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Evaluation of the Influence of Changing the Parameters of a High-Voltage Induction Motor and the Loads on the Behaviour of an Aggregate Driven - Centrifugal Pump

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Abstract

On the one hand, electric drives are the main consumer of electricity: over 60% of all electricity produced is converted to mechanical work by electric drives, and, at the same time, a relatively large number of objects where electrical energy is transformed into a mechanical one are simple, usually unregulated widespread devices such as fans, pumps, and so on. These are primary consumers which accounts for about half of the deficient electrical energy, and there are rich opportunities for real savings. Electric drives naturally turn out to be the focus of the experts who develop and test the electrical equipment and technologies where they are applied.
At present, a significant number of pumping installations are used in all industrial plants, mines, construction, utilities, agriculture, etc. Pumping units are one of the most common mechanisms and occupy a significant part in the power consumption. Machines and mechanisms that operate on a centrifugal principle are characterized by a static shaft resisting torque, which is a function of the second degree of angular velocity – fans, centrifugal pumps and compressors, ship propellers (screws).
The studies are devoted to the evaluation of the combined effect of the changing parameters of the medium voltage induction motor and the load on the operation of the driven centrifugal pump. Research has been done through a mathematical model of electro-mechanical system.

Keywords: induction motor, high-voltage drive, transient analysis, pump load, modeling, electro-mechanical system.

1. Introduction

Pump units serve to transport liquids, primarily water, but also fuels, oils, hydraulic mixtures. In turn, centrifugal pumps are the most used hydraulic machines. In addition to the main technical and economic matters for electric motors, the specifics of centrifugal pumps must be taken into account to ensure continuous and reliable operation. The production mechanisms operate economically and with the highest performance when the drive motor most fully meets the technological requirements. When making the right choice of an electric motor, both its electromechanical properties and the static resisting moment of the mechanism during operation must be taken into account.

One of the basic equations in the analysis of transient processes in electric drives is the motion equation.

Generally speaking, medium voltage (MV) drive is used at high power of driven loads, but the range of capacities in which technical means are available to implement both low and medium voltage drive is large and covers a large number consumers in different industries.

There are no basic differences in the elements of the medium and low voltage electric drive systems, but it is necessary to take into account the specificities of the MV drives.

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The differences in the principle of operation and the structure of equipment for different voltage levels are decreasing increasingly with the increase in power and the fall in prices of semiconductor equipment. So solutions that in the recent past were appropriate and possible only for a low voltage level are already available for MV drives.

The need to control the speed of MV drives is obvious when the process itself requires it. Electricity savings can be achieved if the process allows for some reduction in productivity by means of frequency control [1].

When running large induction motors, frequency control can be applied, with the frequency converter gradually increasing the frequency of the stator voltage. At the same time, the frequency and voltage are regulated, so the magnetic flux in the motor remains practically invariant. Due to the large size and cost of the inverters (usually designed for the full power of electric motors), the application of frequency control is narrow-mindedly, yet [2].

The effect of the supply voltage deflection and the magnitude of the inertia masses attached to the motor shaft under the considered high-power electric drive for a pump aggregate on the occurring impact torques and currents, as well as on the start-up time, have been modeled in [3].

During the operation of the induction electric drives there is the occurrence of voltage deflection in some cases. This is close connected with reliability of electric drive and production mechanisms driven. The combined effect of the voltage deflection and the value of the total moment of inertia on the power losses in a high-power electrically driven pump is estimated in [4].

The values of the individual components of the energy losses in the driving rotating electrical machine for non-nominal values of the supply voltage and inertia coefficient, i.e. at different inertia moments of the whole electro-mechanical system have been obtained in [5].

Many applications in the electric drive industry are pumps of certain safety degree for power plants – thermal or nuclear. The values of the various types of energy losses in the MV induction motor have been obtained at varying the initial resisting torque [6].

The total harmonic distortion (THD) changes the power factor (PF) of the machine. In [7] has been found that the displacement power factor (DPF) is greater than the PF in active inductive character in loads. This influences the shape of the current and voltage in transient processes in induction motors.

Frequency control is known to significantly reduce energy demand and firsthand affects the environment through lower emissions of carbon dioxide and other greenhouse gases from power plants.

The combined effect of the magnitude of the supply voltage and the frequency on the power losses for different initial resisting torques in a frequency controlled high-power electric motor for a pump is estimated in [1].

As a follow-up to the previous studies, an assessment was made for combined influence of changing high-voltage induction motor parameters and loads on the behavior of a centrifugal pump driven.

The following assumptions in the studies have been done:

- The parameters of each electric motor (active and inductive resistances of stator and rotor) directly affect currents flowing and power consumption;
- The energy performance of electric drives deteriorates compared to their nominal values when operating under full load (in established modes) or overloading (short time).

Mathematical modeling allows to carry out the study of electrical drive systems in both static and dynamic modes with a high degree of accuracy. Using such an analysis method makes it possible to carry out the most complete examination of electric drives, which should be the basis for the improvement of design, setting up and operation.

The stated intention of the study is to extend previous researches which would allow getting a better picture of the performance of a pump unit driven by a MV induction motor.

2. Material and method

2.1. Theoretical principles and considerations – features of induction motor electric drives

In all the variety of electric drives implementations, the same fundamental physical process is always carried out – electro-mechanical transformation of energy, always electrical energy is transformed into mechanical work, it always takes place in a specific material environment, always part of the energy in this transformation is lost. Generally speaking, all electrical machines, such as converters of electrical energy to mechanical, including induction motors, are heat-generating. For induction motors, the electrical losses in the rotor are commensurable to the slip and are therefore economical at low slip values of 1 to 4%.

The transient processes in rotating electric machines are determined by the electro-magnetic processes associated with the creation of fields in the machine and the electro-mechanical processes determined by the change in rotor speed. Electro-mechanical processes are mainly determined by the inertia torque of the rotor [2].

The transient processes in real machines are diferent from processes obtained by modeling with computational microprocessor devices, however, the differences are usually small. The more factors that affect the transient processes to be considered, the more complex the equations are. Complicating the mathematical description is not always possible. In many cases, on the contrary, the skill is required to simplify the task, leaving the information needed for the engineering solution. Also, in many cases, complicating the mathematical description of the task studied does not yield the expected results. To analyze workflows in a real machine, it is first and foremost necessary to know that the solution to this task can only be approximated.

The set of transient processes in electrical machines is conditioned by the diversity of parameter matching, their nonlinear relationships, the stator and rotor components impact, the feedback links, type of movement and design features [8].

2.2. Mathematical model of medium voltage pump unit electric drive

For the development of theoretical assumptions about electromechanical energy conversion, an important step is the implementation of mathematical models that sufficiently reflect the dynamic performance of induction motors.

The mathematical model of a simplified electric machine does not account for the presence of many circuits in the stator and the rotor, as well as the infinite range of harmonic field components in the air gap of the actual electric machine. Usually, the mathematical model of a simplified electric machine does not take into account the availability of multiple circuits in the stator and rotor, as well as the countless components of the harmonic field in the air gap of the real electric machine. It is obvious that there can not be a precise mathematical description of the processes of electro-mechanical transformation of energy in the real electrical machine.

The mathematical model, despite its complexity, is usually comprised for a one-dimensional machine with a one degree of freedom (in this model there is a rotating part – the rotor) [8]. Differential equations for electro-mechanical energy transformation describe the transient and invariable modes of electric motors [2].

The study of transient processes in case of varying rotational speeds is only possible using a computational microprocessor devices, since differential equations contain multiplications of variables and have no analytical solution. In the mathematical models of electric machines, the multiplications of voltages and currents have a profound meaning. The widespread deployment of computing process technology in recent decades has allowed the whole range of tasks previously considered to be inaccessible to be solved. This is obtained by means of high resolution accuracy, which is not imperative to achieve for most applied cases. Although the description of the electro-mechanical energy conversion processes is always approximated, the computational processing technique allows to obtain sufficient accuracy in most cases occurring in electro-mechanics. On the other hand, practical test results can only be used to obtain an estimate. To evaluate the adequacy of a real object model, the results obtained with experimental ones should be compared.

Below is a complete system of differential equations (1) describing the behavior of a high-power MV electric drive of pump unit [1], [6].

The four equations for the model voltages of the stator and rotor windings are converted to *Cauchy* form, thus producing four equations for the model currents. Fifth equation is fundamental As the fifth equation the principal binding expression between torques, so called equation of motion [9] has been used. The variables involved in it are the torque developed by the electric motor and the resisting torque of the pump unit.

The use of a synchronous rotating coordinate system has the advantage that the important parameter of the induction motor *slip s* is included in the equations [6].

In the study, we use a system of relative units to represent the individual variables, i.e. they are without measurement units.

The accuracy of a solution of the equations for electromechanical energy transformation depends not only on how the equations are compiled but also on the accuracy of the parameters involved in these equations [2].

Parameters of electric machines are the coefficients that stand in front of the independent variables in the equations for electro-mechanical transformation of energy. Depending on the type of recording of the equations, the parameters can be the active and inductive resistances and the torque of inertia. Machine parameters determine its performance: mass, efficiency, power factor, impact currents and torques, as well as price and reliability.

The great influence of the electric machine's operation is the saturation of its magnetic system, i.e. the non-linearity of the inductances involved in the voltage equations.

$$\left|\begin{aligned}
\frac{di_{sx}^*}{d\tau} &= \frac{L_r^*.L_m^*}{L_e^*}\left[\frac{u_{sx}^*}{L_m^*} - \frac{u_{rx}^*}{L_r^*} - \frac{r_1^*}{L_m^*}.i_{sx}^* + \frac{r_2^*}{L_r^*}.i_{rx}^* + i_{sy}^*.\left(\frac{L_s^*.L_r^* - s.L_m^{*\,2}}{L_r^*.L_m^*}\right) + (1-s).i_{ry}^*\right] \\
\frac{di_{sy}^*}{d\tau} &= \frac{L_r^*.L_m^*}{L_e^*}\left[\frac{u_{sy}^*}{L_m^*} - \frac{u_{ry}^*}{L_r^*} - \frac{r_1^*}{L_m^*}.i_{sy}^* + \frac{r_2^*}{L_r^*}.i_{ry}^* + i_{sx}^*.\left(\frac{s.L_m^{*\,2} - L_s^*.L_r^*}{L_r^*.L_m^*}\right) - (1-s).i_{rx}^*\right] \\
\frac{di_{rx}^*}{d\tau} &= \frac{L_s^*.L_m^*}{L_e^*}\left[-\frac{u_{sx}^*}{L_s^*} + \frac{u_{rx}^*}{L_m^*} + \frac{r_1^*}{L_s^*}.i_{sx}^* - \frac{r_2^*}{L_m^*}.i_{rx}^* + i_{ry}^*.\left(\frac{s.L_s^*.L_r^* - L_m^{*\,2}}{L_s^*.L_m^*}\right) - (1-s).i_{sy}^*\right] \\
\frac{di_{ry}^*}{d\tau} &= \frac{L_s^*.L_m^*}{L_e^*}\left[-\frac{u_{sy}^*}{L_s^*} + \frac{u_{ry}^*}{L_m^*} + \frac{r_1^*}{L_s^*}.i_{sy}^* - \frac{r_2^*}{L_m^*}.i_{ry}^* + i_{rx}^*.\left(\frac{L_m^{*2} - s.L_s^*L_r^*}{L_s^*.L_m^*}\right) + (1-s).i_{sx}^*\right] \\
\frac{ds}{d\tau} &= -\frac{pT_b}{I_{TOT}\omega_b^2}\left[\frac{pu_b i_b L_m^*}{T_b\omega_b}\left(i_{sy}^* i_{rx}^* - i_{sx}^* i_{ry}^*\right) - T_{L_{INIT}}^* - \left(T_{LN}^* - T_{L_{INIT}}^*\right)(1-s)^2\right]
\end{aligned}\right. \quad (1)$$

where

u_b, i_b, ω_b, T_b basic values of voltage, current, angular speed, torque respectively;

$i_{sx}^*, i_{sy}^*, i_{rx}^*, i_{ry}^*$ model stator and rotor currents (p.u.) respectively;

u_{sx}^*, u_{sy}^* model stator voltages; model rotor voltages $u_{rx}^* = 0$ and $u_{ry}^* = 0$ since the rotor motor is squirrel-cage type;

r_1^*, r_2^* stator and rotor ohmic resistance (p.u.) respectively;

$L_s^*, L_r^*, L_m^*, L_e^*$ stator, rotor, mutual and equivalent inductance (p.u.) respectively;

p pole pair number;

I_{TOT} total inertia torque of the electric drive;

$T_{L_{INIT}}^*$ initial resisting torque of the load (p.u.);

T_{LN}^* rated resisting torque of the load (p.u.).

The electromagnetic torque of the electric motor is determined by all possible combinations of multiplications of currents running in the stator and rotor contours. In most cases, the electromagnetic torque is considered to be equal to the rotating torque (neglecting mechanical losses) [8].

It needs to be mentioned that the rotating magnetic field acting together with the stator winding currents produces a torque that strives to rotate the stator in a direction opposite to the rotor rotation. This torque is numerically equal to the torque of the rotor and is transmitted by the stator supports to the foundation on which the machine is mounted.

In squirrel-cage induction motors, the torques and starting currents depend on the ratio of the parameters. In the electro-mechanical energy conversion equations there are optimal ratios between the parameters where the electric motor has a maximum efficiency, a high power factor, a minimum mass, or a desired type of output characteristics, that is, the best energy and mass-overall size indicators. It should be specified that the minimum values of the currents in the equations (dependent variables) do not yet mean an optimal machine [8].

As so far conducted studies have shown, startup processes are determined by the initial values of the parameters determined by slip s=1. The character of non-linear variation of the parameters in the spinning process of the motor is of secondary importance [2].

The starting torque of the induction motor reaches the maximum provided that the ohmic resistance of the rotor is equal to the leakage reactance of the machine The maximum value of the induction motor starting torque is achieved if the ohmic resistance of the rotor is equal to the leakage reactance of the machine $x_k = x_1 + x_2^{'}$, in that x_1 and $x_2^{'}$ are stator and rotor leakage reactance, accordingly.

The maximum torque is obtained with greater slip, the higher the ratio $r_2^{'} / x_k$, that is, the greater the ohmic resistance of the secondary circuit. The maximum torque is important for the induction machine as a motor. Often this motor torque is called an overturning torque. The explanation is that when the motor runs with slip, less than the maximum one, but close to it, accidental overloading can cause it to stop if, in a short time, the resistive torque is greater than the motor torque.

With an increase in $r_2^{'}$, the initial starting torque increases as long as it equals the maximum. With the subsequent raising of $r_2^{'}$, the starting torque lowers anew.

When the $r_2^{'}$ increases, the starting current of the motor continuously decreases.

The magnitude of the maximum torque does not depend on the ohmic resistance of the rotor; it depends only on the maximum slip, where the torque reaches the highest value. This greatest value is obtained with greater slip, the higher the ratio $r_2^{'} / x_2^{'}$, and in particular, with greater slip, the greater the ohmic resistance of the rotor.

The resistances x_1 and $x_2^{'}$ are usually significantly larger than the resistances r_1 and r_2'.

In practice, most drives operate in modes with time-varying load levels. In addition, considering the ultimate accuracy of load estimation, electric machine builders foresee some stock when determining their calculation values of the quantities. As a result, very often the real load is less than the rated one.

When designing electric motors the target is the maximum efficiency to be obtained at 60-80% of the nominal load as they work for a long time with a underloading of 15-25%. In order to achieve maximum efficiency in the rated load or overload area, the windings must have an increased cross-section and reduce electrical losses in the motor [2].

In order to reduce the electrical losses in the rotor and to improve efficiency, slip is required to be small, which in turn is related to the requirement for a little r_2'. The determination of losses in an induction motor by the parameters of the equivalent circuit is as follows:

$$\begin{aligned}\Delta P_\Sigma &= 3I_1^2 r_1 + 3I_2'^2 r_2' + 3I_{ma}^2 r_m = \\ &= 3I_2'^2 r_2'\left(1 + r_1 / r_2'\right) + 3I_{mr}^2 r_1 + 3I_{ma}^2 r_m = \\ &= M\omega_0 s\left(1 + r_1 / r_2'\right) + M\omega_0\left(r_1 r_2' / x_m^2 + r_2' / r_m\right)/ s\end{aligned} \tag{2}$$

where

I_1 and I_2' stator and rotor current, respectively;

$I_{0\alpha}$ and I_{0r} active and reactive component of the magnetizing current;

$r_m = 3U_{rated}^2 / \Delta P_{STEEL.rated}$ computational resistance of the magnetizing circuit;

x_m magnetizing reactance;

ω_0 angular speed of the rotating electromagnetic field.

By introducing the computational resistance r_m in the equivalent circuit, the influence of the stator steel losses on the motor characteristics is taken into account. In this case, it is assumed that the active power consumed therein is equal to the power covering the core losses in the real motor related to one phase.

After differentiation of the expression (2) with respect to slip s and equating the derivative to 0, there is an analytical expression for the slip s_{OPT} corresponding to the minimum of the losses:

$$s_{OPT} = \frac{r_2'}{x_m}\sqrt{\frac{x_m^2 / r_m + r_1}{r_2' + r_1}} \tag{3}$$

Similarly, following the differentiation of analytical expressions for stator current and active power consumption with respect to slip s, slip ratios are determined to provide:

- minimum stator current

$$s_I = r_2' / x_m\,; \tag{4}$$

- minimum power consumption

$$s_P = r_2' / \sqrt{1 + x_m^2 / r_m r_1} / x_m\,. \tag{5}$$

For the study of transient processes in a high-power MV electric drive of pump unit the appropriate MathCad® software has been used and in particular the embeded functional method "Rkadapt" – a calculus for solving systems of differential equations with a non-fixed unequal approaching spacing.

3. Results obtained

The parameters of the T-shaped equivalent circuit of the motor which we use in our research are approximately obtained and given by the manufacturer when slip is taken to be $s = 1$.

Our considerations are focused on an induction motor with double-cage rotor, manufactured by IHB Electric JSC, Bulgaria. Its parameters for slip $s = 1$ could be seen in Appendix.

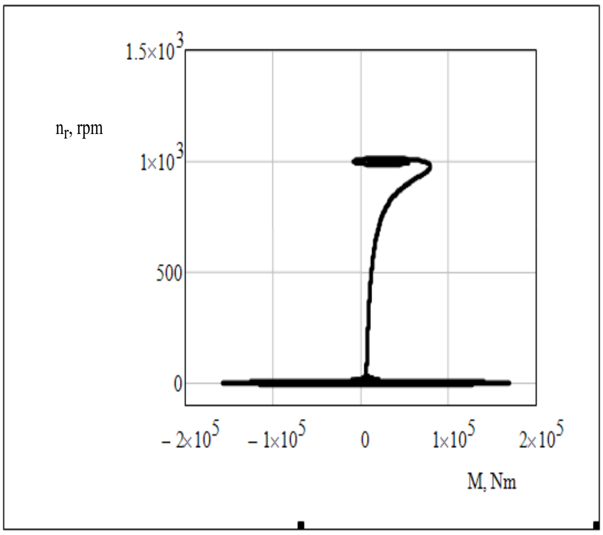
We set the total inertial torque of the electromechanical system I_{TOT} by increasing the inertia torque of the electric motor with a coefficient of inertia *FI.* Studies have been carried out with the calculated optimal value *FI=2.92* [1], the purpose being neither to overestimate the inertial torque of the load nor to reduce it unreasonably.

Various characteristics of the dynamically changing electrical and mechanical quantities and parameters of the studied electric motor as a component and the electrical drive as a whole are obtained. Some of the results obtained are presented in Table 1. A part of the values of these characteristics which we have got are given in Table 1.

Table 1. Influence of initial torque and rotor resistance

r_2' [Ω]	T_{INIT}* –	T_{IMPACT}* –	t_{START} [s]	$\Delta P_{\Sigma min}$ [W]	s_P –	s_{opt} –	s_I –
	0.16	5.32	155	59 x 10^3			
	0.15	5.32	115	64 x 10^3			
0.046	0.12	5.29	88	77 x 10^3	0.06882	0.02219	0.00132
	0.10	5.05	82	86 x 10^3			
	0.05	4.99	62	263 x 10^3			
	0.19	5.79	170	86 x 10^3	0.08079	0.02502	0.00155
	0.18	5.79	155	97 x 10^3			
0.054	0.15	5.76	78	274 x 10^3			
	0.10	5.72	38	274 x 10^3			
	0.05	5.41	25	274 x 10^3			
	0.21	5.96	80	284 x 10^3	0.09276	0.02769	0.00178
	0.20	5.96	68	284 x 10^3			
0.062	0.19	5.94	49	284 x 10^3			
	0.15	5.89	32	284 x 10^3			
	0.10	5.82	23	284 x 10^3			
	0.15	6.77	93	294 x 10^3	0.10473	0.03020	0.00201
	0.12	6.64	41	294 x 10^3			
0.070	0.11	6.62	35	294 x 10^3			
	0.10	6.61	32	294 x 10^3			
	0.05	6.55	22	294 x 10^3			
	0.21	6.57	24	303 x 10^3	0.11669	0.03258	0.00223
	0.20	6.56	23	303 x 10^3			
0.078	0.19	6.55	22	303 x 10^3			
	0.18	6.54	20	303 x 10^3			
	0.15	6.51	18	303 x 10^3			

Fig. 1 represents a dynamic mechanical characteristic for the case of values of the ohmic resistance of the rotor $r_2^{'} = 0.062$ (rated value) and initial resisting torque of the load (p.u.) $T_{LINIT}^{*} = 0.15$.



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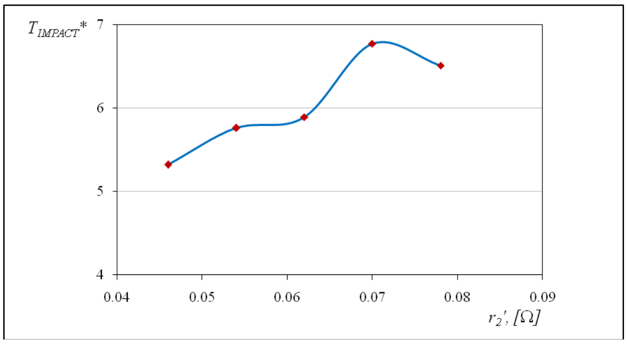

Fig. 2. Impact torque of the motor (p.u.) vs. the induction motor rotor ohmic resistance

Fig. 2 represents the change of impact torque of the motor (p.u.) with respect to induction motor rotor ohmic resistance, Fig. 3 – slip change at minimum power consumption in function of induction motor rotor ohmic resistance.

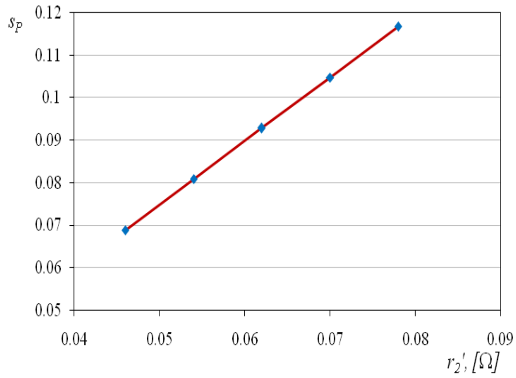

Fig 3. Slip change at minimum power consumption vs. the induction motor rotor ohmic resistance.

4. Conclusions

The presented model affords an opportunity for investigation of the electric motor operation by means of the initial resisting torque and rotor ohmic resistance variability. This does not deplete all possible questions which can be clarified worked on the model. However, it indicates the effectiveness of the mathematical modeling as regards induction motor investigations.

Dynamic behavior depends on the torque balance, i.e. as the load on the motor shaft increases, the slip also increases, which in turn reduces the ohmic resistance of the rotor. As a consequence, the current in the rotor increases and hence the shaft torque. That is, all the quantities inherent in the induction motor change according to the dynamic slip alterations.

The values of the initial resisting torque of the driven pump and the ohmic resistance of the rotor of the induction motor are largely determining the duration of the start-up and acceleration times.

During startup, the torque grows with the increase in the ohmic resistance of the induction motor rotor and is not affected so much by the reducing this parameter.

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Appendix

Induction Motor Data and Electric Equivalent Circuit Parameters

S.N	Description	Value
1	Rated power (P_{rated})	2850 kW
2	Rated stator voltage (V_{rated})	6000 V
3	Operating frequency (f)	50 Hz
4	Line stator current (I_1)	335.841 A
5	Rated torque (T_{rated})	27442 Nm
6	Pole pair number	3
7	Rotor speed (n_r)	992.263 rpm
8	Power factor	0.845
9	Rotor torque of inertia (I_r)	275 kgm^2
10	Stator resistance (r_1)	0.05 Ω
11	Rotor resistance (r_2')	0.062 Ω
12	Stator leakage reactance (x_1)	0.957 Ω
13	Rotor leakage reactance (x_2')	2.237 Ω
14	Magnetizing reactance (x_m)	34.826 Ω
15	Rated steel power losses ($\Delta P_{STEEL.rated}$)	13032 W