Use of Modern Software Supports Specialized in Designing Induction Motors with Special Destinations

In this paper, the authors propose to approach the design of three-phase induction motors with special destinations, using the modern specialized software supports. In this respect, by creating and exemplifying clear procedures for defining and simulating the generic model of a three-phase induction motor with squirrel-cage rotor, it is possible to respond quickly to the demands of the beneficiaries and to provide them optimal constructive variants. In this study, the software support “ANSYS Electronics Desktop” was used for the modelling and simulation from the electromagnetic point of view of an induction motor with a squirrel-cage rotor of 6 kV medium voltages having the rated power 225 kW, intended for the electrical pumping systems. The motors of this type drive mineral oil pumps for starting boilers or heavy fuel oil transfer pumps, within the own services of a thermoelectric power station. Thus, it was used for the analysis of the studied motor, the product ANSYS RMxprt Design which is an additional software tool to the ANSYS Maxwell Design solution, dedicated to electric machines designers. The software generates as interfaces, the simulation results of the analysis performed on the studied motor (performances, complete detailed design data, curves). The performances of the studied motor will constitute the input data for the subsequent analysis of the electromagnetic field performed by the finite element method. The simulation is performed both in operating regime at rated load and no load, starting, running with blocked rotor, the software also providing the consumption of materials necessary for motor construction. The software generates a custom file with the design data of the analyzed three-phase induction drive motor, which contains: general data; stator data; rotor data; consumption of materials; operation at rated load; operation no load; starting; operation with blocked rotor; detailed data when operating at rated load; the arrangement of the windings. With the help of this software product, the performances of the machine were calculated at different load levels in the domain (0.25 ... 1.25)∙P_N. Due to the facilities offered by the “Optimetrics” module of the software product used, a number of technical characteristics could be compared, such as the variation as a function of speed of: efficiency, η = f(n); power factor, cosφ = f(n); developed (useful) output power, P_2 = f(n); the developed couple, M = f(n); the supply current from the stator winding, I = f(n), etc. Thus recommendations could be made regarding the adoption of solutions to ensure the efficient operation of this motor in terms of loading regime.

Keywords: ANSYS RMxprt design, computer-aided design, induction motors, loading regime, modern software supports, “Optimetrics” module

Introduction

The induction motors are relatively complex physical systems that perform the electromechanical energy conversion. Specifically, they receive „at the terminals” the electrical energy W_{1 (el)} and after covering the losses (of about 5 ...)
8) % of the received energy, provide „at the shaft” the useful mechanical energy $W_{2}^{\text{mec}}$.

In order to describe their behaviour in different conditions and operating regimes, simulations are used, requiring prior mathematical modelling (use of conventional representations - geometric constructions, electrical circuits, conventional schemes, etc.) [1].

The analysis of the optimal design methods of induction motors highlights the fact that the wider use of their command with the help of static voltage and frequency converters allowed the transition to functional-constructive optimization of induction motors, the performances obtained being outstanding. This is the main reason that has required the use of induction motors with special destinations, in various domains where speed regulation is required (e.g. squirrel cage rotor induction motors of 6 kV that drive mineral oil electric pumps for starting of thermoelectric boiler, transfer (moving from a tank in another) of heavy oil, condensate within the own (ancillary) services of a thermoelectric power plant), increase of maximum torque, overload capacity compared to rated power - frequent starts and stops (e.g. traction induction motors that drive the driving bogies of electric locomotives, frames and trains of railway traction [2]) but also other complex operating regimes that fall within strictly delimited time and space conditions.

An optimal design is preceded by the investigation of the conditions in which the machine will work, namely: the working environment, which mainly determines the choice of the degree of protection of the machine, conditions imposed by the technological process, mechanical requirements and the operating regime of the working machine.

The ability to predict by calculation the behaviour of an induction motor with special destination (having one of the destinations mentioned above), a prognosis that can allow the achievement of the rational safety-risk balance, is the essence of the design activity.

The need for this approach requires obtaining information as close as possible to reality on the complex working regimes of such an induction motor and the influence of various parameters on them.

All these working regimes were conventionally approached a long time ago, but only the use of modern means of calculation allows the valorisation of complex models that take into account the effects of the values of an increasing number of machine parameters. This information allows the anticipation of phenomena and simplifies the activity of design and construction of the induction motors with special destinations.

The calculation methods based on the comparison of several variants are long and laborious depending on the experience of the designer. Reducing the design time while investigating a large number of variants to obtain the optimal solution can be achieved by using modern computing technology.
Elaboration and Exemplification of Clear Procedures regarding the Definition and Simulation of the Generic Model of an Induction Motor with Squirrel Cage Rotor

In this case study, the “ANSYS Electronics Desktop” software support was used for the electromagnetic modelling and simulation of an medium voltage induction motor with a squirrel cage rotor with rectangular deep copper bars, intended to work within the own (internal) services of a district thermoelectric power plant with groups of 60 MW using black fuel oil, which drives the mineral oil pumps for starting the thermoenergetic boiler or the transfer pumps (moving from one tank to another) of black fuel oil, of the type of two similar induction motors, the main technical characteristics of which are shown in Table 1.

Table 1. The Structure of 6 kV Medium Voltage Consumers (Motors and Transformation Substations) within the Own (Internal) Services of a District Thermoelectric Power Plant with Groups of 60 MW using Black Fuel Oil

<table>
<thead>
<tr>
<th>Aggregate name</th>
<th>P_{S}/S_{N} [kW]/[kVA]</th>
<th>Total units</th>
<th>In continuous operation</th>
<th>I_{N} [A]</th>
<th>n_{N} [rpm]</th>
<th>η_{N} [%]</th>
<th>cos φ_{N}</th>
<th>L/I_{N}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed pump</td>
<td>4000</td>
<td>2</td>
<td>1</td>
<td>419.2</td>
<td>2985</td>
<td>96.2</td>
<td>0.91</td>
<td>6.3</td>
</tr>
<tr>
<td>Flue gas fan</td>
<td>800</td>
<td>2</td>
<td>2</td>
<td>96.3</td>
<td>743</td>
<td>92.5</td>
<td>0.86</td>
<td>6.4</td>
</tr>
<tr>
<td>Air fan</td>
<td>400</td>
<td>2</td>
<td>2</td>
<td>90.5</td>
<td>991</td>
<td>90.5</td>
<td>0.84</td>
<td>5.8</td>
</tr>
<tr>
<td>Circulation pump</td>
<td>320</td>
<td>2</td>
<td>2</td>
<td>40.8</td>
<td>370</td>
<td>91</td>
<td>0.83</td>
<td>6.0</td>
</tr>
<tr>
<td>Boiler starter</td>
<td>200</td>
<td>1</td>
<td>-</td>
<td>26.0</td>
<td>1480</td>
<td>90</td>
<td>0.82</td>
<td>5.8</td>
</tr>
<tr>
<td>Mineral oil pump</td>
<td>1000</td>
<td>2</td>
<td>-</td>
<td>188.3</td>
<td>1480</td>
<td>94</td>
<td>0.87</td>
<td>5.6</td>
</tr>
<tr>
<td>Winter heating pump</td>
<td>1600</td>
<td>1</td>
<td>1</td>
<td>26.0</td>
<td>1480</td>
<td>90</td>
<td>0.82</td>
<td>5.8</td>
</tr>
<tr>
<td>Transfer pump</td>
<td>200</td>
<td>1</td>
<td>-</td>
<td>49.8</td>
<td>1480</td>
<td>92</td>
<td>0.84</td>
<td>5.7</td>
</tr>
<tr>
<td>Acid wash pump</td>
<td>400</td>
<td>1</td>
<td>-</td>
<td>97.4</td>
<td>1480</td>
<td>93</td>
<td>0.85</td>
<td>6.0</td>
</tr>
<tr>
<td>Summer heating pump</td>
<td>800</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internal services transformer</td>
<td>750</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chemical treatment transformer</td>
<td>1000</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel household transformer</td>
<td>630</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lighting transformer</td>
<td>630</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hot steam boiler transformer</td>
<td>400</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power station transformer</td>
<td>400</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>General services transformer</td>
<td>750</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The machine (motor) on which the numerical models were made is represented by a three-phase induction machine with squirrel cage rotor having the following characteristics: the rated power $P_N = 225$ kW; the rated voltage $U_N = 6000$ V (Wye connection on stator); the synchronism speed $n_s = 3000$ rpm; the rated speed $n_N = 2976$ rpm; the rated frequency $f_N = 50$ Hz; the number of pairs of poles $p = 1$; the number of stator slots $Z_1 = 48$; the number of rotor slots $Z_2 = 38$; the maximum supported temperature $T = 120$ °C; the length of ferromagnetic armatures: 450 mm (stator) and 450 mm (rotor); the air gap $\delta = 2$ mm.

**Analysis with ANSYS® RMxprt Design of the Studied Motor**

Thus, the ANSYS RMxprt Design product was used for the analysis of the studied motor, which is an additional software tool to the ANSYS Maxwell Design solution, dedicated to electric machine designers [3], [4], [5]. To this end, the following steps must be completed:

- **Filling in the input parameters** of this software, which are given in the form of a list, is done by taking each line from the list of parameters: machine (Three Phase Induction Motor - Figure 1), stator - Figure 2, Figure 3 (stator slot - Figure 4, stator winding - Figure 5, Figure 6), rotor - Figure 7 (rotor slot - Figure 8, rotor winding - Figure 9), shaft - Figure 10.

**Machine**

In the interface assigned to the machine that can be seen in Figure 1, the values of the following parameters must be filled in:

- ✓ Machine Type: Three Phase Induction Motor
- ✓ Number of poles of the machine: $2p = 2$
- ✓ Stray Loss Factor: 0.005
- ✓ Frictional Loss: 2000 W
- ✓ Windage Loss: 3.3466 W
Figure 1. RMxprt Interfaces - Machine Type

Stator
In the interface assigned to the stator that can be seen in Figure 2, the values of the following parameters must be filled in:

- Outer diameter of the stator core: $D_{ext} = 595$ mm
- Inner diameter of the stator core: $D_{int} = 300$ mm
- Length of the stator core: $l_{(Fe)} = 450$ mm
- Stacking factor of the stator core: 0.95
- Steel Type: M19_24G
- Number of slots of the stator core: $Z_{s(1)} = 48$
- Slot type of the stator core: 6 - Rectangular
- Lamination Sectors: 0
- Skew width measured in slot number: 0

Figure 2. RMxprt Interfaces - Stator
The next step is to assign the material and check the material properties of the stator core (M19_24G - laminated material - core) which can be seen in Figure 3.

**Figure 3. RMxpert Interfaces - Assignment Material for the Core - Material Properties and Magnetization Curve of the Stator B = f(H)**

![Image of RMxpert Interfaces - Assignment Material for the Core](image)

**Stator Slot**

**Figure 4. RMxpert Interfaces - Slot Type Selection, Stator Slot**

![Image of RMxpert Interfaces - Slot Type Selection](image)

**Stator Winding**

In the interfaces assigned to the stator winding that can be seen in Figure 5 and Figure 6 the values of the following parameters must be filled in:

- ✓ Number of winding layers: 1
- ✓ Stator winding type: Whole coiled
- ✓ Number of parallel branches of stator winding: 1
- ✓ Number of conductors per slot, (0 for auto-design): 36
- ✓ Number of strands (number of wires per conductor), (0 for auto-design): 2
- ✓ Double-side wire wrap thickness, (0 for auto-pickup in the wire library): 0
Wire size, (0 for auto-design): The optimal variant is obtained by repeated runs of the software. Width of the stator conductor, $b_{c1} = 9$ mm, Height (thickness) of the stator conductor $h_{c1} = 1.4$ mm.

The software selects from its library $b_{c1} = 8.25$ mm and $h_{c1} = 1.45$ mm, the closest values (Figure 5).

**Figure 5.** RMxprt Interfaces - Stator Winding, Distribution of Stator Windings on Slots and Phases

It is also noted that Figure 6 requires the numerical values of a series of parameters related to the ends of the stator winding and the stator slot insulation, respectively, such as: insulation thickness (insulating sheath) $b_{nl} = 1.67$ mm, wedge thickness ($h_p = 2$ mm), the limit value for the filling factor of the stator slot ($k_{uc} = 0.95$ mm).

**Figure 6.** RMxprt Interfaces - Ends and Stator Winding Insulation
Rotor

In the interface assigned to the rotor that can be seen in Figure 7, the values of the following parameters must be filled in:

- Stacking factor of the rotor core: 0.95
- Number of slots of the rotor core: \( Z_{r(2)} = 38 \)
- Slot type of the rotor core: 3 - Rectangular
- Outer diameter of the rotor core: \( D_{r ext} = 295 \text{ mm} \)
- Inner diameter of the rotor core: \( D_{r int} = 135 \text{ mm} \)
- Length of the rotor core: \( l_{(Fe)} = 450 \text{ mm} \)
- Steel Type: M19_24G
- Skew width measured in slot number: 0
- Casted rotor / Rotor squirrel-cage winding is cast
- Half-shaped slot / un-symmetric.

**Note** The rotor with copper bars welded to the ends of the short-circuit rings was chosen as a constructive variant.

**Figure 7. RMxprt interfaces - rotor**

Rotor Slot

In the interfaces assigned to the rotor slot that can be seen in Figure 7 (by which the slot type is selected - 3) and Figure 8, the values of the following sizes must be filled in: The width (opening) of the isthmus \( B_{s0} = 3.8 \text{ mm} \), the height of the isthmus \( H_{s0} = 2.5 \text{ mm} \), the height of the rotor slot \( H_{s2} = 40 \text{ mm} \), \( H_{s1} = 0 \text{ mm} \), the width of the rotor slot \( B_{s1} = B_{s2} = 6.4 \text{ mm} \), the radius of curvature of the bottom of the rotor slot \( R_s = 0 \).
In the interface assigned to the rotor winding through which the type of conductive bars and of the conductive ring - of short-circuit (made of copper) - is selected that can be seen in Figure 9, the values of the following dimensions must be completed:

- Single-side end extended bar length: 135 mm
- One-side width of end rings/in axial direction: \( b_i = 35 \) mm
- Height of end rings/in radian direction: \( h_i = 75 \) mm

In the interface assigned to the machine shaft, that can be seen in Figure 10, it is specified that it is made of magnetic material.
Figure 10. RMxprt Interfaces - the Magnetic Shaft

- General Configuration (Setting) of Rated Data Analysis

It is specified according to Figure 11 and Figure 12, a series of rated input parameters of the machine (operating type, load type, rated output power (useful mechanical power for the type of operation as motor, $P_N = 225$ kW), rated voltage (effective value (rms) stator line voltage applied, $U_N = 6000$ V), rated speed, $n_N = 2976$ rpm, operating temperature, $T = 75$ °C).

Also it is specified according to Figure 12, the (stator) supply winding connexion: Wye (in this study case) or Delta and the supply voltage frequency.

Figure 11. RMxprt Interfaces - General Setting of Rated Data Analysis

- RMxprt Analysis Results

The software generates in the form of interfaces, the results of the simulation of the analysis performed on the studied motor (performance, complete design data, curves).

It also generates an interface that contains the performances of the studied motor that will constitute the input data for the subsequent analysis of the
electromagnetic field performed by the finite element method with the ANSYS® (2D / 3D) Maxwell Design product.

**Figure 12. RMxpert Interfaces - Analysis General Setting - Winding Connexion, Frequency**

![RMxpert Interfaces](image)

The simulation is done both in operation regime at maximum load and in no-load regime, the software also providing the consumption of materials necessary for the construction of the motor.

The software generates custom interfaces for: stator parameters (slot, tooth, winding), rotor parameters, steady state parameters (permanent regime).

The software also generates the scheme of the power supply parameterized circuit of the motor (motor parameterized model (Figure 13)).

In principle, the realization of the equivalent power supply scheme of a three-phase asynchronous motor (induction machine) aims at parameterizing the windings [6].

In Figure 13, the induction machine is connected to a three-phase power supply composed of 3 components which are independent sources of sinusoidal voltages ET1, ET2 and ET3. For the ET1/ET2/ET3 (sinusoidal) voltage source the following parameters are specified:

- **AMPL** - the maximum value of the phase voltage
  \[
  V_A = V_B = V_C = \sqrt{2} \cdot \left( \frac{6000}{\sqrt{3}} \right) = \sqrt{2} \cdot \left( \frac{U_N}{\sqrt{3}} \right) = 4898.98 \text{ V}
  \]

- **FREQ** - the supply voltage frequency \( f_N = 50 \text{ Hz} \)

- **PHASE** - phase angle \( 0/-120/-240 \text{ degree} \)

The parameters of the induction machine appearing in the scheme in Figure 13 represent the input data for the finite element transient analysis, namely:

- The phase resistance of the stator winding at the regime temperature (terminal resistance) \( R_A = R_B = R_C = 0.588931 \text{ Ω} \)
- The leakage inductance of the stator phase \( L_{\text{Phase}A} = L_{\text{Phase}B} = L_{\text{Phase}C} \)
The leakage inductance of the stator winding ends \( L_A = L_B = L_C = 0.0298686 \, \text{H} \).

The software also generates a series of curves, for the analysis of which it allows a series of facilities (for example the display of the maximum value) such as the variation as a function of speed: of the efficiency, \( \eta = f(n) \) (Figure 14); the power factor, \( \cos \phi = f(n) \) (Figure 15); the output (useful) power developed at the shaft, \( P_2 = f(n) \); the useful torque developed at the shaft, \( M = f(n) \) (Figure 16); the supply current in the stator winding, \( I = f(n) \) etc.

**Figure 13. ANSYS Electronics Interfaces - the Motor Supply Scheme**

Analytical Validation of the Simulations Performed Using ANSYS® RMXPRT Design of the Studied Motor

a. The mechanical characteristic electromagnetic torque = \( f(\text{speed}) \), \( M = f(n) \), for \( U = U_N \)

It is known that in the study of the operation of the induction machine, the mechanical characteristic \( M = f(s) \) is of special importance.
Figure 14. ANSYS Electronics Desktop Interface - the Variation of the Efficiency Depending on the Speed, $\eta = f(n)$

Figure 15. ANSYS Electronics Desktop Interface - the Variation of the Power Factor Depending on the Speed, $\cos\phi = f(n)$

On the other hand, in the analysis of electric drive systems (as is the case of the assembly of the centrifugal electric pump driven by an induction motor) is used mainly the representation of the electromagnetic torque in the $M - \Omega$ or $M - n$ plane of the mechanical quantities [7].

In this sense, in order to validate the simulation results with the product ANSYS RMxprt Design, is presented the following algorithm for constructing by calculation the mechanical characteristic electromagnetic torque $= f($speed$), M = f(n)$, for $U = U_N$, which involves traversing the next steps:

- **The expression of the stationary electromagnetic torque** $M$ can be done with the complete Kloss relation (canonical form), accessible if the parameters of the equivalent scheme [8], [9] are known.
But considering that the studied motor power is in the range of medium and high powers, it can be used with very good accuracy, the simplified Kloss relation (1), accessible if only the catalogue data are known, $M_m$, $s_N$, frequently used in electric drives, as is this case study.

$$M(s) = \frac{2M_m}{s + \frac{s_m}{s}} [\text{Nm}]$$  \hspace{1cm} (1)

- The evaluation of the critical slip $s_m$ for the use of the relation (1) is possible if the simplified Kloss relation is customized for the rated operating point. The unknown of the resulting second degree equation is the critical slip $s_m$.

$$\frac{M_N}{M_m} = \frac{2}{s_N + \frac{s_m}{s_N}} \Rightarrow s_m^2 = 2 \frac{M_m}{M_N} s_m s_N + s_N^2 = 0$$  \hspace{1cm} (2)

Solve the equation and choose one of the solutions given by relation (3), namely the solution that verifies the inequality $s_{m1} > s_N$ because the other solution that verifies the inequality $s_{m2} < s_N$ is not viable (Figure 17), the operating point being located on the unstable portion of the curve.

$$s_{m1,2} = s_N \left[ \frac{M_m}{M_N} \pm \sqrt{\left( \frac{M_m}{M_N} \right)^2 - 1} \right]$$  \hspace{1cm} (3)

It is noted that to solve the algebraic equation (2) the authors used the facilities offered by the use of the Mathcad mathematical software package [10] related to the application of the polyroots (v) function, where v is the vector containing the polynomial coefficients (starting with the free term on the first position) and which determines all the roots of a polynomial.
• Defining the mechanical characteristic (1) in the form \( M = f(n) \),
  according to the relation (4), taking into account the linear dependence
  between the slip \( s \) and the speed \( n \).

\[
M(n) = \frac{2M_m}{60 \cdot f - n} \left[ \frac{60 \cdot f - n}{p} + \frac{s_m}{s_m} \right] [\text{Nm}]
\] (4)

• Representation in the same system of coordinate axes, of the mechanical
  characteristics obtained by calculation and simulation, according to
  Figure 18.

In order to bring these characteristics in the same \( M - n \) plan, for the graphs
obtained explicitly by running the specialized software ANSYS RMxprt Design,
the authors resorted to reading the corresponding data from external ASCII type
files provided by the mentioned software packages [5]. To read these data files,
the READPRN ("file_name") function was used, which returns a vector or array
containing the values from the ASCII file [10]. Then the data thus read were
graphically represented using our own design programs, developed in the
Mathcad programming environment.

**Figure 17. Regarding the Choice of Critical Slip \( s_m \)**

Analyzing Figure 18, the following findings can be made:
- The mechanical characteristics electromagnetic torque = \( f \) (speed), \( M = f(n) \),
  for \( U = U_N \) obtained by calculation and simulation are almost identical in the
  area of stable operation of the motor corresponding to the range \( n_s = 3000 \text{ rpm} > \)
  \( n > 2891.05 \text{ rpm} \) (\( s_{\text{m1}} > s > 0 \)) when for a shaft-resistant torque \( M_r \neq 0 \), the speed
  \( n \) is fixed at a value for which \( M = M_r \) and the stability condition is met. The
  superposition of the two curves exists up to speed \( n \approx 2670 \text{ rpm} \) and the
difference between them is maximum at start-up, decreasing as the speed increases up to 2670 rpm, when this difference becomes zero.

Also according to Figure 18 the simulations show the improvement of the starting performance \( (n = 0) \) of this induction motor with squirrel cage rotor built with rotor cage in special construction with deep bars, when it develops an electromagnetic torque whose value \( 468.064 \text{ Nm} \) is higher than the value obtained by analytical calculation \( 115.828 \text{ Nm} \).

- Regarding the variation of the useful torque developed at the shaft (obtained by simulation) it can be seen that this output torque is lower due to covering mechanical and ventilation losses than the electromagnetic torque obtained by simulation over the entire speed variation range, and this condition is verified compared to the analytical model, only in an area \( (n_s = 3000 \text{ rpm} > n > 2310 \text{ rpm}) \) that includes the stable operation area.

Regarding the difference between the electromagnetic torque and the useful torque developed at the shaft, it is known that it is equal to the loss torque, which depends proportionally on the mechanical and ventilation losses.

It should be noted that the procedure followed for defining and simulating the generic model of the induction motor requires the introduction as initial data of the value of mechanical losses (by friction) and ventilation losses. The sum of these losses can be considered almost constant because the motor speed is almost stable in the stable operating area. These losses are difficult to obtain by calculation, which is why in practice they are used, most of the time, relations obtained empirically, following experimental tests [11], [12]. Therefore, the accuracy of the simulations also depends on the accuracy of the pre-assessment of this category of losses.

**Figure 18.** Comparison between the Mechanical Characteristics: the Electromagnetic Torque = \( f \) (speed), \( M = f \) (n), for \( U = U_N \) Obtained by Calculation (Red), Simulation (Blue) and the Developed Useful Torque = \( f \) (Speed) (Green)
b. The operating characteristics: efficiency $\eta = f(\beta)$; power factor $\cos \varphi = f(\beta)$

In the drive systems of the type referred to in the case study, it is of maximum interest to know the behaviour of the induction drive motor to the load variation.

With the help of the ANSYS RMxprt Design software product used for simulations, the performance of the machine (energy efficiency indicators - efficiency and power factor) was obtained at different degrees of load ($\beta = 0.25; 0.50; 0.75; 1.00; 1.25$) in the range $(0.25 \ldots 1.25)P_N$ i.e. for $P_2 = 56.25\, \text{kW}; 112.5\, \text{kW}; 168.75\, \text{kW}; 225\, \text{kW}; 281.25\, \text{kW}$.

Due to the facilities offered by “Optimetrics” interfaces it was imported the parametric sweep using the Maxwell (2D or 3D)>Optimetrics Analysis>Add Parametric from File command [4]. Thus a number of characteristics could be compared.

“Optimetrics” interfaces with ANSYS Electromagnetics products enable the optimization of a wide variety of design parameters based on variable geometry, materials, excitations, component values, etc. “Optimetrics” modifies the variable values until the minimum of a user-defined cost function is reached with acceptable accuracy.

In order to calculate the electric efficiency $\eta$ to a load $\beta$ of the drive motor, the analytical expression (5) [13] was used.

Figure 19. The Efficiency Characteristics Depending on the Load Degree $\eta = f(\beta)$ Obtained by Calculation (Red) and Simulation (Blue)

$$\eta(\beta) = \frac{\beta}{\beta + \chi(\gamma + \beta^2)}$$

(5)

where:
$\beta$ - load coefficient (load degree) given by the ratio between the useful mechanical power at the shaft (in technological load) $P_2$ and the rated mechanical power (useful at the shaft) $P_N (\beta = P_2 / P_{2N})$;
\( \gamma \) - the ratio between constant losses and variable losses \( (\gamma = p_0 / p_{vN}) \);
\( p_0 \) - the no load losses of the motor, which are constant at a given connexion;
\( p_{vN} \) - the variable losses of the motor at the rated load;
\( \chi \) - a calculation constant for a given connexion of the windings, is determined
with the relation (6):
\[
\chi = \frac{1 - \eta_N}{(1 + \gamma) \cdot \eta_N}
\] (6)

Analyzing Figure 19 we can see a very good concordance between the
analytical model and the curve constructed by the points obtained by simulations
using the “Optimetrics” interfaces. The maximum value of the efficiency is
obtained in this case for \( P_2 = P_N \).

The analytical expression (7) was used to calculate the power factor of the
induction motor, as it is known from the speciality literature [13], [14], [15].

\[
\cos \varphi(\beta) = \frac{\beta}{\sqrt{\beta^2 + (a + \beta^2 (1-a))^2 \tan^2 \varphi_N}}
\] (7)

where:

\( a \) - the ratio between the magnetization reactive power and the rated reactive
power \( (a = Q_0 / Q_N) \);

The rated reactive power, \( Q_N \) is determined with the relation (8), \( \varphi_N \) being the
rated phase angle:
\[
Q_N = P_{eN} \cdot \tan \varphi_N = P_{eN} \cdot \tan(\arccos \varphi_N)
\] (8)

where: \( P_{eN} \) - the electrical power absorbed from the network on the terminals of
the stator winding.

The magnetization reactive power \( Q_0 \) is determined with the relation (9):
\[
Q_0 = 0.25 f \cdot B^2 \left[ \frac{V_F}{\mu} + \frac{V_S}{\mu_0} \right] \approx \sqrt{3} U_N I_0 [\text{Var}]
\] (9)

where: \( f \) - the frequency of the supply voltage, [Hz]; \( B \) - the working magnetic
flux density in the magnetic circuit, [T]; \( \mu = \mu_0 \cdot \mu_r \) - magnetic permeability,
[H/m]; \( U_N \) - the working rated voltage, [V]; \( I_0 \) - the no load current of the motor,
[A].
Figure 20. The Power Factor Characteristics Depending on the Load Factor 
\[ \cos \varphi = f(\beta) \] Obtained by Calculation (Red) and Simulation (Blue)

From Figure 20 it can be seen that by simulation lower values of the power factor are obtained than those obtained by calculation, at the same load, but with a good accuracy. Thus, at the rated load \( \beta = 1 \) results a percentage deviation of the value of the calculated power factor higher by 4,612% than the corresponding value obtained by simulation.

Also as can be seen in Figure 21, the curve of the power factor \( \cos \varphi = f(\beta) \) is similar in appearance to the efficiency characteristic for the studied induction motor working with the Wye connection of the stator windings, the differences between values being greater in the area of the low loads.

Conclusions

The paper addresses a topical issue, as the electric drive systems with induction motors are developing more and more, especially due to the indisputable advantages of the induction motors with squirrel cage rotor.

An overview of electric drive systems shows that among the technological processes commonly encountered in the electric drives, there is also the use of centrifugal pumps (turbomachines) as working machines, driven by induction motors. The drive induction motors must meet these special destinations, which are mainly characterized by the need to adjust the flow of these pumps. It is also frequently necessary for technological reasons to adjust the pressure in steps / continuously in the range: \( p_{\text{min}} \ldots 120\% p_n \).
Figure 21. The Variation of the Energy Efficiency Indicators of the Studied Motor Depending on the Load Degree: $\eta = f(\beta)$ - Calculation (Red) and Simulation (Blue); $\cos \varphi = f(\beta)$ - Calculation (Green) and Simulation (Magenta)

Such electric drive systems (pump - drive electric motor) are frequently found in the thermoelectric power plants, the supply being made at medium voltage, as is the case study presented in this paper.

In this sense, the authors systematized a clear procedure for defining and simulating the generic model of an induction motor with a squirrel cage rotor with deep bars, whose main steps they exemplified for a concrete application.

Then the simulations performed on the studied motor, using the specific software product ANSYS® RMxprt Design, were validated and interpreted accordingly by comparing the results obtained with the analytical models adapted for a series of operating characteristics of major importance for the drive systems in which these motors operate (the mechanical characteristic $M = f(n)$, the operating characteristics that decisively characterize the energy efficiency performances: $\cos \varphi = f(\beta)$, $\eta = f(\beta)$ etc.).

Defining and simulating the generic model using “ANSYS Electronics Desktop”, of the studied induction motor with the squirrel cage rotor allows the choice of the best variant that meets an optimization criterion, for example as in this case study, the operating characteristics (power factor, $\cos \varphi$; efficiency, $\eta$). It can thus be found that the value of the rated efficiency ($\beta = 100 \%$) that characterizes the chosen variant is higher than that corresponding to the basic series of high voltage induction motors of the same gauge, by 3.89 %.

It should also be mentioned that in order to perform the calculations according to these laborious calculation algorithms, the authors designed calculation programs developed using the facilities offered by the Mathcad mathematical software package, which also allow the validation of calculated values by accessible verifications.

The developed procedures have the advantage that they can be used to analyze all the usual ranges of induction motors existing in the national power system, highlighting the urgent need to correlate them with a numerical
modelling of the configuration of power and distribution networks in which these consumers operate such that to choose the configuration that leads to minimal power losses and a high power factor.

References


