# *Single Phase Variable Reluctance Motor Design Using Particle Swarm Optimization*

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# Single-Phase Variable Reluctance Motor Design using Particle Swarm Optimization

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*Abstract*— Electrical engines are built under electromagnetism concepts to create mechanical power, those can be seen as simple machines, as it depends on reluctance, even being called as "reluctance motor", what gives this engine the possibility of being widely used for many purposes. The main objective of this research is to minimize copper losses of a single-phase 6x6 variable reluctance synchronous motor. For that, a Particle Swarm Optimization (PSO) algorithm will be used to obtain the optimum configuration through the Finite Elements Method (FEM). In this context, electric motor design equations were dimensioned based on similar machines. The next procedure was to use FEMM (Finite Element Method Magnetics) software, that allows the magnetic flow density analysis inside the motor air gap. Finally, it is noteworthy that the copper losses results were analyzed before and after the variable reluctance motor optimization with computational tools.

*Keywords—single-phase reluctance motor, finite element method, particle swarm optimization*

## I. Introduction

Variable reluctance synchronous motors (VRSMs) are common engines with simple building aspects low computational and financial costs, but with a wide range of applications. These are the main reasons why reference [1] considered these motors competitive. The VRSMs dual capacity of acting like a motor and a generator, which avoids high inrush currents, reduce costs and operates under constant rotation, that are aspects of engines without windings and magnets and with a single source of incitation applied to the stator windings, what intends to minimize all the resistive losses of machinery winding that occur in the stator current flow.

Therefore, it is possible to estimate an optimal motor, based on specifications of power and size of a previous model [2]. In this context, the research objective is to minimize the copper losses, of a variable reluctance motor (VRM), by using the particle swarm method (PSO algorithm). This way, dimension parameters were used to design the original motor and the optimum motor was designed after applying the finite elements method. Finally, after the optimization process, copper losses and magnetic flow densities were evaluated and the results of both original and optimum motors were compared

## II. Literature Review

This section will be divided in three parts: Particle Swarm Optimization, Finite Elements Method and Variable Reluctance Motor Design.

### A. Swarm Particle Optimization

The PSO algorithm is a computational method that aims to optimize a problem through a proceeding that generates a sequence of approximate solutions that at each interaction, tend to converge to an optimum solution [3]. Comparative studies about the PSO (Particle Swarm Optimization) aspects were inspired on animal behavior, where each individual, of an equally dispersed population inside the problem area, efficiencies were compared. At each executed interaction, the individuals tend to group in smaller spaces around the best solution, therefore, an inertia constant can be estimated, based on the group tendency to find the best solution and considering each individual's best solution.

After a sequence of interactions performed by each individual, the optimum solution for the problem is found [4]. Next the algorithm implementation steps:

- Initially, each swarm particle has a position $x_i$ inside the search space and the speed $y_i$, where the positions are automatically generated;

- For each swarm particle executed interaction, the particle position $pbest$ and the group position $gbest$ are updated, in case they are better than the previous.

During the interaction, the speeds and positions of each swarm particle are updated by the Equations 1 and 2, respectively, to obtain the new position: $x_i$;

$$v(k+1) + \omega v k_i + c_1 r_1 (pbestk_i - xk_i) + \ldots$$
$$\ldots + c_2 r_2 (gbest - xk_i) \qquad (1)$$

$$x(k+1)_i = xk_i + v(k+1)_i \qquad (2)$$

where $v(k+1)_i$ is the updated term for particle speed, $k+1$ is the actual instant, $k$ is the previous instant, $\omega$ is the algorithm inertia constant, $C_1$ is the individual acceleration coefficient responsible for controlling the particle movement distance in one interaction, $C_2$ is the group acceleration coefficient, responsible for controlling a particle movement distance in one interaction, $pbest$ is the best particle position, $gbest$ is the most visited position by the particles, $r_1$ and $r_2$ are aleatory numbers inside the research space [0,1], $x(k+1)_i$ is the new particle position, $xk_i$ is the previous particle position. So, if the stop criterion is not verified, the algorithm returns to Step 2, to start the next interaction, otherwise, $gbest$ will be used as the intended solution.

It is possible to understand that the particle swarm optimization has 3 (three) main steps, knowing the number of interactions is the factor that determines the number of times where the system was evaluated and updated. The main steps, for that, are the following:

- Start: set the parameters and the population (initialize $x_i$ and $y_i$ randomly for each particle/individual);

- Evaluate: analyze the actual position of each particle: $gbest$ and $pbest$;

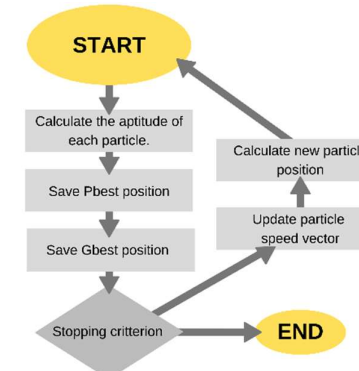- Update: update speed and position of each particle ($x_i$, $t+1$ and $v_i$, $k+1$).



Fig. 1. PSO algorithm flowchart

Figure 1 represents the flowchart with the description of the adopted method. This way, it can be considered that the particle swarm optimization comes partially from concepts and mathematical operators for implementation. During the computational process becomes fast and of low cost in terms of speed and memory.

### B. Finite Elements Method

The Finite Elements Method (FEM) is a set of different numerical methods that approximate problem solutions with Partial or Ordinary Differential Equations (PDE and ODE, respectively) through a geometry subdivision in smaller elements, known as finite elements. Knowing that the exact solution for this problem is very similar to the result of the approximate solution found through this method [5], [6], [7].

The magnetostatic design equations for magnetic circuits operation are based on Ampère and Gauss generalized laws, and they can be described as:

$$rot\, H = J + \frac{\partial D}{\partial t} \qquad (3)$$

$$div\, B = 0 \qquad (4)$$

Where: $H$ is the magnetic field *(A/m)*, $J$ is the current superficial density $(A/m^2)$, $D$ is the electrical induction $(C/m^2)$, and $B$ is the magnetic flow density *(T)*.

A magnetic field can be formed by a current in conductive materials, and due to the local form of the building relations, it is known that the flow and the magnetic field $H$ are related, because the final magnetic permeability $\mu$ product with the field is, by definition, the magnetic flow density $B$:

$$B = \mu * H \qquad (5)$$

The magnetic permeability describes the degree of opposition of a material to the passage of a flow [6]. In general, the relative permeability of a substance, related to the air permeability, is given by:

$$\mu_r = \frac{\mu}{\mu_0} \qquad (6)$$

### C. Single-Phase Variable Reluctance Synchronous Motor Design

Design equations are an essential part of the optimization processes, once the motor size affects the current flow and its distribution along the engine parts. Figure 2 shows the main engine dimensions that must be determined in order to obtain the rotor and stator projects.
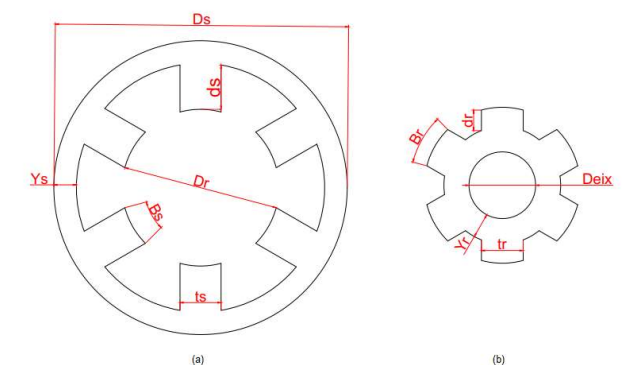


Fig. 2. Dimensions: (a) stator e (b) rotor, of the single-phase variable reluctance 6x6 motor

The rotor diameter can be calculated through the input power.

$$Dr = \left( \frac{4 * P}{TRV * k1 * w * \pi} \right)^{\frac{1}{3}} \qquad (7)$$

where $P$ is the input power; $k1$ is a format constant; $TRV$ is the engine volume set; $w$ is a conversion unit from *RPM* to *rad/s* [8]. And then, the pile length ($L$) can be considered a multiple of the rotor diameter ($Dr$):

$$L = k1 * Dr \qquad (8)$$

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Later, the number of poles inside the stator (*Nps*), will define the poles angles (*Bs*):

$$Bs = \frac{180^o}{Nps} \qquad (9)$$

An important consideration is that the smaller the engine air gap, the highest the current flow. With this information, reference [9] considers that the engine air gap size must be close to 0,50% of the rotor diameter. Another possible consideration is to work under the percentage of 0,25%:

$$g = 0,0026 * Dr \qquad (10)$$

The engine breech can be considered as the difference between the rotor diameter and the poles, and it can stand half the current that goes through the poles. Its size is defined by:

$$Y_s = 1,1 * \left[ \left( g + \frac{Dr}{2} \right) * \left( sin \left( \frac{Bs}{2} \right) \right) \right] \qquad (11)$$

Relations between the rotor diameter (*Dr*) and the external stator diameter (*Ds*) must be inside an interval of 0.40 to 0.70. The following relation adopted a standard of 0.55 for the relation previously defined [1]:

$$Ds = \frac{Dr}{0,55} \qquad (12)$$

The poles width (*ts*) are another important information, that happens because the flow passes intensely through this material. This measure can be calculated using:

$$ts = 2 * \left[ \left( g + \frac{Dr}{2} \right) * \left( sin \left( \frac{Bs}{2} \right) \right) \right] \qquad (13)$$

By adding the stator pole width to twice the size of the engine air gap length, the rotor pole width can be found, as can be seen:

$$tr = ts + (2 * g) \qquad (14)$$

Besides that, the rotor polar arc (*Br*) is given by:

$$Br = 2sin^{-1} \left( \frac{tr}{Dr} \right) \qquad (15)$$

A crucial information to the motor proportions is the rotor pole height (*dr*), that can be obtained by:

$$dr = \frac{ts}{2} \qquad (16)$$

And another important measure is the engine breech height (*Ys*), that can be calculated by using the width of the rotor pole (*tr*) with an addition of 20 to 40%. In this case, the chosen addition was of 20% [9].

$$Yr = 1,2 * \frac{tr}{2} \qquad (17)$$

After calculating the rotor diameter, its height and breech, the axis diameter (*Deix*) can be calculated:

$$Deix = Dr - 2 * (dr + Yr) \qquad (18)$$

And the stator pole height (*ds*) can be found with:

$$ds = \frac{Ds - Dr}{2} - g - Ys \qquad (19)$$

However, the number of turns, per phase (*Ne*), is a result of the interaction between the saturated magnetic flow density (*Bsat*), the peak current (*Ip*) and the engine air gap width, as can be seen in the equation:

$$Ne = \frac{2 * g * Bsat}{Ip * \mu_b} \qquad (20)$$

Given that the wire that must be used to form the turns has its transversal section (*ac*) calculated after the peak current divided by the maximum current flow (*Jc*) and the square root of the number of phases (*q*):

$$a_c = \frac{Ip}{Jc\sqrt{q}} \qquad (21)$$

This calculus can provide the copper loss results. The first step to understand the losses is to calculate the coil resistance:

$$Rf = \frac{\rho_0 * 2 * L * Ne}{ac} \qquad (22)$$

where $\rho_0$ is the copper resistivity and *ac* the wire transversal section, what allows finding the losses of copper (*Pcopper*) and total (*Ptotal*). The first one is calculated by multiplying the coil resistivity (*Rf*) by any current (*l_m*) that passes through the motor. The total losses are copper losses in all wire turns.

$$Pcopper = Rf . I \qquad (23)$$

$$Ptotal = Pcopper . Nps \qquad (24)$$

At the resistive losses (or copper losses), as in the total losses, the results are estimates that can work as a good comparison between analytical and simulated values.

## III. Methodology

A literature review over mathematical models for electrical motors design will be used for modeling the single-phase VRMs. With these models, a PSO algorithm will be executed under the assumptions of the finite element method. The main aim with this procedure is to reduce the copper loss inside this equipment.

Therefore, the simulations will happen through a software that develops numerical models by using electromagnetism concepts. For better understanding about purposes of this text, some items must be highlighted:

1. Set the main parameters for the motor design;
2. Define the necessary equations to model the motor;
3. Study and run the particle swarm optimization algorithm;
4. Write the objective function and the vector parameters to generate the copper loss minimization;
5. Use FEMM software to model, discretize and generate the post processing from before and after the optimization;
6. Verify and compare results between the traditional methodology of electromagnetic device design and the data generated after minimizing the objective function;
7. Generate the motor magnetic flow density and verify the copper loss before and after using the PSO.

In this context, the intention is to write the necessary equations to minimize the single-phase variable reluctance motor copper loss and, later, evaluate through FEMM software the magnetic flow density in order to achieve the research objectives.

## IV. Development and Discussion

In this section, discussions and results will be presented in three parts: original motor, optimization and optimum motor.

### A. Original Motor

To start comprehending the problem, a single-phase motor with 6 poles was chosen, with the specifications listed on Table I. This is a model by WEG that has characteristics of an induction motor.

TABLE I.    Original Motor's Variables

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| Constant k1 | 1.4363 | Efficiency | 0.8 |
| Set per engine volume TRV | 16000 | Voltage | 220V |
| Power CV | 7.5 | Magnetic flow density before saturation | 1.5T |
| RPM | 1760 | Magnetic flow density for saturation point | 2.2T |
| Number of stator poles | 6 | Magnetic permeability | $4\pi * 10^{-7} H/m$ |
| Input power | 5500W | Current density | 6 A/m² |

Therefore, a MATLAB algorithm was developed to generate the dimensions of the 6 poles variable reluctance motor stator and rotor, as well as its coils, which took to the construction of the motor via AUTOCAD with a few adjusts, and later exporting this model to FEMM, setting materials and borders. In this way, just enter the file menu and click import .dxf finally open the CAD Drawing file and the drawing will be imported into FEMM. After developing the motor project equations and running the algorithm, the main parameters were found, as shown in Table II.

TABLE II.    Dimensions of the Original Motor

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| *Dr* | 118.4 mm | *Tr* | 31.34mm |
| *L* | 170mm | *Br* | 31º |
| *Bs* | 30º | *Dr* | 15.39mm |

| | | | |
|---|---|---|---|
| *g* | 0.3077mm | *Yr* | 18.8mm |
| *Ys* | 16.9mm | *Ds* | 33.16mm |
| *Ds* | 215.2mm | *Ne* | 20 |
| *ts* | 30.78mm | *ac* | 5.133mm² |

In order to verify the electromagnetic device, the peak current of 53.34 A is considered, this current was obtained by the sum of the nominal current with the efficient nominal current. This means that the magnetic flow density applied to the peak current (*Ip*) must not have a module superior to the material magnetic flow saturation density.

The steel saturation is, approximately, of 2.2T. Figures 3 and 4 represent the motor magnetic flow density and the highest value is close to 2.2T, although inferior. In general, single-phase VRMs work close to saturation, if compared to other motors, besides that, the motor performance is still good.
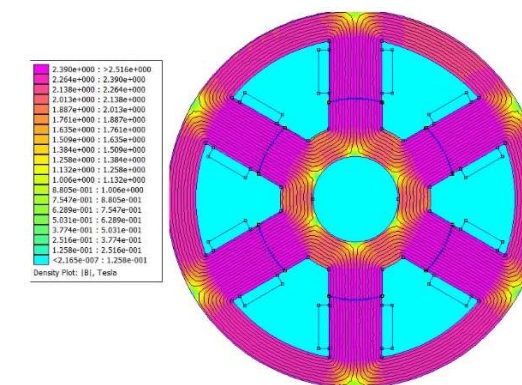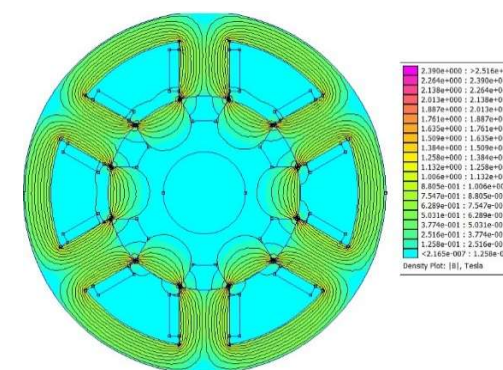


Fig. 3.   Original motor aligned



Fig. 4.   Original motor misaligned

After computational simulation through FEMM software, the total copper loss was found for a peak current of 190.54W, with the analytical solution, the result is 194.52W. Therefore, the error between methods was of 2.04 %. It is concluded that with the increase of input current, the magnetic flow density is increased inside the motor air gap with a proportional relation.

The total losses had a significant scale value, which means specific optimizations will be required to reduce the power loss in the windings.

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### B. Optimization

Following the PSO steps and considering the Equation 24 as the objective function (OF) of the problem, the objective becomes minimizing the single-phase variable reluctance motor copper losses. Some of the variables, parameters and limits were listed on Table III.

TABLE III. VARIABLE, PARAMETER AND LIMITS

| Variable | Parameter | Minimum limit | Maximum limit |
|---|---|---|---|
| $x(1)$ | $Dr$(mm) | 110 | 130 |
| $x(2)$ | $Ys$(mm) | 15 | 20 |
| $x(3)$ | $Yr$(mm) | 17 | 22 |
| $x(4)$ | $Deix$(mm) | 30 | 60 |
| $x(5)$ | $g$(mm) | 0.3 | 0.6 |

The Objective Function will be Equation 24, in addition, we used lateral constraints that delimit a range of variation for each design variable. It is worth mentioning some settings of the PSO algorithm, such as:

- Population size: 50;
- Generations number: 50;
- Inertia weight: 1;
- Inertia weight damping ratio: 0.99;
- Personal learning coefficient: 1.5;
- Global learning: 2.0.

Thus, the processing time was less than five minutes and the computational cost was also low, followed the settings of the notebook used in the optimization: i5, 10GB and SSD 256GB.

TABLE IV. PARAMETER VALUES AFTER THE PSO ALGORITHM IS RUN

| Parameter | Optimal value |
|---|---|
| $x(1)$ | 114 (mm) |
| $x(2)$ | 18.4 (mm) |
| $x(3)$ | 20 (mm) |
| $x(4)$ | 45.0 (mm) |
| $x(5)$ | 0.305 (mm) |
| $OF$ | 45.2 (W) |

After executing the algorithm, other two parameters were described, as well as the objective function, as seen on Table IV, where a saturation current of 27.65A and the copper losses were considered as 58.59W.
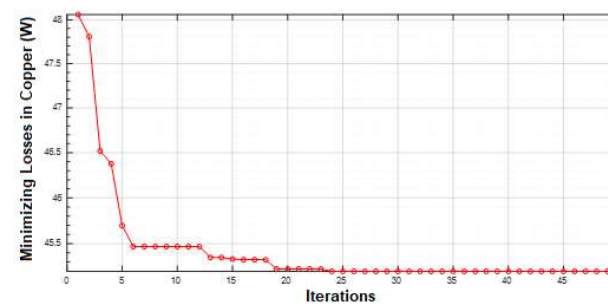


Fig. 5. Minimization of Losses in VRM Copper through PSO

In general lines, the problem is based on a mono-objective function, that with the optimization, reduced the copper loss in 29.62% when using the saturation current, as can be seen in Figure 5.

### C. Optimum Motor

After running the algorithm 10 times in the test, it was possible to observe the standard deviation and mean of the design variables and the objective function. Table V shows the details of the executions, showing the optimum motor parameters.

TABLE V. PARAMETER VALUES AFTER THE PSO ALGORITHM IS RUN

| Tests | OF | x(1) | x(2) | x(3) | x(4) | x(5) |
|---|---|---|---|---|---|---|
| 1 | 45.0 | 113.8 | 18.3 | 20 | 45,2 | 0,305 |
| 2 | 45.2 | 114.0 | 18.4 | 20 | 44,9 | 0,305 |
| 3 | 45.3 | 114.2 | 18.3 | 20,1 | 44,9 | 0,305 |
| 4 | 45.6 | 114.0 | 18.3 | 20 | 45 | 0,305 |
| 5 | 45.3 | 114.0 | 18.4 | 19,9 | 45,2 | 0,304 |
| 6 | 45.2 | 114.1 | 18.4 | 19,8 | 45,3 | 0,304 |
| 7 | 45.3 | 114.0 | 18.3 | 20,1 | 45,1 | 0,306 |
| 8 | 45.2 | 114 | 18,2 | 20 | 44,8 | 0,305 |
| 9 | 45.1 | 114,2 | 18,5 | 20 | 44,9 | 0,306 |
| 10 | 45.0 | 114,1 | 18,4 | 20 | 45,1 | 0,305 |
| Standard Deviation | 0.175 | 0,117 | 0,085 | 0,087 | 0,164 | 0,305 |
| Average | 45.2 | 114,0 | 18,4 | 20,0 | 45,0 | 0,305 |

An interesting observation is that the measures were reduced, except for the parameters ($Yr$) and ($Ys$), the rotor and stator breeches had a measurement increase.
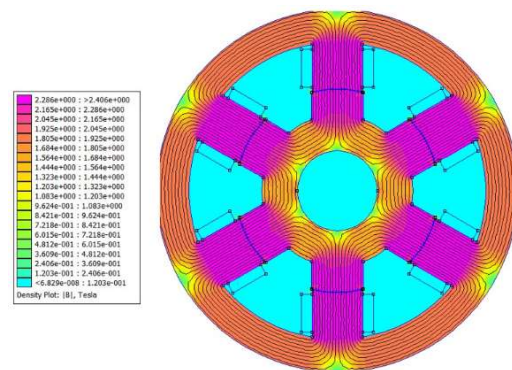


Fig. 6. Optimum motor aligned

Figures 6 and 7 indicate the magnetic flow density inside the VRM with the peak current after the optimization process.
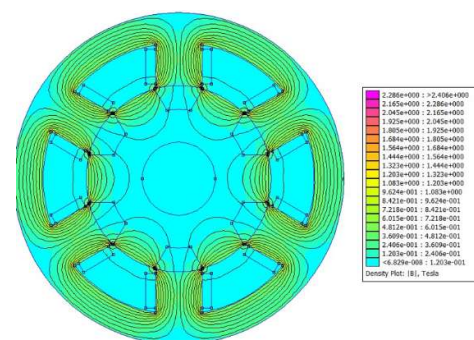


Fig. 7. Optimum motor misaligned

After the optimum motor computational simulation with FEMM software, a total copper loss for a peak current of 183.63W was found. With analytic calculus, the value was 180.78W. This means that the error between analytical and simulated results for the optimum motor is of 1.57%. It can be concluded that the magnetic flow density on the motor after the optimization reduced, what means they are under the material saturation of 2.2T. In this context, it can be observed that the PSO algorithm is effective for the convergence of the mono-objective functions, what means that the total copper loss was successfully reduced.

### D. Magnetic Flow Density Analysis

The single-phase variable reluctance motors, in general, work close to the saturation, when compared to other motors, even so, their performance is good. Figures 8 and 9 represent the total airgap length when submitted to the peak current, in the original and the optimized motor.
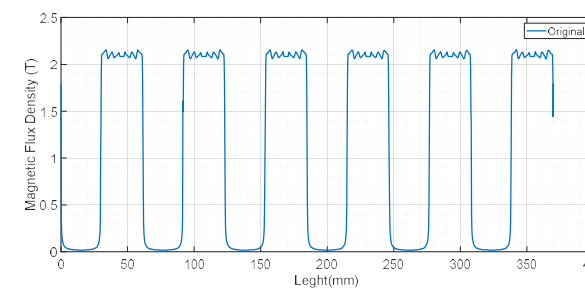


Fig. 8. Magnetic flux density for peak current of original motor
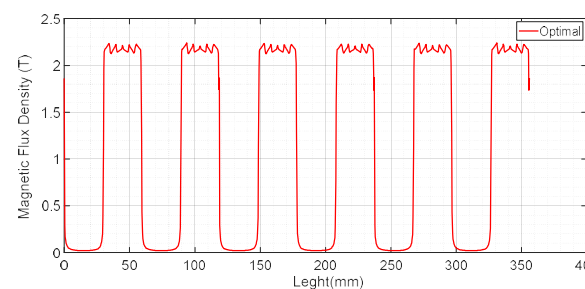


Fig. 9. Magnetic flux density for peak current of optimal motor

As the magnetic flow density in the airgap to a motor on its original and optimal unalignment, the flow density is low, therefore the data was not proven through graphics, but the flow gets thinner on the gap between stator and rotor. It can be concluded that with the increase of the input current, there is an increase to the magnetic flow inside the airgap of the single phase VRM, therefore, they have a directly proportional relation. The same behavior can be observed with the copper losses. In general, simulations stay under the iron saturation value of 2.2T, when simulated until the peak current. During the optimization procedure, the copper loss was reduced and the magnetic flow density in the airgap was under the saturation point.

### V. CONCLUSIONS

Reducing the copper loss and reducing magnetic flow density, guarantees efficiency improvement during the motor operation, in a way that the equipment can convert energy more efficiently. Comparing the properties between both motors: the original and the optimum, it can be considered that the optimization was successful, once the main objective of reducing copper loss was achieved, as well as the ideal measures were presented. It might be necessary to take into consideration the optimization of other parameters, since not all the motor measures were reduced, but some even had some increase. This is an important factor for further research.

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Dullian is a Civil Engineering student at the Federal University of Paraná (UFPR), who currently performs scientific initiation (PIBIC-CNPq) under the topic of PSO algorithm optimization of a 6x6 monophase motor's airgap copper loss and magnetic flow. He's a student representative at the Civil Engineering course's collegiate at UFPR and has got a scholarship at the geoprocessing data laboratory (LAGEAMB-UFPR). Dullian is also a technitian in eletromechanics by the Federal Institute of Santa Catarina (IFSC-SC) with emphasis in procedures and projects.
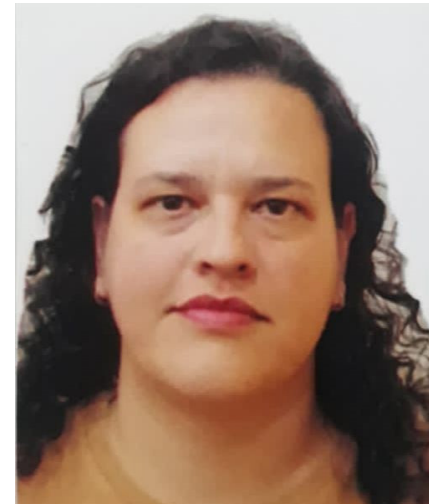
## Juliana Malagoli

Juliana Almansa Malagoli was born in Uberlândia (Minas Gerais) and is graduated in Electrical Engineering with emphasis in computing by the Federal University of Uberlândia (UFU). Became a master in Electrical Engineering by UFU in 2012, same year when she started her doctorate thesis on the field of energy systems at the same university. In 2016 she has accomplished her doctorate degree in Electrical Engineering. Juliana has participated of the Electromagnetic Device Design and Analysis Group of the Federal University of Santa Catarina (GRUCAD-UFSC) during the period of 2012-13 and is now the lead researcher of the Study Group on Modeling, Environmental and Intelligent Systems of the Federal University of Paraná (GEMSAI-UFPR), where she is a professor of higher education at the Pontal do Paraná Campus – Center for Marine Studies (CPP-CEM UFPR) and a collaborative professor at the Graduate Program in Electrical Engineering (PPGEE-UFPR) in Curitiba.

## Cinthia Silva Coelho

Has a bachelor's degree in Industrial Electrical Engineering from the Universidade Tecnologica Federal do Paraná (2013) and a master's degree in Electrical Engineering from the Universidade Federal do Paraná (2017). She is currently a professor in the Department of Electrical Engineering at the Pontifical Catholic University of Paraná. She has experience in the field of Electrical Engineering, with emphasis on Electrical and Industrial Installations, working on electrical projects for hydroelectric power plants, dams, airports, and other industrial and infrastructure facilities. Her main areas of expertise include electrical installations, lightning protection systems (SPDA), power flow, and state estimator.