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Improvement of Energy Efficiency of Boiler Feed Pumps in Thermal Power Plants through Intelligent Prediction and Operational Optimization

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This paper describes the various methods for enhancing the energy efficiency of Boiler Feed Pumps (BFP) in thermal power plants. The specific auxiliary power used by BFPs vary between 2.2 to 3.6 % of the total gross energy generation for units ranging from 30 MW to 800 MW units. The average specific power used by BFPs for 210 MW plants is 2.4 to 3.2 % of gross energy generation. The energy efficiency improvement of BFPs by reducing the re-circulation flow, pressure drop across feed water circuit elements, enhancing overall efficiency of BFPs, etc., are discussed with case studies. The implementation of energy conservation measures reduce the average auxiliary power used by BFPs for 210 MW plant from average value of 3.6 to 2.3 % of gross energy generation and release an additional power of about 10.9 MU/year for one 210 MW unit.

Keywords: *Energy efficiency, Boiler Feed Pumps, Auxiliary power, pump efficiency, SEC, Energy conservation*

1.0 INTRODUCTION

The total installed power generation capacity in India is about 260 GW, out of which the generation from coal fired power plant is about 56 %. The average auxiliary power used for coal fired thermal power plant is 8.44 % of gross energy generation at an average plant load factor (PLF) of 73.3 % [1]. Among the auxiliary equipment BFPs are the major energy consuming equipment that forms 30 % of total auxiliary power used by thermal power plants [2]. The estimated auxiliary power used for BFPs of coal fired thermal power plants in India is about 4420 MW and average estimated CO_2 emission is about 36 million tonne per year on account of auxiliary power used by BFPs.

The thermal power plant availability & reliability depends largely upon the operational reliability of auxiliary equipment like BFPs and also the capability of the auxiliary system [3]. The auxiliary power consumption is on higher side in Indian power plants as compared to other developed countries due to poor plant load factor, poor coal quality, excessive steam flow, internal leakage in equipment, inefficient drives, lack of operational optimization of equipment, ageing of equipment, hesitation in technology up-gradation, obsolete equipment, design deficiencies, oversizing of equipment, use of inefficient controls, etc. [4]. The auxiliary power consumption of BFPs can be reduced by improving the plant load factor of the plants, by operational optimization, adoption of advanced control techniques and implementation of energy conservation measures [5]. The operating overall efficiency of BFPs is in the range of 54.3 – 73.45 % as compared to design value of 80 %. By improving the overall efficiency of BFPs by average value of 7 – 10 % will reduce the average auxiliary power of BFPs

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by 480 MW and equivalent reduction of CO_2 emission is 3.9 million tonne per year.

Boiler Feed Pumps (BFP) are the major energy consuming equipment which are essential to increase the feed water pressure in a coal fired thermal power plants. In a 210 MW power plant BFP is supplied along with Booster pump which is mounted on the same shaft. The Booster pump increases the feed water pressure from 0.5 – 0.66 MPa (Deaerator pressure) to intermediate pressure of about 1.2 – 1.4 MPa and BFP main pump increases the FW pressure from Booster pump discharge to about 17 – 18 MPa (Drum pressure). In a typical 210 MW power plant, three numbers of multistage pumps with hydraulic scoop coupling to control the feed water flow. Booster pumps are of centrifugal pumps.

Boiler feed pumps are axial split multistage, horizontal, barrel type, high capacity, high speed (about 5000 rpm), centrifugal pumps. There are three BFPs with HT induction motors of 6.6 kV and the motor rating will be of either 4.0 MW or 3.5 MW in a 210 MW power plants [6]. Two pumps will be working continuously and third pump will be stand-by. The feed water flow will be regulated by scoop (fluid coupling) control and 3 element feed control valve station. There are two types of driving systems are used for Boiler Feed Pumps i.e., steam operated turbine drive or motor drive system. Generally in 500 MW above plant size, Turbine (steam operated) Driven BFP (TDBFP) are used because the motor size will be very big of the order of about two numbers of 10 MW size. Starting current of these motors will be very high and influence the voltage and other supply parameters in the network. The auxiliary steam at cold re-heat line will be used to run TDBFP. This steam is already taken part in producing partial output power in High Pressure Turbine (HPT). The overall efficiency of conversion from thermal energy (coal) to hydraulic output at BFP output is higher in case of TDBFP compared to motor driven BFP. The average conversion efficiency of coal to hydraulic power in TDBFP is about 62 % whereas at MDBFP is 26 %. But in 210 MW and lower size units adopt motor driven BFP due to lower operation & maintenance and also to optimize the space utilization.

Figure 1 is the auxiliary power used by different equipment in a 210 MW power plant. The average specific auxiliary power used by BFP is 2.42 % of gross power generation at maximum continuation rating (MCR) and is high compared to design value of 2.28 % at MCR condition.

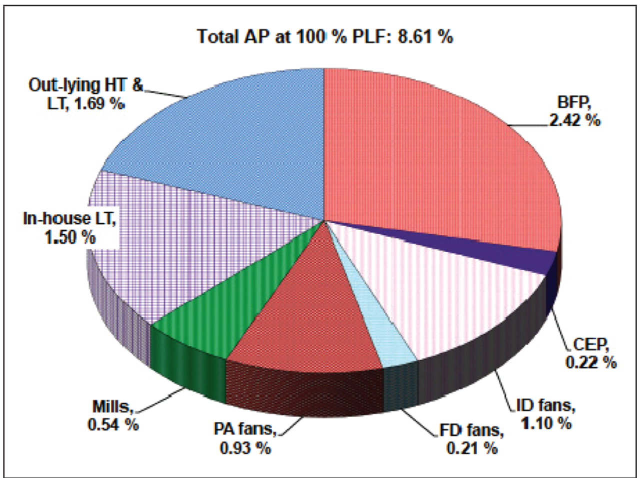

FIG. 1 AUXILIARY POWER OF MAJOR HT EQUIPMENT

2.0 PERFORMANCE EVALUATION OF BFP

Figure 2 is the schematic of FW circuit and the main purpose of BFP is to increase the FW pressure to meet the main steam pressure (superheated steam) at turbine inlet i.e., HPT & IPT. While transferring the state from FW to steam, the feed water has to flow through various elements like HPH, FRS, ECO, Water walls, SH and RH which cause the hydrodynamic resistance for FW flow.

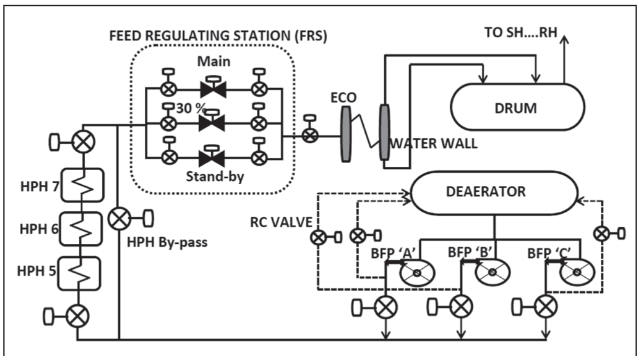

FIG. 2 SCHEMATIC OF FW CIRCUIT

The BFP had to overcome the pressure drop across all these elements. In order to evaluate the performance BFP along with motor, the power loss in motor, pumps, hydrodynamic resistive elements like HPH, FRS, ECO, Water Walls, SH and RH are evaluated.

The BFP motor efficiency is computed based on IEEE standard 112 Method E1 where the magnitudes of five losses like stator copper loss, rotor copper loss, core loss, stray load loss and friction & windage losses are computed [7, 8]. The power loss (kW) in each hydrodynamic resistive element is computed by:

$$L_{FW} = \frac{10^6}{3600}\left[\sum_{i=1}^{i=4}\left(\frac{\Delta P_i \, x \, \overset{o}{m}_{FW}}{\rho_i}\right)_i + \frac{\Delta P_{RH} \, x \, \overset{o}{m}_{CRH}}{\rho_{CRH}}\right] \quad ....(1)$$

Where ΔP_i is pressure drop in feed water across each element i.e., i=1 for HPH, i=2 for feed regulating station, i=3 for Economizer, i=4 for Water walls, & i=5 for SH, $\overset{o}{m}_{FW}$ is the feed water flow at BFP discharge (t/h), ρ_i is the density of feed water at input of each element in (kg/m^3), ΔP_{RH} is pressure drop in steam across Re-heater (MPa), $\overset{o}{m}_{CRH}$ is the steam flow in Re-heater (t/h) and ρ_{CRH} is the density of steam at cold re-heat in (kg/m^3).

The hydraulic power (kW) used for auxiliary steam is computed by:

$$L_{AS} = \frac{P_{AS} \, x \, \overset{o}{m}_{AS} \, x \, 10^6}{3600 \, x \, \rho_{AS}} \quad ....(2)$$

Where P_{AS} is the auxiliary steam pressure which is tapped after superheater through pressure reducing station (PRS) (MPa), $\overset{o}{m}_{AS}$ is the auxiliary steam flow (t/h) and ρ_{AS} is the density of auxiliary steam in (kg/m^3).

The power loss (kW) in pump is computed by:

$$L_{BFP} = \left[\frac{P_{in-BFP} \, x \, \eta_{M-BFP}}{100} - \left(\frac{\Delta P_{BFP} \, x \, \overset{o}{m}_{FWS} \, x 10^6}{3600 \, x \, \rho_{BFP}}\right)\right] \quad ....(3)$$

Where $P_{in\text{-}BFP}$ is the electrical power input measured at BFP motor input (kW), $\eta_{M\text{-}BFP}$ is the motor efficiency (%), ΔP_{BFP} is pressure gain in BFP (including booster & main pump) (MPa), $\overset{o}{m}_{FWS}$ is the feed water flow at BFP suction (t/h) and ρ_{BFP} is the density of feed water at BFP suction in (kg/m^3).

The power loss (kW) due to passing in re-circulation valve is computed by:

$$L_{RC} = \frac{P_{BFP} \, x \left(\overset{o}{m}_{FWS} - \overset{o}{m}_{FW}\right) x 10^6}{3600 * \rho_{BFP}} \quad ....(4)$$

Where P_{BFP} is BFP discharge pressure (MPa).

The BFP pump efficiency (%) is computed by

$$\eta_P = \left[1 - \left(\frac{L_{BFP} \, x 100}{P_{in} \, x \, \eta_M}\right)\right] x 100 \quad ....(5)$$

The useful work output (kW) to HPT and IPT is computed as

$$P_{output} = P_{in} - \left(L_M + L_{BFP} + L_{RC} + L_{AS} + L_{FW}\right) \quad ....(6)$$

3.0 SIMULATION STUDIES

The input power to pump-motor depends on the efficiency of pumps, motors, pressure gain (net head i.e., dynamic head & velocity head) across pump and flow [9].

$$P_{in} \alpha \frac{\Delta PR \;\; x \, \overset{o}{m}_{FW}}{\eta_m \, x \, \eta_p} \quad ....(7)$$

Where P_{in} is input power, ΔPR is the pressure gain across pump, $\overset{o}{m}_{FW}$ is the feed water flow, η_m is the motor efficiency and η_p is the pump efficiency.

The feed water (FW) circuit consists of hydrodynamic resistive elements like HP heaters, Feed regulating station (FRS) where the FW pressure will be regulated to obtain final main steam pressure at turbine inlet, Economizer coils, Water Walls, Superheaters and Reheaters (Boiler circuit). BFPs have to overcome these pressure drop offered by all these hydrodynamic resistive elements. The pressure drop (MPa) across all these elements influences the pressure gain across BFP.

$$\Delta PR = \Delta P_{HPH} + \Delta P_{FRS} + \Delta P_{ECO} + \Delta P_{Boiler} + P_U \quad ....(8)$$

Where ΔP_{HPH} is FW pressure drop across HP heaters, ΔP_{FRS} is FW pressure drop across Feed regulating station, ΔP_{ECO} is FW pressure drop across Economizer coils, ΔP_{Boiler} is FW pressure drop across Water walls, Superheaters & Reheaters and P_U is useful pressure available for turbine (i.e., main steam pressure at boiler outlet).

All the above variables are directly dependent on the plant load factor and all these variables (array) are plotted with variation in plant load factor (array). The Pearson product moment correlation method is used for finding the correlation coefficient (R^2) between x-axis array (i.e., PLF independent variable) and y-axis array (i.e., P_{in}, ΔPR, ΔP_{HPH}, ΔP_{FRS}, ΔP_{ECO}, ΔP_{Boiler}, $\overset{o}{m}_{FW}$ and η_O dependent variables)

$$r = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \quad ....(9)$$

Where x is the mean of array 1 of PLF, y is the mean of array 2 of dependent variables i.e., P_{in}, ΔPR, ΔPR, ΔP_{HPH}, ΔP_{FRS}, $\Delta P_{ECO,}$ $\overset{o}{m}_{FW}$ and η_O, $\bar{x}$ and $\bar{y}$ are variables from array 1 & array 2 respectively.

As the plant load on the unit increases, the discharge pressure at pump increases to provide the necessary steam pressure at turbine inlet. The variation of pressure gain is curve fitted to second order polynomial and is:

$$PR = 14.87445 + 0.00673xPLF + 0.00016092xPLF^2 \quad ....(10)$$

The deviation in pressure gain with variation in plant load factor from 70 % to 100 % (MCR) is computed by using the MATLAB software average value got from the regression analysis (best curve fit of second order polynomial $R^2 = 0.9861$):

$$DP_r = \frac{(PR_{MCR} - PR_T)x100}{PR_{MCR}} \quad ....(11)$$

Where DP_r is the deviation in pressure gain (%), PR_{MCR} is the pressure gain at MCR condition (MPa) (i.e., 17.16 MPa at MCR) and PR_O is the pressure gain at tested plant load (MPa). The PR_T at 70 % PLF is 16.13 MPa. The deviation in pressure gain for operating the plant at 70 % of MCR is 6 %.

The FW pressure drop across HPH, FRS, ECO and BOILER are plotted with plant load factor and are curve fitted value for second order polynomial:

$$DP_{HPH} = 0.48946 - 0.00048xPLF + 9.0494x10^{-6}xPLF^2 \quad ....(12)$$

$$DP_{FRS} = 0.50604 + 0.00063xPLF + 3.0012x10^{-6}xPLF^2 \quad ....(13)$$

$$DP_{ECO} = 0.1649 + 0.00005xPLF + 1.8734x10^{-6}xPLF^2 \quad ....(14)$$

$$DP_{Boiler} = 1.2102 + 0.0012xPLF + 9.2411x10^{-6}xPLF^2 \quad ....(15)$$

The average (curve fitted value) FW pressure drop across HP heaters is 0.53 MPa at MCR and 0.50 MPa at 70 % PLF. The deviation in pressure drop at HPH for operating the plant at 70 % PLF is 5.98 %. FW pressure drop across FRS is 0.60 MPa at MCR and 0.56 MPa at 70 % PLF. The deviation in pressure drop at FRS for operating the plant at 70 % PLF is 5.73 %. FW pressure drop across Economizer coils is 0.19 MPa at MCR and 0.18 MPa at 70 % PLF. The deviation in pressure drop at Economizers for operating the plant at 70 % PLF is 5.90 %. FW pressure drop across water walls, superheters & reheaters (Boiler) is 1.42 MPa at MCR and 1.34 MPa at 70 % PLF. The deviation in pressure drop at Boiler for operating the plant at 70 % PLF is 5.84 %.

The variation of FW flow is curve fitted of second order polynomial (R^2 = 0.9902):

$$\overset{o}{m}_{FW} = 1.75149 + 8.804xPLF - 0.0099797xPLF^2 \quad ....(16)$$

The deviation in FW flow is computed by using average value through best curve fit of second order polynomial.

$$D\overset{o}{m}_{FW} = \frac{\left(\overset{o}{m}_{FW\ MCR} - \overset{o}{m}_{FW-T}\right)x100}{\overset{o}{m}_{FW\ MCR}} \quad ....(17)$$

Where $D\overset{o}{m}_{FW}$ is the deviation in FW flow (%), $\overset{o}{m}_{FW\,MCR}$ is the FW flow at MCR condition (m^3/h) (i.e., 782.35 m^3/h at MCR) and $\overset{o}{m}_{FW-T}$ is the FW flow (m^3/h) at tested plant load. The FW flow at 70 % PLF is 569.13 m^3/h. The deviation in feed water flow for operating the plant at 70 % of MCR is 27.25 %.

Similarly, the deviation in overall efficiency is computed by using average value through best curve fit of second order polynomial (R^2 = 0.9458).

$$D\eta_O = \frac{(\eta_{O-MCR} - \eta_{O-T})x100}{\eta_{O-MCR}} \quad ....(18)$$

Where

$$\eta_O = \frac{\eta_m\, x\, \eta_p}{100} \quad ....(19)$$

Where $D\eta_O$ is the deviation in overall efficiency (%), $\eta_{O\text{-}MCR}$ is the overall efficiency at MCR condition (%) (i.e., 70.97 % at MCR) and $\eta_{O\text{-}T}$ is the overall efficiency at tested plant load (%). The overall efficiency at 70 % PLF is 59.25 %. The deviation in overall efficiency for operating the plant at 70 % of MCR is 16.5 %.

The deviation in power input is computed by using average value through best curve fit of second order polynomial (R^2 = 0.9514).

$$DP_{BFP} = \frac{(P_{BFP-MCR} - P_{BFP-T})x100}{P_{BFP-MCR}} \quad ....(20)$$

Where DP_{BFP} is the deviation in power input (%), $P_{BFP\text{-}MCR}$ is the power input at MCR condition (kW) (i.e., 5083 kW at MCR) and $P_{BFP\text{-}T}$ is the power input (kW) at tested plant load. The power input at 70 % PLF is 4241 kW. The deviation in power input for operating the plant at 70 % of MCR is 16.56 %.

In order to evaluate the auxiliary power used by BFPs, the specific auxiliary power is computed and is the ratio of Power input to plant load. The specific auxiliary power for BFP motors is computed as

$$AP_{BFP} = \frac{P_{in}}{PL\, x10} \quad ....(21)$$

Where P_{in} is measured power (kW) and PL is the plant load at generator output (MW).

The deviation in specific auxiliary power (%) is computed by using average value through best curve fit of second order polynomial.

$$DAP_{BFP} = \frac{(AP_{BFP-MCR} - AP_{BFP-T})x100}{AP_{BFP-MCR}} \quad ....(22)$$

Where DAP_{BFP} is the deviation in specific auxiliary power (%), $AP_{BFP\text{-}MCR}$ is the specific auxiliary power at MCR condition (100 % PLF) (%) (i.e., 2.42 % at MCR) and $AP_{BFP\text{-}T}$ is the specific auxiliary power (%) at tested plant load. The specific auxiliary power at 70 % PLF is 2.88 %. The deviation in specific auxiliary power for operating the plant at 70 % of MCR is increased by 19.3 %.

The specific energy consumption (SEC) (kWh/ m^3/h) is one of the performance parameters for pumps and is computed by:

$$SEC_{BFP} = \frac{P_{in}}{\overset{o}{m}_{FW}} \quad ....(23)$$

The SEC is decreased with increase in plant load factor. The variation of SEC is curve fitted with PLF (best fit R^2=0.8992).

The mechanical power output of pump is directly related with pressure gain and feed water flow. Figure 3 gives the variation of deviation in power input, pressure gain, FW flow and overall efficiency with plant load factor for operating the plant at partial load. The electrical power input to BFP motor terminals is also directly related with mechanical power output along with motor and pump efficiency (i.e., overall efficiency). But all these parameters will not have the similar kind of variation trend for different plant load conditions. The deviation of performance parameter for operating the plant load at 70 % PLF are:

a) Deviation in pressure gain is 6 % and the variation is less because all the turbines operate on a constant pressure mode operation where the main steam pressure at turbine inlet will be same for different plant load but marginal variation is observed.

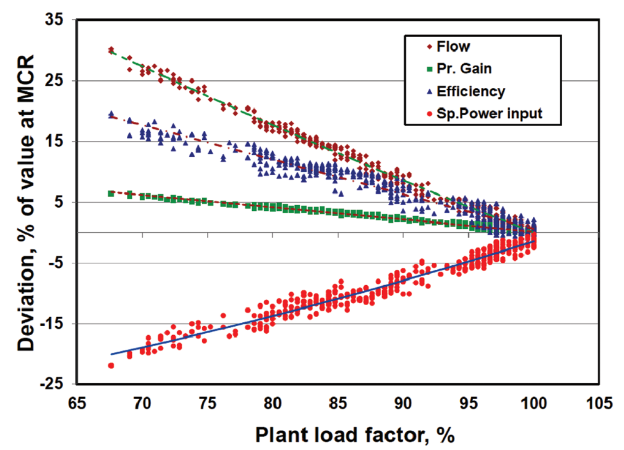

FIG. 3 DEVIATION IN POWER INPUT, PRESSURE GAIN, FLOW & EFFICIENCY

b) Deviation in FW pressure drop across HPH is 5.98 %, across FRS is 5.73 %, across Economizer coils is 5.90 % and across boiler circuit is 5.84 %.

c) Deviation in feed water flow is 27.3 % and the variation is more compared to pressure variation because the power output directly proportional to feed water flow (i.e., main steam flow).

d) Deviation in overall efficiency is 16.6 % and the variation is moderate but high level of noise level in data because the drop in motor efficiency at partial load is less influential compared to variation in pump efficiency at partial load.

e) Deviation in power input is 17 % and the variation is moderate and depends on all three parameters described above.

In order to predict the variation of power input to BFPs with plant load factors, all the above mentioned variables are considered for simulation. The simulation of variation of auxiliary power with plant load is carried out with respect to variation in pressure gain, pressure drop across hydrodynamic resistive elements (HPH, FRS, ECO & Boiler), feed water flow and overall efficiency. An intelligent Artificial Neural Network (ANN) feed forward technique is adopted to simulate the variation of power input. In this technique, three layer model is adopted i.e., input layer, hidden layer and output layer.

ANNs are computational models which simulate the function of biological networks that composed of neurons [10]. The unique concept of ANN is the multi layered feed forward neural networks. Figure 4 is the ANN architecture. In this case three layer concept is adopted i.e., input layer, hidden layer and output layer. A node in one layer is connected to all nodes in the next layer i.e., feed forward architecture [11]. The input layer takes all the input parameter, the information is transmitted to hidden layer where they will be processed and output is computed in output layer [12]. In this study, the input layers are chosen as plant load factor, pressure gain, feed water flow, overall efficiency, measured electrical power input and Pressure drop across HPH, FRS, ECO & Boiler [13]. Back propagation training algorithm which is a gradient descent technique to minimize the sum of square errors is used [14]. The output layer is the predicted power input to BFP motor.

$$E = \sum_{i=1}^{N} \sum_{j=1}^{Q} \left(AP_{PR} - AP_{BFP} \right)^2 \qquad ....(24)$$

Where AP_{PR} is the predicted power input (%), i is input data set value from 1 to N, j is the output data set value from 1 to Q. The simulation will try to minimize the error near to zero.

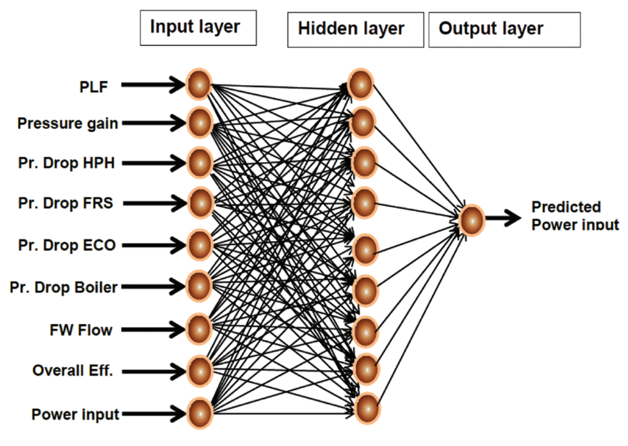

FIG. 4 ANN ARCHITECTURE FOR BFP

An input data set of 422 for all input variables taken for predicting the output parameter. All these input data set are normalized in the range of 0.1 to 0.9 by using the following technique:

$$D_n = \frac{(D_T - D_{T-\min})x\,0.8}{(D_{T-\max} - D_{T-\min})} + 0.1 \quad ....(25)$$

Where D_n is the normalized value, D_T is the measured data, $D_{T\text{-max}}$ is the maximum value of measured data and $D_{T\text{-min}}$ is the minimum value of measured data.

4.0 RESULTS AND DISCUSSION

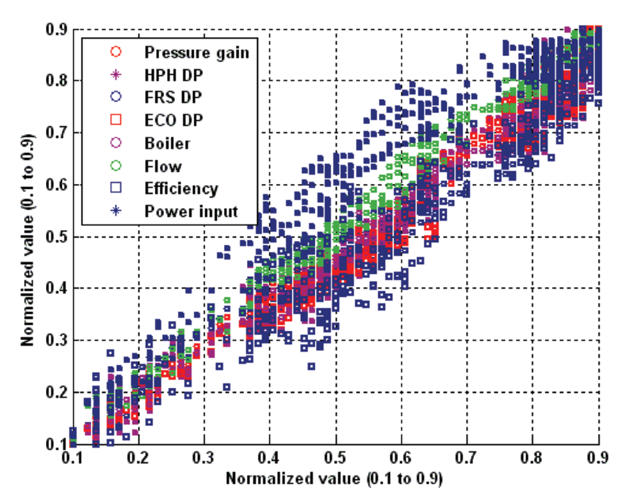

FIG. 5 NORMALIZED VALUE OF VARIABLES

Figure 5 is the variation of normalized values in the range of 0.1 to 0.9 for all the input parameters. The data spread (noise level) is more for overall efficiency compared to other variables.

Figure 6 is the variation of measured power input and predicted power input and Figure 7 represents the variation of specific power input and predicted specific power. The Predicted power at 100 % PLF is 5070 kW and at 70 % PLF is 4246 kW as compared to measured value of 5083 kW at 100 % PLF and 4241 kW at 70 % PLF.

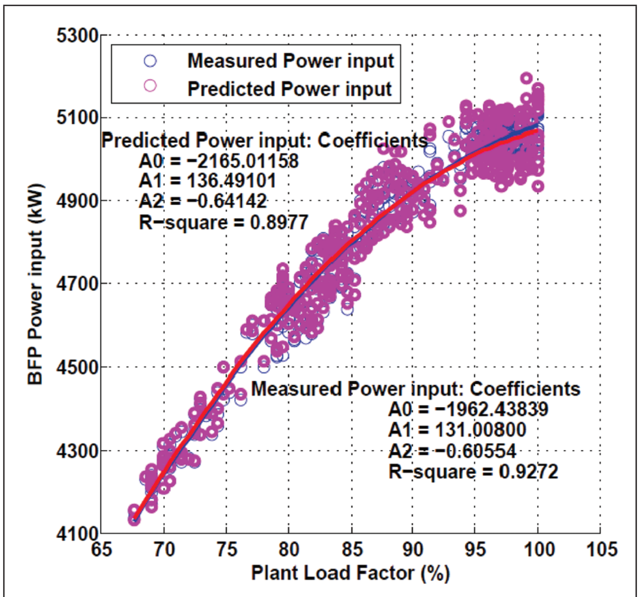

FIG. 6 MEASURED & PREDICTED POWER

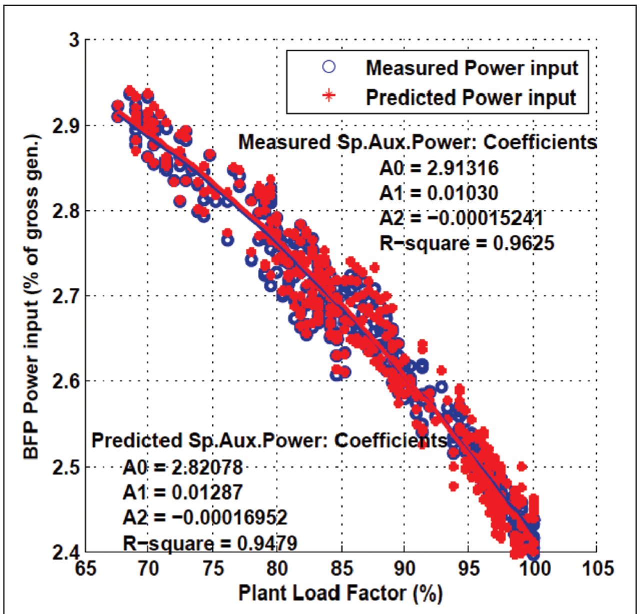

FIG. 7 MEASURED & PREDICTED SPECIFIC AUXILIARY POWER

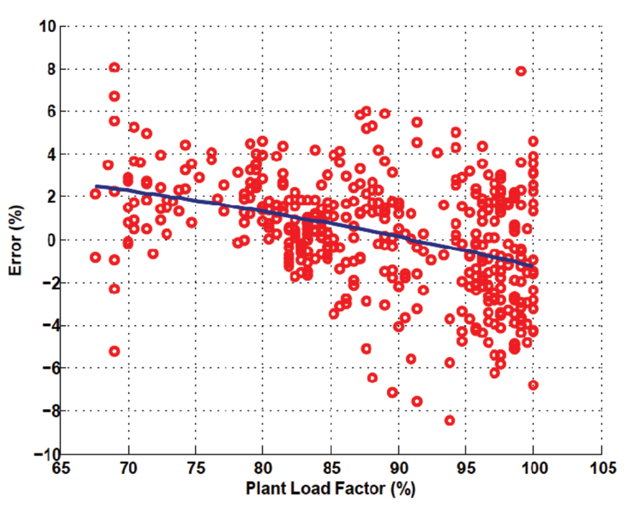

FIG. 8 ERROR BETWEEN MEASURED & PREDICTED POWER

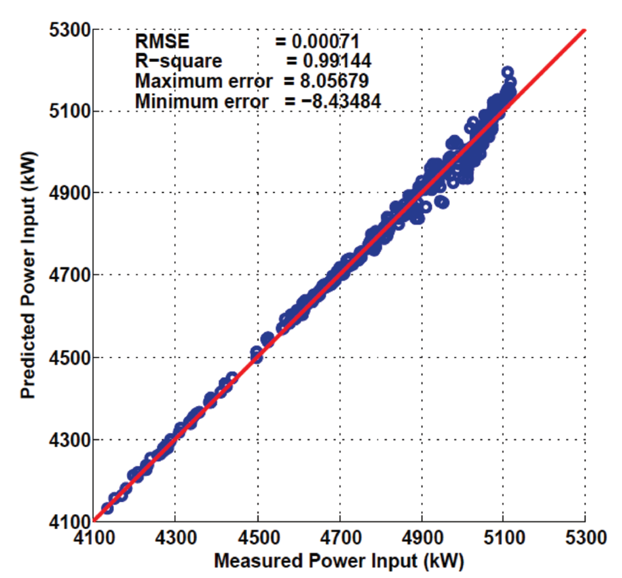

FIG. 9 CORRELATION COEFFICIENT BETWEEN MEASURED & PREDICTED POWER

The Predicted specific auxiliary power at 100 % PLF is 2.42 % and at 70 % PLF is 2.88 % as compared to measured value of 2.41 % at 100 % PLF and 2.89 % at 70 % PLF. The Pearson product moment correlation coefficient (R^2) value for measured power input is 0.9514 is improved for predicted power input is 0.9566.The error between actual measured value (% of measured input power) is varying between -8.4048 to 8.0568 % (Figure 8). The error is slightly negative as the plant load factor increases. The correlation coefficient between the measured input power and predicted power is plotted in Figure 9. The correlation coefficient computed (as per Pearson product moment correlation method) (R^2) is 0.9914 and Root Means Square Error (RMSE) for the correlation between predicted power input to measured power input is 0.00071 [15]. The error is negative for lower plant load and is slightly positive at higher PLF. At lower PLF operation of the plant will be less stable compared to plant operating above 80 % PLF.

The noise level of data will be less at a PLF more than 80 %. At present Indian power plants average PLF of 210 MW power plants is about 82 % and is lower may be due to use of poor coal quality and ageing of the plants [16, 17].

Based on the results obtained from the MATLAB simulation, the data are plotted in excel spreadsheet, best linear curve fit is computed for good operating plants and plants operating below average (Figure 10). The performance of BFPs varies widely because the performance tests are conducted at different plant load for different plants and different operating conditions:

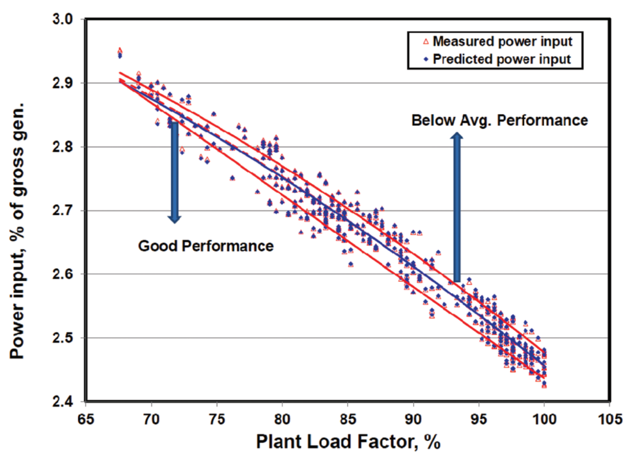

FIG. 10 BETTER AND BELOW AVERAGE OPERATING PLANTS

5.0 VALIDATION OF RESULTS

The MATLAB Simulink programming is done to evaluate the performance of BFPs (Figure 11). This Simulink program input the simulated and curve fit values from the ANN

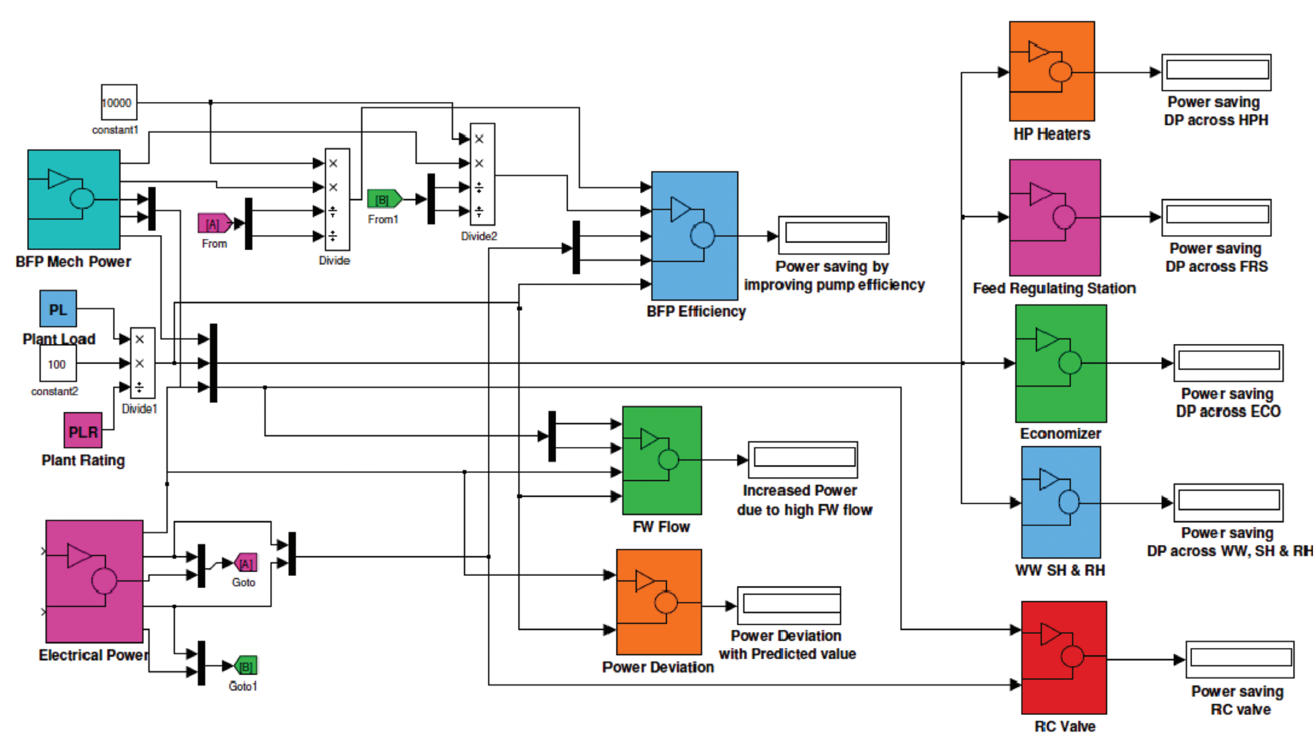

FIG. 11 MATLAB SIMULINK PROGRAM FOR BFP PERFORMANCE

program. The following performance parameters are computed in Simulink program:

a) Power input to motor based on measured 3-phase voltage, currents and power factor for individual BFP

b) Mechanical power output

c) Motor, pump and overall efficiency

d) Power loss in hydrodynamic resistive elements like HPH, FRS, ECO & Boiler

e) Power loss due to passing in Re-circulation valve

f) Power due to higher feed water flow (the value above the standard curve fit value).

g) Power due to reduced overall efficiency of pump-motors.

The performance tests are conducted for 210 MW power plants at different plant load conditions. The measured data are compared with the simulated data. The variations in power due to variation of different parameters are discussed.

Table 1 gives the performance results of BFPs at Unit 1 at Raichur Super Thermal Power Station (RTPS), Raichur, Karnataka, India [18].

The performance test is conducted at an average plant load of 170 MW (PLF: 80.95 %). The observations from the study are as follows:

a) The total power input for both BFPs is 5630.16 kW (3.31 % plant load) and is higher than the average predicted Power input i.e., 2.74 % at 80.95 % PLF. The power input is even above the economical operating band i.e., 2.71 – 2.74 %.

b) The main reason for increase of FW flow is mainly due to passing in re-circulation valve and higher specific steam consumption of turbines.

c) Since BFP is the multistage high pressure pump during start-up of the pump, the FW flow is bypassed to deaerator through re-circulation valve. During normal operation of the plant, the re-circulation valve will be closed. But due to passing in these valves, the FW flow is increased in BFP. The additional FW flow increases the power of BFP. The replacement of valve seat of re-circulation valve for both pumps reduced the power of BFP by 0.30 MU/month. The investment for replacing the valve seat of re-circulation valve is Rs. 36.0 lakhs and payback period is 4 months. The reduction in specific auxiliary power is 0.25 % of plant load.

d) The pump efficiencies are in the range of 57.09 to 57.40 % and are lower compared to predicted pump efficiency at 80.95 % PLF of 67.42 %. The pump efficiency is low due to more clearances inside the pump. The pump impeller set (cartridge set) is replaced in both pumps. The replacement of BFP cartridge had enhanced the pump efficiency by average of 7 % [19] and had reduced the power of BFP by 0.40 MU/month. The investment for replacing the pump cartridge is Rs. 45.0 lakhs and payback period is 5 months. The reduction in specific auxiliary power is 0.32 % of plant load.

TABLE 1

PERFORMANCE RESULTS OF BFPS AT RSTPS

Sl. No.	Particulars	Unit	Predicted value at 80.95 % PLF	BFP 1B	BFP 1C
01	Plant load	MW	-	170.0	
02	BFP Motor rating	MW	4.00	4.00	4.00
02	Booster pump suction pressure	MPa	-	0.56	0.56
03	BFP discharge Pressure	MPa	-	14.20	15.84
04	Pressure gain	MPa	16.47	13.64	15.28
05	FW flow	m^3/h	325.4	393.78	363.63
06	Electrical power	kW	2330	2775.92	2854.24
07	Load factor of motor	%	54.17	64.10	65.94
08	Motor efficiency	%	93.00	92.36	92.42
09	Electrical power input to pump	kW	2166.90	2563.84	2637.89
10	Mechanical power output	kW	1460.92	1464.10	1514.57
11	Main pump & Booster pump efficiency	%	67.42	57.09	57.40
12	Overall efficiency	%	62.70	52.73	53.05
13	Specific Energy Consumption	$kWh/m^3/h$ of FW flow	7.16	7.76	8.64
14	Specific Auxiliary Power	% of plant load	2.74	3.31	
15	Increased power due to increased FW flow	kW	-	481.95	309.28
16	Reduction in power due to reduced pressure gain	kW	-	-476.91	-190.22
17	Increased power due to poor overall (motor+pump) efficiency	kW	-	440.88	405.18
18	Net increase in power	kW	-	445.92	524.24

Table 2 gives the performance results of BFPs at Unit 3 at Guru Gobind Singh Super Thermal Power Station (RGGSTPS), Rupnagar, Punjab, India [20].

TABLE 2

PERFORMANCE RESULTS OF BFPS AT RGGSTPS

Sl. No.	Particulars	Unit	Predicted value at 100 % PLF	BFP 3A	BFP 3B
01	Plant load	MW	-	210.0	
02	BFP Motor rating	MW	4.00	4.00	4.00
02	BFP Pump (Booster) suction pressure	MPa	-	0.56	0.56
03	BFP discharge Pressure	MPa	-	17.90	18.60
04	Pressure gain	MPa	17.16	17.34	18.04
05	Pressure drop across HP heaters	MPa	0.25	0.28	0.28
06	Pressure drop across FRS	MPa	0.10	0.35	0.35
07	Pressure drop across Economizer	MPa	0.15	0.16	0.16
08	Pressure drop across water wall & SH	MPa	1.25	1.31	1.31
09	Pump discharge FW flow	m^3/h	391.03	394.56	390.63
10	Re-circulation flow	m^3/h	-	1.29	38.18
11	Total FW flow in pump	m^3/h	391.03	395.85	428.81
12	Electrical power	kW	2578.45	3022.19	3216.86
13	Load factor of motor	%	59.95	70.05	65.94
14	Motor efficiency	%	93.00	92.72	92.91
15	Electrical power input to pump	kW	2397.96	2802.17	2988.78
16	Mechanical power output	kW	1828.50	1464.10	2107.99
17	Main pump & Booster pump efficiency	%	76.25	66.75	70.53
18	Overall efficiency	%	70.91	61.89	65.53
19	Specific Energy Consumption	$kWh/m^3/h$ of FW flow	6.59	7.63	7.50
20	Specific Auxiliary Power	% of plant load	2.46	2.97	
21	Increased power due to higher Pr. Drop across HP heaters	kW	-	4.56	5.89
22	Increased power due to higher Pr. Drop across FRS	kW	-	38.01	49.10
23	Increased power due to higher Pr. Drop across Economizer	kW	-	1.52	1.96
24	Increased power due to higher Pr. Drop across Water walls & SH	kW	-	9.13	11.78
25	Reduction in power due to reduced net pressure gain at boiler outlet	kW		-25.85	-33.38
26	Increased power due to passing in re-circulation valve	kW	-	8.59	315.47
27	Increased power due to increase in FW flow (higher SSC)	kW		23.51	-3.30
28	Increased power due to poor overall (motor+pump) efficiency	kW	-	384.27	290.89
29	Net increase in power	kW	-	443.74	638.41

The performance test is conducted at an average plant load of 210 MW (PLF: 100 %). The observations from the study are as follows:

a) The total power input for both BFPs is 6239.05 kW (2.97 % plant load) and is higher than the average predicted Power input i.e., 2.46 % at 100 % PLF. The power input is even above the economical operating band i.e., 2.43 – 2.49 %.

b) The increased power due to higher pressure drop across High Pressure (HP) Heaters is 10.45 kW, across Feed Regulating Station (FRS) is 87.11 kW, across Economizer is 3.48 kW and across Water walls & super-heaters (SH) is 20.91 kW. The power change due to higher pressure available at Boiler outlet is 59.23 kW. The net power increased due to change in pressure drop across feed water circuit elements is 62.72 kW that forms 0.03 % of plant load.

c) Reducing the pressure drop across HP heaters by acid cleaning of HP heater tubes reduced the pressure drop from average value of 0.28 MPa to 0.24 MPa. This had reduced the auxiliary power of BFP by 6.5 MWh/month. The investment is Rs. 2.1 lakhs and the payback period is 11 months.

d) Reducing the pressure drop across FRS from an average value of 0.35 MPa to 0.10 MPa by operational optimization, will reduce the auxiliary power of BFP by 50.2 MWh/month.

e) The replacement of valve seat of re-circulation valve for BFP 3B reduced the power of BFP 3B by 0.18 MU/month. The investment for replacing the valve seat of re-circulation valve is Rs. 18.0 lakhs and payback period is 4 months. The reduction in specific auxiliary power is 0.12 % of plant load.

f) The pump efficiencies are in the range of 66.75 to 70.53 % and are lower compared to predicted pump efficiency at 100 % PLF of 76.25 %. The pump efficiency is low at BPF 3A due to more clearances inside the pump. The pump impeller set (cartridge set) is replaced for BFP 3A. The replacement of BFP cartridge had enhanced the pump efficiency by average of 7 % and had reduced the power of BFP by 0.14 MU/month. The investment for replacing the pump cartridge is Rs. 22.50 lakhs and payback period is 6 months. The reduction in specific auxiliary power is 0.12 % of plant load.

6.0 CONCLUSION

Predicted power output obtained from ANN technique for the BFP is having error in the range of -10.9138 to 1.9798 % and is quite good. The Predicted power at 100 % PLF is 2.46 % and at 70 % PLF is 2.87 % as compared to measured value of 2.45 % at 100 % PLF and 2.88 % at 70 % PLF. The Pearson product moment correlation coefficient (R^2) value for measured power input is 0.9514 is improved for predicted power input is 0.9566. The error is slightly high at lower plant load factor due to higher noise level in measured data. The specific auxiliary power of BFP at 100 % PLF is about 2.46 % of gross energy generation and is increased for operating the plant at reduced PLF of 70 % is 2.87 % of gross energy generation. Reducing the passing in re-circulation valve will reduce the auxiliary power of BFP in the range of 10 – 15 % of BFP power and 0.2 – 0.4 % of gross energy generation. Improvement of pump efficiency by changing the impeller will enhance the BFP efficiency by about 7 – 10 % that will reduce the auxiliary power of BFP by 0.40 MU/month for one 210 MW plant. Operational optimization of BFPs and implementation of energy conservation measures for BFPs will reduce the auxiliary power of BFPs from average value of 3.6 to 2.3 % of gross energy generation and release an additional energy of about 10.9 MU/year for one 210 MW unit into grid.

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