The prototype of a vertical hydraulic turbine with a rotor attached to the stator and axes positioned axially to the fluid flow

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Abstract—This article presents the development of a vertical hydraulic turbine combined with an electric generator, developed inside its own rotor. For energy use of the amount of movement of water flows of any nature, whether artesian wells with positive pressure, sewage water flows, domestic distribution water flows, river beds, channels, and others. Regardless of the existing pressure level or whether the water flow is continuous or not. If there is full energy use of any laminar and / or turbulent water flow, according to the dynamics of the fluids, this water flow goes through the rotor, which is cylindrical and is in line as a generator that is coupled the turbine. The vertical hydraulic turbine proposed in this article is compact, robust and low cost. One of humanity's greatest challenges is finding solutions to the growing scarcity of drinking water. The vertical hydraulic turbine is an alternative technology for the use of water.

Keywords—Water flow, Cylindrical rotor, Sustainable Alternative Technology, Vertical hydraulic turbine.

I. INTRODUCTION

Since antiquity, man has always sought to improve his quality of life and energy has assumed a fundamental role in the evolutionary process. In order to modify and improve the community's living standards, man uses energy to live more and better.Creating a dependency on energy resources. Thus, there is a growing concern with environmental issues and worldwide awareness of promoting development on a sustainable basis and encouraging the development of technological development research by renewable sources. The Brazilian energy matrix - energy offered to society to produce goods and services has large consumers, mainly industry and the residential sector, which increased due to the expansion of the National Interconnected System - NIS and social inclusion programs, such as light for all.The National Interconnected System consists of companies from the South, Southeast, Midwest, and part of the North. Approximately 1.7% of the country's electricity production

capacity is outside the NIS, in small isolated systems located mainly in the Amazon region.

In Brazil, isolated systems are mainly supplied by diesel-powered generating plants, in most cases located in regions with difficult access.These systems supply about 3% of the national population, located in an area that corresponds to more than 40% of the Brazilian territory.The northern region has a good portion served by the isolated Brazilian system. The northern region of Brazil is the most extensive with 3.869,637 km[2] and has seven states: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins.This region has 60% of Brazil's hydroelectric potential. However, a good part of this resource has environmental, technological and economic restrictions for exploration, as they are found in areas of environmental protection or indigenous reserves.In this way, a considerable portion of the population in this region does not have access to electricity, especially isolated systems.The generation in these systems is predominantly thermal, based on diesel oil

and fuel oil, and is characterized by several small generating units and large supply logistics difficulties.

These generating units are mostly outdated, inefficient, with high levels of pollutant emissions and high costs.Consumers not served by the NIS system, the so-called isolated communities, seek to ensure the supply of electricity through small diesel generator sets.These communities live in areas that are difficult to access due to the particularities of the region, such as great distances between villages, low population density, flooded areas, vast hydrographic network, dense and compact forest.This article presents the constructive development of a vertical hydraulic turbine combined with an electric generator, developed within its own rotor as a viable alternative to generate clean and sustainable energy in isolated, indigenous and quilombola communities in the Amazon with significant social gains

II.   MATERIAL AND METHODS

To develop the vertical turbine, the theoretical basis, construction, will be described.

A.   The theoretical foundation of the vertical turbine

The vertical turbine is a self-excited induction generator. Because the induction generator has become quite attractive when driven by alternative renewable sources. In this way, for an induction machine to work as a generator, a bank of capacitors must be connected in such a way that the necessary initial magnetization current can be generated.

In self-excitation, two conditions must be satisfied: i. The rotor must have sufficient residual magnetism; ii. The three-phase capacitor bank must be of sufficient value. The main advantageous features are:

- Low cost compared to the synchronous generator

- Robustness

- Low maintenance demand;

- Small Size compared to other power generating machines

- Good dynamic behavior

- Control simplicity

- Used in many applications up to 100 kW

- Operates connected to the mains and isolated

- No brushless

- No mechanical keys

- Self-protection against overload.

Although the induction generator (IG) has numerous advantages and easy implementation when connected separately or driven with variable speed, it has some

disadvantages.The main disadvantages are the unsatisfactory voltage regulation and the load-dependent variable frequency.In this way, the use of a control mechanism is necessary for the regulation of voltage and frequency, in order to compensate the reactive loads connected to the terminals of the self-excited induction generator (SEIG).The primary machines connected to the SEIG can be of variable speed, such as hydraulic turbines and wind turbines, or of constant speed like internal combustion engines, for each case controls based on electronic power devices can be used [1], [4].

With the advancement of semiconductor device technology, countless circuits have emerged aiming to improve SEIG-based plants.Plants that use constant frequency primary machines applied to low-cost electricity generation systems can be a good option because they simplify SEIG control. Being an asynchronous machine, that is, it works at a frequency slightly different from the imposed frequency, an induction machine's main characteristic is reversibility, that is, the ability to operate either as a motor or generator[3].When operating as a motor, it works below the synchronous speed imposed by the network, but as a generator, it works above the generated frequency [8].

Figure 1.0 shows the characteristic curve of the three-phase induction machine in steady-state.
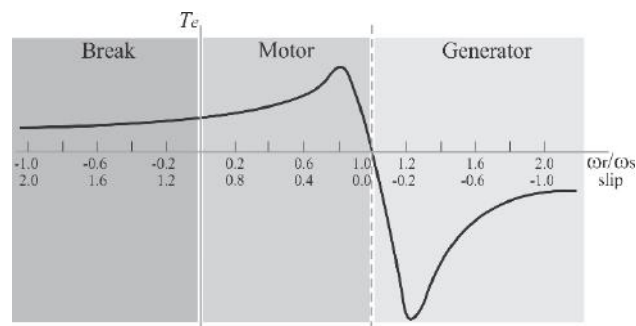

Fig.1: Characteristic curve of the three-phase induction motor in steady-state [15]

The phase equivalent circuit of a steady-state induction machine is also known as the phase equivalent model and is limited to the case of sinusoidal voltage and balanced excitation. Note that the induction machine (IM) is represented by a transformer, this is due to the fact that the magnetization curve for both electrical machines is similar [15].
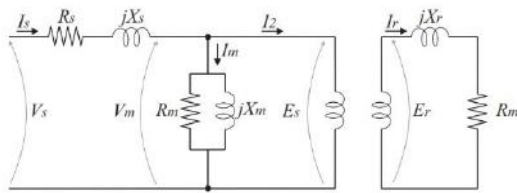
Fig.2: Equivalent model per phase of the IM [15].

Where, V_S is the stator supply phase voltage, V_m is the magnetization voltage($V_m \cong V_S$), R_S is the stator resistance, X_S and the stator reactance, R_m is the resistance of losses, X_m is the magnetization reactance, R_r is the rotor resistance, E_s is the stator primary voltage, E_r is the rotor secondary voltage. To understand the phenomenon of induction in an asynchronous generator, one must understand what happens with the voltage when the rotor is blocked, in this condition the rotation of the stator ω_s is equal to the rotation of ω_r and the voltage induced in the rotor E_r is directly proportional to the slip factor s. Thus, the voltage induced in the rotor will be:

$$E_r = sE_{r0} \qquad (1)$$

Where E_{r0} is the voltage induced in the rotor in a blocked condition.

$$s = \frac{f_s - \frac{p}{2}\frac{n_r}{60}}{f_s} = \frac{n_s - n_r}{n_s} \qquad (2)$$

If s is the slip (dimensionless), p is the number of poles, n_s is the speed of the stator (rpm), n_r is the rotor speed (rpm), $(n_s - n_r)$ is the relative speed between the stator speed and the speed of the rotor magnetic fields (rpm) e f_s is the frequency of the stator given by $pn_s/120$ (Hz).

Thus:

$$f_r = \frac{p}{120}(n_s - n_r)\frac{n_s}{n_r} = sf_s \qquad (3)$$

$$\omega_r = (1 - s) * \omega_s \qquad (4)$$

Where f_r is the rotor frequency and ω_r is the angular speed of the rotor. Therefore, the rotor's own inductance will be affected by the slip factor, which in turn alters the rotor's reactance. Thus, the rotor reactance will be:

$$X_r = 2\pi f_r L_{r0} = 2\pi s f_s L_{r0} = sX_{r0} \qquad (5)$$

Where X_{r0} is the blocked rotor reactance. In this way, the equivalent circuit can be demonstrated depending on the slip factor, according to figure 3.0.
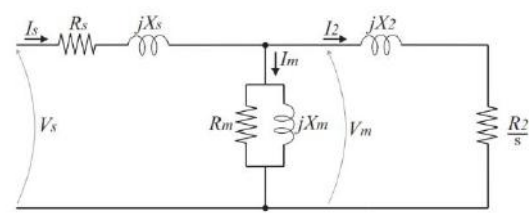

Fig.3: Characteristic curve of the three-phase induction motor in steady-state [12].

Where X_2 is the rotor reactance seen by the stator (reactance referred) and R_2 is the rotor resistance as a function of slip (referred resistance) seen in the stator.

Likewise, analyzing the equivalent circuit, the power balance can be extracted:

$$P_{saída} = P_{entrada} = P_{perdas} \qquad (6)$$

Efficiency(η):

$$\eta = \frac{P_{entrada} - P_{perdas}}{P_{entrada}} 100\% \qquad (7)$$

Being three-phase voltage, 120 ° out of phase and balanced, the output power can be rewritten as:

$$P_{saída} = \sqrt{3}V_l I_l \cos(\phi) \qquad (8)$$

B. Mathematical Modeling of the Self Excited Induction Generator by Capacitor Bank

The model $d - q$ is the most reliable and accurate. Thus, using stator and rotor currents as state variables, and stator voltages as another group of state variables. Therefore, the model presented here can be used to study loads and/or a combination of capacitors in symmetrical and asymmetric configurations, in particular performance can be obtained during balanced and unbalanced failures [9], [14]. The index s indicates that the applied property is related to the stator, the index r is related to the rotor, the index m is related to losses in the (mutual) induction machine and e the q and d indices to the transformation axes $d - q$.
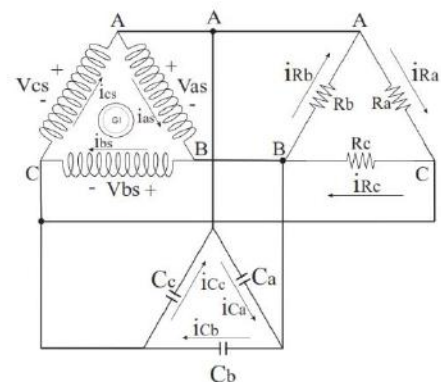

Fig.4: Schematic diagram connected in triangle connection of the Self-excited Induction Generator.

C. Features of the Induction Machine

Table 1 and Table 2 show the main parameters of the induction motor used as a generator. It is worth mentioning that some parameters are obtained through tests. The tests are proposed by the IEEE 112/2004 (IEEE 112,2004) standard, currently in force.

Table 1 - Characteristics of the induction generator.

Parameter	Value	Unity
Power	3	kW
Angular speed	3545	RPM
Poles	2	
Power factor	0,89	
Frequency	60	Hz
Phase voltage	220	V (delta)

Table 2 - Test parameters.

Parameter	Value	Unity
R_s	0,66	Ω
X_s	0,929	Ω
L_s	0,002464249	H
R_r	0,25	Ω
X_r	0,929	Ω
L_r	0,002464249	H

The magnetization curve of the three-phase induction motor is similar to Figure 5.0, and is obtained by the proposed tests (IEEE112,2004). These tests are a set of records of the voltage produced by a variable source and the current required by the stator.Thus, the capacitor bank must supply the reactive power of the isolated induction generator (IG) operating without load, for this, it is necessary to extract the magnetization reactance from the IG operating point, given by:

$$X_M = V_f/I_m \qquad (9)$$

Where V_f is the phase voltage of the operating point (design specification) and I_m is the magnetization current, these two values are extracted from the magnetization curve raised from the IG.
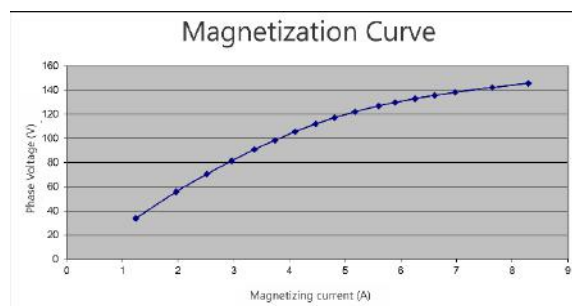

Fig.5: Induction Generator Magnetization Curve.

Thus, by matching the reactance of the capacitor bank X_{CA} with the magnetizing reactance X_M, one can calculate the capacitance of the capacitor bank that will supply the reactive power of the IG operating at no load.

$$X_{CA} = X_M \qquad (10)$$

$$C_{CA} = \frac{1}{2\ pi\ f\ X_{CA}} \qquad (11)$$

Analyzing the point of interception of the operating curves of the IG and the capacitor bank illustrated in Figure 6.0, it is possible to determine the operating voltage (127 V) and the frequency (60 Hz).
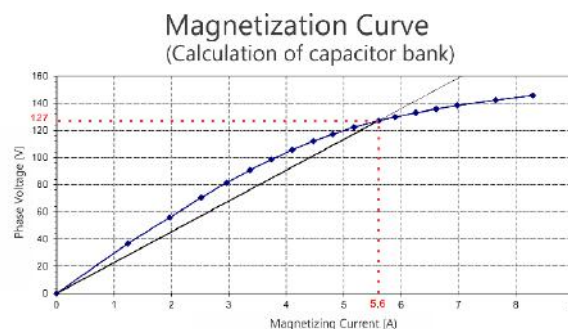

Fig.6: Magnetization curve of the induction motor at 127 V and 5,6 A.

So from the equations above, assuming a constant speed at 3600 rpm and a generated frequency of 60 Hz, the capacitance value for the tested motor is obtained, which is equal to $117,072\mu F$, and because the capacitors are connected in delta, the capacitance found should be divided by three. The value found for each capacitor in the bank is approximately $39\mu F$, whereas in the commercial range the closest value is $40\mu F$ for each excitation capacitor.

D. Prototype construction

The developed model of a self-excited induction generator with a rotor built in the turbine body and coupled to an armored stator is composed of the following parts:

1. One stator

2. Onemagnetic package

3. Onerotor with paddles helical

4. Twofixing coversbearings

5. Twobearings

6. Twothreaded supports (2")

Figures 7 and 8 show the coupled parts of the turbine.
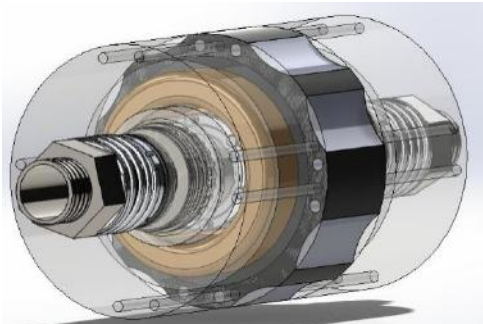
Fig.7: Structure of the prototype with the turbine axis inserted in the rotor of the electric machine and, this, in the stator

Figure 8.0 shows the three-phase stator - 2 poles.Capable of delivering approximately 1.10 kW at 3.500 RPM.
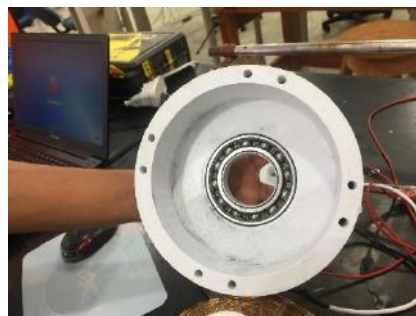

Fig.8: Three-phase stator

The images of the prototyped ABS plastic parts, the rotor and the stator used in the electric machine are shown below.
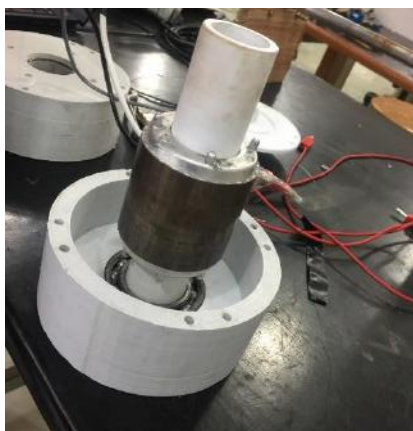
Fig.9: Induction rotor coupled to the turbine rotor and fitted to the bearing of one of the covers

The covers that support the bearings are shown in figure 10.

Fig.10: Support with the bearing

The covers of the bearing housings will be screwed to the threaded supports for coupling with the hydraulic test network.

Fig.11: Screw cap for coupling the turbine to the test pipe

The assembly of the rotor, covers and top support is shown in the figures below.

Fig.12: Mounting the turbine

The figures below show the lower coupler of the Vertical Turbine. Observe the details of the part to install the seal ring. To prevent leaks.

Fig.13: Bottom Threaded Coupler

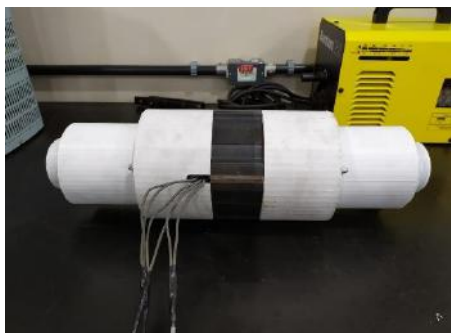Figure 14 below shows the Prototype with all parts assembled.

Fig.14: Complete assembly of the vertical turbine

III.   RESULTS AND DISCUSSION

The vertical hydraulic turbine combined with an electric generator developed inside its own rotor was subjected to two bench tests. One dry test and another flow test. The purpose of the dry test bench is to test the generation conditions of the prototype.The bench consists of a three-phase ABB 800 series inverter, a 1 HP WEG motor, two contactors for switching the capacitor bank, two contactors for switching loads, three voltmeters, and two sets of 300 W loads.The generator is coupled to an induction motor controlled by a three-phase inverter of the ABB 800 series. Fig. 15 shows that the generation test was successful.

Fig.15: Test bench in the laboratory

In the bench test, to verify the generation conditions, the prototype performed well and, as described in the literature, the output voltage varies according to the load, the results are in table 3.

Table 3 - Testsperformed

Speed (RPM)	Capacitor (µF)	Phase voltage (V)	Charge (W)
1860	25	85	0
3587	25	110	0
3587	30	110	300
3587	35	110	600
3587	40	150	600

The proposed vertical turbine was placed to be tested on the flow bench at different speeds.

Fig.16: Vertical turbine tests, pump motor

   (a)   500 rpm   (b)   1000 rpm

Fig.17: Vertical turbine tests, pump motor

   (a)   2500 rpm   (b)   3500 rpm

Table 4 shows the measurement of the rotation of the turbine rotor as a function of the rotation of the water pump motor.

Table 4 - Measurement of the rotation of the turbine rotor

Pump motor (RPM)	Flow rate(m 3/h)	Flow rate (m3/s)	Flow speed in the tube (m/s)	Flow speed in the turbine rotor (m/s)	Rotation speed measured in the turbine (rpm)
1.000	10	0,003	1,15	4,00	255,85
1.500	16	0,004	1,84	6,39	614,04
2.000	22	0,006	2,53	8,79	1.125,75
2.500	25	0,007	2,87	9,99	1.279,26
3.000	30	0,008	3,44	11,99	1.535,11
3.500	33	0,009	3,79	13,19	1.688,62

IV. CONCLUSION

This article aimed to present the innovative concept of a self-excited induction generator with a rotor incorporated in the turbine body and coupled to an armored stator.

Part of the prototype was built with the polymeric material (ABS), which allowed greater versatility in the preparation of parts, avoiding waste of time and resources with lathes and other services.

In addition to elucidating the issue of the electric machine, the tests on the dry bench allowed the mechanical adjustments of the parts in the polymeric material, making possible the establishment of parameters for the construction of the next prototype. Although the electric machine has a configuration designed to work around 3,600 RPM, at 1,860 RPM, it has already presented phase voltage around 85 V.

Thus, we proceeded with an initial test on a bench of controlled hydraulic flow without, however, subjecting it to excessive pressures, which could cause breaks in the bearing support caps that are made of polymeric material (ABS).

With the system flow at 10 m^3 / h the rotation started, and, at the flow of 15 m^3/h, it reached 614 rpm. And at the nominal pump speed, 3.500 rpm, the flow reached 33 m^3/h and the turbine was already turning at 1.688 rpm. In the analysis of the leakproofness test, no leaks were verified from 2000 rpm, for the part of the electrical machine.

The innovative concept of the vertical turbine with the electric generator on the rotor was proven by the tests.

For more rigorous tests, the next prototype should be made of metallic material.

This vertical turbine can provide significant social and environmental gains.

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