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Enhancement of Energy Efficiency of Hydro Turbine Generators by Energy Conservation Techniques

Rajashekar P Mandi* and Udaykumar R Yaragatti**

This paper describes the results of enhancing energy efficiency of hydro turbines by implementing the energy conservation measures for hydro turbine generators. The procedure for evaluating the on-line performance of generators is discussed. The energy saving in generators by maintaining optimum generator terminal voltage, by reducing the stator winding temperature, by improving the performance of coolers and reducing the excitation loss by appropriate tuning of excitation system are enumerated in detail with case studies. The implementation of energy conservation measures has a techno-economic feasibility with a payback period of 1–5 years.

Keywords: *Generator, Hydro turbine, Energy efficiency, Stator copper loss, Rotor copper loss, Generator cooling, Generator excitation.*

1.0 INTRODUCTION

The power generation has increased from 1360 MW during 1947 to 200 GW as on March 31st 2012 [1]. The total installed capacity of hydro power plant is 39 GW that forms 19.5 % of total installed capacity. Hydroelectric generation is a continuous production process in which hydraulic energy is converted into mechanical energy and finally converted into electric energy. It is a clean, renewable and low cost of energy production. Energy generation through hydropower makes great sense because this helps in reduction of fossil or nuclear fuel burning. The hydraulic energy is a valuable natural resource, and increasing the efficiency of hydropower production is a long-term goal in the field of hydropower engineering because it greatly contributes to the economy and environment. Hydro stations need very less number of auxiliaries to run the plant and its auxiliary power will vary between 0.5 and 0.7 % of gross energy generation [2]. The major hurdls in implementing the hydro stations are site-specific and stochasticity in nature.

At present, many of the hydro stations are operating as run of the river plant due to non-availability of water source and regulations laid for water for irrigation purpose. This had caused lowering of plat load factor of hydro power stations. Many of the hydro stations are not provided with water flow measurement and are not evaluating the performance of the plants. The energy audit study in more than 55 hydro power plants had shown that there are ample scopes for improving the performance of hydro turbine generators and also reduction in auxiliary power.

2.0 GENERATOR

In most of the hydro power stations, the generator (Indian manufactured) terminal voltage will be

*Energy Efficiency and Renewable Energy Division, Central Power Research Institute, Bangalore, India. E-mail: mandi@cpri.in
**National Institute of Technology Karnataka, Surathakal, Mangalore, India. E-mail: udaykumarry@yahoo.com

11 kV for the generators. Few imported units have different generator terminal voltage of 13.8 kV also. This terminal voltage will be stepped up to grid voltage (i.e. 132 kV, 220 kV or 400 kV) by either one three-phase generator transformer (usually surface-based power plants) or three numbers of single-phase generator transformers (usually underground power plants).

The energy input (Wh) to turbine is hydraulic energy and can be computed as [3]:

$$E_h = \int_{t_1}^{t_2} g\rho HQ.\,dt \tag{1}$$

where g is acceleration due to gravity in (m/sec^2), ρ is density of water in (kg/m^3), H is net head in (m), Q is mass flow of water (m^3/sec), t_1 is initial time and t_2 is final time in (h).

The energy output (Wh) from turbine generator is the electrical energy and is measured as

$$E_O = \int_{t_1}^{t_2} P_O.\,dt \tag{2}$$

where P_O is the output power measured at generator output terminals by using power analyser in W.

The combined turbine and generator efficiency (%) can be computed by measuring hydraulic energy at water turbine input and electrical energy output at generator terminals. But it is slightly difficult to compute either turbine or generator efficiency individually. The hydro turbine-generator efficiency (overall efficiency) can be computed by [4,5]

$$\eta = \frac{E_O}{E_h} = \frac{\int_{t_1}^{t_2} P_O.\,dt}{\int_{t_1}^{t_2} g\rho HQ.\,dt} \tag{3}$$

In order to evaluate the energy generator efficiency (%), the loss evaluation method is adopted and is computed as:

$$L_{iron/core} = \frac{V_{operating} \times F_{operating} \times L_{iron/core-design}}{V_{design} \times F_{design}} \tag{4}$$

where P_{out} is the power output at generator terminals in MW, L_{sc} is stator copper loss in kW, L_{rc} is rotor copper loss in kW, L_{Ex} is excitation loss in kW, L_{stray} is stray load loss in kW, $L_{f\&w}$ is the friction and windage loss in kW and $L_{iron/core}$ is the iron or core loss in kW.

1. The stator copper loss (kW) is proportional to square of the stator current and winding resistance and is computed as:

$$L_{sc} = \frac{(I_R^2 + I_Y^2 + I_B^2) \times R_a}{1000} \tag{5}$$

where I_R, I_Y and I_B are stator current, respectively, for R-phase, Y-phase and B-phase in Ampere, R_a is the actual (working) stator winding resistance which will be extrapolated from the design winding resistance (Ω/phase) at design temperature (i.e. 20^{o}C) and is computed as:

$$R_a = R_d = \left(\frac{234.5 + T_a}{234.5 + T_d}\right) \tag{6}$$

where R_d is stator winding resistance at design temperature in Ω/phase, T_d is stator winding temperature at design value in degree centigrade (°C) usually at 20°C, T_a is the measured or actual stator winding temperature in degree centigrade (°C)

2. Generally, three types of field excitation systems are being used:

   (a) **Rotary magnetic system,** where exciter will be mounted on the same shaft of generator and the pilot exciter will excite the exciter and the main exciter will provide excitation for the field. The rotor copper loss (kW) is computed as:

$$L_{sc} = \frac{I_f \times V_f}{1000} \tag{7}$$

   where I_f is the field current (DC) in Ampere and V_f is the field excitation voltage (DC) in Volts.

   (b) **Static excitation system,** where the power will be tapped at generator bus and the voltage will be stepped down to either 600 V or 400 V by the excitation transformer. The total excitation loss (kW) will be measured by measuring voltage, current and power factor at excitation transformer primary side by using power analyzer. The total excitation loss including rotor copper loss is computed as:

$$IL_R = \frac{V_R \times I_R \times PF_R + V_Y \times I_R \times PF_R \times + V_B \times I_R \times PF_R}{1000} \tag{8}$$

where V_R, V_Y and V_B are generator terminal phase voltage, respectively, for R-phase, Y-phase and B-phase in Volts, I_R, I_Y and I_B are excitation current at primary side of Excitation transformer, respectively, for R-phase, Y-phase and B-phase in Ampere and PF_R, PF_Y and PF_B are power factors, respectively, for R-phase, Y-phase and B-phase.

(c) The rotor copper loss is computed in a similar way as given in above equation (4).

(d) The excitation loss (kW), i.e. conversion loss from AC to DC is computed by

$$L_{EX} - TL_{EX} = L_{RC} \tag{9}$$

(e) Third type is **brushless excitation system;** in this, rotor copper loss (kW) is evaluated by:

$$L_{YC} = \frac{I_f^2 \times R_f^2}{1000} \tag{10}$$

where I_f is the field current (DC) in Ampere and R_f is the field resistance in at operating temperature which can be extrapolated by using equation (3).

Stray load loss is difficult to measure on-line during performance test and will be taken as constant based on the design value.

It is difficult to measure the friction and windage loss on-line and will be taken as constant based on the design value.

The iron or core loss will be assumed approximately directly proportional to the frequency and voltage and is computed as

$$L_{iron/core} = \frac{V_{operating} \times F_{operating} \times L_{iron/core-design}}{V_{design} \times F_{design}} \tag{11}$$

where $V_{operating}$ is operating phase or line voltage in Volts, V_{design} is design phase or line voltage in Volts, $F_{operating}$ is operating frequency in Hertz and F_{design} is design frequency in Hertz, i.e. 50 Hz.

2.1 Performance Test

The performance test is carried out by maintaining the load nearly constant at full load or part load for a period of 60 minutes (one hour) and logged all the performance parameters simultaneously throughout the test period of 60 minutes. The variations in critical parameters are monitored. The power supply parameters at generators are logged in the power analyzers. The field current and field voltage, stator winding and core temperature readings are recorded from the control desk. The auxiliary power is logged at primary side of UAT by using power analyzer. The power (for static excitation system) at excitation transformer primary side is measured by using power analyzer and the power at GT output is also measured through power analyzer. All these power measurements were carried out simultaneously during the performance test for a period of one hour by power analyzers of having same make and same accuracy level.

2.2 Case Study 1

In a case study at hydro power plant, four numbers of 120 MW generators are studied for energy conservation. The performance results of one of the four generators are discussed. The generator terminal voltage is 13.8 kV and is stepped up to 400 kV through three numbers of single-phase generator transformers of 50 MVA for each unit. The rated full load stator current is 5690 A.

The generator cooling is provided through ventilating air circulation. Six surface air coolers are mounted on generator stator frame. Flow of cooling air through the machine is maintained partly by two opposing axial flow fans, mounted on the rotor rim and partly by the centrifugal pumping action of the rotor. The axial flow fans force the air into the air gap and the space between the poles and out through ducts in the core into the stator frame. Some of the air passes by parallel paths over the stator end windings through holes in the stator top and bottom rings into the stator frame. The centrifugal action created by the rotor draws the air into the rotor center through holes in the upper disc and the air is forced out through air ducts in the rotor rim into the air gap and the pole gaps and finally forced out through ducts in the core into the stator frame. Four numbers of surface air coolers are placed around the outside of the stator frame for each generator. The porTable water passes through the surface air coolers and the water cools the air passing through the cooler. The air coolers are provided with 90/10 copper-nickel alloy tubes wound with copper wire fixed in an MS frame. The porTable water is again cooled in the shell and tube heat exchangers. Each unit is provided with one heat exchanger along with one raw water pump and one porTable water pump. One standby heat exchanger along with raw and porTable water pumps are provided in case of failure of unit heat exchangers [6].

The measured energy, voltage, current and computed load and voltage unbalance between 3-phases at generator output during the performance tests are presented in Table 1. The voltage at generator terminal during test 1 was on lower side in the range of 13.35 kV–13.37 kV, which is lower than the design value of 13.8 kV due to lower grid voltage at a reduced terminal voltage, the stator copper loss will be more. The voltage unbalance between 3-phases is on lower side of 0.09–0.15 %. The current unbalance between 3-phases is in the range of 2.44–2.95 % and is also normal but it depends on the grid condition.

The measured frequency, power, power factor, stator winding temperature, circulating water inlet and outlet temperature values are given in Table 2. Figure 1 gives the variation of stator winding temperature during performance test. The stator winding temperature is increased from 52°C to 55°C during Test 1 because the unit

TABLE 1

MEASURED VOLTAGE, CURRENT, AND VOLTAGE AND CURRENT UNBALANCE BETWEEN 3-PHASES AT GENERATORS

Sl. No.	Energy (MWh/h)	Terminal voltage (kV)				Stator current (A)			
		RY	YB	BR	Un(%)	R	Y	B	Un(%)
1	45.68	13.37	13.37	13.35	0.09	2077.58	2153.04	2191.34	2.95
2	103.24	13.81	13.81	13.78	0.14	4603.22	4742.89	4809.00	2.44
3	117.12	13.80	13.80	13.77	0.15	5132.19	5297.62	5367.18	2.53

TABLE 2

MEASURED FREQUENCY, POWER FACTOR, POWER, STATOR WINDING TEMPERATURE, FIELD VOLTAGE AND CURRENTS AT GENERATORS

Sl. No.	Fre-quency, Hz	Power, MW	Power factor	Stator Winding temp. avg., °C	Cold air temp,°C	Hot air temp., °C	Field current, A	Field voltage, V
1	49.54	45.73	0.92	53.83	25.00	45.33	713.33	71.63
2	49.27	105.07	0.93	80.50	26.67	54.00	1272.17	135.48
3	49.42	119.22	0.95	90.50	28.00	57.67	1314.50	143.96

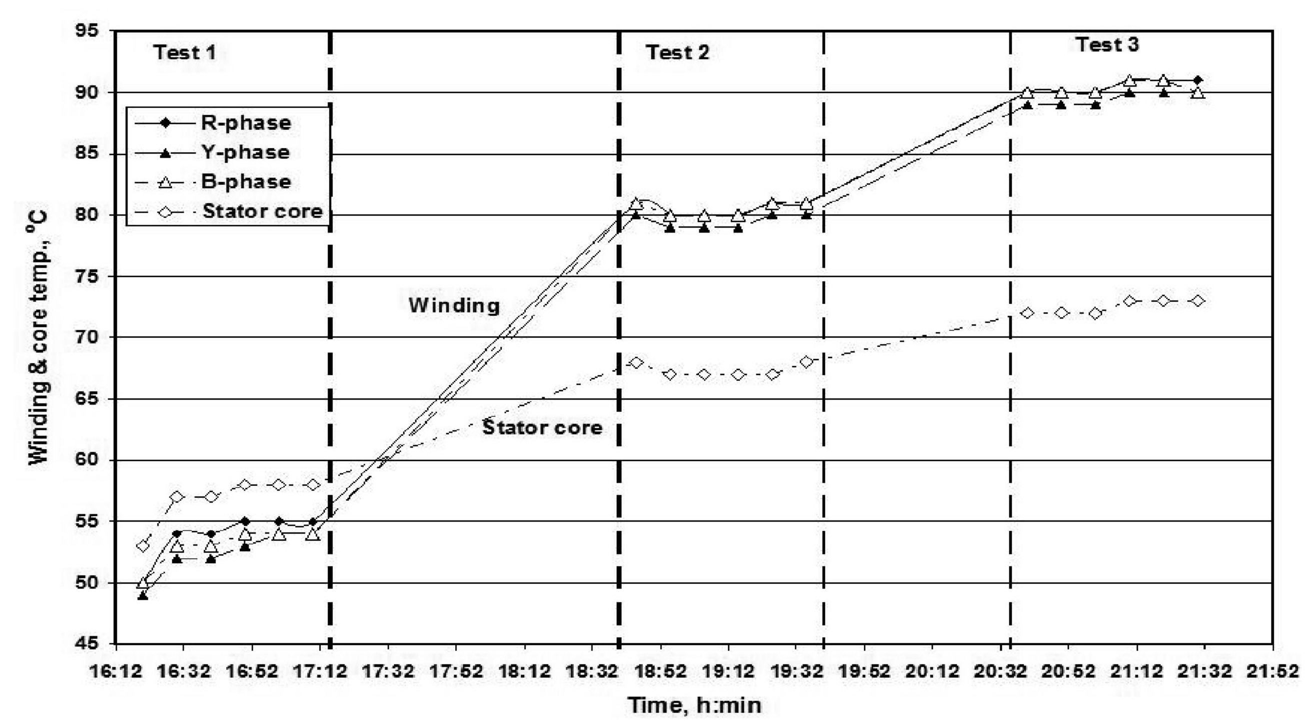

FIG. 1 VARIATION OF STATOR WINDING AND CORE TEMPERATURE

was running at lower load just before the start of test. Therefore, the stator winding temperature is increased. During Test 2, the winding temperature is increased from 65°C to 76°C and during Test 3, the stator winding temperature is increased from 83°C to 86°C. Similarly, the stator core temperature also increased from 50°C to 55°C during Test 1, increased from 79°C to 81°C during Test 2 and increased from 89°C to 92°C during Test 3. It can be seen from the Figure that the stator winding and core temperatures are increased as the plant load increases due to increased stator and rotor copper loss. The stator winding and core temperatures are on par with design value of rise in 75°C above ambient temperature. Figure 2 gives the variation of cold air and hot air temperature during performance test. It can be seen from the Figure that as the plant load increases the hot air and cold air temperatures are increased and the temperature drop across cooler also increased. The cold air temperature at surface air coolers is slightly on higher side, may be due to scaling in tubes or blockage of tubes [7,8]. However, the air outlet temperature is lower than the maximum limit of 41.4°C at air inlet temperature of 67°C. The drop in temperature across surface air coolers is varying between 11°C–18°C. The cleaning of tubes of surface air coolers to improved the effectiveness of cooler which reduced the winding temperature. This reduced the *energy consumption 3.4 MWh/month by reducing winding temperature by about 3°C.*

The computed apparent power, plant load factor, stator copper loss, total loss and generator efficiency are given in Table 3. Figure 3 gives the variation of active and reactive power during the performance test.

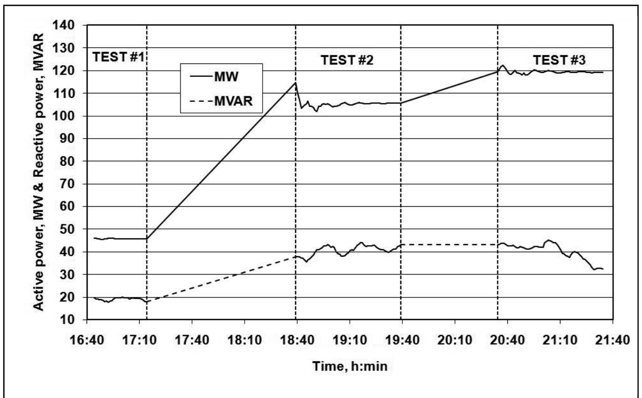

FIG. 2 VARIATION OF COLD AND HOT AIR TEMPERATURE

TABLE 3

PERFORMANCE RESULTS OF GENERATORS

Sl. No.	Apparent power (MVA)	Plant load (%)	Stator copper loss (kW)	Rotor copper loss (kW)	Total Excitation loss (kW)	Total loss (kW)	Gen eff. (%)
1	49.434	33.63	75.20	51.10	73.51	1302.05	97.23
2	113.104	77.26	399.08	172.35	223.50	1786.47	98.30
3	126.108	87.66	512.82	189.24	243.40	1921.13	98.39

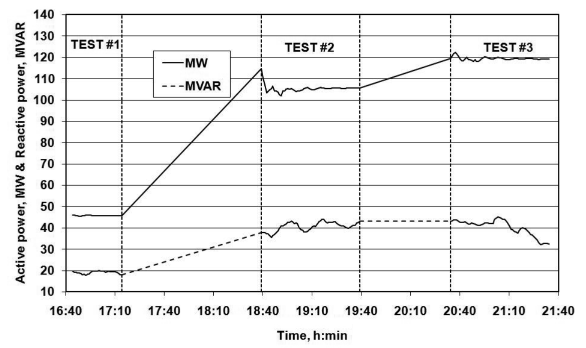

FIG. 3 VARIATION OF POWER AT GENERATOR DURING PERFORMANCE TEST

The generator is running almost at unity power factor, and reactive power sharing by this generator is less but the power factor on this machine is derived from the grid conditions. Therefore, the increased loss in stator winding due to poor power factor is less. The load on generator is maintained nearly constant for a period of one hour for each test. About 5 minutes is taken for settling period while changing the load. The energy and all other parameters for each test are taken for 55 minutes and extrapolated for a period of one hour.

The stator copper losses at generator are computed for all three tests in the range of 75.20 kW–512.80 kW. The losses are on lower side, may be due to lower winding temperature and operating at almost unity power factor.

The rotor copper losses at generator are computed based on the measured excitation voltage and current at generator for three tests and are varying in the range of 51.10 kW–189.24 kW. The rotor copper losses are on lower side because all the generators are operating at unity power factor always. At unity power factor, the excitation power required will be less in generators. The total excitation losses (from AC power at excitation transformer input to DC power at field windings) are measured by using power analyzers and are varying in the range of 73.51 kW–243.40 kW. These total excitation losses are also lower than the design value of 250 kW at 0.90 power factor. These losses are on lower side, may be because of operating the generators at unity power factor. At unity power factor, the excitation power required will be less in generators.

The generator efficiencies for three tests are computed and are in the range of 97.23 %–98.39 %. The generator efficiencies are on par with design values of 98.42 % at 0.90 PF and 98.49 % at unity PF.

2.3 Case Study 2

In a case study to evaluate the performance of hydro power station generators, three generators of 35.1 MW for water turbines are considered. The generator cooling is provided through ventilating air circulation. Eight air coolers are mounted on generator stator frame and the cooled air is supplied into the space between coolers and generator barrel from which part this air will return to the fan below the rotor through the ducts in the foundation below the air coolers and the remainder of the cooled air will return in the fan above the rotor. The air is then circulated through the closed system by the combined action of the rotor poles and of the fans. The air in the cooler is cooled by the circulating water. The air coolers are provided with 90/10 copper-nickel alloy tubes wound with copper wire fixed in an MS frame. The generator terminal voltage is 11 kV and the rated full load stator current is 2050 A. 11 kV is stepped up to 132 kV through three single–phase generator transformers for each unit.

Performance tests were conducted on generators of units 1–3 at different load conditions varying from 8 to 32 MW.

Figure 4 shows the variation of stator copper loss with plant load factor during performance test. Figure 5 shows the rotor copper loss with plant load factor. Figure 6 shows the variation of stator winding temperature with plant load factor during performance test. The temperature drop across generator air coolers is given in Figure 7. The generator efficiency is computed and is presented in Figure 8. Annex-1 shows Photographs of inservice hydro generators under test. The energy conservation measures from the detailed energy audit study are as follows:

(a) The load unbalance between 3-phases is computed by taking the deviation in current at all 3-phases. The load unbalance between 3-phases at stator terminal varies between 9.19 % and 12.11 % at Unit #1, 7.16 % and 10.80 % at Unit #2 and 7.39 and 10.87 % at Unit #3. The load unbalance is on higher side and the increased stator copper loss due to load unbalance is varying between 0.05 kW and 0.27 kW. The increased load unbalance also reduced the generator capacity. The load unbalance is primarily dependent on the loading pattern of grid and little control action from individual plant.

(b) The maximum stator winding temperature was varying in the range of 58.1°C–75.3°C at Unit #1, 69.3°C–80.1°C at Unit #2 and

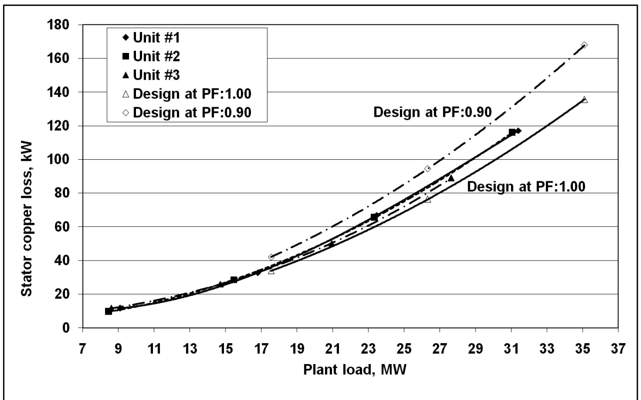

FIG. 4 VARIATION OF STATOR COPPER LOSS WITH PLANT LOAD

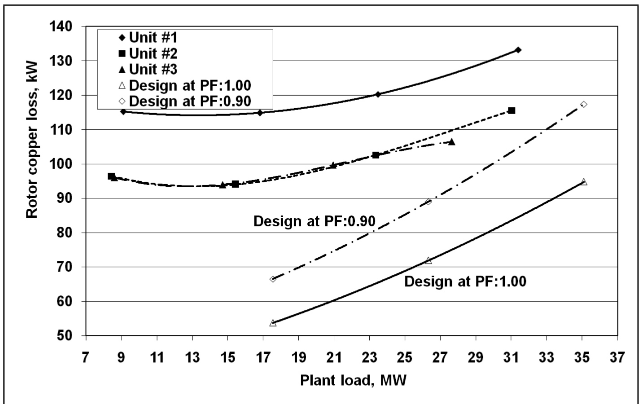

FIG. 5 VARIATION OF ROTOR COPPER LOSS WITH PLANT LOAD

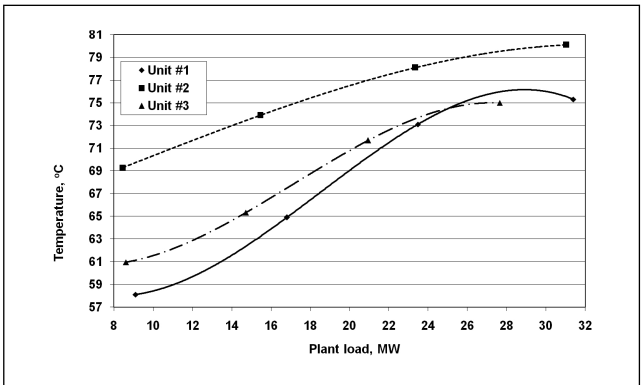

FIG. 6 VARIATION OF MAX. STATOR WINDING TEMP WITH PLANT LOAD

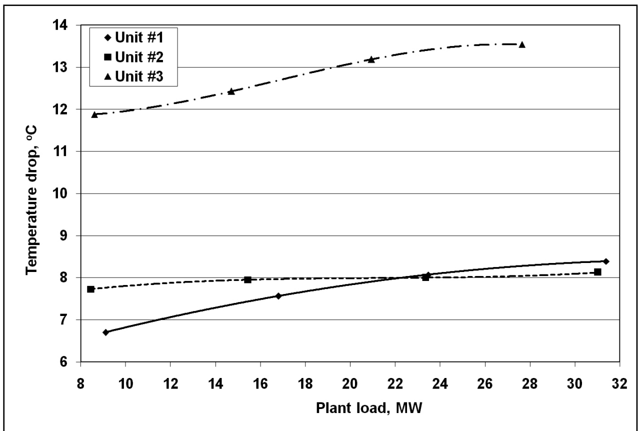

FIG. 7 VARIATION OF TEMPERATURE DROP IN AIR COOLER WITH PLANT LOAD

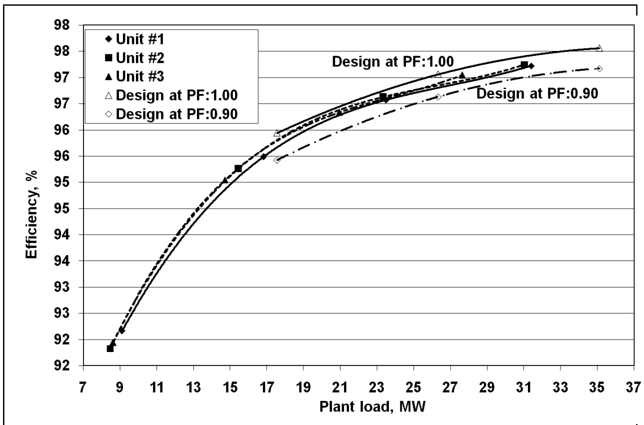

FIG. 8 VARIATION OF GENERATOR EFFICIENCY WITH PLANT LOAD

60.96°C–75.0°C at Unit #3. The overhauling of air coolers and replacement of blocked tubes reduced the winding temperature below 75°C. This had reduced the *energy consumption by 5.9 MWh/month*.

(c) The temperature drop across air coolers was varying between 6.7°C and 8.93°C at Unit #1, 7.73°C and 8.13°C at Unit #2 and 11.88°C–13.54°C at Unit #3. The performance results of air coolers of Units 1 and 2 are poor and that of Unit #3 are normal.

(d) The terminal voltage at generator was varying between 10.4 kV and 10.9 kV (variation of –5.45 % to –0.91 %) and is very low compared to design value of 11 kV. The grid voltage (i.e., GT output) is varying between 130 kV and 136 kV (variation of –1.52 % to +3.03 %) and is normal. The generator transformer tap was in the 2nd position and was changed to the 3rd tap that had increased the generator terminal voltage by 2.5 %. Changing of generator tap to the 3rd position had reduced the *stator copper loss by 14.5 MWh/month* with same power output and also enhanced the current carrying capacity of generators by 3.18%.

(e) The overall stator copper losses are lower than the design value at 0.90 PF (design value) and higher than the design value at Unity Power Factor (UPF). Most of the time, all the generators operate near to unity power factor (UPF). The stator copper losses are higher due to higher load unbalance between three phases and slightly higher winding temperature and the losses are varying between 9.55 kW and 117.09 kW.

(f) The total excitation loss was varying in the range of 115.2 kW–133.2 kW at Unit #1, 96.46 kW–115.56 kW at Unit #2 and 96.0 kW–106.46 kW at Unit #3. The excitation losses were on higher side compared to design values. The excitation losses can be controlled by proper tuning of Analogue Voltage Regulator (AVR) system. The present excitation system can be replaced with new static Digital Voltage Regulator (DVR) excitation system which will reduce the excitation losses from average value of 124.38 kW to 95.94 kW. This measure reduces the *energy consumption by 61.4 MWh/month.*

(g) The generator efficiencies were varying between 92.16 % and 97.22 % at Unit #1, 91.82 % and 97.25 % at Unit #2 and 91.94 % and 97.04 % at Unit #3. The generator efficiencies are slightly lower than the design value.

3.0 CONCLUSIONS

At lower generator terminal voltage, increases the stator copper loss but very high voltage will strain the stator winding insulation that reduces the life of generators. Setting the generator voltage near to design value will reduce the stator copper loss. The unbalanced stator current increases the stator copper loss and reduce, the capacity of generators. The higher winding temperature increases the stator copper loss and the winding temperature can be reduced by cleaning the surface air coolers. Optimizing the stator water flow through coolers by circulating water pumps will reduce the energy consumption. Tuning the static excitation system will reduce the excitation losses and replacement of AVR by DVR for static excitation system will reduce the energy losses in excitation system.

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ANNEX-1

VIEW OF GENERATOR-1

VIEW OF GENERATOR-2