Optimization Based Dynamics Setpoint Control to Improve Cycle Power Efficiency of The Lm6000pf+ Aero Gas Turbine

Viriya Kongratana and Wissanudech Tawangkan and Napasool Wongvanich *

Abstract— **The efficiency of the Aero Gas Turbine in a combine cycle power plant (CCPP) is maximum under the conditions that the combustion chamber temperature is highest, the compressor is working at full capacity and all bleed valves are closed. The Inlet Air Heating System is therefore used to improve the efficiency of the machines in low power generation conditions. To ensure stability in response to air temperature and machine capacity changes, this work thus proposes an optimization-based automation system designed to stabilize the CCPP. Results show that under changing conditions, the overall efficiency of the air compressors in low load conditions increases by 3%, shortening the system start time of 15 minutes and improving the efficiency of the combined cycle power plant by an average of 100 BTU / kw.hr. The average fuel cost is reduced by approximately 600,000 baht per month.**

Index Terms— **Gas Turbine, Compressor, Combined Cycle Cower Plant (CCPP), Efficiency.**

I. Introduction

ELECTRICAL power generation is one of the cornerstones that drives the global economy. Natural gas is one of the main fuels used for power generation, with 61.75% of the power plants operating from natural gas in Thailand [1] by using Combine Cycle Power Plants (CCPP). The fuel costs of a power plant comprise a gargantuan 75% of the total costings throughout the machine's life cycle [2], motivating the developments of cost effective models and operations.

Gas Turbine is a power generation machine that generates combine cycle systems, with many desirable properties such as an increasing combustion chamber temperature, the development of the cooling system and the improvement of the temperature resistance properties of the material [3]. Temperature and relative humidity in the air are key factors affecting gas turbine performance. Reducing the air temperature effectively results in an increase in electrical outputs, thereby improving the efficiency of the machine. Gas turbine is most effective when operating at full efficiency. If the capacity is reduced, the air ratio from the air compressor will be reduced, resulting in a decrease in the efficiency of air compressors and gas turbines [4].

Aero Gas Turbine is most effective when the combustion chamber temperature is highest, the air compressor (works at full efficiency, all bleed valves are closed. However, the machine's performance will be dropped when the machine's idling performance or production is reduced due to bleed valve openings in an attempt to reduce the amount of air entering the machine and lower exhaust temperature to increase the efficiency of the machine during low production capacity. Therefore, the Inlet Air Heating System is used to improve the efficiency of machines in low load conditions by increasing the intake air temperature to reduce exhaust air discharge from the air compressor, increasing the combustion chamber temperature and exhaust temperature, which result in better overall efficiency of combine cycle Systems [5].

Inlet air temperature has considerable potential for improving gas turbine efficiency due to the increase in compressor and turbine efficiency. This finding is different from traditional viewpoints. Meanwhile, each partial load has an optimum heating temperature which becomes higher when the load is lower. [10] Inlet Air Heating System is designed to provide a constant supply of the required air temperature by the machine operator. The operator will enter the temperature increase until the guide vanes to remain fully open. As a result, there are no issues involving a pressure drop ahead of the compressor stages or flow separation, and high overall efficiency is possible, even at a low fraction of full-load output, this process allows the inlet guide vanes to be fully opened, so that the compressor runs in the most efficient range. [10]. But it is difficult and the system needs to be monitored regularly in response to air temperature and machine capacity changes. Attempts at developing controllers to stabilize the CCPP have been studied in the literature. Eslami et al. [8] applied an artificial bee colony (ABC) algorithm to design an optimal PID-based low pass filter for a gas power plants. A fractional-order PID controller was also proposed in ref. [9] to enhance the CCPP temperature and frequency responses. This work thus proposes an optimization-based dynamics setpoint control to improve the cycle power efficiency of the LM6000PF+ aero gas turbine.

II. LM6000PF+

The LM6000PF+ gas turbine is an aero gas turbine manufactured by GE, with structural features consisting of

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double stacked shafts. The inner shaft drives the electric generator and the low-pressure compressor in 5 stages. The outer shaft drives the oil control unit and the high pressure compressor in 14 states with a device to control the amount of air to enter the combustion chamber properly and prevent damage of all 5 air compressors, namely Variable Inlet Guide Vane (VIGV), Variable Bleed Valves (VBV), Variable Stator Vane (VSV), ST8, and Compressor Discharge Pressure (CDP) as shown in Fig. 1.

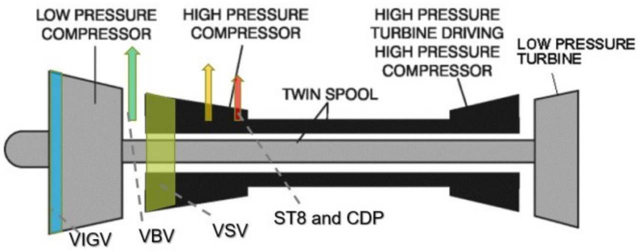

Fig. 1 The air volume control components and units of the LM6000PF + gas turbine.

VIGV acts as a switch to adjust the angle of collision, in order to reduce the air volume of the low-pressure compressor. VBV acts on and off to control the amount of air optimally from low pressure compressor to high pressure compressor. VSV acts as a switch to adjust the collision angle to increase the air volume of the high pressure compressor. ST8 and CDP controls the air volume to suit the combustion of machine.

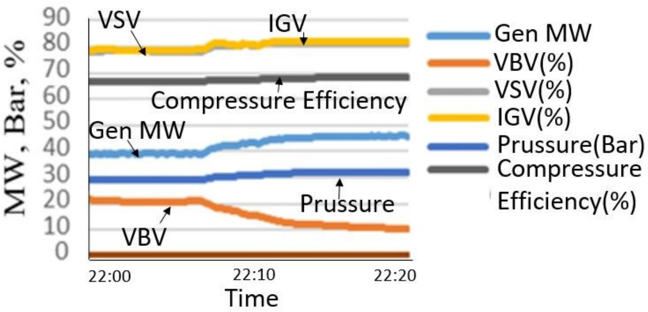

Fig 2. The operation of the air volume control unit and performance of the air compressor.

In times of high capacity demand, a large amount of air is required to enter the combustion chamber. In this case the VIGV is opened, while the VBV is opened less. The ST8 and CDP will gradually close to increase the amount of air resulting in the air compressor working at full efficiency. However, when the machine is needed to reduce production capacity, there must be a reduction in the air volume for combustion. VBV will be opened up, ST8 and CDP will be reopened again. This increased opening is considered to release air energy into the atmosphere without entering the combustion process, and consequently results in lower air compressor performance at low production conditions.

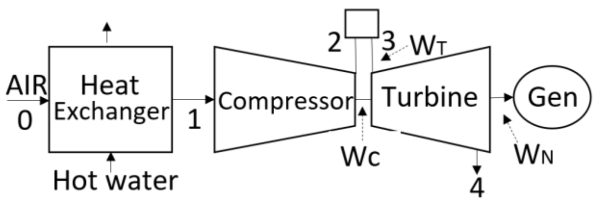

Fig. 3. The Gas turbine cycle.

Gas Turbine works by compressing air from the atmosphere (0) through an air filter system (1) through a compressor to obtain air with high pressure and temperature (2), during which the air and fuel will be brought to combust. The resulting energy from the combustion (3) will be used to drive a gas turbine, where the residual hot gas from the gas turbine (4) can be used for further thermal utilization. Figure 3 show the turbine is connected to the same shaft as the compressor and connected to the generator. Equation (1.1) – (1.2) describe the work-net of the generator. The mechanical efficiency of the machine is given in Equation (1.3).

$$W_N = W_T - W_C \qquad (1.1)$$

$$\frac{Wn}{Wt} = 1 - \frac{Wc}{Wt} \qquad (1.2)$$

$$EFF = 1 - \frac{Wc}{Wt} \qquad (1.3)$$

where W_N is the work-net at the generator will be given; W_T is the work-net that a gas turbine receives from combustion; W_C is the work-net used to drive the air compressor, and EFF is the mechanical efficiency of the machine. From Equation (1.3) it is seen that if the air compressor has good efficiency, it uses less net to drive to get the same air volume, resulting in better mechanical efficiency. The efficiency of the air compressor is calculated from Equation (2).

$$N = \frac{T2' - T1}{T2 - T1} = \frac{(P2/P1)^{\frac{Y-1}{Y}} - 1}{\frac{T2}{T1} - 1} \qquad (2)$$

where T is air temperature, P is air pressure, Y is air specific heat ratio equal to 1.4.

III. Combined Cycle Power Plant

The combined cycle power plant is a combination of the technology of power plants, gas turbines and steam turbines. The exhaust from the gas turbine power plant, with excessive heat of 500 degrees Celsius is passed through the Heat Recovery Steam Generator and transfer to drive a steam turbine that is connected directly to the generator.

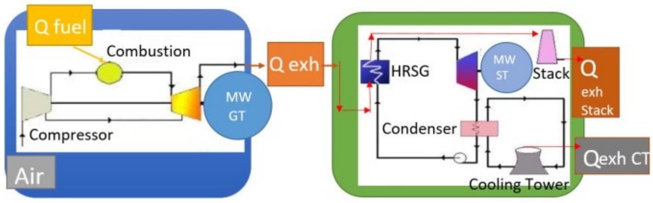

Fig. 4 The combined cycle power plant

The power plant consists of two gas turbines and one steam turbine. The thermal energy from natural gas is converted into electrical energy at the gas turbine. The residual heat is then used as energy to generate steam to be converted into electrical energy at the steam turbine. There is heat loss at the boiler vents and cooling towers used for condensing steam from electricity generation to recycle water by increasing the temperature of the hot steam from the gas turbine by 10 degrees Celsius, resulting in more steam produced, allowing the steam turbine to generate up to 1.9% more electricity [6]. In addition, increasing the

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temperature of the steam before entering the steam turbine results in a more efficient cycle, enabling fuel savings of 8 BTU / kw.hr. [7]

IV. Inlet Air Heating Systems

The Inlet air heating system is designed to increase the air temperature before entering the gas turbine to improve the efficiency of the machine in low load conditions by increasing the intake air temperature to reduce the exhaust air from the air compressor, increase combustion chamber temperature and machine outlet temperature, which consists of 2 sets of heat exchangers: Water-Air Heat Exchanger (HE1) to increase the air temperature from hot water, with a pump to control the flow rate of water in a closed heat exchanger system; and a steam-to-water heat exchanger (HE2) whose job is to increase the water temperature by steam, with a valve (LCV) regulating the water level in the heat exchanger to control the amount of steam flow, as well as the amount of heat available in the system. Opening the valve will drain the water in the heat exchange and turns the heat out, increasing the contact area between the heat exchanger and the steam, and the system will get a higher amount of heat as shown in Fig. 5.

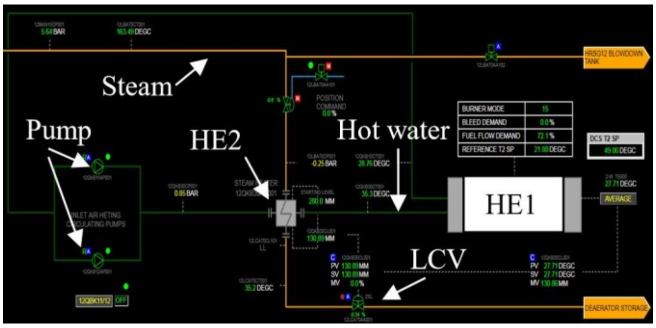

Fig. 5. The inlet air heating system

The control of the air temperature rise is achieved by solving the optimization problem:

$$\min \int_0^{T_f} \left| t\left(T_{gas,d} - T_{air}\right)\right| dt \qquad (3)$$

subjected to the constraints:

$$0 < u_{heat}(t) < u_{heat,\max}$$

where $T_{gas,d}$ represents the desired gas turbine temperature level, T_{air} is the current air temperature, $u_{heat}(t)$ represents the heat required to keep the temperature at the desired set point. The required heat is, in turn, controlled by adjusting the control valve position, which solves the optimization problem online:

$$\min \int_0^{T_f} \left| t\left(Q_{req} - Q_{air}\right)\right| dt \qquad (4)$$

subjected to the constraints:

$$0 < u_{valve}(t) < u_{valve,\max}$$

Where Q_{req} is the required heat and u_{valve} is the control valve position. In terms of the implementation, an engineer then enters the Distributed Control System (DCS) the desired gas turbine (T1MAN), as well as the current air temperature (TT1). Additional settings also include control valve position (LCV). The implementation settings are shown in Figure 6.

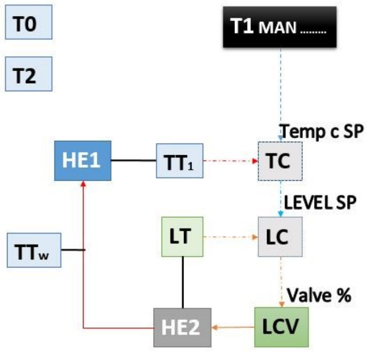

Fig. 6 Schematics of the controller for the inlet air heating system

The designed control system can control the air temperature before entering the gas turbine, to within an acceptable range. However, the air compressor outlet temperature could change as the engine itself changes its capacity. This means that the machine will not be able to achieve its optimal efficiency at the maximum outlet temperature of the air compressor. A major consequence of this is that the operator then has to increase the temperature carefully. This scenario is shown in Fig. 8.

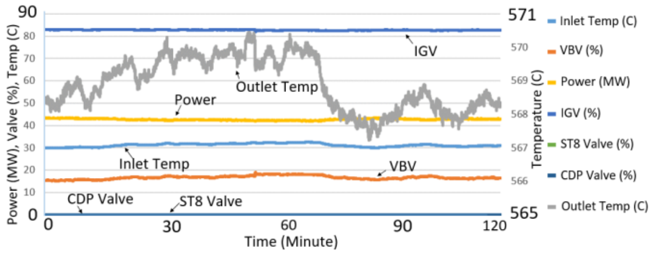

Fig. 7 Show the controls by entering values with the operator.

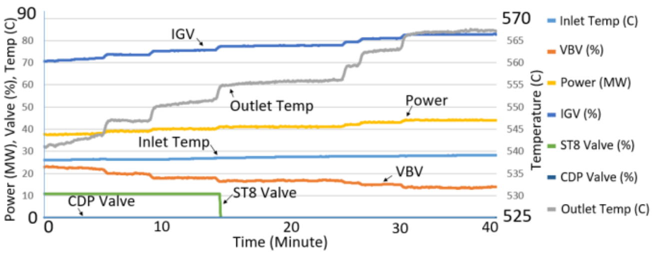

Fig. 8 Control system startup

V. Automatic Set Point

To alleviate such a problem effectively, an automatic set point system is employed. This system is designed to automatically enter the inlet air temperature control value(T1AUT) to change the air temperature by keeping the air temperature being exited from the compressor (T2) in order to keep the machine at the best performance throughout the operation. Changes in the inlet air temperature. (ΔT1) affects the temperature change of the outlet air. (ΔT2) which will yield the following relationship:

$$\Delta T1 \rightarrow \Delta T2$$

$$T1set = T2set - T2(t) + T1(t) \quad (5)$$

With the dynamic setpoint system in place, the control then solves the following optimization problem:

$$\min \int_0^{T_p} \left| t\left(T_{1,set} - T_1\right) \right| dt$$

Subjected to the following relations:

$$T_{1,set} = T_{2,set} - T_2 + T_1$$

$$T_{1,set(auto)} - T_0 = T_{hotwater} \pm 2$$

Note that the second constraint is such that the water temperature to be controlled must not be higher than two degrees than the temperature of the hot water to prevent the occurrences of overheating of the overall system. Figure 9 shows the overall implementation of the system.

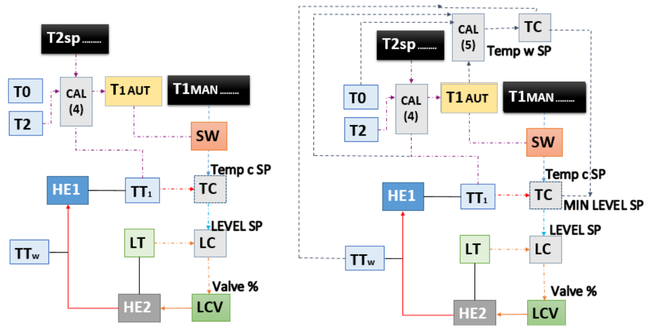

Fig. 9. Schematic of the implementation of the automatic set point controller

VI. EXPERIMENTAL RESULTS

A simple experiment was conducted on the automatic inlet air heating system prior to entering the gas turbine during a lower load gas turbine phase. The efficiency of operation of the power plant was measured prior to implementing the designed system, as well as after implementing the control which control the inlet air heating temperature by operator compare to dynamic set-point. During production, constant air compressor outlet temperature at the optimum point (568 to 570-degree C refer to machine performance test) is achieved through adjusting the heating so that the temperature prior to entering the air compressor changes appropriately with the static error of the air compressor outlet temperature being no more than 0.5 degrees Celsius as shown in Figure 10. During the gas turbine power reduction, the air compressor outlet temperature, the combustion chamber temperature and the hot gas entering the boiler are lower; this lowers the efficiency of the air compressor, and in turn lowers the boiler steam, thereby affecting the overall efficiency of the power plant as a whole. As the automatic inlet air heating system is implemented, the guide vanes to remain fully open and stops the exhaust air from the compressor. This in turn causes the outlet temperature from the air compressor, the combustion chamber temperature and the hot gas entering the boiler to be increased, resulting in a 3% and 100 BTU / kw.hr per day improvement of the compressor and power plant respectively. In addition, the system start time was shorter than manual set point by operator by a significant 15 minutes, reducing a sizeable fuel cost of the power plant by up to 600,000 baht (19000 USD) per month. Table 1 summarizes the comparison of the experimental results of the automatic inlet air heating system.

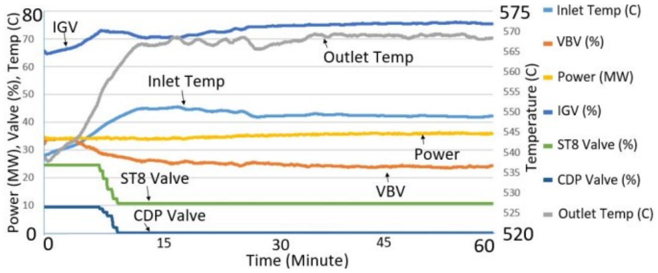

Fig. 10. Control system implementation by Autofill

Table 1: Efficiency improvement of the combined cycle power plant with the automatic inlet air heating system before entering the LM6000PF + gas turbine.

Parameter	Before	After	Variation
Heat rate (BTU/kW)	8491	8348	-143
VIGV (%)	65.3	70.6	5.3
VBV (%)	32.8	25.1	-7.7
ST8 (%)	24.6	10.8	-13.8
CPD (%)	9.5	0	-9.5
Power (MW)	34	34	0
T1 (Degree c)	28	45	17
T2 (Degree c)	539	569	30
Compressor Eff (%)	88	91	3
HRSG Temp. Inlet (Degree c)	508	523	15

VII. CONCLUSION

System was designed to regulate the air compressor outlet temperature by changing the machine inlet air temperature in the state of changing air temperature and capacity and keeping the guide vanes open, bleed valve closed. This design has resulted in significant efficiency increments of the air compressor in low load situations by about 3%; thereby shortening the system start time of 15 minutes and improving the efficiency of the combined cycle power plant by an average of 100 BTU / kw.hr which can reduce the average fuel cost of 600,000 baht per month. However, whether the inlet air heating is acceptable must be analyzed in accordance with the characteristics of different gas turbine units and Heat.

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