Electromagnetic Design of a PM Synchronous Generator for a 20kW Ultra-Low Head Hydro Turbine

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***Abstract*— Despite the technical requirements associated with building a tidal power station there is a considerable amount of sites identified in Portugal suitable for this purpose however most of them imply an unbearable investment due to the low revenue in the short term that discourages the investors.**
The revenue of a tidal power plant is mainly related with the initial capital invested on the acquisition of the generators and on the profit obtained, highly dependent on the generator efficiency.
This project aims to execute the electromagnetic design of a permanent magnet synchronous generator for a 20 kW Ultra-low Head Turbine that surpass the electromechanical characteristics of the *Ginlong PMG-20K*, the most profitable solution for the Portuguese sites with tide currents under 3 m/s.

***Keywords*— Tidal Power, Electromagnetic Design, Permanent Magnet Synchronous Generator, Winding Harmonics, Rotor Losses**

I. Introduction

Due to the availability, the hydropower renewable energies are a priority to the Portuguese economic strategy, especially the Tidal Energy: electric power production using the water movement (currents) generated by tides. Despite the set of disadvantages related with the construction tidal power plants there is an identified group of locations in Portugal that respect these constraints and are available to receive this technology. Since the capital costs are a major factor on any renewable energy project and this technology often does not have fast economic revenue, the tidal energy production relies on its ability to be a complement on other forms of energy since its power production is easily predictable and it can be an auxiliary when the others are not available**.**
The identified sites on the portuguese coast have different characteristics but the focus will only be given to locations where the currents are strongly influenced by tide action and the maximum speed is close to 3 m/s. The capital costs of a plant project are highly dependent on the costs of the generators and electric components used, *Costa* (2013) in his master thesis [1] made a study to find the cheapest solution to this type of sites. He made a research on the market and concluded that the generator produced by *Ginlong Technologies*, the *Ginlong PMG-20K* in a direct drive system was the solution that would produce more energy and at the same time guaranteed the greatest revenue to the investor.

A. *Aims and Objectives*

The main goal of this project is to design a generator with electromechanical characteristics in the range of 100 rpm, 550 V and 20 kW and that at the same time surpass the *Ginlong PMG-20K*, at least in one of the following features: higher efficiency, smaller volume, lower material costs.
In order to achieve the previous features the project is divided in two separate parts consisting on two specific objectives:

Objective 1: Optimization – Create a software to calculate the optimal generator winding arrangement and geometric dimensions
To a given number of slots, poles, phases, layers and material electric characteristics the program randomly generates various combinations of winding arrangements and parts dimensions, such as the length of the rotor yoke, magnet, air gap, stator and slot mouth width. The simplified models of the generator calculate the values for the objective functions: the generated torque using the model of *Strous* (2010) [2], the balanced condition using the model of *Delgado* (2009) [3], the rotor losses using the model of *Fornasiero* (2010) [4], the generator volume and the material costs. The optimization algorithm outputs the optimum solution for the winding arrangement and geometric dimensions.

Objective 2: Verification – Build a generator model and simulate the electromagnetic operation
This part consists on using the optimal solution of the winding arrangement and geometric dimensions to design the generator on a computer aided design program and simulate the generator electromagnetic operation on finite element software.

II. Theoretical Background and Modeling

The working operation of a permanent magnet synchronous generator is linked and associated to a full set of electromagnetic laws and principles used to create a model for

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the most important phenomena occurring in these machines and to build the optimization software. Despite that only the electromagnetic operation is being described it is also important to remember that as an electromechanical device the generator electric phenomena have also mechanical implications.

A. System Model

The model in use is the radial flux slot winding permanent magnet synchronous generator. The slot winding machines are characterized for the interconnected concentrated windings confined to a slot disposed on the interior surface of the stator.

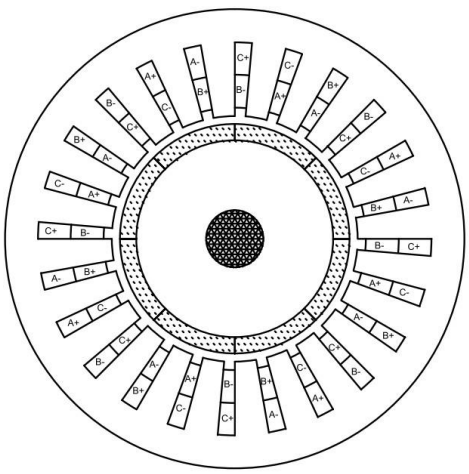

Figure 1 - Typical Design of a Radial Flux Slot Winding Permanent Magnet Synchronous Machine

The slot winding machines are characterized by their ability to create a high torque density, low torque ripple and high efficiency. However, the slot winding machines are also characterized by high contents of space harmonics on the air gap *MMF* distribution. Those harmonics are moving asynchronously with the rotor and inducing currents that consequently produce losses in all rotor conductive parts.
Due to the amount of calculations needed to represent the exact geometry of the slot machines it is used a simplified model. This model uses an analytical approach based on Maxwell equations in a two dimensional space. The simplified rotor model uses a cylindrical geometry with layers composed by four different zones: air-gap, magnet, rotor yoke and shaft.

B. Permanent Magnet Synchronous Machine Electromotive Force and Torque Model

To predict the complex operation of a permanent magnet synchronous machine with precise results without over complexify the model run under some assumptions that reduce the amount of variables and consequently the computation time. The goals are the determination of the electromagnetic force and the generated torque expressions [2] that will be used by the optimization software.

The analytical expression of the tooth magnetic flux density, B_t, will be used to calculate the magnetic flux distribution along the machine and secondly the electromagnetic force induced in the coils of the winding. The modeling will use the magnetic circuit representation of the permanent magnet synchronous generator under the following assumptions:

- Full pitch winding configuration, the number of slots equal to the number of poles ($N_p = N_s$)
- No load applied

Despite that the fringing and the constant rotation of the magnetic field produce an inhomogeneous flux density distribution over one slot pitch the calculation of the average flux density in the air gap use the following assumptions:

- The flux crosses the air gap perpendicular
- The flux density distribution in the air gap over one magnet pitch is homogeneous
- The saturation effects are neglected

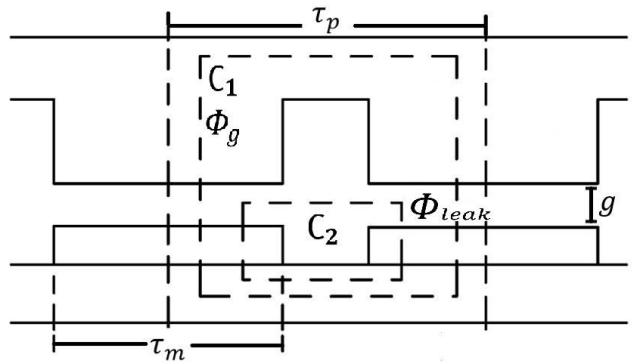

Figure 2 - Effective Flux Contour and Leakage Flux Contour

Not all the flux generated by the magnets is going to contribute to the production of induced voltage since portion of it is leaked through the air gap. Using all the assumptions and constraints previously defined the machine operation can be represented in the following magnetic circuit,

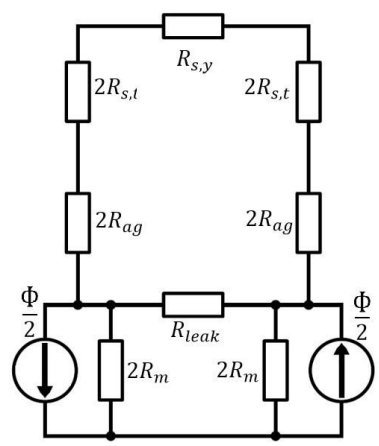

Figure 3 – Relutance Circuit Representation of the Permanent Magnet Flux Model

The magnetic flux density distribution magnitude in the stator tooth is

$$B_t = 2\frac{\Phi_g}{w_{s,t} l_{ef}} \tag{1}$$

The continuous movement of the rotor will produce a change on the magnetic field inducing a voltage in the stator coils. The induced voltage *EMF* will be derived under the following assumptions:

- Balanced three phase system
- The induce voltage is purely sinusoidal

$$B_t(\theta) = B_t \cos(\theta) \tag{2}$$

- The flux linkage is given by

$$\lambda_t(t) = N_n \iint_S B_t(\theta)\, dS_t \tag{3}$$

The induced voltage is

$$E_t(t) = -\frac{d\lambda_t(t)}{dt} = -N_n l_{ef} r_{rot} \frac{1}{N_p} \frac{-2B_t \cos(\theta)}{dt} \tag{4}$$

The expression for the *EMF* induced in a single coil is given by

$$E_t(t) = 2\omega_m N_n l_{ef} r_{rot} B_t \sin(\omega_e t) \tag{5}$$

The total *EMF* induced in a phase winding is the sum of the voltages across the coils but because the winding assigned to each phase is distributed in the stator slots the *EMF* induced on different slots are not in phase and their sum is less than the numerical sum therefore this effect can be translated as a factor, the winding factor k_w, and the expression is given by

$$E_{ph}(t) = 2\frac{N_s}{N_{ph}} k_w \omega_m N_n l_{ef} r_{rot} B_t sin(\omega_e t) \tag{6}$$

Using the previous expression it is possible to calculate the applied output torque

$$T = 3\sqrt{2}\frac{N_s}{N_{ph}} k_w N_n l_{ef} r_{rot} B_t I_{ph} cos(\varphi) \tag{7}$$

C. Winding Harmonics Model

The current on the coils of a generator originates a magnetic interaction between the phase windings creating a magnetic field that generates a magnetomotive force in the air gap. The harmonics of the air gap *MMF*, also called space harmonics, have undesirable effects on the generator operation.

Given the possible dispositions and arrangements of a winding it is used a simplified procedure that allows a general method for the calculation of the harmonics. The method [3] is based on the conductor density distribution for each coil located on the interior surface of the stator.

For a single coil the conductor density distribution is defined as

$$C_n = \frac{N_n}{b_s} \tag{8}$$

, where b_s is the stator slot mouth and N_n is the number of turns per coil. The conductor density distribution signal is defined by the sense of the current flowing in the coil, as shown in Figure 4.

Each coil is defined by the following parameters:

- Coil Axis x_n: middle point of the coil across the stator coordinate system.
- Coil Span α: distance between two coils centers.

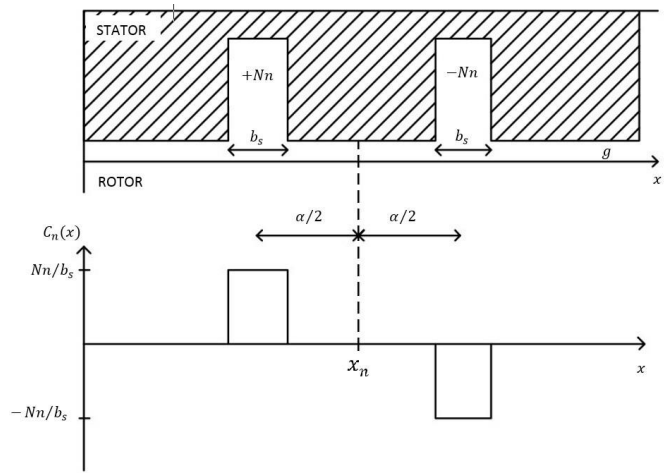

Figure 4 – Planar Configuration of Stator and Rotor of a Fractional Slot Generator

Using the complex Fourier analysis to calculate the conductor density distribution for a series of coils the contributions of all the coils have to be summed. The winding W consists of c number of coils then the conductor density distribution is

$$C_w(x) = \sum_{\nu=-\infty}^{\infty} \overline{C_w} e^{-\frac{j2\nu}{d}x} \tag{9}$$

, where v-th harmonic complex conductor distribution $\overline{C_w}$ is

$$\overline{C_w} = = -\frac{2jN_n}{\pi d}\left(\frac{\sin\left(\frac{kb_s}{2}\right)}{\frac{kb_s}{2}}\right)\sum_{n=1}^{c} sin\left(\frac{k\alpha}{2}\right) e^{-jkx_n} \tag{10}$$

Using the conductor density distribution and the current in the winding to calculate the air gap magnetic flux density for a single coil:

$$B_g(x,t) = \frac{j\mu_0}{kg} i_{ph}(t) C_n(x) = \frac{j\mu_0}{kg} i_{ph}(t) \sum_{k=-\infty}^{\infty} C_n(x) e^{-jkx} \tag{11}$$

,where g is the air gap length.

Using the follow simplifications:

- Number of coil turns: N_n
- Coil Position at x_n
- Narrow slot-mouth, $K_{bs} \approx 1$

$$B_g(x,t) = i_{ph}(t) \sum_{k=1}^{\infty} \frac{4\mu_0}{kg}\frac{N_n}{\pi d} sin\left(\frac{k\alpha}{2}\right) \cos(k(x - x_n)) \tag{12}$$

The air gap *MMF* is obtained by the relation with the magnetic field strength:

$$F_g(x,t) = gH_g(x,t) = \frac{g}{\mu_0} B_g(x,t) \tag{13}$$

For a group of coils connected in series the expression for the air gap *MMF* is

$$F_w(x,t) = 2N_n i_n(t) \sum_{\nu=-\infty}^{\infty} \frac{1}{\nu} \left(\sum_{n=1}^{c} sin\left(\frac{k\alpha}{2}\right) \cos(k(x - x_n)) \right) \tag{14}$$

The total magnitude of the air gap *MMF* harmonics is obtained summing the expression for the total amount of coils connected in series per phase

$$\left|\overline{F_g}\right| = \left(\sum_{r=1}^{number\ of\ phases} \left|\overline{F_w}^{\,r}(x,t)\right| \right) \tag{15}$$

D. *Rotor Losses Model*

Permanent magnet machines with slot windings are usually the solution used for direct drive applications because of their high torque density, low torque ripple and high efficiency however they also have a high content of space harmonics that mainly cause losses. The model [4] in usage simplifies the geometry of the materials composing the rotor to concentric cylindrical layers and the expressions used to determine the losses are Fourier series expansions of the Bessel functions.

The rotor losses are calculated using the four layers straight-lined model neglecting the border effects in the machine along L_x, being the $L_x = 2\pi r_{stat,in}$ where $r_{stat,in}$ is the stator inner radius. Each one of the four regions are composed by the following materials:

1. Region I: Air Gap
2. Region II: Magnet
3. Region III: Rotor Yoke
4. Region IV: Shaft

Each air gap *MMF* harmonic induces an alternate current in the air gap region linear along the z axis. That source is assumed to be a linear current density with the following expression,

$$\overline{K_s}(x) = \widehat{K}_s e^{j\pi x/\tau_\upsilon} = k\left|\overline{F_g}^{\,\upsilon=\upsilon_n}\right| e^{j\pi x/\tau_\upsilon} \tag{16}$$

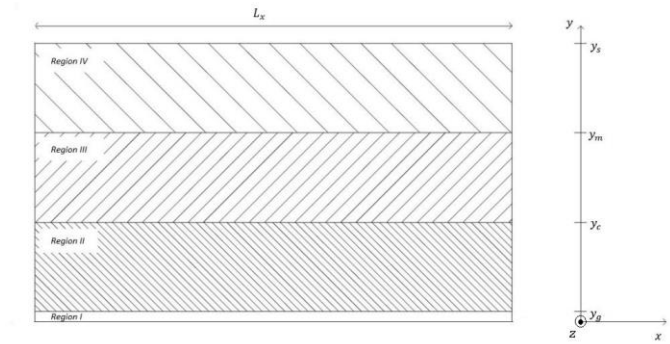

Figure 5 – Four Layer Rotor Regions

Applying the Maxwell´s equations using the magnetic vector potential $\bar{A}$:

$$\nabla^2 \bar{A} - j\omega\mu_0\sigma\bar{A} = 0 \tag{17}$$

The magnetic vector potential $\bar{A}$ can be expressed in terms of two other functions $\bar{X}(x)$ and $\bar{Y}(y)$ and due to the symmetry the currents only have component on z :

$$\bar{A}(x,y) = \bar{X}(x)\bar{Y}(y)u_z \tag{18}$$

In the air-gap region:

$$\overline{A_z^I}(x,y) = \bar{X}(x)\bar{Y}(y) \tag{19}$$

$$\overline{A_z^I}(x,y) = (\overline{c_1^I} e^{j\bar{c}^I x} + \overline{c_2^I} e^{-j\bar{c}^I x})\,(\overline{c_3^I} e^{\bar{d}^I y} + \overline{c_4^I} e^{-\bar{c}^I y}) \tag{20}$$

In order to determine the coefficients it is necessary to fix some boundary conditions. Along the surface at $y = 0$, where the linear current density follow:

$$\overline{H_t^I}(x, y=0) = \overline{\dot{K}_s}(x) \tag{21}$$

$$\frac{1}{\mu^I}\bar{X}(x)\bar{c}^I\left(\bar{c}_3^I - \bar{c}_4^I\right) = \widehat{K}_s e^{j\pi x/\tau_\upsilon} \tag{22}$$

At the boundary between the regions I and II the following equations are true,

$$\begin{cases} \bar{H}_t^I(x,y_g) = \bar{H}_t^{II}(x,y_g) \Leftrightarrow \frac{1}{\mu^I}\frac{\partial \bar{A}_z^I(x,y)}{\partial y}\Big|_{y=y_g} = \frac{1}{\mu^{II}}\frac{\partial \bar{A}_z^{II}(x,y)}{\partial y}\Big|_{y=y_g} \\ \bar{B}_n^I(x,y_g) = \bar{B}_n^{II}(x,y_g) \Leftrightarrow -\frac{\partial \bar{A}_z^I(x,y)}{\partial x}\Big|_{y=y_g} = -\frac{\partial \bar{A}_z^{II}(x,y)}{\partial x}\Big|_{y=y_g} \end{cases} \tag{23}$$

,where H_t is the tangential component of H and B_n is the normal component of B.

<u>Note:</u> The relations between the coefficients $\dot{c}_3^{II}$ and $\dot{c}_4^{II}$ are obtained by these equations as for all the other regions.

Using the surface loss density function to calculate the losses in each region,

$$q_i = \frac{\omega^2\sigma_i}{2}\int_{y_{i-1}}^{y_i} \bar{A}^i \bar{A}^{i*} dy \tag{24}$$

The total rotor losses, in W, are given by

$$P_{r\_loss} = r_{rot} * l_{ef} * \sum_{i=1}^{4} q_i \qquad (25)$$

,where r_{rot} is the rotor radius and l_{ef} is the machine depth length.

III. Optimization Software Development

The best solution for a certain machine should be given by its ability to fit the constraints predefined by the designer. This challenge can be translated to mathematic language as an optimization problem where the constraints identified by the designer are the objective functions. Due to the problem characteristics the optimization algorithm in use is the Genetic Algorithm [5] and the objective functions for this generator are:

1. Maximization of Generated Torque
2. Minimization of Rotor Losses
3. Balanced Electrical Phase System
4. Minimization of Generator Volume
5. Minimization of Generator Material Costs

A. Optimization Problem Definition

For the given machine model was defined an individual composed by two genome parts:

1. Winding Arrangement
2. Geometric Dimensions

Each one of them is defined separately although they are part of a single genome and it is used by the Genetic Algorithm as the unit that classifies each individual.

1. Winding Arrangement:

For a given number of slots, poles, phases and layers there is a search space with a respective dimension. Due to the characteristics of the slot winding it is possible to calculate the total number of feasible arrangements using the equation that gives the number of possible circular permutations with repeated elements since:

- the stator has no right or left end;
- any slot can be the first one;
- the repeated elements are the positive and negative coil sides per phase.

<u>For example:</u>
Single Layer Winding with 12 slots:

randperm(12) = [1 6 2 4 3 5]

Table 1 – Coil Sides of a 12 Slot, 3 Phase, Single Layer Winding Correspondence to Number Variables

Variables	*Coil Sides*
1	$+A$
2	$+B$
3	$+C$
4	$-A$
5	$-B$
6	$-C$

2. Components Geometric Dimensions:

Not every part of the machine has its size defined because it can be obtained from other parts sizes or is arbitrarily defined due to its lower relevance on the model defined.
On the rotor the components defined are:

- Rotor yoke length
- Magnets: width and length
- Air gap length

On the stator the component defined is:

- Slot-mouth width

And additionally for the whole machine is also defined:

- Machine length

The components geometric dimensions are defined using a function that generates a random integer value.

3. <u>Genome Configuration:</u>

Using an example of 6 slots, 3 phases and 2 poles, single layer an individual can have the following genome:

$+$	$-$	$+$	$-$	$+$	$-$						
A	C	B	A	C	B	1	20	80	5	10	20

B. Objective Functions

Each one of the objective functions is a mathematical translation of the constraints the designer puts on the generator:

1. [Maximization] *Generated Torque:*

$$T = 3\sqrt{2}\frac{N_s}{N_{ph}} k_w N_n l_{ef} r_{rot} B_t I_{ph} cos(\varphi) \qquad (26)$$

The objective is to maximize the main torque production.

2. [Minimization] *Total Rotor Losses:*

$$r_{losses} = \sum_{v=1}^{\infty} \sum_{i=1}^{num\ of\ regions} \frac{\omega^2 \sigma_i}{2} \int_{y_{i-1}}^{y_i} \bar{A}^i \bar{A}^{i*} dy \qquad (27)$$

The objective is to minimize the losses on the rotor, increasing the efficiency of the machine and decreasing the damage on the materials.

3. *Balanced Condition:*

For the balanced condition is created a quantitative classification that evaluate the magnetic balance created by the winding arrangement.
Using the example of a 3-phase winding with conductor density distribution of the winding per phase,

$$Cn_{ph}(x) = \sum_{v=-\infty}^{\infty} \overline{Cn_{ph}^{v}} e^{-\frac{j2v}{d}x} \tag{28}$$

Supplied by a balanced sinusoidal current of frequency ω.
The total stator surface current density is,

$$j_s(x,t) = is_a(t)Cn_a(x) + is_b(t)Cn_b(x) + is_c(t)Cn_c(x) \tag{29}$$

$$\Leftrightarrow j_s(x,t) = Re\left\{\sqrt{2}\overline{Is}\left[\sum_{v=1}^{\infty}\left\{\left(\overline{Cn_a^v} + e^{-\frac{2\pi}{3}v}\overline{Cn_b^v} + e^{\frac{2\pi}{3}v}\overline{Cn_c^v}\right)e^{-\frac{j2v}{d}x} + \left(\overline{Cn_a^v}^* + e^{-\frac{2\pi}{3}v}\overline{Cn_b^v}^* + e^{\frac{2\pi}{3}v}\overline{Cn_b^v}^*\right)e^{\frac{j2v}{d}x}\right\}\right]e^{j\omega t}\right\}$$

From this expression it is possible to take two others that are necessary conditions for the balanced condition:

$$\begin{cases} \overline{Cn_a^v} + e^{-\frac{2\pi}{3}v}\overline{Cn_b^v} + e^{\frac{2\pi}{3}v}\overline{Cn_c^v} = Real \\ \overline{Cn_a^v}^* + e^{-\frac{2\pi}{3}v}\overline{Cn_b^v}^* + e^{\frac{2\pi}{3}v}\overline{Cn_b^v}^* = 0 \end{cases} \tag{30}$$

The objective is to minimize this function because unbalanced machines may cause losses and damage on the machine. In this model the value 0 for balanced condition is strictly necessary to guarantee the generator operation mode without adding any supplementary converters.

4. [Minimization] *Volume:*

$$vol = l_{ef} * \pi(r_{total})^2 \tag{31}$$

, where r_{total} is the dimension of the outter radius of the stator. The objective is to minimize the volume of the machine and consequently its weight.

5. [Minimization] *Material Costs:*

$$p = w_{iron} * p_{iron} + w_{pm} * p_{pm} + l_{copper} * p_{copper} \tag{32}$$

, where w_{iron}, w_{pm} and l_{copper} are the weight of iron and permanent magnet of the machine and the length of the copper wire respectively multiplied by the price per weight p_{iron} and $p_{pm}$and price per length p_{copper}.

IV. Generator Design and Testing

The goal is to design a permanent magnet synchronous generator with electromechanical characteristics in the range of:

- Rotation Speed: $100\ rpm$
- Nominal Voltage: $550\ V$
- Nominal Output Power: $20\ kW$

The electromechanic characteristics desired for the synchronous machine, especially the rotation speed, provide information to calculate the best combination of number of poles, slots and phases for the generator. These characteristics are used as a guide and every decision made takes in account the solutions that could provide the best performance possible.

A. *Generator Design Characteristics*

Number of Phases:
The utilization of power electronic converters should be avoided in a system that is desired to be direct drive. Since the connection is made to the grid, three-phase system, then the output of the generator should also be three-phase, therefore

$$N_{ph} = 3$$

Number of Poles and Slots:
The reference number of poles for a machine operating at $100\ rpm$ is

$$N_p = \frac{120f}{n} = \frac{120.50}{100} = 60\ poles$$

Despite the fundamental winding factor being lower when using double layer when compared with the one layer also the self and mutual inductances are lower, the *EMF* is more sinusoidal, the harmonic content on *MMF*, the eddy current losses and the overload torque capability are lower. Looking for the best performance on a machine the advantages of using the double layer winding are superior to the ones given by using the one layer winding. The higher number of slots per pole per phase, q, the more sinusoidal the magnetomotive force and consequently the lower torque ripple and higher efficiency but there isn´t a proportional relation between q and the fundamental winding factor. Because the winding assigned to each phase is distributed in the stator slots the *EMF* induced on the different slots are not in phase and their sum is less than the numerical sum, the winding factor should be the biggest possible to potentiate the *EMF* induced. The Figure 6 shows how the fundamental winding factor depends on the number of slots per pole per phase.

The fundamental winding factor is maximum in three points that correspond to three different numbers of slots per pole per phase. Taking in account that :

1. The number of coils/windings must be multiple of the number of phases
2. The number of coils/windings is equal to the number of slots.

Despite the fact that the fundamental winding factor has a bigger value other combinations with higher number of slots the combination chosen is $60\ poles, 54\ slots$ because allows the machine to have characteristics closer to the specified.

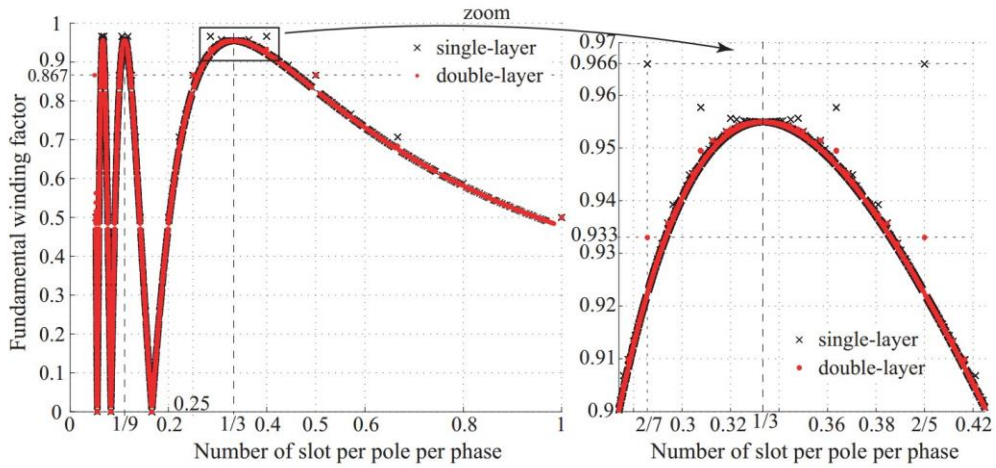

Figure 6 - Fundamental Winding Factor vs Number of Slots per Pole per Phase [7]

The number of slots chosen is

$$N_s = 54\ slots$$

and the number of poles is

$$N_p = 60\ poles$$

being the value for the synchronous speed, as previously calculated, $n = 100\ rpm$.

B. Software Run

The values of the machine structure previously calculated will be used on the software to run tests to determine the best possible solution for the machine design and construction. Some features of the software input data can not be determined by auxiliary calculations, such as material characteristics, winding type remanent and flux density for the permanent magnets, so they will be tested to find the solution that fits better the machine requirements. At the end it will be presented the final solution, with components sizes and winding arrangement, that will be a guide for the machine design.

For the best solution the score of the objective functions:

- Generated Torque: $2\,406\ Nm$
- Rotor Losses: $320\ W$
- Balanced Condition: 0
- Volume: $0{,}0823\ m^3$
- Material Costs: 2 881€

The geometric dimensions and the ending arrangement are:

- Air gap length: $1\ mm$
- Magnets: length: $29{,}2\ mm$
- Rotor yoke length: $112{,}0\ mm$
- Shaft length: $35\ mm$
- Magnet width: $12{,}3\ mm$
- Slot-mouth width: $10{,}1\ mm$
- Machine length (depth): $114{,}7\ mm$
- Winding Arrangement:

A	**-A**	**A**	**C**	**-C**	**C**	**B**	**-B**	**B**
A	**-A**	**A**	**C**	**-C**	**C**	**B**	**-B**	**B**
A	**-A**	**A**	**C**	**-C**	**C**	**B**	**-B**	**B**
-A	**A**	**-A**	**-C**	**C**	**-C**	**-B**	**B**	**-B**
-A	**A**	**-A**	**-C**	**C**	**-C**	**-B**	**B**	**-B**
-A	**A**	**-A**	**-C**	**C**	**-C**	**-B**	**B**	**-B**

Also some other useful values were obtained from the simulation:

- Number of coil turns: 84
- Power Factor: 0.8

These values will be used on the following sections as a guideline to design the machine and test its electrical operation, simulated in a finite element software as showed by the results in Figure 7.

C. Simulation

Working in discrete time problem the main concern should be the step time used because it affects the quality of the final results. Knowing that the machine have repeated electrical cycles in every rotation, the study will take advantage of that repetitions and will only be focused on one electrical cycle. A full electrical cycle for this machine corresponds to the following mechanical interval angle,

$$\theta = \frac{2}{N_p}\ \gamma = \frac{2}{60} * 360 = 12° \tag{33}$$

For a complete electrical cycle the rotor has to rotate 12° (mechanical degrees). Taking this calculation in account the step chosen was 0,1° and the total number of samples taken from the simulation is 120.

The number of symmetries in the winding layout for a certain number of poles and slots is given by the greatest common divisor of those numbers

$$symmetric\ parts = GCD(60{,}54) = 6 \tag{34}$$

Using the symmetries, the study of the electrical operation can be reduced to a smaller part of the machine,

$$\begin{aligned} 54\ slots \div 6\ symmetric\ parts \\ = 9\ slots/symmetric\ part \end{aligned} \tag{35}$$

The simulation runs and calculates the magnetic flux density along the entire machine showing the results as can be seen in Figure 7. This distribution corresponds to the stationary study when the rotor as an rotation angle of 0°.

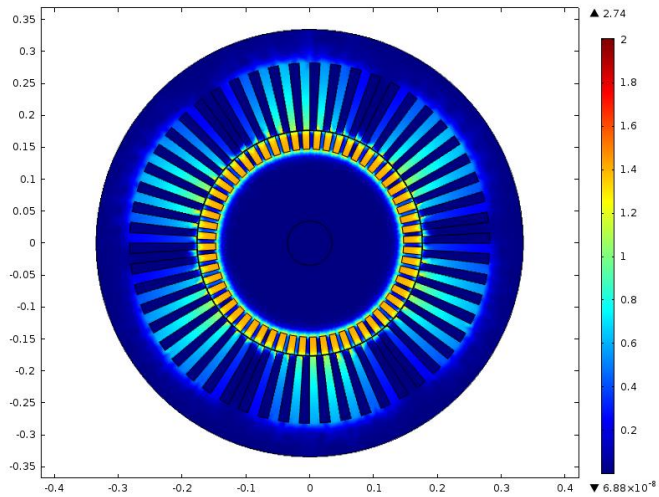

Figure 7 - Magnetic Flux Density Norm Distribution

Using a parameterized curve crossing in each one of the predetermined nine consecutive teeth of the machine, as exemplified in one tooth on Figure 8, and calculating the radial magnetic flux density across that line.

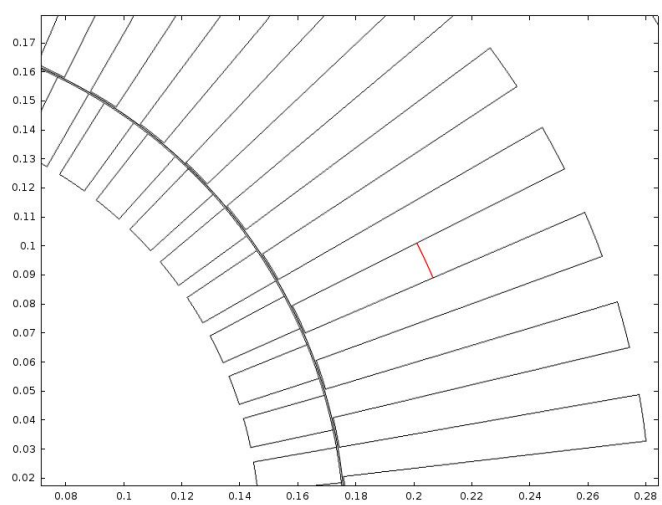

Figure 8 - Parameterized curve on the generator tooth

The results unit is Wb/m because the model is two dimensional meaning that, for example, a measure of 2 Wb/m in a machine with depth of 1 m gives a radial magnetic flux density of 2 Wb. These results correspond to the magnetic flux simulated in two dimensions and further calculations are required to obtain the generator characteristics descried in the following steps:

- Multiply each magnetic flux density per meter sample by the generator depth giving the magnetic flux density (Φ_B)

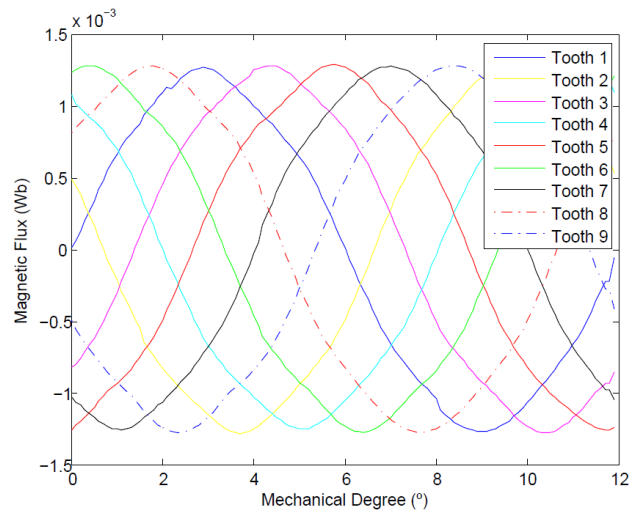

Figure 9 - Magnetic flux vs rotor mechanical degree

- Knowing the symmetries on the winding layout assign each tooth of the machine with the correspondent magnetic flux density
- Calculate the derivative of the magnetic flux density of each tooth $\left(\frac{d\Phi_B}{dt}\right)$
- Multiply the resultant value by the number of winding turns, calculating the electromotive force (emf)
- Assign each tooth with the respective winding phase and direction (as in the winding layout arrangement)
- Sum the electromotive force of teeth corresponding to same winding phase (emf_A, emf_B, emf_C)

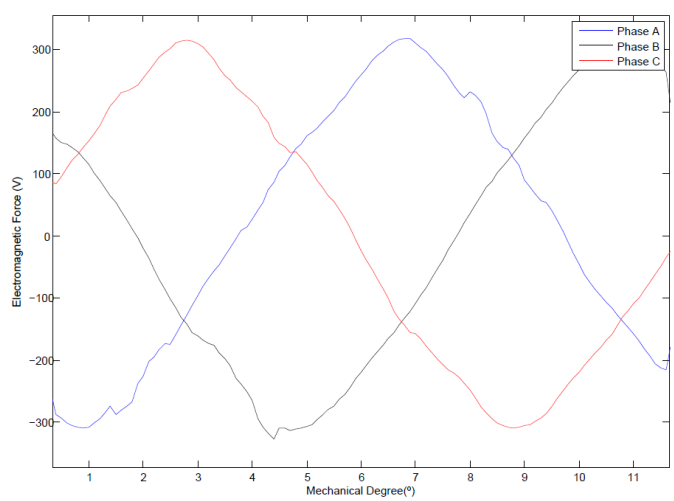

Figure 10 – Electromotive force of each phase vs rotor mechanical degree

- Calculate the complex electromotive force of the generator

$$emf_{tot} = 317 * \sqrt{3} \approx 550\ V \quad (36)$$

The electromechanical specifications desired for the generator are fulfilled:

- **Rotation speed:** 100 rpm
  The generator rotor rotation speed is given by relation of the number of pole pairs and electric frequency from the grid, the generator rotates at the specified speed.

- **Nominal voltage:** 550 V
  The nominal voltage is given by the peak value of the complex electromotive force produced by the generator. This chapter shows in detail that specific generator characteristic and the value is around the nominal voltage specified.

- **Nominal output power:** 20 kW
  The nominal output power is calculated using the nominal voltage
  $P = emf_{tot} * I_{ph} * pf = 550 * 48 * 0.8 = 21\ 120\ W$

For simplification purposes the generator designed will further on be designated as *PLF PMSG20K*.
As referred previously, the studies made by *Costa* (2003) [1] in his master thesis determined the permanent magnet synchronous generator *Ginlong PMG-20K* to be the cheapest solution and also the one to guarantee a higher revenue. The further comparisons between both generators should take in account that the PLF PMSG20K is a designed generator with reference values and the Ginlong PMG-20K is an already commercialized machine.

The calculation of the copper losses are described and the losses of magnetic parts in *Strous* (2010) [2] as following stated

$$P_{mag} = \frac{\sigma_m \omega_m^2 \pi^2 f^2 B_{max}^2}{6} V_m \quad (37)$$

$$P_{Cu} = N_{ph} R_{ph} I_{ph}^2 \quad (38)$$

Summing up all losses

$$P_{losses} = P_{rot} + P_{Cu} = 258{,}9 + 360{,}2 = 619{,}1\ W \quad (39)$$

D. *Comparison*

The electromechanical characteristics compared showed that the *PLF PMSG20K* is in some cases equal and other cases better than the *Ginlong PMG-20K*. The materials costs are also an important characteristic in comparison but there is no way to be sure of the real values for the material costs of the chinese generator.

Table 1 - *Ginlong PMG-20K* vs *PLF PMSG20K*

	Ginlong PMG-20K	*PLF PMSG20K*	*PLF vs Ginlong*
Rotation Speed (rpm)	100	100	0,0 %
Nominal Voltage (V)	550	550	0,0 %
Nominal Output Power (W)	20 000	≈ 21 120	+ 5,6 %(1)
Torque at Rated Power ($N.m$)	2 129	2 406	+ 13,0 %
Losses (W)	–(2)	619,1	– %
Volume (m^3)	0.110(3)	0.082	– 25,5 %
Material Costs (€)	1 600 – 3 200 (3)	2 880	–(4)

(1) The losses were only calculated for the rotor and winding therefore is not possible to calculate the difference between nominal output powers of both. However the rotor losses represent most of the total losses of in this kind of generators therefore the output powers should be close.
(2) The specifications data sheet 0 does not provide information regard any kind of losses neither the generator efficiency.
(3) The volume is calculated using the dimensions of the capsule involving the generator
(4) The specifications data sheet does not provide information regard material costs neither provides geometric sizes that could be used to calculate an approximation to those specific costs. Instead it was used the selling price (8 000€) and a typical range for ratio between material costs and selling price, usually around 20% to 40%.

The comparison between the characteristics of the Ginlong PMG-20K and the PLF PMSG20K show that:

- Rotation speed and nominal voltage are equal for both generators
- Nominal Output Power is similar in both generators
- The torque generated at rated power is bigger in the *PLF PMSG20K*
- The loss of efficiency related with rotor losses in the *PLF PMSG20K* is around 1,6% and there is no information available about the *Ginlong* generator

- The *PLF PMSG20K* is 25% smaller than the *Ginlong PMG-20K*
- The material costs of the prototype version of the *PLF PMSG20K* are in the range of the commercialized version of the *Ginlong PMG-20K*.

V. CONCLUSION

The results obtained on the electromagnetic simulation are very close to the ones obtained from the modeling. The results were used to make further calculations that allowed a more reliable comparison between the *Ginlong PMG-20K* and the *PLF PMSG20K*. The generators have the same electromechanical characteristics operating both at $100\ rpm$, $550\ V$ and $20\ kW$ making them competitors for the same market. Despite having the same elctromechanical characteristics the *PLF PMSG20K* generates more torque than the *Ginlong* generator and also have rotor losses around $619\ W$.Despite being possible to discuss this value, it leads to a decrease of $2,9\%$ on the generator efficiency which have a minor impact considering the main role that the rotor losses play on the total losses in the generator. Looking to the geometry of both generators it is possible to verify that the *PLF PMSG20K* has a bigger radius but at the same time a smaller depth. Further conclusions about the internal geometry are not available because that is not described in the *Ginlong* specifications data sheet. The decrease on 25% of the volume is considerable and represents a great chance of also reducing the generator weight.

Taking in account the positive results on the comparison made with the *Ginlong* generator it is possible to verify that the production of the *PLF PMSG20K* mainly relies on the material costs. Despite not having conclusive values for the material costs for the active parts of the *Ginlong PMG-20K* it is possible to verify that both generators are in the same range of costs even considering the prototype version of the generator projected..

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