Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

"Modeling of a Power Plant (A Case Study of Savannah Sugar Power Plant)."North-Eastern Nigeria.

J.M. Gumpy* and J. D.Jiya **

*Department of Mathematical Sciences,
Adamawa State University, Mubi, *Nigeria.*
(e-mail: mishon_jerry@yahoo.com,mishonjgumpy@gmail.com)
**Electrical and Electronics Engineering Programme,
Abubakar Tafawa Balewa University (ATBU), Bauchi, Nigeria.
(e-mail:jibjiya27@gmial.com)

Abstract: The system under scrutiny in this paper is a thermal power plant in Savannah Sugar Company Numan (SSCN) factory, Nigeria. The final power output of the plant is affected by random events such as equipment failures. Whenever such random events occur, the power plant's output is unstable due to the electrical power demand by the factory instruments and estate. Unavailability of plant means shorter production periods and hence profit loss, these effects should be minimized, which is not a trivial matter because the plant is a highly complex system. This paper presents the principal dynamic phenomena that determine the model of boiler-turbine-generator system. The formation of the model is based on fundamental physical and thermodynamic laws. The nonlinear nature of the model is made up of differentials and algebraic equations, steam tables and the use of algebraic polynomial formulae provided the means of obtaining required data for the modelling. Raw data was taken from this power plant for period of two years. The derived model is realized in the MATLAB/SIMULINK 7.10 environment using the SSCN power plant raw input data. Validation result shows that the plant's outputs (Steam Pressure and Electrical Power) are within acceptable range of the manufacturer's recommended values. This model can be said to be the true representation of SSCN power plant.
Keywords: model, dynamic phenomena, raw data, simulation, steam pressure, electrical power, algebraic equation, differential equations.

INTRODUCTION

The SSCN Thermal Power Plant Unit (TPPU) supplies 3200kPa steam at 0.2083kg/s which rotates turbine-generator at 6000rpm for the production of 4.8 MW power.
The electrical power production is dependent on steam generated from boiler system but due to its complexity and flexibility, it requires a simulator (model) to predict the plant behaviour (Stefano, 2000).

Using models cut down the time of project realization and reduce all the risks associated with the work on the real object.To facilitate this study; mathematical models are derived to represent the plant (Flynn and O' Malley, 1999 and Baligh et al., 2010).
The modelling of power plant is divided into four stages based on thermodynamic engineering principles (Cellier, 1982; Jiya and Gumpy, 2008, Maffezzoni, 1997 and Bolis et al., 1993).

2 The Savannah Sugar Company Numan power plant

This plantl produces electric power from fossil fuel through several energy conversion processes, using water as a working fluid (Thermal Power Plant). The chemical energy of the fossil fuel is transformed into steam thermal energy by the boiler; it is transformed into rotational mechanical energy by the turbine, and finally the generator produce electrical power energy by electromagnetic induction principle. Concurrently, the working fluid in the boiler is alternately vaporized and condensed in a closed circuit following a thermodynamic cycle (Leva and Maffezoni, 2003 and Yu et al., 2010). The block diagram of the energy conversion process is shown in figure1.

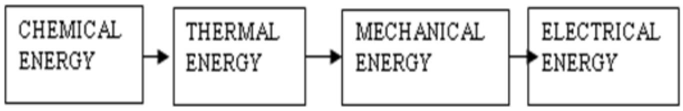

Figure 1: Block diagram of the Energy Conversion processes.

2.1 SSCN thermal power plant process diagram

The steam boiler in a power plant serves for energy conversion to transform the input chemical energy of oil, into the mechanical energy acting on the turbine and generator as shown in figure 2, (Jiya and Gumpy, 2008; Wen and Fang, 2008; Tor-Martin and Carl-Johan, 2006 and Bolis et al., 1993).

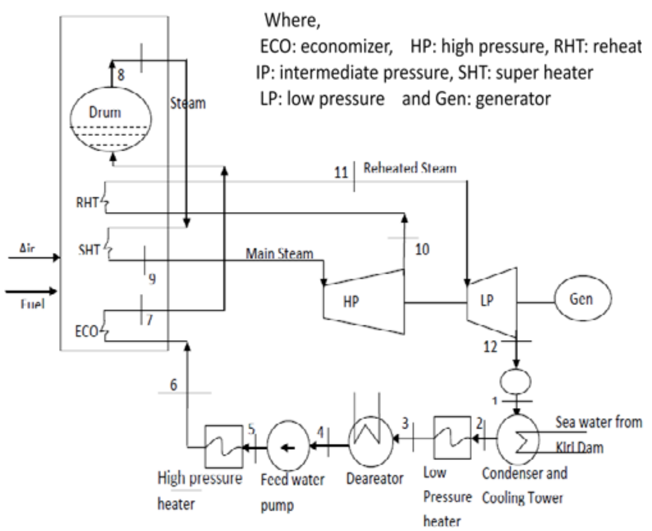

Figure 2 SSCN Thermal Power Plant process diagram

The block diagram of boiler-turbine-Generator system is shown in figure 3.

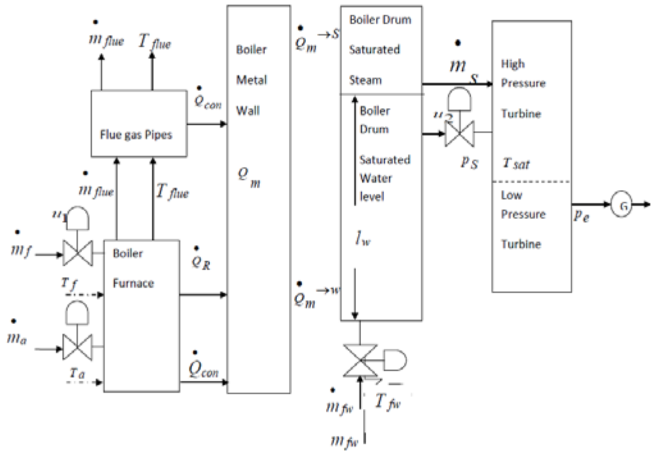

Figure 3 Block diagram of modeled boiler-turbine-generator system Source: Solberg et al., (2005).

Where

G is generator, L_{sw} is saturated water level in meters, P_s is steam pressure in kilo pascal, P_e is electrical power in megawatt, $\dot{m}_a$ is air mass flow rate in kilogram per second, $\dot{m}_f$ is oil mass flow rate, in kilogram per second, $\dot{m}_s$ is steam mass flow rate in kilogram per second, $\dot{m}_{fw}$ is feed water flow rate in kilogram per second, $\dot{m}_{flue}$ is flue mass flow rate in kilogram per second, T_a is air temperature in degree Celsius, T_f is oil temperature in degree Celsius, T_{flue} is flue temperature in degree Celsius, T_{fw} is feed water temperature in degree Celsius, $\dot{Q}_{con}$ is conduction heat flow in kilojoules, $\dot{Q}_{m \rightarrow s}$ is metal heat flow to steam is in kilojoules, $\dot{Q}_{m \rightarrow sw}$ is metal heat flow to saturated water is in kilojoules, u_1 is oil flow control valve, u_2 is steam flow control valve and u_3 is feed water control valve.

The corresponding changes in the thermodynamic cycle offigure 2 are shown in Figure 4, in which, a “point” refers to a physical location.

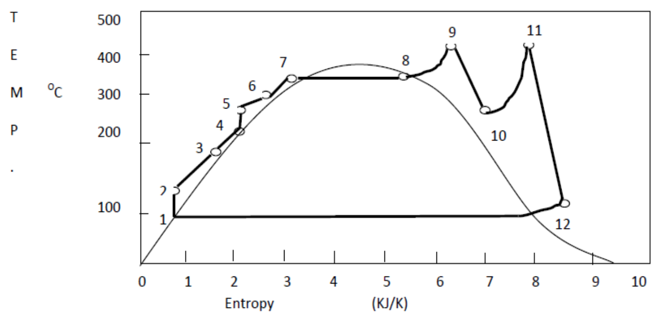

Figure 4 SSCN Temperature-Entropy diagram

3.0 THE STUDY AREA

The plant is located in Numan and Guyuk Local Government areas of Adamawa State in north-east Nigeria. The plant consists of three baggasse/oil fired “Clark Chapman” steam boilers with cane handling and milling systems. The boiler supplies 3200kPa high pressure steam to turbine for 4.8MW electrical power generation. The turbine 2700kPa exhaust steam is discharged into the process house for processing sugar. A small portion of the high pressure steam is supplied directly from boiler to mill for its operation.

3.1 Data collection

The raw data was taken using pressure, temperature gauges and electrical power meter during the plant’s normal operation for a period of two years.

3.2 Savannah Thermal Power Plant Manufacturer’s Data

The control valve’s position is determined using the rate values in table1, while table 2 are the manufacturer’s plant specifications and table 3 are the steam table values of enthalpies and densities at specified points (see figure 4).

TABLE I: CONTROL VALVES ACTUATOR CHARACTERISTICS

S/N	VALVE	POSITION	RATE
1	Fuel Oil	$0\leq u_1\leq 1$	$0.80\leq \frac{du_1}{dt}\leq 28.1$
2	Steam to Turbine	$0\leq u_2\leq 1$	$4.90\leq \frac{du_2}{dt}\leq 190$
3	Feedwater to Drum	$0\leq u_3\leq 1$	$1.65\leq \frac{du_3}{dt}\leq 53.8$
4	Steam to Reheater	$0\leq u_4\leq 1$	$4.90\leq \frac{du_4}{dt}\leq 190$

SSCN Power Plant Manufacturer's Manuals (BMA Germany)

Table II: SSCN POWER PLANT RATED OPERATION CONDITIONS

S/N	SPECIFICATION	VALUE	UNIT
1	Electric Power	4.2	MW
2	Steam Flow	13.9	kg/s
3	Drum Steam Pressure	3000	KPa
4	Super Heater Steam Temperature	420	°C
5	Feedwater Temperature	168	°C
6	Mass of water in System	35000	Kg
7	Fuel Oil Calorific Value	10278	Kcal/kg
8	Volume of Drum	35	m^3
9	Inlet Steam Pressure to Turbine	3200	KPa
10	Turbine Inlet Steam Temperature	420	°C
11	Turbine Speed	6000	Rpm
12	Turbine Exhaust Pressure	1.723	KPa
13	Drum Saturation Temperature	345	°C
14	Boiler Feedwater Temperature	125	°C
15	Length of steam Drum(l_d)	9.4	M
16	Drum Diameter (D)	1.21	M
17	Saturated water Level (l_{sw})	100	MmWG
18	Satureted Water Volume(V_{sw})	17.5	m^3
19	Turbine Mechanical Power($p_m^{\,0}$)	475	Hp
20	Turbine shaft Damping factor(D)	0.8	-

Source:SSCN Power Plant Manufacturer's Manuals (BMA Germany)

TABLE III: BOILER-TURBINE STEAM TABLE DENSTITY AND ENTHALPY VALUES

S/N	VARIABLE	TEMP.	VALUE	UNIT
1	Feed water enthalpy(h_{eco})	168 °C	527.8020	KJ
2	Feed water density(ρ_{fw})	168 °C	941.0560	kg/m³
3	Drum saturated steam density(ρ_{ss})	345 °C	135.9477	kg/m³
4	Drum saturated steam enthalpy(h_{ss})	345 °C	1202.8850	KJ
5	Drum saturated water density(ρ_{sw})	345 °C	814.6110	kg/m³
6	Drum saturated water enthalpy(h_{sw})	345 °C	1825.4250	KJ
7	Steam to Turbine enthalpy(h_s)	420 °C	2802.3	KJ
8	Reheater steam enthalpy(h_{rht2})	414°C	3115.3	KJ
9	Condensate enthalpy(h_c)	125 °C	712.6	KJ

Source: Thermodynamic Steam Tables and Polynomial formula

3.3 Modelling of SSCN power plant.

Assumptions:

(i) the hot gases flow upwards through the combustion chamber is surrounded with the water-tubes embedded in the walls, water is evaporated to steam;
(ii) the hot flue gases pass over the tubes of the superheater, superheating the steam.
(iii) the hot gases may then pass over the steam reheater where the steam drawn from the turbine is re-superheated.
(iv) the hot gases pass through the economizer where heat is absorbed to raise the temperature of the feed water.
(v) the drum is a perfect cylinder;
(vi) the heat exchanger surface between steam and water is planner;
(v) all the feedwater enters the downcomer tubes directly and returns through the water walls at fluid saturation conditions;
(vi) the circulation through the downcomers and water walls is constant;
(vii) the water in both phases (water and steam) at the steam/water drum is at saturated conditions.
(viii) the energy stored in the steam and water is released or absorbed very rapidly when pressure changes.
(x) that boiler maintains a constant pressure to the STTCV regardless of steam input;
(xi) that the pressure at the input to the turbine is 100% of rated pressure regardless of whether the unit is at full load or partial load;
(xii) that the entire 100% of the rotor inertia is used for the accelerating of the rotor.

3.4 Control Valves (Actuators)

The first group of equations relates the input control valve actuator positions to the input mass flow rates for fuel-to-furnace, steam- to-turbine and feedwater-to-drum which are respectively given in equation 1-3(Astrom and Bell, 2000).

$$\dot{m}_f \propto u_1 \tag{1}$$

$$\dot{m}_s \propto u_2 \tag{2}$$

$$\dot{m}_{fw} \propto u_3 \tag{3}$$

The mass flow rates equations for Oil flow, steam and feedwater are given by the fluid flow equations as:

$$\dot{m}_f = k_1 u_1 \sqrt{\frac{\Delta p}{G}} \tag{4}$$

$$\dot{m}_s = k_2 A_{cv} P_s T_s^{-1} \quad (5)$$

$$\dot{m}_{fw} = k_3 u_3 \sqrt{\frac{\Delta p}{G}} \quad (6)$$

Where G =1 for water and 1.3 for oil, (Astrom and Bell, 2000), Δp is change in pressure and k_2, k_3 are valve constants.

The global mass balance equation for the boiler is given by equation (7)

$$\frac{dm}{dt} = \dot{m}_f - \dot{m}_{fw} \quad (7)$$

At steady state, equation (7) becomes

$$\dot{m}_f = \dot{m}_{fw} \quad (8)$$

The drum level, steam pressure to turbine and turbine-generator models is respectively given by equations (9)-(11).

$$\frac{dl_{sw}}{dt} = \frac{\left(\dot{m}_{fw} - \dot{m}_s\right) - \left[V\frac{d\rho_{ss}}{dt} + V_{sw}\left(\frac{d\rho_{sw}}{dt} - \frac{d\rho_{ss}}{dt}\right)\right]}{A_0\left(\rho_{sw} - \rho_{ss}\right)} \quad (9)$$

$$\frac{dP_s}{dt} = \frac{\dot{m}_{fw} h_{fw} - \dot{m}_s h_s + Q_{fur} - \frac{\left(\rho_{sw} h_{sw} - \rho_{ss} h_{ss}\right)\left(\dot{m}_{fw} - \dot{m}_s\right) + \left[V\frac{d\rho_{ss}}{dt} + V_{sw}\left(\frac{d\rho_{sw}}{dt} - \frac{d\rho_{ss}}{dt}\right)\right]}{\rho_{sw} - \rho_{ss}}}{V_{sw}\left[\left(\rho_{sw}\frac{\partial h_{sw}}{\partial p} + h_{sw}\frac{\partial \rho_{sw}}{\partial p} - 1\right) - \left(\rho_{ss}\frac{\partial h_{ss}}{\partial p} + h_{ss}\frac{\partial \rho_{ss}}{\partial p} - 1\right)\right] + V\left(\rho_{ss}\frac{\partial h_{ss}}{\partial p} + h_{ss}\frac{\partial \rho_{ss}}{\partial p} - 1\right)} \quad (10)$$

where equations (9)-(11) variables are described in tables 2 and 3 and

$$\frac{dP_e}{dt} = M\left\{\dot{m}_s\left(K_{HP} + K_{LP}\right) - P_e^0\right\}\left(\omega_r^0 + \omega_r\right) \quad (11)$$

Where

Variables with superscript (0) are the manufacturer's rated values.

K_{HP} is turbine high pressure side constant .

K_{LP} is turbine low pressure side constant .

$$V_{sw} = l_d\left[r^2\right]\cos^{-1}\left(\frac{r - l_{sw}}{r}\right) - \left(r - l_{sw}\right)\sqrt{2rl_{sw} - l_{sw}^2} \quad (12)$$

Where

l_d is the boiler drum length in meters

r is the boiler drum radius in meters

$$k_{HP} = \frac{k_4\left(h_s^o - h_{rht}^o\right)}{P_m^o} \quad (13)$$

$$k_{LP} = \frac{k_5\left(h_{rht}^o - h_c^o\right)}{P_m^o} \quad (14)$$

3.5 Savannah Sugar Company Thermal Power Plant Models

Using data of tables 1, 2 and 3; the level of water in boiler drum, the steam pressure to turbine and the plant's electrical output power models are in equations (15)-(17) respectively.

$$\frac{dl_{sw}}{dt} = \cup_{11} - \cup_{12} - \cup_{10} \quad (15)$$

$$\frac{dp_s}{dt} = \cup_{21} - \cup_{22} + \cup_{23} + \cup_{20} \quad (16)$$

$$\frac{dp_e}{dt} = \cup_{31} + \cup_{32} + \cup_{33} - \cup_{30} \quad (17)$$

Where

$\cup_{10} = \frac{A_3}{A_0 A_1}$, $\cup_{11} = 0$, $\cup_{12} = \frac{\dot{m}_s}{A_0 A_1}$, $\cup_{13} = \frac{\dot{m}_{fw}}{A_0 A_1}$,

$\cup_{20} = \frac{A_3}{A_4}$, $\cup_{21} = \frac{\left(T_{flue} - T_{flame}\right)}{A_4}$, $\cup_{22} = \frac{\dot{m}_s\left(A_2 - A_1 h_{ss}\right)}{A_4}$,

$\cup_{23} = \frac{\dot{m}_{fw}\left(A_1 h_{sw} - A_2\right)}{A_4}$,

$\cup_{30} = M * P_e^0 \omega_r^o$, $\cup_{31} = 0$,

$$\cup_{32} = \frac{M * \dot{m}_s}{P_m^0}\left[\left(h_s^o - h_{rht}^o\right) + \left(h_{rht}^o - h_c^o\right)\right]\omega_r^o,$$

$\cup_{33} = 0$

$A_0 = 2l_d\sqrt{2rl_{sw} - l_{sw}^2}$, $A_1 = \rho_{sw} - \rho_{ss}$, $A_2 = \rho_{sw} h_{sw} - \rho_{ss} h_{ss}$,

$A_3 = V\frac{d\rho_{ss}}{dt} + V_{sw}\left(\frac{d\rho_{sw}}{dt} - \frac{d\rho_{ss}}{dt}\right)$ and

$$A4 = V_{sw}\left[\left(\rho_{sw}\frac{\partial h_{sw}}{\partial p} + h_{sw}\frac{\partial \rho_{sw}}{\partial p} - 1\right) - \left(\rho_{ss}\frac{\partial h_{ss}}{\partial p} + h_{ss}\frac{\partial \rho_{ss}}{\partial p} - 1\right)\right] + V\left(\rho_{ss}\frac{\partial h_{ss}}{\partial p} + h_{ss}\frac{\partial \rho_{ss}}{\partial p} - 1\right)$$

Substituting variables from tables 1, 2 and 3 into equations (4), (5), (6), (12) and (14), the constants values are calculated as shown tabulated in table 4.

Table IV: Calculated values of SSCN thermal power plant

S/N	Constant(K_i)	Constant Value
1	K_1	-276376348.072
2	K_2	74620851.454
3	K_3	0.0988
4	K_{HP}	0.00896
5	K_{LP}	0.00598

4.0 SIMULATION, RESULTS AND DISCUSSIONS

Substituting values from table 4 into equations (15)-(17), a simulation diagram of SSCN thermal power plant is constructed as in figure 5.

4.1 Simulation

Figure 5 is simulated using MATLAB 7.1 environment for production of final SSCN power plant outputs.

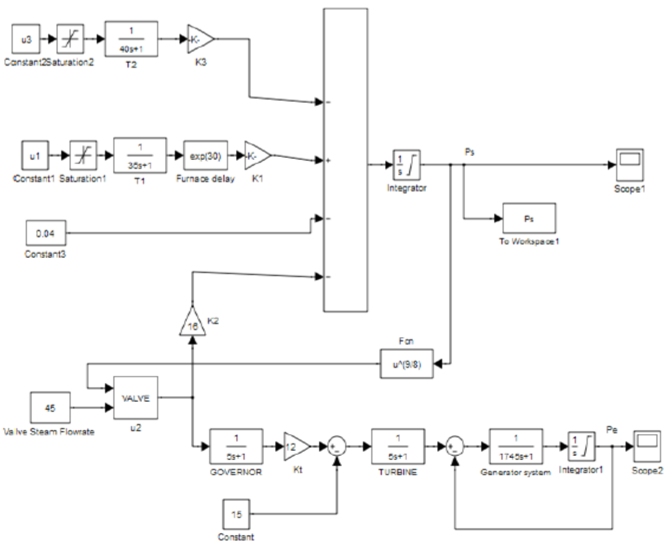

Figure 5 Overall SSCN Power Plant Simulink

To obtain the manufacturer's Plant's output value, the SSCN simulink is simulated resulting in new constant values as tabulated in table 5.

Table V: Simulated constant values of SSCN power plant

S/N	Constant(K_i)	Constant Value
1	k_1	225
2	k_2	-0.024
3	k_3	-0.0005
4	K_{HP}	563
5	K_{LP}	-15

Substiting the simulated constant values into equations (15)-(17) gives equations (18)- (20).

$$\frac{dP_s}{dt} = 225u_1 - 0.024u_2 P_s^{\frac{9}{8}} - 0.0005u_3 - 9 \tag{18}$$

$$\frac{dP_e}{dt} = \left(563u_2 - 15\right)P_s^{\frac{9}{8}} - P_e \tag{19}$$

$$\frac{dL_{sw}}{dt} = \left(0.014u_2 P_s - 0.005u_3 - 33946463\right) - L_{sw} \tag{20}$$

Assume that the water level in the drum is steady. Thus, the change in level will be zero, that is

$$\frac{dL_{sw}}{dt} = 0 \tag{21}$$

To obtain the plant's output, equations (18) and (19) are solved using Runge-Kutta (4,5) and the Dormand-Prince method. The scaling factors are tuned to give the required specified outputs, giving us the SSCN thermal power plant models as

$$\frac{dP_s}{dt} = 47u_1 - 0.019u_2 P_s^{\frac{9}{8}} - 0.0005u_3 - 0.4 \tag{22}$$

$$\frac{dP_e}{dt} = \left(12u_2 - 15\right)P_s^{\frac{9}{8}} - P_e \tag{23}$$

4.2 Result

Input data u_1 and u_3 (Figures 6 and 7) are imported into the MATLAB 7.10 environment (Figure 5) simulink. The simulation of the circuit after necessary turning of the constants shown in table 5 gives the SSCN power plant's output result shown in figures 8 and 9 respectively.

4.2.1 SSCN boiler system input data

Oil flow rate into boiler furnace is shown in figure 6.

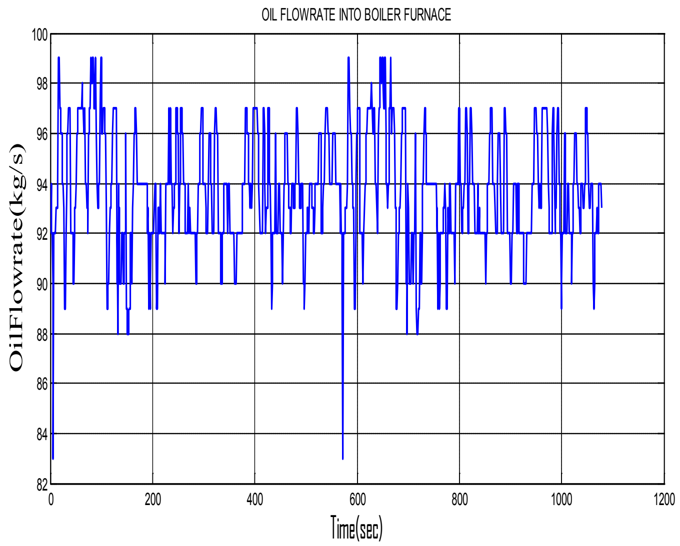

Figure 6 Oil Flowrate

Feed water into the boiler drum through the risers is shown in figure 7.

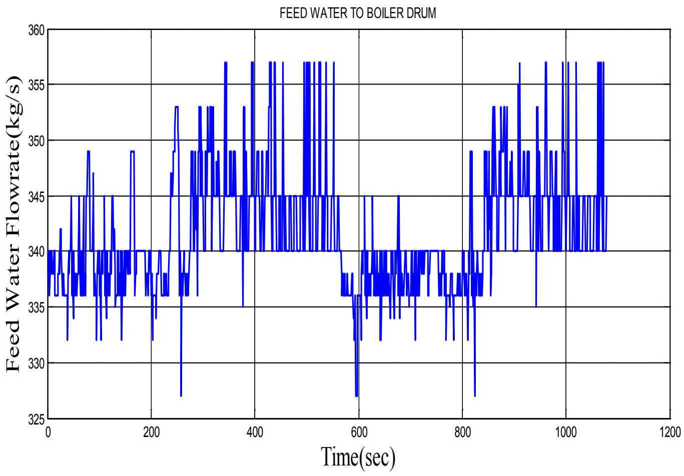

Figure 7 Feedwater Flowrate

4.2.2 Model outputs

Model simulation using the oil and feedwater flowrates into boiler gives the result ploted in figures 8 and 9.

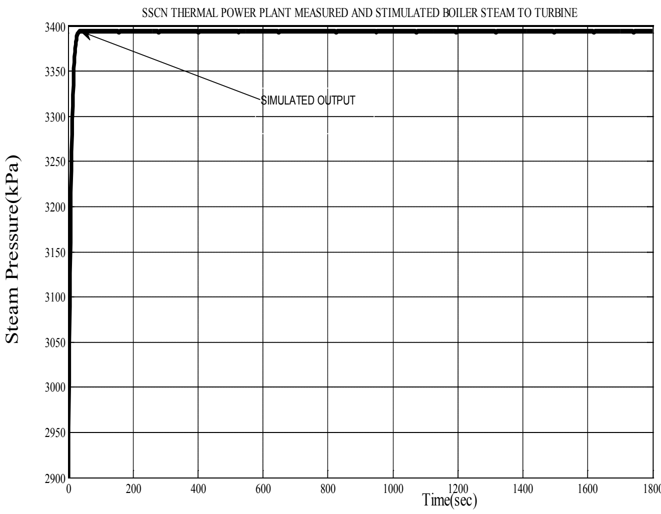

Figure 8 Boiler Steam Pressure to Turbine

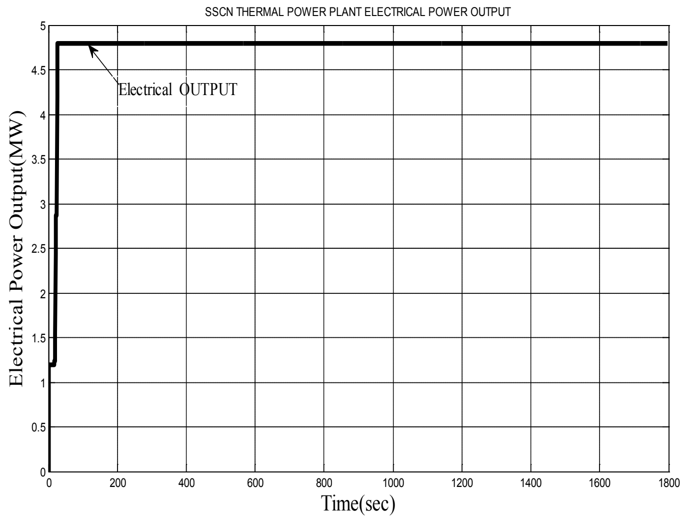

Figure 9 SSCN Power Plant's Electrical Output

4.3 Model validation

The data measured from the SSCN thermal power plant, are plotted against the simulated output obtained from the simulation circuit (Figure 4). The results of the measured data and simulated output for steam pressure and electrical output are shown in figures 10 and 11.

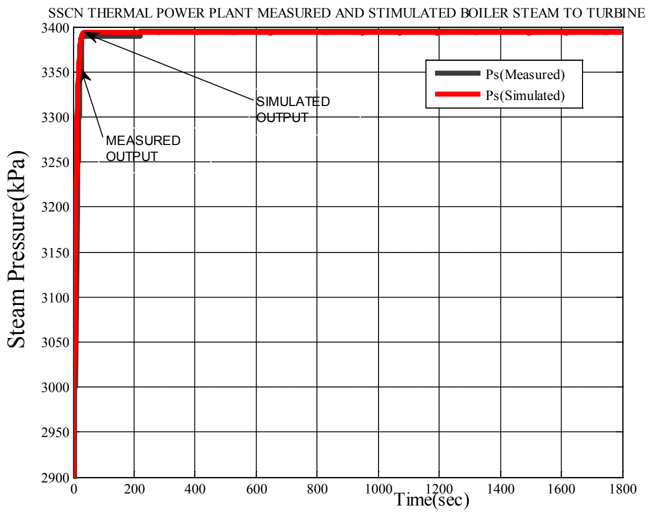

Figure 10 Measured and simulated SSCN Boiler Steam Pressure to Turbine

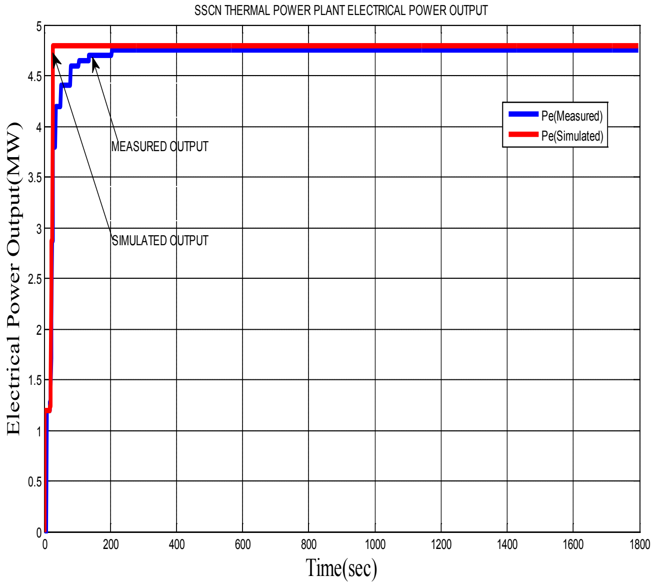

Figure 11 Measured and simulated SSCN Power Plant's Electrical Power output

5.0 DISCUSSION

The model simulated result in figures 8 and 9 is the same with the manufacturer's specifications. This is proven by using the measured steam pressure to turbine and electrical power generated by the existing plant data with the simulated output plots to investigate the steady state error of the plant. From the initial calculated values of the SSCN power plant, it shows that the plant is old and needs refurbishment. It can be seen in figure 10 that there is small steady state error from 20 secs to 210 secs which is clearly reflected in the plant electrical power generated shown in figure 11. The simulation output is seen to have steady state error from the measured output, which is seen to ramp from 20 to 200 secs from where a steady state error is maintained throughout.

5.1 Conclusion

The result obtained showed the electrical output has a steady state error of 2%. This means that the plants outputs are within acceptable range of the SSCN thermal power plant manufacturer's recommended values for boiler steam pressure and the generated electrical power. The validation of the plant shown in figures 10 and 11 clearly shows that the model can be used for dynamical study of the SSCN thermal power plant.

REFERENCES

Astrom, K.J. and Bell, R. D. (2000). *Drum boiler dynamics.Automatica* Vol.36. pp. 363-378,.

Baligh, E. H., Daniel, B. and Gregrory L. (2010*). Dynamic modeling of a combined cycle power plant with thermosyspro*.Eurosyslib Project. France, 2011.Journal of Process.

BMA Germany, Savannah Sugar Company Numan power Plant operational manuals.

Bolis, V. C., Maffezzoni and Ferrariri, L. (1993). Synthesis of the Overall Boiler-Turbine Control system by single Loop Auto-Turning Technique. Italy.

Cellier, F. E. (1982). *Progress in modeling and Simulation*. Academic press,.

Flynn, M. E and O' Malley, M. J. (1999). *A Drum Boiler Model for Long Term Power System Dynamic Simulation*. IEEE Transactions on Power Systems, Vol. 14, no. 1, 209-217.

Jiya J.D. and Gumpy J.M. (2008). *Design of Decentralized Generalized Predictive controller for Oil-Fired Boiler System*. Journal of Engineering and Technology (JET) Vol.3 no.2.

Leva and Maffezoni (2003). *Modeling and Simulation.Part1*, Chapter 2: Modeling of power Plants.pg 17-46.

Maffezzoni, C. (1997) Boiler Turbine dynamics in power plant control.Control engineering practice,vol.5.No 3, 301-312 Elsevier Science Ltd. Pergamon.

Reid and Renshaw (1971). ***Steam***. Cole publications, Melbourne, pp.26, 50, 84, 228,-1014.

Stefano B.(2010). Simulation Models of steam drums based on the heat transfer equations. Applied mathematical sciences Vol.4, No.74 pp 3687-3712.
Tor-Martin, T. and Carl-Johan, F. (2006). Multi-period steam turbine optimization part II: development of a muti- period MINLP model of utility system. Applied thermal.

Wen T. and Fang F. (2008). Linear Analysis and Control of a Boiler-Turbine Unit**.** Proceedings of the 17th World Congress. The International Federation of Automatic Control Seoul, Korea.

Yu, T., Chan, K.W., Tong, J.P., Zhou, B**.** and Li D.H, (2010). Coordinated robust nonlinear boiler-turbine-generator control systems via approximate dynamic feedback linearization.