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DIAGNOSTIC EVALUATION OF TURBINE EFFICIENCY PROFILES AND DATA

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Abstract

Hydraulic turbines are tested in the field to determine their efficiency profile for several well established, basic reasons. The testing methods and protocols are also documented in published test codes. Although seldom used, a diagnostic evaluation of the condition, operation, repair history, and need for maintenance of various components of the generating equipment can be done concurrently with such testing and subsequent data reduction. This paper provides an explanation, description, and examples of some of these various diagnostic techniques.

Introduction

The efficiency testing of hydraulic turbines in the field is normally done for any of several reasons, the most common of which is to verify contract compliance. That is, to ensure that the equipment as supplied by the manufacturer meets the procurement specifications of the purchaser. A second reason is to optimize the performance of individual units, such as by determining the optimum blade to gate cam curves for Kaplan turbines. A third reason is to determine performance data to establish a baseline for historical trending of the individual unit's performance profile for maintenance purposes.

In the course of testing for the above stated reasons, however, there is another advantage which is seldom recognized. In particular, the very nature of the testing and the subsequent data reduction may be used as diagnostic tools to evaluate the condition of various components of the equipment, to examine the mechanical and electrical features which may indicate additional means to optimize generation efficiency, and to identify areas for future maintenance attention.

Diagnostic Areas

If the field efficiency testing of hydraulic turbines is done with diagnostic evaluations included as an accompanying goal, there are several

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field procedures that can be easily added to the testing schedule. First, a number of powerhouse gages and meters can be calibrated. Second, the determination of head loss upstream of the turbine may be used as a measure of the accuracy of project surveyed elevations and/or any bias in the absolute flow measurement. Third, the data reduction procedure of plotting the "Smooth Curves" of 1) power versus gate and 2) flow versus gate allows an evaluation of any changes in windage and friction, changes in the vent area of the runner, and any effect caused by the combined operation with adjacent units. Fourth, if the efficiency profile is carefully constructed from the Smooth Curves, rather than from the individual efficiency data test points , it may be interpreted to reveal a number of effects, such as the improper closure of vacuum breaker air valves. Fifth, if the efficiency data of the unit is measured in the "as found" condition, even before the governor cabinet door is opened, any degradation in efficiency, such as caused by a less than an optimum cam in a Kaplan turbine, may be determined. Also, any hysteresis in the gate or blade control linkages, such as caused by worn bushings, can be measured.

Calibrations

While setting up for the field test, a consultation with the powerhouse operators will reveal the gages and meters on which they normally rely and which may be calibrated during the test. Typically, if the gate servomotor stroke is read during the test with a machinist's rule on the operating rod, then the gate position gages in the control room may be also read during the test and a calibration can be calculated during the data reduction. Similarly, if the power is measured from the rotating standard with the timing of a stopwatch or other method, then the power meter may be read and later calibrated. If tailwater and forebay elevations are read from surveyed staff gages, then the elevations displayed in the control room may also be read. If flow is measured by an absolute method, which determines the actual volume flow rate in cubic feet per second, then the relative flow measuring systems, such as the Winter - Kennedy or Joseph Peck piezometers, may also be calibrated.

The actual calibration is usually done using a linear regression program and often may be done directly from an electronic spreadsheet. A linear regression produces a straight line correlation of the form:

actual value = slope(meter value) + intercept

The intercept may be interpreted as the "zeroing" error in the meter and the slope is the proportionality between the meter and actual value. Higher order correlations such as polynomials, logarithms, and trigonometric functions seldom add any increase in the accuracy of the calibration and obscure the interpretation of an intercept. In addition, if a simple linear regression is not sufficiently accurate, the meter instrumentation being evaluated has other more significant problems that may need to be addressed. In the course of having tested dozens of hydraulic turbines, a considerable loss of generation has been found several times to have been occurring for years because of faulty powerhouse instrumentation.

Head Loss

Often during the performance of the field test, data is recorded which allows the determination of head loss, particularly the intake loss or the loss upstream of the net head station into the turbine. Frequently, the correlation equation for this loss is determined as:

$$\text{head loss} = (\text{flow rate})^{\text{exponent}}$$

where the exponent is determined empirically as a best fit to the data. However, this total upstream loss is a combination of the losses from: 1) the intake, which is a function of the velocity profile at the inlet and includes losses from trash racks and any impinged debris; 2) shape changes such as gate slots, transitions and valves; and 3) boundary and internal friction. Each of these loss components is a function of the flow squared. In other words, since head loss is a loss of fluid energy per pound of fluid, only the flow rate to an exact square is correctly proportional to this quantity of fluid energy per pound. Therefore, this squared relation itself may be used as a diagnostic tool and the head loss evaluated in the form of:

$$\text{head loss} = \text{slope}(\text{flow rate})^2 + \text{intercept}$$

In this form, any nonzero intercept is a diagnostic evaluation of any error in determining project elevations such as the elevation of a deck from which a water column is measured.

Alternatively, if the project elevations have been precisely surveyed, this correlation may be recomputed in the form of:

$$\text{head loss} = \text{slope}(\text{bias error x flow rate})^2 + 0$$

where a constant bias error, as a percentage of flow, is statistically determined for each data point such that the intercept of the correlation equation is reduced to zero. In this form, head loss may serve to diagnostically evaluate the bias or systematic error in the flow measurement.

Diagnostics of Data Reduction using Smooth Curves

After the test is completed and the data entered into a spreadsheet, the first data reduction procedure is usually to convert the power and flow measurements to their equivalent values at a common head. Where the common head is within a couple of percent of the test head, use of the Affinity Laws for this conversion is sufficient. These laws stipulate that power is changed by the ratio of common to test head to the 3/2 exponent, while the discharge is changed by the square root of the same ratio. When the common head is further from the individual test heads, the relation of the power and discharge curves versus head from the model test, if available, should be used to convert the individual field tested power and flow measurements to their equivalent values at the common head.

Next, power and flow measurements converted to a common head are plotted separately versus gate servomotor stroke. These two resulting graphs are called the "Smooth Curves." Their primary purpose is to minimize precision (random) test errors. Efficiency curves can be very irregular and unpredictable in shape and therefore difficult to draw. However, the Smooth Curves have a consistent, well behaved, shape and are much easier to graphically interpret and draw. For instance, they are always positively sloped with the lower third to half of the gate stroke portion of the graph approximating a straight line. The upper half of the gate stroke portion has a gentle bend referred to as the "knee" which transitions into a shallow curve, both of which are easy to draw to a high degree of accuracy. Consequently, the use of Smooth Curves largely eliminates random test errors and the associated scatter of the individual efficiency test data points.

These two Smooth Curves can be very powerful diagnostic tools. First, they can be used to evaluate the accuracy of the individual flow and power measurements separately from each other, which is not possible when they are combined into an efficiency value. Other diagnostic features of these Smooth Curves which are seldom utilized include speed-no-load servostroke setting, the extent of the straight line portion, and the effect of adjacent units.

If the straight line portion of the power versus gate servostroke Smooth Curve is extrapolated down to zero power, its intercept precisely identifies the servostroke of speed-no-load. If the same extrapolation is then done for the flow versus gate servostroke Smooth Curve, the flow at the servostroke of speed-no-load may be determined. These values reflect the fluid energy that is needed to overcome the windage and friction of the rotating components of the turbine and generator. Any change in these values from previous tests at the same head can provide an indication of a changed condition for the unit which should be investigated further.

The previously mentioned lower portion of each Smooth Curve approximates a straight line because the gate opening is much smaller than the vent area or the smallest cross section of flow passage of the runner. Even though portions of both the power and flow Smooth Curves are straight lines, they are at different slopes and consequently the resulting efficiency profile in that portion is still curvilinear. As the gate opening is increased, the vent area begins to exert some hydraulic flow control. As the gates continue to open further, the vent area actually starts to throttle and may even, at very large gate openings, act as the complete flow control. Peak efficiency usually occurs around the larger gate servo stroke end of the knee where the gates and vent area are exerting an equal hydraulic control on the flow. If the Smooth Curves plot as a straight line over the entire range of gate servo stroke, it may be readily diagnosed that the vent area is too large, such that no amount of hydraulic control is ever shifted to the runner. Consequently, the machine can never develop the hydraulic efficiency of which it is otherwise capable. Such enlarged vent areas have been found to develop following severe cavitation weld repairs and subsequent grinding at the runner's trailing edges without using profile templates.

The operation of adjacent units usually alters the velocity profiles at both the intake and discharge of a particular unit. Occasionally, such alterations may change the corresponding head loss, resulting in a different efficiency profile on a gross head basis. Given the usual scatter of efficiency test points, such an alteration of the efficiency profiles is generally difficult to detect from the efficiency data points only. However, on the Smooth Curves for a common gross head, the effect of an increase in head loss is much more readily diagnosed as a reduction in power and flow at a given gate servo stroke. In addition, from the different curves on both of the Smooth Curves, different efficiency profiles may be constructed to show the actual effect of any changes in efficiency due to the operation of adjacent units.

Figure 1. shows both the power and flow versus gate Smooth Curves on a gross head basis of a Francis unit in South Carolina. The solid line is when only the unit under test is in operation and the dashed line is when both units on either side are also in operation.

Diagnostics of Data Reduction by Constructing Efficiency Profiles

Developing efficiency profiles may be done simply by plotting the efficiency test points and drawing some type of best fit curve through the data. However, a much more accurate procedure, as described in the Test Codes, is to "construct" the efficiency profile by interrogating both power and flow Smooth Curves every one or two percent of gate servostroke, computing an efficiency value, plotting the loci of these computed points, and connecting them to construct an efficiency profile for the given head. Then afterwards, the actual efficiency test points may be plotted as an overlay. This procedure is also used by the older ASME Test Code to adjudge the accuracy of the test. This procedure provides that if any field efficiency point is more than 1- 1/2% from the constructed efficiency profile, that entire data point should be removed from the data set, the Smooth Curves redrawn, and the efficiency profile reconstructed.

Figure 2. shows both the Smooth Curves (lower half) and constructed efficiency profiles (upper half) of a Francis unit at a project in Tennessee. These Smooth Curves show a hysteresis or a difference in the indicated gate servostroke position for the same power and flow depending on whether the gates are moving in the opening or closing direction. The gate servostrokes extrapolated to speed-no-load both intercept their respective flow Smooth Curves at the same flow (125 cfs) indicating the same gate opening. Therefore, this unit's hysteresis is interpreted to be in the gate position indicator and not in the position of the gate itself.

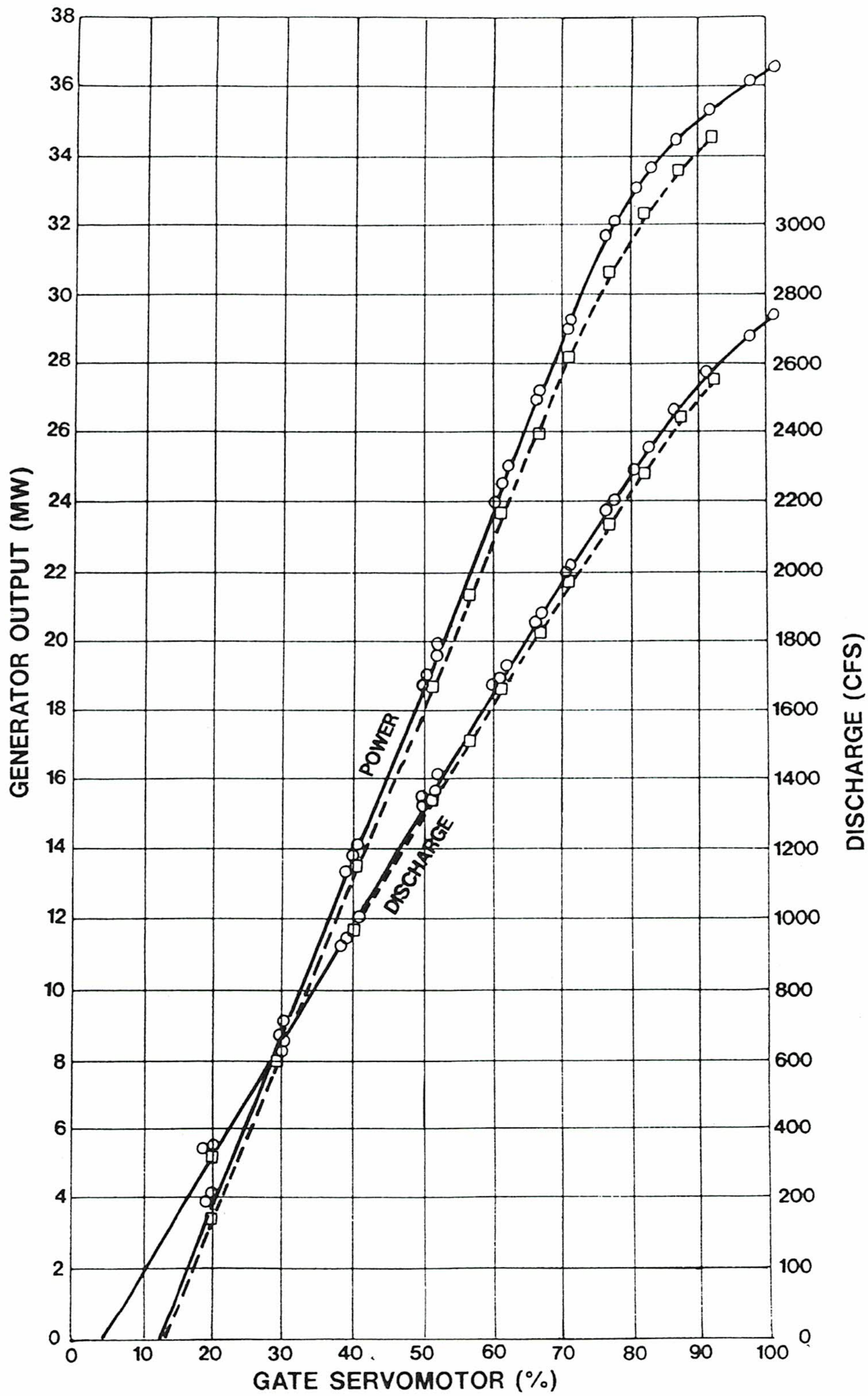

Figure 1. Smooth Curves of a Francis turbine on a gross head basis. The solid lines are when only the tested unit is operating, the dashed lines show the effect when both adjacent units on each side are brought on line.

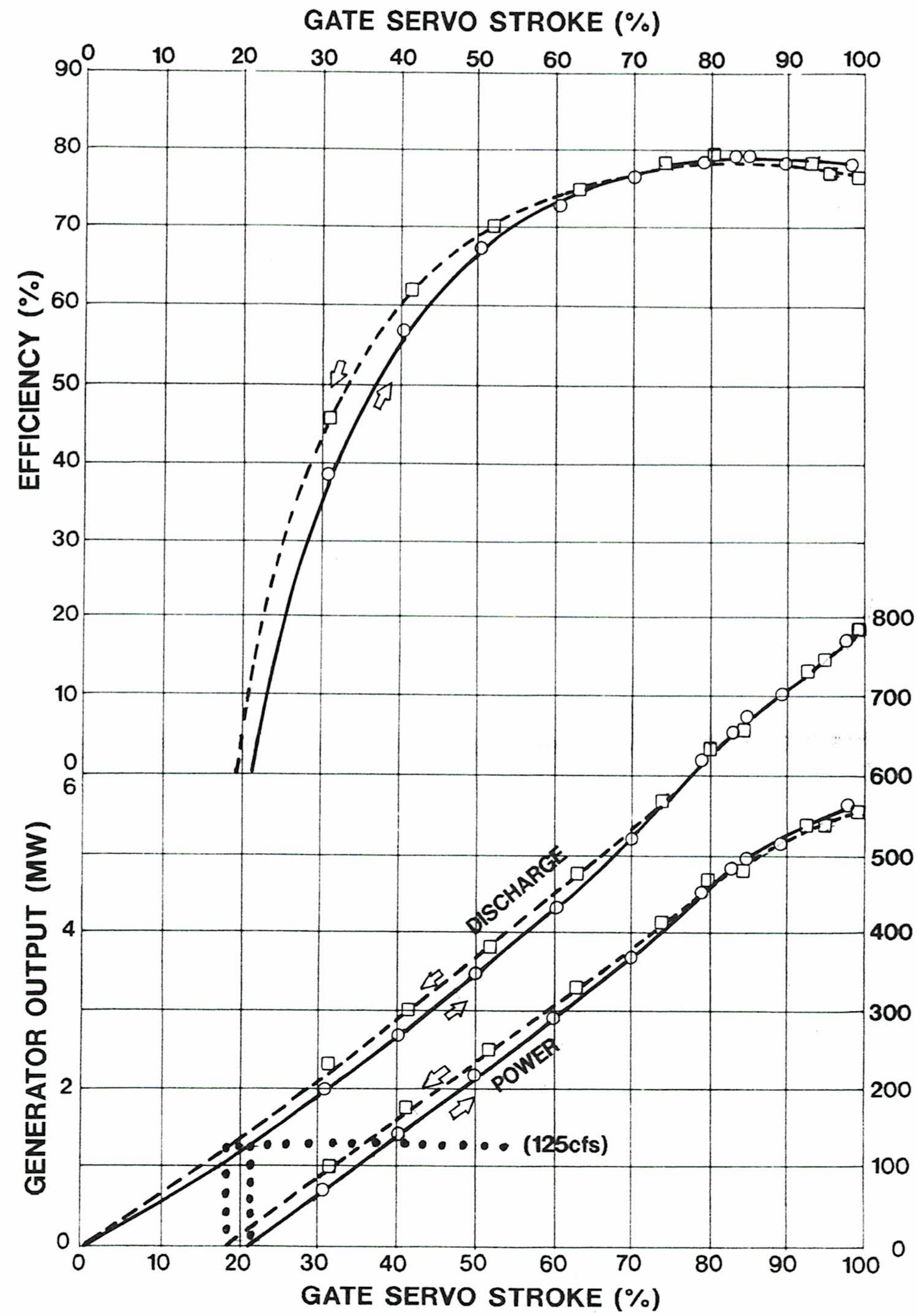

Figure 2. Smooth Curves (lower half) and constructed efficiency profile (upper half) of a Francis turbine. The Smooth Curves show the effect of a hysteresis in the gate position indicator between gate opening and gate closing direction and an extrapolation to speed-no-load.

This graphical construction procedure not only provides the most accurate efficiency profile, but also is a diagnostic tool. Small dips and depressions in the efficiency profile that would otherwise be overlooked may be highlighted in the process of constructing the efficiency profile in fine increments of gate servostroke. Such localized distortions indicate ranges of power where generation efficiency should be more closely examined. A classic cause of such localized distortions is the operation of the vacuum breaker at an incorrect gate servostroke. In fact, one method to determine where to set the closure of the air valve is to test and construct the efficiency profile with the air valve both full open and full closed. Where the two efficiency profiles meet or cross is where the air valve should be set to operate.

Figure 3. shows the efficiency profile carefully constructed from the Smooth Curves for a Francis unit in New York. The efficiency points from the field test were then added as an overlay. The dip under the dotted line in the actual efficiency profile was later found to be due to operation of the air valve at too large a gate opening.

As Found Data

When first starting to record the field test data, the first test runs should be of the "as found" condition of the machine. That is, these initial runs are taken before any adjustments of the governor, air valve, cam curve, cooling water, or any other controllable item are changed. This also serves to orient the field personnel to the testing procedure and identifies any problems with the testing methods. These "as found" test data points should be taken incrementally in a constant and uniform gate opening direction and then in a gate closing direction. This "as found" data is not used in conjunction with any Smooth Curve, but when plotted as an overlay directly on the constructed efficiency profile becomes a very strong diagnostic tool. First, the comparison with the constructed efficiency profile allows for diagnosis of any degradation that has been occurring due to the manner in which the machine is being operated, such as may be caused by an incorrect Kaplan blade to gate cam curve. Also, the comparison of the "as found" efficiency profiles in a gate opening and gate closing direction allows a diagnosis of the effect of any hysteresis in the gate control linkages of any type of machine as well as the blade control linkages of a Kaplan. Such hysteresis may be caused by worn bushings, stretched restoring cable, or insensitive position sensor instrumentation. Information from this graphical comparison will indicate areas to be closely examined during any subsequent maintenance outage.

Figure 4. shows the efficiency profile of the tangent curve to a series of fixed blade efficiency profiles for a Kaplan turbine in Tennessee. The line underneath connecting the "as found" data points shows the degraded efficiency profile in the gate closing direction due to the unit not having the optimum blade to gate cam curve in the governor.

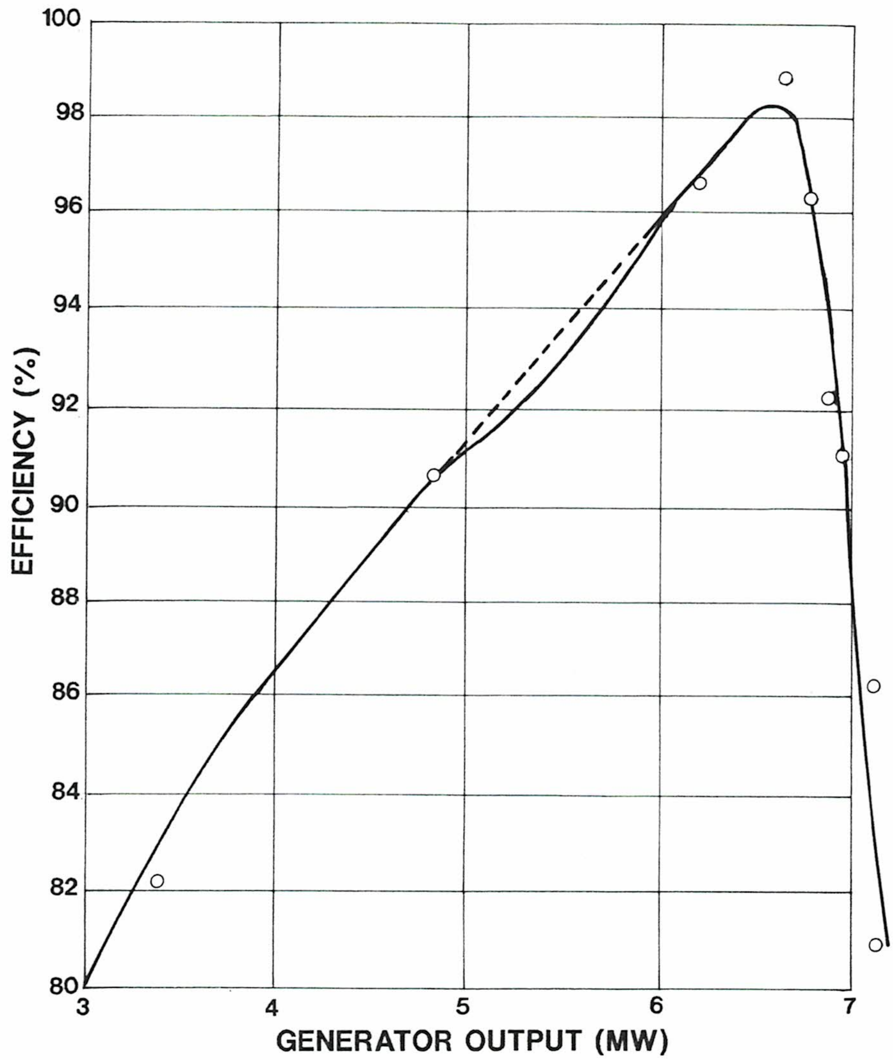

Figure 3. Efficiency profile of a Francis turbine constructed from Smooth Curves, with efficiency points from the field test added as an overlay. The dip of the actual profile under the dashed line is due to the operation of the air valve at too large a gate opening.

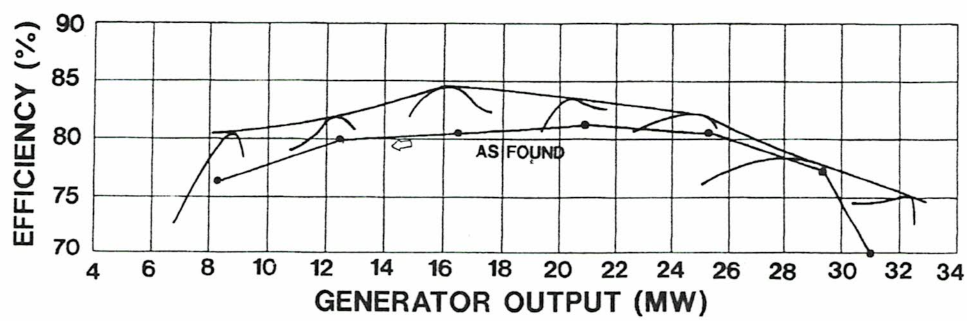

Figure 4. Efficiency profile of the tangent curve to a series of fixed blade efficiency profiles of a Kaplan turbine. The degraded efficiency profile underneath connects the "as found" efficiency data points measured in the field first and in this case, in the gate closing direction.

Conclusion

Efficiency testing of hydraulic turbines in the field is done for several recognized and established reasons. What is often overlooked is that such testing may also be used an a diagnostic tool to evaluate a machine's condition, method of operation, repair history and future maintenance needs. As cited in examples herein, it may be used to: calibrate powerhouse gages and meters; evaluate the accuracy of powerhouse elevations or the bias error in measuring flow; evaluate the accuracy of the test itself; detect changes in windage and friction, changes in vent area, and changes due to the effect of operation of adjacent units; determine correct operation of the air valves; and evaluate any degradation due to the manner of the unit's operation and any hysteresis in the mechanical linkages.

References

1) Hydraulic Prime Movers, ASME PTC 18-1949
2) Hydraulic Turbines, ASME PTC 18-1992
3) Field Acceptance Tests, IEC 41-1991

KEY WORDS

calibration
diagnostic
efficiency
flow
head loss
hysteresis
optimization
power
testing
turbine