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Ambient Temperature Effect on the Performance of Gas Turbine in the Combined Cycle Power Plant

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ABSTRACT/RESUME

Abstract: *Recently, combined-cycle power plant systems are the most efficient concept used for generating electricity. The advanced closed loop steam cooling system which involves the gas turbine and steam turbine cycles has produced one of the most environmentally adequate existing power generation systems. Gas turbines (GTs) were developed quickly and used in many applications especially in combined cycle power plants, due to their higher efficiency and lower emissions in carbon dioxide (CO_2), compared to other categories such as diesel engines. Therefore, increasing attention in the study of heavy-duty gas turbines (HDGT) models has been acquired with diverse amounts of difficulty and merit. Thus, modeling and simulation of the HDGT behavior under accurate operating conditions play a significant role for efficient design as well as reliable manufacturing practice. Thus, the improvements of their efficiency will significantly reduce (CO_2) emissions.This paper focuses on the impact of ambient temperature on the gas turbine performance in the combined cycle power plant. The study presents modeling and analysis of the gas turbine behavior based on the frequency dependent model (FD model), using Matlab/Simulink. In our approach, simple time delays are integrated to the FD model, taking into consideration the effectiveness and accuracy of the model. This is achieved by a complementary analysis study, of the temperature effect on the efficiency of the gas turbine (GT), and then the combined cycle power plant.*

I. Introduction

Among the studies about the impact of the coronavirus pandemic and his effects on energy and the environment, (Liu et al.) reveal that about 29% of the decrease in emissions global greenhouse gas (GHG) were from industry, during the first trimester of 2020 [1]. Today, the disturbance of energy systems and the environment make a challenge in the emerging technology production systems. It provides imperative opportunities to invest in the environment and clean energy through directing interference. Due to their attractive performance characteristics and low emission combustion system, combined cycle installations have considerable merits in power generation plant. On the other hand, important increase efficiency can be reached by using natural gas instead of fossil fuels [2], particularly in advanced effectiveness combined cycle power plants. A significant analysis achieved by authors [2] shows that the increasing efficiency and reducing natural gas losses can improve the environmental gains. Recently there is an increasing interest to the combined cycle power generation plant, especially in countries endowed with huge natural gas resources. This type of power plant reached a high efficiency by producing great output power with low carbon dioxide emissions, compared to the conventional power plants [3], such as the simple cycle power plants. The mainly approach to improve the effeciency of the combined cycle power plant is to maintain the inlet air temperature of the compressor around 15°C (ISO) and relative humidity of 100% of the gas turbine [4]. Recently, various studies of GT behavior in combined cycle plants have been achieved based on different mathematical modeling approach [5]. Due to their specific characteristics, industrial power plant gas turbines (IPGT) are adopted worldwide for electrical power generation [6]. A gas turbine is a complex system and critically nonlinear in its whole behavior, so, as the complexity increases, the accuracy of the simulation model decreases. Nonetheless, whatever the adopted GT model, there are two main quantities that determine the turbine behavior, namely the output torque and the exhaust gas temperature [7-10]. These quantities come along with two control loops: the speed governor control loop and the exhaust temperature control loop. The temperature control of a gas turbine limits the exhaust temperature by reducing the fuel flow (and hence the power output) as the air flow decreases with the shaft speed [11]. The gas turbine performance mainly depends on the efficiency of the compressor, which is directly reliant on the airflow, as well as the ambient temperature [12]. However, the ambient temperature changes, thus, the performance of the gas turbine can be affected. At high temperature, the air is less dense; consequently, this can decrease the gas turbine's performance [13]. The study of results obtained by [12] demonstrates that the output power and the thermal efficiency of the gas turbine depend on the ambient temperature. Therefore, it is necessary to consider the environmental conditions to characterize correctly the thermodynamic process in GT [5].

In this paper, a 265 MW single shaft gas turbine is considered; its parameters defined in [14] (the parameters are given in appendix). In the first section, brief descriptions of the above mentioned FD model is given, besides of the expected simulation results. As mentioned in [11], the model is not intended for simulation of start-up, shutdown. In order to investigate the model performance, the considered model is simulated under nominal operation conditions without acceleration control loop. Speed reference is equal to one pu during all simulations. It is necessary to mention that simple time delays are introduced in the model. The simulation is performed for various ambient temperatures.

II. Gas turbines performance in the combined cycle power plant

Gas turbines are the key to the industrial power production and the important part of the design of power generation plant. The main components of GT are compressor, combustion chamber (combustor), and turbine. Compressor and turbine are connected by the central shaft and hence they rotate together.

The complications working of GT are appeared in the thermal process, which requires fluids to work under very high temperatures and pressures [15]. Gas turbine is as an internal combustion engine which uses the gaseous energy of air to convert chemical energy of fuel to mechanical energy.

The whole work of a GT based on thermodynamic processes, recognized by Brayton cycle, based on the compression of air by the compressor and transferred to the combustion chamber. After that, this compressed air is mixed with the fuel for generating high temperature flue gases that is transformed to mechanical power in the turbine [16], and then converted into electrical power by the coupled generator. In the combined cycle power plant, the extended exhaust flue gases of the GT used to drive the steam turbine by transmitting these gases through the heat recovery steam generator (HRSG). The mechanical power produced by the steam turbine is converted into electrical power.

III. Mathematical modeling of gas turbine

Literature study shows that there is a wealthy source of research activities in the field of modeling, simulation, and control systems. The requests for the exploring of gas turbine performance and reduce the cost of designing new engines had led to develop several dynamic simulation models, in order to achieve a deeper analysis of the system. Dynamic modeling and simulation employed to the analysis of the unstable behavior of power plants and to improve the development of control strategies and tuning of control parameters. Significant advances and improvement of mathematical modeling based on physical phenomena prove their pact with the results of experimental measurements [6]. Among these models, the frequency dependent model (FD model) is the main object of this study.

III.1. Frequency dependent model

The frequency dependent (FD) model presents a process that may enable parameter estimation of the frequency dependency from the output power of the turbine and ambient temperature [11, 17-19]. However, for the purpose of the development of an appropriate structure, this model based on mathematical equations is deduced from physical principles. Hence, a new formulation of the gas turbine thermodynamic characteristics has been developed for revealing the effects of shaft speed [11].

- Air flow equations

$$Wa = q(Ta,Pa)U(\Delta N)\frac{sin(\theta_{IGV}-\theta_0)}{sin(\theta_{Max}-\theta_0)} \quad (1)$$

$$q(Ta,Pa) = \left(\frac{Pa}{Pa0}\right)\sqrt{Ta0/Ta} \quad (2)$$

$$U(\Delta N) = 1 + (A_0\Delta N) + (A_1\Delta N^2) + (A_2\Delta N^3) \quad (3)$$

$$\Delta N = N(\sqrt{T_{a0}/Ta}) - 1 \tag{4}$$

Where:Ta=288K, which is the ambient temperature, and Pa=1 atm, which is the atmosphere pressure.

- Compressor Pressure Ratio (CPR) equation,

$$CPR = \left(A_5 W_a + A_6 W_f\right)\left(\frac{P_{a0}}{P_a}\right) + A_7 \tag{5}$$

- Exhaust temperature Equation,

$$Tx = Ta + \frac{A_3\left(\frac{Pa}{Pa_0}\right) + A_4 W_f}{W_a} \tag{6}$$

Where,
$A0 = 0.945, \quad A1 = -7.8, A2 = 39,$
$A3 = 126.7, \quad A4 = 461.6, \quad A5 = 11.6$
$A6 = 4.64, \quad A7 = -0.85, \theta0 = 8.73°,$
$\theta max = 88°, T_{a0} = 288°K,$
$P_{a0} = 1$ atm, $\quad W_{f0} = 0.23,$
$T_{trb} = 0.2$ sec.

However, the parameters (A0, A1, and A2) can be estimated. In [11, 17], we can find more details about the structure of the model and the mathematical equations used in FD model. Furthermore, most of the parameters of the gas turbine thermodynamics can be estimated from loading test data in the steady state characteristics, except for their frequency dependency [11, 17]. The airflow may be regulated by Inlet Guide Vanes (IGVs) and is a function of ambient air temperature (Ta), atmosphere pressure (Pa), and shaft speed (N). CPR is defined as the discharge pressure of the compressor divided by the inlet air pressure [11, 17, 20].

III.2. Stability of control loops and time delays

Based on the frequency dependent model proposed in [11], the temperature control adjusts the fuel flow (Wf) and airflow (Wa) based on the measurement of the exhaust temperature and the compressor discharge (CPR), which is defined as the discharge pressure of the compressor divided by the inlet air pressure. The discharge pressure increases with increasing airflow and with increasing energy, in the gas, proportional to the fuel flow.The utility of Low-Value-Select (LVS) is to select one of the two control loops (frequency or overheat) by switching the lower value (Tc or Fd).

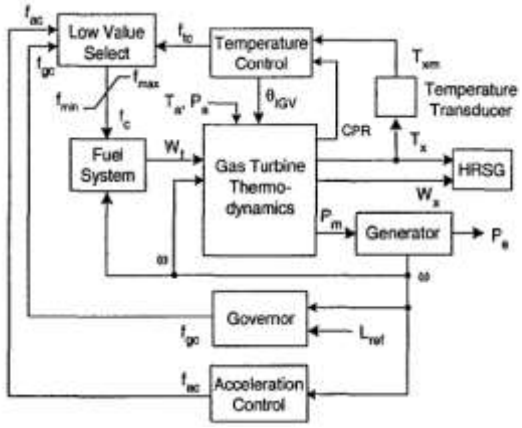

Figure1.*Frequency dependent model (FD model) [11]*

III.2.1.Load - frequency control

The first loop consists of the speed governor (load - frequency control), which is necessary for the stability of the system; it detects frequency anomaly and regulates the fuel request signal. The fuel control is directly related to the rotor speed. Thus, the rotor speed and the frequency have a direct influence on air and fuel consumption [3].

III.2.2.Temperature control

The temperature control process is one of the safe regulation tasks of the power plant. In fact, the temperature control loop has a significant role in the power plant operation, by reducing the fuel demand when the frequency falls, in consequence, the output power decreases [21]. Thus, in one hand, the increasing of ambient temperature allows to an increasing of the exhaust temperature, at this time the temperature control acts and reduces the fuel demand [22]. In the other hand, when the ambient temperature decreases, the exhaust temperature decreases also, so, the load frequency control loop activates.

III.2.3.Time delays function

The dynamic model of gas turbine requires the introduction of small delays and lag time constants, which are added to avoid an immediate switching of different components of the power plant. Essentially, there is a minor delay between the fuel injection and heat release in the combustor, which is called combustion reaction delay; it is generally on the range of some milliseconds. It is assumed that there is a time delay between the fuel injection until burning in the combustor and a time delay between the fuel combustion and exhaust temperature measuring. This delay is making to transport the fluid to the measuring points, and it is depending mainly on the size of the GT and the average fluid speed. A relatively conservative value of 40ms delay for air and combustion products transfer to the temperature measuring point is assumed [17].

IV. Simulation results and discussion

Simulation results of the Gas turbine behaivior for ambient temperature variation from 288k to 318k (15°C-45°C), are shown in figures 2, 3 and 4.

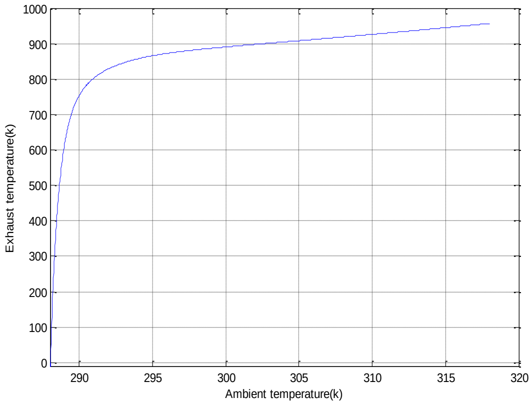

Figure 2. *Exhaust temperature variation for different ambient temperatures.*

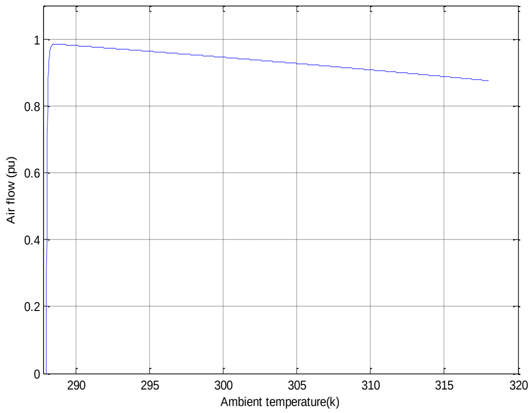

Figure 3. *Airflow variation*

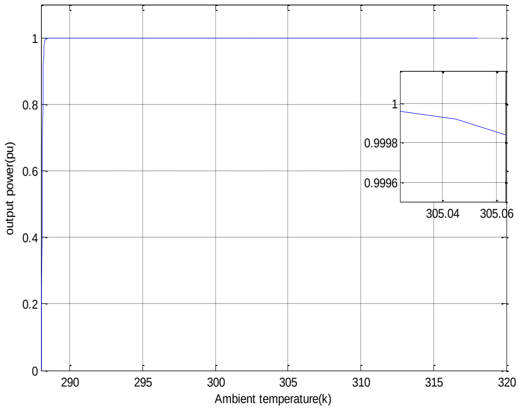

Figure 4. *Output power variation*

As shown in figure 2, the Exhaust temperature increases whith increasing of the ambient temperature, until his rated value around 850k where it tends to stabilize because of the action of the control loops. This is clear in figure 3, which represents the reaction of airflow to the variation of ambient temperature. The airflow tends to decrease with the increasing of ambient temperature, in order to decrease the extended exhaust temperature. This reaction improved in figure 4, where the output power still around his rated value of 1pu, in spit of small variation for a height ambient temperature, at t=100s. Therefore, the obtained simulations results highlight theusefulness of the FD model, which presents a considerable level of precision, and impact time delay. Moreover, the reliable role of control loops in this model. The influence of the ambient temperature on the various parameters of the turbine is given in Table 1.

Table 1. *Influence of the ambient temperature on the various parameters of the turbine.*

Ambient temperature	**Exhaust temperature**	**Air flow**	**Out put power**
288 k	857.32 k	0.98 pu	1.00 pu
298 k	887.97 k	0.93 pu	0.99 pu
308 k	922.04 k	0.91 pu	0.99 pu
318 k	960.29 k	0.87 pu	0.98 pu

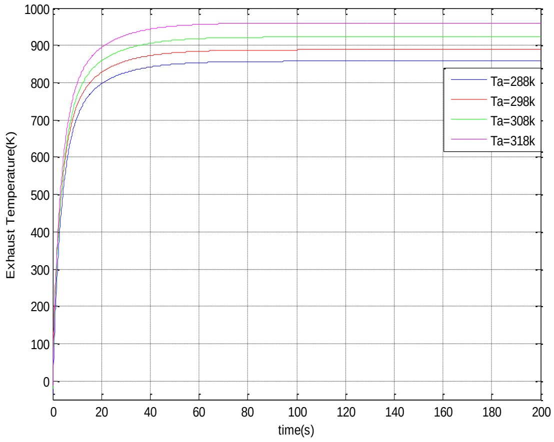

Figure 5. *Exhaust temperature variation*

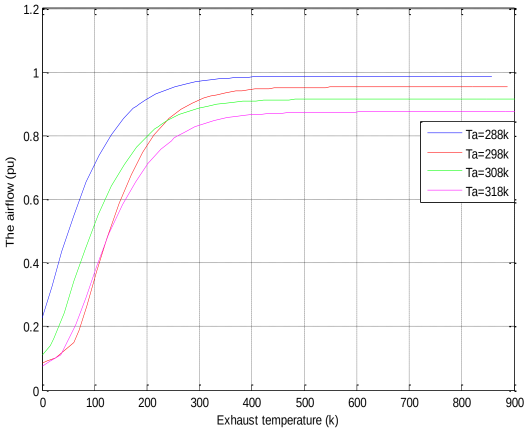

Figure 8. *Airflow function of Exhaust temperature*

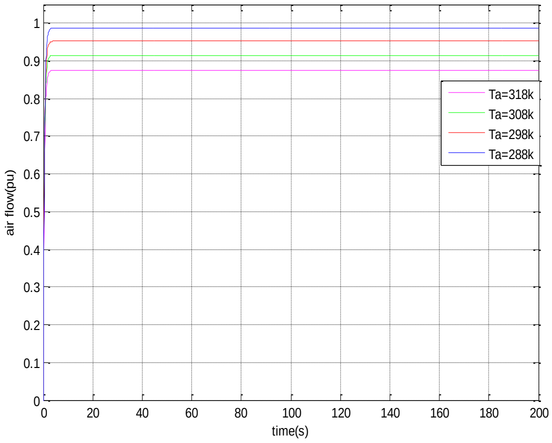

Figure 6. *Airflow variation*

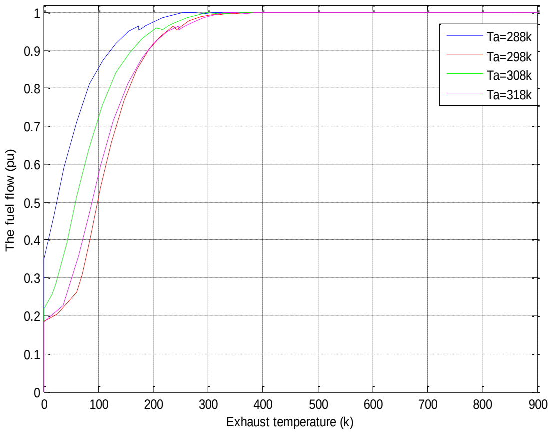

Figure 9. *Fuel flow function of Exhaust temperature*

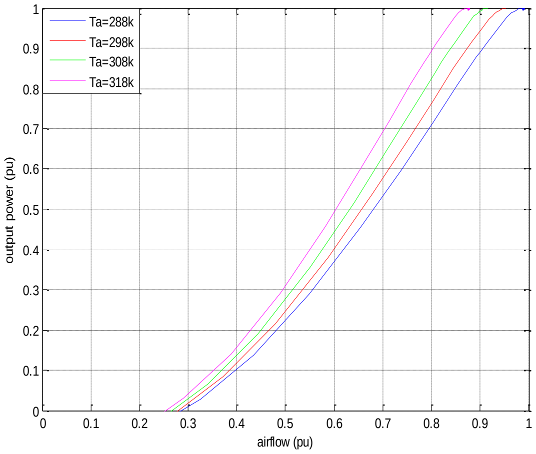

Figure 7.*Output power function of airflow*

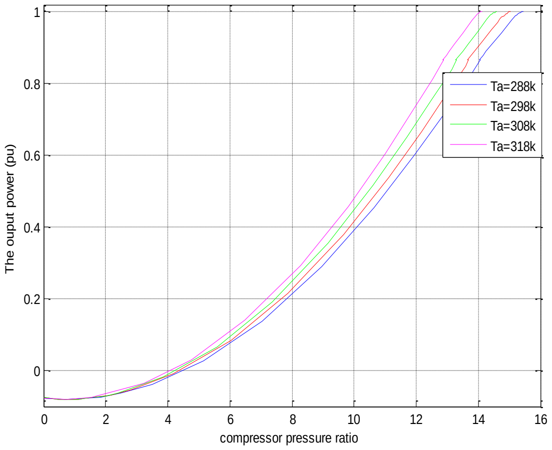

Figure 10.*Output power function of compressor pressure ratio*

In figures 5-10, the behavior gas turbine for four different values of ambient temperatures is illustrated such as the Exhaust temperature, airflow, fuel flow and mechanical output power.

The increasing in the ambient temperature leads to a dropping in the gas turbine output. Thus, more power output can be obtained but it would cause a rise in the temperature (see Fig.5). The exhaust temperature of the gas turbine is an important parameter, which has to be maintained by increasing fuel flow and airflow (see figures 8-9). In order to raise the output power, the fuel demand increases, and the turbine temperature is regulated by adjusting the airflow as shown in Fig.6-7.

V. Influence of the ambient temperature on the gas turbine parameters

As shown in simulation results, the increasing in the ambient temperature leads to an output power drop, and hence, an efficiency reduction of the gas turbine. Otherwise, in high ambient temperature, the air is less dense, so, the airflow decreases contrarily to the exhaust temperature which rises. In this time, the consumption of fuel decreases in order to maintain the Exhaust temperature a round its rated value. Consequently, the temperature control of a gas turbine limits the exhaust temperature by reducing the fuel flow (and hence the power output) as the airflow decreases with the shaft speed.

VI. Conclusion

In this paper, an analysis of the effect of the ambient temperature transients on the performance of the gas turbine behavior in the combined cycle power plant is investigated. It has been mentioned that the simulation modeling is based on the modified frequency dependent model. The GT performance depends on the environmental operating conditions, mainly the ambient temperature. Thus, the ambient temperature is linearly proportional to the exhaust temperature. Meanwhile, the rising in the ambient temperature leads to increase the fuel consumption, consequently it results in flue gases losses, thermal efficiency drop, and hence more carbon dioxide emission. It can be noted that at high temperature, the turbine components may damage. The increasing in the ambient temperature leads to the gas turbine output drop. For that reason, recently, there is an observable attention to the cooling system in order to reduce the inlet temperature of the air compressor.

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Appendix

Table 2. *HDGT parameters of 265 MW [14].*

Parameter	Symbol	Unit	MW HDGT Values
Speed governor gain=1/droop	W	MW_{pu}/N_{pu}	25
Speed governor lag time constant	Y	Sec	0.05
Fuel demand signal upper limit	$MaxF$	Pu	1.5
Fuel demand signal lower limit	$MinF$	Pu	0.135
No load fuel Consumption	K_{NL}	Pu	0.16
Fuel system external feedback loop gain	K_F	Pu	0
Valve positioner time constant	B	Sec	0.04
Fuel system transfer function coefficient	C	--	1
Fuel system time constant	T_{FS}	Sec	0.31
Combustion reaction time delay	E_{CR}	Sec	0.05
Turbine and exhaust delay	E_{TD}	Sec	0.04
Compressor discharge volume time constant	T_{CD}		0.142
Turbine rated exhaust temperature	T_R	°C	585.6
Gas turbine torque block parameter	A	--	-0.117
Gas turbine torque block parameter	B	--	1.1169
Gas turbine torque block parameter	C	--	0.5
Gas turbine exhaust block parameter	D	°C	492.6
Gas turbine exhaust block parameter	E	°C	351.36
Radiation shield parameter	G_{HS}	--	0.85
Radiation shield time constant	T_{SH}	Sec	12.2
Temperature controller parameter	G_{TC}	Sec	3.3
Temperature controller integration rate	T_T	°C	250
Compressor efficiency	η_C	Pu	0.895
Turbine efficiency	η_T	Pu	0.899

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