Investigation of the IGT25 Turbo-Compressor Control Logic Behavior Coupling with a 25MW Consumer under Dynamic Loading

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ABSTRACT

Implementing control logic in dynamic modeling of gas turbines is one of the important and effective methods in analyzing the performance of IGT25 gas turbine; because, in dynamic modeling, various results would be achieved, through different control philosophies. To do so, using behavioral analysis of the performance of IGT25 gas turbine under different ambient conditions and different fuel compositions, appropriate control logic could be extracted. In the paper, method of extraction and entering the control logic in modeling dynamic condition of IGT25 gas turbine coupled with a 25MW consumer has been studied under different ambient conditions such as various ambient temperature and pressure, relative humidity, and fuel compositions. Primarily, various scenarios existing in relation to gas turbine control have been studied; then, studying the dynamic behavior of IGT25 gas turbine under the aforementioned condition, considered control logic has been reviewed. Data obtained are at the nominal load and the condition in which the turbine's temperature controller has been set to higher temperatures so that the maximum output load is achieved for the consumer.

Keywords: *Gas Turbine; Gas Compressor; Dynamic Model; Control Logic*

Introduction

Due to the importance and wide range of usage in various industries, gas turbines are designed in a way that they would be capable of operation under different working conditions. Through the change of temperature, pressure, and relative humidity of air and fuel composition, performance specifications of each of IGT25 gas turbine components could be changed; as a result, power and efficiency level of the gas turbine would be changed. Recognizing IGT25 gas turbine behavior under the dynamic conditions and adopting appropriate control logic for its performance in the dynamic modeling is one of the important and effective sections in terms of its performance.

In the paper, the effects of changes in ambient conditions such as temperature, pressure, the relative humidity of the air, and changes in fuel composition would be studied on performance parameters of the gas turbine. In the end, the control logic of the gas turbine would be explained through the change of ambient condition and composition of consumed fuel.

To extract control logic in the paper, a dynamic model reaching a steady-state has been used. From among dynamic phenomena used in the gas turbine model, reference could be made [1] to:

1. Shaft dynamics;
2. Gas dynamics in compressor, turbine, and combustion chamber;
3. Dynamics of heat transfer between blades, combustion chamber, and turbine flow;
4. Fuel pipes volume dynamic,
5. Dynamics of control valves (time-lags).

Here, dynamic modeling of a turbo-compressor containing one 10-stage axial air compressor; one 2-stage gas generator turbine; one 2-stage power turbine; and, one 7-stage gas compressor would be explained in brief, in addition to the method of modeling main components of the compressor [2, 6].

Due to the classic relation between pressure (expansion) ratio and modified gas flow, the performance of the compressor and turbine would be defined along the speed lines. Also, turbine and compressor's efficiency would be determined by the relationship between the ratio of temperature and pressure ratios along fixed speed lines [4, 7]. In modeling axial compressor, the same intrinsic curves have been applied. Intrinsic curves are used as the ratio of dimensionless pressure based on dimensionless mass flow, and dimensionless efficiency based on dimensionless pressure ratio. Using the method has some advantages including simple method of calculation and lack of need to geometrical details of the motor. Intrinsic curve resulted for compressor would be produced from axial compressor modeling through the quasi-three-dimensional method of stream line curvature which is capable of estimating compressor's performance up to 25% of designed rated speed (rounds), under low speeds [8,4]. Conditions in zero rounds for turbine and compressor would be defined with zero mass flow and unit pressure ratio; and, fixed speed lines would be obtained through interpolation between zero rounds and 25% of designed rated speed [9].

Pressure drop within the chamber and diffuser would be estimated by pressure drop curve based on loading, within the full performance range of turbine. Loading parameter is an equation based on temperature, pressure, and mass flow rate of inlet air to the combustion chamber, calculated by CFD (computational fluid dynamics) simulation [10].

Aforementioned curves have been produced based on the three-dimensional solution of the flow inside the chamber through software packages developed for solving fluid dynamics. Stagnation pressure drop in the chamber also would be calculated by CFD simulation and estimated through an equation. Moreover, thermal energy resulted from combustion can be obtained as the heat transferred into the combustion chamber and energy balance equation would be obtained as follows [1, 6]:

$$Q = \eta_{comb} \dot{m}_f (LHV + \Delta H_{T_0 - T_f}) \tag{1}$$

where 0 shows reference point with low heat value, T_f is flame temperature, $\dot{m}_f$ is fuel mass flow rate, and η_{comb} is combustion efficiency obtained through three-dimensional analysis, entered into the next zero models as combustion efficiency curves based on loading parameter.

Like a compressor, turbine also would be modeled; however, intrinsic curves of the turbine in various rounds are almost fit. Anyway, high cooling technology of today's axial turbines turns to model to a complicated procedure. The undertow air from air compressor enters the stage's rows so that turbine blades would be cooled; and, it affects the specification of the stage. Due to the same reason, a row by row forecasting method of cooling for the turbine has to be taken into consideration so that its performance specifications would be achieved. In the turbine cooling method, the rotor would be modeled in an integrated form; and, outlet flow after the rotor would be mixed with cooling flow. To calculate the cooling flow rate in each row, its type of technology including the layer or internal cooling has to be specified. Then, the maximum gas temperature would be calculated based on the pattern factor in the chamber. If this temperature would be higher than the authorized temperature of the blade surface, the cooling flow would be considered for the same row [11]. Under dynamic and outside design conditions, expansion pressure ratio would be obtained through the following equation:

$$\frac{\dot{m}_{in}\sqrt{T_{T,in}}}{P_{in}} = K\sqrt{1-(\frac{P_{out}}{P_{in}})^2} \tag{2}$$

Where *in* and *out* are indicative of inlet and outlet conditions and **K** indicates a parameter obtained from design point which will remain fixed under outside design conditions. Cooling flow rate entering turbine blade rows under outside design and dynamic conditions would be calculated through the following formula:

$$\dot{m}_c = K_c P_c \sqrt{\frac{2(1-\frac{P_T}{P_c})}{RT_c}} \tag{3}$$

Where, (C) is related to cooling fluid, (T) is related to gas flow inside the turbine, and R is gas universal constant [7].

Gas turbine-related components have been already studied. Modeling principles of the gas compressor is similar to that of air compressor; and, in figure (1) gas flow path and equipment used in it are shown. Accordingly, natural gas enters separator through the entry line of the station so that liquid drops would be separated from the main gas flow. Also, solid particles existing in gas that has entered the main flow in the transmission path would be separated, through the filter. This way, the natural gas flow would be entering gas compressors. In gas compressor and through an increase in gas pressure up to pressure level of discharging line of the station; natural gas can enter this line. If the natural gas temperature would be increased more than a certain level, before the gas entrance to discharging line, high temperature condensed gas will enter the station’s cooler outlet and its temperature would be decreased so that gas pipelines would not be damaged from heat [2].

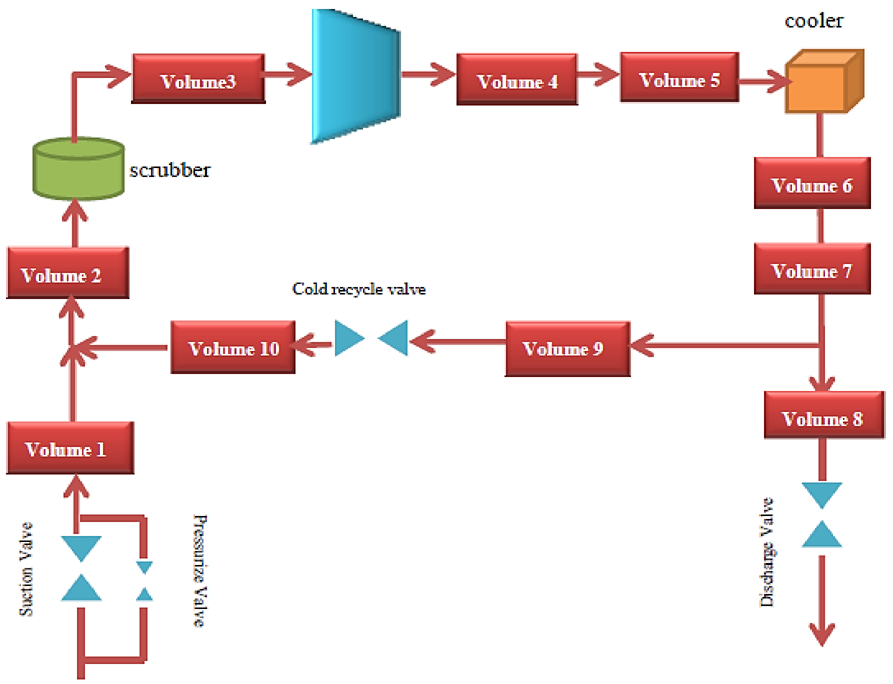

Figure 1- Placement method of dynamic volumes and heat transfer for a gas compressor with auxiliary equipment [2].

Gas Dynamics

Gas dynamics is one of the important phenomena under the transient condition of gas turbine which mass, energy and the momentum stored in the chamber of main components would be taken into consideration. This is, in fact, equal to the inertia of motion within a pipe. Inertia resulted from gas dynamics in air compressor, combustion chamber, turbine, and gas compressor would be resulted in the behavioral difference between outside design and dynamic performance conditions. Considering the phenomenon in designing control system is necessary and important so that instabilities such as Serge and Humming would be taken into consideration [8].

Gas dynamics is modeled by one-dimensional equations of mass, energy and momentum conservation for any specified component from among main components of the motor that would be placed in control volume (plenum). Simpler models only consider mass conservation. In these models, pressure in total volume is assumed to remain fixed.

Mass and energy conservation equations for control volume are written as follows:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{d}{dt}(m_{vol}) = \frac{V}{\sqrt{RT}} \frac{dP}{dt} \tag{4}$$

$$H_{in} - H_{out} + \dot{q} = \frac{d}{dt}(m_{vol} \cdot C_v \cdot T) = C_v(\frac{Tdm_{vol}}{dt} + m_{vol}\frac{dT}{dt}) \tag{5}$$

Where, *in* is the condition for entrance to control volume, *out* is exit condition from control volume, m_{vol} is the mass remained in control volume, and C_v is the thermal capacity of gas in a fixed volume. Solving differential equations, relationships, and outputs of these two equations i.e. temperature and pressure would be calculated. The program input is flow rate output from the chamber.

Integration of turbo-compressor dynamic models in the form of a single model

In figure (2) integration method of turbo-compressor various dynamics are shown. Gas dynamics phenomenon is considered within control volumes. Considering the point that compressor is divided into four groups, four control volumes are considered for it. One control volume is also considered for the combustion chamber. Turbine containing two high and low-pressure sections in total includes four stages [10]. In gas compressor section also, the flow path is divided into the following volumes: after suction valve to cross-section of recirculation path, as first volume; from recirculation cross-section to separator and in addition to it,, as second volume; distance from separator to gas compressor, as third volume; gas compressor as fourth volume; distance between gas compressor and cooler, as fifth volume; cooler as sixth volume; distance between cooler to exit point of the circulation path, as seventh volume; from exit point of recirculation to drain valve, as eighth volume; from exit point of recirculation to recirculation valve, as ninth volume; and finally, from recirculation valve to cross-section of recirculation path and suction path, as tenth volume.

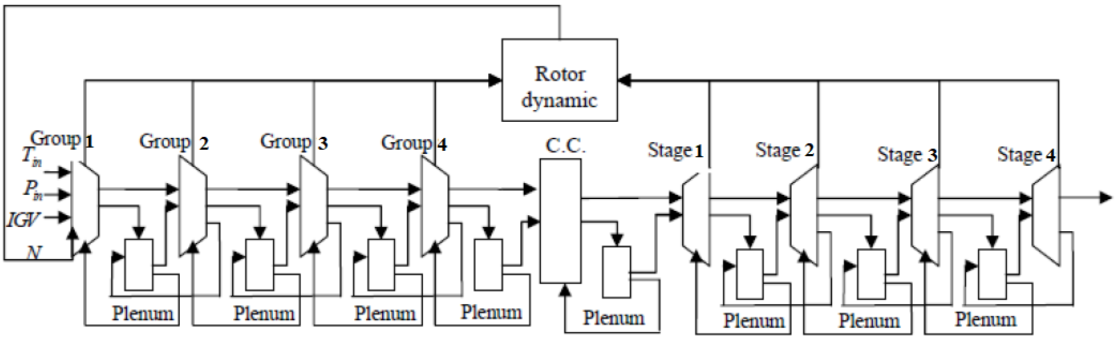

Figure 2- Integration method of various gas turbine dynamics [1]

Heat transfer and stress dynamics in the compressor, combustion chamber, and turbine have been considered separately in the developed model. To study the effect of changes in each section of the model on the model as a whole, each of control volumes will be linked to other volumes, through compatibility equations. At the end of each time step, specifications of gas turbine and gas flow would be converged in a way that all of the compatibility equations would be satisfied.

Extracting control logic based on changes in ambient conditions

To extract control logic through changing ambient conditions and running modeling code, it could be found that which performance parameters of gas turbine remain fixed because of its control logic; and, gas turbine control logic could be extracted, as a result. From among scenarios presentable as for control dynamic conditions of the gas turbine, reference could be made to maintaining inlet temperature to the turbine, maintaining outlet temperature from the turbine, and, maintaining inlet air flow rate to the compressor. In continuation, these scenarios would be studied and control logic would be extracted therefrom.

Change of the environment’s temperature

In figure (3), changes of such parameters as outlet pressure from high pressure and power turbine, ratio of air compressor pressure, amount of fuel consumed, rated (rounds) speed of power and high pressure turbines, turbine’s inlet temperature, turbines outlet temperature, turbine’s gas outlet mass flow rate, and net power output of gas turbine based on changes made in the environment temperature are shown. It should be noted that modeling results have been obtained at the design point of turbo-compressor with 25MW consumed the power of gas compressor and under ISO condition, with consideration of consumed fuel (100% methane). Also, parameters shown have become dimensionless, based on full load point's results under steady-state.

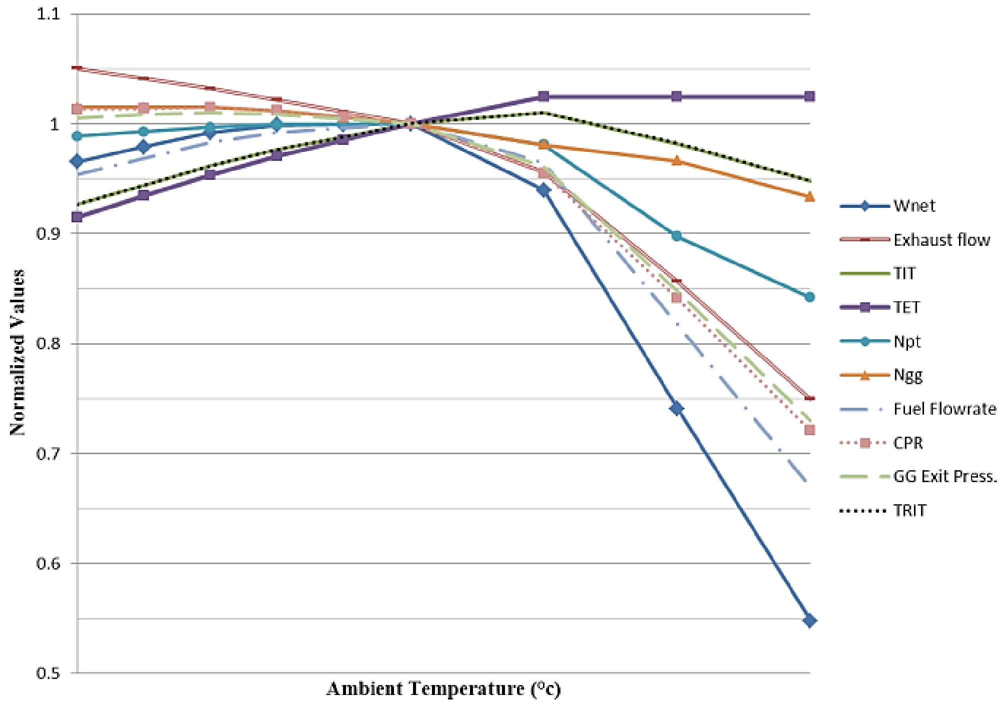

Figure 3- Changes in dimensionless parameters of the gas turbine under different temperatures of the environment.

With consideration of figure (3), inlet temperature to the high-pressure turbine (TTT-time temperature transformation) and outlet temperature from power turbine follow a certain procedure; and, in a certain temperature, the procedure would be changed. That is inlet temperature to high-pressure turbine would be reduced, in lower temperature than that; and, outlet temperature from turbine also will have little changes in higher temperatures than that, due to T7 controller activation. For lower temperatures than the outlet temperature, there would be a decreasing trend of temperature. Through increase made in the environment's temperature, air compressor's pressure ratio, rated speed (rounds) of high-pressure turbine, high pressure and power turbines' outlet pressure, amount of consumed fuel, rated speed of power turbine, mass flow rate of outlet gases from gas turbine, and net outlet power of the gas turbine will be decreased.

Change of height from sea level (change of ambient pressure)

In figures (4) and (5), changes in various performance parameters turned to dimensionless parameters are shown based on changes of height from sea level, compared to full load point of IGT25 gas turbine, where it is coupled with a 25MW gas compressor. Modeling results have been obtained in full load point under ISO condition, considering fuel composition of 100% methane.

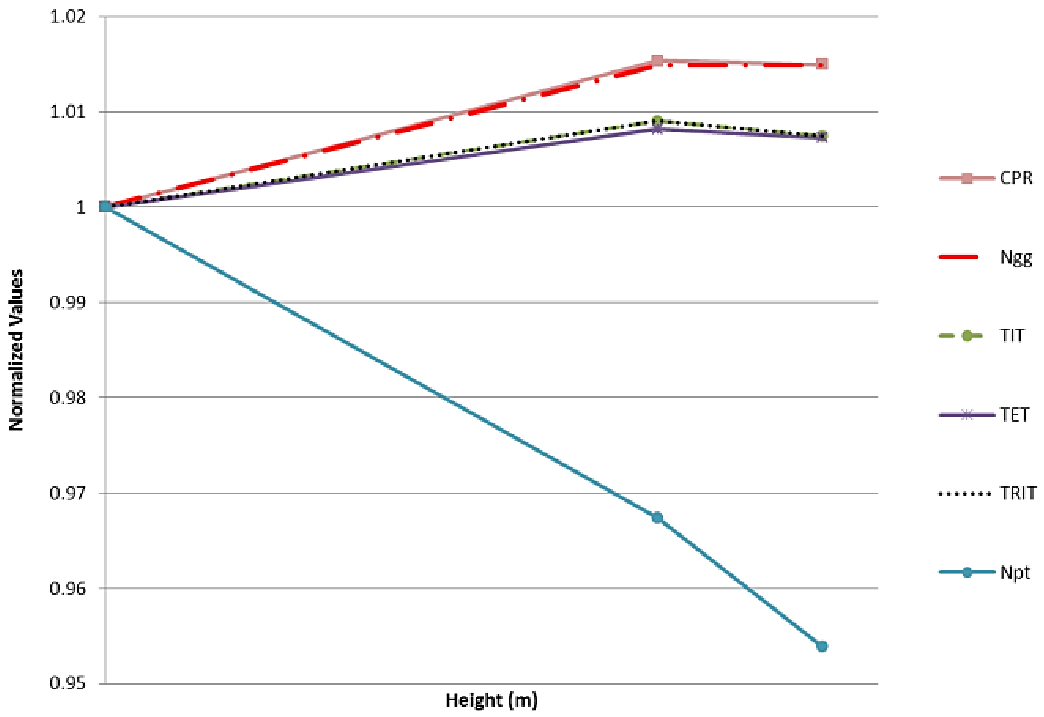

Figure 4- Changes in dimensionless parameters of the gas turbine under various heights of the environment

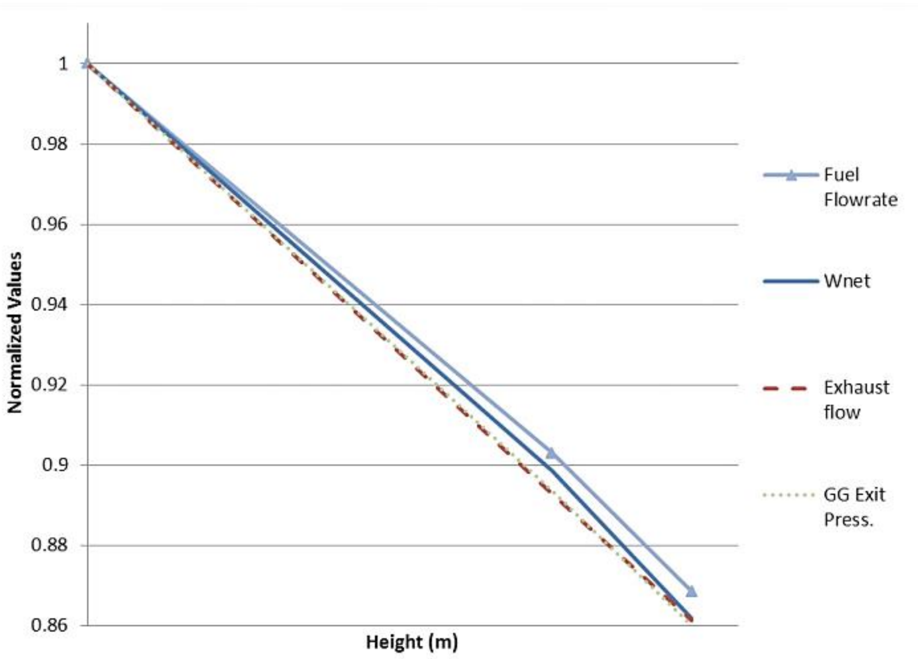

Figure 5- Changes in dimensionless parameters of the gas turbine under different heights of the environment

Considering these diagrams, turbine's inlet and outlet temperatures are almost fixed through changes in air pressure of the environment (because turbine performance is fixed in terms of inlet temperature which is imposed by the control system). Also, through the increase of height from seal level, pressure ratio of air compressor and rated speed of high-pressure turbine would be a little increased; and, outlet pressure from high pressure and power turbines, amount of consumed fuel, rated speed of power turbine, mass flow rate of outlet gases from gas turbine, and net outlet power of gas turbine would be reduced. The reason is that air pressure would be increased through the increase of height from sea level; and, inlet air flow rate to the turbine would be decreased. Since inlet temperature to the turbine is a fixed value (it has reached to its authorized maximum level); net outlet power of gas turbine would be decreased through decrease made in inlet flow rate, according to equation (6).

$$W_t = C_P \dot{m}(TIT - TET) \tag{6}$$

Change of relative humidity of the atmosphere

In figure (6), changes of various performance parameters turned dimensionless are shown, compared to full load point of IGT25 gas turbine based on changes made in relative humidity of the environment (made dimensionless). Modeling results have been obtained in full load point under ISO condition and with consideration of fuel composition being 100% methane. Modeling results under dynamic condition also have been obtained under the same condition and according to the changes made in relative humidity of the environment. As it is observed, when the relative humidity of environment changes from 10 to 90%, performance parameters of turbo-compressor are relatively fixed and lower than 0.07%.

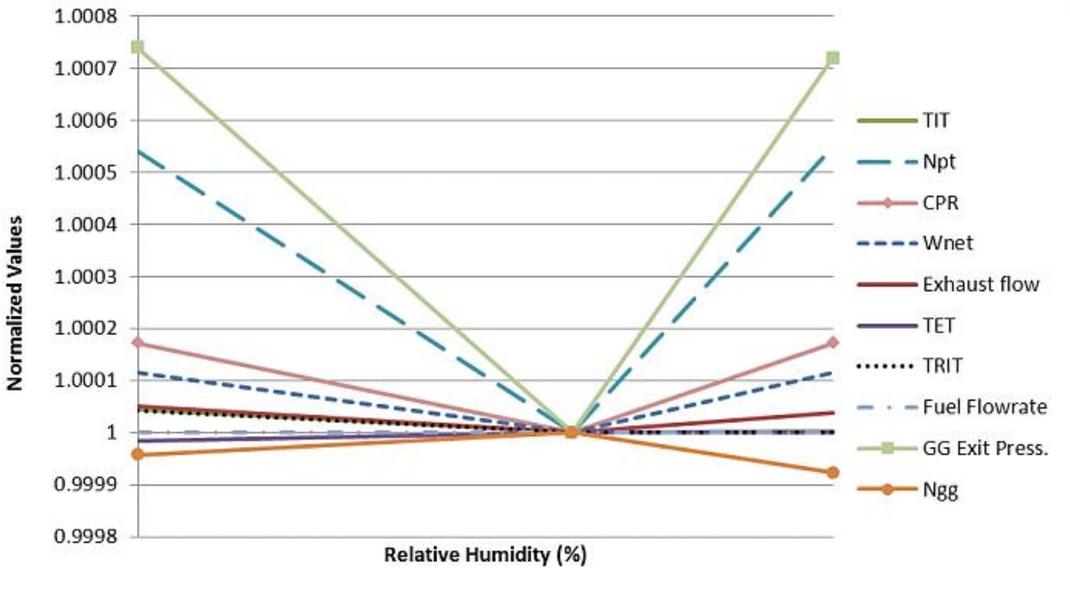

Figure 6- Changes in dimensionless parameters of the gas turbine under different relative humidity of the environment.

Changing fuel composition

Changing fuel composition (changing mole fraction of fuel compositions, e.g. methane, ethane, propane, butane, and etc.) has an effect on the thermal value of the fuel. On the other hand, various products would result in combustion process with various fuel types so that if fuel thermal value would be reduced, energy amount in inlet gases to turbine would be also reduced, and less power would be produced.

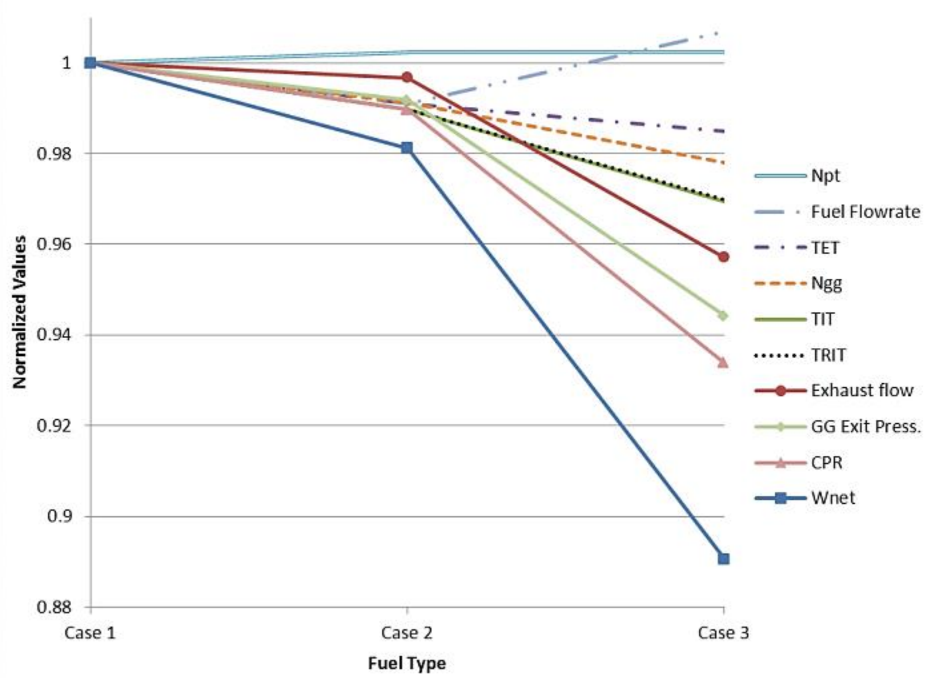

Figure 7- Changes in dimensionless parameters of gas turbine in different fuel compositions

To study the effect of these changes on IGT25 turbo-compressor through changes made in mole fraction of fuel compositions resulted in different thermal values; behaviors of performance parameters resulted from these changes would be studied for three different types of fuel. In figure (7), dimensionless parameters' changes of IGT25 gas turbine are provided, compared to changes in dimensionless thermal value, in comparison to design point.

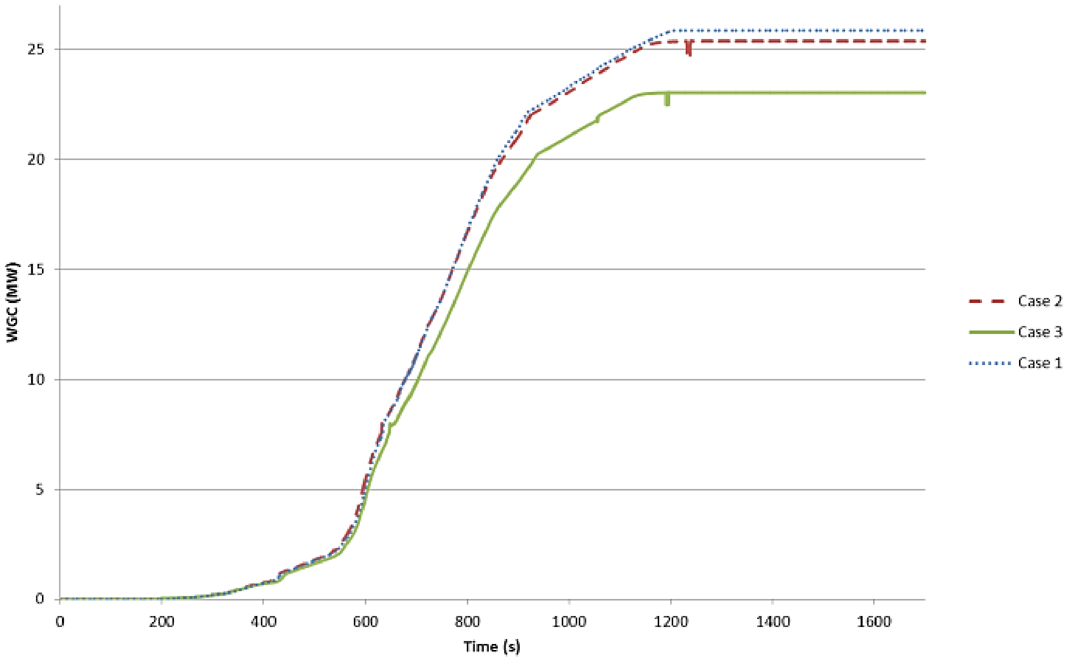

Figure 8- Power changes in gas compressor based on changes in gas turbine

As far as the gas compressed is of similar composition with fuel gas, changes in fuel compositions would result in a considerable change in net power produced by power turbine. The reason is the direct effect of change in fuel composition on gas compressor enthalpy, and change made in consumed power, as a result. These changes are shown in figure (8). As it is observed, the reduction of low thermal value results in power produced by power turbine. Considering the overall power of turbo-compressor imposed by the gas compressor; change in fuel composition would severely affect net power produced by the gas turbine. Also, the inlet temperature to the high-pressure turbine (TTT) and outlet temperature from the low-pressure turbine would be increased through increase made in the thermal value of the fuel. Aforementioned phenomena can be considered to be resulted from an increase in flame adiabatic temperature because of the increase made in fuel thermal value. Considering diagrams provided in figure 7- dimensionless parameters of turbo-compressor would be prone to considerable changes, through changes made in the type of fuel.

Conclusion

In the paper, the method of extracting control logic and entering it into IGT25 gas turbine dynamic conditions modeling under various ambient conditions including temperature and pressure, as well as fuel compositions have been studied. Primarily, different existing scenarios as for gas turbine control has been studied; then, the dynamic behavior of IGT25 gas turbine performance parameters have been studied under different ambient conditions and various fuel compositions so that considered control logic would be reviewed. Data obtained have been studied for base load mode when the T7 controller also has been activated in high temperatures.

According to the results, under dynamic conditions, inlet temperature to the high-pressure turbine (TTT) has experienced decreasing trend through changes in the environment's temperature and temperature lower than a certain temperature (maximum inlet temperature to high-pressure turbine takes place at this certain temperature). Also, changes in outlet temperature from the turbine at those temperatures higher than this would be insignificant and would be decreased in those temperatures lower than this certain temperature. Changes in other parameters show a decreasing trend, based on increase made in temperature. So, gas turbine control logic seems to follow two fixed TTT and TET (turbine entry temperature) approaches respectively in temperatures lower and higher than this certain temperature, based on the change of the environment's temperature.

Changes in the pressure of the environment are of almost fixed effect on inlet and outlet temperatures to and from the turbine. Increase in height from seal level (ambient pressure decrease) would be resulted in pressure ratio of air compressor and rated speed of high pressure turbine to be a little increased; and, decrease would be made in outlet pressure from high pressure and power turbines, amount of consumed fuel, rated speed of power turbine, mass flow rate of outlet gases from gas turbine, and net outlet power of gas turbine. Considering the above results, it could be concluded that the control logic of gas turbine in different heights could be fixed TTT and/or fixed TET.

Changes in relative humidity also have not much effect on parameters studied. Increase in thermal value of fuel would result in net produced power of the gas turbine, inlet temperature to the high-pressure turbine, and outlet temperature from the low-pressure turbine.

In general, under different climate conditions such as temperature, height, and relative humidity, gas turbine control logic seems to be based on fixed TTT and/or fixed TET; unless, those cases in which life cycle constraint of the gas turbine would be taken into consideration. Under such condition, the fixed TET option in control logic would be of higher importance.

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