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MEASUREMENT OF TEMPERATURE VARIATION IN WATER USING CORRELATION MICROWAVE RADIOMETER

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ABSTRACT
Hydro-turbine efficiency measurement by thermodynamic method involves accurate measurement of temperature difference of water upstream and downstream of the hydro-turbine. Conventionally, Standard Platinum Resistance Thermometers or thermistor based sensors with associated precision instrumentation equipment are used for the same. A novel microwave based thermometer is proposed in this paper. Traditionally, microwave sensors are used in remote sensing to quantify atmospheric parameters and their distribution. This is done by measuring the microwave radiation from the scene. The proposed methodology, which is non-intrusive, does not require drilling of penstock or inserting thermo-wells. In this method, signal-processing techniques like cross-correlation, filtering and time-domain integration enhance the accuracy of measurement system. Studies are in progress on adapting the methodology to yield measurement accuracies of the order of a few mK.

KEYWORDS: Correlation Microwave Radiometer, Thermodynamic Method, Turbine Efficiency, Temperature difference

1.0 INTRODUCTION
Field efficiency test is a contractual obligation by hydro-turbine supplier to be completed typically within 6 months from commissioning of machine. The Test helps determine efficiency of a new hydro-turbine system under as installed condition and evaluate any difference against committed design performance. The tests are undertaken according to IEC-60041: 1991 or ASME PTC-18: 2011 [1],[2]. Electrical and mechanical losses in the system are separately determined. They could also be determined at factory test facilities and do not necessitate a field test. Turbine efficiency, which can only be determined in the field, also has an equal if not greater influence on the net efficiency of the hydro power plant. For large turbines of capacities between 45 MW and 400 MW, the efficiency tests assume greater importance due to the economic value of the power generated during the expected life of machine.

Turbine efficiency depends on a multitude of parameters such as discharge, head across the turbine, machine speed, power output, losses, etc. The IEC-60041 and ASME PTC-18 provide an array of methods to determine turbine efficiency and a suitable method from the same is chosen depending on site constraints and conditions including discharge measurement options, penstock layout, measurement sections, etc. At numerous sites, the turbine installation is such that the penstock is not having sufficient exposed area, or penstock not having ideal straight lengths suited to discharge measurement. Site constraints sometimes dictate the conduct of tests in non-ideal conditions calling for use of CFD / Numerical modelling techniques in conjunction with field efficiency tests to arrive at appropriate results. However, the standards do not define the nature of corrections for the various disturbance conditions / constraints.
Scientific literature [3],[4] suggests that thermodynamic method for determination of the turbine/pump efficiency is best suited for tests in adverse conditions such as

short straight length availability for flow measurement, high head Pelton wheels, etc. The thermodynamic method relies on determination of temperature differential between the measurement sections at upstream and downstream of a machine very accurately.

2.0 THERMODYNAMICS OF THE TURBINE-WATER SYSTEM

The overall efficiency of a turbine-generator system is given by:

$$\eta = \eta_h \eta_m \quad (1)$$

where
η_h is the hydraulic efficiency of the turbine
η_m is the mechanical efficiency of the generator

The hydraulic efficiency of the turbine is the ratio of specific mechanical energy to its specific hydraulic energy.

$$\eta_h = \frac{P_m}{P_h} = \frac{E_m}{E \pm \frac{\Delta P_h}{P_m} E_m} \quad (2)$$

where
P_h is the hydraulic input power
P_m is the mechanical power of the runner/impeller
E_h is the specific hydraulic energy of the machine
E_m is the specific mechanical energy of the runner or impeller

$$E_h = \frac{p_1 - p_2}{\rho} + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2) \quad (3)$$

where
p_1, p_2 are the absolute pressures
v_1, v_2 are the velocities of water
g is the average acceleration due to gravity
h_1, h_2 are the geodetic heads
ρ is the average density of water

$$E_m = \frac{p_1 - p_2}{\rho} + C_p(\theta_1 - \theta_2) + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2) \quad (4)$$

where
θ_1, θ_2 are temperatures, C_p and a are the specific heat of water and reciprocal of density corresponding to $\frac{p_1 + p_2}{2}$ and $\frac{\theta_1 + \theta_2}{2}$

The determination of specific mechanical energy therefore requires accurate information on the temperature difference (of the order of a few mK) in the water flowing through the turbine.

3.0 MEASUREMENT TECHNIQUES USED IN THERMODYNAMIC METHOD

At present, the temperature difference is measured using Platinum RTDs or Precision thermistors which are inserted into small insulated measurement chambers that draw a continuous stream of water from the measurement points at the penstock as in Figure 1.

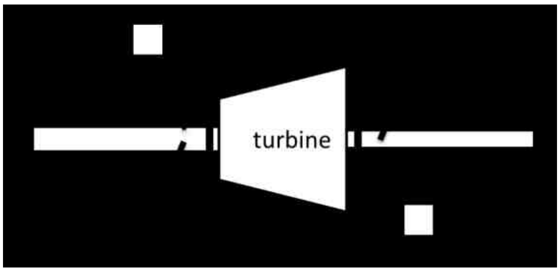

Figure 1: Thermodynamic method to determine turbine efficiency – present method

Since a precision thermometer cannot be introduced directly into flow owing to its delicate construction and risk of damage due to fluid forces in penstock, high fluid velocity, etc., temperature is measured by allowing a part of the main penstock flow to enter a measuring section (bypass). Two measurement sections, one at upstream and one at downstream are typically used and the pressure and temperature in the two measuring sections (chambers) are accurately determined. The water flowing through measuring sections are therefore associated with phenomena such as heat exchange with the atmosphere, the penstock pipe and structures at the measuring section, thermal effects at the sampling points at penstock, etc. Many of these are corrected in differential arrangements and similarity of measuring sections and probes. However, site conditions may dictate that not all of thermal losses / heating are completed eliminated or corrected for at the specific sites.

4.0 PROPOSED ALTERNATE METHOD OF TEMPERATURE DIFFERENCE MEASUREMENT

Microwave thermometers are proposed as a non-intrusive solution to measure the temperature difference of water. The thermal emission in microwave range is picked up and its power of emission is used to determine the brightness temperature. Brightness temperature is the temperature of a black body which would emit the same amount of radiation as the measurement scene at a given frequency.

Microwave correlation radiometers have been in use in radio astronomy and microwave remote sensing for more than about four decades especially in ground based systems [5]. They have made possible differential measurements by applying the statistical technique of correlation to eliminate systematic errors and effects of instrument noise and background radiation.

The proposed system comprises of two microwave based correlation radiometers as in Figure 2. The thermal emission in the microwave frequency from the scene and distilled water are detected by the antenna. They are amplified and passed through a 90° hybrid coupler. The outputs of the hybrid are band passed and amplified. These signals are phase shifted, cross-correlated and integrated. This process is performed to improve the signal to noise ratio. The integrated signals from both the radiometers are again cross-correlated to obtain the differential temperature.

4.1 DESIGN ASPECTS OF THE MICROWAVE CORRELATION RADIOMETER

This correlation radiometer is based on the principle of digital cross-correlation spectrometer. A Field Gate Programmable Array (FPGA) is used to perform the cross-correlation in frequency domain to cancel out uncorrelated noise arising from microwave background and the instrument noise, thus improving the sensitivity or resolution of the system. The cross-correlated outputs from the water upstream and downstream of the turbine are again cross-correlated with each other to obtain the power which is directly proportional to the temperature difference of water.

Expectations from the measurement technique:

1. Root mean square error (RMSE) in the temperature difference – order of 1 mK.
2. Minimum detectable temperature – around 10 mK.

4.1.1 Sensitivity of correlation radiometers

The minimum detectable temperature difference is given by

$$\Delta T \propto \frac{T_{receiver} + T_{antenna}}{\sqrt{B.\tau_{int}}} \qquad (5)$$

where

$T_{receiver}$ is the equivalent noise temperature of the receiver system
$T_{antenna}$ is the brightness temperature of the scene observed by the antenna
B is the bandwidth of the receiver
τ_{int} is the integration time. This can also be increased post-measurement

Observing the measurement scene at $2.65\ \mathrm{GHz}$, with a bandwidth of about $500\ \mathrm{MHz}$ and assuming $T_{antenna} = 300\ K,\ T_{receiver} = 250\ K$ will facilitate the detection of $2\ \mathrm{mK}$, if integrated for 5 minutes.

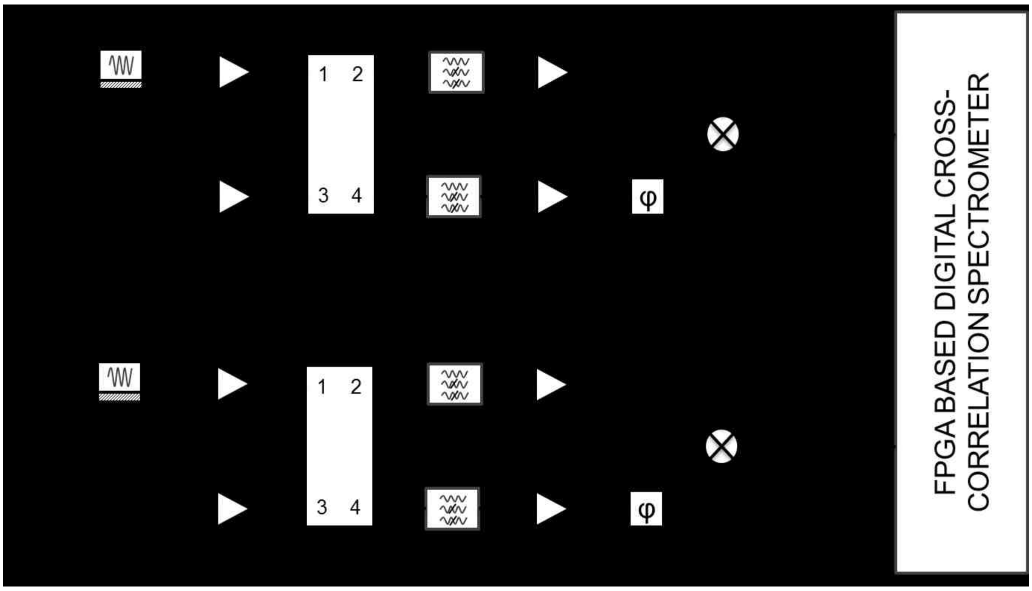

Figure 2: Correlation Radiometer design for measuring temperature difference in the water in the high-pressure and low-pressure sections (i.e. upstream and downstream) of the turbine.

4.1.2 Correlation Radiometer

Considering the radiometer connected upstream, the signals after the 90° hybrid are S_{1_a} and S_{1_b}.

$$S_{1_a}(\omega) = \frac{E_{X_1,us}(\omega)}{\sqrt{2}} + \frac{E_{dw_1,s}(\omega)}{\sqrt{2}} + N_{1_a}(\omega)$$

$$S_{1_b}(\omega) = \frac{E_{X_1,s}(\omega)}{\sqrt{2}} + \frac{E_{dw_1,us}(\omega)}{\sqrt{2}} + N_{1_b}(\omega)$$

Multiplying both the signals in the complex domain,

$$C_1(\omega) = S_{1_a}(\omega).S_{1_b}{}^*(\omega)$$

$E_{X_1,us}(\omega)$, $E_{dw_1,s}(\omega)$ are the electric fields of the radiation measured from the source and distilled water at a specific frequency ω by the radiometer located upstream.

$$C_1(\omega) = \frac{1}{2}\left(\left|E_{X_1}(\omega)\right|^2 - \left|E_{dw_1}(\omega)\right|^2 + f_1(\omega)\right)$$

$$f(\omega) = F(\omega)e^{i\varphi_E(\omega)}$$

$f(\omega)$ consists of the uncorrelated components of S_{1_a} and S_{1_b}. $\varphi_E(\omega)$ is a random phase term. $f(\omega)$ has a zero mean value. Hence, integrating for a long time will average it out to zero.

$$< C_1(\omega) > = < I_{X_1}(\omega) - I_{dw_1}(\omega) >$$

Similarly for the radiometer attached downstream,

$$< C_2(\omega) > = < I_{X_2}(\omega) - I_{dw_2}(\omega) >$$

The integrated signals from the two radiometers are cross-correlated again. The output is proportional to the temperature difference of water.

$$C(\omega) \propto \left(T_{X_2} - T_{X_1}\right) \tag{6}$$

5.0 CONCLUSION

The new technique proposed to measure the temperature difference is a combination of a very sensitive microwave receiver and a digital cross-correlator. This technique will also nullify the effect of receiver noise, thereby improving the sensitivity of the system. In conjunction with signal processing techniques, the proposed method is expected to help achieve a desired accuracy of 1 mK for the differential measurement. This method being non-intrusively is likely to provide numerous benefits besides helping improve methodology for undertaking thermodynamic based field efficiency tests. Studies are in progress in development of microwave probe mechanism for undertaking non-intrusive measurements.

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REFERENCES
[1] IEC 60041, "Field Acceptance Tests to Determine the Hydraulic Performance of Turbines, Storage Pumps and Pump Turbines", 1991
[2] ASME PTC 18-2011, "Hydraulic Turbines and Pump-Turbines Performance Test Codes", ASME, New York, 2011.
[3] Shantaram S. Patil, H.K. Verma, Arun Kumar, "Efficiency measurement of hydromachine using thermodynamic method", IGHEM, October, 2010.
[4] Petr Sevcik, "Turbine efficiency measured using Thermodynamic method against using Ultrasonic Flowmeter", IGHEM, August, 2016.
[5] Corinne Staub, Axel Murk, Niklaus Kämpfer, Dino Zardet, Bruno Stuber, "Development of a 22 GHz Correlating Radiometer for the Observation of Stratospheric Water Vapor", IEEE Conference Proceedings – MICRORAD 2008.
[6] John J. Faris, "Sensitivity of a Correlation Radiometer", Journal of Research of the National Bureau of Standards – C.Engineering and Instrumentation, November, 1966
[7] A. J. Harris, S. G. Zonak, G. Watts, R. Norrod, "Design Considerations for Correlation Radiometers", NRAO GBT Memo 254, October 2007.
[8] J. B. Hasted, "Water – A Comprehensive Treatise – Volume 1 – The Physics and Physical Chemistry of Water - Chapter 7 – Liquid Water: Dielectric Properties", Springer US, 1995.