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DEVELOPMENT OF A STAND FOR TEST OF ELECTRICAL MOTORS AND GENERATORS

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ABSTRACT: The aim of this work was the development (study, project and construction) of a stand for test of rotating electrical machines, for both motor and generator functions. The stand is composed by frequency inverters, ammeters, voltmeters and wattmeter's, charge cell (torque sensor), tachometer and resistive load bank and motor/generator functioning as a primary machine. In tests as generator, a motor, activated by the inverter, turns the axis of the generator, and the charge cell detects the torque in the axis between the machines. Through a tachometer the angular speed of the axis is measured. With this data, it is possible to obtain the mechanical power. Turning on the resistive load bank and the output of the generator, it is measured the power as well as the voltage and the electrical current, obtaining then the electrical power and the mechanical power in the input. The efficiency of the machine will be the ratio between the output electric power and the input mechanical power. The same stand can test a machine functioning as a motor, being necessary only that the input electric power be measured, utilizing a generator as load of the motor. In this case the efficiency will be the ratio between the output mechanical power and the input electric power. Preliminary tests performed in a synchronous machine with sintered cores and permanent magnets, resulted on an estimated efficiency of 90%.

Keywords: Stand for Test of Electric Machines, Motor and Generator, Efficiency of Electrical Machines, Powder metallurgy

1. INTRODUCTION

1.1. Rotary Electric Machines

The generation of alternating electric energy is carried out from rotating electrical machines, in which, the field windings, fed by direct current, induce the voltage, generally three-phase, in the armature windings, where it is generated the electric power of the generator. In some machines, the field windings are replaced by magnets of Nd-Fe-B [1,2]. Other sources such as batteries and photovoltaic cells, generate direct voltage that eventually generate alternating voltage, single-phase or three-phase from the inverters.

Considering the three-phase generators, these should be activated by a primary machine, such as a combustion motor, in the case of power-generator groups (gasoline, alcohol, diesel, gas) or a turbine such as Eolic, hydraulic, steam. It should be noted that thermoelectric (coal) or nuclear (uranium) plants, reactions from these products boil the water, generating steam, which will trigger a turbine [3].

Rotating electrical machines have two basic parts which are the stator and rotor cores. These cores, with rare exceptions, are constructed from thin metal blades having a thickness of less than 1 mm, grouped into sheet metal packages. Some higher-performance machines, such as generators, are built with silicon steel sheets with about 3% silicon. The total process to confection these cores consists basically to the lamination process, stamping, electric isolation process, packaging and fastening. Based on the low carbon steel sheets, the isolation process has been a thermal treatment, in which the packages of steel sheets are placed in ovens in during a certain amount of time, occurring the oxidation of the surface of the plates and consequently, a formation of an isolated layer of iron oxide between adjacent plates. Some types of silicon steel plates come with an oxide-based painting in one of the surfaces, depending on the manufacturer [1,2,3].

Magnetic cores surrounded by coils, where alternating currents circulate, generate an alternating magnetic flux. For this reason, these cores are the subjected to the parasite currents, also called by Foucault currents, which are responsible by a considerable loss in the power in these cores. The construction of these magnetic cores from the electrically isolated steel sheet reduces partially the parasite currents, lowering the losses by the Foucault currents.

However, using Powder Metallurgy (P/M) processes, it is possible to construct these cores in single solid blocks with high magnetic permeability and higher electrical resistivity compared to conventional steel, which reduces the parasite currents [4,5]. In the case of the application of this process in the construction of rotary electric machine cores, it can result in machines with some advantages over those with conventional cores. Thus, as so far as it is possible to build cores in single and massive blocks, fewer stages will be present in the construction of the machines and less energy will be consumed in the manufacture of the same. It is also emphasized that with the use of magnetic resistivity alloys in the construction of the stator and rotor cores, there will be a reduction in losses due to parasitic currents, a higher performance, resulting in savings of electric energy.

Currently the application of P/M in electric machine cores is restricted to special electric motors for which performance is not the most important criterion, as in the case of complex geometry mini-motors, in some servomotors in which the armature windings are fed with high frequency electric current and parts of machines where there is no variation of flux, such as rotor cores of synchronous machines. However, some studies are being carried out on other types of

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machines obtained from the P/M in order to prove or discard the application of this technology in these devices [5].

1.2. Three-phase Electric Generators with Permanent Magnets

Regarding the constructive aspect, the three-phase machines consist essentially of two parts [1,2,3]:

Stator: Fixed part of the machine constructed of laminated steel sheets in which the three-phase capacity armature windings, phase shifted at 120°, are placed. The windings are arranged spatially so that the currents of all phases contribute positively to the generation of a rotating magnetic flux wave or rotating field.

Rotor: Rotating part of the machine also constructed of laminated steel sheets in which the field windings are placed. In some synchronous three-phase machines, the field windings are replaced by permanent magnets.

The evolution of synchronous machines is related to the progress and discoveries in magnetic materials. The substitution of the field windings by permanent magnets of high energy product allowed significant advances for the machine, which today is considered as having the most variations of size, shape, geometry and configurations. The use of permanent magnets has brought advantages of these machines compared to those with field windings, such as [6]:

- Simplification of technology.
- Reduction of approximately 10% of its volume.
- Elimination of external power supplies, brushes and collector rings.
- Development of equipment with a higher power to volume ratio of material.
- Reduction of mass and inertia moment.

The magnets produced with materials called rare earths, such as samarium-cobalt and neodymium-iron-boron, are the ones that presented the best results in applications that require high performance or require light and compact machines [6].

Synchronous machines with permanent magnets can be classified according to the orientation of the magnetic flux density of the air-gap excitation in two main types: radial and axial. The radial flow machine, shown in Figure 1, has the direction of magnetic flux density perpendicular to the rotor axis. The magnets used are magnetized with radial direction and are located on the surface or inside the rotor. These machines have rotors with reduced diameters and low inertia, low losses and have the largest axial length in relation to their diameter. They are more easily found on the market today because of their robustness and easy mechanical construction [1,2,6-9].

The axial flow machines have the direction of the magnetic flux density of excitation in the air gap parallel to the axis of rotation and the air gap is located in a plane perpendicular to the axis. Figure 2 shows the topology of this type of machine. The magnets used have axial magnetization and are fixed to discs which, depending on the configuration, can be rotating or stationary. These machines are characterized by having a disc-like geometry, with a much larger diameter than if longitudinal length. It is an excellent alternative for applications requiring high torque at low speeds [1,2, 6-9].

There are a third type of flux in machines with permanent magnets which is the machine with transversal flux [10].

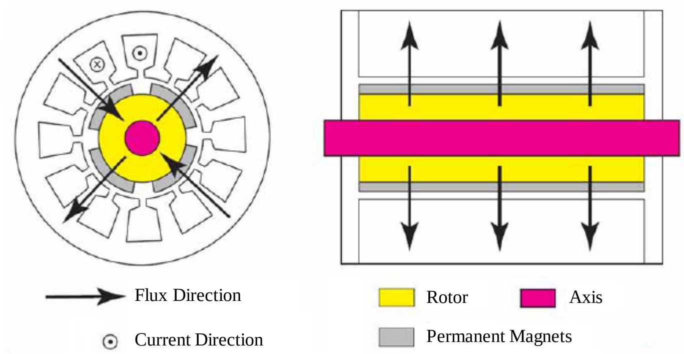


Figure 1 – Radial flux machine [7]

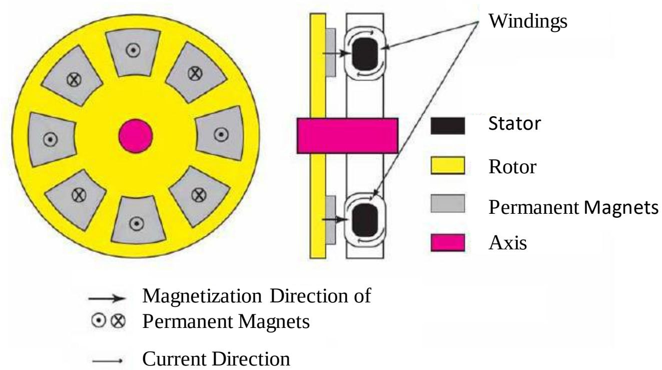
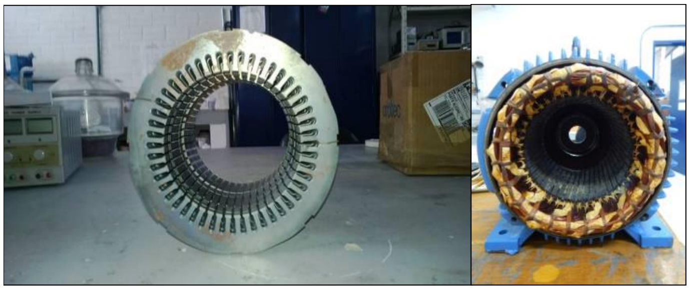


Figure 2 – Axial flux machine [7]

The LdTM (Laboratory of Mechanical Transformation) of UFRGS has been developing partnerships with other institutions, such as Universities FEEVALE, ULBRA and other institutions in projects of three-phase electric machines to be used in small wind turbines up to 10 kW. In these studies, the housing, axle, covers and bearings are of a three-phase induction motor of 10 cv. The stator core was constructed of sheet or synthesized material, and three rotor topologies with synthesized material and permanent magnets were studied and constructed.

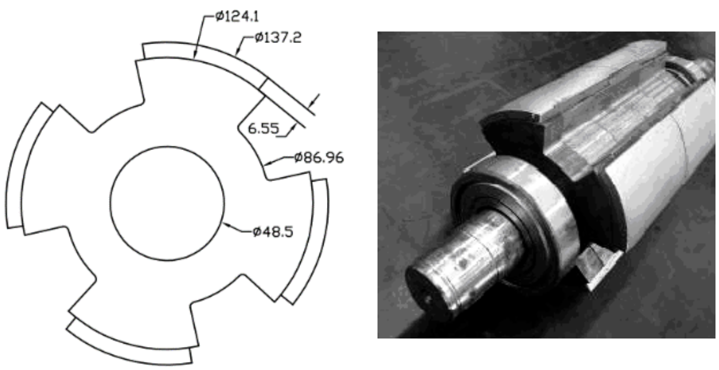
Figure 3-a shows the core of the stator of the machines utilized as base, and figure 3-b shows the stator embedded in the housing of the machine (Voges Motors).



(a) (b)

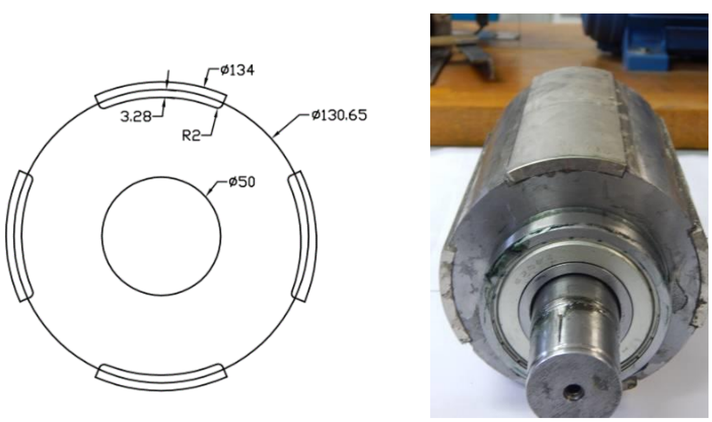
Figure 3 – Motor utilized as base – (a) Stator – (b) Stator embedded in the housing [6]

Figure 4 shows the rotor of protruding poles, the Figure 5 shows the smooth pole rotor and Figure 6 the rotor with embedded magnets.



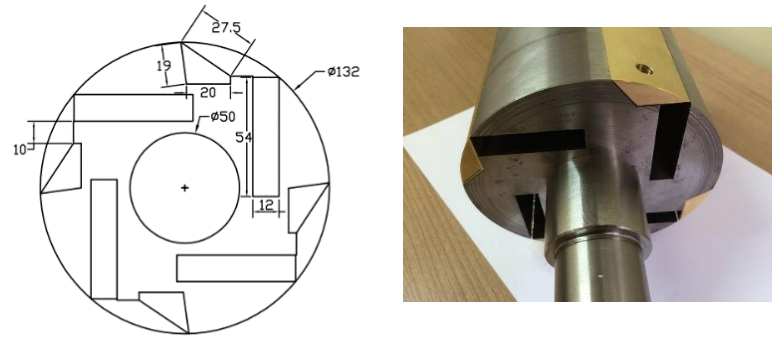
(a) (b)

Figure 4 – Rotor of protruding poles – (a) Schematic drawing – (b) Rotor assembled [11]



(a) (b)

Figure 5 – Smooth pole rotor – (a) Schematic drawings – (b) rotor assembled [6]



(a) (b)

Figure 6 – Rotor with embedded magnets – (a) Schematic drawing – (b) rotor assembled [12]

1.3. Efficiency of electrical machines

In an ideal rotary electric machine, in the operation as generator or motor, the mechanic power is calculated as[13]:

$$P_{mec} = \tau_{ext}.w \qquad [1]$$

where $\mathbf{P_{mec}}$ is the mechanic power [W], $\boldsymbol{\tau_{ext}}$ is the torque developed in the axis [N.m] and **w** the angular speed [rad/seg].

The electric power is calculated as[13]:

$$P_{ele} = VI \qquad [2]$$

where $\mathbf{P_{ele}}$ is the electric power [W], **V** the voltage [V] and **I** the electric current [A].

For an ideal machine, without losses, the principle of energy conservation establishes that the mechanic power ($\mathbf{P_{mec}}$) must be identical to the electric power ($\mathbf{P_{ele}}$), thus[13]:

$$P_{mec} = P_{ele} \Rightarrow \tau w = VI \qquad [3]$$

However, for ideal rotary electric machines, operating as a motor, not all electric power delivered to the machine is converted into mechanical energy. The same analogous reasoning can be done for operation as a generator. This occurs because there are losses in the electric machines. These losses can be evaluated from the principles of electromechanical energy conversion, where electric energy is transformed into mechanical energy, as shown in Eq. 3. In the operation as a motor of a rotary electric machine, Eq. 3 can be rewritten as[13]:

$$P_i = P_o + P_{Ra} + P_{mag} + P_M + P_d \qquad [4]$$

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Where all the factors represented in the equation C.4 are powers given in [Watts], and represent[13]:

- **P_i** ⇒ Input electric power, supplied by the voltage power supply;
- **P_o** ⇒ Output mechanic power, supplied by the load coupled in the axis of the motor;
- **P_{Ra}** ⇒ power dissipated in the armature windings, which represent the losses in the windings of the machine
- **P_{mag}** ⇒ power representing the magnetic losses by hysteresis cycle and Foucault current;
- **P_M** ⇒ power representing the mechanic losses to ventilation of the machine and friction between the axis and the bearings;
- **P_d** ⇒ power representing other losses.

The same analogy reasoning can be done for operation as a generator. The performance of a machine can be measured from its efficiency η, which considers the losses in the machine relating the input power and output power, ie[13]:

$$\eta = \frac{P_o}{P_i} \qquad [5]$$

An important factor in the performance of rotating electric machines is the magnetic losses. Factors such as increased electrical resistivity and decreased magnetic coercivity of the stator and rotor cores reduce these losses, increasing machine efficiency.

2. MATERIALS E METHODS

2.1. Electrical Machine Testing

The cited machines, such as those in Figures 4, 5 and 6, were bench tested to verify their performance as well as the visualization of voltage waveforms. The machine to be tested as Motor (Figure 7 on the left), is coupled to a generator (Figure 7 on the right), which in turn feeds resistive load up to the nominal power of the machine, both of the Motor being tested and the generator. Figure 7 further shows a load cell between the machines for measuring the resulting torque between the axes thereof (see Figure 7-c).

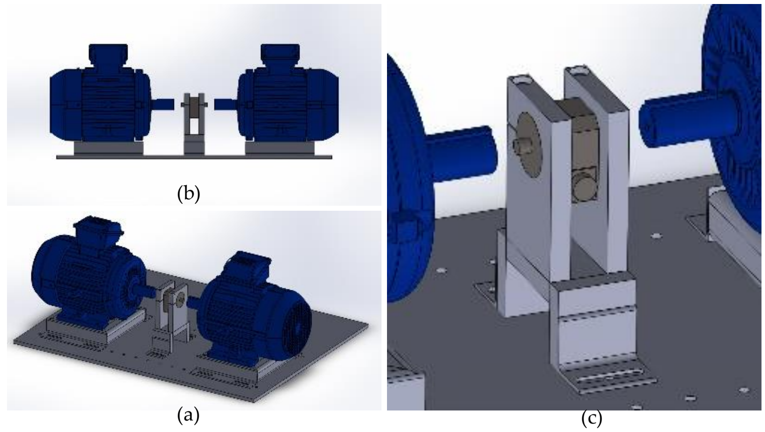

Figure 7 – Schemes for tests of Rotatory Electric Machines – (a) Perspective view – (b) Front view – (c) Load cell detail

Figure 8 shows a general scheme of a test bench of rotatory electric machines, both as Motor and as Generator.

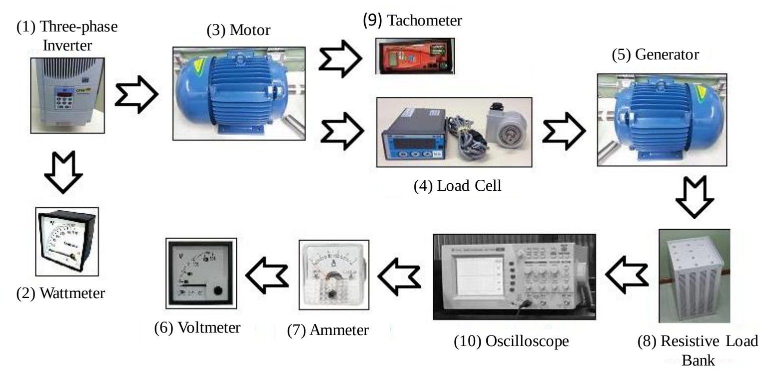

Figure 8 – Scheme of the proposed bench

From Figure 8 it can be seen:

(1) – Three-phase inverter
(2) – Wattmeter
(3) – Motor
(4) – Load cell
(5) – Generator
(6) – Voltmeter
(7) – Ammeter
(8) – Resistive Load bank
(9) – Tachometer
(10) - Oscilloscope

In operation as a motor, the machine to be tested (3) is activated by the three-phase inverter (1), which, in addition to providing a variation in the speed of the machine, also informs the Voltage and Current, making it possible to determine the Apparent Power. From the Wattmeter (2) it is possible to determine the Active Power at the Motor input. The Generator - Conventionally Acquired in the Market - (5)

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functions as Load for the Engine (3) and both are coupled from a Load Cell (4) with which it is possible to measure the torque on the axis and hence the load. The Generator (5) feeds a Resistive Load Bank (8), and from the Voltmeter (6) and Ammeter (7) it is possible to determine the Active Power at the output of the Generator (5). From the Tachometer (9) it is possible to measure the Angular Speed in RPM (rotation per minute) on the axis between the machines. From the speed and torque, it is determined the Mechanical Power between the axes of the machines. An oscilloscope (10) is connected at the output of the Generator (5) for the visualization of Voltage waveforms thereof.

In this condition, the Motor is set and Rotated to Nominal Speed, and loads are coupled to the Generator output, up to the rated power. Thus, the yield of the Motor is calculated from Eqs [1] and [5].

$$\eta = \frac{P_o}{P_i} = \frac{P_{mec}}{P_{ele}} = \frac{\tau_{ext}.w}{P_{ele}} \qquad [6]$$

Where τ_{ext} is the torque [N.m] observed from the load cell, and **w** the angular velocity [rad/seg] observed from the tachometer.

The Power Factor is determined by the relation:

$$FP = \frac{P_{ativa}}{P_{Aparente}} = \frac{3.P_W}{\sqrt{3}.V_L.I_L} \qquad [7]$$

Where P_W is the Active Power at the Motor Input, observed from the Wattmeter (in this case Wattmeter Monophasic, for this reason multiplied by 3), VL and IL are Voltage and Line Current respectively, observed from the Inverter.

In the case of tests of the machine as Generator (5), the Motor is Conventional - Acquired in the Market - (3), and in this case, it is very important to view the Voltage Waveforms from the Oscilloscope (10). The machine yield is calculated as:

$$\eta = \frac{P_{ele}}{P_{mec}} = \frac{3.V_F.I_F}{\tau_{ext}.w} \qquad [8]$$

Where V_F e I_F are the Voltage and Phase Current, observed from the Voltmeter and Ammeter respectively (in this case multiplied by 3 for being from phase - to three - phase).

2.2. Bench Design and Assembly

The proposed workbench has the devices shown in Figure 8, and Figure 9 shows the design (schematic drawing) thereof. Figure 10 shows the assembled bench, and Figure 11 shows the same bench with a more detailed view of the load cell. It should be noted that the workbench is in the final stage of assembly and the final finishing is still missing as well as some connections.

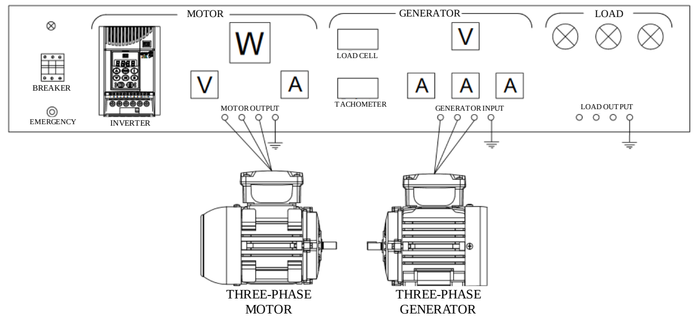


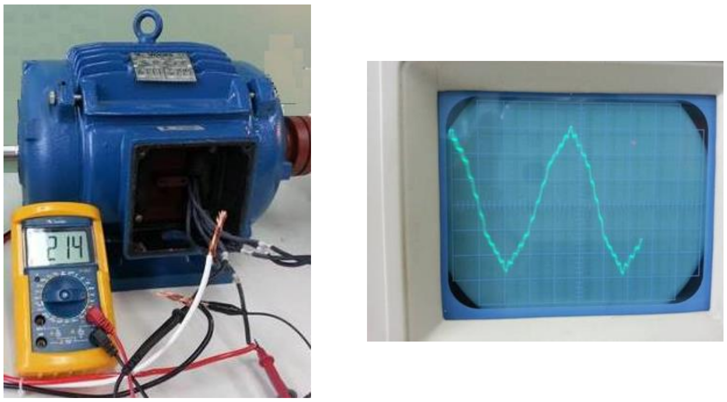
Figure 9 – Schematic drawings of the proposed bench.

Figure 10 – Proposed bench in final phase of assembly

Figure 11 – Proposed bench (Load cell detailed view).

3. RESULTS AND DISCUSSIONS

The synchronous machine with permanent magnets or more specifically the three-phase generator shown in Figure 6 was preliminarily tested on the proposed bench, however in the previous assembly thereof. From the inverter of the primary machine (induction motor coupled to the right of the machine), it was possible to vary its angular velocity, causing the generator axis to vary at the same speed. Thus, it started at low speeds, increasing slowly up to 60 Hz of the line, or 1800 RPM of the axis of rotation of the machines (4 poles), observing the voltage generated at the output of the Generator (figure 12-a) and waveforms (Figure 12-b).



(a) (b)

Figure 12 – Generator test – (a) Voltage Reading – (b) Waveform [12]

Next, the lamps were connected in a triangle connection at the output of the generator by varying the speed of rotation of the shaft, measuring voltage and current, both at the input to the three-phase induction motor (primary machine) and at the output of the wind turbine, observing the waveforms for these frequencies as well. Table 1 shows the measured values, for current frequencies of 15, 30, 45 and 60 Hz, equivalent to rotor angular speeds of 450, 900, 1350 and 1800 RPM. Figure 12-b shows the generated waveform for one of the generator phases for a 45 Hz voltage and current (1350 RPM) frequency.

Table 1 – Variations of Voltage and Current as a function of Frequency of axis rotation.

Turns [RPM}	Voltage Vi [V]	Current Ii [A]	Voltage Vo [V]	Current Io [A]
450	101	0,44	80	0,03
900	197	0,72	163	0,18
1.350	294	1,02	245	0,25
1.800	390	1,41	326	0,30

Where **Vi** and **Ii** is the voltage and current at the input of the primary machine, and Vo and Io are the voltage and current at the output of the generator, that is, at the lamps.

From Table 1 it can be concluded that at 1800 RPM the voltage at the generator output was 325 for a star connection, and this should be 380 V, that is, below this value. However, there were small differences in the execution of the project, compared to the simulations due to constructive problems. Such an adjustment is relatively simple, with the machine rewinding being sufficient, increasing proportionally the number of turns per winding per phase. With respect to the peaks observed in the sine wave shown on the oscilloscope (Figure 12-b), this is due to the fact that the stator plates are not inclined with relation to the direction of the rotor magnets, ie due to the constructive aspects of the machine.

Due to these distortions it was not possible to accurately determine the performance of the developed machine. However, as the base on which it was mounted, is the shell and stator of a Voges induction motor whose data are well known, it was possible to estimate the efficiency of the same, based on the data of this machine and the tests performed. Thus, from the observed power at the input of the primary machine and at the output of the wind turbine and knowing the losses and yield of the machine used as base, an efficiency of approximately 90% is estimated for this machine, which is relatively close to yield of this type of machines indicated in the bibliographical references [1,2,3].

4. CONCLUSIONS

The preliminary tests of the bench proposed in this work, indicated an efficiency for a certain machine tested, in the range of the expected values, however it should be noted that due to the fact that the bench is in the final assembly and testing phase, the exact yield of the machines tested may only be disclosed in future work.

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