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Generator Efficiency Measurement by Calorimetric Method: Case of UT3A HEP 60MW

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Abstract
The paper presents the calculation of hydro generator absolute efficiency using calorimetric method. The losses were calculated by using total loss method and segregated loss method. In total loss method, the heat taken by coolant, convection heat loss from surface and external heat loss is considered. In segregated loss method, the heat generation from each component is taken for loss calculation. The case of Upper Trishuli 3A Hydro Electric Project, 60MW, located at border of Rasuwa and Nuwakot district of Nepal, is taken for elaboration purpose. The test was performed for four heat run and one load adjustment run. The weighted generator efficiency is found 97.71%. Both methods have given the efficiency value with 0.02% absolute error. The arrangement of measuring equipment for generator efficiency measurement at the site is also discussed in the paper.

Keywords
Hydro-generator, Generator efficiency, Calorimetric method, Losses measurement

1. Introduction

Generator efficiency measurement is one of the important tasks while commissioning and acceptance of new hydro power plant. The installed generator should meet the guaranteed efficiency. The generator efficiency is the relation of input and output power of generator. The output power can be easily measured by accurate watt-meter, while input power to generator is determined by direct or indirect method [1]. In direct method, the mechanical power input to generator is directly measured. In the other hand, in indirect method the input power to generator is determined by adding the global losses to the electrical power measurement at the generator terminals. The various methods for loss measurement includes: calibrated machine method, retardation method, calorimetric method(heat transfer), separate drive method and electrical input method etc. [2]

In calibrated machine method, the calibrated motor is used for driving the generator, which acts as generator input for efficiency measurement. In retardation test method, the machine is rotated to slightly greater speed than its synchronous speed and suddenly disconnected. The retardation of speed depends upon unit inertia and involved loss. By performing this test for several operating condition, the losses can be determined for efficiency calculation. In calorimetric method, the heat taken by coolant, heat loss from surface and external losses are measured. The grand losses plus generator output gives the input power value to the generator for efficiency calculation. [3]

Now a day, due to the technical and economic issues,

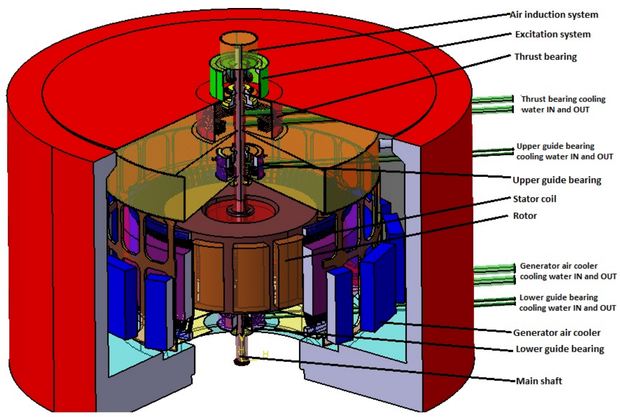

Figure 1: 3D model of UT3A generator

along with the instrumentation evolution, the calorimetric method has become an interesting option to determine hydro generator losses . This paper presents the theoretical basis for calculation of generator efficiency using the calorimetric method and also it discusses the test setup arrangement and measurement of generator efficiency of Upper Trishuli 3A Hydro Electric Project (UT3A HEP). UT3A HEP is located at the border of Rasuwa Nuwakot District of Nepal with two units of 30.6MW capacity each and uses 36MVA generator with 11KV rated voltage and 1889.5A rated current. The rated excitation voltage is 200V and rated excitation current is 635A. The 3D model diagram of generator of UT3A HEP is shown in Figure: 1. The principles and mathematical equations used in this paper are consistent as per [4, 5]. Some of the data for making calculations are taken from [4, 6] .

2. Calorimetric method

2.1 Method Principle

All losses generated within generator would become heat dissipated from generator pit and transferred to cooling media. Therefore, we could measure the heat to evaluate generator losses, then to calculate generator efficiency; this is called the calorimetric method [6].

2.2 Reference surface

This is a surface completely surrounding the machine such that all losses produced inside it are dissipated through it to the outside [5]. The Figure: 2 shows the modified image of reference surface in [5]. The outer dotted line in the Figure: 2 shows the reference surface.

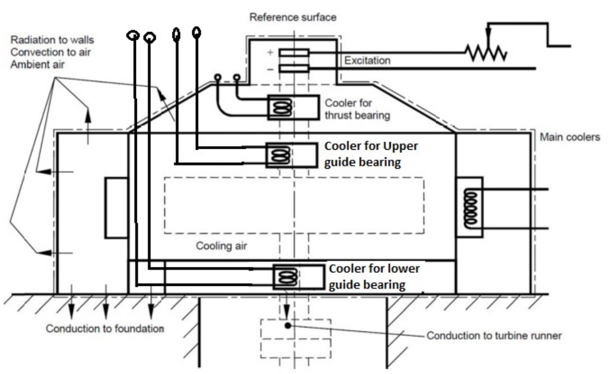

Figure 2: Modified reference surface figure from IEC 60034-2-2

2.3 Calculation

There are two sub-methods for efficiency calculation, using calorimetric method: total loss method, segregated loss method.

2.3.1 Total loss method

In this method, total loss from the machine is obtained by measuring heat absorbed by coolant, heat dissipation from reference surface and external heat loss.
Heat taken by coolant includes the heat gain of thrust bearing coolant (P_{TB}), upper guide bearing coolant (P_{UGB}), lower guide bearing coolant (P_{LGB}) and generator air cooler coolant (P_{GA}). The general formula to calculate heat gain ($P_{c(i)}$) in coolant is

$$P_{c(i)} = C_p Q_a \rho (T_e - T_i) \tag{1}$$

Where, water specific heat capacity (C_p) and water density (ρ) shall be taken from [4] as per average of inlet and outlet temperature of cooling water. The machine should be run at rated speed at different test run and the corresponding parameters are measured. Coolant flow rate (Q_a) shall be measure by calibrated magnetic flow meter. The temperature at exit (T_e) and inlet (T_i) shall be measured by calibrated Pt100s thermometer installed at cooling water line.
Loss contribution of thrust bearing cooler is divided for generator and turbine loss. The generator loss contribution is calculated as,

$$P_{TBG} = P_{TB} \frac{weight_{rotor}}{weight_{rotor} + weight_{runner} + weight_{thrust\,force}} \tag{2}$$

Heat dissipated from reference surface to surrounding by convection and radiations ($P_{d(i)}$) includes heat loss from generator upper cover, lower cover, air induction system and generator pit liner. This shall be calculated as,

$$P_{d(i)} = hA(T_s - T_a) \tag{3}$$

Where, h is convective heat transfer coefficient, which is calculated by empirical formula $h = 11 + 3v$, v is the air velocity, generally taken as 1m/s. Here, exposed surface area (A)is taken from construction drawing, surface temperature (T_s) and nearby ambient air temperature (T_a) are measured by calibrated surface temperature thermometer and calibrated ambient air temperature thermometer respectively.
The external heat loss (P_e) mainly includes excitation system loss. Its value is obtained from technical

document.
The total loss (P_L) is calculated as.

$$P_L = \sum all \quad bearing \quad loss(P_1) + \sum all \quad surface \quad loss(P_2) + \sum external \quad loss(P_e) \quad (4)$$

The generator efficiency in this method is calculated as,

$$\eta_{G1} = \frac{P_o}{(P_0 + P_L)} \quad (5)$$

Where, P_0 is actual output from the generator, which is measured my accurate watt meter.

2.3.2 Segregated loss method

In this method, losses in each component are measured and added to get the total loss. For measuring the losses in each component, machine is subjected to four different test runs as listed below:

(i) Mechanical loss heat run (at rated speed, no excitation)

(ii) Core loss heat run (at rated speed, open circuit, excited)

(iii) Copper loss heat run (at rated speed, armature terminal short circuited, excited)

(iv) Full load loss heat run (at rated speed, excited, full load, power factor=0.85)

The calculation of losses in each component can be listed as below:

(a) Bearing Loss
In this article, the generator with three bearings: thrust bearing (P_{TBG}), upper guide bearing (P_{UGB}), lower guide bearing (P_{LGB}), is considered, as shown Figure: 1. Bearing loss (P_{GB}) is measured similarly as the total loss method. Here, the heat taken by coolant in each bearing is measured and sum of them gives the total losses in the bearing (P_{GB}). It is calculated as,

$$P_{GB} = P_{TBG} + P_{UGB} + P_{LGB} \quad (6)$$

Bearing loss is the constant loss. It is calculated for all test run. Bearing loss at rated output loss heat run test value shall be used for efficiency calculation.

(b) Brush loss
Brush loss (P_b) consists of mechanical and electrical loss components. Mechanical Loss is calculated as,

$$P_{b\_mech} = VA\mu P_{cb} \quad (7)$$

Where, V is tangential velocity, A is contact area, μ is friction coefficient and P_{cb} is contact pressure. This P_{b_mech} value is generally obtained from manufacturer.
Electrical loss of brush is calculated as,

$$P_{b\_elec} = 2UI_f \quad (8)$$

Where, U is brush voltage drop and I_f is excitation current loss. Generally, the electrical loss at rated field current is obtained from manufacturer but for other value of field current, electrical loss is calculated by proportionate it with square of field current. The total bearing loss (P_b) is given as,

$$P_b = P_{b\_mech} + P_{b\_elec} \quad (9)$$

The mechanical component of brush loss is constant for all test run, but the electrical component of brush run varies with excitation current. Total brush loss value at mechanical loss heat run is used for finding windage loss value and at rated output loss heat run value is used for efficiency calculation.

(c) Windage loss
Windage loss (P_w) is mainly caused by ventilation and mechanical friction. It is the constant loss for all test. For calculating this loss, machine is run at mechanical loss heat run (rated speed with no load and no excitation) and the total loss is measured. The subtraction of guide bearing loss (P_{GB}) and brush loss (P_b) from total loss at mechanical loss heat run gives the windage loss.

$$P_w = P_1 + P_2 - P_{GB} - P_b \quad (10)$$

The windage loss at rated output loss heat run is used for efficiency calculation, which is same for all test run.

(d) Rotor copper loss
The rotor copper loss (P_r) is obtained for core loss heat run, copper loss heat run and rated

power output loss heat run and can be calculated as,

$$P_r = I_f^2 R_{f(\theta)} \tag{11}$$

Where, I_f is excitation current at no load test and $R_{f(\theta)}$ is rotor direct resistance, obtained from commissioning report, converted to reference temperature, θ. This can be converted as,

$$R_{f(\theta)} = \frac{(235 + T_s)}{(235 + T_1)} R_1 \tag{12}$$

Where, R_1 is resistance at temperature T_1 and T_1 is reference temperature. The rotor copper loss at rated output loss heat run is calculated and use for efficiency calculation.

(e) Excitation system loss
Excitation system loss (P_{ex}) consists of two parts, one is for no load loss and another is for rated load loss. Both are obtained from technical document. The intermediate loss is obtained by using the relation,

$$P_{ex(atxload)} \propto I_{fatx} V_{fatx} \tag{13}$$

where, I_{fatx} is excitation current at that load and V_{fatx} is excitation voltage at that load. The excitation system loss at rated output loss heat run is used for efficiency calculation.

(f) Stator core loss
On the basis of operation mode, loss can be separated into stator core loss (P_{FE}), rotor windage copper loss (P_r) and windage loss (P_w). The stator core loss in no load test run is calculated as,

$$P_{FE} = P_1 + P_2 - (P_r + P_w + P_{GB} + Pb) \tag{14}$$

Here, all data used are from core loss heat run. The stator core loss value proportionate to square of armature winding current to calculate the stator core loss at rated output loss heat run, which is used for efficiency calculation.

(g) Stator winding copper loss
The stator winding copper loss (P_s) can be calculated as,

$$P_s = 3 I_a^2 R_{s(\theta)} \tag{15}$$

Where, I_a is average armature current during test run and $R_{s(\theta)}$ is stator winding resistance, obtained from commissioning report, converted to reference temperature, θ.

$$R_{s(\theta)} = \frac{(235 + T_s)}{(235 + T_{s1})} R_1 \tag{16}$$

Where, R_1 is resistance at temperature T_1 and T_{s1} is reference temperature. This is calculated at copper loss heat run and rated output loss heat run. The stator winding loss at rated output loss heat run is used for efficiency calculation.

(h) Stray load loss
Stray load loss (P_{LL}) at short circuit run can be calculated as

$$P_{LL} = P_1 + P_2 - (P_r + P_w + P_{GB} + P_b + P_s) \tag{17}$$

Here, all data used are from copper loss heat run. The stray load loss is proportionate to square of armature winding current to calculate stray load loss at rated output loss heat run , which is used for efficiency calculation.

The total loss (P_{SL}) in segregated loss method is calculated as,

$$P_{SL} = P_{GB} + P_w + P_b + P_r + P_{ex} + P_{FE} + P_s + P_{LL} \tag{18}$$

Here, all the data used are of rated output loss heat run test or equivalent. Guide bearing loss and windage loss is the constant loss for a machine, other losses are variable losses.
The generator efficiency (η_{G2}) by segregated loss method is calculated as,

$$\eta_{G2} = \frac{P_0}{(P_0 + P_{SL})} \tag{19}$$

2.3.3 Weighted efficiency

If the weightage value at x_1, x_2, x_3, x_4 load is given as w_1, w_2, w_3, w_4 respectively, in the contract, and the corresponding measured efficiency values are η_1, η_2, η_3, η_4 respectively then, the weighted efficiency is given as,

$$\eta_{wG} = \frac{w_1 \times \eta_1 + w_2 \times \eta_2 + w_3 \times \eta_3 + w_4 \times \eta_4}{w_1 + w_2 + w_3 + w_4} \tag{20}$$

3. Apparatus arrangement

For the measurement of flow rate of coolant at guide bearing and air cooler, four calibrated magnetic flow meters are placed at inlet pipe. For measurement of inlet and outlet coolant temperature, 8 calibrated thermometers are placed at inlet and exit of cooling water pipe. The Figure: 3 shows the arrangement of magnetic flow meter and PT100s thermometer placement at cooling water pipes. Magnetic flow meter should be placed in a straight section and the length from bend to inlet side of magnetic flow meter should be more than ten times its diameter. The length of section from outlet side of magnetic flow meter to another side bend should be more than five times its diameter.

Figure 3: Flow meter and thermometer arrangement at cooling water pipes

For the measurement of surface heat loss from upper cover, side and top cover of slipping ring room, the surface temperature thermometer and ambient temperature thermometer are placed as shown in Figure 4. The ambient temperature thermometer should be at one meter away from surface. The surface temperature thermometer should be placed on surface covering by adhesive tape.

For the heat loss measurement from the side wall, the surface and ambient temperature thermometer are placed as shown in Figure 5.

Similarly, for lower cover, surface heat loss measurement, the surface temperature thermometer and ambient temperature thermometer are placed as shown in figure 6.

The list of surface and ambient temperature thermometer placement is shown in table 1.

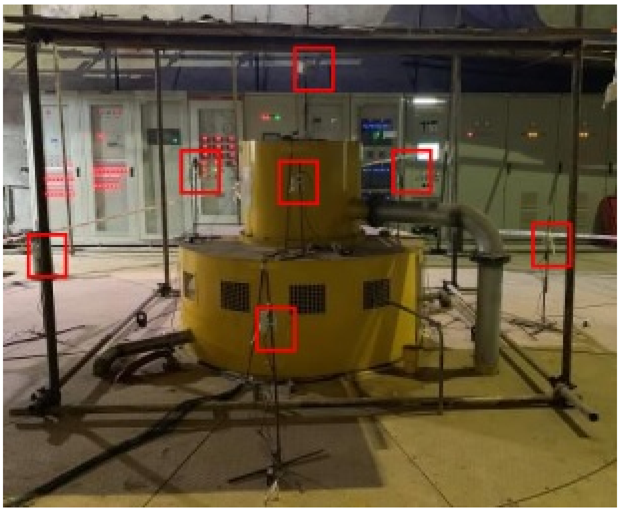

Figure 4: Surface and ambient temperature thermometer placement at upper surface

Figure 5: Surface and ambient temperature thermometer placement at upper surface

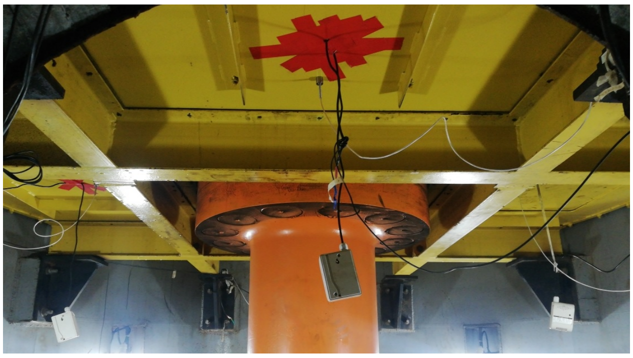

Figure 6: Surface and ambient temperature thermometer placement at lower cover surface

The data from all measuring instruments were brought to junction box, then from junction box to power transmitter and from power transmitter to data picker

Table 1: Surface and ambient temperature thermometer list

Location	Surface temperature thermometer	Ambient temperature thermometer
Upper cover	4	4
Slip ring room side	4	
Slip ring room top	5	5
Bottom cover	4	4
Side wall	4	4
Total	21	17

at computer.

List of the equipment used for generator efficiency measurement in UT3A HEP is tabulated in table 2.

Table 2: List of equipment used in generator efficiency measurement of UT3A

Instruments	Model	Range	Quantity
Data acquisition	NICDAQ9147	—	1
Power transmitter	FPW - 301	± 288w	1
Surface temperature sensor	SBW - D - 100T	-50 ∼ 100°C	21
Ambient temperature sensor	WZYB	-50 ∼ 100° C	17
Magnetic flow meter	LDG – MIK	$0 \sim 318$ m^3/hr	2
Magnetic flow meter	EFM8301	$0 \sim 30$ m^3/hr	2
PT100s	SBWZ2480	$0 \sim 50°$ C	8

Power meter measures the active power output.

4. Result and Discussion

4.1 Test Condition

The generator efficiency test consists of 5 runs, as 4 thermo-equilibrium periods: mechanical loss heat run , core loss heat run , copper loss heat run and rated output loss heat run, and 1 period of unit load adjustment by steps. Readings are taken at thermal equilibrium conditions, when temperature change remains within 1 K/hr. The calculation below are taken from the case of UT3A HEP.

4.2 Efficiency by total loss method

The table 3 shows the total heat taken by cooling water. Vertical column shows different heat run test and horizontal rows shows loss value taken by coolant.

Table 3: Heat loss taken by coolant calculation, unit (kw)

Items	mech. loss run	core loss run	copper loss run	rated output run
Air Cooler	217.0882	362.4088	332.8760	559.5962
UGBC	6.3630	6.6173	7.3162	7.2683
LGBC	22.9466	25.6708	19.8323	24.1141
TBC	30.9665	30.7839	27.8879	20.4817
Total(KW)	277.3643	425.4808	387.9129	611.4603

Table 4 shows the total heat dissipated from the surface. Vertical column shows different heat run test and horizontal rows shows loss value dissipated from different surfaces. The negative sign for generator side wall loss at copper run loss and rated output run loss means heat gain by surface from the surrounding air. It is due to increase in ambient temperature during this test due to rise in temperature of excitation transformer. As, Ambient temperature sensor is placed very close to excitation transformer. The temperature difference was 0.34 and 0.31 Kelvin respectively.

The external loss includes the excitation system loss. At rated load, the excitation system loss is 6.2609 KW, taken from technical document.
The rated generator output is 29.99MW. The total loss, sum of all loss, is equal to 619.0982KW. The generator efficiency by total loss method is calculated as,

$$\eta_{G1} = \frac{29.99}{(29.99 + 0.619098)} = 97.98\%$$

4.3 Efficiency by segregated loss method

Table 5 shows the heat loss in individual components. Vertical column shows different heat run test and horizontal rows shows loss in different components.

At rated load, generator output is 29.99MW. The total loss at rated output is 624.3209KW. The generator efficiency by segregated loss method is calculated as,

$$\eta_{G2} = \frac{29.99}{(29.99 + 0.6243209)} = 97.96\%$$

Table 4: Heat loss from surface dissipation , unit (kw)

Items	mech. loss run	core loss run	copper loss run	rated output run
slip ring top cover loss	0.1155	1.1490	0.1418	0.2020
slip ring side cover loss	0.2996	0.3533	0.3487	0.4315
air supply top cover loss	0.0409	0.0480	0.0457	0.0532
Generator top cover loss	0.5128	0.8546	1.0255	0.2103
Generator side wall loss	0.9908	0.4279	-0.7656	-0.6981
Generator bottom cover loss	0.0396	0.1593	0.1672	0.1781
Total	1.9992	1.9921	0.9633	1.3770

Table 5: Heat loss in individual components, unit (kw)

Item	mech. loss run	core loss run	copper loss run	rated output run
Windage loss	217.7874	-	-	217.7874
Bearings loss	60.2761	63.0721	55.0369	51.8641
Field copper loss	-	27.0955	22.1801	111.6237
Core loss	-	117.4087	-	134.7475
Stator copper loss	-	-	84.9780	89.6944
Stray load loss	-	-	8.9060	9.4003
Brush loss	1.3	2.1093	2.0322	2.9426
Excitation system loss	-	-	-	6.2609
Total (KW)	-	-	-	624.3209

4.4 Verification of Calorimetric method

The generator efficiency by total loss method is 97.98% and by segregated loss method is 97.96%. The absolute error is 0.02%. Since the absolute error is very less, less than 0.05%, the calculation result is consistent and reliable.

4.5 Load efficiency curve deduction

For load efficiency curve deduction, the machine was run for nine different loads as 5.99, 9.25, 12.26, 15.48, 18.75, 21.49, 24.76, 27.50, 29.74 MW at 0.85 power factor. The generator efficiency was calculated by using segregated loss method and found the efficiency for each load as 93.17, 95.33, 96.32, 96.95, 97.35, 97.57, 97.77, 97.90, and 97.97 % respectively. Figure 7 shows the generator efficiency versus generator output curve.

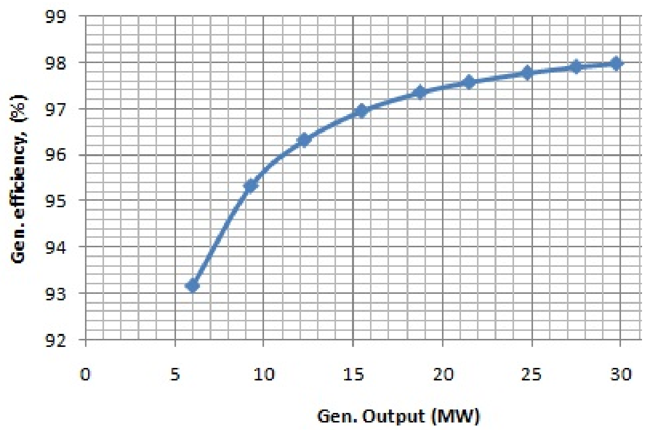

Figure 7: Generator efficiency versus generator output curve

From this data, fourth order polynomial curve fitting equation is obtained as,

$$Y = -(4.3745E-07)x^4 + (3.8772E-05)x^3 - (1.2975 E-03)x^2 + (2.0160E-02)x + (9.9966E-01)$$

Where, x is generator efficiency and y is generator output value.

4.6 Weighted efficiency

By using above generator efficiency formula, the efficiency value are calculated at 60%, 70%, 80% and 100% load. For given load, corresponding weighted values of efficiency in contract are given 10, 20, 40, 30 respectively. The calculation of weighted efficiency is presented in table 6.

Table 6: Weighted generator efficiency

Item	100% load	80% load	70% load	60% load
Gen. o/p	30.5	24.4	21.35	18.3
Gen. eff.	97.93%	97.75%	97.53%	97.28%
weighted factor	30	40	20	10
weighted efficiency				97.71 %

5. Conclusion

This paper enlist the mathematical formulation of generator efficiency measurement using calorimetric method as per IEC 60034-2-1. It presents the apparatus arrangement for two methods, total loss method and segregated loss method, which were used to calculate the generator efficiency of UT3A HEP.
The generator efficiency was found 97.98 % by total loss method and 97.96 % by segregated loss method. Both methods gave the consistent result with 0.02% absolute error. The weighted efficiency based on weighted value of contract was found 97.71%, which is more than guaranteed value i.e. 97% .Which means the calculation result is reliable. Furthermore, the installation of measuring instruments were found very simple and easy for this method. Thus, the calorimetric method is reliable and easy method for calculating the absolute efficiency of generator for higher capacity.

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