Three-Phase Induction Motor Preliminar Design Assisted by CAD Software based on Brazilian Standards

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Abstract

Energy efficiency of electric motors is a challenge for the national industry in many countries, although their efficiency has been increased gradually over the years. This paper deals a computer-aided tool for the design of N-type (similar NEMA B-type) three-phase Induction Motor (IM). Such tool will bring flexibility for the design engineer during the project development. The software has the following main objectives: 1) to analyze the input data parameters of the IM project, according to Brazilian technical standards (NBR) 17094-1:2008 and 15623-1:2008, printed by the Brazilian Standards Organization (ABNT); 2) to design an IM with all electrical specificity, based on a known project method; 3) to evaluate the designed motor's performance with the same methodology. The program has a friendly graphical user interface (GUI) and it was developed by using the GUI development environment tool from MATLAB®. This paper also describes the logic programming through flowcharts and equations. The software main purpose is to produce a computer-aided tool for designing IM at the first conception step. It will evaluate the performance of the project (no built) and seek alternatives to improve its efficiency before the motor`s assembly. Knowing that the Brazilian standards requirements induce to achieve higher levels of efficiency (equivalent for other national standards) in an IM design, their technical features will be taking into account, and probably it may change the previously used IM design method. Changes on the methodology shall be highlighted in the paper.

1. Introduction

The energy efficiency of electric motors is one of the biggest challenges for the national industry in several countries, e.g. Brazil, USA and EU countries. In recent years, these countries have reviewed the minimum efficiency levels of motors [1] [2] [3], believing in the gradually increase of energy efficiency, which are already shown experimentally in [4] [5] and also theoretically [6]. It is observed in this challenge the opportunity to improve the design tools, commonly used in an electric motor design.

Brazilian standards require some necessary values for the induction motor design, as well as NEMA and IEC standards. These standards deal with the input parameters to be specified at the beginning of the design, such as: rated voltage, service factor, insulation class [7], minimum or maximum values like: torque, starting torque, casing (frame type), relation between the starting apparent power and rated power [8] and the minimum efficiency level [3] [9].

The proposed software evaluates the design process during some of these limiting design parameters, not for all, but the sufficient to achieve the main purpose of the design engineer. The software was developed in MATLAB ® and it fulfills the analytical approach of induction motor design, using the already known techniques presented in [7]. The software does not verify the typical parameter values like: flux density and current density, usually verified in numerical technique such as finite element or other. The motivation of this work is to provide a tool, which can carry out a fast evaluation, but not necessarily the final solution to the project [10].

2. Brazilian Technical Standards

The main Brazilian standards which have importance in the induction motor design are the standards described in [8] and [9]. In [9] are presented the standard dimensions for rotary electrical machines, like: the relation between the frame sizes and the height of end shaft (H), the diameter of the rotor shaft and the recommended rated power in kW. The relation between the frame sizes and the height of end shaft (H) is presented on [9].

Among the standard horsepower ratings of electrical motors in the range from 1 hp to 50 hp, the recommended power rates are 0.75 kW (1 hp), 1.1 kW (1.5 hp), 1.5 kW (2 hp), 1.8 kW (2.5 hp), 2.2 kW (3 hp), 3 kW (4 hp), 3.7 kW (5 hp), 4 kW (5.5 hp), 4.5 kW (6 hp) , 5.5 kW (7.5 hp), 6.3 kW (8.5 hp), 7.5 kW (10 hp), 10 kW (13.5 hp), 11 kW (15 hp), 13 kW (17.5 hp), 15 kW (20 hp), 17 kW (22.8 hp) 18.5 kW (25 hp), 20 kW (26.8 hp), 22 kW (30 hp), 25 kW (33.5 hp), 30 kW (40 hp), 32 kW (43 hp) and 37 kW (50 hp). It is important to point out that the table recommends power rate values up to 1000 kW (1340 hp). The standard shaft diameters have the following values in mm: 7, 9, 11, 14, 16, 18, 19, 22, 24, 28, 32, 38, 42, 48, 55, 60, 66, 70, 75, 80, 85, 90, 95, 100 and 110.

In [8] are presented, the motor duty cycles (S1 to S10, where S1 is the continuous duty), the supply voltages (220 V, 380 V or 440 V), the supply frequency of 60 Hz for products to be commercialized in Brazil, the motor design (N, H and D), which is similar to NEMA motor design (B, C and D), minimum values for starting torque (in pu), locked rotor KVA (limits for inrush current) and maximum torque (in pu). The minimum starting torque and maximum torque are function of the rated motor power, the number of poles and the motor design (N, H). For the motor design D, it is standardized only the starting torque at a fixed value of 2.75 pu.

The locked rotor KVA is given by the following expression, where S_p is the starting apparent power, P_n is the rated power, I_p/I_n is the starting current in pu, η is the efficiency at full load and PF is the power factor at full load. The standard shows the maximum values for the ratio S_p/P_n (only for the motor design N and H), depending on the motor's rated power.

$$\frac{S_p}{P_n} = \frac{I_p/I_n}{\eta \cdot FP} \tag{1}$$

The standard distinguishes the motors with star/delta starter (NY and HY). These motors feature the same characteristics given for the categories N and H. The only the standard recommendation is that the starting torque in pu should have 25% of the value for categories N and H. Moreover, the mechanical load should be reduced, since the starting torque could be insufficient for its own starting.

The standard specifies when and how the service factor should be different than one ($\neq$1). If the motor design project agrees with the rising temperature limits of the standard, they must have the unit service factor (=1). Otherwise, it is necessary to specify a service factor greater than one (>1). For electric motors with the power rates from 0.75 kW (1 hp) to 150 kW (200 hp), the service factor it can be modified to 1.15. Fractional motors vary this modification between the values of 1.15 and 1.4. In case of a higher overload capability, it is recommended to use a standardized motor with a rated power higher than the original.

In [8] is displayed, the minimum efficiency levels for induction motors. The values are standardized according to the motor rated power and its synchronous speed. One section of the standard table is shown in Figure 1. The recommendation of the reference temperature for the appropriate insulation class (temperature correction of resistance) is also standardized, even if there are no references on this temperature in high-efficiency motors. The standard also provides a match between the frame size, the rated power and the machine synchronous speed. This correspondence is restricted to induction motors IP44, IP54 or IP55, thermal class B or F, motor design N, 60 Hz frequency, low voltage and height of end shaft between 63 mm and 355 mm, in continuous duty.

Rated power		Synchronous rotation (rpm)	
kW	cv	3600	1800
		Frame	
0,37	0,5	63	71
0,55	0,75	71	71
0,75	1	71	80
1,1	1,5	80	80
1,5	2	80	90S
2,2	3	90S	90L
3	4	90L	100L
3,7	5	100L	100L
4,5	6	112M	112M
5,5	7,5	112M	112M
7,5	10	132S	132S

Figure 1 – Relationship between rated power, synchronous rotation speed and frame sizes [8]

3. Design Methodology for Induction Motor

The used design methodology is described in [7]. The design algorithm is shown in Fig. 3.

3.1 Stator core sizing

This methodology is based on output coefficient design concept, which gives the inner stator diameter calculation (D_{is}).

$$D_{is} = \sqrt[3]{\frac{2p_1}{\pi\lambda}\frac{1}{C_0}\frac{p_1}{f_1}\frac{K_E P_n}{PF \cdot \eta}} \tag{2}$$

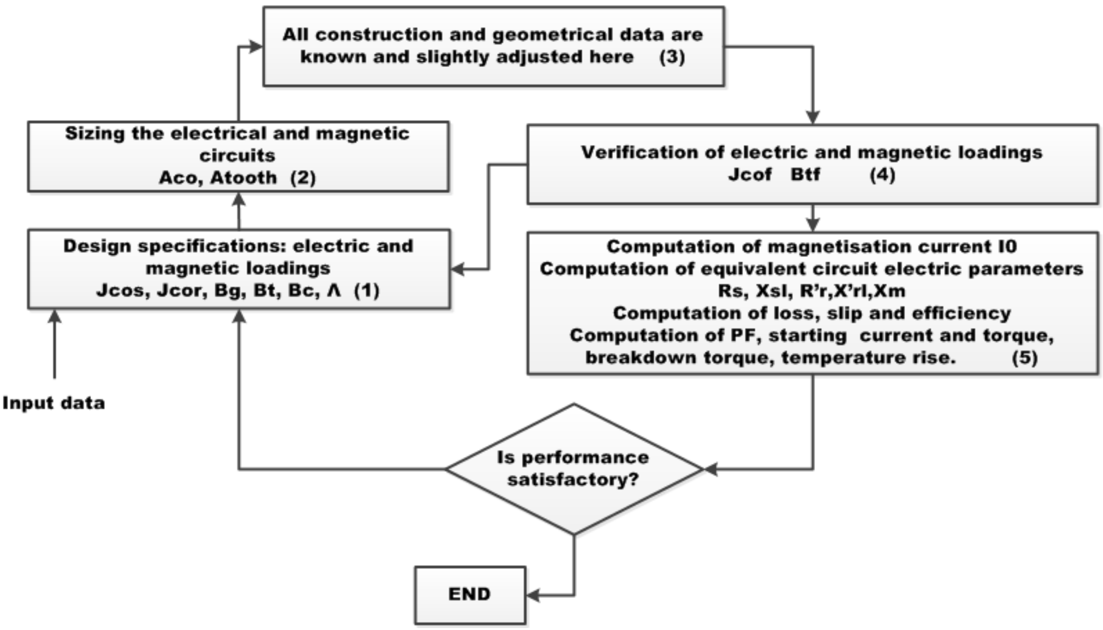

Figure 2 – Design algorithm [7]

For equation 2, it is necessary to define the number of pole pairs (p_1), the ratio between the stack length and the pole pitch (λ),the Esson's constant (C_0), the emf coefficient (K_E) and the input parameters (P_n , PF , η e f_1). The Esson's constant is a function of the number of poles, the apparent power.

From the teeth saturation coefficient ($1+K_{st}$), the voltage form factor (K_f) and the flux density shape factor (α_i) are specified. Together the winding factor (K_{w1}) and the airgap flux density (B_g) , determines the specific stator current load (A_1).

$$A_1 = \frac{C_0}{K_f \cdot \alpha_i \cdot K_{w1} \cdot \pi^2 \cdot B_g} \tag{3}$$

With all the above calculated values, others stator settings are required such as: the design current density ($J_{\cos}$), the slot fill factor (K_{fill}), the tooth flux density (B_{ts}), stator back iron flux density (B_{cs}) stator slot height (h_s), the core radial height (h_{cs}) and finally the outer stator diameter (D_{out}).

For stator slot sizing, it should be computed the stator slot opening (b_{os}), the height of the stator slot opening (h_{os}), the wedge height (h_w), the slot upper width (b_{s2}), the slot lower width (b_{s1}) and the tooth width (b_{ts}). The tooth width, for manufacturing reasons, should not be less than 3.5 mm. This slot is called semi closed trapezoidal slot.

3.1.1 Stator winding

Knowing the number of stator slots (N_s) from the number stator slots per pole (q), the winding type (double layer chorded winding or single layer) is defined. The calculation of the number of turns per slot is given in the following:

$$W_1 = \frac{K_E \cdot V_{1ph}}{4 \cdot K_f \cdot K_{w1} \cdot f_1 \cdot \phi_g} \tag{4}$$

where (V_{1ph}) is the phase voltage and (ϕ_g) is the air-gap flux.

The number of conductors per slot (n_s) is given by:

$$n_s = \frac{a_1 \cdot W_1}{p_1 \cdot q} \tag{5}$$

where (a_1) is the number of paths in parallel, such parameter may be $a_1 \geq 1$.

Therefore, the magnetic wire cross section is calculated from the rated current (I_{1n})

$$A_{\cos} = \frac{I_{1n}}{a_1 \cdot J_{\cos}} \tag{6}$$

3.2 Rotor core sizing

For the number of rotor slots (N_r) should be chosen avoiding the alignment between the rotor and stator teeth, thus minimizing the reluctance torque. The designer's expertise is very important at this moment. In general the number of stator slots must be different from the number of rotor slots. The rounded semi-closed rotor slot can be found high efficiency motors. [7]

Since the magnetomotive force (MMF) in the stator and rotor do not have equal magnitudes, it is possible to calculate the values of rotor bar current (I_b) from a relationship between the mmf of the rotor and the stator.

$$K_I = \frac{FMM_r}{FMM_s} = \frac{I_b \cdot N_r}{2 \cdot m \cdot W_1 \cdot K_{w1} \cdot I_{1n}} \approx 0.8 \cdot PF \tag{7}$$

From the rotor bar current, the end ring current can be computed (I_{er}), and with the current density in the rotor bar (J_b), the rotor slot area is determined (A_b). Linking the end ring current with the current density in the end ring (J_{er}), we obtain end ring cross section.

$$A_{b,er} = \frac{I_{b,er}}{J_{b,er}} \tag{8}$$

The design is accomplished by calculating the air gap length (g) (should not be less than 0.35 mm for manufacturing reasons [7]), rotor diameter (D_{re}), the rotor tooth flux density (b_{tr}), the upper slot diameter (d_1), the lower slot diameter (d_2), slot height (h_r),the height of the rotor slot opening (h_{or}) and rotor slot opening (b_{or}).

3.3 Application of Brazilians standards in design methodology

Figure 4 shows the moment where the generated design data will be handled by the Brazilian standard requirements.

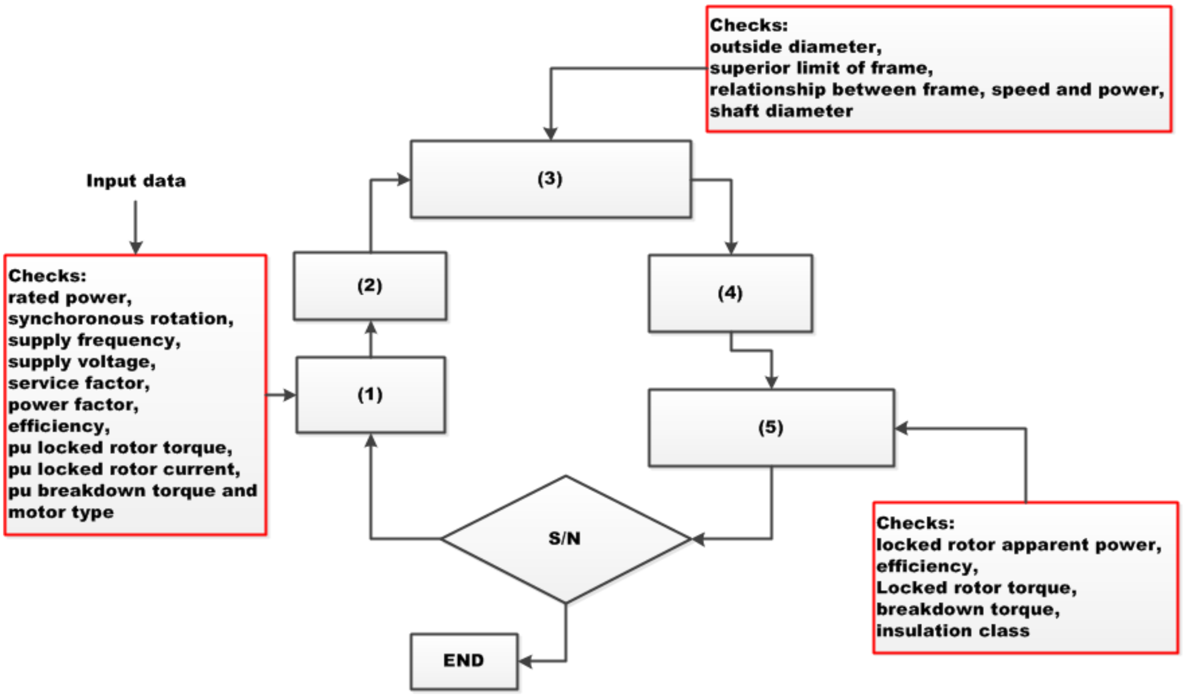

Figure 3 – Design algorithm taking into account the highlighted requirements of the Brazilian Standards

The step number five (see Fig. 4) is related to motor performance and uses the IM equivalent circuit with calculated parameters from the design data [7]. After the calculation of the equivalent circuit parameters, locked rotor KVA, efficiency, locked rotor torque, breakdown torque and the rising temperature are checked.

4. CAD (Computer Aided-Design) Software

The developed software has a sequential simple and structure, where the steps are described in flowcharts in this section. The first flowchart shown in Figure 4, presents the first part of the software that is the verification of input data by some requirements shown in section 2.

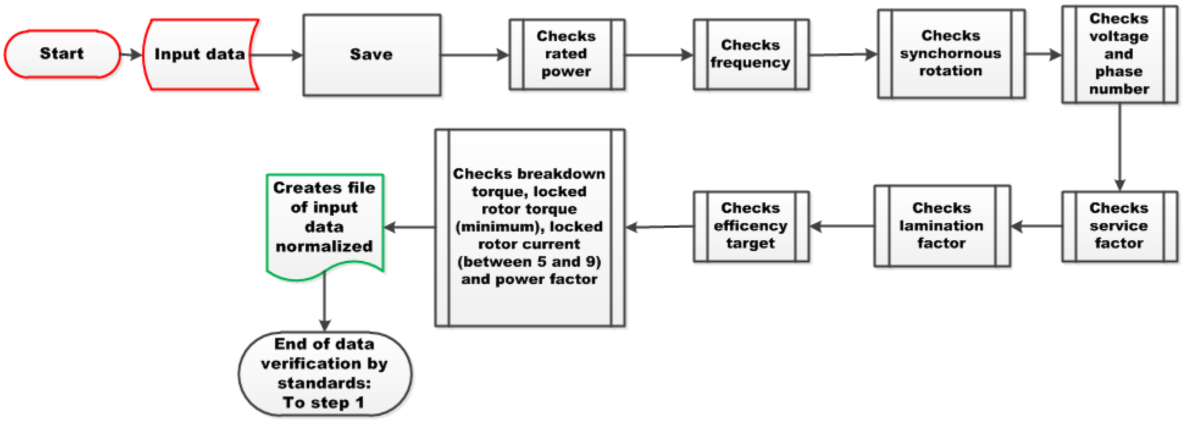

Figure 4 – Standards input data verification

In Figures 6 and 7 are shown the steps 1, 2, 3 and 4, as in Figure 3. Figure 5 introduces the equivalents process of the stator and winding sizing and Figure 6 introduces rotor and squirrel-cage/end-ring sizing.

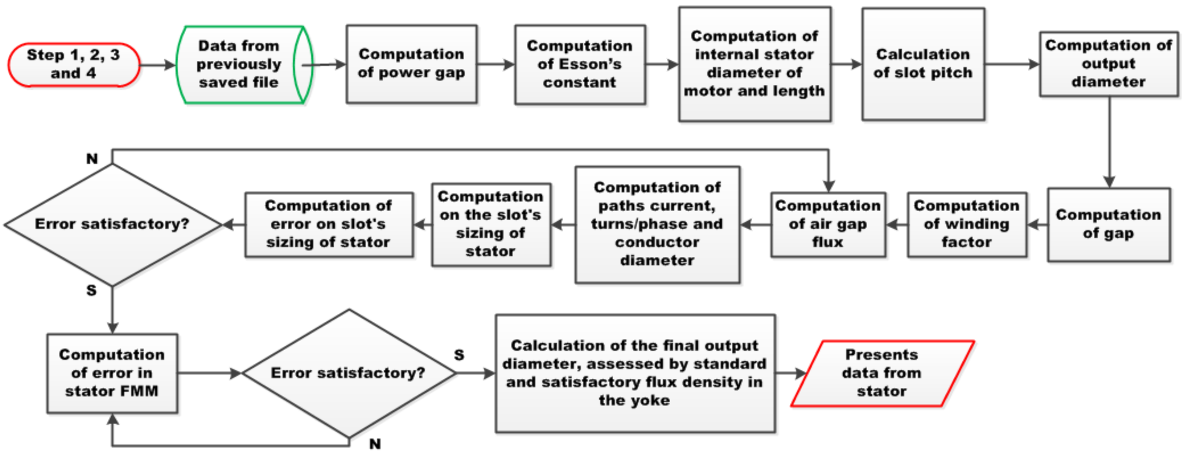

Figure 5 – Step 1, 2, 3 e 4 – Part 1 – Stator Sizing

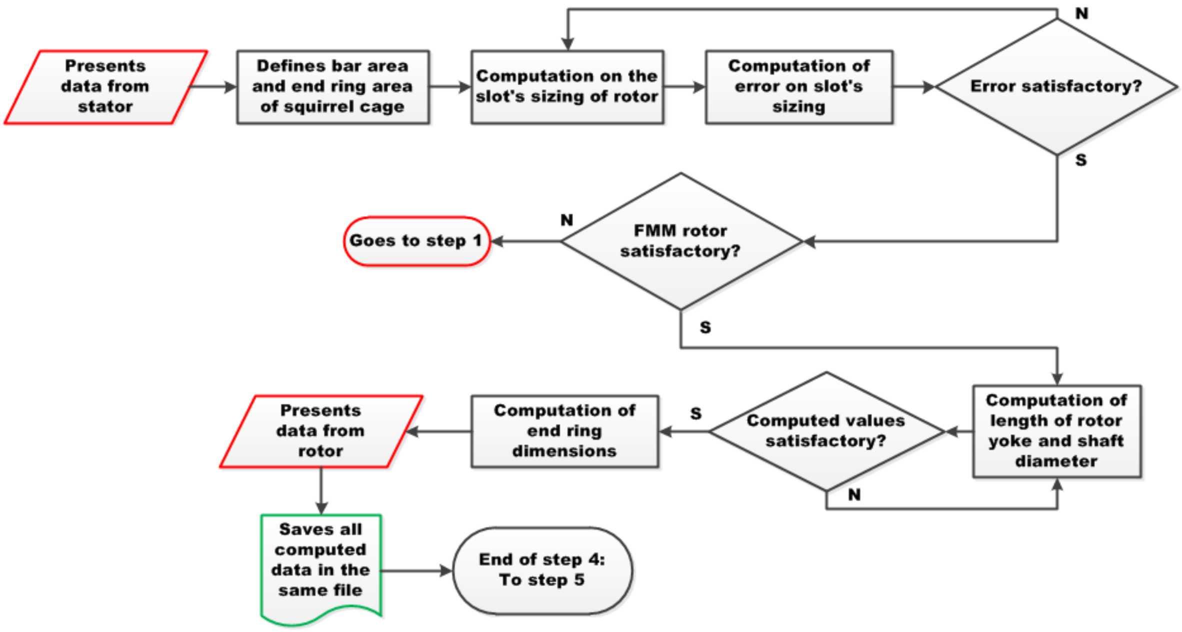

Figure 6 – Step 1, 2, 3 e 4 – Part 2 – Rotor Sizing

The last step of the software (step 5) is displayed in Figure 7. In this step are carried out the performance calculations. Moreover, these calculations are in agreement with the standards utilized in this work.

The software has a window user interaction, showing design information and sets the required inputs to the project. Several screens were designed for the various stages of the project. This was created in efforts to make the software more user friendly for new our infrequent users. This paper will not display all the developed windows, so that only the main windows are presented.

Figure 8 shows the main input data window. All the windows were developed in Portuguese language. The input data are: rated power, synchronous rotation, supply frequency, supply voltage, phase number, service factor, lamination factor, and the target parameters are: power factor, efficiency, locked rotor torque, breakdown torque and locked rotor current.

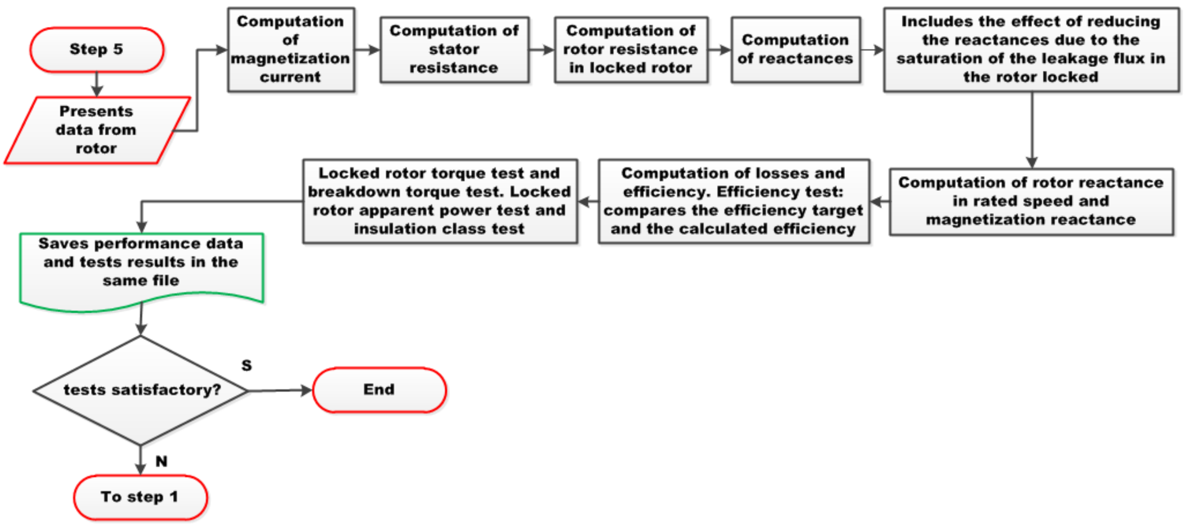

Figure 7 – Step 5 – Motor performances.

Figure 8 – Main window

Figure 9 shows the stator results window. Furthermore, it presents several sizing results, like: stator slot, teeth, output diameter and internal stator diameter

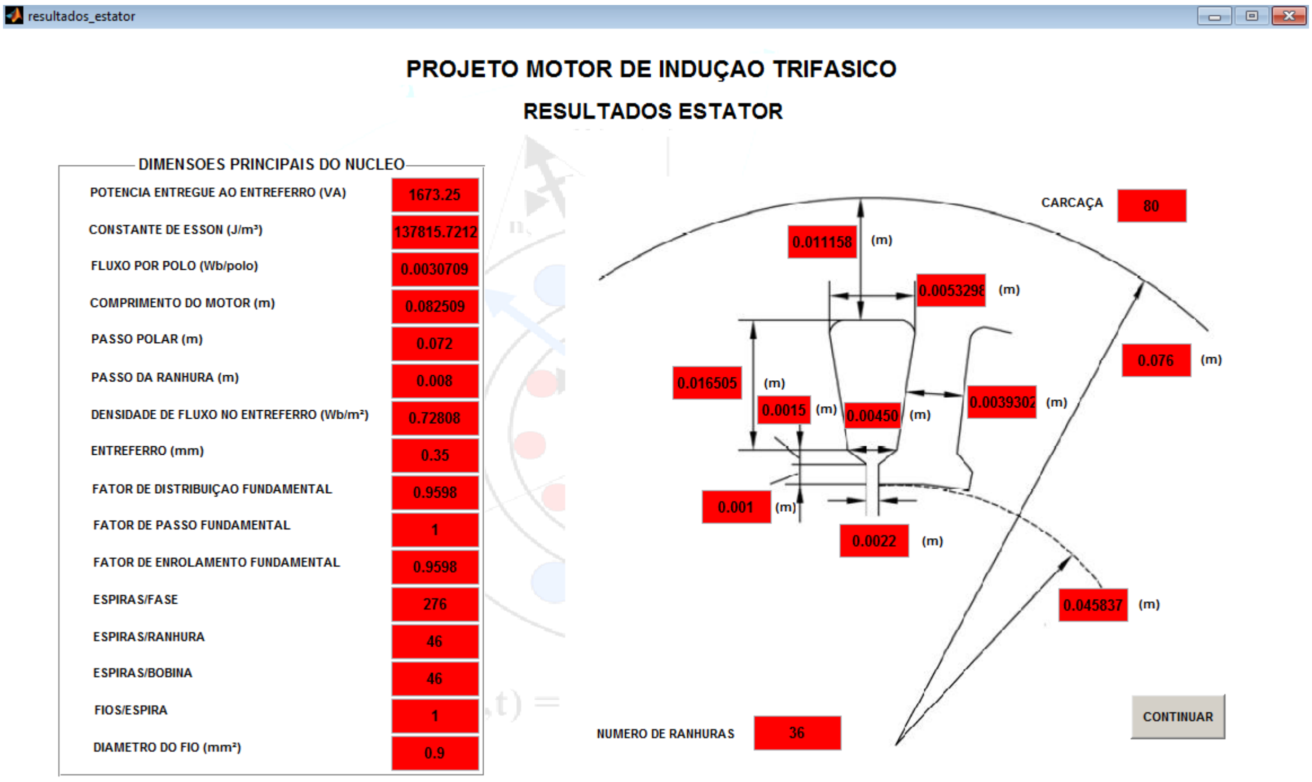

Figure 9 –Stator results window

Figure 10 presents the rotor sizing result window. It shows several sizing results, like: slot rotor, shaft diameter, internal rotor diameter and the bar/end ring sizing.

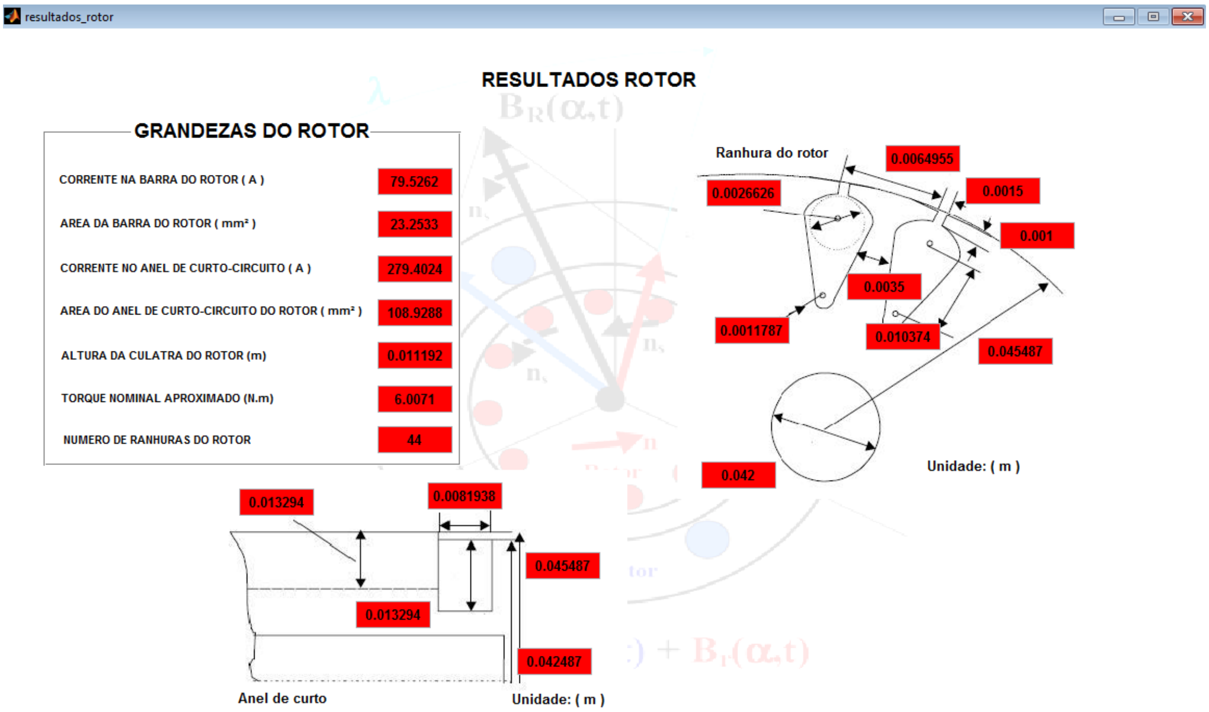

Figure 10 –Rotor results window

All computed motor design data are stored in a spreadsheet and the performance test results as well.

5. Design

This section aims to introduce CAD design of an induction motor with 1.5 hp, 380 V, design N (similar to NEMA design B), 4 poles, 60 Hz, unit service factor load, targeted efficiency 81.5%, targeted power factor 0.79, 1.9 pu locked rotor torque and 2 pu breakdown torque. The ferromagnetic core should be made of steel-silicon alloy (3.5%) with thickness of 0.5 mm. The stator winding has 3 slots/pole/phase, full pitch coils, without currents path in parallel, fill factor 40% and 1.5 aspect ratio. According to [8] the motor must have frame size type 80.

The flux density in the air gap around should be around 0.7 T, the tooth flux density between 1.5 T and 1.65 T and the back core flux density between 1.4 T and 1.7 T. Insulation class is B, however it is a high-efficiency motor with a reference temperature of 80º C [7]. The bar skewing is equivalent to the rotor slot pitch length. The current density in the stator winding is 4.5 A/mm² and current density in the rotor bars is 3.4 A/mm².

Analyzing only the stator winding, it can be seen that motor design has the important properties shown in Table 1. It can be verified that the performance tests were satisfactory, but for the purpose motor design only the efficiency is introduced in Table 1.

Increasing the number of paths current to reduce area of the coil conductor (without modifying the slot area), is likely to increase the motor efficiency. The modified data in the design are shown in Table 2. The new fill factor value is 0.56 and it is set the number of current paths equal to 2.

After the slot sizing (keeping the slot area constant), the Table 2 shows the resizing of the motor winding (increasing the path currents in parallel), resulting in a better efficient.

This section describes the software versatility to obtain the motor sizing and subsequent adjustments were necessary to improve the design requirements, especially in the improved efficiency as shown in Table 2.

Table 1 – Winding design results

Winding parameters	Calculated values
W_1	276
n_s	46
N_b	46
n_{cond}	1
d_{cond}	0.9 mm
a_1	1
K_{fill}	0.4
A_{slot}	73.2 mm²
η	83.3%

Table 2 – Modified winding design results

Winding parameters	Calculated values
W_1	552
n_s	92
N_b	92
n_{cond}	1
d_{cond}	0.75 mm
a_1	2
K_{fill}	0.56
A_{slot}	73.2 mm²
η	84.8%

6. Conclusions

The paper introduces that the constructive aspects of the induction motor using a CAD tool is interesting, fast and serves like an initial step to improve the machine design, consequently, the efficiency. The software does not exclude other techniques, which can refine de design, e.g. finite element methods, being its main advantage.

It is highlighted that such techniques improve the efficiency without extra tooling costs is important after use of software. Since just the number of paths current was increased, without changing the area of the stator slot, the increase on number of turns/phase reduces the conductor area, increasing the wire cost in the motor construction. Since the price/km for second calculated wire (see table 2) is 20% less than the price/km of the first calculated wire (0.9 mm diameter) and the first calculated wire coil/phase length is 114 m (276 turns/phase), the cost of copper increases 60% because the coil length is 228 m (552 turns/phase). Furthermore, the software allows testing different motor techniques, such as: increase of the motor length, which should also increase the motor efficiency [5].

A future software upgrade will include the parameter of minimum torque as recommended in the Brazilian standard [8]. The minimum torque is developed from the torque-speed curve of an induction motor. Another software improvement is to provide the software to downloading on a website and an English-language version.

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