Analysis of synchronous and induction generators used at hydroelectric power plant

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Abstract. In this paper is presented an analysis of the operating electric generators (synchronous and induction) within a small capacity hydroelectric power plant. Such is treated the problem of monitoring and control hydropower plant using SCADA systems. Have been carried an experimental measurements in small hydropower plant for different levels of water in the lake and various settings of the operating parameters.

1. Introduction

In this age increasing demand of energy has forced us to look at the other options to make electrical energy, different from conventional means of exploiting energy as conventional sources of energy are exhaustible. The starting point energy crisis was the oil crisis [1], [2].

As the awareness came in early seventies also came the search for the alternatives. Also it was required that the alternatives should be such that, they should not be the major changes required in the system. Renewable energy emerged as the best option. The major renewable are hydro, solar, wind and biomass. The beauty of these renewable energy systems is that they are non-exhaustible [1-3].

Hydropower is one of the most promising available energy sources in the world. However, with limited potential and other problem like high construction cost, environmental concerns due to impounding of river water and long gestation period of large hydro have ceased to be offering any long-term solution for our increasing power demand problem. Small hydropower on the other hand, can be built in less time and are likely to create less environmental problems [2], [3].

Of all the non-conventional energy sources, small hydro represents the highest density resource and stands in the first place in generation of electricity from such sources throughout the world [3], [4].

Hydropower plants are complex installations where hydraulic energy of natural or artificial water falls is converted into mechanical energy through hydraulic turbines and then into electricity in power generators.

The potential to produce electricity depends on the drop and water flow. Their operating principle is to transform the potential energy of water abstraction in lakes into mechanical energy. From the lake, through the penstock, water falls on a hydraulic turbine blades rotating shaft. This drives the electric generator, which converts mechanical energy into electricity [3].

After the power produced, hydro are of three kinds: hydroelectric plants with an installed capacity exceeding 100 kW, small hydopower plants with installed capacity of 5 to 100 kW and micro plants built on brooks, do not have the Barrage and installed capacity under 5kWh [3].

A hydraulic turbine is composed of three main bodies:
- a distributor that prints the fluid speed and direction convenient size for the attack rotor in desired optimal conditions with minimal load losses;
- a rotor fitted with blades or buckets that aims to transform the hydraulic energy into mechanical energy;
- a vacuum device, which recovers the form of pressure, the kinetic energy of the water that has to exit from the rotor and draining downstream. This piece is missing in action turbines.

**Table 1.** Classification of types of turbines

| Turbine type | Fall of, m |
|--------------|------------|
|              | Big        | Medium    | Small     |
|              | (150...2000 m) | (50...150 m) | (3...50 m) |
| Action       | Pelton     | Banki     | Banki     |
|              | Turgo      | Turgo     |            |
| Reaction     | -          | Francis   | Propeller |
|              |            |            | Kaplan     |

**Figure 1.** Pressure-flow characteristics of different types of turbines

**Figure 2.** Nomogram of selecting the turbines for small hydropower plant

**Figure 3.** Efficiency-flow rate characteristics of different types of turbines

Type selection, turbine geometry and dimensions depend mainly on falling, the fluent flow and rotor speed (Figure 1). Turbine used for small or medium failures are most often the reaction and include turbines Francis and Kaplan turbines with blades fixed or variable. The turbines used for high
dropping arrangements are acting. These include Pelton turbines, Turgo and Banki (cross flow) (Figures 2, 3) [3].

Before the existence of automation, qualified personnel operated the equipment manually called as the manual system where the automatic system reads the information on the equipment status operation and then activates commands or controls to optimize the output production. Therefore the need for automation for a small hydroelectric power plant is to improve the efficiency, productivity and the operating management of the system which solves the problem of production needs [1], [2], [5].

2. The main equipment used in hydropower plant
At hydropower plant to which were made measurements were use two generators: induction made by Marelli (Figure 4) having characteristics $P_n = 232$ kW, $\cos \varphi = 0.9$, $n = 1500$ rpm and synchronous made by AVK (Fig.5) with the characteristics $P_n = 950$ kW, $\cos \varphi = 0.9$ and $n = 600$ rpm [6-8].

![Figure 4. Induction generator](image)
![Figure 5. Synchronous generator - side view](image)

![Figure 6. Vertical Francis turbine FV 335/330](image)
![Figure 7. Horizontal Francis turbine FO 285/720 – spiral room and director device](image)

Also in the same hydropower plants uses a vertical Francis turbine FV335/330 (Figure 6) and a horizontal Francis turbine FO 285/720 (Figure 7) powered by penstock from a barrage situated within the distance of about 350 m and a net height of 30 m. Vertical Francis turbine coupled to the induction generator and executes 1500 rpm and horizontal Francis turbine coupled to the synchronous generator and runs at 600 rpm [6-8].
3. Monitoring and control of a hydropower plant using SCADA system

The automation system is realized modular PLCs Schneider: TWD LCDE 40DRF – module CPU (24xDIN + 16xDout), TM2 DDI 32DK – extension module (32xDIN), TM2 AMI 4LT – extension module (4xAIN), TM2 DDO 16TK – extension module (16xDOUT), TM2 AMI 8HT extension module (8xAIN), TM2 ARI 8LT – extension module (8xAIN), TM2 AVO 2HT – extension module (2xAOUT) and software [1], [4], [9].

In Figure 8 is shown SCADA system interface from hydro plant for horizontal turbine is connected to the synchronous generator AVK type. From here it can run the command to the device director. Generally, director device works in automatic mode and helping it move, depending on the water level and pressure in penstock. There is the risk not to achieve production set when the device director remains locked. In this case, it will switch to manual mode and adjust the extent to unlock. At the top of the interface seeks instruction (power provided by the operator) and measure (what power achieved by generator) [1], [4], [5], [10].
At the time shown in Figure 9 HA circuit breaker is coupled to the network, this is indicated by the red vertical line in the figure, and induction generator is disconnected from the network, this is indicated in the figure by the horizontal green line. "Cold reserve" indicates that the generator does not qualify the conditions to startup. When all conditions are met it will show "hot reserve". At the top the diagram continues with oil transformer (Trafo 1250 kVA; 20/6/0.4 kV) this raising voltage of 4 kV to 6 kV. The grounding separator (CLP) can be closed only if the disconnector (bar) is open, and the disconnector (bar) can be closed only if the grounding separator (CLP) is open. The diagram ends with 6 kV underground lines. From this interface is the option to disconnect the transformer from the red button [9–12].

![Diagram](image)

**Figure 10.** The interface for viewing the main electrical parameters (active power, reactive power, voltage, current, power factor) to horizontal hydro-aggregate and turbine FO management

In interface shown in Figure 10 the operator has the ability to start and stop the horizontal hydro-aggregate. Also, the operator can adjust the active power and reactive power of synchronous generator. The reactive power of synchronous generator must not exceed 10% of its active power.

In the middle of interface can be viewed using virtual instruments placed on interface, the active power and reactive power of synchronous generator, and the operating current and voltage generator. Also, for this interface it can view the speed at which the hydro-aggregate, the speed at which the final product packaging of hydro-aggregate, power factor of the synchronous generator, and the number of starts and hours of rotation of the synchronous generator.

In interface shown in Figure 11, the operator has an opportunity to start and stop vertical hydro-aggregate unit and can adjust the active power of induction generator. In the middle interface can be viewed using virtual instruments placed on interface the active power induction generator and reactive power as well as voltage and current on which they operate the generator. Also, this interface can view the speed on which they operate hydro-power vertical unit, the speed at which the final product packaging hydro-power and the number of starts and hours of rotation of the induction generator [9-12].
4. Experimental results

In the hydropower plant analyzed operation of AVK synchronous generator and operation of induction generator Marelli, at different levels of water in the lake and various settings of the operating parameters. Hydro-aggregates from hydro plant can operate in two modes: automatic mode - when the unit director of the turbine is automatically adjusted according to pressure inside penstock, and manual mode - when the unit director of the turbine is adjusted by the operator (manual) [6-8].

For operation of AVK synchronous generator at the lake by 292.40 mdM (meters over sea) (N1) and 290.50 mdM (N2), in manual mode, adjusting of the opening director device from 25% to 100%, the ambient temperature being 15 °C and in the hydropower plant hall being 22 °C have been obtained measured values from Table 2.
Table 2. Parameters measured when operating synchronous generator of hydropower plant

| AD (%) | P₁ (kW) | P₂ (kW) | Q₁ (m³/s) | Q₂ (m³/s) | p₁ (bar) | p₂ (bar) |
|--------|---------|---------|-----------|-----------|----------|----------|
| 20     | 169     | 147     | 1.10      | 1.03      | 3.00     | 2.85     |
| 25     | 323     | 236     | 1.38      | 1.41      | 2.99     | 2.80     |
| 30     | 374     | 302     | 1.65      | 1.69      | 2.97     | 2.77     |
| 35     | 400     | 352     | 1.91      | 1.92      | 2.94     | 2.74     |
| 40     | 436     | 392     | 2.16      | 2.11      | 2.90     | 2.71     |
| 45     | 489     | 428     | 2.41      | 2.30      | 2.85     | 2.67     |
| 50     | 550     | 468     | 2.67      | 2.51      | 2.80     | 2.62     |
| 55     | 606     | 512     | 2.93      | 2.75      | 2.75     | 2.55     |
| 60     | 648     | 546     | 3.17      | 2.93      | 2.70     | 2.50     |
| 65     | 671     | 552     | 3.35      | 2.96      | 2.67     | 2.49     |
| 70     | 680     | 555     | 3.50      | 2.93      | 2.64     | 2.50     |
| 75     | 684     | 553     | 3.63      | 2.92      | 2.60     | 2.50     |
| 80     | 696     | 554     | 3.75      | 2.93      | 2.55     | 2.50     |
| 85     | 650     | 553     | 3.87      | 2.94      | 2.51     | 2.53     |
| 90     | 645     | 555     | 4.00      | 2.93      | 2.50     | 2.54     |
| 95     | 640     | 546     | 4.05      | 2.97      | 2.43     | 2.54     |
| 100    | 640     | 542     | 4.09      | 3.00      | 2.39     | 2.53     |

Due to some calculation errors in the design of penstock and the FO turbine is observed (in Figure 14) from the power curve that after opening the unit director at bigger value than 80%, the achieved power across generator drops, water consumption increases and the pressure inside penstock decreases.

For operation Marelli induction generator at lake level of 289.80 mdM (meters over sea) (N3) in manual mode, adjusting the opening unit director from 20% to 100%, the ambient temperature being 10 °C, and in small hydropower plant hall being 15° C (Figure 15 ) were obtained measured values from Table 3.
For the operation of synchronous generator AVK type in parallel (simultaneously) with induction generator Marelli at lake level of 293 mdM in manual mode, adjusting the opening unit director from 20% to 100%, ambient temperature being 20 °C, and in small hydropower plant hall temperature being 27 °C (Fig. 16) were obtained measured values shown in Table 4.

Table 3. Parameters measured when operating induction generator of hydropower plant

| AD (%) | P (kW) | Q (m³/s) | p (bar) |
|--------|--------|----------|---------|
| 20     | 25     | 0.30     | 2.85    |
| 25     | 41     | 0.43     | 2.84    |
| 30     | 50     | 0.54     | 2.82    |
| 35     | 58     | 0.62     | 2.79    |
| 40     | 65     | 0.69     | 2.77    |
| 45     | 73     | 0.75     | 2.74    |
| 50     | 80     | 0.82     | 2.73    |
| 55     | 88     | 0.88     | 2.70    |
| 60     | 95     | 0.92     | 2.68    |
| 65     | 104    | 0.97     | 2.67    |
| 70     | 115    | 1.02     | 2.64    |
| 75     | 129    | 1.06     | 2.60    |
| 80     | 145    | 1.12     | 2.55    |
| 85     | 160    | 1.14     | 2.50    |
| 90     | 165    | 1.14     | 2.44    |

Table 4. Measured parameters for parallel operation of the generators from hydro power plant

| ADₐ₀ (%) | ADᵥ (%) | Pₐ₀ (kW) | Pᵥ (kW) | P_total (kW) | Q (m³/s) | p (bar) |
|----------|---------|----------|---------|--------------|----------|---------|
| 20       | 20      | 133      | 36      | 169          | 1.10     | 2.85    |
| 25       | 25      | 193      | 52      | 245          | 1.38     | 2.80    |
| 30       | 30      | 247      | 66      | 313          | 1.65     | 2.73    |
| 35       | 35      | 297      | 80      | 377          | 1.92     | 2.67    |
| 40       | 40      | 344      | 92      | 436          | 2.19     | 2.66    |
| 45       | 45      | 389      | 105     | 494          | 2.53     | 2.62    |
| 50       | 50      | 433      | 117     | 550          | 2.97     | 2.56    |
| 55       | 55      | 477      | 128     | 605          | 3.30     | 2.50    |
| 60       | 60      | 511      | 137     | 648          | 3.60     | 2.50    |
| 65       | 65      | 528      | 142     | 670          | 3.71     | 2.45    |
| 70       | 70      | 536      | 144     | 680          | 3.86     | 2.45    |
| 75       | 75      | 541      | 146     | 687          | 3.95     | 2.44    |
| 80       | 80      | 545      | 147     | 692          | 4.04     | 2.43    |
| 85       | 85      | 549      | 148     | 697          | 4.15     | 2.43    |
| 90       | 90      | 547      | 149     | 696          | 4.22     | 2.42    |
| 95       | 95      | 545      | 148     | 693          | 4.35     | 2.39    |
| 100      | 100     | 544      | 146     | 690          | 4.44     | 2.33    |

For the operation of synchronous generator AVK type at lake level of 293.05 mdM (N4) in automatic mode, within 24 hours, with two different power set on the operator panel, the ambient temperature being 15 °C, and in the hydropower plant hall temperature 22 °C were get measured parameters shown in Table 5.
Table 5. Measured parameters for the functioning hydro-aggregate FO in automatic mode, within 24 hours

| Hour | Scheduled power [kW] | \( P_{HA-FO} \) [kW] | Energy produced [kWh] | \( Q_t \) [m³/s] | \( p \) [bar] |
|------|---------------------|----------------------|-----------------------|-----------------|-------------|
| 0    | 650                 | 315                  | 664                   | 1.80            | 3.10        |
| 1    | 300                 | 315                  | 312                   | 1.80            | 3.10        |
| 2    | 300                 | 315                  | 312                   | 1.80            | 3.10        |
| 3    | 300                 | 315                  | 312                   | 1.80            | 3.10        |
| 4    | 300                 | 315                  | 312                   | 1.80            | 3.10        |
| 5    | 300                 | 315                  | 312                   | 1.80            | 3.10        |
| 6    | 300                 | 315                  | 316                   | 1.80            | 3.10        |
| 7    | 300                 | 315                  | 316                   | 1.80            | 3.10        |
| 8    | 300                 | 665                  | 343                   | 1.80            | 3.10        |
| 9    | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 10   | 650                 | 665                  | 664                   | 3.30            | 2.84        |
| 11   | 650                 | 665                  | 669                   | 3.30            | 2.84        |
| 12   | 650                 | 665                  | 662                   | 3.30            | 2.84        |
| 13   | 650                 | 665                  | 662                   | 3.30            | 2.84        |
| 14   | 650                 | 665                  | 660                   | 3.30            | 2.84        |
| 15   | 650                 | 665                  | 669                   | 3.30            | 2.84        |
| 16   | 650                 | 665                  | 669                   | 3.30            | 2.84        |
| 17   | 650                 | 665                  | 669                   | 3.30            | 2.84        |
| 18   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 19   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 20   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 21   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 22   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
| 23   | 650                 | 665                  | 667                   | 3.30            | 2.84        |
5. Conclusions

Hydraulic energy conversion into electrical energy is not polluting, requires relatively low maintenance costs, no problems with fuel and is a long-term solution [3].

Hydropower plants have the lowest operating costs and highest lifetime compared to other types of power plants. There are more than a century of experience in the development and operation of hydropower plants, which makes them reach levels high technical performance [3].

Advantages of hydropower plants consist of low cost electricity, requires no fuel, requires low maintenance and operating personnel, do not pollute, they have high operational safety and high efficiency.

By using hydropower plants can be solved free public lighting and supply of electricity for public buildings. Small hydropower plants can benefit from green certificates, so basically they can sell at a price of 3-4 times greater energy produced if connecting to the national system electricity power supply. Also, small hydropower plants does not pollute nature, does not emit carbon dioxide, and the maintenance and operating costs are very low [3].

SCADA systems provide major added reliability and productivity at the level factories in every type of industry, and implicitly to hydropower plants, offering both operators and process engineers or managers, a full overview of all production equipment. Viewing the production values of both real-time and in the past, it helps increase the speed and quality in decision-making, offering operators a reliable tool in performing the daily tasks [1], [2], [4], [5], [9-12].

By implementing algorithms for instant alarm for exceeding the normal parameters of the production is increase the reliability and efficiency of the hydropower plant equipment, operators can avoid timely damage which could lead to production stops. Also, the presented solution enables the operator to replace the quickly the elements that could be damaged (sensors, transducers, actuators, etc.).

It is observed that the measurements made in the hydropower plant functions both hydro-aggregates only when the water level exceeds 293 mdM (meters over sea). When the lake level is very low (less than 290 mdM quota) will operate only vertical hydro-aggregate, and when the lake level is medium (between 290 mdM and 293 mdM quota) will only operate horizontal hydro-aggregate unit.

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