American Journal of Hydropower, Water and Environment Systems
Publisher: Acta Editora/LAWG-IAHR
DOI:10.14268/ajhwes.2017.00046
ISSN: 2317-126X
Subject Collection: Engineering,
Subject: engineering, measurement, environment Systems

Design and Build-up of a Small Hydroelectric Power Plant for Engineering Teaching

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ABSTRACT

The majority of power generation in Brazil is made by hydroelectric power plants and projections shows that this scenario will hold into the future. Therefore it is essential to study the process of energy conversion, from the water movement until its consumption in electric form. That study will contribute in the formation of human resources and development of engineers at the field of energy production and conversion. The objective of this work is to project and build-up a hydro power plant inside the Thermofluids Laboratory of University of Brasilia-Gama Campus. The project encompasses the assembly of a water pipe to give the plant its head, the installation of a small Indalma turbine, a coupling device and a load center composed by lamps to assess the energy consumption. The project consists in evaluate the head losses at the water pipe, measurements for the hill diagram of the turbine, design and installation of the coupling between turbine and generator, and the design of the load center. In order to analyze the energy generated, tests with the generator and the turbine separated from each other were performed to obtain the output voltage, the me chanical power and efficiency of the turbine in nominal conditions. The hydraulic circuit and the coupling operated adequately after its installation. When the generator was coupled to the turbine, the latter had to operate below its optimal operation point due to a limitation of the generator. The load center was able to consume the electrical power given by the generator. Despite the generator limitations, the build-up of the power plant was successful, where one could observe the entire process of energy conversion.

KEYWORDS: Indalma Turbine. Hydropower Plant. Teaching methods. Coupling.

1. INTRODUCTION

According to data from [1], over 60% of the power plants in Brazil are hydroelectric. Likewise, close of 30% of the power plants in construction in Brazil are also hydroelectric. Therefore, one can note the predominance of this kind of power generation at the Brazilian energetic context, even with the availability of other sources. Those power plants are composed by a turbine-generator combination, that transforms mechanical power output of the hydraulic turbine in electric power.

That combination is obtained by a mechanical device that couples both machines. Power plants that has small values of power represent also a form to address the energy demands in Brazil, mainly in isolated communities. Those plants have small environmental impact compared with big power plants due to its dimensions [2, 3].

In order to address the energy demands, hydro power plant rehabilitation [4] and the use of small hydro power plants are studied in order to take the most of those enterprises. As a consequence, there is constant research for new technologies and equipment for energy generation, conversion and transmission. These research brings additional demands for human resources with specialized and transversal competencies in renewable energy. Because of that demand, engineering teaching must address those demands.

Within the context of engineering schools, the use of a power plant model allows to correlate the learning of theories involved in such a plant with practice experiences. This model would facilitate the learning of basic turbomachinery concepts, power analysis and management of the power output. The thermofluids laboratory of University of Brasilia - Gama Campus has a experimental setup of a hydraulic turbine, that allows the experimentation of small turbine models. This setup can be transformed into a complete power plant that can be use into research and human resources formation. The entire process of energy conversion, transmission and consumption, from the flow to the generator outlet can be mapped and studied.

The energy engineering undergraduate course of UnB-Gama Campus aims to graduate engineers with competence to study modern energy conversion problems, such as generation, transmission, regulation and final use of that energy. Also, environmental and social issues are also present at the course curriculum. Its profile is of a electro-mechanical engineer with studies into portions of mechanical, chemical and electrical engineering, and studies into economics and regulation laws. Concerning hydroelectric plants, the student gets in touch with concepts of transport phenomena, fluid dynamics, turbomachinery, up to a course into hydroelectric power plants.

Therefore, the main goal of this work is the build-up and setup of a hydro power plant for teaching purposes at the thermofluids laboratory of UnB-Gama campus. The setup of the hydraulic circuit, the turbine, generator, its coupling, and the load center will be shown. Results concerning head losses, turbine experiments, coupling project and load center testings will be presented.

2. MATERIALS AND METHODS

In order to provide the turbine the mechanical power, a hydraulic circuit was projected and constructed at the laboratory, as shown in figure 1. This circuit has a 1000-liters reservoir, a water pump of 25 CV, and tubes of 0,1016 m and 0,1524 m. The water pump is controlled by a frequency inverter, allowing a better control of the flow rate and pressure of the circuit. The circuit has manual valves that can set a constant head, conducting any additional water to a drain pipe. This valve setup avoids unnecessary turbulence at the flow, which can impact at the turbine eciency. The entire hydraulic system was developed to allow the measurement of all data with simple analogical

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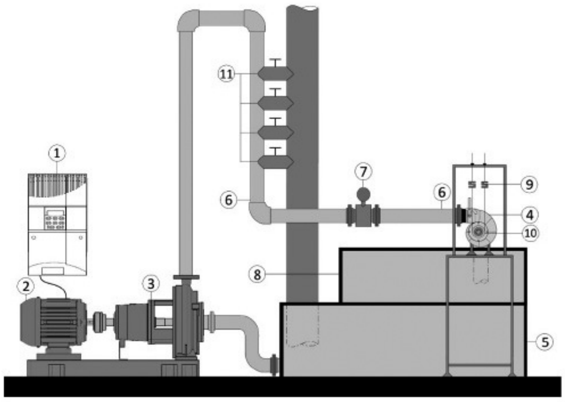
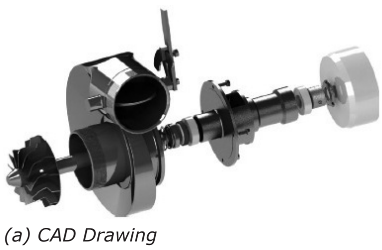
instrumentation and additional instrumentation coupled with computers. Data of head, flow rate, rotation force and rotation speed can be measured by those instrumentations. This setup allows a maximum gross head of 7 meters.



[Figure 1: Bench parts.]

Where:
1. Frequency Inverter;
2. Electrical Motor;
3. Water Pump;
4. Indalma Turbine;
5. 1000 l-Water Tank;
6. Turbine Water Intake Tube;
7. Flow Rate Sensor;
8. Triangular Spillway;
9. Load Cells;
10. Inductive Sensor;
11. Manual Valves

The turbine used was a Indalma turbine, as showed in figure 2. This turbine was developed as a modification of a Francis turbine. Its main innovation is the use of aspects of impulse turbines and reaction turbines into a configuration that allows its functioning without a distributor. The Indalma turbine was developed to work into hydro power plants with power output below to 10 kW up to 1000 kW at the Amazon region. This region has demands for turbomachinery of easy assembly and simplified operation and maintenance. Since the turbine does not have distributor or a mechanical control for power output and flow rate, it simplifies its use into those kinds of hydro power plants. The turbine was also equipped with a DI15 Digital Indicator that is coupled with a rotation sensor. The indicator shows the rotation speed at the axis of the turbine in RPM.

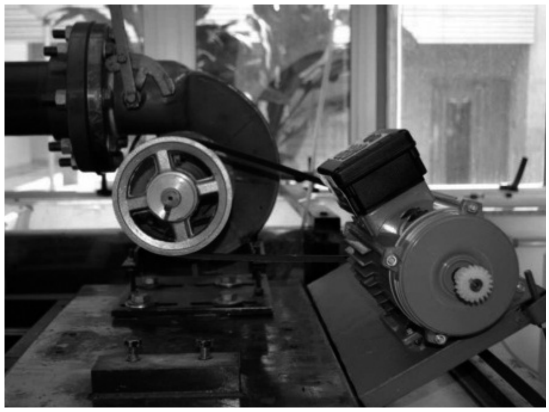


(a) CAD Drawing

(b) Installed Indalma Turbine

[Figure 2: Indalma Turbine.]

One form to couple two rotative machines is using transmission elements. Those elements are flexible and transmit mechanical power or rotative movement. Typical examples of transmission elements are belts with pulleys, axis and cables. The use of a belt as a transmission element allows the transmission of rotation movement from one axis to another, where each axis has a pulley at its extremities [5]. The belt employed is a 90 cm length, V-section belt, who fits at the pulleys without sliding. A moving base was employed to adapt the generator to the turbine height and to allow the traction of the belt between the pulleys. The generator was bolted at the base to allow this adaptation, as showed in figure 3.



(a) Turbine-Generator Coupling

(b) Generator

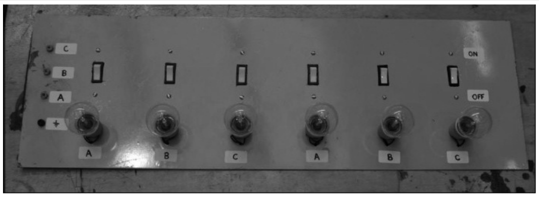
[Figure 2: Turbine-Generator Setup.]

The employed generator is a three-phase synchronous machine with one pair of poles (Figure 3(b)) and an excitation system MPL-3305M MINIPA (0 to 32 V and 0 to 5 A). A multimeter was used to measure the output voltage at the machine terminals during the test.

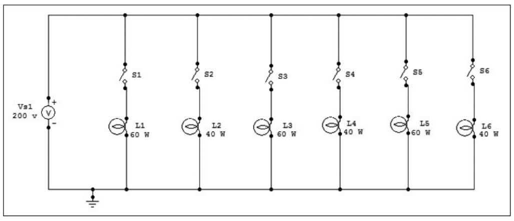
The load is composed by six lamps, where three of them has 60W-220V and the other three has 40W-220V. Their choice is justified by the fact that they behave like resistors and the electrical power consumed is visibly noticed.

In a first moment, a monophasic circuit where all lamps are set in parallel was assembled. Each one has a switch to allow the load variation. However, connecting a monophasic load in a triphasic machine allows the machine to be unbalanced. This unbalance can cause the appearance of a negative-sequenced electrical current, vibration and a decrease in the nominal rotation. Because of that the load cell circuit has to be transformed into a triphasic circuit.

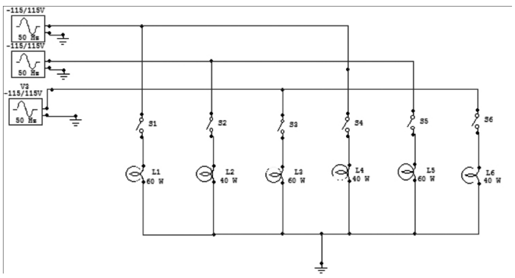
The result of this transformation is a circuit with a star connection. All the phases of this circuit are composed by two parallel-assembled lamps, each one connected to a switch, according to figures 4(b) and 4(c). Also, for the tests, a rectifier, a voltage source and a voltage regulator were employed to control and provide a direct current to excite the generator. The load setup is showed at figure 4(a).



(a) Load Center



(b) Monophasic connection



(c) Triphasic connection

***[Figure 4:** Load Center.]*

3. RESULTS

3.1. Head Losses

The Darcy-Weisbach equation (Equation 1) was employed to evaluate the head loss h_f at the hydraulic circuit [6]:

$$h_f = f\frac{L}{D}\frac{u^2}{2} \quad (1)$$

Where f is the friction factor, L is the tube length, D is the tube diameter and u is the flow velocity. The flow ratio Q was measured by a electronic flow ratio sensor. With the water flow rate and the diameter, the Reynolds number was calculated using equation 2 for both diameters:

$$Re = \frac{QD}{A\nu} \quad (2)$$

Where A is the round section area and ν is the kinematic viscosity. A measured flow rate of 0,0512 m^3/s yield the Reynolds number values displayed on table 1:

***[Table 1]:* Reynolds Number for each tube.**

Diameter (m)	Area (m2)	Re
0,1016	0,0081	642212,35
0,1524	0,0182	428729,67

One can note that the Reynolds number for both cases is above 2300. According to [6], the flow is fully turbulent with those values of Reynolds number. Therefore, the Moody diagram is employed to evaluate the friction factor f . With this data, one can calculate the head losses at the straight tubes. For the head losses at parts of the hydraulic circuit, all the components are listed at table 2, with their respective head losses:

***[Table 2]:* Minor head losses.**

Part	Head Loss (m)
Two Bends	0,0595
Four Tees	0,0151
One Elbow	0,0026

The total head loss of the entire hydraulic circuit, including the minor losses, is hf= 0,1588 m.

The majority of the head losses at the circuit is at the upward tubes. However, in order to obtain the net head delivered to the turbine, one must take only the loss at the pipes where the water is going downward. This head loss is equal to hf d= 0,0447 m, where the upward tubes and all the minor losses before the downward tube were subtracted from the total head loss.

3.2. Hill Diagram and Power Output

The used gross head for the hydraulic circuit is equal to 6,385 meters of water column (mwc), which is below the maximum head for safety reasons. By subtracting the downward head loss calculated above from the gross head, one can conclude that the net head is equal to 6,34 mwc.

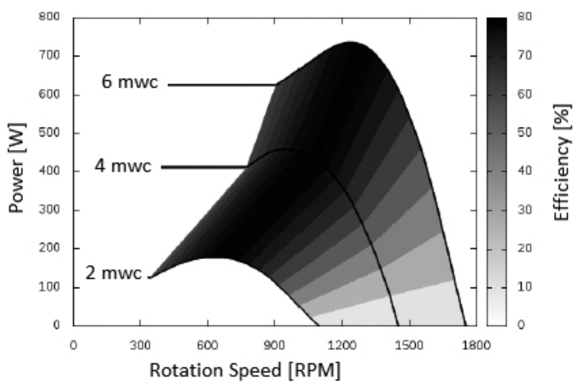
With this head, it is possible to obtain the mechanical power output of the turbine.

With the flow rate and the net head, one can estimate the hydraulic power received by the turbine. The overall eciency for both the turbine and the generator is 0,675, therefore one can estimate the power that the turbine will deliver to the generator using equation 3:

$$P = \eta Q g H \quad (3)$$

Where P is the power in kW, η is the eciency and g is the gravity. Several operating conditions of the turbine regarding the rotation, the power output and the eciency of the turbine were performed. These tests allowed the plotting of the hill diagram of the turbine, showed at figure 5.

The diagram shows where are the best functioning points to operate the turbine.



***[Figure 1:** Bench parts.]*

Using the eciency and equation 3, the power output will be equal to 0,3004 kW. However, the mechanical power output of the turbine is too high for the generator. In order to be able to employ the described generator and to be able to use the projected load center, the turbine functioning was adjusted to fit the needed power value of the generator. To reduce the power output to the desired value, the hill diagram was employed to evaluate the new operation point. The chosen condition for the turbine provides 200 W of power is if the turbine rotation speed is set at 1080 RPM. This power and rotation values were used to the following calculations of the present work. To achieve those values, the head was adjusted with the valves and the pump rotation, using the hill diagram as a guide. The output power value given by the hill diagram was confirmed by the load cells.

3.3. Coupling and Voltage Output

The need of the coupling comes of the fact that the turbine has a nominal rotation speed of 1080 RPM and the generator has a nominal rotation speed of 3000 RPM. Therefore, the coupling aims to increase the rotation output of the turbine. To achieve this objective, a set of two pulleys and a belt were employed. The pulley that goes at the turbine has a diameter of D_1=14,2 cm.

Therefore, having the rotations and this diameter, one can calculate the diameter of the generator pulley using equation 4:

$$\frac{n_1}{n_2} = \frac{D_2}{D_1} \tag{4}$$

Applying the previous data, one can find that the generator pulley must have a diameter of D_2 = 5,11cm. For the assembly of the coupling a 5-cm pulley and a V-shaped belt of 90 cm of length were employed. A support composed by a moving base was attached to the generator to allow the belt traction and the proper rotation of the pulleys. This setup gave a 3067,2 RPM rotation to the generator for the turbine rotation, which is above the minimum required by the generator.

With the coupling operational, empty tests on the generator were performed in order to measure the output voltage. In the first test, the generator was excited with a voltage of 200 V, alongside a rectifier that provided a direct current to excite the generator. This test provided an output voltage of 9000,01 V, which is incompatible with the generator and its functioning, because the output is too high. The following tests were made by varying the pump rotation speed and employing a excitation voltage and current of 4 V and 0,02 A respectively. The measured values of output voltage for those tests can be seen at table 3:

[Table 3]: *Generator Output for a Excitation Tension of 200 V.*

Pump Rotation (RPM)	Tension (V)
100	1000±01
80	720±01
60	410±01

After those tests, the generator was excited with 8 V and 0,03 A and the tests were repeated.

Although the measured output voltage dropped, it is still high for the generator. The use of a fixed voltage to excite the generator produced high values of output voltage, which prevented the use of this output for the load center. Also, it was noted the occurrence of a voltage decrease. To solve those issues, a voltage regulator was connected to the excitation apparatus in order to alter the voltage output to acceptable values. The tests with the voltage regulator produced line values of 46,415 V and phase values 2205 V, that allowed the use of this output to the load center. The tests with this configuration can be seen in table 4:

[Table 4]: *Generator Output for a Excitation Tension of 8 V.*

Pump Rotation (RPM)	Line Tension (V)	Phase Tension (V)
100	200±5	115±475
80	160±5	92±385
60	100±5	57±735

3.4. Load center

When the load center was assembled, tests were performed to observe the right connection of each phase of the load, and to find any short circuit caused by wrong connections. The center was connected to 220 V. After these tests, another set of tests were conducted to check the connection between phases. The results showed that the load center is correctly connected. The next step was connect the load center to the generator. As previously mentioned, a voltage regulator was connected to the generator excitation to avoid the voltage decrease and to control the voltage output. The turbine rotation was fixed at 1080 rpm, which gave a generator rotation of 3067,2 rpm. The excitation voltage is 975 V in direct current. The voltage at the line and the phase are 346,415 V and 2205 V respectively. Those values were acceptable by the load center, and the result of this voltage at the center are shown at figure 6:

[Figure 6: Generator.]

One can note that the mechanical power generated by the turbine was converted into electrical power and consumed by the load center. Tests where the center unbalanced the electrical load were performed. For those tests, lamps of 40 W and 60 W were employed and some of those lamps were turned o to achieve the unbalance. The current frequency and values for each phase A, B and C are showed at table 5:

[Table 5]: *Phase Currents.*

Phase	Current (A)
A	0,150±01
B	0,180±01
C	0,200±01

When the electrical load was changed, one noted that the remaining phases divided the electrical power. That fact was visibly at the load center, where some lamps lose their luminous intensity with the increase of the load. With those tests, the build-up was completed and the bench was fully operating as a 200 W hydroelectric power plant.

4. CONCLUSIONS

The present work described the setup and build-up of an experimental bench of a small turbine and generator to act as a hydroelectric power plant. This plant aims to be used as learning and teaching tool for the Energy Engineering students of University of Brasilia - Gama Campus. The design of the hydraulic circuit, turbine operation points, its coupling with the generator and the tests of the generator and the load center were showed.

Calculations were made to evaluate the head loss from the water inlet to the turbine inlet. With those results, the available mechanical power given by the fluid and its given head were calculated too. In order to compensate for the generator, the used turbine power output is lower than the maximum. Its value was calculated by the hill diagram after several tests with the turbine. The coupling was able to transmit the mechanical power to the generator, but the output voltage and current were too high for the load center. To solve this issue, an excitator and a voltage regulator were employed and acceptable values of current and tension were obtained and used at the load center. The center functioned adequately with and without all the lamps turned on.

Before the build-up, the experimental setup was able to perform experiments of pump performance and turbine eciency. Now, with the coupling with an generator and a load center, the setup can perform complete experiments of energy conversion, even with a limited generator. The energy engineering course at University of Brasilia-Gama Campus can now exploit transversal experiments on energy conversion, generation, transmission, regulation and consumption, which covers both mechanical and electrical areas simultaneously. Also, research on mechanical load variation and regulation of the turbine with its eects on energy conversion and transmission can be exploited.

Concluding, the experimental setup was successfully transformed into a hydro power plant, but the generator limited the electrical power output. Further work will be performed into the use of a new generator, and the diversification of the load center, where more lamps and electrical equipments will be added to the center. Also, other points at the hill diagram will be used to evaluate the performance of the turbine and the generator. In the future, it is planned to perform research into energy generation management and quality with the educational use of the setup.

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