Hydro Energy Generation and Instrumentation & Measurement: Hydropower Plant Efficiency Testing

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Hydroelectric power generation was one of the first forms of large-scale electrical energy generation. In recent years, the hydro power industry has reached a new summit with China's Three Gorges Dam providing an amazing generation capacity of 22 500 MW of renewable energy. In 2012, around 16 % of the world's consumed electricity was generated from hydropower [1]. Hydropower has a number of advantages compared to other types of electrical energy generation. One of them is using a renewable source of energy: water. By using water reservoirs as the source of energy, hydroelectric power plants can easily and quickly vary their power output. Water in hydropower plants' large reservoirs is used as a valuable energy storage resource (in the form of potential energy) in low-demand periods and transformed into electricity when desired. For large turbine-generator units, the mechanical-to-electrical energy conversion process can have a combined efficiency of over 90%.

The reversible nature of the pumped-storage hydroelectric plants take this concept one step further by pumping the water back into the reservoir during low-demand periods of the day when electricity costs are low. Although bound by the efficiency constraints of the process, the same water can then be recycled when it is most needed.

Even though water in rivers is technically free, power plant designers want to optimize the electricity production done with this precious resource. Design engineers strive to get maximum power out of every cubic meter of water that passes through their power plants. To maximize the efficiency of hydroelectric plants, engineers must carefully consider the given environment to design the generator and turbine correctly. Parameters such as water head, river flow, seasonal flow variations, and generator output power have an impact on the design.

Once the turbine-generator unit specifications are set, a manufacturer is chosen. Usually, performance guarantee clauses are added to the contract between the manufacturer and the power plant owner. The clauses stipulate the required generator and turbine efficiencies. These clauses can represent a multimillion-dollar penalty (or bonus) for the manufacturer. Therefore, accurate measurement of the turbine and generator efficiencies is critical for the verification of the contract clauses. Thus, it has to be competent, unbiased, and accepted by both the manufacturer and the owner. Since measurement errors and uncertainties are closely related to finances, using accurate instrumentation and measurement methods is a necessity. The instrumentation measures electrical quantities such as generator voltages, currents and output power, and non-electrical quantities such as water head and level (length), water flow (discharge), pressure, temperature, and rotational speed. To take the measurements and get all of the data needed, a lot of instrumentation is brought on site in addition to the instrumentation permanently installed [2] in a hydro-power plant for monitoring, control, and billing purposes.

To measure the turbine and generator efficiency, the mechanical energy at the input of the turbine and the electrical power at the output of the generator have to be determined. To measure water discharge (flow) entering the turbine, several techniques can be used, such as current-meter, acoustic, thermodynamic, and pressure-time methods. Each method requires a particular instrumentation and has its advantages and disadvantages depending mainly on the power plant configuration. This article provides a brief overview of hydropower plant components and discusses the instrumentation and measurement techniques for measurement of hydroelectric units' efficiency.

Hydropower Plant Overview

To produce electricity, hydropower plants convert the potential and kinetic energies of the water into electrical energy. The amount of energy generated depends on the head of the power plant, the water discharge (flow), and the efficiency of the machines. The head is defined as the difference between the water level upstream and downstream of the power plant. For large hydroelectric power plants, the industry standard is to use three phase synchronous generators. A direct current is used to excite the spinning rotor. AC power is generated by the fixed stator winding. Synchronous generators produce 3-phase voltages at 50 Hz or 60 Hz. Most of the large hydro generators have an output voltage between 6 kV and 19 kV. The lower the operating voltage, the higher the output current is for the same output

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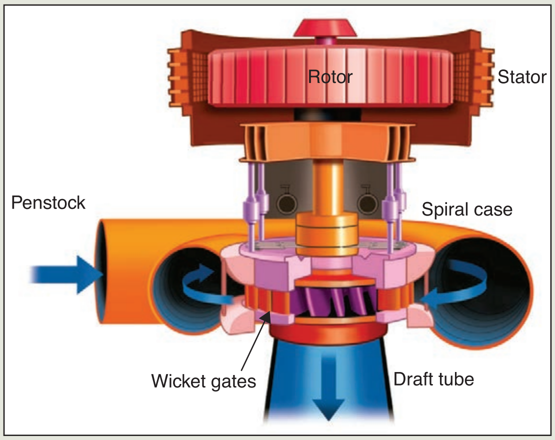

Fig. 1. Turbine and generator cross section.

power. The rotational speed of hydro generators is relatively low compared to the speed of generators used to produce electricity from fossil fuels. The speed of a typical vertical shaft hydro generator is between 80 and 300 r/min (rotations per minute).

$$Generator\ speed(rpm) = \frac{Network\ Frequency(Hz) \times 120}{Number\ of\ rotor\ poles}$$

The generator output is connected to the electrical grid through a generator step up (GSU) transformer which increases the voltage for transmission. The GSU transformer is the link between the power plant and the transmission network. Typical ac transmission line operating voltages are between 120 kV and 750 kV which can be more than 55 times the generator output voltage. The generator voltage is stepped up to lower the power losses in transmission lines. The GSU transformers are normally located outside of the power plant. They are exposed to frequent voltage changes due to load shedding or switching operations.

Fig. 1 shows a cross-section of a typical large Francis vertical shaft hydro unit. The water flows down the penstock and enters the spiral case. The amount of water entering the turbine is controlled by the opening of the wicket gates. Once the water passes through the turbine, it goes down the draft tube and returns to the river.

Depending on the design, power plants can also have various types of guard gates upstream of the spiral case to shut down the discharge. The turbine type is chosen depending on the power plant environmental characteristics. The four main types of large hydro turbine are: Pelton, Francis, Kaplan, and propeller.

Efficiency Measurement

There are many compelling reasons for measuring efficiency of hydroelectric turbine-generator units. The first is to verify whether the contractual performance guarantees are being met. The second is to help verify the return on investment after a unit is refurbished or replaced. The third is to improve power plant operation based on the information obtained during the tests. Based on day-to-day operating conditions, such as the head, the power output can be adjusted so that maximum energy is obtained under any condition. Therefore, test engineers have to choose the right methods and instruments for accurately measuring the turbine, generator, and overall combined turbine-generator efficiencies.

To determine the efficiency of any turbine-generator unit, two parameters are needed: the turbine input mechanical energy, which is determined from the water flow and pressure, and the generator electrical output power.

$$\text{Unit efficiency} = \frac{\text{Generator output power}}{\text{Turbine input power}}$$

$$\text{Turbine efficiency} = \frac{\text{Turbine output power}}{\text{Turbine input power}}$$

To calculate the turbine efficiency, the turbine output power needs to be determined. It is calculated by adding the losses attributed to the generator during operation (mechanical, electrical and magnetic losses) to the generator output power. These generator losses are measured separately as elaborated later in a section on generator losses.

Electrical Output Power Measurement

For better accuracy, the measurement technique used for the output power measurement is done using the three-wattmeter method when the neutral of the generator is grounded through a reactance [3]. As stipulated in [4], the three-wattmeter method must be used in the case of an electrical machine with a neutral line, unless the absence of current can be verified in the neutral line.

The generator output power is measured by means of three voltage transformers (VTs), three current transformers (CTs), and a three-phase precision electronic wattmeter according to the following equations:

$$P_{total} = P_a + P_b + P_c$$

$$P_{total} = V_a I_a \cos(\phi_a) + V_b I_b \cos(\phi_b) + V_c I_c \cos(\phi_c),$$

where subscripts a, b, and c refer to the three phases A, B, and C.

The voltage of each phase is measured using portable calibrated voltage transformers which provide a higher level of accuracy since they can be calibrated before and after the test. A precision wattmeter with a high voltage input impedance is used to reduce voltage drops in the cables connecting the PT secondaries to the wattmeter voltage inputs [4].

The permanent metering CTs on the generator are connected to the precision wattmeter. After the insertion of the measuring equipment in the CT circuits, the burden [5] is adjusted to the rated value with variable resistances and inductances. The CTs were calibrated at the rated burden before commissioning.

Generator Losses

To obtain the turbine output power, the generator losses are added to the corrected generator electrical output power for the specific operating conditions. Four main methods exist, as described in [6] and [7]. The generator losses considered are the:

Fig. 2. Three types of current meters: (left) an auto-compensating current meter for water intake measurements, (center) one for conduits, and a small current meter used close to walls.

core losses, bearing and brush friction losses, stray load losses, rotor winding losses, stator winding losses, and ventilation losses. Experience shows about 5% accuracy of the generator loss measurements. After the unit and turbine efficiency measurements, the segregated generator losses are calculated for each specific operating condition. Once the turbine output power is determined, the turbine input power is still required for obtaining the turbine and the turbine-generator efficiency.

Input Power Measurement

Turbine input power depends on physical properties and the head of the water. The head is relatively easy to measure following the methods described in IEC 60041—1991 [4]. However, it is also proportional to the water discharge (flow) passing through the turbine. Four main methods can be used to measure water discharge, which is often the most demanding part of efficiency measurements. They are: current meters; acoustic measurements (transit time, acoustic scintillation and Doppler velocimetry methods); the pressure-time method; and the thermodynamic method.

Current meters: The use of *propeller-type* current meters is probably the most obvious way to measure water discharge. They are calibrated in a controlled environment so that the current meter rotational speed is linked to local water velocity. With the measurement of velocity at multiple points in a cross-section of the conduit, it is possible to obtain the velocity profile. To have an accurate velocity profile, it is important to cover the cross-section with more current meters in the boundary layers, where the flow is the most turbulent or irregular. The discharge is calculated by integrating the velocity over the area of the conduit cross-section.

Fig. 2 shows different types of *current meters*. On the left is an auto-compensating current meter for water intake measurements. In the middle is a current meter for conduits. On the right is a small current meter that is used close to walls.

Measurements are commonly taken with the current meters installed on a fixed frame in a section of the penstock. They can also be installed on a moving frame inserted in the stoplog gate, which scans the water intake. Especially in the first installation, obstruction of the frame must be minimal and taken into

Fig. 3. Current meters installed in a penstock.

account. The cross-section should be chosen where the flow is regular, symmetric, and far from singularity. Fig. 3 shows current meters installed in a penstock. While the complexity of the mounting structure and the large number of measurement points required are inconvenient, the versatility and the robustness of the current meter method makes it often the best solution.

Acoustic measurements: The *transit-time acoustic method* of discharge measurement uses the difference in the travel time of acoustic pulses transmitted downstream versus upstream on a given path crossing the conduit to determine the average velocity of water along that path. To do this, the propagation speed of the acoustic signal is added vectorially to the flow velocity. Discharge is computed by integrating the velocity of multiple paths, assuming a fully-developed velocity profile.

To increase the accuracy of the results, the velocity profile at the measuring section should be stable, axially symmetric, and fully developed. Therefore, the section should be as far away as possible from any disturbances. The IEC Std 60041—1991 [4] recommends ten conduit diameters of straight length upstream and three downstream. The water also needs to be clean and have a minimum velocity of 1.5 m/s.

On the other hand, the transit-time method has the advantage of being simple and often easy to install. The acoustic flow meter communicates with the probes, performs all of the signal processing and computes the flow with only a minimal configuration. This makes the method more convenient for most users but complicates the troubleshooting.

Acoustic scintillation and Doppler velocimetry method applications require the presence of turbulence (scintillation) or

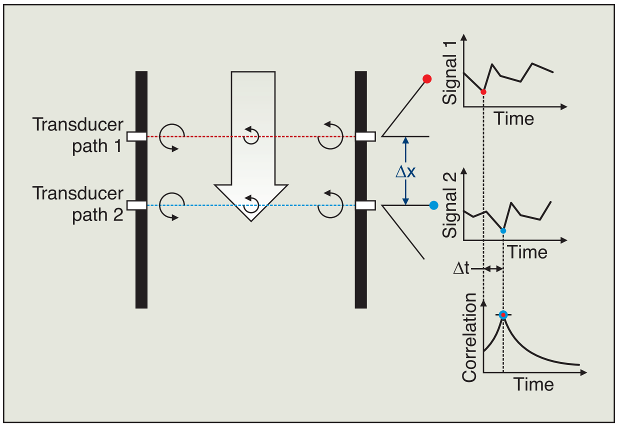

Fig. 4. Acoustic scintillation.

particles (Doppler) in the water flow, in opposition to the transit-time acoustic method, which works best with a steady flow of clear water. The principle of acoustic scintillation is that the variation of the refractive index of water due to turbulence causes random fluctuations in the intensity of acoustic signals traveling along a path. If two close paths are used (≈35 mm), the signals along these paths will be time delayed. Velocity in the direction of the paths corresponds to the gap between the two paths over that time delay. The use of a third path allows for measurement of the flow angle.

Doppler velocimetry measures the velocity of water in a remote sampling volume using the Doppler shift effect with the reflection of an acoustic wave on the particles contained in the flow. Fig. 4 shows the acoustic scintillation principle. In both cases, the water discharge is integrated from the velocity profile obtained by the use of multiple paths or sampling volumes. These methods are still under development and are not yet accepted as standards.

The pressure-time method: Measurement of the flow of hydraulic turbines is also known as the Gibson method. It was originally developed by N.R. Gibson of the 1920s [8]. It consists of measuring the pressure at two sections of the penstock during an interruption of the flow caused by the rapid closure of the turbine wicket gates. The pressure wave can be represented by one differential or two separate chart diagrams. When the geometry of the conduit between the sections of measurement is known, the interrupted water flow can be calculated by performing time integration of the pressure transient. The leakage flow at the gates must be added to this flow as described in [4].

The pressure is measured by a differential sensor using a water-to-air filter. The use of an air cushion damps rapid fluctuation and allows for easier processing of the pressure data. The integration of the pressure transient requires an experienced analyst for the calculations and the interpretation of the results, as several parameters must be adjusted to give an accurate and reliable water discharge.

The pressure-time method has the advantage of being simple to perform since it relies only on pressure sensors. It is rather inexpensive to perform when pressure taps are already present and the conduit geometry is known. On the other hand, the equipment installment cannot be permanent and causes disturbances on the electric power grid since it requires generator power variation to perform the test. The method's likelihood of success also greatly depends on the configuration of the power plant, including the water head and the wicket gates closure rate.

The thermodynamic method: This method uses the principle of energy conservation to determine the efficiency of a hydraulic turbine by measuring performance variables such as pressure, temperature, velocity, and level. Unlike the previous methods, it measures the efficiency of the turbine directly and then computes the discharge using the generator output and losses. The accuracy of the method increases with the increase of hydraulic energy measured. This is why it is preferable to use this method for the assessment of high-head turbines (head > 100 m), as stated in [4].

With the thermodynamic method, efficiency is defined as the ratio of specific mechanical energy to specific hydraulic energy. Both of these specific energies are measured as differences between a high-pressure section upstream and a low-pressure section downstream of the turbine (Fig. 5). Specific hydraulic energy is commonly measured for efficiency testing, and a good precision is relatively easy to achieve. However, computing specific mechanical energy accurately requires measuring water temperature differences of only a few milliKelvins. The most common way to achieve this is to extract sampling discharges with probes in the high-pressure section while scanning the low-pressure section with thermometers to determine the temperature profile.

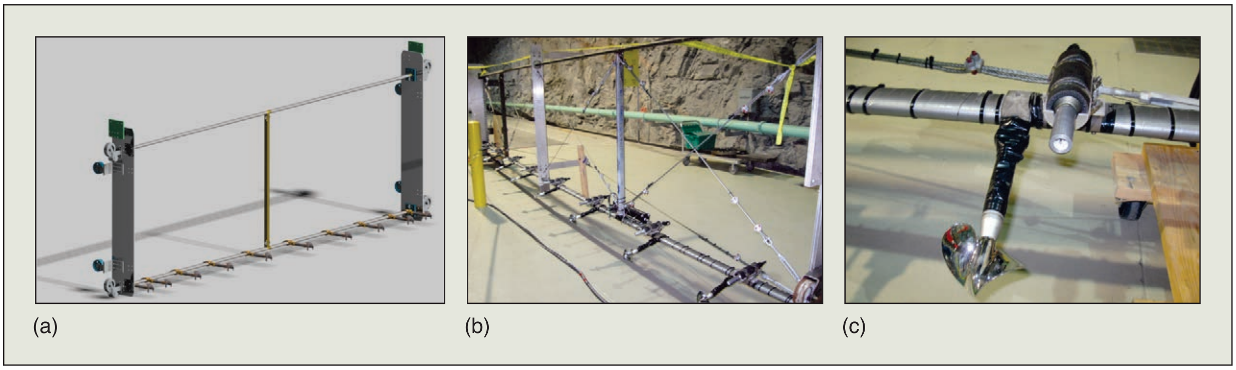

Fig. 5. Low-pressure measuring frame: (a) A representation of a measuring frame used for scanning the flow and determining the temperature profile, (b) shows the eight thermometers, and (c) shows a close-up of the current meter and thermometer.

When a sampling discharge is extracted, temperature is immediately measured in the probe. A pressure sensor is positioned just outside the conduit at the outside end of the probe. After passing by the temperature and pressure sensors, the water circulates around the thermometer, which insulates it from ambient temperature, and finally crosses a small propeller type flow meter before going down the drain. All of the piping is insulated to minimize heat exchanges with the ambient air.

For each operating point, the frame scans the flow vertically in the stoplog gates at the end of the draft tube. The frame is equipped with eight thermometers equally spaced along the lower horizontal profiled rod. A current meter beside each thermometer measures water velocity. Fig. 5 shows the instrumentation in the low-pressure section where (a) is a representation of a measuring frame used for scanning the flow and determining the temperature profile, (b) shows the eight thermometers, and (c) shows a close-up of their current meter.

Gathering data over the entire measuring section allows for the computation of temperature and velocity profiles. The temperature profile is then integrated and weighted with the velocity profile to obtain an average temperature for the low-pressure section. The pressure is read on static pressure taps located on the side walls. While the thermodynamic method is often the most accurate way to measure the efficiency of high head turbine-generator units, it requires a steady and uniform energy distribution in the water flow and a configuration that minimizes energy exchanges with the environment.

Conclusion

Hydroelectric turbine-generator units are equipped with different types of permanent monitoring sensors mainly for maintenance and safety but not for the efficiency measurement. Acceptance tests such as the efficiency measurement require additional precision instrumentation. Several measurement techniques exist to perform the testing and making the choice depends on the power plant configuration and the instrumentation capability. The best method is the one that is the easiest to implement for the given turbine-generator unit and that gives reliable results. Although performed on site, the accuracy requirements for these tests are very stringent and are key factors for the successful completion of tests and their acceptance from both the manufacturer and the end user. Finally, measuring the efficiency of a hydraulic generating unit is essential for the optimization of its operation, which means more electrical energy and revenue for the same amount of water.

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For additional information and technical details, see our sister publication, the *IEEE Transactions on Instrumentation and Measurement*.

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