# Generator Power Measurements for Turbine Performance Testing at Bureau of Reclamation Powerplants

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## Abstract

To achieve low uncertainty in a hydroelectric turbine performance test, the measured parameters should be obtained in accordance with the American Society of Mechanical Engineers (ASME) Power Test Code for Hydraulic Turbines and Pump-Turbines (PTC-18) or the International Electrotechnical Commission (IEC) International Code for the Field Acceptance Tests of Hydraulic Turbines (IEC 60041).

When the results of past runner replacement acceptance tests have indicated that a runner did not meet performance specifications, Reclamation has undertaken several investigations to determine if the problem was with the test method or data rather than the runner. Potential errors in the measured parameters such as head, flow, and power were investigated. For the turbine power measurement, the generator is used as a dynamometer whereby power out of the generator is measured and the generator losses are added back to obtain the turbine output. The power output of the generator is calculated by a wattmeter connected to the secondary voltage and current outputs from the unit potential and current transformers (PTs and CTs). This equipment can be calibrated, but it is difficult because of the magnitudes of the high-side values and the physical size of the transformers.

This paper will describe the steps taken to investigate the uncertainty of the flow measurement, electrical power measurement, and generator losses as well as error sources that were found. It also will address methods that can be used to reduce the uncertainty of hydroelectric turbine performance test results by improving the accuracy of these measurements.


## Background

The Bureau of Reclamation is a United States federal agency that was created in 1902 to undertake water storage and irrigation projects in the 17 Western States to "reclaim" the west for human use and encourage settlement. Reclamation has constructed more than 600 dams including the Hoover Dam on the Colorado River and the Grand Coulee Dam on the Columbia River. Reclamation is the largest wholesaler of water in the country and the second largest producer of hydropower with 58 hydroelectric powerplants and 194 generating units which range in output from 350 kW to 805 MW producing 44 billion kilowatthours of power annually.

Since the mid 1990s, Reclamation has focused primarily on managing existing water and power related facilities. The Technical Service Center located in Denver, Colorado has 480 professionals with expertise in all aspects of water and power related projects. A turbine and generator rehabilitation program, including field turbine efficiency testing, is an integral component of Reclamation's focus on maintenance of existing infrastructure. Turbine testing is used to help investigate uprate potential, re-allocate unit dispatch based on turbine efficiency (optimization) and, most importantly, verify that replacement runners meet contract guarantees. Measuring the parameters to calculate turbine efficiency is a relatively easy task, but achieving a low uncertainty on each of the measurements is relatively difficult, requiring expertise, experience, and the ability to adapt to each individual hydro unit.

To achieve low uncertainty in a hydroelectric turbine performance test the measured parameters must be obtained in accordance with the American Society of Mechanical Engineers (ASME) Power Test Code for Hydraulic Turbines and Pump-Turbines (PTC-18) ) or the International Electrotechnical Commission (IEC) International Code for the Field Acceptance Tests of Hydraulic Turbines (IEC 60041). Electrical measurements are covered in section 4D of the 2002 ASME code. Reclamation has been performing field turbine testing for decades and has been active on the PTC-18 committee for many years.

When the results of runner replacement acceptance tests indicate that a runner did not meet performance guarantees, investigations are undertaken to determine if the problem is with the test, test data, or the runner. Some of the measurement methods that are investigated include the flowmeter installation and the generator power output measurement. When testing to calculate runner efficiency, the generator is used as a dynamometer. Power out of the generator is measured and the generator losses are added back to obtain power input to the generator which is the turbine output. The accuracy of the generator loss data also has been investigated.

**Flow Measurement**

The measurement that often has the highest uncertainty is the flow rate. At Grand Coulee the flowmeter in the G-17 penstock was an eight-path time-of-flight acoustic meter with the metering section just downstream of a 21-degree reducing bend. The transducers were installed by the flowmeter manufacturer as part of the rehabilitation contract.

To investigate the accuracy of this measurement, the meter was upgraded by the flowmeter manufacturer to an 18-path meter to achieve lower uncertainty. The addition of 10 paths to the flowmeter resulted in a slight correction factor to the flow measurement. The calculated turbine efficiency increased by 0.15 percent because the additional acoustic paths better represented the velocity profile downstream of the penstock reducing bend.

**Generator Power Measurement**

The power output of the generator is calculated by a wattmeter with inputs of voltage and current measured at the secondary side of the PTs and CTs. PTs and CTs simply transform generator line voltage and current to lower values that can be safely measured by normal plant instruments. The calibration of the PTs and CTs and the burden on each can be measured, but it is difficult because of the magnitudes of the high-side values and the physical size of the transformers.

*Grand Coulee G-17 Power Measurement Investigation*

Following the runner acceptance test the electrical power measurement uncertainty was investigated. The electric power output was measured by a calibrated two-element wattmeter connected to the secondary voltage and current outputs from the unit PTs and CTs. These outputs are accessible at the unit control board. The uncertainty of the power measurement was originally estimated to be the root square sum (RSS) of the nameplate uncertainty of the PT, CT, and watt transducer. Additional tests were performed to determine the uncertainty of plant PTs and CTs, which is always a concern, and secondary circuit burden, which also will affect transformer accuracy.

*Potential Transformer Error*- The two unit metering PTs are connected in an open delta configuration and have a stated nameplate rated voltage of 14,400 V, a ratio of 120:1, and an accuracy class of 0.5 percent. The PTs were tested by removing them from the generator, connecting them in parallel with a calibrated standard PT, and energizing them with an external test voltage. The output magnitudes from the plant and standard PTs were measured simultaneously using high-accuracy digital multimeters. The test measurements were controlled and recorded by an attached laptop computer. The phase angle between the standard and plant transformer output also was measured using a phase angle meter.

The plant PTs were tested at a burden equal to their corresponding plant load as measured prior to testing. The measured burdens for each plant PT were not equal, with a PT burden on phase AB six times larger than phase CB. These burdens did not exceed the nameplate PT rating, but the larger phase AB burden did affect the PT accuracy. Ratio correction factors as calculated for the PTs are as follows:

$\varepsilon_{pt1}$ = 1.00443 - Phase-AB PT $\varepsilon_{pt2}$ = 1.00116 - Phase-CB PT

The maximum phase angle error for phase-AB PT was -0.14 degree and phase CB -0.01 degree. Applying these correction factors reduces the maximum error associated with G-17 PTs to about 0.06 percent.

The PT burden also created an additional voltage error at the watt transducer. The PT cubicle is separated from the control cabinet, the location of the watt transducer, by approximately 40 meters, and two 10-amp fuses are used to protect the secondary circuitry. The voltage drop along the control cable and fuses was calculated. The resulting ratio correction factors to correct for this voltage drop are as follows:

$\varepsilon_{c1}$ =1.00753 – Phase-AB Circuit $\varepsilon_{c2}$ =1.00192 – Phase-CB Circuit

*Current Transformer Error*- The two metering CTs have a stated nameplate ratio of 6000:5 and an accuracy class of 0.25 percent. Calibration of the CTs was performed by removing them from the unit and energizing them with an external current source. To achieve rated current, 14 turns of AWG 2/0 cable were wound through the plant CT and standard (calibrated) CT. The output magnitudes from the plant CT and standard CT were measured simultaneously using high-accuracy digital multimeters controlled and recorded by an attached laptop computer. The phase angle between the standard transformer output and plant CT output also was measured.

The plant CTs were tested at a burden equal to their secondary burden as measured prior to testing. These burdens did not exceed the nameplate CT rating. Ratio correction factors as calculated for the CTs are as follows:

$\varepsilon_{ct1}$=1.00100 - Phase-A CT $\varepsilon_{ct2}$=1.00112 - Phase-C CT

Applying these correction factors reduces the maximum ratio error associated with the plant CT to approximately 0.07 percent.

*Watt Transducer Error* - The two-element watt transducer used for these measurements has a nameplate accuracy of ±0.1 percent. However, its accuracy is dependent on the accuracy of the phase angle between the current and voltage for each element. The two-element watt transducer at unity Power Factor (PF) can be represented by the following equation:

$$P_{total} = P_{element1} + P_{element2}$$

$$P = V_{ab} I_a \cos(30 - \delta_1) + V_{cb} I_c \cos(-30 - \delta_2)$$

Where $\delta_1$ = phase error between Vab and Ia
$\delta_2$ = phase error between Vcb and Ic

From the calibration measurements, by far the largest phase angle shift occurred on the phase AB transformer with an error of -0.14 degree. The other phase angle shifts were less pronounced and in order to simplify the calculation these phase angle errors were neglected. The effect of secondary circuit reactance also was calculated and found to contribute about -0.02 degree of additional phase shift for a total phase error of -0.16 degree. Appling these data to the two-element watt transducer equation results in the following correction factors:

$\varepsilon_{\delta 1}$=1.00161 -Watt transducer element 1 $\varepsilon_{\delta 1}$=1.0 - Watt transducer element 2 (assumed)

*Cumulative Effect of Multiple Correction Factors* - The cumulative effect of the correction factors as identified in the previous sections can be combined using the two-element watt transducer equation as follows:

$$P = \varepsilon_{\delta 1}(\varepsilon_{pt1}\varepsilon_{c1}V_{ab}\varepsilon_{ct1}I_a \cos(30)) + \varepsilon_{\delta 2}(\varepsilon_{pt2}\varepsilon_{c3}V_{cb}\varepsilon_{ct2}I_c \cos(-30))$$

where $\varepsilon_{xx}$ is defined in the previous sections.

This equation can be reduced given that Vab≈Vcb and Ia≈Ic

$$P_{corrected} = \frac{\left(\varepsilon_{\delta 1}\varepsilon_{pt1}\varepsilon_{c1}\varepsilon_{ct1} + \varepsilon_{\delta 2}\varepsilon_{pt2}\varepsilon_{c2}\varepsilon_{ct2}\right)}{2} \cdot P_{measured}$$

Thus the eight correction factors identified above can be combined into a single correction factor. For the G-17 power measurement the overall correction factor is:

$$P_{corrected} = 1.00942 \cdot P_{measured}$$

Calibrations of the G-17 unit PTs and CTs found nearly a 1 percent error in the electric power measurement which resulted in a runner efficiency measurement equally low.

*Glen Canyon G-8 Power Measurement Investigation*

Prior to runner efficiency tests, the unit PTs and CTs were calibrated to reduce the uncertainty of the electric power measurement and to identify and account for additional power measurement errors as identified in the Grand Coulee calibration tests. The electrical power output of the generator was measured by a calibrated three-element wattmeter connected to the secondary voltage and current outputs from the unit PTs and CTs. These outputs are accessible at the unit control board.

The unit metering PTs are connected in a grounded wye configuration. The three PTs have a stated nameplate rated voltage of 14,400 V and a ratio of 120:1 with an accuracy class of 0.3 percent. The PT test procedure as described for Grand Coulee was followed and the following ratio correction factors were calculated.

$\varepsilon_{pt1}$ = 0.99817 - Phase-A PT $\varepsilon_{pt2}$ = 0.99849 - Phase-B PT $\varepsilon_{pt3}$ = 0.99823 - Phase-C PT

A maximum phase angle error of 0.02 degree was measured for all readings.

The PT cubicle is separated from the control cabinet, the location of the watt transducer, by over 150 meters, and three 10-amp fuses are used to protect the secondary circuitry. The voltage drop along this circuit was calculated, and ratio correction factors to account for this drop are as follows:

$\varepsilon_{c1}$ =1.00132 - Phase A Circuit $\varepsilon_{c2}$ =1.00208 - Phase B Circuit $\varepsilon_{c3}$ =1.00107 - Phase C Circuit

The three metering CTs have a stated nameplate ratio of 8000:5 and an accuracy class of 0.3 percent. The test procedure as described for Grand Coulee was followed with the exception that the plant CTs were not removed from the bus but rather were tested in place. The windows on these CTs were large enough to contain the generator bus plus 16 turns of AWG 2/0 cable that were wound through the plant CT and standard (calibrated) CT. The following ratio correction factors for these CTs were calculated:

$\varepsilon_{ct1}$ =1.00519 - Phase-A CT $\varepsilon_{ct2}$ =1.00137 – Phase-B CT $\varepsilon_{ct3}$ =1.00097 – Phase-C CT

A maximum phase angle error of 0.03 degree was measured for all readings.

The three-element watt transducer has a nameplate accuracy of ±0.1 percent. A benefit of using a three-element watt transducer over a two-element transducer is that the effect of a phase angle error between the current and voltage for each element is much smaller. The three-element watt transducer can be represented by the following equation:

$$P_{total} = P_{Element1} + P_{Element2} + P_{Element3}$$
$$= V_a I_a \cos(\phi_a) + V_b I_b \cos(\phi_b) + V_c I_c \cos(\phi_c)$$

Where PF = cos(ø)

At unity PF (Ø=0) the effect of a small phase angle error at the watt transducer can be neglected and correction factors for the watt transducer are not required.

The cumulative effect of the correction factors can be combined, as in the previous section, by using the three-element watt transducer equation.

$$P_{total} = \varepsilon_{pt1}\varepsilon_{c1}V_a\varepsilon_{ct1}I_a\cos(\phi) + \varepsilon_{pt2}\varepsilon_{c2}V_b\varepsilon_{ct2}I_b\cos(\phi) + \varepsilon_{pt3}\varepsilon_{c3}V_c\varepsilon_{ct3}I_c\cos(\phi)$$

where $\varepsilon_{xx}$ is defined above.

This equation can be reduced given that Va≈Vb≈Vc and Ia≈Ib≈Ic

$$P_{corrected} = \frac{(\varepsilon_{pt1}\varepsilon_{c1}\varepsilon_{ct1} + \varepsilon_{pt2}\varepsilon_{c2}\varepsilon_{ct2} + \varepsilon_{pt3}\varepsilon_{c3}\varepsilon_{ct3})}{3} \cdot P_{measured}$$

Thus, the nine correction factors identified above can be combined into a single correction factor. For the G-8 power measurement the overall correction factor is:

$$P_{corrected} = 1.00229 \cdot P_{measured}$$

Calibrations of the G-8 unit PTs and CTs found only a 0.2 percent error in the electric power measurement. This is less than the RSS of the uncertainty of the individual power measurement devices.

*Power Measurement Observations*

The uncertainty of plant PT and CT ratios can be reduced significantly if the appropriate correction factors are determined. The PTs used at Grand Coulee Powerplant had an uncertainty of 0.5 percent. Calibration tests demonstrated that this uncertainty can be reduced to about 0.06 percent. The CT had an uncertainty of 0.25 percent. Calibration tests reduced this to 0.07 percent.

Voltage errors introduced due to long PT secondary leads can be significant. Because of the rather large burden on the plant PTs, the inherent fuse resistance, and long secondary circuit lead lengths at Grand Coulee, the voltage drop on this circuit was significant for these tests. It introduced an error of about 0.75 percent, which was the largest error encountered during this investigation. This underscores the importance of checking the burden on PTs. Not only does a high burden affect the accuracy of the PT, it also can result in a voltage drop along the control cables which will affect electric power measurements.

The use of a two-element watt transducer can lead to a higher uncertainty than a three-element transducer. The calibrated output of a two-element watt transducer is very dependent on the phase angle at each element. At unity power factor the phase angle at each element is 30 degrees (e.g. the phase angle between Vab and Ia) compared to a three-element transducer where the angle is 0 degrees (e.g. the phase angle between Va and Ia). Because the cos(x) function has a much steeper slope at 30 degrees than 0 degrees, the effect of a small phase error on a two-element transducer is much greater than for a three-element transducer. At Grand Coulee this led to an additional error of about 0.16 percent in the watt transducer.

Multiple voltage and current correction factors can be combined into a single correction factor for power measurements. This allows the use of individually calibrated PTs, CTs, and watt transducers to measure power. As discussed above, these correction factors are multiplicative. At Grand Coulee these individual correction factors resulted in an electric power correction factor that increases the measured power by nearly 1 percent. However, the Glen Canyon data showed that the accuracy of the power measurement can be very accurate with the correction factor for this data less than the uncertainty of the measurement.

**Generator Loss**

One of the factors that historically has been difficult to deal with in runner efficiency testing is the generator loss data. Generator losses typically are measured when the units are commissioned and are assumed to remain stable over time. The losses which are added back to the generator output include: windage and friction, core loss, stray load loss, and armature $I^2R$ loss.

The use of loss data that can be several decades old can be a contentious point, especially if a runner does not meet a guaranteed efficiency. In particular core losses are often inferred to have increased as the core has aged. This may be a valid point, but each situation must be examined on a case-by-case basis as many factors such as core materials used, design, and operational history can affect the life of a core and possibly cause an increase in core losses as the core approaches end of life.

*Core Losses-* The core of rotating machines consists of layers of stacked laminations designed to carry magnetic flux of approximately 1 Tesla. Lamination thicknesses usually are between 0.3 mm and 0.65 mm. Laminations are coated with insulation, referred to as core plate, which is designed to limit/reduce the flux-induced currents in a core. These currents form a loop in the axial and radial direction creating heat losses commonly referred to as eddy current losses. If the core plate breaks down over time, the eddy current losses (core losses) will increase.

Electrical core steel used for laminations contains a small percentage of silicon which has been in use in the States starting around 1903 (patent date). Silicon core steel does not lose its magnetic properties. Thus core losses as related to the magnetic properties of the steel do not change.

Up to the mid to late 1940s, hot-pack rolled steel was used in generator cores. The steel was rolled out in packs or stacks. Thickness varied by up to 25 percent and this steel had convex surfaces. To ensure a tight core, very high clamping forces were needed and a very strong clamping structure (frame) was required. This resulted in very rigid cores with little vibration and/or movement-related problems. Prior to the 1940s the machines were not that large, thus there were very few core stability issues. Cores for these machines are often thought to last about 100 years. However, several other factors can reduce this life span as noted below.

After the mid to late 1940s cold-rolled strip steel was used for laminations. The electrical properties were similar to hot-pack steel but the thickness deviation was reduced to less than 3 percent. Cold rolled steel has a mirror-like surface, while hot pack steel has a dull matte surface. About this time, generators started to grow in size and rating; cold-rolled cores became standard and core clamping pressures were reduced. It was no longer possible to restrain a core, and thus cores and frames were designed to allow for radial expansion and contraction per thermal cycling-related forces. If not designed properly, cores would warp, become wavy, or develop chevrons at the core splits. Vibration and/or movement between laminations also can occur. Cores for these larger machines are often thought to last about 60 years. However, core distortion or lamination movement can accelerate the deterioration of the core plate which in turn can increase core losses and reduce core life.

Many old cores designed for a class-B stator winding used type C-3 class core plate insulation systems designed to operate below 90 ºC. C-3 is an organic varnish/enamel coating. Today, most large machine laminations are coated with C-5 class insulation for use with a class-F stator winding. C-5 is an inorganic coating. C-5 results in lower electrical losses and good high-temperature stability. Organic insulation will break down at a lower temperature than inorganic. Thus, an organic core plate that has been exposed to high hot-spot temperatures may have higher core losses and a reduced life span.

*Grand Coulee Motor Loss Investigation-* In 1998 Reclamation tested a 65,000-horsepower motor that was placed in service in 1952. Measurements were performed to determine losses in preparation for testing a 1360-cfs pump after an impeller replacement. Rotating machine efficiency was determined using a series of retardation tests. The unit loss and efficiency results were then compared to original results measured during the unit commissioning tests performed 46 years prior to these tests. A summary of data is found in Table 1.

Table 1. Summary of Unit Losses and Efficiency Data

| Percent Rated Load (65,000 HP) | 100 | |
|---|---|---|
| Load in Kilowatts | 48490 | |
| Test Data | Original (1952) | recent (1998) |
| Windage and Friction Loss (kW) | 370 | 355 |
| Core Loss (kW) | 430 | 430 |
| Stray Load Loss (kW) | 134 | 136 |
| Armature $I^2R$ Loss (kW) | 132 | 130 |
| Motor Loss (kW) | 1066 | 1051 |
| Motor Efficiency [100- Losses·100/(Load + Losses)] | 97.85 | 97.88 |

Unit losses decreased about 15 kW compared to the original commissioning data resulting in a slight increase in motor efficiency from 97.85 percent to 97.88 percent (or +0.03 percent). This decrease in losses is the result of a decrease in windage and friction loss from 370 kW to 355 kW. Core loss, $I^2R$ loss, and stray-load loss all remained essentially constant over the past 46 years. The measured change in windage and friction loss may be the result of reduced friction due to an improvement in the bearing lubricant, and/or a change in the air housing humidity and temperature between tests. These tests demonstrated that motor losses essentially have remained constant over the last 46 years.

Following these tests the motor was rewound based on the age and suspected deterioration of the stator winding insulation. Inspection of the original stator core revealed signs of heating in one quadrant. The heating was localized and it appeared to have originated from the area closest to the winding. The original core appeared to be physically tight, with the core laminations and core plate intact. There were no signs of heating originating from the core. This physical inspection corroborates the unit core loss data in that there were no signs of core heating that would have increased core losses.

## Conclusion

Reclamation has investigated potential errors in runner replacement acceptance test data. Measured parameters such as flow, power, and generator losses have been investigated. The test data are often found to be very accurate but at times the error can be greater than originally anticipated. In one particular case, the results of the electric power measurement have been found to have nearly a 1 percent error. However, correction factors for the equipment used in the power measurement were calculated to account for this error. This greatly improved the accuracy of the runner replacement acceptance test results.

## Photos

Figure 1 - PT Calibration Testing at Grand Coulee Powerplant
(Computer and DMM shown on table, standard PT located behind table.)

Figure 2 – Grand Coulee Powerplant - CT Calibration
(Fourteen loops of cable pass through both the larger plant CT and smaller standard CT located in the middle of the table.)

**Biography**

James DeHaan is an electrical engineer for the Hydropower Technical Services Group at the Bureau of Reclamation, Denver, Colorado. He has an MS degree in electric power engineering. His responsibilities include research and field testing in the areas of safety, power system diagnostics, and specialized instrumentation development. For the last several years, Mr. DeHaan has led research projects that are focused on improving the accuracy of electric power measurements.

David Hulse is the Manager of the Mechanical Equipment Group, Technical Service Center, of the Bureau of Reclamation, Denver, Colorado. He has 26 years experience in hydroelectric powerplant and pumping plant design as well as pump and turbine performance testing and is currently a member of the ASME PTC 18 committee.

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