

## **PERFORMANCE TESTING OF A LOW HEAD SMALL HYDRO POWER (SHP) PLANT-ZHO SUWEI (TAIWAN) –A CASE STUDY**

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## **SYNOPSIS**

Kirloskar Brothers Ltd. (KBL), India, one of the leading companies in the world in the field of fluid handling equipments, has designed, manufactured, installed and commissioned Electro-mechanical equipments for several Small Hydro Power (SHP) projects across the world. Recently, KBL has commissioned a Run-of-the-River (ROR), low head, SHP plant –Zho Suwei (1 X 3607 kW) at Taiwan. Performance testing of the Electro-mechanical equipments has been subsequently carried out as part of the contractual obligation and also for obtaining strategic inputs for introspection of our design and manufacturing process.

This paper presents the experience of carrying out the Performance Test encompassing the techno-commercial intricacies involved in executing that for an international project. The choice of the methods should not only comply with the technical requirements of the standard/ codes in vogue but also the commercial implications of the chosen method should justify the scale of the project. A cross plane, external mounted, ultrasonic transit Time Flow Meter (UTTF) and Vertical Acoustic Doppler Profiler (VADP) have been used for discharge measurement. Mix of Pressure Transducer (in penstock) and level sensors (at draft tube exit) have been used to calculate the net head. Justification for those choices and calculations involved to arrive at the result are also discussed.

## **I. INTRODUCTION:**

Performance test of Electromechanical Equipments is part of the contract obligation and also provides strategic input for revisiting the design and manufacturing process. Also reconfirms the accuracy and authenticity of the claimed model tests results. The “performance” of a turbine is quantified generally under the following reference: the efficiency of the machine within specified range of output and head variation should meet the guaranteed efficiency; the turbine power output should meet the guarantee as a function of the net head and discharge available. The performance also includes safe operation of the machine without being subject to cavitation or fatigue in the specified head range. The machine behavior under load throw-off condition is also in some cases constitute performance test. In addition to these performance tests done during acceptance, it becomes relevant several times in the operational life of the turbine in the course of operation, as wear and cavitation pitting occur on critical parts of the turbine and as a result efficiency decreases. This test result becomes paramount for the policy decision regarding rehabilitation.

Typically performance test of a Hydro Power plant includes:

- (a) Inspection of all components, systems and station auxiliaries.
- (b) Functional checks of simpler devices and systems.

- (c) Testing of measuring instruments.
- (d) Secondary injection tests on protective relays.
- (e) Operational tests on control systems.
- (f) Measurement of the parameters critical for generation.
- (g) Measurement of maximum power output of generating units.
- (h) Determination of efficiency of generating units, combined and individually.

## CODES/ STANDARDS FOR PERFORMANCE TESTING

The ASME “Performance Test Code 18 (PTC 18): Hydraulic Turbines,” [1] Specifies procedures for the field performance testing of hydraulic turbines and of pump/turbines operating in the turbine mode. PTC 18 provides guidelines measuring discharge (Q), head (H), and power output (P) to calculate turbine power output and efficiency and finally quantifying turbine performance. Required pretest arrangements are also included, specifications of the instruments to be used, methods of measurement, methods of calculation, and constituents of test reports are also elaborated. The specified test procedures can limit the total uncertainty for calculated turbine power output at 1.2% and at 2.0% for calculated efficiency, calculated in accordance with PTC 19.1 and PTC 18 respectively. Any test with uncertainties greater than the above shall not qualify as an ASME Code test. Further smaller uncertainties should occur where good measurement conditions exist and best methodology can be used.

The other code which is most widely referred by the performance testing professional of hydraulic machines is the IEC 41 (1991): “Field Acceptance Test to Determine the Hydraulic Performance of Hydraulic Turbines, Storage Pumps and Pump- Turbines” International Electrotechnical Commission (IEC), Publication No. 41 [2]. This Code defines methods for all size and type of turbines (impulse, reaction), storage pump, or pump turbine. The Code provides guidelines for determining whether the performance guaranteed under contract has been met. Like PTC 18, it also includes rules governing these tests as well as the methods of computing the results and the content of the final test report.

## II. SALIENT FEATURE OF THE PROJECT UNDER CONSIDERATION– ZHO SUWEI (1 X 3607 kW)

The site under consideration is a Run-of- the-River; Small Hydro Project built on the irrigation canal drawn from river- Zho Suwei at Douliou, Taiwan. The design head and discharge is 13.86 m and 30 Cumecs respectively. Water is carried to the fore bay through trapezoidal; RCC power channel of 1500 m in length. Buried penstock of 30 m in length carries the water from the fore Bay to the turbine. The spill way bypasses the excess water to the tail race and sluice gate removes the silt deposition from the fore bay floor. The salient features of the project are appended below:

- (a) Location : 23°42'27"N, 120°32'38"E
- (b) Name of the Place : Douliou, Taiwan
- (c) Type of Turbine : Kaplan
- (d) Orientation : L-Type (Vertical)
- (e) Generator : 6.6 kV, 30 P, Synchronous
- (f) Coupling : Direct
- (g) Maximum net head : 16.50 m
- (h) Design net head : 13.86 m
- (i) Minimum net head : 13.00 m
- (j) Turbine rated speed : 240 rpm
- (k) Rated generator output : 3607 kW
- (l) Rated turbine output : 3742.5 kW
- (m) Rated Flow : 29.68 Cumecs
- (n) The specific gravity of water at site  $\rho$  (at 19°) : 998.38 kg/m<sup>3</sup>
- (o) The gravity acceleration at site (g) : 9.7868 m/sec<sup>2</sup>
- (p) Penstock Diameter : 3400 mm
- (q) Runner Diameter : 2440 mm
- (r) Shaft diameter : 360 mm
- (s) Hydraulic thrust : 78480 kgf

### III. DETERMINATION OF TURBINE EFFICIENCY AND MEASUREMENTS INVOLVED:

Turbine Efficiency:  $\frac{\text{Mechanical Power Produced}}{\text{Hydraulic Power Available}} \dots\dots\dots \text{Mechanical Power (Turbine)}$   

$$\frac{P_m = P_g / \eta_g + P_{th} + P_{gd} + P_{au} + P_{gb}}{P_h = g \times H_n \times \rho \times Q}$$

Where,

- $P_g$  = Generator output
- $\eta_g$  = Tested generator efficiency.
- $P_{th}$  = Thrust bearing loss corresponding to turbine.
- $P_{gd}$  = Mechanical power dissipated in guide bearing.
- $P_{au}$  = Electrical Power supplied to auxiliary equipment
- $P_{gb}$  = Mechanical power loss in Gear Box

In case of Zho Suwei as the orientation is vertical, the generator is directly coupled to the turbine hence Mechanical power loss in Gear Box ( $P_{gb}$ ) component is eliminated. Again Electrical Power supplied to auxiliary equipment ( $P_{au}$ ) can be eliminated by measuring the generator output at its terminals before any consumption. Further in Small hydro power machines the bearing losses are negligible and as these are within the scope of the turbine manufacturer hence are not considered separately.

Hence Turbine Efficiency:  $\frac{P_g / \eta_g}{g \times H_n \times \rho \times Q} \dots\dots\dots(i)$

The measurements involved in determining the efficiency are:

- (i) For determining the Hydraulic power
  - (a) Discharge (Q)
  - (b) Head (m)
  - (c) Specific gravity of water ( $\rho$ ) ....from IEC 41 [2]
  - (d) Acceleration due to gravity (g) ....from IEC 41 [2]
- (ii) For determining Mechanical Power
  - (a) Electrical Power Out Put
  - (b) Generator efficiency ....from Generator test report

The subsequent section deals with the methods adopted for measurement of each parameter required for quantifying the efficiency of the hydraulic turbine. Figure I depict the Instrument Allocation Scheme for carrying out performance testing of the E & M equipments. Although efforts have been made to comply with the recommendations of IEC 41, site specific applicability is also considered while making the choice of the measurement methods to make the test economical and less labor intensive to suit the small scale of the project.

#### A. MEASUREMENT OF DISCHARGE (Q)

The discharge measurement methods applicable in hydropower plants, which are recommended by the International Standard IEC 60041–1991 and American National Standard ASME PTC 18–2002, are:

1. Current meter method
2. Pitot tube gauging
3. Pressure-time method (Gibson method)
4. Tracer methods
5. Ultrasonic method
6. Weirs
7. Standardised differential pressure devices
8. Volumetric gauging method
9. Relative discharge measurement: Index Test

Though choices are many but which of these methods are to be used in the respective power plants is a matter of choice based on main numerous governing factors, some of them are enumerated below:

Factors governing the choice of the discharge measurement methods [3]:

1. Site Specific Applicability
2. Adaptability to variable operating conditions
3. Accuracy requirements
4. Cost justifiable for the scale of the project.
5. Legal constraints
6. Range of flow rates
7. Head loss
8. Operating requirements
9. Response to sediment and debris
10. Longevity of device for given environment
11. Maintenance requirements
12. Construction and installation requirements
13. Device standardization and calibration
14. Field verification, troubleshooting, and repair
15. Availability of expertise and user acceptance of new methods
16. Vandalism potential
17. Impact on environment

In addition to these, dominant factors ergonomics of the Instruments, Lead time of the Instrument supplier, Time required for Installation at site, time and laborer required for performing the measurement are also plays a major role in making the choice especially for the international projects, as the cost involved is immensely sensitive to all of these. The applicability of each methods and their relative advantage and disadvantage are juxtaposed in table II [4].

After carefully weighing all the options cross plane Ultrasonic Transit time Flow (UTTF) Meter is found to be suitable for measurement of discharge at the penstock. United States Department of the Interior Bureau of Reclamation (USBR) has reported the acoustic method to be a major contributor to shorter and less expensive performance testing based on their wide experience of testing pumps and turbines in last two decades [5]. Other feasible option was current meter at the intake gate. But Current Meter method is more time consuming, costly and labor intensive [6]. Current meter method of discharge measurement also tends to be erroneous when subjected to swirl and secondary flow which is a common phenomenon in low head plants [7]. Analysis of the velocities in each acoustic path exhibits the pattern of swirl and secondary flows, which goes unnoticed and neglected in case of current meter and this affects the current-meter readings adversely.

A Vertical Acoustic Doppler Profiler is chosen as the second method of discharge measurement at the tail race. Purpose of this is to cross verify the readings of the readings of UTTF installed at the penstock. The model used is River Surveyor S5 manufactured by Sontek. Both of these discharge measuring instruments were sourced locally from Taiwan Power Research Institute at Taiwan to reduce the time component and capital investment required for procurement. The comparison of the readings of both of these instruments is presented in table I.

**Table I. Comparison of Flow Readings**

		LOAD			
		100 %	75 %	50 %	30 %
<b>UTTF</b> <b>Model: Yokogawa</b>	<b>Discharge</b> <b>(Cumecs)</b>	28.42	21.8	14.5	9.44
VADP Model: River Surveyor S5 Make: Sontek	Discharge (Cumecs)	28.10	22.0	14.65	9.59

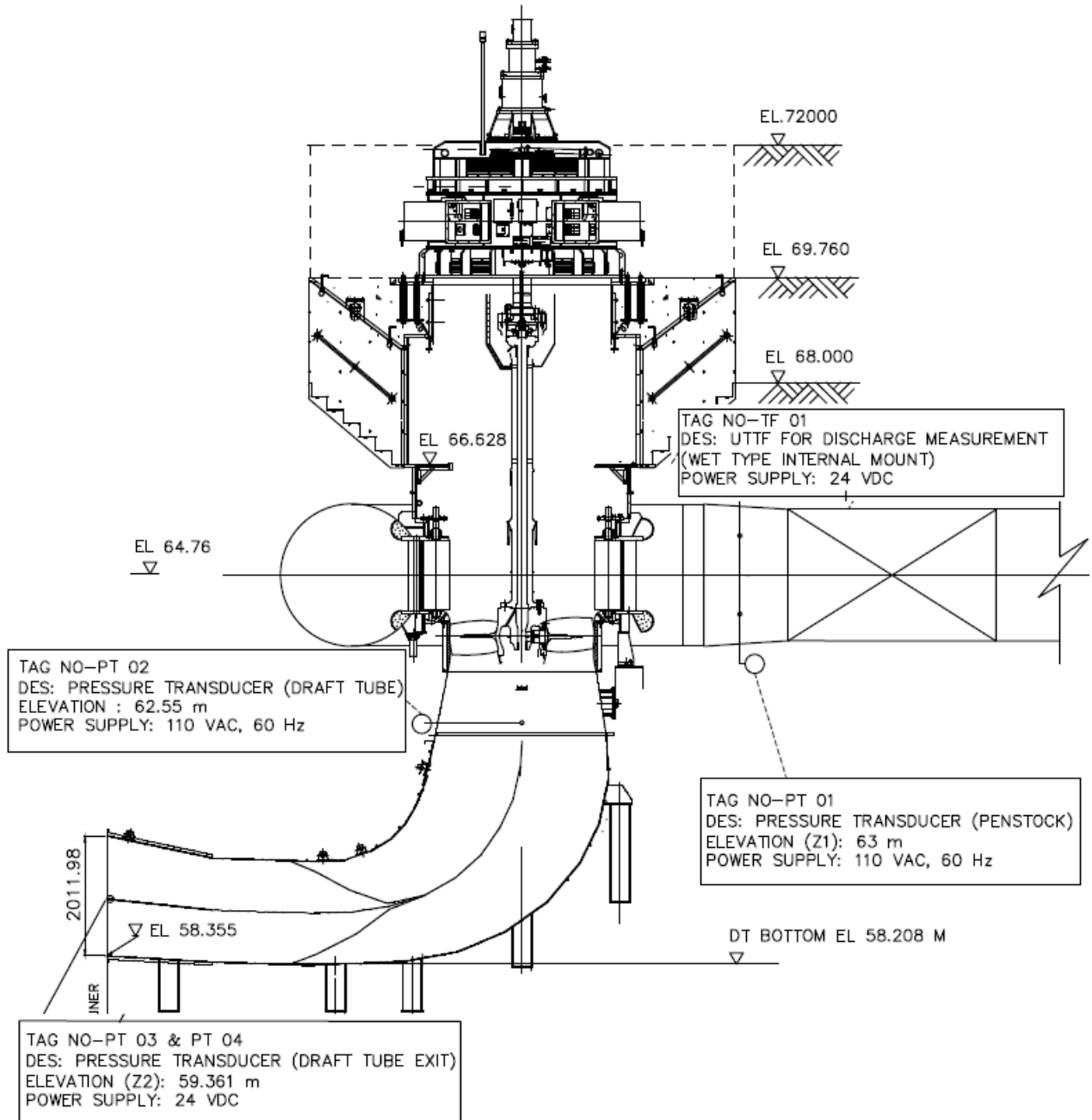
**Table II.**

Method	Description	Application	Advantages/ Disadvantages	Ergonomics	Cost Implication	Expected Uncertainty	Site Suitability
Pressure-Time (Gibson)	Flow is derived from the change in pressure when the mass of water decelerates to zero velocity.	<ul style="list-style-type: none"> <li>In penstock with downstream valve or gate.</li> <li>Not applicable in open channels.</li> <li>Penstock Length <math>L &gt; 10</math> m</li> <li><math>LX</math> velocity <math>&gt; 50</math> m/s</li> </ul>	<ul style="list-style-type: none"> <li>Operation is Relatively simple</li> <li>Less hardware requirements</li> <li>The provision should be accommodated in design</li> <li>Several times closing of gates hence shut downs of the plant is required for measurement</li> </ul>	**	\$\$\$	1.5 % to 2.3 %	No Suitable Position.
Dye or Tracer Dilution	Flow is derived by measuring concentration of tracer relative to the introduced concentration. ...	<ul style="list-style-type: none"> <li>Suitable where tracer mixing is achievable to a satisfactory degree.</li> <li><math>L &gt; 150</math> D</li> </ul>	<ul style="list-style-type: none"> <li>Relatively inexpensive.</li> <li>Conduit cross sectional area need not to be measured.</li> <li>No requirement of minimum straight conduit length.</li> </ul>	***	\$\$\$	1.0% to 2.0%	Suitable Length not available
Acoustic / Ultrasonic Flow meters	time of travel or Doppler shift of frequency of acoustic pulses sent diagonally across the conduit is measure to calculate velocity and in turn $Q$ .	<ul style="list-style-type: none"> <li>Close conduit</li> <li>Open channel</li> </ul>	<p>A certain minimum length of straight, uniform conduit or open channel is required upstream and downstream.</p>	Clamp on ***** Internal ** VADP **	\$\$\$\$	0.5% to 1.5%	Suitable
Current Meters	Velocity of water at several specific points in a well defined cross- section is measured, and integrated by area velocity method.	<ul style="list-style-type: none"> <li>closed conduits</li> <li>channels</li> <li>Upstream-20 D,</li> <li>Down Stream 5D required</li> </ul>	<ul style="list-style-type: none"> <li>Has applicability to almost all types of plant;</li> <li>Multiple instruments to be installed in the passage.</li> <li>Areas to be accurately computed.</li> <li>Additional fabrication cost.</li> </ul>	*	\$\$\$\$\$	1.0% to 2.0%	No Suitable Position.
Dye Transit Time	Velocity is measured by sensing transit time of dye or salt to travel a length of conduit. Flow is derived by area-velocity method.	Injection pipe to 1 <sup>st</sup> detector 7D, and between 1 <sup>st</sup> and 2 <sup>nd</sup> detector 7D length required.	Specialized equipment required for the preparation and injection of dye or brine.	***	\$\$\$	1% to 1.5 %	No Suitable Position.

Method	Description	Application	Advantages/ Disadvantages	Ergonomics	Cost Implication	Expected Uncertainty	Site Suitability
Acoustic Scintillation Flow Meter	Flow rate is measured in terms of the time of travel of turbulence within flow over a small distance between two parallel paths perpendicular to the flow.	Acoustic paths are normal to the flow direction, hence can be mounted on a rack or frame and inserted into a bulkhead or gate slot.	<ul style="list-style-type: none"> <li>Allows for continuous flow metering in bulkhead or slotted intakes.</li> <li>The acoustic noise affects the accuracy adversely if not positioned strategically</li> </ul>	***	\$\$\$	1.0% to 2 %	Experience Limited
Winter-Kennedy method (Index Testing)	The differential pressure between the outer & inner dia of Scroll casing is proportional to the square of the flow rate.	<ul style="list-style-type: none"> <li>Relative measurement at not tested operating points</li> <li>To quantify performance changes resulting from turbine modifications or wear.</li> </ul>	<ul style="list-style-type: none"> <li>Once installed, measurements can be accomplished often without outage</li> <li>Taps must be flushed regularly for accuracy.</li> </ul>	*****	\$	2.0 to 2.5 % [4]	Suitable as Relative Measurement
Volumetric Gauging	With the availability of a suitable reservoir, volumes of water passing through the machine can be measured in terms of change in level of the pond's surface.	<ul style="list-style-type: none"> <li>Suitable for controlled conditions like labs.</li> <li>Steady state flow and a captive pond are required.</li> </ul>	<ul style="list-style-type: none"> <li>Basic measurements.</li> <li>Availability of required size of pond for SHP is unlikely.</li> <li>Head available to the machine will vary with accumulation of the water in the pond.</li> </ul>	****	\$ (with pre-existing reservoir)	1 % to 2 %	Not Suitable
Venturi Meter	The differential pressure across a Venturi tube is converted into flow rate using a calibrated curve.	<ul style="list-style-type: none"> <li>Application for SHP is limited.</li> <li>Straight sections of pipe required.</li> </ul>	<ul style="list-style-type: none"> <li>Accurate, reliable.</li> <li>Pipe Dia 65-500 mm</li> </ul>	****	\$\$	1 % to 1.5 %	Not Suitable
Weir	The flow over a weir is a function of the height of water above the weir crest suitably estimated discharge coefficient.	Talraces and intake channel.	<ul style="list-style-type: none"> <li>Basic, reliable.</li> <li>Well defined sections is required for accurate estimation of the discharge coefficient.</li> </ul>	*	\$\$\$	1.7 to 3 %	Not Suitable

\* No of asterisk indicate the ease & man hour of installation, and demobilization and measurement. Five asterisk indicate most ergonomic instrument [4].

\$ No indicate the relative comparison of cost of the instrument, fabrication requirements, cost of demobilisation. Five indicate most costly [4].



**Figure 1: Instrument Allocation Scheme, ZHO Suwei (1 X 3607 kW) Performance Testing**

**B. NET HEAD CALCULATION**

Net head available to the turbine can be calculated either by deducting the calculated head loss from the gross head measured or by deriving from the measured static pressure at the inlet and the outlet of the turbine. The first method has an element of estimation in it. The accuracy of such measurement depends substantially upon the loss coefficient selected. However, the loss coefficients adopted from the standards and codes [8],[9] does not cater for the actual condition of the surface of the hydraulic passage hence has a possibility of being influenced by inaccurate estimation. Hence the later method is adopted for calculation of net head.

$$\begin{aligned} \text{Net Head, } H_n &= \frac{P_1 - P_2}{\rho g} + \frac{V_1^2 - V_2^2}{2g} + (Z_1 - Z_2) \\ &= \frac{\Delta P}{\rho g} + \frac{V_1^2 - V_2^2}{2g} + (Z_1 - Z_2) \end{aligned}$$

Where,

$P_1$  = Pressure at up stream (U/S) of the turbine

$P_2$  = Pressure at Down stream (D/S) of the turbine

$V_1$  = Velocity at Location of Pressure Gauge Installation at U/S

$V_2$  = Velocity at Location of Pressure Gauge Installation at D/S

$Z_1$  = Level of U/S pressure Gauge

$Z_2$  = Level of D/S pressure Gauge

Up stream pressure ( $P_1$ ) have been measured using manifolded pressure taps on the penstock. A high accuracy battery operated portable pressure transducer was installed to the manifold for taking the reading. For the down stream pressure gauges were installed at two locations. One digital pressure gauge at the draft tube cone, i.e. just below the runner and the other one pair of hydro static pressure gauge at the end of steel liner of draft exit. How ever it was observed during testing that the readings from either of them were not stable, as the one at the draft tube cone were subject to turbulence of the runner. The reading of the hydro static type pressure transducer is highly influenced by its relative orientation with the velocity of water. Hence it was mutually agreed to consider the free surface level at the draft tube gate as the down stream pressure of the turbine ( $P_2$ ).

In that case the formula for net head calculation becomes:

$$\text{Net Head, } H_n = \frac{P_1 * 10^4}{\rho} - L_{tw} + H_v + a$$

Where,  
 $P_1$  = Upstream pressure (kg/cm<sup>2</sup>)  
 $H_v$  = Velocity Head (m) =  $\frac{V_1^2 - V_2^2}{2g}$   
 $V_1$  = Velocity at upstream pressure measurement section (m/s).  
 $V_2$  = Velocity at end of steel liner of draft tube (m/s).  
 $L_{tw}$  = Water level above draft tube exit center line (m)

$a$  = Position head (m) =  $b + (c-d)$   
 $b$  = Level difference between pressure transducer and penstock center line (m)  
 $c$  = Elevation of penstock center line (m)  
 $d$  = Elevation of center line of draft tube section (m)  
 $\rho$  = Specific gravity of water (kg/m<sup>3</sup>)

### C. MEASUREMENT OF POWER

IEC 41 requires electric power output measurement by a Watt meter connected through a current transformer (CT) and potential transformer (PT) of class 0.2 or better. The CT and PT installed at site are of accuracy class 0.2 hence as another step towards making the test economic those were calibrated and used for performance testing. A watt meter of accuracy class 0.1 was locally sourced from Taiwan Power Research Institute (TPRI).

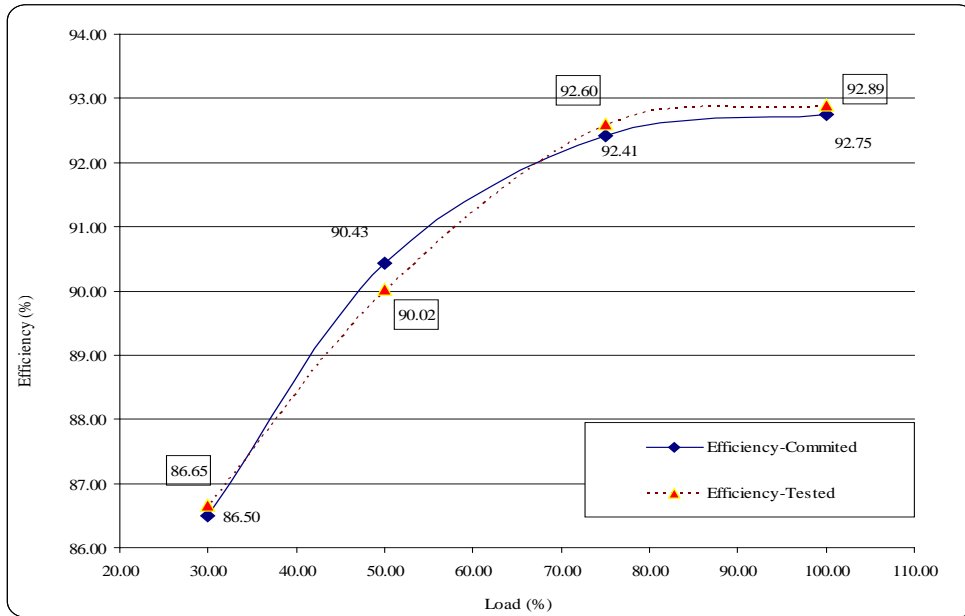
## IV. INTERPRETATION OF RESULTS

Table III. Test Results

Load	Q m <sup>3</sup> /s	Vel Head (m)	Net Head (m)	Hydraulic Power (kW)	Mechanical Power (kW)	Efficiency (%)
100 %	28.42	0.171641855	14.37164185	3973.357	3691	92.89
75 %	21.8	0.100992248	14.68099225	3113.429	2883	92.60
50 %	14.5	0.044679783	15.25467978	2151.782	1941	90.02
30 %	9.44	0.018937343	15.85893734	1456.375	1262	86.65



The result of all the measurements and calculations are presented in table III. The comparison of the tested efficiency with that of predicted efficiency form model test data is plotted in Figure II. It can be observed that there is a marginal deviation of the tested results from the predicted performance and in most of the operating points the tested results were better. At 50 % power output the actual efficiency is observed to be less than the predicted/ committed efficiency but the deviation is within the upper limit of combined uncertainty of the measurement.



**Figure II: Efficiency Tested vs. Efficiency Committed**

## V. CONCLUSION.

In case of performance testing of small scale power plants, where the economy and labor intensiveness becomes critical, careful selection of instruments becomes is very important. Various options are required to be weighted considering the lead time of the instrument supplier, man-hour required for installation, additional fabrication requirement of frame etc, ergonomics of the instrument, time required to demobilize and total down time required in addition to the estimated uncertainty of the equipments. Instrument based on new technological innovations like Doppler Profiler and UTTF may be resorted to, to obtain a balance between the accuracy and economy and ergonomics. A little modification in the methods to suit the site requirement like calculation of net head can bring in increase in ease and better accuracy in measurement.



**Fig. III. Installation of UTTF**



**Fig. IV: Surface Preparation for Sensors**



Fig. V: Q Measurement using Riversurveyor

Fig. VI: Manifold for Upstream Pressure

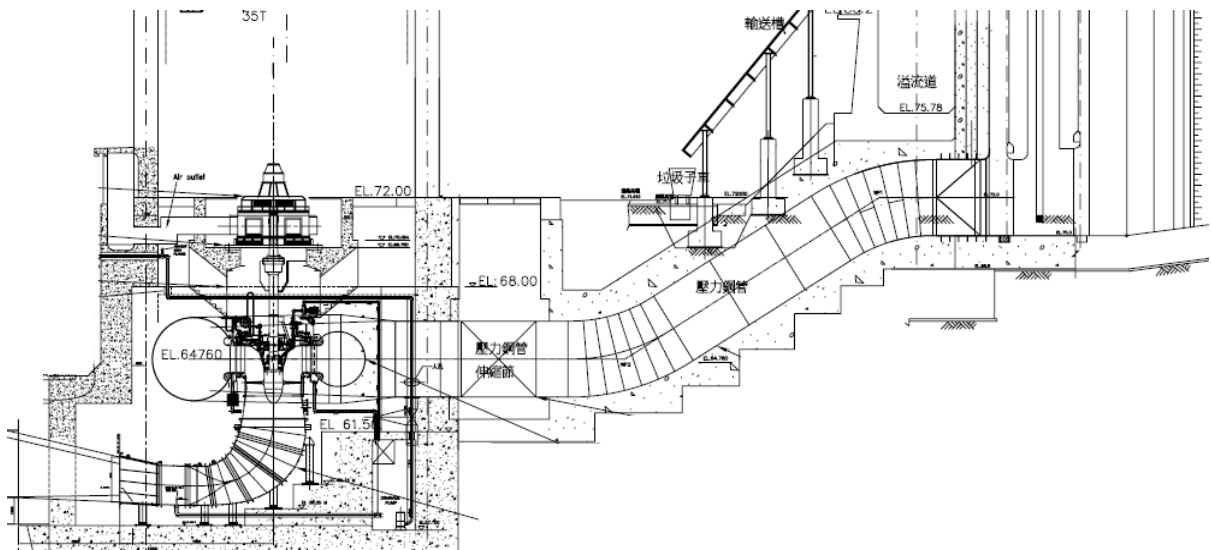


Fig. VII: Sectional View-Power House

## REFERENCE

- [1] PTC 18-2002: The American Society of Mechanical Engineers (ASME) Performance Test Code 18.
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### BIOGRAPHY

**Mr. Santosh Ghosh** graduated in Electrical Engineering from The Institution of Engineers (India) and did his masters from Alternate Hydro Energy Center at Indian Institute of Technology (Roorkee) in 2009. He has worked in Indian Navy from 2000 to 2007 and specialized in Control and Navigation System of new generation war ships from Naval Academy, Russia. Presently he is working with Kirloskar Brothers Ltd. (India) in corporate R&D division in Turbine design group and also involved in new energy efficient product development for application in the field of renewable energy.

**Dr. Jagadish Kshirsagar** graduated in Mechanical Engineering from Nagpur University in 1976. He obtained his ME and PhD from Indian Institute of Science, Bangalore in 1978 and 1989 respectively. His research interest includes 3D flows in turbo machinery, Numerical Analysis of fluid handling equipments. He has 28 years of industrial, academic and research experience in the field of turbo machinery. Presently he is working with Kirloskar Brothers Ltd, India in the capacity of vice president of R&D division. He is member of various professional societies like ASME, FMFP, Indian Hydraulic Society, fellow of Institute of Engineers and recognized as chartered Engineer. He is recipient of two US patents for innovative design of fluid handling system.

**Mr. Sudhir Mali** graduated in Mechanical Engineering in 1995 and subsequently did his Masters in Design from College of Engineering, Pune (COEP). Since 1995 he is associated with Corporate R&D of Kirloskar Brothers Limited (KBL), India. Presently, he is heading the design and engineering of hydro turbines division. He has been instrumental in KBL for the technology transfer from the collaborators and bringing in innovation in turbine design. He has worked on the mechanical design and engineering for about 30 various small hydro projects done by Kirloskar Brothers Limited including Kaplan, Francis and Pelton turbines.