Measurement of real time turbine efficiency

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Water, once viewed simply as a boundless source of energy, is now seen to have the same restrictions as other resources; that is, the supply is limited. Electricity generating authorities worldwide are now concerned with the problem of using this limited resource effectively by improving the efficiency of their existing plants. The aim of this article is to discuss one method of optimizing hydropower, that is, real time hydro turbine efficiency measurements.

A HYDRO PLANT may have ten generating units but may only need five to supply the required demand. It is the plant operator's decision which five will be used. It is in making this decision that a real time efficiency measurement system can be of benefit.

The operator has virtually no help in determining which units to use. Typically, he takes the power demand, divides it by the power rating of each of his units, and chooses the ones to be used. If one of them has a partially plugged trashrack, he has no way of knowing and as a result may operate that unit several per cent below its normal efficiency. Or a unit may be in need of repair which again may not be obvious to the operator.

Optimization of the working condition of the selected units is far beyond the capabilities of the operator and cannot even be attempted. He has no tools to assist him in determining the optimum set points for each of the units he must bring in to meet the demand. The power required by the area controller typically does not always allow the operator to run each unit at its optimum efficiency, even if he knew what that efficiency was at that time. Therefore, he must choose whether to put several units on line at what he considers to be optimum efficiency and run-up a swing unit to pick up the balance, or he must run all units at a point off optimum. Operators today have no help in optimizing the plant's performance; experience and some broad baselines are his only guides.

Benefits

The economic benefit to be gained from a real time efficiency measurement system is well recognized by the US utilities. Approximately 75 000 MW of the nearly 600 000 MW of power available in the USA is from hydro sources. This represents a revenue of more than $1 million per hour to the utilities, which underlines the economic importance of this source.

A real time efficiency system can help the operator in several ways and as a result save money. The most significant features of such a system are:

- selection of operating points for each of several turbine generators to optimize the system overall efficiency;
- identification of loss of unit efficiency;
- selection of turbine/generator maintenance interval based on efficiency; and,
- identification of inlet piping pressure gradient changes.

Savings can be made in at least three prime areas. Consider the loss caused by using a less efficient turbine/generator than available. If the net effect of this is a loss of efficiency of 1 per cent on a 100 MW machine for one year, the cost exceeds $300 000. Another area of saving is a reduction in the pressure gradient loss. A decrease in the inlet head to the turbine of as little as 0.1 ft (3 cm) could cost about $100 000 per year per machine. This loss could be caused by an increase in friction in the penstocks which might be undetected (see also Example).

Example – savings achievable using real time efficiency measurements

500 MW electrical powerplant		
90 per cent plant operating capacity	450 MW	
1 per cent power lost without accurate flow	4.5 MW	
Annual cost to produce, at $30 per mwh	$262 800 cost per MW year	
Total loss in one year		$1 182 600
Typical LEFM accuracy	0.5 per cent	
Potential power gained with LEFM*	2.25 MW	
Typical real time hydro plant efficiency measurement system		
Electronics and transducers	$200 000	
Installation	$50 000	
Total system costs		$250 000
First year savings		$932 600

* Leading edge flowmeter

Shut down for maintenance of large powerplants is expensive both because of the cost of the actual maintenance costs and the loss of revenue that a unit normally generates. A continual monitoring of each unit's performance with time allows a more informed decision regarding management and scheduling of outages for maintenance, the third area for potential savings.

System description

The availability of low cost computers has made the continuous measurement of hydroelectric power generation efficiency practical. To have on-line efficiency available requires a great deal of data to be collected and processed. To optimize the power generation of a large powerplant requires differential equations to be solved. Today's computers can satisfy these requirements economically in addition to providing a convenient means of recording this information for record-keeping, all on a continuous basis. For the on-line measurement of hydropower plant efficiency to be useful, it must be continuously available so it can guide the operator and be recorded and trends (perhaps indicating maintenance) can be recognized.

The Table shows a possible error budget, listing the information required to make an efficiency measurement of a hydroelectric turbine/generator. To achieve the accuracy listed, the most difficult and critical measurements are that of flow.

ASME and IEC code approved systems do not offer the accuracy nor the continuous readings necessary for hydroelectric power generation efficiency. Ultrasonic

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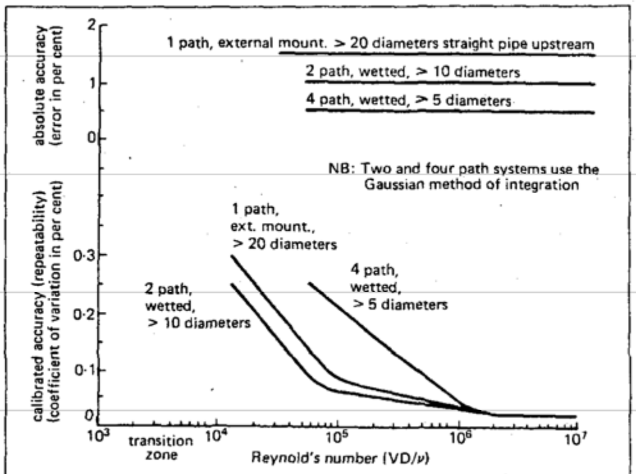

Fig. 1. Performance capabilities of the Westinghouse Leading Edge Flowmeter (LEFM). For absolute accuracy the determining factors are: pipe dimensions; upstream hydraulic configuration; integration technique; number of paths; and, Reynold's number. The determining factors for repeatability are: upstream hydraulic configuration; integration technique; number of paths; and, Reynold's number.

systems can provide those continuous, accurate readings. However, ultrasonic systems are not yet code approved although progress is being made to gain code acceptance. Nevertheless, unless the efficiency system is to be used for turbine acceptance as well, code approval is irrelevant.

Fig. 1 shows the performance of which the four-path Westinghouse ultrasonic flowmeter* is capable. Sound is transmitted from one transducer to another as water flows through the measuring pipe, and the travel time is accurately measured. Then the role of each transducer is reversed. Sound travelling with the flow travels faster than that travelling against it. From the measured travel times the flow velocity over the path travelled can be determined.

Integrating the flow across the pipe is by the Gaussian quadrature method of integration. The velocity is measured along four chords on the pipe, weighted according to the Gaussian method, and summed to give the total volumetric flow rate.

Although the exact configuration of a particular real time efficiency measurement system may change for some applications, they generally will have the basic components shown in Fig. 2. Flow, generator output and turbine inlet pressure are the key inputs which usually determine the accuracy capability of the efficiency measurement. In some cases, other parameters such as tailrace water level may vary enough to warrant a separate measurement. A second common feature of any system is a computer and printer. To permit a real time determination of a turbine's efficiency requires a moderate data handling and computing facility. The printer is a convenient output because it records all computation results to provide a historic record of the powerplant's operation. Using a computer with keyboard entry allows the operator to input certain constants and to communicate with the computer.

Typically several outputs would be required from the system such as turbine efficiency, penstock losses, overall plant efficiency and performance at rated head. The equations for these parameters are well known and will not be repeated here. The overall plant efficiency is, however, worthy of some discussion.

The mathematical solution to the problem of setting the operating point of a hydroelectric plant for maximum overall efficiency is based on use of the Lagrange multiplier. It is assumed that different machines are in operation, each with an individual efficiency curve. It is desired to minimize the total flow rate input given by:

$$q=q_1+q_2+q_3+\ldots+q_n$$

subject to the constraint that total power output (P) given by:

$$p=p_1+p_2+p_3+\ldots+p_n$$

is fixed at a specified value. This is accomplished by finding the stationary points of the function

$$F=q+\lambda p$$

where λ is the Lagrange multiplier. These occur where

$$\partial F/\partial q_1=1+\lambda\partial p/\partial q_1=0$$

$$\partial F/\partial q_2=1+\lambda\partial p/\partial q_2=0$$

$$\partial F/\partial q_n=1+\lambda\partial p/\partial q_n=0$$

The obvious solution is:

$$\partial p/\partial q_1=\partial p/\partial q_2=\ldots=\partial p/\partial q_n=-1/\lambda$$

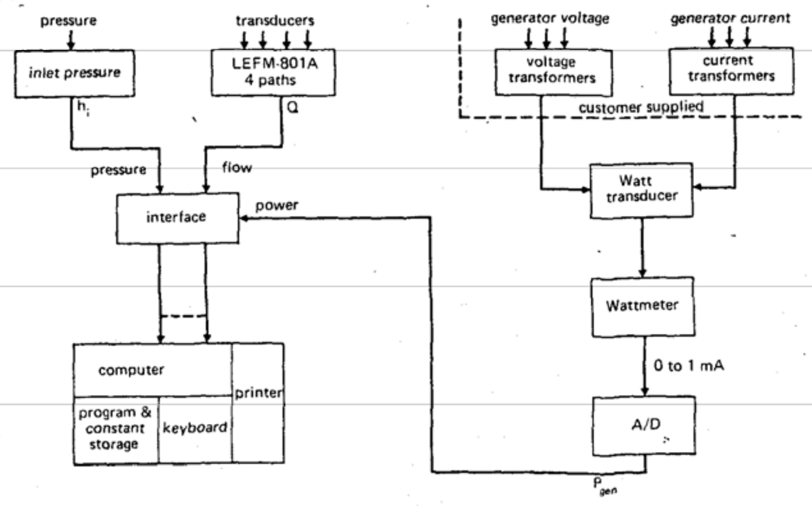

Fig. 2. Efficiency measurement system block diagram.

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* The Leading Edge Flowmeter, LEFM.

Information required to make an efficiency measurement

Required data	Source	Required accuracy	Resultant effect on efficiency measurement per cent
Flow rate	Measurement	± 0.55 per cent	± 0.5
Generator power output	Measurement	± 0.2 per cent	± 0.2
Inlet head	Measurement	± 0.2 per cent	± 0.2
Leakage	Measured once	± 10 per cent	± 0.1
Generator efficiency	Specified by manufacturer	± 0.1 per cent	± 0.1
Gauge height	Supplied by utility	± 2 inches	nil
Tailrace water level	Supplied by utility or measured	± 2 inches	nil
Turbine centre elevation	Supplied by utility	± 2 inches	nil
Gravity at turbine centre	Smithsonian Tables	–	nil
Turbine inlet area	Turbine manufacturer	± 1 per cent	nil
Rated head	Turbine manufacturer	–	–
Turbine outlet area	Turbine manufacturer	± 1 per cent	nil
Weight of water	PTC-18 Tables Modified by local gravity forces	± 0.1 per cent	± 0.1
Water temperature	Supplied by utility	± 1°F	nil
Reservoir level	Measured	± 0.2 per cent	nil
Current transformer	Supplied by utility	± 0.2 per cent	± 0.2
Voltage transformer	Supplied by utility	± 0.2 per cent	± 0.2
			± 0.7 resultant r.m.s.

For well behaved efficiency curves, in particular, if near the operating point:

$$\partial^2 p/\partial q_1^2 < 0$$

for each machine, then, the above solution leads to the maximum overall efficiency for the specified power output.

This development shows that for any selected set of different machines, maximum efficiency is attained by adjusting the operating point so that slopes of all the efficiency curves are equal. If the specified power output is not so great as to require operation of all the machines in the plant, then formal solution of the problem of finding maximum overall plant efficiency requires the comparison of the solutions for all of the combinations of machines capable of producing the specified output.

If the efficiency curves have been defined in sufficient detail from the beginning, it is a straightforward matter to achieve a computer solution which defines this optimum selection of machines and the adjustment of the operating point. If available information beforehand is not sufficiently detailed, or if it is desired to account for possible changes in machine efficiency over extended operating periods, then the history of on-line measurements may be used in this optimization.

Measurements of at least three different operating points for each machine are required to define a useful efficiency curve. This permits a simple analytical solution based on the fit of a quadratic efficiency curve to the measured data. Thus, if for each machine the curve is defined as:

$$p_i = a_{0i} + a_{1i}\, q_i + a_{2i}\, q_i^2$$

then the maximum efficiency occurs where:

$$a_{11} + 2a_{21}\, q_1 = a_{12} + 2a_{22}\, q_2$$

$$= \ldots = a_{1n} + 2a_{2n}\, q_n$$

Substitution into the equation defining total power output yields a quadratic equation in one variable which may be solved analytically. The use of a quadratic fit over a limited range of the efficiency curve permits a quite useful solution, even if more than three measurements are available. More precise fits, for example by higher order polynominals, generally would require numerical procedures to compute the optimum operating point.

The Table gives the data required along with an indication of its source and the necessary accuracy. The contribution of each to the resultant efficiency error clearly shows the importance of the flow rate measurement.

With a 0.5 per cent accurate flow measurement, the resultant efficiency error is only 0.7 per cent. The reservoir level contributes little to the efficiency error but is essential for an accurate measure of the penstock losses. Depending on the final system and the desired outputs, the reservoir level may or may not require a separate, accurate measurement.

Summary

Real time efficiency measurement of hydroturbine generators can be provided today. The utilities recognize the need in terms of the loss in revenue that inefficiencies create, as indicated by research referred to in June 1980 at a workshop sponsored by EPRI. Losses of more than $100 000 per turbine per year can result from either turbine efficiencies or increased penstock losses. These losses can go undetected for some time because of the difficulty in identifying them.

A system designed to satisfy these requirements has been built by the Oceanic Division of Westinghouse. Designated the LEFM-824, the system includes a Hewlett Packard HP-85 desktop computer to perform the necessary computations.

Whether this or a simpler system (such as one using an LEFM-801 and the plant computer) is used, on-line, overall plant efficiency measurement is available today at virtually no risk to the utility. The economic payback period of such a system could be as little as six months. ☐