thanks to the optimal control of the EM depending on the load, the consumption of electricity in pumps, fans, compressors and other units is reduced by 40÷50%, and the starting currents, which are 600÷700% of the rated ones and are a scourge for the equipment for starting and control, disappear completely. Thus, the use of adjustable electric drives based on frequency converters allows to create a new energy-saving technology that not only saves electrical energy, but also increases the service life of EMs and technological equipment in general.

Both a frequency regulator and a softstarter can be used to start and stop pumps. A softstarter reduces the effect of hydraulic shock when starting and stopping and is usually less expensive. A frequency regulator can do the same job, and in addition, it can also control the speed of the pump EM, respectively its flow rate, during operation.

Softstarters and electronic speed regulators have integrated protections. Modern speed regulators guarantee comprehensive EM overload protection as well as protection for themselves. Based on the current measurement and speed information, a microprocessor calculates the motor's temperature rise and issues an alarm or disconnect signal in the event of excessive overheating.

In addition, the information generated by the thermal protection integrated in the speed controller can be transmitted to a programmable logic controller or control system via the bus interface that newer speed controllers and starters have.

Some softstarters have limited ability to adjust the low speeds when starting and stopping. For example, for an EM with 1800 rpm possible low speeds are 18÷270 rpm. forward and backward. Maintaining low speeds is possible within a matter of minutes due to the temperature rise in the thyristors and in the EM.

Frequency converters provide continuous and complete speed control at all times, from start to stop, with the ability to maintain a given speed for hours. This is because the frequency is adjustable. Although both the frequency converter and the softstarter can operate at low speeds, the length of time they can be maintained is determined by the EM and the load. The degree of EM heating, if running at low speed, depends on the duration of operation. In order not to let it run too long at low speed, a temperature limit is provided in the softstarter – the aim is to protect the thyristors and the EM. Continuous operation of the frequency regulator at a frequency below 5 Hz imposes limitations on the permissible operating conditions.

Modern AC motor control systems work with electronic converters. To supply a EM with a voltage of variable frequency and variable amplitude, a rectifier-inverter system is used. By appropriate control of the inverter, a variation in both the frequency and the amplitude of the output voltage supplied to the EM can be provided.

Energy efficiency is a very important indicator that users of products and systems care about, and suppliers are working hard to improve it in their product range. In fact, according to the generally accepted opinion, the investment in the purchase of electrical equipment, as well as the costs due to the stoppage of the technological cycle in connection with its installation and commissioning, are compensated by the reduced energy consumption as a result of more energy efficient operation.

Electric motors often need large amounts of energy when accelerating rapidly to full speed. Both softstarters and frequency converters can be used to reduce impact currents and limit torque – thus protecting expensive equipment and extending EM life by reducing heating during frequent starts and stops. The choice between a softstarter and a frequency converter depends on the mode of application, the system requirements and the costs (both for purchase and implementation, and during the entire service life).

Mechanical shocks during start-up and load pulsations must also be considered. Any sudden change in torque from the EM side, or from the load side, leads to mechanical loads and fatigue in the shafts. In pumping units, sudden 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 during frequent starting (S4 mode), to favor soft-start methods, using a softstarter or frequency converter.

Directly related to the operation of rotating electric machines is the application of mathematical modelling, which plays a very important role in the design, exploitation and control of electric drives. Modelling and computer simulation, whether with regard to electric drive or in other branches of engineering, that is adequate and effective reduces the time needed and the cost of gaining an optimum design of a drive and its control system [8].

There are many definitions for optimization from the viewpoints of mathematics, science, and economics. A concise definition is given in [9]: "Optimization is the act to obtain the best results under given circumstance." For EM, the optimization could be applied in the machine (drive) design process in order to obtain the best machine (drive) performance according to a given criteria with minimum production cost, or it can be used in the drive control [10].

As pump requirements must match system characteristics, analysis of the overall system is necessary to establish pump conditions [11]. At best, the steady-state torque–speed characteristics could approximate the average of this dynamic response; it could not predict the complete dynamics during normal load torque changes for the larger motors [5].

When considering the dynamics of the electric drive, it is not possible to work with the effective values of the quantities, which is the approach when deriving the static characteristics. The processes in the electric drive in this case are described by differential equations. It is believed that electromagnetic processes lead to the appearance of an electromagnetic torque, which drives the shaft of the IM and, accordingly, initiates a mechanical transient process.

The startup properties of IMs are characterized by the initial startup and maximum torque, as well as the initial startup current. In IMs with squirrel-cage rotors, the torques and the startup currents depend on the ratio of the parameters. The parameters are the active and inductive resistances of the stator and rotor windings, the mutual inductance resistance and the moment of inertia of the rotor.

Very often, studies of electric drives with IMs are limited only to the determination of the initial startup and maximum torque and the initial startup current. This approach gives only approximate information about the startup properties of the EM and can lead to an error in determining the overload capability of the EM due to the inaccurate determination of the maximum slip. Therefore, it is advisable to fully determine the startup characteristics for the entire range of variation of the slip from startup to values corresponding to a mode close to the rated one.

According the specific methodology used – a developed mathematical model has been used to study the transient processes in the electric drive of pump unit with medium voltage IM [12]. The coordinate system, in which the voltages of the stator and rotor windings of IM are presented in relative units, rotates at synchronous speed. Using this coordinate system provides the convenience that in the system of differential equations attend important parameter of the IM *slip s.* Some more important data values and parameters for the considered IM are given in the Appendix. The parameters of the T-shaped replacement circuit of the EM are used in the research, which are determined by the calculation methodology for slip $s=1$.

After converting the equations for voltages of windings and presenting in the form of *Cauchy*, we get four equations for model stator currents, as well as an equation for the electromagnetic torque. We use system of relative units. In this system voltages, currents, power and parameters are expressed in parts of the underlying values of those variables. Rated values of current, voltage, power, torque, speed, resistances serve as basic values.

The mechanical equipment is presented by means of a single-mass model using fundamental relation between torques, so-called *equation of motion*. After transformation for the equation of motion has been obtained [13]:

$$\frac{ds}{dt} = -\frac{p}{J_{\Sigma}\omega_b}(T - T_L), \tag{1}$$

where

- p – pole pair number
- T – electromagnetic torque developed by the motor
- T_L – resisting moment of the driven mechanism
- J_{Σ} – total inertia moment of the of the electric drive (EM together with mechanism driven), reduced to the EM shaft
- ω_b – base angular velocity (equal to the synchronous one – ω_0)

In the equation of motion of the electric drive, the reduced moment of inertia of the system must be inserted. The reduced moment of inertia of a given system is the moment of inertia attributed to one shaft (usually that of the EM chosen as the defining component) which, at the angular velocity of that shaft, will cause the same kinetic energy as in the real system. When calculating the dynamic characteristics of an EM, the moments of inertia of the mechanisms attached to its shaft are also taken into account. Their values are brought to the frequency of rotation of the rotor.

Assuming the mechanical connections between the individual masses to be absolutely rigid (with rigidity coefficient $c = \infty$), the mentioned one-mass dynamic model has been obtained. Since a multi-mass dynamic model of the mechanisms is not always available, and its development is labor-intensive, the results obtained with a single-mass model, for which J_{Σ} has been obtained by the so-called *factor of inertia* (*FI*), are of interest:

$$J_{\Sigma} = FI \times J_M, \tag{2}$$

where

- J_M – EM inertia moment (total of the rotor and the shaft)

As for the moment of inertia of the load reduced to the rotor axis, it can be significantly greater than that of the EM rotor. It should be clear that the higher the total inertia, the slower the acceleration and vice versa. However, it is usually assumed that the total inertia is not likely to be more than twice the EM inertia, and this is certainly the case for most loads [14]. In model studies, a value of *FI* = 2 has been set.

Moment of inertia is analogous to mass in reciprocating motion, i.e. moment of inertia determines the inertial properties of bodies in rotational motion. AC electric motors generally have less mechanical inertia than DC motors due to the absence of a collector and frictional brushes.

The moment of inertia also participates in the so-called *electromechanical time constant*, which characterizes the speed of a given EM in the process of its rotation [15].

With regard to the resisting moment of the centrifugal pump as a driven mechanism – it depends on the magnitude of the angular velocity to a certain degree, and the characteristic is parabolic and is represented by a general expression, the so-called *Blanc equation*:

$$T_L = T_{L0} + \left(T_{Lrated} - T_{L0}\right)\left(\frac{\omega}{\omega_{rated}}\right)^k, \tag{3}$$

where

- T_L – resisting moment of the mechanism at speed ω
- T_{L0} – resisting moment of the mechanism at speed $\omega = 0$ (initial moment of resistance)
- T_{Lrated} – rated resisting moment at speed $\omega = \omega_{rated}$
- k – power indicator characterizing the degree of change of the resisting moment from the speed, k=2÷6

For powerful IMs losses at rated load and rated speed is allocated to the rated power as: losses in the stator steel – from 1.95 to 2%; electrical losses in the stator windings – from 0.9 to 1.1%; electrical losses in the rotor windings – from 0.8 to 0.9%; mechanical losses – from 1.3 to 1.5%; additional losses – from 0.5 to 1%, [14, 16].

Electrical losses in the stator and rotor windings are variable losses, since their magnitude depends on the values of the currents in these windings [12, 17]. Electrical losses in the rotor are directly proportional to slip.

The variable electrical losses in the stator and rotor can be given as follows [18]:

$$\Delta P_V = \Delta P_1 + \Delta P_2 \approx 3I_1^2 r_1 + 3I_2'^2 r_2', \tag{4}$$

where

- ΔP_1 – stator electrical losses; ΔP_2 – rotor electrical losses
- I_1 – stator current; I_2' – rotor current reduced to the stator
- r_1, r_2' – stator and reffered rotor phase resistance, respectively

When operating IM in the area of small slips (not more than the rated value), it follows

$$I_1^2 \approx I_2'^2 + I_0^2, \tag{5}$$

where:

- I_1, I_2', I_0 – stator, rotor and magnetizing current, respectively

Therefore, the following applies to IM:

$$\Delta P_V = 3I_2'^2\left(r_1 + r_2'\right). \tag{6}$$

Since

$$I_2' = \sqrt{\frac{T\omega_0 s}{3r_2'}}\,, \tag{7}$$

then the representation of the total electrical losses takes the form

$$\Delta P_V = \Delta P_1 + \Delta P_2 = T\omega_0 s\left(1 + \frac{r_1}{r_2'}\right). \tag{8}$$

The starting time is the main quantity that determines the heating of the EM during the starting process – the longer this time, the harder the starting process and the higher the EM heating temperature will be. This time is determined by the criterion that two adjacent values of the rotation frequency do not differ by more than 1%. This means that the electromechanical transient processes are complete, and the electromagnetic transient processes are known to terminate much earlier.

3 Simulation results

Appropriate software MathCAD has been used to solve the system of differential equations describing the transient processes occurring during the start-up of a MV induction EM driven pump unit [19]. The analysis of the transient processes has been carried out under the generally accepted assumptions, which do not have a significant impact on the final results, and on the other hand, make it easier to understand the physical nature of the processes studied. The start-up of the electric drives is accompanied by a redistribution of the consumed power between the output power and the losses. Of greatest interest are the losses in the rotor, which, with frequent starts, can lead to damage to its windings. At the same time, in their determination through a definite integral for the release time, the moment of inertia is involved as a quantity.

The results of the model studies on the influence of the control way applied on the impact stator currents and torques of the EM, as well as on the electrical power losses and startup time are systematized in Table 1 and Table 2. For a better understanding, some of the dependencies obtained have been presented graphically in Figure 1 ÷ Figure 9. In order to establish the relevant trends corresponding polynomial dependencies have been derived.

Table 1. Results for softstarter applied at changing the voltage from 30% to 100% of rated one.

Quantities				
***U/U$_{rated}$*, %**	T_{imp}^*	i_{imp}^*	$\Delta P_{electric}$, x10^4 W	t_{start}, s
30	2.088	4.964	4.410	2.903
40	3.709	6.805	2.398	1.912
50	5.790	8.397	1.519	1.151
60	8.328	10.445	1.051	0.826
70	11.319	12.366	0.771	0.623
80	14.761	13.859	0.589	0.477
90	18.646	15.106	0.466	0.435
100	22.970	16.331	0.377	0.358

All quantities considered are modified in a different way, which is explained under each respective figure.

Table 2. Results for control applied by law U/f^2 = const.

Quantities					
***f*, Hz**	***U*, V**	T^*_{imp}	i^*_{imp}	$\Delta P_{electric}$, x10^4 W	t_{start}, s
20	960	1.481	2.715	6.532	2.798
25	1500	2.889	4.381	3.107	1.377
30	2160	4.985	6.286	1.764	0.834
35	2940	7.907	8.369	1.103	0.652
40	3840	11.788	10.852	0.742	0.543
45	4860	16.705	13.454	0.518	0.431
50	6000	22.970	16.331	0.377	0.358
55	6000	20.940	17.128	0.419	0.423
60	6000	19.231	17.526	0.446	0.427

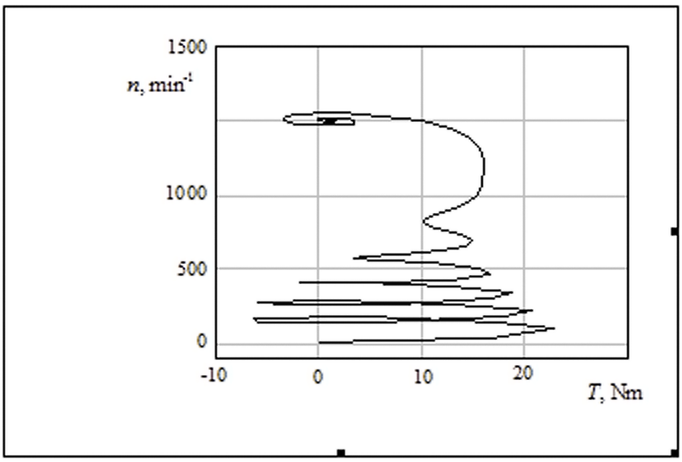

Fig. 1. Torque-speed characteristic for DOL starting.

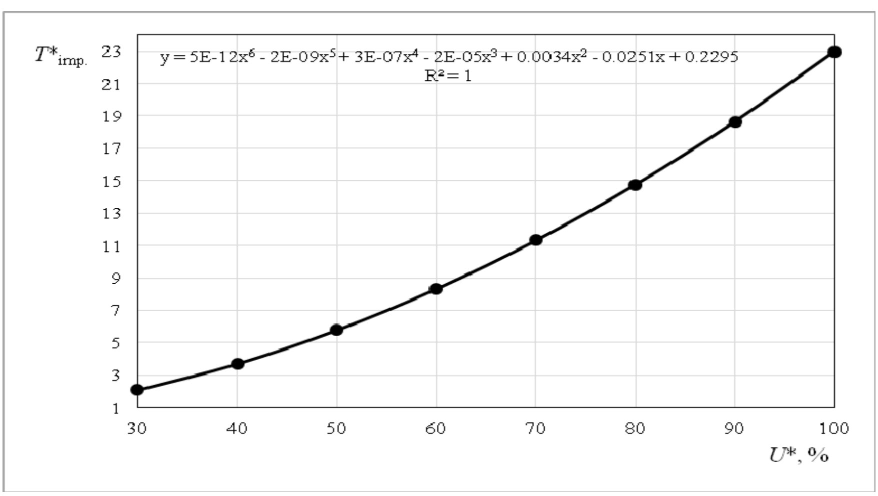

Fig. 2. Variation of the impact torque relative to the supply voltage during soft start.

The arising impact torque can be reduced over 10 times compared to DOL-starting. It is known that motor torque capability is proportional to the square of the applied voltage.

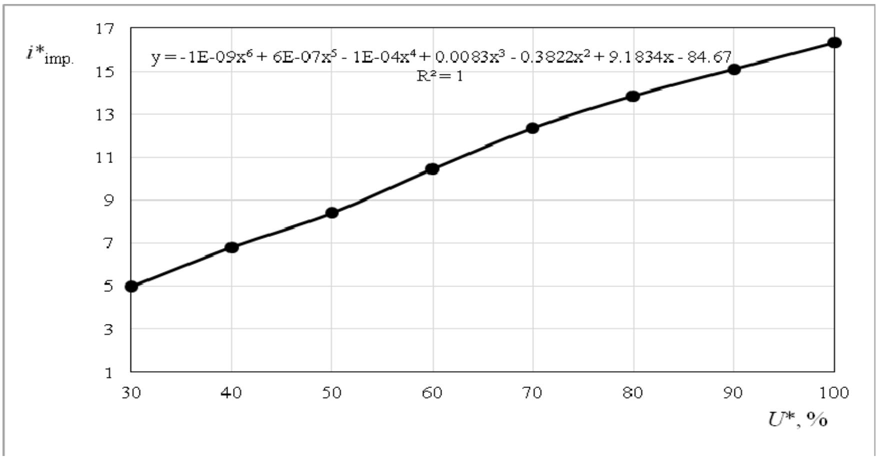

Fig. 3. Variation of the impact current relative to the supply voltage during soft start.

The resulting impact stator current can be reduced more than 3 times, compared to DOL-starting.

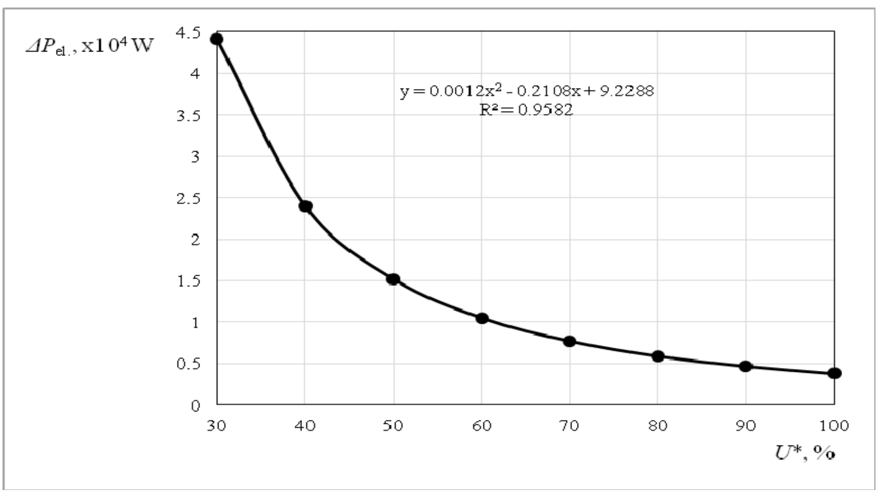

Fig. 4. Variation of electrical power losses relative to supply voltage during soft start.

Electrical power losses increase significantly with each decrease in the value of the supply voltage.

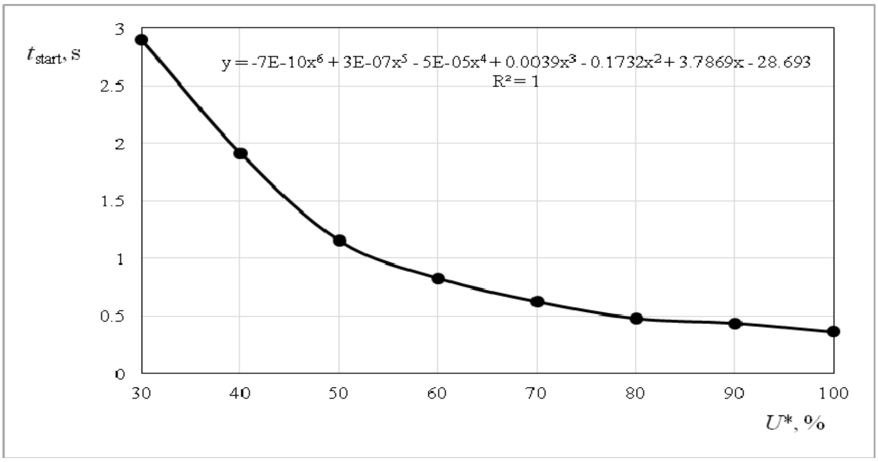

Fig. 5. Variation of starting time relative to supply voltage during soft start.

The start-up time is noticeably increased with each decrease in the value of the supply voltage.

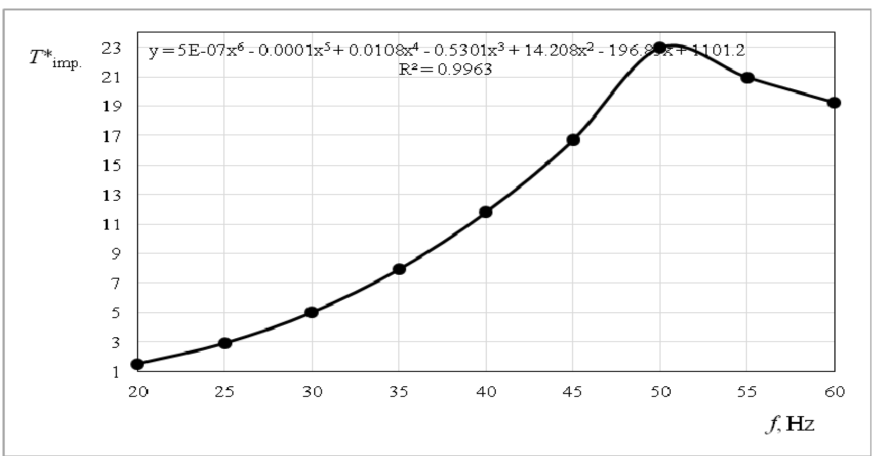

Fig. 6. Variation of the impact torque relative to the frequency of the supply voltage during control U/f^2 = const.

The resulting impact torque has a peak value at the rated frequency of the supply voltage value. At over-synchronous frequencies, its reduction begins, which is positive and could be applied in some cases.

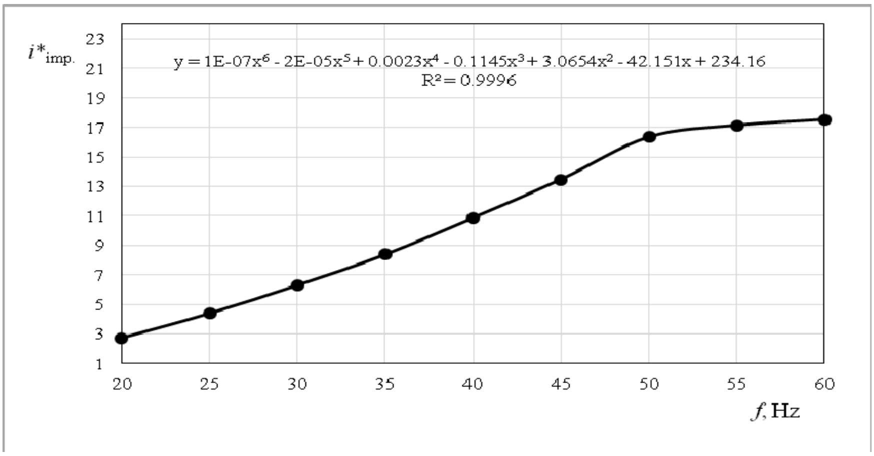

Fig. 7. Variation of the impact current relative to the frequency of the supply voltage during control U/f^2 = const.

The resulting impact stator current can be reduced over 6 times compared to DOL-starting.

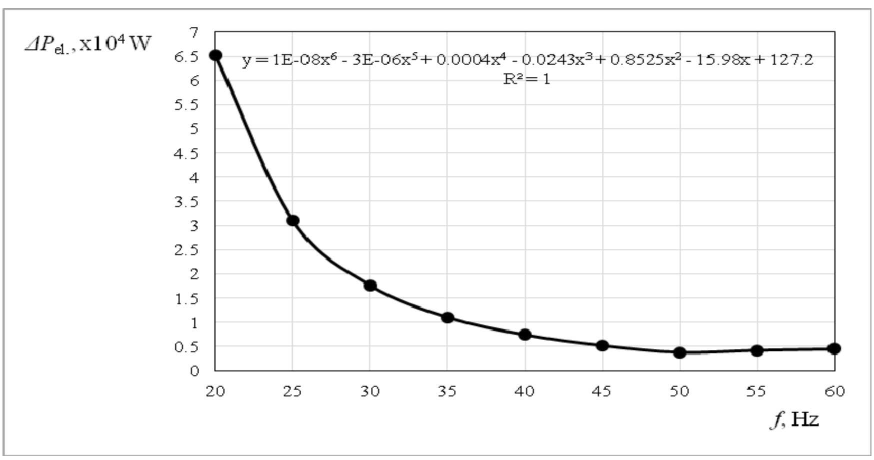

Fig. 8. Variation of electrical power losses relative to the frequency of the supply voltage during control U/f^2 = const.

The change in electrical power losses with frequency control is similar to that with the application of a softstarter.

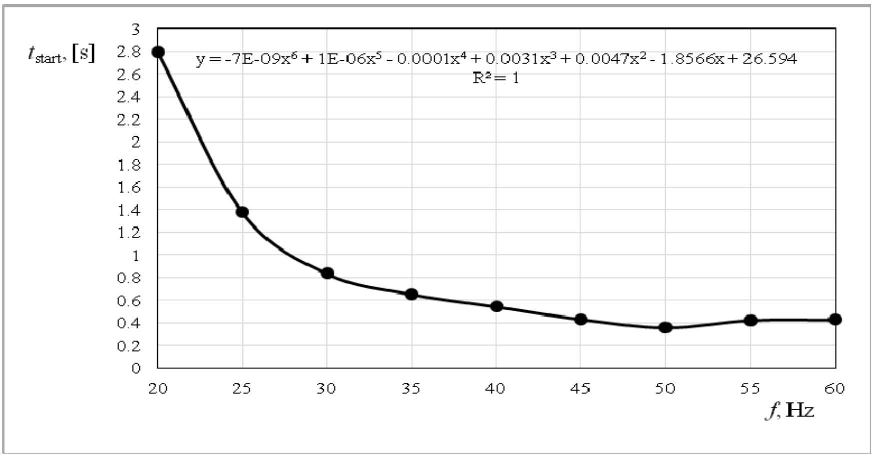

Fig. 9. Variation of starting time relative to the frequency of the supply voltage during control U/f^2 = const.

The starting time has a minimum value at rated voltage and frequency.

4 Conclusion

The application of softstarter and frequency control gives good results in terms of reduction of impact torques and currents. The specifics in the given case are:

- the large values of electrical power losses are at higher slip values in the interval 0÷1: in this case it is about the start-up process, in established mode these losses are significantly smaller, on the order of up to 2%
- starting times are also affected by the reduced voltage level in both modes of control.

Speed control by changing the frequency is the most acceptable option for IMs, as it provides speed control over a wide range without significant losses and reducing the motor's overload capabilities.

The obtained results could be of great practical importance when considering a way of starting and possibly controlling the speed of IM.

Measurements of electrical quantities of the specific IM under consideration are foreseen, which implies providing a measurement technique with increased accuracy and a certain period of time.

As a summary – there is a clear interest in cleaner, greener energy, and hence also for such a world. This implies actions to support energy optimization, environmental protection and resource saving both at the design stage and in operation of electric drive systems.

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Appendix

Technical data and parameters for induction motor considered

Quantity	Value
Type	A 121-4
Rated power	400 kW
Rated stator voltage	6000 V
Operating frequency	50 Hz
Line stator current	46.5 A
Pole pair number	2
Shaft speed	1480 rpm
Power factor	0.89
Efficiency	93.1%
Rotor moment of inertia	22.5 kg.m2
Multiple of the maximum torque	2.1
Multiple of the maximum current	5.1
Stator phase resistance	1.574 Ω
Referred rotor resistance	0.811 Ω
Stator leakage reactance	4.257 Ω
Referred rotor leakage reactance	0.662 Ω
Magnetizing reactance (saturated)	157.954 Ω