STUDY AND ENERGY EFFICIENCY IMPROVEMENT IN THE DESIGN OF AN INDUCTION MOTOR BASED ON INTERACTIVE CAD SOFTWARE

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***Abstract* – This paper presents a CAD software which uses a methodology to resize the induction motor (IM) winding, by increasing the number of parallel conductors as a means of increasing the efficiency. Such winding resize does not change the shape of the core and slots. Here, parallel conductors with smaller diameters are utilized in the chorded coils. As result, the efficiency and the cost for the resized IM are presented and discussed.**

***Keywords* –Brazilian standards, Winding resizing, Chorded coils, Parallel conductors, Costs.**

I. INTRODUCTION

In recent years, some countries (including Brazil) have reviewed the minimum efficiency levels of three-phase induction motors (IM) and new policies about energy-efficiency motors are gradually changing [1][2][3].

Improvements in the motor efficiency are connecting by incremental increases that modify the motor class (to be more efficient classes). By [2], the level EFF2 (IE1) and the standard motor [3] are similar. The level EFF1 (IE2) is similar to the new efficiency motor's levels in Brazil, and they are called as “high-efficiency efficiency motors" [3]. The level EFF3 (IE2 with 10% -15% fewer losses) are still not available in Brazil. In U.S.A., the IE1 is similar to standard motor by NEMA, IE2 is the same NEMA Energy Efficient/EPCAT and IE3 is similar to NEMA Premium [1].

Many ways of increasing the efficiency of induction motors have been presented. In [4] is presented a technique of increasing the axial length of the motor for increase efficiency. In [5] is presented a technique for improving the fan’s performance and consequently increase efficiency. In [6] the use of copper rotors shown an increase in motor efficiency. Recently, there was an increase in efficiency from the use of soft magnetic material compound (SMC), according to [7]. In some of these studies is presented economic variables.

Winding resizing is presented as a technique to be performed before rewinding machine) [8] (who already have a mechanical failure in the coils). In [8] informs this technique increases the efficiency (depending on the new winding) and provides an opportunity when this subject is the issue. In [9] is presented a technique for increasing efficiency based on changing of connections of the stator windings of motor and without changing the number of parallel conductors of the turn. The same technique is used in Line-Start Permanent Magnet Synchronous Motors (LSPMSM) recently [10] without considering once again the possibility of using the parallel conductors to form the turn.

This paper presents a CAD (computer aided-design) software based on a known method [11] and including the Brazilian standards requirements [12] [13]. The paper’s next step is to resize the stator winding, and this is accomplished utilizing the already designed motor shape with no slot area modification.

The new stator winding has a fixed slot area, and then the resizing includes: the increasing of the number of parallel conductors and the use of the chorded coils (short-pitch) with correction on the MMF (magnetomotive force). It is expected changes in the fill factor, but there are mechanical limits for such increase.

II. CAD SOFTWARE

The CAD software is based on the design methodology for induction motors (IM) below 100 kW and constant voltage and frequency supply [11]. This is a common used methodology for IM design. Figure 1 shows the steps of the project.

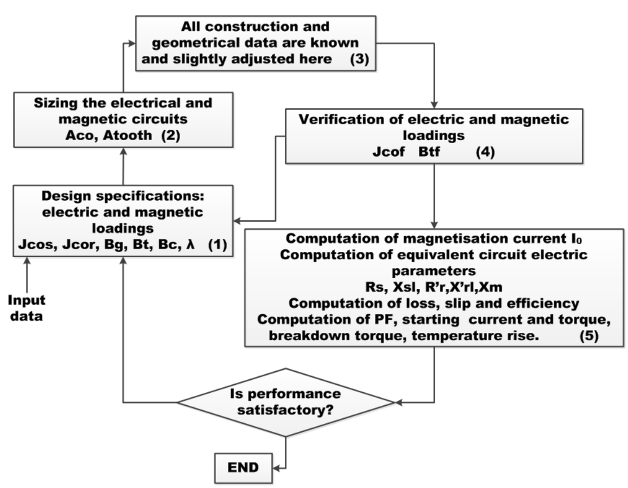

Fig. 1. Flowchart describing the methodology for the IM design.

In Fig. 2, it can be observed the steps where some parameters based on requirements of Brazilian standards are checked [12] [13].

Figure 3 presents the pre-processing of the input data utilizing the constraints of the Brazilian standards. Figure 4 and 5 presents the sizing of the stator and rotor, respectively.

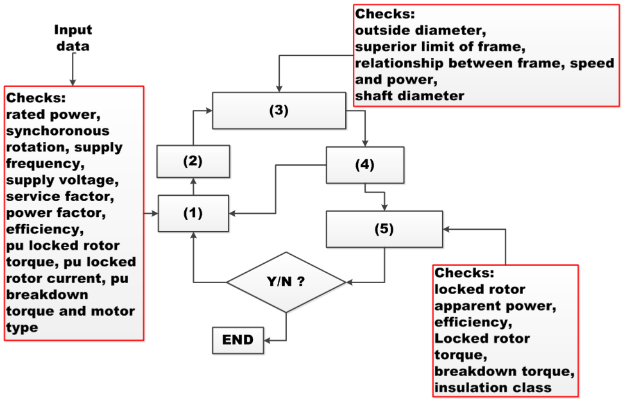

Fig. 2. Flowchart including the Brazilian standard requirements in the methodology for the IM design.

The fifth step is the performance computation of the motor, as shown in Fig. 6. It checks the locked rotor torque, the locked rotor apparent power, the efficiency, the breakdown torque and temperature rise.

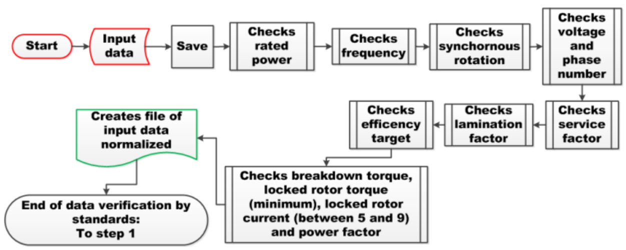

Fig. 3. Flowchart with the steps 1, 2, 3 and 4 – input data pre-processing.

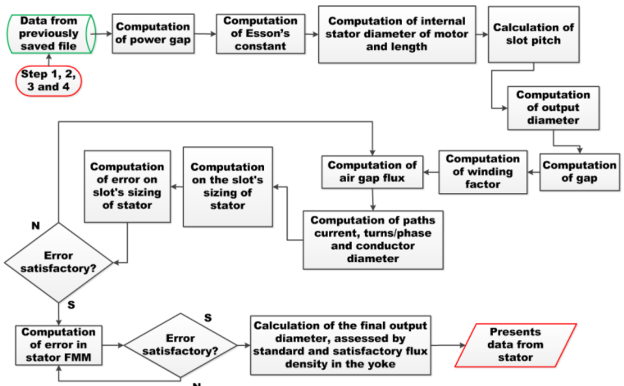

Fig. 4. Flowchart presents steps 1, 2, 3 and 4 – stator sizing.

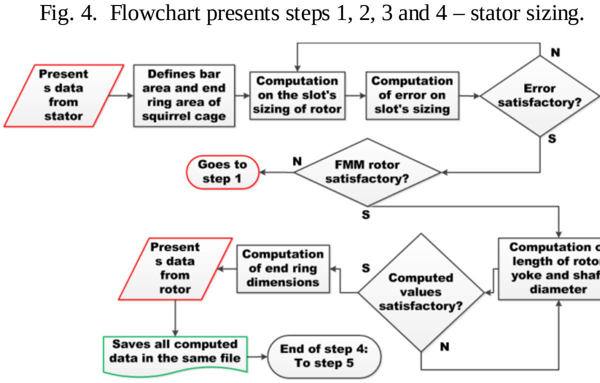

Fig. 5. Flowchart presents steps 1, 2, 3 and 4 – rotor sizing.

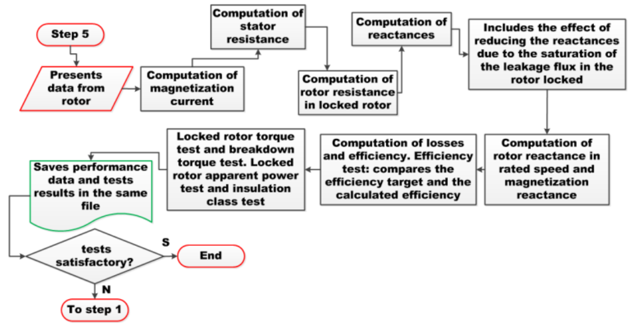

Fig. 6. Flowchart presents step 5 – performance tests.

The software was developed in MATLAB® and it used the GUIDE function to create the graphic user interface. Figure 7 presents the main window used to insert the desired input data.

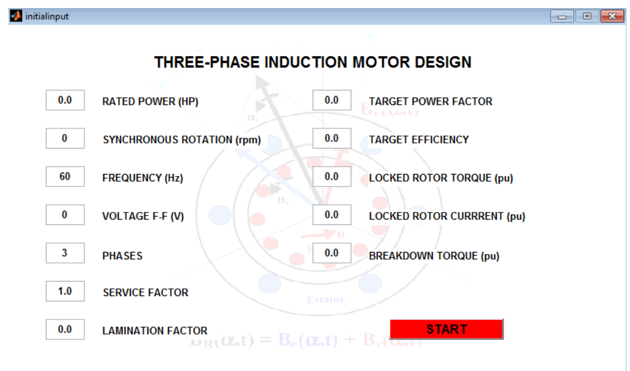

Fig. 7. Main window –input data.

III. RESIZING OF THE STATOR WINDING

The stator winding resizing must be carried out after the end of the project. The software, previously shown, makes a complete IM design with the requested type of stator winding, rotor bars and slots.

The increasing number of parallel conductors is only carried out when some limitations in the sizing of the section of coil wires are crossed [4]. Many other design techniques (techniques included here reported in specific readings of this matter) do not take into account of the resizing of the coils for a particular purpose (In this paper, efficiency).

Moreover, the IM shape (slots, outer and inner diameters, gap, and shaft type) is confirmed with magnetic and electric circuit analysis. Afterwards, the efficiency and performances indexes are calculated.

Figure 8 illustrates the losses in an IM motor. Clearly, the half of the losses is in the stator winding. However, the stator cost may be a limiting factor in the choice of the winding.

Starting the design process with full pitch coils, and a defined number of slots/pole/phase, it will be described a complete design using the developed CAD software. Thereby, the dimensions of the slots in the stator and rotor are defined, as well as its slot areas.

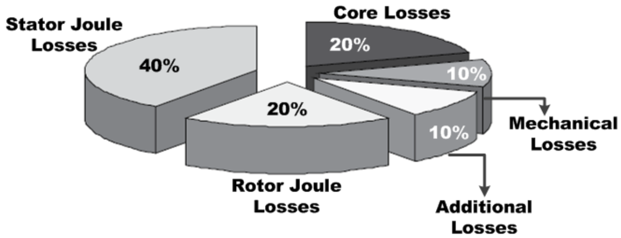

Fig. 8. Average distribution of losses on IM. [14]

A. Increase of the number of parallel conductors

The number of turns per phase (W_1) on an IM is a function handled by the supply voltage (phase voltage – V_Y or line voltage – V_Δ) and the winding factor K_{w1} (product between chording factor and distribution factor), given by:

$$W_1 = K_A \cdot \frac{V_Y}{K_{w1}} \tag{1}$$

Where:

K_A - Constant which dependents of the magnetic flux per pole, the form factor and the frequency.

The number of turns/slot (n_s) is described as:

$$n_s = \frac{a_1 \cdot W_1}{p_1 \cdot q} \tag{2}$$

Where:

a_1 - Number of current paths in parallel.
p_1 - Number of pole pairs.
q - Number of slots/pole/phase.

Stator resistance (R_s) is given by:

$$R_s = \rho_{co} \cdot \frac{l_c}{A_{co}} \cdot \frac{W_1}{a_1} \tag{3}$$

Where:

ρ_{co} - Resistivity of material.
l_c - Coil length.
A_{co} - Conductor area.

The coil length is given in function of the number of poles and the coil span (y). The relationship between the chording (β) and the pole pitch (τ) is given by:

$$\frac{y}{\tau} = \beta \tag{4}$$

The coil length is described as:

$$l_c = \begin{cases} 2 \cdot y - 0.04 \rightarrow p_1 = 1 \\ 2 \cdot y - 0.02 \rightarrow p_1 = 2 \\ \left(\pi/2\right) \cdot y - 0.018 \rightarrow p_1 = 3 \\ 2.2 \cdot y - 0.012 \rightarrow p_1 = 4 \end{cases} \tag{5}$$

All equations are found in [11].

To use this technique, it is necessary to know that the conductor's area connected in parallel reduces the resistance value. By (3), the product between R_s and A_{co} is a constant, unless it be modified by changing the size of coils or the conductor material. R_s' is the new resistance value after changing the number of parallel conductors a_p (less than the original). After resizing, we have a new conductor's area A_{co}' which is less than the initial value. The function that represents all reductions is given by:

$$\frac{R_s'}{R_s} = \frac{1/a_p}{\left(\frac{A_{co}'}{A_{co}}\right)} \tag{6}$$

The plot in Fig. 9 represents the behavior of the ratio shown in (6) for two parallel conductors.

Clearly, there will be an increase in the slot fill factor and the cost of the IM. Therefore, it's important to measure the gain in efficiency and calculates the final cost of these implementations.

It can be observed the relationship between the number of parallel conductors, the conductor area and the current density (J_{cos}), given by:

$$A_{co} = \frac{I_{1n}}{J_{\cos} \cdot a_p} \tag{7}$$

Where:

I_{1n} - Rated current (A).

B. Use of chorded coils

It is possible to use chorded coils in the previously designed core. Then, the coil length should be calculated again in (5), taking into account the new coil span which differs from the pole pitch length.

After calculated, the new coil span changes the stator resistance (3) and the IM cost. Another point is the use of parallel conductors in chording coils. Certainly, this new design may bring a better resistance value and a lower final cost.

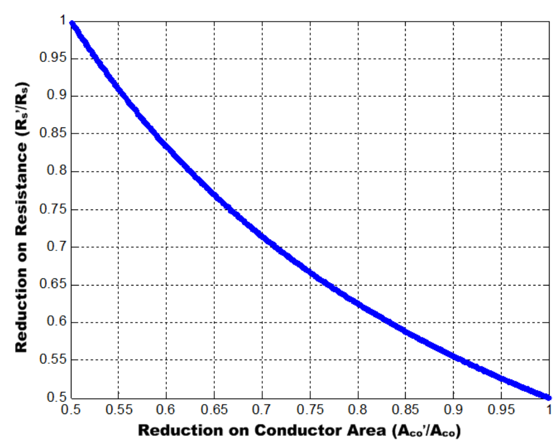

Fig. 9. Relationship between the reduction of the conductor area and the reduction of the stator resistance.

The number of turns/phase should be increased with the use of the chorded coils. Coils have their own number of turns (W_1) and winding factor (K_{W1}). The new number of turns / phase (W_1') should be calculated, taking into account the new winding factor (K_{W1}'), described as:

$$W_1' \cdot K_{w1}' = W_1 \cdot K_{w1} \tag{8}$$

IV. COMPUTER AIDED DESIGN OF A SMALL INDUCTION MOTOR

For the proposed analysis, it's designed a small IM with 1.5 HP, 380 V, 4 poles, 60 Hz, service factor equal to 1.0, target efficiency 81.5%, target power factor 0.79, 1.9 pu locked rotor torque and 2 pu breakdown torque. The ferromagnetic core must be made by steel-silicon alloy (3.5%) with 0.5mm of thickness. The stator winding has 3 slots/pole/phase, full pitch coils, no current paths, 40% of fill factor and aspect ratio equal to 1.5. According to [12] the motor must have frame size type 80.

The flux density in the air gap should be around 0.7 T, the tooth flux density between 1.5 T and 1.65 T, and the back core (yoke) flux density between 1.4 T and 1.7 T. The insulation class is B, however it is a high-efficiency motor with a reference temperature of 80º C [11]. 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. Table I shows the main values for the stator winding resizing.

The rated current is equal to current/turn and the relationship between stator losses and total losses is 39.2%, as shown in Table I. All future modifications in the stator winding will change the values shown in Table I. There will be modifications in all parameters, except number of wires/turn.

The total conductor length to produce a single motor is the necessary length of copper to assembly one stator winding. The change of the coil span will increase the number of turns/phase.

TABLE I
Winding design results

Winding Parameters	Calculated Values
Turns/phase - W_1	276
Turns/slot - n_s	46
Turns/coil - N_b	46
Wire/turn – a_p	1
Conductor diameter - d_{cond} (mm)	0.9
Current Paths in Parallel - a_1	1
Fill Factor - K_{fill} (%)	0.4
Stator Slot Area - A_{slot} (mm²)	73.2
Efficiency – η (%)	83.3
Stator current density - J_{cos} (A/mm²)	4.5
Rated Current – I_{1n} (A)	2.61
Current/wire – I_{1n}/a_p (A)	2.61
Stator Losses - P_s (W)	89.1
Total Losses - P_t (W)	227.2
Coil length – l_c (m)	0.413
Total conductor length to produce a single motor (m)	114.0

V. TYPES OF RESIZING IN STATOR WINDING

In this section, it will be presented the three resizing cases (two parallel conductors, coil span reduction, and two parallel conductors in a reduced coil span).

A. Case 1 - Two parallel conductors

The reduction in the conductor area reduces the stator resistance up to 70% of the initial value as shown in Fig. 9. As an example, a reduction of 25% in the conductor area decreases 33% of the stator resistance, as depicted in Fig. 9.

The conductor reduction is higher than 70%, and then the new conductor diameter should be greater than 0.753 mm. The commercial chosen diameter is 0.8 mm (or 20 AWG). Table II shows the calculated parameters that should be compared with Table I. The use of two parallel conductors increases the efficiency in 1.5% in the design.

TABLE II
Resizing of Stator Winding – Case 1

Winding Parameters	Calculated Values
Turns/phase - W_1	276
Turns/slot - n_s	46
Turns/coil - N_b	46
Wire/turn – a_p	2
Conductor diameter - d_{cond} (mm)	0.8
Current Paths in Parallel - a_1	1
Fill Factor - K_{fill} (%)	0.63
Stator Slot Area - A_{slot} (mm²)	73.2
Efficiency – η (%)	84.8
Stator current density - J_{cos} (A/mm²)	2.6
Rated Current – I_{1n} (A)	2.61
Current/wire – I_{1n}/a_p (A)	1.31
Stator Losses - P_s (W)	56.4
Total Losses - P_t (W)	194.5
Coil length – l_c (m)	0.413
Total conductor length to produce a single motor (m)	228.0

B. Case 2 – Reduction on coil span

To be used a reduction on the coil span, it is necessary to know the number of slots for one pole. In this case, one pole is composed by nine slots, thus the reduction in the coil span may be of one or two slots (8/9 or 7/9). Table III presents the resizing of the original winding by using the chording coils.

Moreover, it is shown that the efficiency increases 0.8% (maximum achieved), utilizing a not usual coil span. The total conductor length to produce a single motor is decreased as expected.

C. Case 3 – Two parallel conductors in a reduced coil span

Following the methodology presented in section V, it is possible to observe changes in the parameters of the motor winding using two parallel conductors with chorded coils.

The use of parallel conductors and chorded coils in the assembly of the winding coil turn is a common technique [11]. In general, this technique is used in order to avoid conductors with unusual diameters (not commercial) [11].

It is displayed in the Table IV, the chorded coil with chording 7/9. There, the IM efficiency will be increased in 2.3 %, keeping the original shape design. Regarding, the chording 6/9, which is not usual, the IM efficiency increases 2.6 %. The changes in the winding motor design are easy to be fulfilled and analyzed in the matter: performance IM.

VI. COST ANALYSIS

The cost for the change of the IM stator winding will be evaluated around the cost value of the original design (using coils full pitch and a single wire/turn).

TABLE III
Resizing of Stator Winding – Case 2

	Chording Coils		
Winding Parameters	**y/τ=8/9**	**y/τ=7/9**	**y/τ=6/9**
Turns/phase - W1	276	288	312
Turns/slot - n_s	46	48	52
Turns/coil - N_b	23	24	26
Wire/turn – a_p	1	1	1
Conductor diameter - d_{cond} (mm)	0.9	0.9	0.9
Current Paths in Parallel - a_1	1	1	1
Fill Factor - K_{fill} (%)	0.4	0.42	0.45
Stator Slot Area - A_{slot} (mm²)	73.2	73.2	73.2
Efficiency – η (%)	83.4	83.8	84.2
Stator current density - J_{cos} (A/mm²)	4.5	4.5	4.5
Rated Current – I_{1n} (A)	2.61	2.61	2.61
Current/wire – I_{1n}/a_p (A)	2.61	2.61	2.61
Stator Losses - P_s (W)	82.2	75.3	68.4
Total Losses - P_t (W)	220.3	213.4	206.5
Coil length – l_c (m)	0.381	0.349	0.317
Total conductor length to produce a single motor (m)	105.2	100.5	98.9

The commercial prices of the enameled wire copper for purchases in large scale (one ton) and for a given wire thickness, are in range from US$ 4/kg up to US$ 8/kg. Using an average price of US$ 14.82/kg (usual price for those who buy less than one ton) and knowing the kg/m relationship for each conductor (0.005814 kg/m for the 0.9 mm conductor and 0.004587 kg/m for the 0.8 mm conductor), it is possible to calculate the average price for an IM winding unit [15].

TABLE IV
Resizing of Stator Winding – Case 3

	Chording Coils		
Winding Parameters	**y/τ=8/9**	**y/τ=7/9**	**y/τ=6/9**
Turns/phase - W1	276	288	312
Turns/slot - n_s	46	48	52
Turns/coil - N_b	23	24	26
Wire/turn – a_p	2	2	2
Conductor diameter - d_{cond} (mm)	0.8	0.8	0.8
Current Paths in Parallel - a_1	1	1	1
Fill Factor - K_{fill} (%)	0.63	0.66	0.71
Stator Slot Area - A_{slot} (mm²)	73.2	73.2	73.2
Efficiency – η (%)	85.3	85.6	85.9
Stator current density - J_{cos} (A/mm²)	2.61	2.61	2.61
Rated Current – I_{1n} (A)	2.61	2.61	2.61
Current/wire – I_{1n}/a_p (A)	1.31	1.31	1.31
Stator Losses - P_s (W)	52.0	47.7	43.3
Total Losses - P_t (W)	190.1	185.8	181.4
Coil length – l_c (m)	0.381	0.349	0.317
Total conductor length to produce a single motor (m)	210.4	201.0	197.8

A. Costs for the resized stator winding

The prices (taking into account just wire copper) of the stator winding are presented in Table V. The increasing in the cost for two wires in parallel are, on average, 57.7% in comparison with the single wire/turn. The cost for two wires in parallel for the unusual chording winding 6/9 is 57.7% higher. Moreover, the cost for the chording winding 7/9 with two parallel conductors compared to the single wire/turn is 57.9%.

TABLE V
Costs for the Stator Winding Resizing

		Chording Coils	
Description		**Conductor diameter (mm)**	**Cost (US$)**
Full pitch winding	Single	0.9	29.47
	2 parallel conductors	0.8	46.50
Chording winding – 8/9	Single	0.9	29.40
	2 parallel conductors	0.8	42.87
Chording winding – 7/9	Single	0.9	25.95
	2 parallel conductors	0.8	40.98
Chording winding – 6/9	Single	0.9	25.56
	2 parallel conductors	0.8	40.32

Figure 10 shows the evolution of the costs of a stator winding in function of the coil chording.

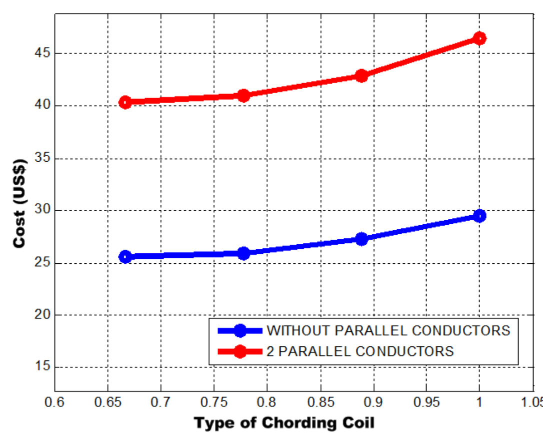

Fig. 10. Cost of each type of chording coils for IM

In Brazil the average price of this motor is US$ 220.00, depending upon the fluctuation of the dollar exchange. Counting the price of these motors designed with full pitch coils and use of parallel conductors, the engine price is US$ 237.00 for increasing the price 7.75%. Considering that the motor is designed with chorded coils there would be increasing 6.12% (8/9), 6.83% (7/9) and 6.71% (6/9).

VII. CONCLUSION

The paper aims to present the effect of resizing the IM stator winding (initially designed with pitch coil without parallel conductors).

The change of the number of parallel conductors and the use of chorded coils presented gains up to 2.6% efficiency and shown that this type of analysis should take into account both changes (parallel conductors and using chorded coils). It is remarkable that the number of parallel conductors (> 2) increases the IM end cost. In the proposed analysis, it was achieved a gain of 2.6% in IM efficiency, followed by an increase in the IM winding cost of 57%. Although not usual, the coil 6/9 does not require additional tooling costs. The increase average selling prices motor is 7% in all studied cases, taking into account only the cost of the copper wire since there are no more tooling costs.

There is interest to improve the developed CAD software for D design induction motors and carry out designs with different types of slots, enabling the design of an IM with double squirrel cage or deep bar. Furthermore, the software should be available on the internet, for the public which uses the Brazilian standards as reference during the design.

As a next step, tests will be performed using software based on finite element method (FEM) to compare results obtained analytically.

Future works will be conducted to improve the IM efficiency utilizing other machine parameters. Moreover, experimental tests will be carried out to confirm the analytically obtained results.

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