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Performance Analysis of CCGT Power Plant using MATLAB/Simulink Based Simulation

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ABSTRACT

Combined Cycle Gas Turbine (CCGT) integrates two cycles- Brayton cycle (Gas Turbine) and Rankine cycle (Steam Turbine) with the objective of increasing overall plant efficiency. In modern gas turbine the temperature of the exhaust gases is in the range of 500 °C to 550 °C. Modern steam power plants have steam temperature in the range of 500 °C to 630 °C. Hence gas turbine exhaust can be utilized by a waste-heat recovery boiler to run a steam turbine based on Rankine cycle. The efficiency of a gas turbine which ranges from 28% to 33% can be raised to about 60% by recovering some of the low grade thermal energy from the exhaust gas for steam turbine process. This paper is a study for the modelling of gas turbine and using this model for optimizing the power of CCGT by varying parameters. The performance model for CCGT plant was developed in MATLAB/*Simulink*.

Keywords : Combined Cycle, optimization, dynamic model, Gas turbine, efficiency

1 INTRODUCTION

Electrical energy is a basic requirement for the sustenance and development of the modern society. Most of the generation today is met by plants utilizing fossil fuels like coal, natural gas and uranium. With the increase in the demand of electric power more generation is required. This problem can be solved by increasing the generation by either increasing the number of generating stations or by increasing the efficiency of the existing plants. As increasing the number of generating stations would be uneconomical and would cause problems related to installation, the generation has to be increased by the later method. The plants using fossil fuels as their source of energy have low efficiency as they are not able to fully utilize the calorific value of the fuel. One to increase the efficiency is by combining the generation of two or more thermal cycles in a single power plant.

The input temperature to a steam turbine is about 540°C and the exhaust can be maintained at the atmospheric pressure, due to design consideration the input temperature is limited and the efficiency of the about 40%. The input temperature of the gas turbine can be as high as 1100°C but the exhaust temperature can be lowered to about 500-600°C, the efficiency of a gas turbine is about 33%. It can be seen that to obtain higher efficiencies the exhaust of the gas turbine can used to drive the steam turbine giving efficiency up to 60%.

The plant consists of a compressor, combustor, gas turbine, waste heat recovery boiler, steam turbine, and generator(s).

The air is provided in the compressor which compresses the air and passes it to the combustion chamber, where the compressed air is mixed with the fuel and burnt. The mixture is then sent to the gas turbine where it expands and rotates the

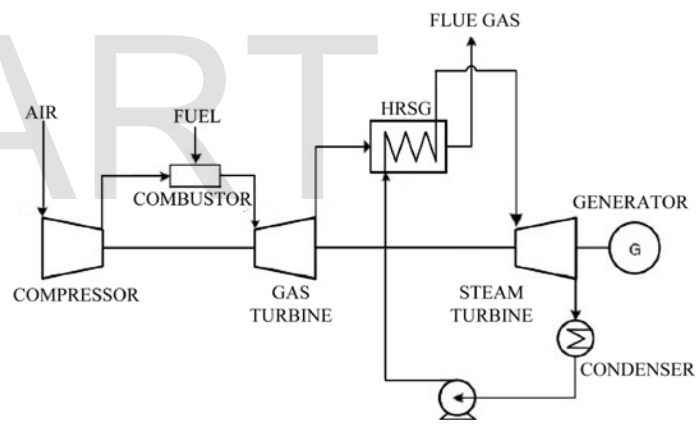

Figure 1. Combined Cycle Gas Turbine

turbine. The heat of the flue gas is recovered in HRSG (Heat Recovery Steam Generator) which is used to supply steam to the steam turbine at proper temperature and pressure. Plant power output is the sum of the gas turbine and the steam turbine outputs. [6-9]

2. CCGT THERMODYNAMICS

The airflow (W) in the gas turbine is given as

$$W = W_a \frac{P_a}{P_{ao}} \frac{T_{io}}{T_i} \qquad (1)$$

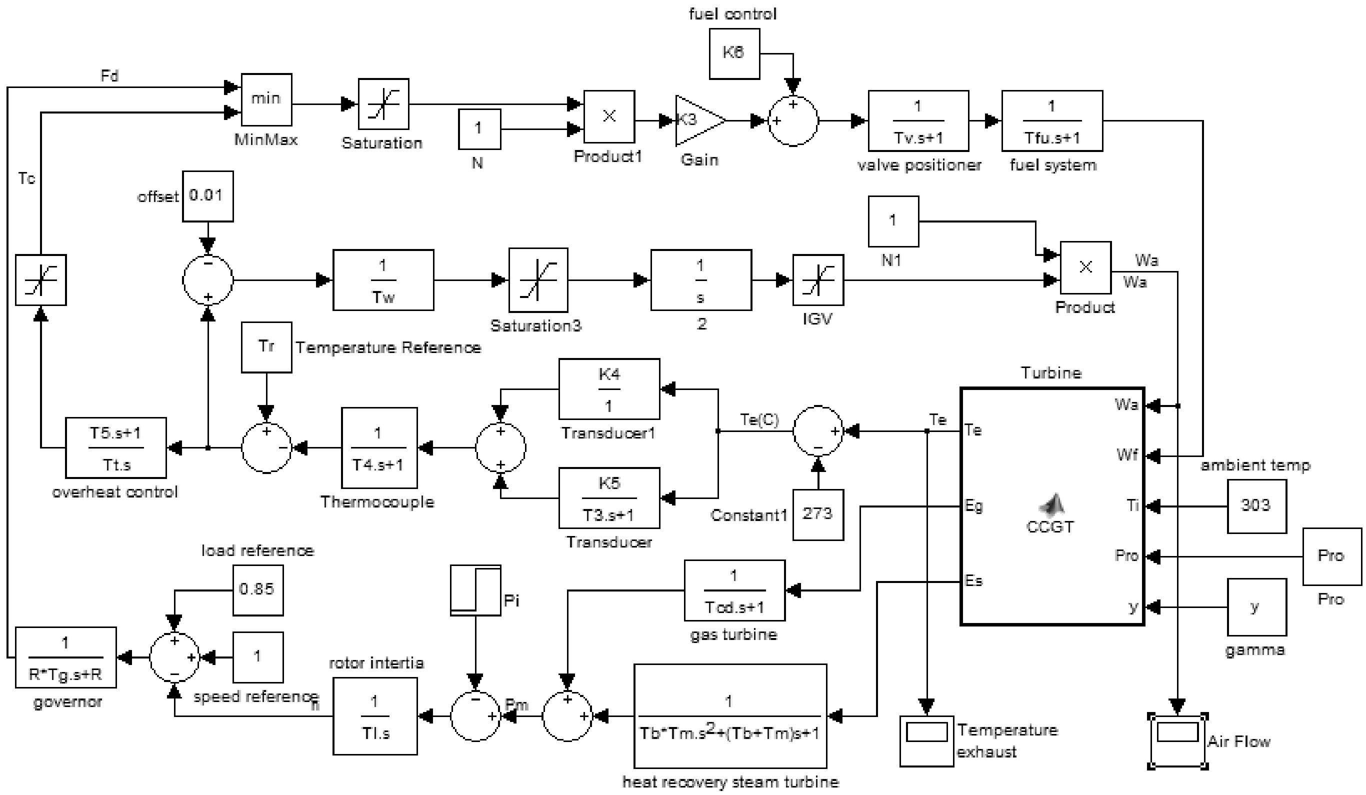

Figure 2. Simulink Model of Combined Cycle Gas Turbine

Where T_i is ambient temperature and P_a denotes the atmospheric pressure.

The compressor discharge temperature is given as

$$T_d = T_i\left(1 + \frac{x-1}{\eta_c}\right) \qquad (2)$$

$$x = (P_{ro}W)^{\frac{\gamma-1}{\gamma}} \qquad (3)$$

P_{ro} is the design compressor pressure ratio and y is the ratio of specific heats.

The gas turbine inlet temperature T_f (K) is given by [1]

$$T_f = T_d + (T_{fo} - T_{do})\frac{W_f}{W} \qquad (4)$$

Where W_f is fuel flow per unit its rated value, 'o' denotes rated value, W denotes the airflow and T_d denotes the compressor discharge temperature.

Gas Turbine exhaust temperature T_e (K) is given by [1]

$$T_e = T_f[1 - (1 - \frac{1}{x})\eta_t] \qquad (5)$$

Where η_t is turbine efficiency. The exhaust gas flow is practically equal to the airflow.

The efficiency of a combined cycle (unfired) is given as, Horlock [6]

$$\eta_{cc} = \eta_{gt} + \eta_{st}(1 - \eta_{gt}) \qquad (6)$$

Where η_{cc} is the efficiency of the combined cycle, η_{gt} is the efficiency of Gas Turbine and η_{st} is the efficiency of Steam Turbine. The thermal efficiency of the simple gas turbine cycle is given as [2]

$$\eta = \frac{(1-\frac{1}{p_p})(a-p_p)}{\eta_c(k_1-1)-p_p+1} \qquad (7)$$

Where, $a = \eta_c \eta_t k_1$

Where p_p is the isentropic temperature ratio (T_2/T_1), k_1 is the cycle maximum temperature ratio (T_3/T_1).

Differentiating (6) gives [7]

$$\frac{\partial \eta_{cc}}{\partial \eta_{gt}} = 1 + \frac{\partial \eta_{st}}{\partial \eta_{gt}}\left(1-\eta_{gt}\right) - \eta_{st} \qquad (8)$$

The overall efficiency improves with the increase in gas turbine efficiency if

$$\frac{\partial \eta_{cc}}{\partial \eta_{gt}} > 0 \qquad (9)$$

From equation (8) and (9) one obtains:

$$-\frac{\partial \eta_{st}}{\partial \eta_{gt}} < \left(\frac{1-\eta_{st}}{1-\eta_{gt}}\right) \qquad (10)$$

3. Description of Simulink Model

Several CCGT models have been developed in past few decades with to describe the behavior of gas turbine. The basic gas turbine model equations (Rowen Model II) [4-5] for a single shaft system were given by Rowen in 1992. Fig. 2 shows a dynamic model of a combined cycle gas turbine.

This model consists of various blocks describing various parameters whose variations have to be studied in order to optimize the performance of combined cycle. There are blocks related with speed/load, temperature control, fuel control, air control and other blocks for gas turbine, waste heat recovery boiler/steam turbine, rotor shaft, and temperature transducer.

The speed/load block (governor) for determining the fuel supply F_d when compared with a reference load and rotor speed deviation (1-N) [3].

The temperature control block (overheat control) is for controlling the exhaust temperature (T_e °C) of the gas turbine so that the gas turbine does not get injured. The temperature is measured with the help of various transducers and compared with a reference temperature. Then the output of the temperature control is combined with speed/load control to determine the fuel demand (using low select value).This control block has been used for plotting the graph in Fig 7.

The fuel control block (valve positioner and fuel control) performs according to the minimum value provided by the speed/load control and temperature control and determines the fuel flow W_f.

The air control block (saturation 3 and saturation 4) is to adjust the air flow in the gas turbine to attain a desired exhaust temperature so that the temperature is kept below a reference temperature by an appropriate offset. This control block is used for plotting the graph in Fig. 8. All the parameters used in the model are given in Table 1.

4. RESULTS AND DISCUSSION

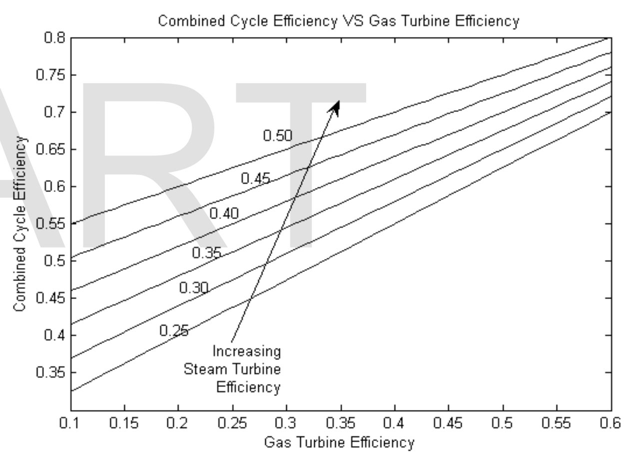

Figure 2. Combined Cycle Efficiency versus Gas Turbine Efficiency

Fig. 3 shows the plot of overall efficiency versus gas turbine efficiency with varying steam turbine efficiency as per equation (6). It can be seen that combined cycle efficiency increases with the increase of both gas turbine efficiency and the steam turbine efficiency.

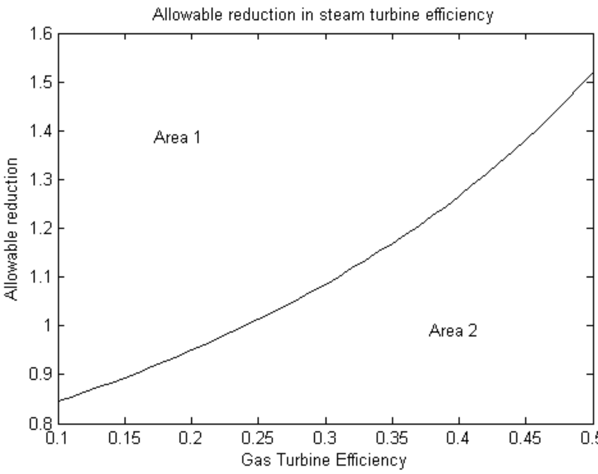

Figure 3. Gas Turbine efficiency versus rate of change of Steam turbine efficiency

Fig. 4 shows the plot of allowable reduction in steam process efficiency with respect to gas turbine efficiency versus gas turbine efficiency for constant steam turbine efficiency equal to 24%. As the gas turbine efficiency is increased the allowable reduction also increases for which the overall combined cycle efficiency increases which is represented by area 2 as per equation (10).

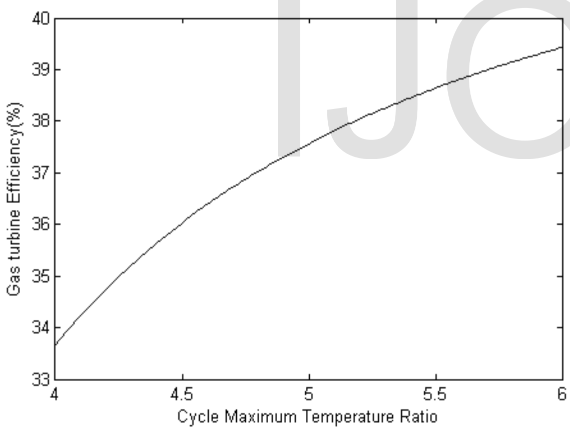

Figure 4. Gas Turbine Efficiency versus Maximum Cycle Temperature Ratio

Fig. 5 shows the variation of gas turbine efficiency with cycle maximum temperature ratio T3/T1=5.679, keeping the pressure ratio constant in accordance to equation (7). It shows that the turbine efficiency can be increased by increasing the maximum temperature ratio of Simple Gas Turbine Cycle. The rate of rise in efficiency of gas turbine decreases as the temperature ratio is increased.

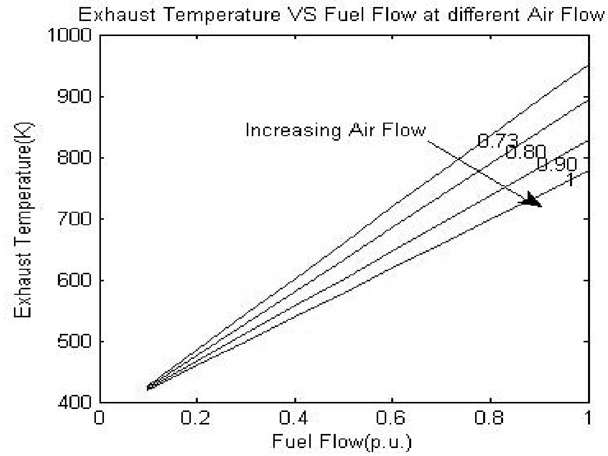

Figure 5. Exhaust Temperature versus Fuel flow

Fig.6. shows how exhaust temperature of the gas turbine varies with the fuel flow as per equation (5). It can be seen that the exhaust temperature increases with more fuel flow as more energy is supplied when the flow is increased and hence increase in temperature. With the increase in air flow there is a decrease in the rate of rise of the temperature.

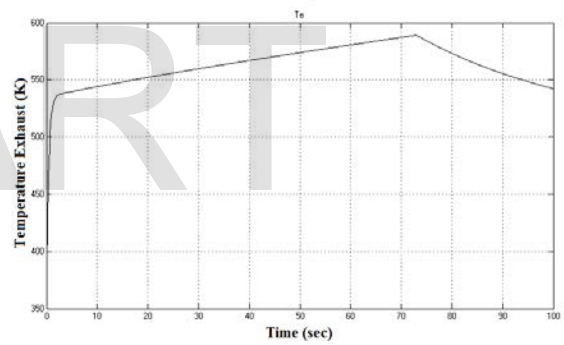

Figure 6. Exhaust Temperature ($^\circ C$) versus Time

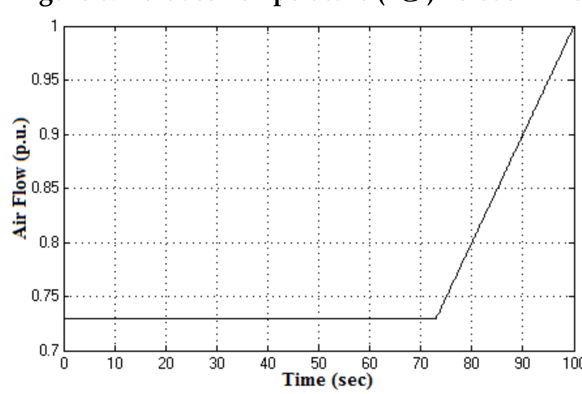

Figure 7. Air Flow (p.u.) versus Time

Fig.7. shows the variation of exhaust temperature with time. The exhaust temperature first increases due to more fuel flow till a reference temperature after which the air flow is increased in the gas turbine to keep the fuel to air ratio constant so that there is specified burning of the fuel in the gas turbine. Due to increase in the air flow in the gas turbine the tempera-

ture of the gas turbine drops. It can be seen that at time~75 sec the exhaust temperature reaches a reference value after which

Symbol	Description	Value
T_i	Compressor inlet temperature	$30\,^{\circ}C$
T_{do}	Compressor discharge temperature	$390\,^{\circ}C$
T_{fo}	Gas turbine inlet temperature	$1085\,^{\circ}C$
T_{eo}	Gas turbine exhaust temperature	$535\,^{\circ}C$
P_{ro}	Compressor pressure ratio	11.5
γ	Ratio of specific heat	1.4
η_c	Compressor efficiency	0.85
η_t	Turbine efficiency	0.85
R	Speed Regulation	0.04
T_t	Temperature control integration rate	0.469
$T_{c\max}$	Temperature control upper limit	1.1
$T_{c\min}$	Temperature control lower limit	0
$F_{d\max}$	Fuel control upper limit	1.5
$F_{d\min}$	Fuel control lower limit	0
T_v	Valve positioner time constant	0.05
T_{fu}	Fuel system time constant	0.4
T_w	Air control time constant	0.4669
T_{cd}	Compressor volume time constant	0.2
K_0	Gas turbine output coefficient	0.0033
K_1	Steam turbine output coefficient	0.00043
T_g	Governor time constant	0.05
K_4	Gain of radiation shield	0.8
K_5	Gain of radiation shield	0.2
T_3	Radiation shield time constant	15
T_4	Thermocouple time constant	2.5
T_5	Temperature control time constant	3.3
K_3	Ratio of fuel adjustment	0.77
K_6	Fuel valve lower limit	0.23
T_m	Tube metal heat capacitance time constant of waste heat recovery boiler	5
T_b	Boiler storage time constant of waste heat recovery boiler	20
T_i	Turbine rotor time constant	18.5

Table 1. System Parameters

it decreases. From Fig.8 it can be seen that the IGV (Inlet Guide Vanes) start opening to allow more flow of air and thus reducing the exhaust temperature as can be seen by the drop in the exhaust temperature after 75 sec.

5. CONCLUSIONS

A model of CCGT was developed and variation of efficiency by varying various parameters was studied. The results of which can be summarized as follows:-

(1) The efficiency of Gas Turbine increases with the maximum cycle temperature ratio. The exhaust temperature of the Gas turbine can be increased up to a limit only due to structural limitations. But inlet Temperature (T1) can be lowered which increases the maximum cycle temperature ratio (T3/T1) which in turn will increase the Gas turbine efficiency.

(2) Improving the gas turbine efficiency does not necessarily mean the increase in the overall efficiency of the combined cycle. The efficiency of gas turbine and steam turbine depend upon the input and the output temperature of the turbine. Increasing the gas turbine efficiency would cause lower input steam temperature for steam turbine for given output temperature so the efficiency of the steam turbine would decrease causing the drop in the overall efficiency of the combined cycle.

(3) The temperature exhaust of the gas turbine is also an important parameter which has to be maintained as by increasing fuel flow more power output can be obtained but it would cause a rise in the temperature but since the temperature has to be limited below a safe value as an increase in temperature can cause the turbine components to get damaged. The temperature is controlled by more air flow in the turbine.

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