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Development of electrical machine with magnets and cores obtained by powder metallurgy

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Abstract

The aim of this work was the development (design, construction and tests) of a Three-phase Synchronous Machine with permanent magnets and four poles to be used in small wind turbines, where the rotor and stator cores, usually constructed from laminated steel sheets, were replaced for massive blocks obtained from the Powder Metallurgy (PM) process. The other parts of the machine, such as housing, shaft, bearings and covers, were obtained from conventional three-phase induction motor of 10 HP. Initially, it was studied sintered alloys from pure iron, Fe-Si, Fe-P and Fe-Ni; eventually these alloys were analyzed in terms of magnetic and mechanical properties as well as electrical resistivity. From this study, it was chosen the use of sintered pure iron for the construction of the rotor and Fe1%P for the construction of the stator. The permanent magnets used were Nd-Fe-B, and the windings calculation was based on the coiling of the three-phase induction motor. According to the tests performed, it was observed the generation of a three-phase sinusoidal wave voltage of 242 VRMS, and the yield of 40.8%.

Keywords: three-phase synchronous machine; magnetic materials; powder metallurgy.

1. Introduction

Rotating electrical machines can function as a motor or generator, and have two basic parts that are the stator and rotor cores. These cores, with rare exceptions, are currently built from thin metal blades (low carbon steel sheets) with thickness less than 1 mm that are stacked together. Some higher-yielding machines such as generators are built with silicon-steel sheet, with percentage of approximately 3% silicon [1,2].

Magnetic cores surrounded by coils, where alternate currents circulate, also generate an alternating magnetic flux. For this reason, these cores are subjected to the action of eddy currents, also known as Foucault currents, which are responsible for significant power loss in these cores [1-4]. According to design engineers of motors manufacturers, with respect the construction, changes in shape and drive of the electric machines are on the limit of technological improvement and only drastic changes in the materials used to build the cores of the electric machines will result in improved performance of that. The same occurs with respect to the drive, where devices from semiconductors such as inverters are also within the limits of technological improvement.

However, using the processes of Powder Metallurgy (PM), it is possible to build the referred cores in massive single blocks with high magnetic permeability and a higher electrical resistivity as compared to conventional steel, which reduces eddy currents [5,6]. In this case, the machines will be constructed with fewer steps, leading to a decrease in the consumption of energy. It should be noted also that using magnetic alloys with higher resistivity in the construction of stator and rotor cores, there will be

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a reduction in eddy current loss, higher yield, thereby resulting in electricity savings [7,8].

Currently the application of PM in cores of electric machines is restricted to special motors where the yield is not the most important criterion, as in the case of mini motors with complex geometry, in some servomotors where the armature windings are supplied with current electrical of high frequency, and parts of machines where there is no change in magnetic flux, as rotor core of synchronous machines. However, some studies are being conducted in other types of machines obtained from the PM in order to prove or dismiss the application of this technology [7].

2. Electrical machines by powder metallurgy

2.1. Synchronous machines with permanent magnets

Rotating electrical machines with three-phase power, usually, can function as a motor or generator and are classified as synchronous or asynchronous. In synchronous motors, the angular velocity of the shaft is constant and independent of the load coupled to the shaft, i.e. up to certain values of power, with the limit the nominal power of the machine. In asynchronous motors, there is a decrease in the angular velocity when load is coupled to the shaft [1,2,8].

With regard to the constructive aspect, the three-phase machines consist mainly of two parts which are the rotor and stator. These ones are, in most cases, made of laminated steel sheets, insulators and juxtaposed in the longitudinal direction of the machine. Thus, there is a considerably reduce in losses by eddy current, leading to an increase of the efficiency of the machine [1,2,8].

Synchronous machines with permanent magnets are rotating three-phase machines in which the rotor windings, usually supplied with direct current, are replaced by permanent magnets of high energy product such as NdFeB. In general, these machines have high yield (greater than 90 %) and, in some applications, such as in servomotors, they are used operating at high speeds and high frequency of armature currents [1,2].

2.2. Physical properties of interest

The physical properties of interest for use of a particular material and process in cores of rotating electrical machines or electric motors are the following:

- Magnetic properties (coercivity, permeability and saturation induction).
- Electrical resistivity.
- Mechanical properties (hardness and compression curves / yield stress).

Regarding the magnetic properties, the materials to be used in cores of electrical machines must have: high magnetic permeability, which reduces the reluctance of the magnetic circuit of iron cores, thus concentrating the entire magnetic field in the air gap; high saturation induction, which enables to work with higher magnetic flux, resulting in greater torque on the shaft; and low coercivity, which reduces the hysteresis cycle losses [1,2,7,8].

Related to electrical resistivity, this parameter must have the highest possible value in order to minimize the effect of eddy currents. Whenever there is the incidence of an alternating flux on a magnetic core, there will be induced currents (eddy currents or Foucault currents) on the core. The stator and rotor are constructed with laminated and insulated sheets, since this isolation between sheets restricts the induced currents to a smaller area of circulation. The eddy current losses in a solid core are significantly larger than the losses in cores made from electrically isolated sheets. The smaller the sheet thickness, the smaller the eddy currents and power losses in these cores. The reduction of induced currents may also be obtained from an increase in the electrical resistance of the piece or from the increasing of electrical resistivity of the material, since resistance (or resistivity) and electrical current are physical quantities inversely proportional. For this reason, high-performance electric machines are built with a silicon steel sheet, which has higher electrical resistivity than the low carbon steel [1,2].

With respect to mechanical properties, materials that could be used in cores of electrical machines must bear the stresses caused by the resistive load torque and vibration, among others. Thus, it should be performed hardness or ductility tests, as well as compression curve *versus* deformation [1,2,8].

2.3. PM and sintered ferromagnetic alloys

Powder Metallurgy (PM) is a relatively recent process of metallurgy processing, where the parts are obtained from the powder constituents. The basic processes of PM are: getting the powders, mixing, compression and sintering. Sometimes a fifth process known as rectification is required. In the PM, the powders, after being mixed, are compressed into dies where they

acquire the shape of the cavity. In the sequence, they are placed into sintering furnaces where mechanical consistency and resistance are achieved. Materials obtained from PM process are also conventionally called sintered [9,10].
The magnetic and electrical properties of the materials obtained by PM are influenced by several factors, such as the formation of alloys, presence of porosity and surface oxidation of the powder particles, particle size of the powders, crystalline lattice of the grain size and presence of impurities. Some of these features are positive, concerning the magnetic and electrical properties as well as the use of these materials in cores of electrical machines [11-14].
The sintered materials most commonly used in electromagnetic device cores as the rotating electrical machines are pure iron, alloy iron-cobalt, iron-phosphorus, iron-silicon, iron-phosphorus-silicon, iron-nickel and ferritic steels [15-17].

2.4. Application of PM in rotary electric machines

The application of PM in rotary electric machines extends from the use of conventional sintered alloys from iron and other elements of alloys such as P, Si and Ni, composites such as Iron-Resin, microencapsulated and materials from the Metals Injection Moulding (MIM), among others. With regard to conventional PM, there are three-phase synchronous machines for use in three-phase generators and wind turbines [18-20], Three-Phase Induction Motor [21], Continuous Current Motor [22,23], Model Airplane [24], Servomotor [25], Step Motor [26, 27], Reluctance Engine [28]. With respect to Composite Materials a construction of a servomotor from iron-resin is cited [29]. In relation to MIM, mini motors injected for endoscopy are cited [30,31]. With regard to microencapsulates, a continuous current motor constructed from the commercial alloy Somaloy 700 3P and 700 1P [32] is cited.
Pelegrini et al. studied the influence of mechanical alloying on the magnetic properties of Fe-Si sintered alloys [33] and Dias et al. analyzed the influence of resin content on iron-resin composites on the physical properties of materials for use in devices Electromagnetic [34].

3. Materials and methods

Initially, the iron powders were mixed, in mass proportions, with phosphorus (1, 2 and 3 %), silicon (1, 3 and 5 %) and nickel (50 %); in the sequence, the specimens were compacted and sintered.
After, physical properties such as saturation induction, magnetic permeability and coercivity, electrical resistivity, hardness and yield stress were evaluated. From this study, it was defined the materials for the construction of the rotor and stator cores. The topology of the synchronous machine developed was based on a conventional induction motor of 10 HP, while retaining the housing, shaft, slots model, bearings and covers. The magnets used were Nd-Fe-B. Finally, the machine was tested with respect to voltage generated as a function of frequency and yield.

3.1. Samples obtained

For the construction of the stator core, several sintered alloys were tested as FeP, FeNi and FeSi and its variations. For analysis of the magnetic properties and electrical resistivity, samples in ring form were obtained. In turn, for analysis of hardness and yield stress, samples in the cylinder form were employed.
The study was conducted from sintered alloy, obtained from iron powders mixed with phosphorus, silicon and nickel, acquired from Hoganas Brazil Ltda. According manufacturer's certificate, the iron powder used was ASC100.29, with 99.4 % particle size between 45 μm and 150 μm. The Fe_3P powder (84 % Fe, 16 % P) has 90 % of its size below 14.58 μm. The powder FeSi 45 (55 % Fe and 45 % Si) has 87 % of its content between 45 μm and 250 μm and the nickel powder has a minimum particle size of 3 μm and a maximum of 7 μm. The iron powder was mixed with phosphorous (1, 2 and 3 %), silicon (1, 3 and 5 %) and nickel (50 %) in a double cone mixer, rotation of 60 rpm for 20 minutes for dispersion of the constituents. It was also added to the mixtures 1 % solid lubricant (zinc stearate). Regarding the compaction pressure, the samples were subjected to an average pressure of 600 MPa [9,10].
Sintering of the specimens was carried out in a tubular muffle furnace with atmosphere composed of 5 % hydrogen and 95 % nitrogen. It was used a heating rate of 10 ºC per minute until the temperature of 500 ºC, remaining the samples at this temperature for 30 minutes to remove the solid lubricant. Thereafter, the temperature was increased to 1,150 °C, occurring the sintering, with a new isothermal level at this temperature for 60 minutes [9,10]. After, the specimens remained in the furnace for slow cooling to room temperature.

3.2. Obtainment of the physical properties

The magnetic properties were obtained from the magnetic curves (hysteresis and magnetization) which relate the magnetic field - H - applied to a material with the resulting magnetic induction - B -. From the hysteresis loop, retentivity and coercivity were achieved. Through analysis of the magnetization curve, it was obtained magnetic permeability and saturation induction, or maximal induction (which it can also be viewed from the hysteresis loop) [35]. The determination of the basic magnetic properties of materials in the form of a ring (toroid) follows the norm ASTM A773 [36]. The magnetic curves were obtained from a TLMP-HCT-14 model device.
The electrical resistivity of the material of the alloys was determined by calculating the electrical resistance. Measuring directly the electrical resistance of the body. However, for a very low electrical resistance measurement, one applies a tension in the specimen and measures the electrical current. Therefore, for determining the resistivity, the sample should be in the form of a thin and long bar. One method is the use of a ring, by cutting a segment of it, making this the shape of a curved bar, i.e. great length and small cross-sectional area. According to Ohm's law (Equation 1) [37]:

$$R = \frac{V}{I} \Rightarrow \rho = R\frac{A}{l} = \frac{V}{I}.\frac{A}{l} \tag{1}$$

where: ρ is the electrical resistivity [μΩ.m]; R the electrical resistance [Ω]; V the applied voltage [V]; I the electric current applied [A]; A the cross sectional area of the bar [m^2] and l represents the length of the bar (segment of a ring) [m].
To evaluate the vibration resistance of a material to be used in a rotating electrical machine, it was also carried out mechanical tests on specimens. Hardness Brinel tests were performed in England Precision durometer according to norm ASTM E10 [38]. Compression tests were conducted on a universal testing machine EMIC DL20000, using a speed of 2.0 mm / min in accordance with norm ASTM E9 [39].

3.3. Specifications and machine design

The synchronous machine with permanent magnets developed in this work was designed from a three-phase induction motor for high performance with four poles and 10 HP (Figure 1), produced by Voges Motors from Caxias do Sul (in Brazil). Thus, the design of the grooves, shaft, housing, covers and bearings was attributed to an induction motor, but the rotor and stator cores were constructed from sintered materials. The data of the machine and stator sheets are shown in Figure 2.

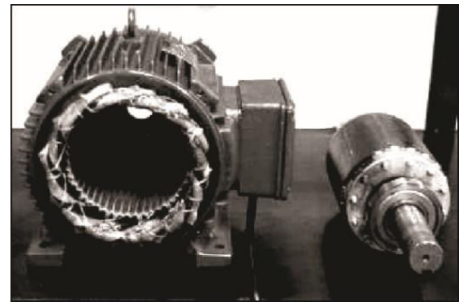


Fig. 1. Three-phase induction motor 10 HP partially disassembled.

The machine of Figure 1 originally has a winding in series being 12 turns per stator slot with 12 AWG wire, and 192 conductors per phase in series. The nominal current used is 14.2 A, for a voltage of 380 V connecting Y.
Motor housing to 10HP; 220V; 60Hz
Number of Poles: 4
Number of slots: 48
Sheets package: 148 mm
Number Sheets: 320

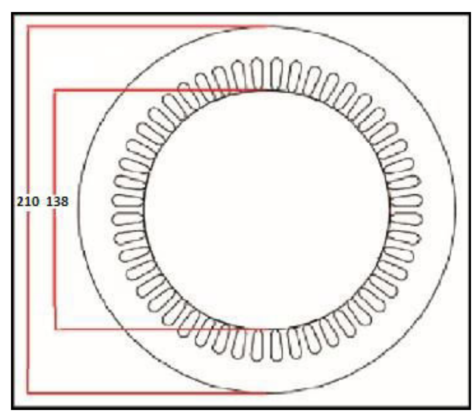


Fig. 2. Schematic of the stator core (dimensions in millimeters).

The topology and the rotor core dimensions were based on the classic design of the conventional reluctance machines [40] from the characteristics and dimensions of the original rotor (Figure 1), thus being possible to design the machine rotor developed. Figure 3 shows the topology of the rotor in the horizontal plane. The relation used to calculate geometry of the rotor defines the height of the salience h_{sal} [mm] in about 50 % of the core radius [8,40].

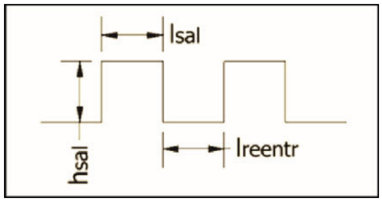


Fig. 3. Rotor topology in the horizontal plane.

The radius of the core r_{nr} [mm] (Equation 2) is:

$$r_{nr} = \frac{\phi_{cm}}{2} - \frac{\phi_{eix}}{2} \qquad r_{nr} = \frac{124.1}{2} - \frac{49.8}{2} = 37.15 \tag{2}$$

According to Equation 3, once it is known that ϕ_{cm} is rotor diameter and ϕ_{eix} is the shaft diameter, then:

$$h_{sal} = \frac{37.15}{2} = 18.575 \tag{3}$$

The width salience l_{sal} [mm] and the width hollow l_{reent} [mm] are defined as the ratio [8, 40] (Equation 4):

$$\alpha = \frac{l_{sal}}{l_{sal} + l_{reent}} \tag{4}$$

The constant **α** relates these widths. In the three-phase synchronous reluctance machines, α varies from 0.6 to 0.7 [8,40]. The rotor perimeter was calculated with the Equations 5 and 6:

$$4(l_{sal} + l_{reet}) = \pi.\phi_{cm} \tag{5}$$

then:

$$l_{sal} + l_{reet} = \frac{124.1\pi}{4} = 97.41 \tag{6}$$

Admitting an α value equal to 0.65 (Equations 7 and 8):

$$l_{sal} = 97.41x0.65 = 63.32 \tag{7}$$

$$l_{reet} = 97.41 - 63.32 = 34.07 \tag{8}$$

In degrees θ_{sal} = 58.5° and θ_{reent} = 31.5°. However, in order to facilitate machining, it was defined θ_{sal} = 55° and θ_{reent} = 35°.

The magnets used are composed of Nd-Fe-B (neodymium-iron-boron) with nickel coating, since they have excellent magnetic characteristics such as higher retentivity and coercivity [35]. The thickness of the magnets in [mm] was defined by the Equation 9 [8, 9]:

$$e_{imãs} = \frac{\phi_{rmi} - \phi_{cm}}{2} = \frac{137.2 - 124.1}{2} = 6.55 \tag{9}$$

The radius curvature of the magnets is equal to half the diameter of the die cavity, that is, 62.05 mm, and the length is equal to 191 mm. Figure 4 shows the dimensions of the magnets.

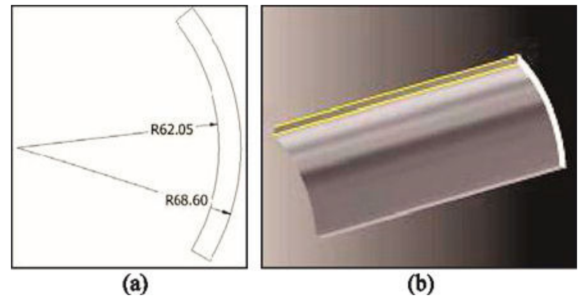


Fig. 4. (a) Dimensions of the cross section; (b) sketch in 3D.

Figure 5 shows dimensional drawing in cross section of the machine to be developed and Figure 6 shows the Three-phase Synchronous Machine with permanent magnets (four poles) and the windings of the motor.

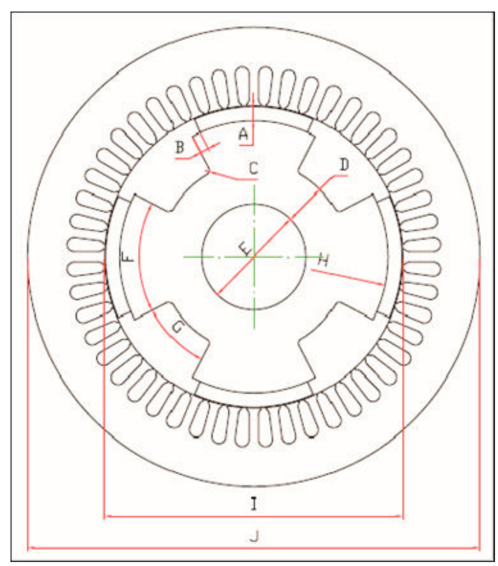


Fig. 5. Rotor quotas in cross-section.

In figure 5, the quotas are: A = 6.55; B = 4; C = 2; D = 18.575; E = 49.8; F = 55°; G = 35°; H = 62.05; I = 138; J = 210. Where: A, B, C, D, E, H, I, J in millimeters.

Figure 6 presents the cross section of the Three-phase Synchronous Machine, in which: 1, 2 e 3 - poles for currents "U", "V" e "W", respectively; 1', 2' e 3' - poles for currents "-U", "-V" e "-W", respectively; 4 - magnets of NdFeB with their respective guidelines; 5 - machine shaft; 6 - rotor and stator cores.

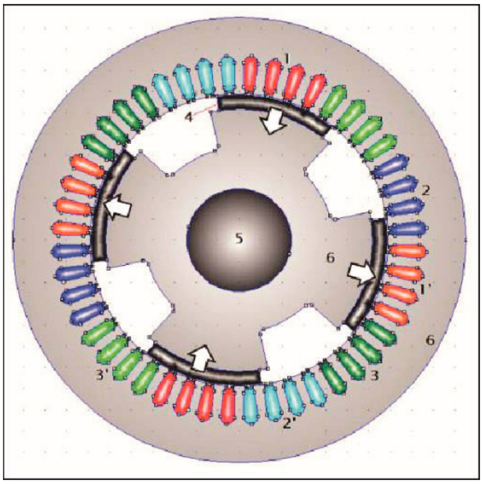


Fig. 6. Cross section of the machine.

The letters U, V and W represent the phases of a three phase supply of armature windings. The saliences and magnets on the rotor originates four poles with polarities reversed in the angle sequence, and the same characteristic should occur with the magnetic field generated by the armature windings, i.e., an inverted sequence of four poles around the perimeter of 360 degrees of the stator. This characteristic of magnetic field coupling results a synchronous electrical machine in which the rotor and the rotating magnetic field (originated from the armature windings) rotate at the same speed with an angular displacement in function of the machine load [1,2].

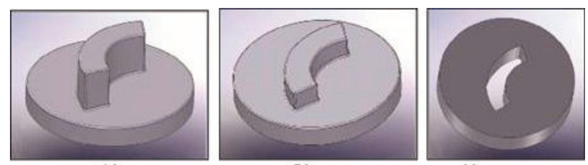
The construction of a three-phase electrical machines such as induction motors is performed with the inclination of the rotor slots (cage). In the case of synchronous machines with permanent magnets, the inclination of the slots occurs in the stator core, due to the difficulty of leaning magnets attached along the rotor [1,2]. Therefore, from the geometry of the sheets of the machine taken as basis (Figures 2 and 5), due to the complexity of the project, it was decided to manufacture the stator in blocks as shown in the sequence of Figure 7. Thus, the block of Figure 7b is composed of 4 segments (Figure 7a), resulting on stator core (Figure 7c) with 6 blocks.

(a) (b) (c)

Fig. 7. (a) Segment, (b) block, and (c) set of six blocks.

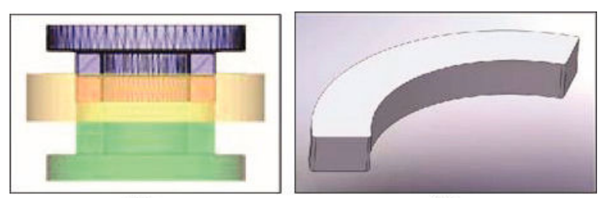
For construction of each segment (Figure 7a), it was required the manufacture of sintered blocks for subsequent machining to final shape with the slots. Thus, a die was developed for the construction of these sintered blocks. In this way, it was performed the die dimensional design and simulations of internal forces in compression.

For the mentioned simulations, the drawing of the die was carried out (Figure 8), as well as the piece to be compacted (Figure 9b). After, these drawings were imported by Simufact software. In the simulations performed, the die (D6 steel hardened) supported the working pressure of 600 MPa. Figure 9a shows the simulation in software Simufact, and Figure 9b the piece to be obtained.



(a) (b) (c)

Fig. 8. Design of die for simulation (a) lower puncture (b) upper puncture (c) cavity.



(a) (b)

Fig. 9. (a) Die for simulation (b) piece form to be obtained.

The machine developed was constructed with rotor core sintered from pure iron and the stator from Fe1%P. For this reason, there were small changes in these coilings, i.e., the prototype machine was coiled with double connection scheme in parallel with wire 38 18 AWG and turns per coil/slot. This coiling feature has small differences from the original induction motor, however, the performance in both cases is the same, according to data of the design engineers of Voges Motors.

3.4. Machine assembly

For the construction of the rotor and stator cores, it was decided to obtain blocks of sintered pieces and subsequent machining into the final form of these cores, since to obtain these components in the final form would be required dies with very high cost. It should be mentioned that this is a classic solution in the development of new products from the processes of the PM having complex geometry [9,10].

After evaluation of the physical properties (magnetic, mechanical and electrical resistivity), it was decided to build the rotor core of sintered pure iron once it showed magnetic properties similar to electrical steels, although having low electrical resistivity. However, as the rotor core presents a little flux variation, the eddy currents are smaller and therefore a high electrical resistivity is not needed. It is worth noting that the sintered pure iron has low hardness, which facilitates the machining of sintered parts to the final shape of the core. Concerning the stator core, the material that showed better physical properties (magnetic and electrical resistivity) was the Fe2%P, but with a high hardness feature. Once the hardness of a material plays an important role in terms of machining it to its final shape, the Fe1%P alloy was chosen due to its low hardness, if compared to the sample Fe2%P.

The rotor was developed consisting of 5 pieces of sintered pure iron, or *billets*, since to compress one single piece of the rotor length would involve large dimensions of die and a compaction pressure very high [7, 8]. For the compression of the billets, it was designed and built a die where the cavity has a diameter slightly larger than the rotor core. The press used for compressing of the billets was the FKL model, with capacity of 750 tons. To hold the die in the press, it was developed a device composed of a steel table and clamping rings.

The features of iron powder used, preparation, compacting pressure and sintering levels were the same of the samples of this material. Thus, it was obtained 5 billets that, eventually, were machined to their final shape. Figure 10a shows the bearings, shaft and the five pieces machined in accordance with the machine design. Subsequently, the pieces were introduced in the machine shaft under pressure using a press. In the sequence, the magnets were placed (attached) to form four poles. Figure 10b shows the rotor of the synchronous machine mounted.

To manufacture the stator core, it was used the die shown in Figure 8 and Fe1%P alloy, where twenty four pieces were compressed and then sintered (Figure 11a). So, the pieces were machined (EDM wire) according to the design of Figure 7, leading to the stator core shown in Figure 11b.

After, the stator blocks were inserted into the housing (Figure 12a), undergoing the machine coiling process (Figure 12b) according to design specifications of the engineers of Voges Motors.

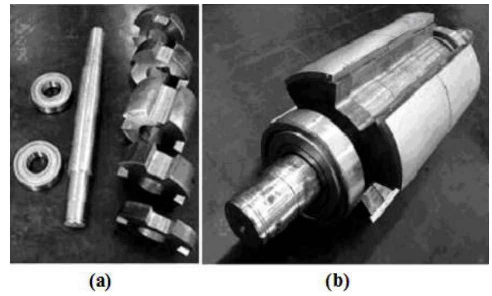


Fig. 10. (a) Pieces of rotor core developed (b) rotor developed with magnets fixed.

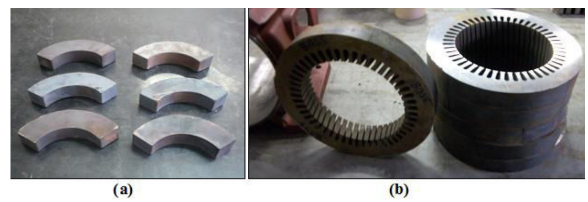


Fig. 11. Machine stator (a) parts compacted and sintered, (b) parts machined with grooves.

Fig. 12. Assembly stator (a) inserted into the housing, (b) machine coiled.

Finally, it was inserted the shaft with the rotor, bearings, covers, blower and other machine parts.

3.5. Machine tests

After the machine construction, tests were performed (LdTM / UFRGS) in order to evaluate the waveforms and the voltage generated as well as the torque and efficiency. Initially, the developed machine was tested in a test bench consisting of:

- three-phase induction motor of 7.5 kW with four-pole (primary machine) to rotate the developed machine;
- load cell (sensor torque);
- three phase inverter (Vector CFW-080280T) with control voltage (0-600 V) and frequency (0-300 Hz);
- voltage and current Meters;
- digital oscilloscope, tachograph, datalogger;
- incandescent bulbs of 70 W for use as load.

Several rotational speeds were tested. The developed machine was connected to a three-phase motor (primary machine). The voltage levels, current and frequency were measured from a digital oscilloscope, ammeters and voltmeters. The rotational speed was measured by a digital tachograph. The output of the generator was connected in star for with three light bulbs of 70 W each.

With respect to the second part of tests, initially the induction motor with 10 HP (drive generator) was put to rotate without load, i.e. without coupling the generator (tested machine). In this condition:

Table 1. Induction motor with 10 HP (without load).

Frequency	f = 60.2 Hz
Phase Voltage Fase	V_F = 220 V
Armature current for Phase	I_a = 10.2 A
Power	P = 650 W
Apparent Power	S = 6732 VA

According to Table 1, the calculation for the yield of the induction motor (7.5 kW) was:

$$\eta = [1 - (650 / 7500) \times 100\%] = 91.3\%$$

In the sequence, the generator (machine developed) was coupled to the motor. In this condition:

Table 2. Induction motor with developed generator coupled.

Frequency	f = 60.2 Hz
Armature current for Phase	I_a = 12.5 A
Power*	P = 5090 W
Apparent Power S	S = 8250 VA

*Observed at the input of the motor from a wattmeter.

4. Results and discussion

4.1. Physical properties of sintered alloys

The definition of the alloys to be used for the construction of the rotor and stator cores occurred from the study sintered alloys from iron and other elements such as P, Si and Ni. It was chosen pure iron to the core of the rotor since this metal presented low hardness with good magnetic properties, which facilitated the machining to the final shape of the rotor. On the other hand, the Fe1%P alloy to the stator core, since this alloy presented higher electrical resistivity with good magnetic properties without a significant increase in hardness. Table 3 shows the results of the density, electrical resistivity, mechanical properties and magnetic properties, from the average values of the three test specimens.

The samples obtained from pure iron and Fe1%P presented density after sintering of 6.63 and 6.71 g/cm^3, respectively, remaining slightly below the bibliographic reference (typical value of 7.2 g/cm^3 for both) [5], as it can be seen in Table 3. The magnetic properties of retentivity and coercivity were observed from the hysteresis curve. The relative magnetic permeability was obtained from the magnetization curves and the maximal induction was observed from the magnetization curve for an applied magnetic field of 6 kA/m. The electrical resistivity was measured from the samples in the shape of rings by cutting a 10 mm segment, using Equation 1.

In Table 3 it can be observed that the average (three specimens) of the electrical and magnetic properties of the materials studied has large differences if compared to the properties indicated in literature [3, 10]. This can be attributed to many variations in the processes of Powder Metallurgy, in which factors such as particle size and shape, compaction pressure, sintering levels and atmosphere influence in the desired density [9-11]. It is also observed that the addition of phosphorus besides to improved magnetic properties (mainly increase of the permeability) also increases the electrical resistivity [41], which is beneficial for use in cores of electric machines, since this aspect reduces eddy currents. For this reason, it was chosen the Fe1%P alloy for the stator core development. As for the rotor core, there is little magnetic flux variation which naturally reduces eddy currents. The yield stress resulted in 137 MPa for pure iron, 118 MPa for Fe3%P and up to 170 MPa for Fe5%Si, based on the average obtained from three tests on three different samples. Steel 1008 presented an average yield strength of 170 MPa. The average hardness obtained was 52.1 HB for pure iron and 124.5 HB to Fe1%P (addition of iron alloy elements increases the hardness). The AISI 1008 steel has hardness of 86 HB [42]. So, regarding the mechanical properties the materials studied in this work presented values next to 1008 steel.

The samples obtained from Fe2%P alloy presented a maximum induction of 1.36 T and relative permeability of 4199, greater than those of Fe1%P (Table 3) which resulted in 1.25 T and 2766 respectively [5]. In this condition, the Fe2%P alloy exhibit better magnetic and electrical properties for the machine cores development, although the increase in hardness must be considered. Another important aspect concerns the material resistivity, since the Fe2%P alloy presented resistivity of 0.36 μΩ.m,

Table 3. Physical properties of the sintered alloys studied.

Material	ρ_m [g/cm^3]	ρ_e [$\mu\Omega$.m]	B_r [T]	H_c [A/m]	B_{max} [T]	μ_r	HB	σ_e [MPa]
Fe Pure	6.63	0.16	0.90	448.2	1.19	1852.6	52.1	137
Fe1%P	6.71	0.20	0.96	215.8	1.25	2766.1	124.5	145
Fe2%P	6.87	0.36	1.00	207.9	1.36	4198.7	202.4	124
Fe3%P	7.00	0.42	0.50	210.7	0.98	919.4	242.9	118
Fe1%Si	6.69	0.27	0.71	246.3	1.03	1959.8	64.5	146
Fe3%Si	6.73	0.44	0.48	225.4	0.85	1258.7	73.2	157
Fe5%Si	6.76	0.48	0.30	216.3	0.67	493.8	101.9	170
Fe50%Ni	7.25	0.37	0.22	112.1	0.93	945.6	101.1	162

where ρ_m is the density, ρ_e electrical resistivity, B_r retentivity, H_c coercivity, B_m saturation induction (observed for a field of 6 kA/m), μ_r relative magnetic permeability, HB hardness in Brinell scale, σ_e yield stress.

while pure iron and Fe1%P alloy showed 0.16 μΩ.m and 0.20 μΩ.m, respectively, in terms of the referred parameter. Regarding these values, if the machine was constructed from the Fe2%P alloy, it would present smaller current parasites, reducing the losses, if compared to the machine developed for this project. It is important to note that the machine developed here was constructed from sintered material pure iron and Fe1%P alloy, since the cores were compressed into billets and later machined to the final shape of the cores. However, when alloy elements are added to the iron, especially phosphorus, there is an increase in hardness, which difficult the subsequent machining. The Fe2%P alloy sintered exhibits a hardness of HB 202.4 which is approximately four times greater than the sintered pure iron (HB 52.1) [5].

According to bibliographic data [28], loss tests were carried out on test specimens of the same dimensions of sintered Fe-50% Ni alloy and low carbon steel plates. The sintered alloy had a loss of 50 W/kg while the loss in the plate core was 10 W/kg, and these losses are mainly due to the parasitic currents.

It is observed that the loss in the sintered core is significant higher, however, in the case where the sintered material is only used in the core in the rotor in a synchronous machine, as there is little variation of magnetic flux there, and consequently few induced currents (or parasites), the difference between the losses are practically null.

In a rotate electrical machine, working as a motor or generator, the torque on the shaft end is a function of the magnetic flux of air gap (maximal induction) and the inclination of the magnetic flux lines in the air gap, also known as load angle for the case the rotate synchronous electrical machines. A rotate electrical machine is therefore a dynamic transducer energy, i.e. as motor, it transforms electrical energy from the armature windings into mechanical energy delivered to a load on the shaft end. As a generator, the opposite occurs, i.e. it transforms mechanical power on the shaft end, from a turbine, into electrical energy. In both cases, the conversion of energy occurs from the magnetic field and the magnetic flux of air gap (or maximal induction) is the determining factor. Because of this, it is considered as better results the machines that operate with higher magnetic flux of gap and the greater final torques [1,2,8].

4.2. Results of testing machine

As a generator, it was analyzed waveforms and voltage levels generated by the machine on five different speeds of rotation. Table 4 shows a relationship between the generated voltage and rotation in RPM. Once the machine studied present four poles and being a synchronous machine, the speed is 1800 RPM. In this condition of angular speed, the generator must produce V_F = 220V (phase voltage) and V_L = 380 V (line voltage), according to Equation 10:

$$V_L = \sqrt{3}.V_F \tag{10}$$

Table 4. Comparative data between rotation and generated voltage.

Angular Velocity [RPM]	Phase Voltage [V]
200	22
600	81
1000	135
1400	189
1800	242

4.3. Tests performed on Voges Motors

The yield tests were performed considering the relationship with the conventional three-phase induction motor of 10 HP (7.5 kW), since the synchronous machine was built in the same housing of the induction motor used for the drive.
Generator star connection:
Output voltage of generator (synchronous machine):

- $V_L = 427$ V, $V_F = 246$ V

Power dissipated in the synchronous machine (values obtained from Tables 1 and 2):

- $P_M = 5090 - 650 = 4440$ W

Approximate yield of Synchronous Machine:

- $\eta = 1 - (4440/7500) \times 100\% = 40.8\%$

The yield resulted in a very low amount of approximately 40.8 %. The induction motor with high performance used in the construction of this machine and also in the testing of it, as a primary machine, presented yield of 91.3 %. A synchronous machine with permanent magnets may present a yield of 94 or 95 % according to the design and materials used in manufacturing [1,2].
Another machine of the same topology, with rotor with permanent magnets and sintered material, but with stator from milled steel sheets, achieved a yield of 88%, very close to conventional machines [19]. It was observed that a stator model motor made from sintered alloy Fe1%P at relatively low frequencies (1290 RPM) achieved a yield of 45.7 %. However, at higher frequencies (5720 RPM), it achieved a yield of 72.7 %. These percentages are related to the original engine that is constructed from steel sheets [24].
This fact justifies the use of materials from Powder Metallurgy processes and their variations, only for certain parts of the machines, or for use at high frequencies, when the use of these materials in the stator is concerned.

5. Conclusions

The application of powder metallurgy in the construction of rotating electrical machine cores is currently restricted to special electric motor cores. These include mini motors of complex geometry, for which efficiency is not the most important criterion, and some servomotors where armature windings are powered by a high frequency electric current.

In addition, powder metallurgy processes reduce manufacturing steps and raw material losses that consist of lower production costs.
With respect to the studied sintered materials, it was observed from the physical properties that they are suitable for use in certain parts of rotate electrical machines, such as rotor core, and there are serious restrictions for the use in the stator cores, except for operating machines at high frequencies.
The increase of the yield of developed synchronous machine would occur if one of the following considerations was implemented:

- new machine design with modifications in the slots and topology, and new coiling project;
- stator core construction from alloys with higher phosphorus percentage as, for example, Fe2%P, Fe3%P alloy or Fe-P-Si alloy that exhibit better magnetic and electrical properties;
- use of dies in the final form of the cores, reducing the subsequent machining, allowing the application of these alloys despite the increase in hardness by the addition of phosphorus.

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