Journal of Petroleum Research and Studies

Open Access
No. 34 part 2, April 2022, pp. 225-242

P- ISSN: 2220-5381
E- ISSN: 2710-1096

DOI: http://doi.org/10.52716/jprs.v12i1(Suppl.).634

Using Fuzzy Inference System in Gas Turbine to Overcome a High Exhaust Temperature Problem

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6th Iraq Oil and Gas Conference, 29-30/11/2021

Abstract

The turbine units are at the forefront of equipment in the process of pumping crude oil and exporting it to the oil ports, where there are many types of turbines used in different sites of Iraqi stations whether pumping oil stations or electrical power production stations. One of the most important types of turbines is the gas turbine, which is frequently used in oil depots. One of the remarkable depots in Iraq is Zubair-1 / Basra that exports around 850,000 barrels per day (B/D). Therefore, Zubair-1 should continue pumping the crude oil 24/7, which has five gas turbines (three Rolls-Royce AVON MK 1533 and two Siemens SGT 400). However, the three Rolls-Royce gas turbines in Zubair-1 have not worked in the summer season since 2016, when the ambient temperature goes high around 11:00 am to 3:30 pm. This paper proposes solution to solve a high exhaust temperature (EGT) shutdown signal (a preventing running turbine signal) without effect on the sequence of turbine running stages. The proposal is adding a fuzzy inference system (FIS) that controls the gas turbine in the first two running stages that demonstrates and controls of speed the turbine from 800 RPM to 3000 RPM. The inputs of FIS are the average temperature of eight combustion chambers (exhaust temperatures) and the speed of the gas turbine, while the output of FIS is the control signal to the flow control valve (FCV) with an amplifier to gain the signal.

The FIS proposal has been applied in all three Rolls-Royce jet pumping turbines since

Open Access
No. 34 part 2, April 2022, pp. 225-242

P- ISSN: 2220-5381
E- ISSN: 2710-1096

April 7, 2021, and they work regularly at all times of the day. The FIS minimizes the maximum average of combustion chambers temperature at midafternoon in June 9, 2021 (48 ˚C ambience temperature) from 689 ˚C to 610 ˚C that means the improvement is around 45%.

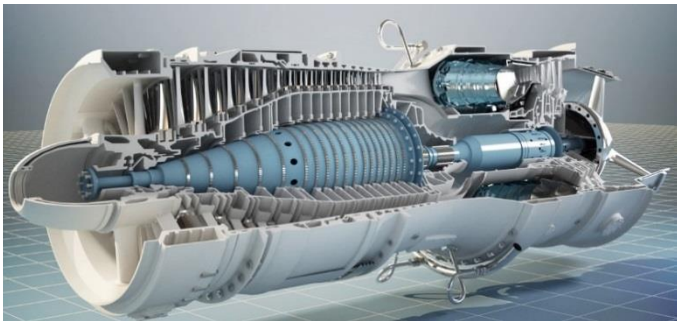
Keywords: Fuzzy Inference System, Gas Turbine, Programmable Logic Controller.

1. Introduction

Jet Turbines are important equipment in the production and exportation of crude oil, due to their great ability to produce kinetic energy (mechanical) through combustion of a mixture of compressed air and fuel. The high combustion products pass through the gas turbine, expand and transform thermal energy into mechanical, and then expel the gases to another equipment (e.g. power turbine (PT) that connect via gear box to pump called *turbo-pumping* or connect to electrical generator called *turbo-generator*). There are turbines in many oil sites in south of Iraq, and the most important and oldest of these sites is the Zubair 1 (ZB1) depot, where it receives crude oil from the isolation stations, and it is stored and pumped to the oil ports.

There are three turbine units in ZB1 depot that are manufactured by Rolls-Royce AVON MK1533-35 as shown in Figure (1), which are called as gas turbine 1 (GT1), gas turbine 2 (GT2) and gas turbine 3 (GT3). Because the gas source is available, close and easy to obtain in south of Iraq (Basra city), the fuel that used in these turbine units is a natural gas.

(b) Real Image



(a) Longitudinal Section [1]

Fig. (1): Rolls-Royce AVON MK1533 (jet turbine)

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The turbine consists of three main elements: The compressor, the turbo converter that is connected to a common shaft and the combustion [2, 3]. Operating a turbine is not an easy process. Whereas the operation of the turbine requires a preparation of auxiliary (secondary) systems with ensuring their completed successful runs. The turbine engine with all related auxiliary systems are controlled and protected via a control system. The control system is considered the mastermind to secure the operation process successfully and without real interruption. Recently, most oil company are using a modern control system called programmable logic controller (PLC), which is an industrial computer that has been robust and adapted for the control of manufacturing processes of any activities that requires high reliability, ease of programming, and process fault diagnosis [4]. The three turbine units at ZB1 (GT1, GT2, GT3) dedicated to pumping and exporting crude oil through Basra ports frequently suffering from failure to operate in the summer time, (i.e. during the noticeably high atmosphere temperatures). This problem has been going on for 5 years that the three turbine units do not work at all in summer time, and the BOC's administrator depended on other turbines (Siemens brand in ZB1 or other depots). In this paper, a proposal is introduced and applied to solve high temperature problem by using an artificial intelligence (AI), which is FIS that will be illustrated in deep in the manuscript. Several companies that are specialized in updating the control system of jet turbines were also attended, and they were unable to overcome this problem since 2016. The preliminaries and details of gas turbine, PLC, FIS are presented in [5] – [12]. Where [5] and [6] show all parts of gas turbine with mechanism of operation. [7] – [11] illustrate how the FIS has an ability to overcome in nonlinear complex problem to control on mobile robot, FCV and to solve maze problem. [12] presents the full explanation about PLC and focus on Allen Bradley PLC brand.

2. Devices and Experiments

This section presents the aspects of problem and proposal solution.

A. Research Methodology

A modern computerized control system (e.g. PLCs) has the ability to store big data of reading sensors (analog and digital signals), events (alarm and trip incidents), and

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even what the operators have been pressed to run or stop the equipment. The PLC of GTs in ZB1 has a large size of data storage in the computer server of PLC, which can appear all historical data. Because of these available important data that can feed the AI algorithms, we use FIS to analyze the data of GTs that is related to the reason for the high-temperature problems in EGT during every summer season. The main parts of the turbine that cause a high-temperature problem in EGT are the fuel system of the gas turbine.

B. Devices

In this paper, Allen Bradley PLC brand (RSlogix studio 5000 software) from Rockwell automation company is used to gather real data from GTs. We use a simulator of Allen Bradley PLC to implement a proposed solution before applying it in actual GTs to overcome all problems. Furthermore, MATLAB (2021a) is used to analyses data via applying FIS to obtain the optimal solutions. Applying the suggested optimal solution to three turbo-pumping jet turbines (Rolls-Royce AVON MK1533) installed in ZB1.

C. Problem Statement

As illustrated before, three turbine units at ZB1 (GT1, GT2, GT3) suffering from failure to operate in the summer. Before addressing the basis and cause of operating failure, we must show the stages of operating the turbine unit for its importance in explaining the cause of the problem and ways to solve it. The three turbine units (GT1, GT2, GT3) are ROLLS-ROYCE AVON MK 1533 and were controlled using PLC type Allen Bradley, as the operating stages of any unit are summarized in [1]. The fourth and fifth stages are used to increase the turbine speed from 800 RPM to idle speed, which is 3000 RPM (called as a minimum governor (min GG) Speed Setpoint) via initially injecting a gas fuel to the eight combustion chambers. The failure of the turbine is concentrated in the fifth stage (state 5), which is: The turbine speed (called as a GG speed) do not reach to a min GG speed after combustion accrued within a specified time. A normal turbine running operation is: The GG speed reaches to 800 RPM (coming from starter motor), and then, an ignition occurs with 1.5 PSI (string injected fuel) to make GG speed reaching to 1400 RPM (called

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as an ignitions speed) gradually, and then, reach to 3000 RPM. The fourth stage is responsible to make GG speed reaching to 1400 RPM from 800 RPM, while the fifth stage is responsible to make GG speed reaching 3000 RPM from 1400 RPM. The GG speed increasing from 800 to 3000 RPM must be within 30 and 120 seconds for the fourth and fifth stages, respectively. The turbine operating failure comes in the fifth stage are:

1) **The first reason:** The turbine unit do not reach the required speed (3000 RPM) within a specified period of 120 seconds, which causes an expired timing failure signal.
2) **The second reason:** An increase in the temperature of eight combustion chambers (exhaust heat average called EGT average) more than 700 ˚C, whether one or more of a temperature exceeding 700 ˚C during an increase in the amount of gas fuel within the fifth stage.

D. Experimental Setup and Studying the Problem

The control system block diagram for the fuel gas entering the turbine unit shown in Figure (2) contains three valves for entering the fuel gas, and they are: Primary shut off valve, secondary shut off valve, and Integrated Fuel Gas Valve (IFV). The primary shut-off valve and secondary shut-off valve are used to close and open the fuel line in a very fast manner, which is very useful in a safety system to prevent continuous gas flow to the gas turbine. IFV is the main valve of the fuel system to control on inlet mass flow rate of fuel gas to the turbine in order to control the speed. The control on this valve depended on various aspects (e.g. EGT temperature and PT speed).

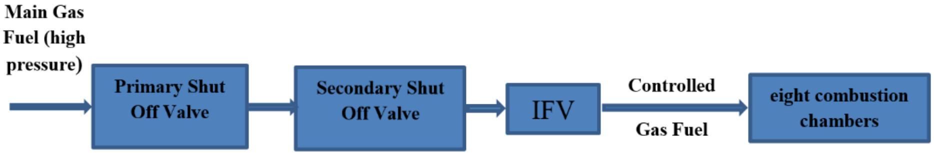

Fig. (2): Block diagram of gas turbine fuel control system

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In the fourth and fifth stages of operating the turbine units, there are five variables (incoming signals on the gas control valve motor, see Figures (3) and (4)) in order to control the gas input in order to increase the GG speed from 800 to 3000 RPM as shown below through attribution initial fuel variable values via IFV (where MW is a unitless):

- Light up fuel minimum = 1.2 MW
- Light up fuel maximum = 4.2 MW
- Light up rate = 0.6 MW/Sec
- Light off fuel maximum = 5.8 MW
- Light off Rate = 1.6 MW/Sec

Fourth stage (800 to 1400 RPM)

Fifth stage (1400 to 3000 RPM)

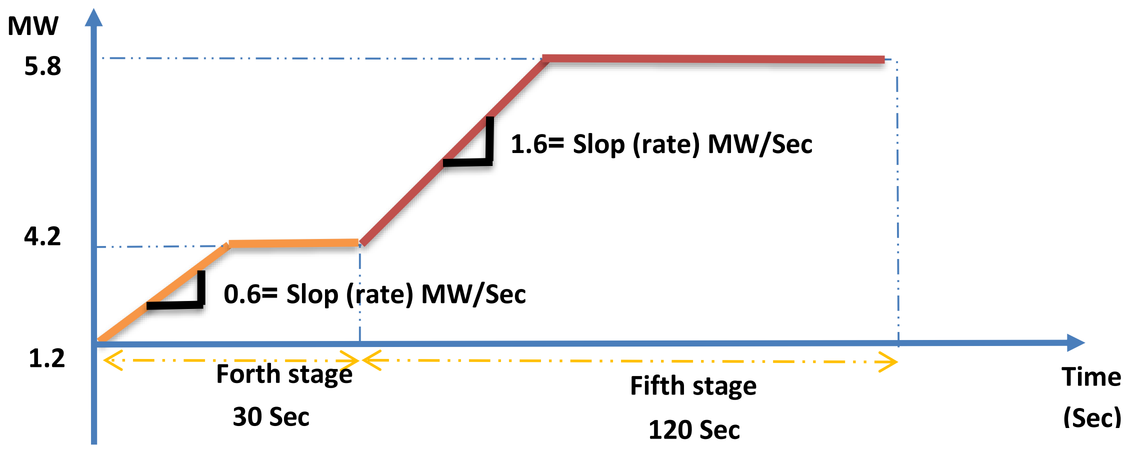

Fig. (3): Timeline for the fourth and fifth stages

After the turbine unit speed reaches 800 through the starter motor, the shut-off valves are closed and the vent valve is opened so that gas with a certain pressure (1.5 PSI) according to the **light up fuel minimum variable** (1.2 MW) will pass to the turbine for initial combustion. Whereas, the operating of increasing fuel is continuous for other IFV values of as shown in Figure (4). The amount of gas in PSI is linearly proportional to the value of MW via multiplying by a constant gain value (amplifier e.g. λ), as shown in Figure (5).

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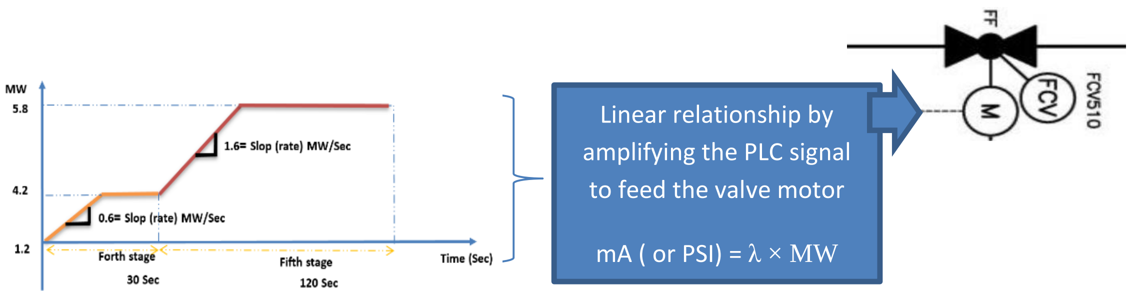

Fig. (4): Main gas valve to control on fuel system (named as FCV 510)

A milliampere (mA) signal (equivalent to outlet gas pressure in PSI to the combustion chambers) that feeds to the motor to operate and control the gas valve (FCV510) depends on the rate of change of the value (MW) per second for each of the fourth (Light up rate) and fifth (Light off rate) stages restricted to a minimum and maximum value for both stages. The failure of the turbine units to operate is due to the selection of the slope value of the curve and the final amount of the fifth stage for two reasons:

First, if the slope of the curve is small, so that the time of the two stages is insufficient, it causes the turbine unit to exit due to the lapse of time without reaching the required value for speed (1400 RPM for the fourth stage and 3000 RPM for the fifth stage). Figure (5) illustrates the human machine interface (HMI) trends of exhaust temperatures with GG and PT speeds for GT1 at failure situation. This failure operation cause of expired the timer of fifth stage (exceeding 120 seconds without GG speed reaching to 3000 RPM) although the exhaust temperature of the eight combustion chambers did not reach to the highest temperatures.

Second, if the slope of the curve is large, it leads to an increase in fuel within a short period, which causes an increase in temperature and, accordingly, the turbine out of work because the exhaust temperature exceeds 700 ˚C by measuring an average of the combustion chamber temperatures (EGT average). The exceeding EGT average is the most common occurrence in the summer, as shown in Table (1).

Table (1) shows the IFV values of the variables of GT2 in ZB1 at the time of peak atmosphere temperature (11:30 am to 2:30 pm) with the status of the unit's operation

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or failure (cause expiring timer or EGT exceeds 700 ˚C) for different times and dates.

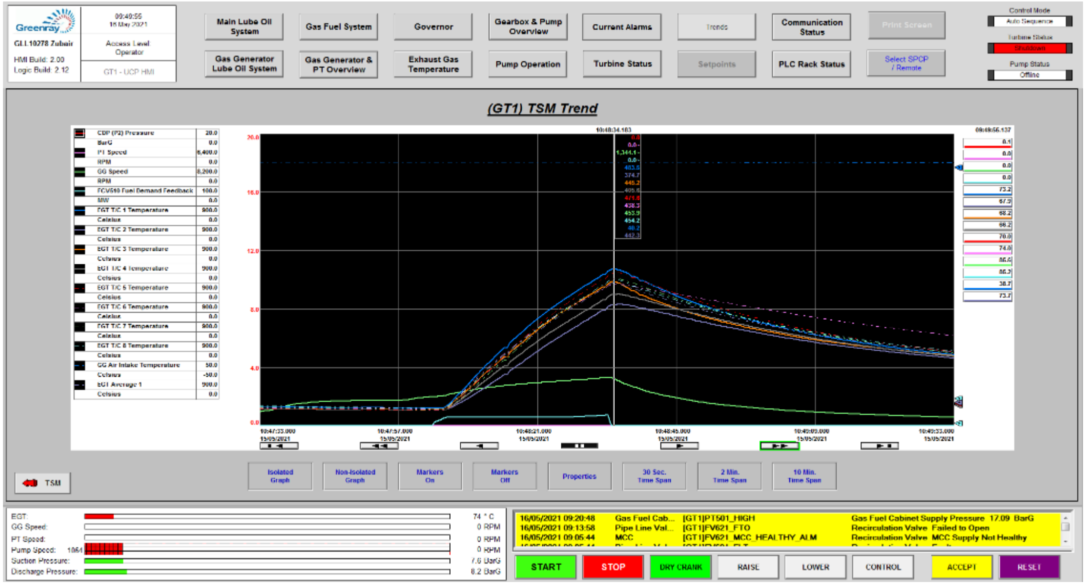

Fig. (5): The expiration of the time of the fifth stage without reaching the GG speed to 1300 RPM, which caused the failure of the turbine to continue running.

3. Suggested and Simulated Proposal Solution

Since the reason for the failure of the turbine to operate is located in the fifth stage (for both reasons), using FIS is proposed to solve the problem by controlling the value of the slope of the fifth stage. Whereas, there are two inputs to FIS (EGT average and acceleration of GG speed) and one output (slop value MW/Sec). We build and simulate the FIS by using MATLAB/Simulink as shown in Figure (6). The x axis of MFs (low, middle, and high temperature) for EGT are temperature from 300 to 700 ˚C.

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Table (1): Samples of IFV values for the fourth and fifth stage variables

Date	1/6/2015	5/6/2016	18/05/2016	22/5/2016	19/7/2017
Operating Status	Run	Failed/Timer	Failed/EGT	Failed/EGT	Failed/EGT
Light Up Fuel Minimum	1.8	1.8	1.2	1.2	1.2
Light Up Fuel Maximum	2.9	2.9	3.8	4	4.1
Light Up Rate	0.2	0.2	0.6	0.8	0.6
Light Off Fuel Maximum	5.8	5.8	5.8	5.8	5.8
Light Off Rate	1.9	1.9	1.8	2.2	1.6
Date	4/8/2018	29/8/2019	6/9/2019 at 8:11 pm	12/7/2020	15-5-2021 at 10:48 am
Operating Status	Failed/EGT	Failed/Timer	Failed/EGT	Failed/EGT	Failed/Timer
Light Up Fuel Minimum	1.2	1.2	1.2	1.2	1.2
Light Up Fuel Maximum	4	4.4	4.4	4.2	4
Light Up Rate	0.6	0.4	0.5	0.5	0.6
Light Off Fuel Maximum	5.7	5.6	5.7	5.7	5.6
Light Off Rate	1.7	1.6	1.6	1.6	1.6

The x axis of membership functions (MFs) (low, medium, and high acceleration) for acceleration of GG speed are calculated from succeed operation trends of GG speed via two points slop rate equations (point 1 is GG speed at time 1, while point 2 is GG speed at time 1 + PLC cycle time). The MFs for slop MW/Sec are decreasing, increasing, and no change in the slop. Figure (7) (a and b) are the MFs of FIS inputs, respectively, while (c) is the MFs of FIS outputs. We have generated the fuzzy rules and MFs manually by using the logical principles to reduce the temperature depending on the amount of gas entering the turbine, as well as the exhaust temperature. The nine rules for FIS are:

1. If (Average_EGT is Low_Temp) and (GG_AccSpeed is Low_Acc) then (Slop_MWperSec is Inc_Slop) (1)
2. If (Average_EGT is Low_Temp) and (GG_AccSpeed is Medium_Acc) then (Slop_MWperSec is Inc_Slop) (1)
3. If (Average_EGT is Low_Temp) and (GG_AccSpeed is High_Acc) then (Slop_MWperSec is Dec_Slop) (1)
4. If (Average_EGT is Middle_Temp) and (GG_AccSpeed is Low_Acc) then (Slop_MWperSec is Inc_Slop) (1)
5. If (Average_EGT is Middle_Temp) and (GG_AccSpeed is Medium_Acc) then (Slop_MWperSec is NoChage_Slop) (1)
6. If (Average_EGT is Middle_Temp) and (GG_AccSpeed is High_Acc) then (Slop_MWperSec is Dec_Slop) (1)
7. If (Average_EGT is High_Temp) and (GG_AccSpeed is Low_Acc) then (Slop_MWperSec is Dec_Slop) (1)
8. If (Average_EGT is High_Temp) and (GG_AccSpeed is Medium_Acc) then (Slop_MWperSec is Dec_Slop) (1)
9. If (Average_EGT is High_Temp) and (GG_AccSpeed is High_Acc) then (Slop_MWperSec is Dec_Slop) (1)

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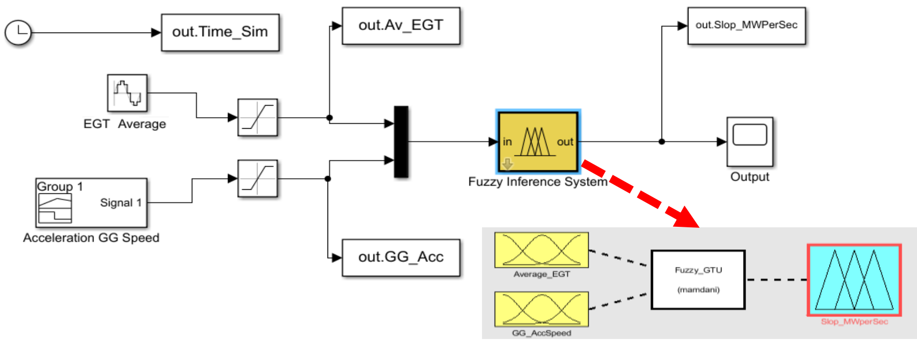
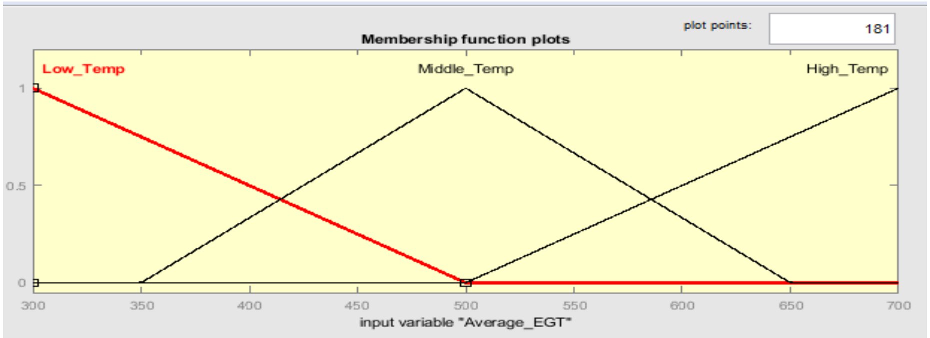
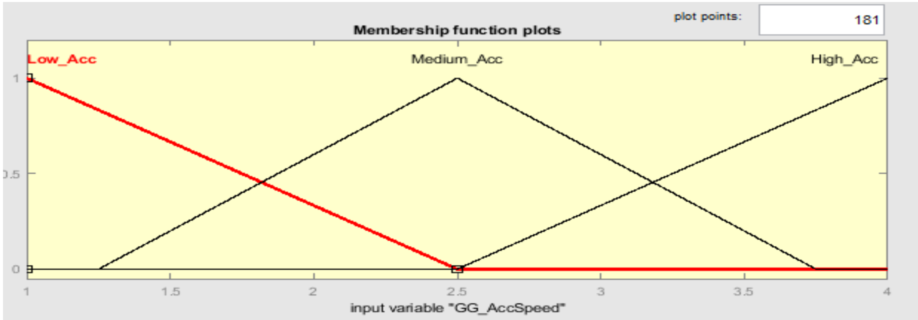


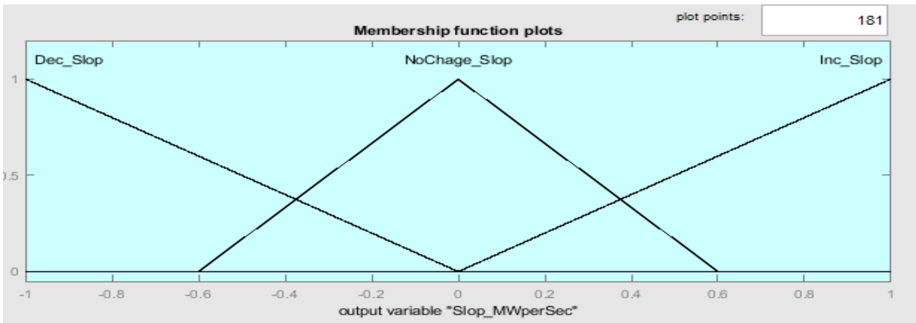
Fig. (6): FIS for control on slop of MW/Sec for fifth stage



(a)



(b)



(c)

Fig. (7): the MFs of FIS inputs and output

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Figure (8) shows the MATLAB/Simulink implementation with increasing and decreasing ramp singles for acceleration of GG speed FIS input, sinusoid signal from 200 to 700 ˚C for EGT FIS input and the slop value of FIS output. The Fig. 8 demonstrates the success of FIS to control on slope value depending on temperature and speed, which is clearly that the slop decreases when the temperature is high and vice versa, and similar with acceleration of GG speed.

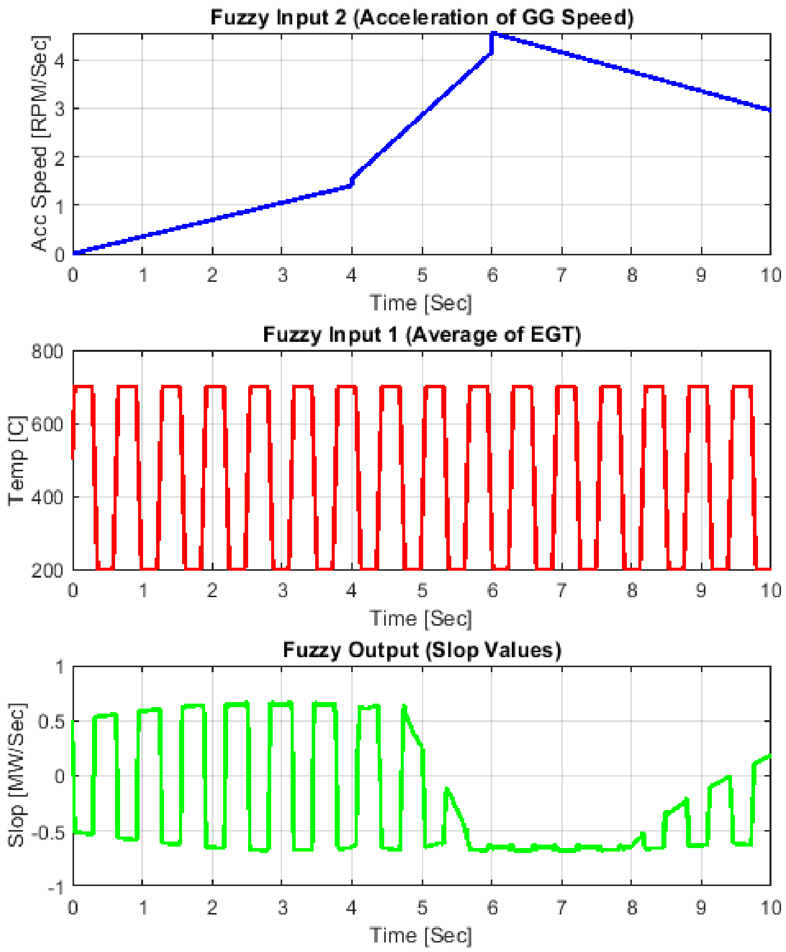

Fig. (8): The input and output singles coming from FIS.

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4. Results and Discussion

This section presents the applying in real engine (jet turbine) through programing of PLC to implement FIS. FIS is coded by using a structured list (ST) PLC language ("Fuzzy0").

Moreover, Figure (9) illustrates the two points slop rate equations (to calculate the acceleration of GG speed as the second input for the FIS) and called as the FIS subroutine, which are written in ladder diagram (LD) PLC languages.

The proposal was implemented on all three turbine units and was tested under the maximum temperature (in the mid-day), which reached 48˚C, where the operation was successful for all attempts with a steady increase in the speed and temperature of the three turbine units on a regular basis.

Fig. (9): the two points slop rate equations and call the FIS

Since the success of operating the three units that work at any required time without focusing on the atmosphere temperature, the administrators of BOC decide to depend on these units to expert the crude oil. These units do not work properly since 2016. Because of the efficiency of the three turbine units and the flow of their work, the administrators of BOC decide to operate two units simultaneously in order to increase the export quantity.

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The operating curves before and after the implementation of the proposal are shown in Figures (10) and (11), respectively, where the second turbine unit (GT2) is taken as a model to show the difference between running before and after the application of the proposal.

Figure (10) shows the (trends) curves of the average exhaust temperature (EGT) of the second turbine unit (GT2) before the proposal is performed, as well as the speed of the turbine unit (GG speed) and other parameters that are taken on the ninth of the May, 2021 at 11:30 am. The ambient temperature is approximately 41 °C (EGT is 687.6 °C) and very close to the peak (Trip Temp=700 ˚C). Figure (10) shows, there are only 12 ˚C disconnect from the unit stops, so the unit does not work in the summer when the heat peaks every year.

Figure (11) shows the (trends) curves for the average exhaust temperature of the second turbine unit (GT2) after performing the solution on it, as well as the turbine unit speed (GG speed) and other parameters that are taken on the ninth of the June, 2021 in the middle of the afternoon (12:00 pm), whereas the ambient temperature is approximately **48 °C** (EGT is **610 °C**). The percentage of improvement (equation (2)) between before and after applying the proposed solution:

$$\frac{610-(48-41)}{687.6+(610-(48-41))} \times 100\% = \mathbf{45.8}\% \qquad \ldots (2)$$

Figure (11) illustrates the improvement of decreasing EGT is presented with smooth increasing in the GG speed.

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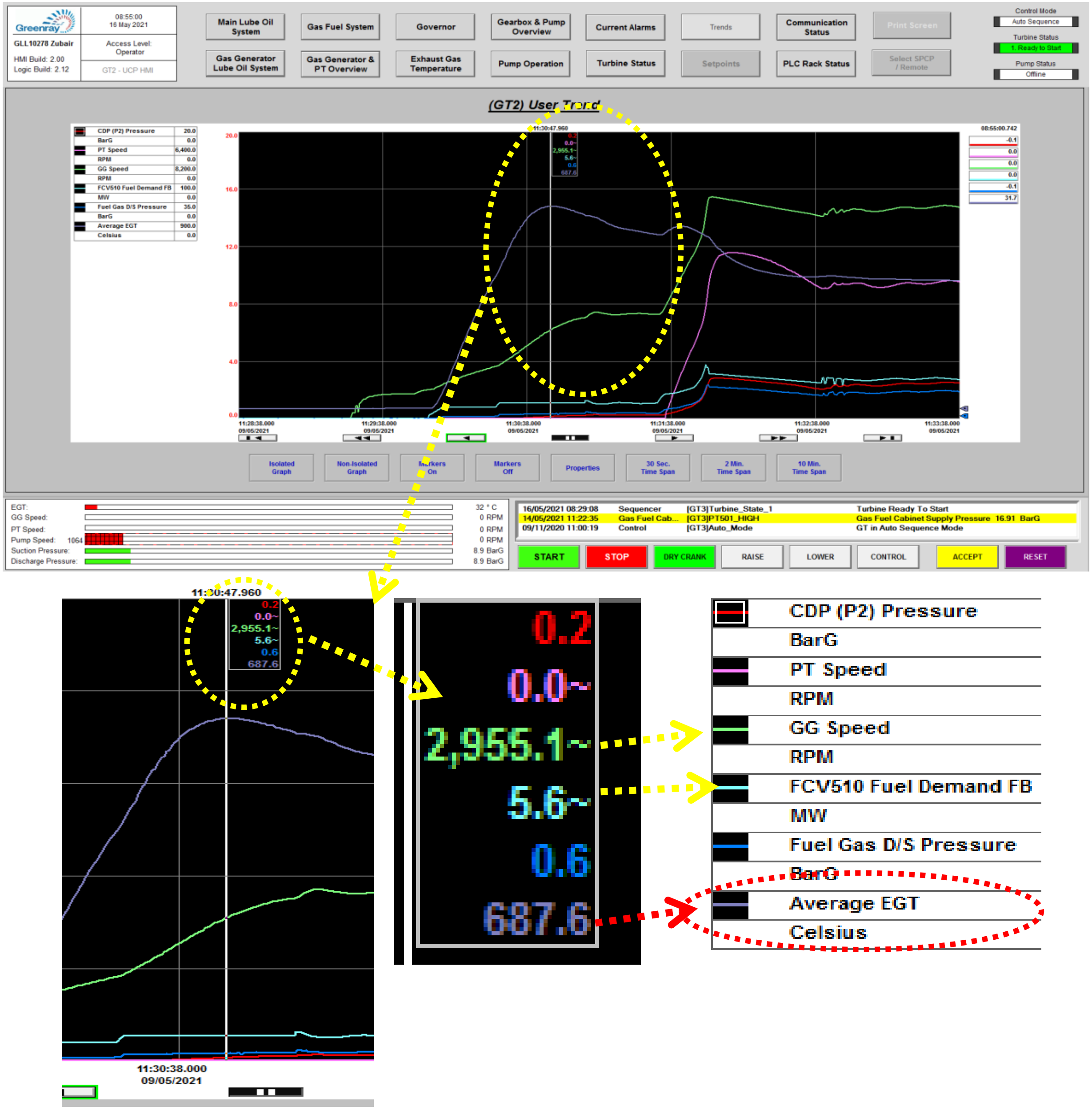

Fig. (10): Curves (trends) of the second turbine unit (GT2) before implementing the proposal solution

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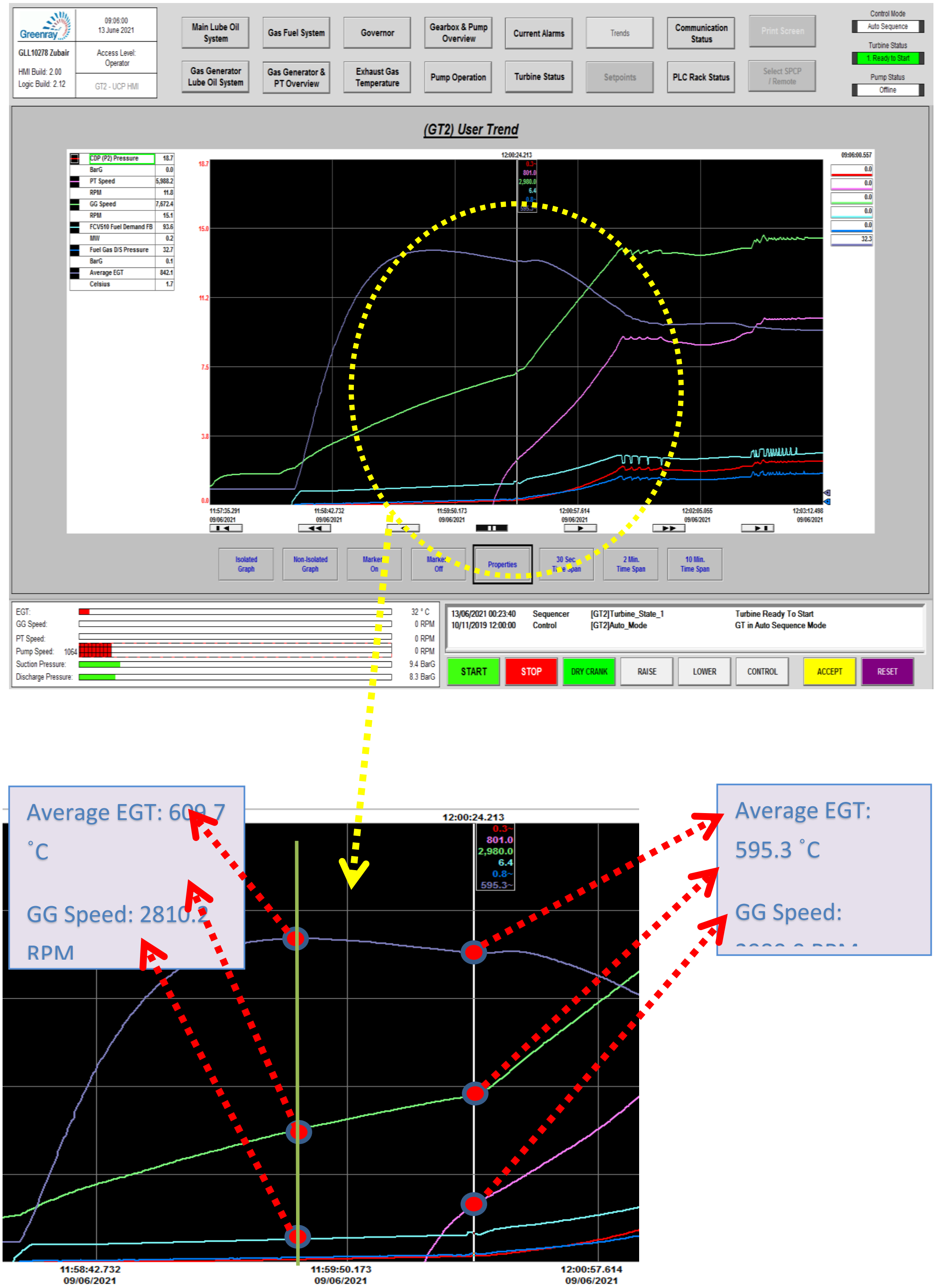

Fig. (11): Curves (trends) for the second turbine unit (GT2) after executing the proposed solution.

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5. Conclusion, Economic Viability and Future Work

In this work, FIS is applied to overcome the exhaust temperatures during summer for three jet turbine units in Basra/ZB1. The proposal is simulated by using MATLAB/Simulink programing to ensure that work perfectly.

The inputs for FIS are average of exhaust temperatures of turbine and acceleration of GG speed, while the output is value of slop rate that inject to main fuel gas valve. After the MATLAB/Simulink gives a great effect result, we use high level language of PLC ST to code the FIS and downloading to PLC. After applying the proposal, the all units are work smoothly and at any time.

Stopping the turbine in one hour leads to a halt in the process of pumping crude oil and exporting it to the port with a quantity of 41,000 barrels, that is, stopping the turbine at the height of the temperature rise for four hours leads to a loss of 164,000 barrels (this is for one turbine), i.e. 492,000 barrels, a loss of four hours for three turbines.

After solving the problem, the authority in BOC decides to operate two turbines at the same time, which is the first operation of two turbines since 2002. In future work, we will extend and develop this paper to be self-learning to control on turbine without human intervention by ST of PLC coding an adaptive dynamic programing [13].

Abbreviations and Acronyms

BOC	Basra Oil Company	PT	Power Turbine
ZB1	Zubair 1	GT	Gas Turbine
PLC	Programmable Logic Controller	HMI	Human Machine Interface
AI	Artificial Intelligence	FIS	Fuzzy Inference System
GG	Gas Generator	MF	Membership Function
IFV	Initial Fuel Variable Values	EGT	Exhaust Temperature
FCV	Flow Control Valve	LD	Ladder Diagram
ST	Structured List		

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