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Improvement of Governing Control System Using Fuzzy Logic Controller in a CCGT Plant

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ABSTRACT: In recent decades, there are considerable progressions research in modelling, simulation and control strategies. The advanced technologies in the combined cycle power plants offers more effectiveness and lower environmental effect compared to the conventional systems. Fuzzy logic control is one of the frequently advanced controllers may well improve the performance of the control system in the power plant. This study focuses on the improvement of governing control system by using fuzzy logic controller. Thus, a combined cycle gas turbine plant has been modelled and simulated on MATLAB/Simulink, and a fuzzy logic controller was implemented. The simulation results are compared with that of conventional PID controller tuned by Ziegler Nichols method.

KEYWORDS: Combined cycle, simulation, control system, governor, fuzzy logic, PID, Ziegler Nichols method.

I. INTRODUCTION

Combined Cycle Gas Turbines (CCGT) have considerable merits and mainly the most frequently researched topics in power generation, due to their attractive performance characteristics and low emission combustion system [1-3]. It is characterized by a great advantage of fast response and high efficiency. Various studies and analysis of the combined cycle plants performance have been achieved, based on different mathematical modeling approach which is necessary for the power system assessment [4-6].

Because of the frequently variation of the power demand, the power output of a CCGT plant is mostly lower than its design capacity. Therefore, improving the performance of the generation power plant during part-load operations is extremely required [7]. On the other hand, a change in power demand throughout the power system is reflected by a change in frequency in the network. Therefore, significant loss in the power system without a suitable control system can cause an extreme frequency disturbance in the network. Governing control system in a the CCGT regulates the output power in order to set up the load change and to bring back the frequency to its nominal value [8, 9]. To ensure the accuracy of a control system, a suitable controller is required.

It is commonly known that the most control strategies used in the generation power plants are the conventional PI and PID controllers, however it is still limited by the assumption of the linearity in the plant, or operates in a linear region where its dynamics unvarying over time [10]. Therefore, an advanced robust controller may well provide better performance. In our study, a fuzzy logic controller is used in order to improve the dynamic performance of the control system. The simulation model of the CCGT has been developed in MATLAB/Simulink. The simulations are dealt for different load disturbances, in order to show the effectiveness of the fuzzy logic strategy, and the results are compared with the simulated response using the traditional control strategy of the PID Ziegler Nichols.

II. COMBINED CYCLE GAS TURBINE PROCESS

The combined cycle gas turbine plants are widely used in the generation power due to their high efficiencies and environmental sustainability compared to the conventional single cycle plants namely gas turbine and steam turbine plants [9].

In a CCGT plant, the gas turbine provides two-thirds of the total unit power output and the steam turbine provides the other one-third. Practically, the overall thermal efficiency of the power plant, in a combined cycle system, increases from 37% to 57–61% [11,12]. In the CCGT, the air is compressed isentropically in the compressor before being fed into a combustion chamber, where it mixes with the natural gas from the fuel supply system and burned to produce hot gases. The energy of the expanding air is then converted to mechanical power in the gas turbine, for driving the compressor and converted into electrical power by a generator [9, 13]. The gases exhausted from the gas turbine are used to drive a steam turbine, by transmitting these gases through the heat recovery steam generator (HRSG). This process is the basis of the combined cycle gas turbine plant. The mechanical power produced by the steam turbine is converted into electrical power by the generator.

A. Mathematical Modeling of the CCGT plant

The thermodynamic process of the gas and steam turbine is modelled by algebraic equations (Spalding and Cole, 1973), consistent on the adiabatic compression and expansion, as well as to the heat exchange in the HRSG [14, 15]. It is assumed that the mixture of air and gas is almost equal to air flow. The ratio of input-output temperatures for isentropic compression is given as follows [14,15].

$$x = (P_{r0}\, W)^{\frac{\gamma-1}{\gamma}} \qquad (1)$$

Where, γ : The ratio of specific heat,

P_r : The actual compressor ratio (for nominal airflow (W=1pu), $P_r = P_{r0}$).

However, the compressor discharge temperature t_d and the gas turbine exhaust temperature t_e can be written respectively as:

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

$$t_e = t_f\left[1-\left(1-\frac{1}{x}\right)\eta_t\right] \qquad (3)$$

Where,

t_i : The ambient temperature,

t_f : The gas turbine inlet temperature,

η_c and η_t are respectively, the compressor and turbine efficiency.

The mechanical output power produced by the gas turbine is given by:

$$E_g = K_0\left[\left(t_f - t_e\right) - \left(t_d - t_i\right)\right] W \qquad (4)$$

The mechanical output power produced by the steam turbine is given by:

$$E_s = K_1\, t_e\, W \qquad (5)$$

In steady state and for initialization purposes, the generation output power of the plant is given by:

$$P = E_g + E_s \qquad (6)$$

The inlet temperature T_f and exhaust temperature T_e (note that for normalized conditions $T_f = T_e = 1$ (pu)) are:

$$T_f = \frac{t_f - 273}{t_{f0}} \qquad (7)$$

$$T_e = \frac{t_e - 273}{t_{e0}} \qquad (8)$$

B. The control system loops

The control system is one of the important units in a power generation plant, where technological improvements control strategies must be applied. It is planned as follows [16, 5]:

1. 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. Our study focuses on this part of control system.
2. The fuel control is directly related to the rotor speed which have a direct influence on air and fuel consumption.
3. The temperature control loop has a significant role in operating system of the power plant, it adjusts the fuel flow (Wf) and airflow (W) based on the measurement of the exhaust temperature, by adjusting the fuel demand when the frequency falls and the output power decreases.
4. The selection of the control loops (frequency or overheat) is achieved by the Low-Value-Select (LVS), and by switching the lower value (Tc or Fd).

III. CONVENTIONAL PID CONTROLLER

About 90% industrial systems are controlled by the proportional-integral-derivative (PID) controller. It provides a proper design for transient and steady-state responses. PID controllers can be tuned in a different ways containing: Cohen-coon tuning, hand tuning Ziegler Nichols and Z-N step response [17, 18]. The transfer function of PID controller is given by:

$$\frac{U(s)}{E(s)} = K_P\left(1+\frac{1}{T_I(s)}+T_D(s)\right) \qquad (9)$$

In this proposed work, a PID controller has been designed, using Ziegler-Nichols method. The PID controller parameters obtained by the Ziegler Nichols technique are calculated by Routh array criteria [17, 18]. The designed parameters Kp, Ti and Td are calculated by the following instruction represented in the table below:

ZIEGLER NICHOLS PARAMETERS

Controller	Gain"Kp"	Integral time "Ti"	Derivative time "Td"
P	0.5 Kcr	∞	0
PI	0.45 Kcr	0.8 Pcr	0
PID	0.6 Kcr	0.5 Pcr	0.125 Pcr

Kcr : The critical gain

Pcr: The corresponding critical period

The designed critical gain and critical period, for our system are: Kcr=5.5 and Pcr= 2.25.

The calculated Ziegler-Nichols PID parameters are: Kp=3.3, Ti=1.125 and Td=0.28125.

IV. FUZZY LOGIC CONTROLLER

Fuzzy logic controllers applied in different control systems namely computer subsystems, linear servo drive, automotive-related applications, industrial applications [4].

In 1965, the theory of fuzzy logic was introduced by Professor Lofti A. Zadeh. This theory is based on the concept of fuzzy sets [9, 12]. The fuzzy logic controller has the ability to deal with imprecise and uncertain data encountered in real life. This has made it a suitable controller for a wide range of applications [19]. The Fuzzy logic strategy is able to address all possibility values of variables taking into consideration the human reasoning [20], contrary to the earlier logic control strategy which take only binary set theory (1 or 0), described by the truth variable or the false one.

A. Fuzzy logic controller units

Fuzzy logic control (FLC) is an intelligent control technique that uses human expert knowledge of the controlled system and incorporates it into a succession of control rules [10]. It provides an algorithm converting linguistic concepts such as: "large", "low", "medium", "high", "few",…etc, into an automatic control strategy [10, 21]. The linguistic variables provide the probable decisions which is described by a membership function (MF). The combination of these variables constitute the linguistic control rules of fuzzy controller [19-21]. A typical FLC system is constituted by the following units [10, 21]:

1. The process of converting the crisp variables to fuzzy variables, called "Fuzzification". These fuzzy values are represented by membership functions.
2. The membership functions consigned to fuzzy variables can be done by using some algorithms or logical procedures or by intuition.
3. Defuzzification, also called "rounding off" method, is necessary to convert the fuzzy variables into crisp variables.

The rule-based form, which uses linguistic variables as its antecedents and consequents. It is, commonly, the canonical rule formation "Assignment statements, Conditional statements, Unconditional statements".

B. The fuzzy logic controller design

The structure of the fuzzy logic controller applied in the speed governor control for our system, has been dispensed step by step:

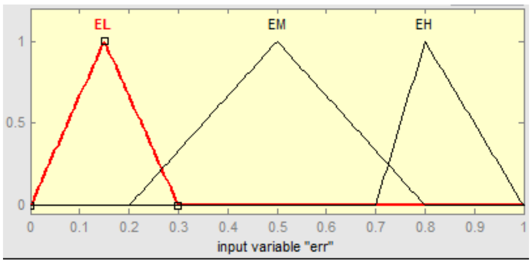
1. The first step to design a fuzzy logic controller is the choice of the suitable Membership Functions. The inputs triangular membership functions (MF) are: Error (err) and the change in error (erch), and the output one represent the control signal (control Signal), shown in Figs. 1, 2 and 3, respectively. The error and change in error of the fuzzy controller is calculated by the following formula,

$e(k) = \omega_{ref} - \omega_r$ (10)

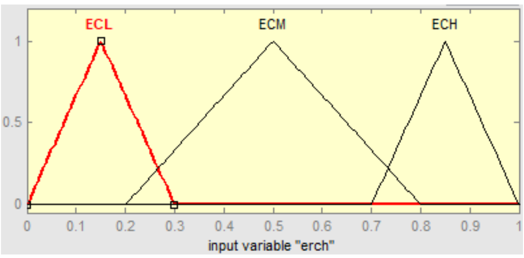
$ce(k) = e(k) - e(k\text{-}1)$ (11)

Where, "ω_{ref}" is the reference speed and "ω_r" is the measured speed.

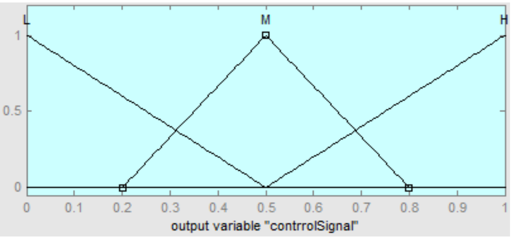
2. The second step is to create the linguistic rule base which is the essential part of designing fuzzy controller. It was formulated using conditional statement "IF - THEN". The rule base is shown in Fig. 4.



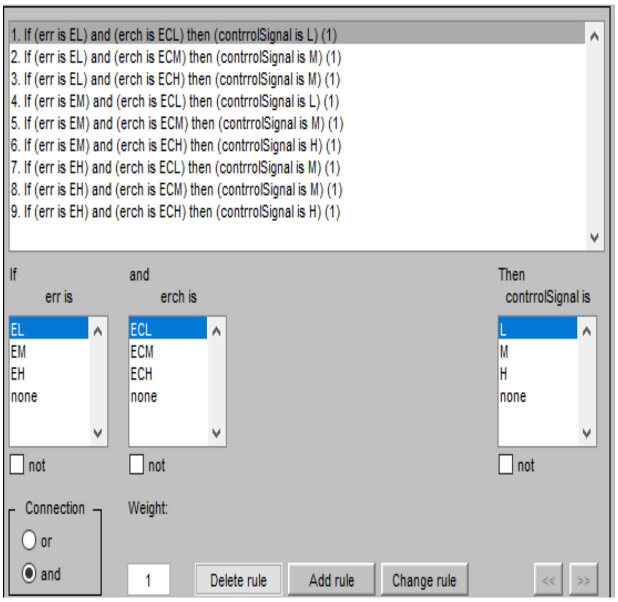
1. *Triangular membership functions for error "err"*



2. *Triangular membership functions for change in error "erch"*



3. *Triangular membership functions for the output variable "controlSignal"*



1. If (err is EL) and (erch is ECL) then (contrrolSignal is L) (1)
2. If (err is EL) and (erch is ECM) then (contrrolSignal is M) (1)
3. If (err is EL) and (erch is ECH) then (contrrolSignal is M) (1)
4. If (err is EM) and (erch is ECL) then (contrrolSignal is L) (1)
5. If (err is EM) and (erch is ECM) then (contrrolSignal is M) (1)
6. If (err is EM) and (erch is ECH) then (contrrolSignal is H) (1)
7. If (err is EH) and (erch is ECL) then (contrrolSignal is M) (1)
8. If (err is EH) and (erch is ECM) then (contrrolSignal is M) (1)
9. If (err is EH) and (erch is ECH) then (contrrolSignal is H) (1)

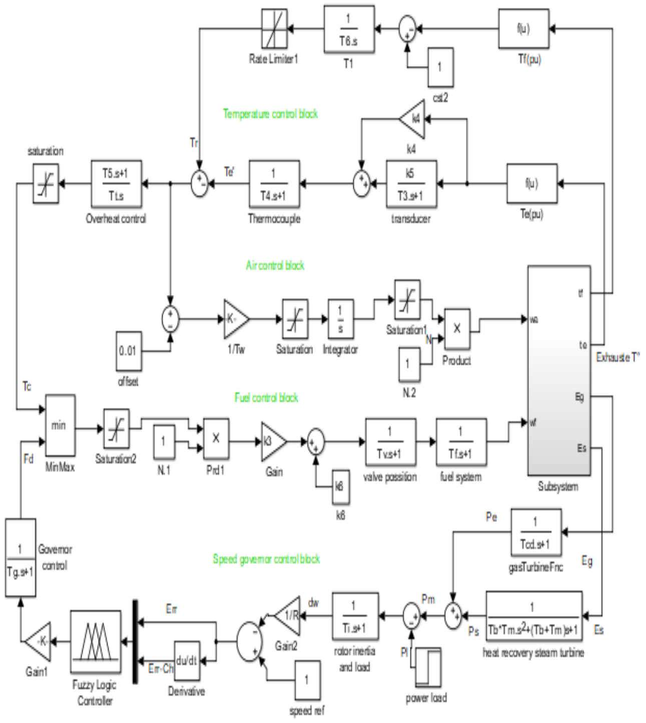
If err is: EL
and erch is: ECL
Then controlSignal is: L
☐ not ☐ not ☐ not
Connection: ○ or ● and
Weight: 1

4. *The linguistic rules for the fuzzy controller*

V. SIMULATION RESULTS AND DISCUSSION

The simulated model consists of two turbines (gas turbine and steam turbine) and one generator. The model is based on the dynamic model proposed by Kakimoto and Baba (2003) [22], which is founded on the simplified transfer function of gas and steam turbines and eventually the control system. Its Simulink model is shown in Fig. 5, and the parameters are given in the appendix.

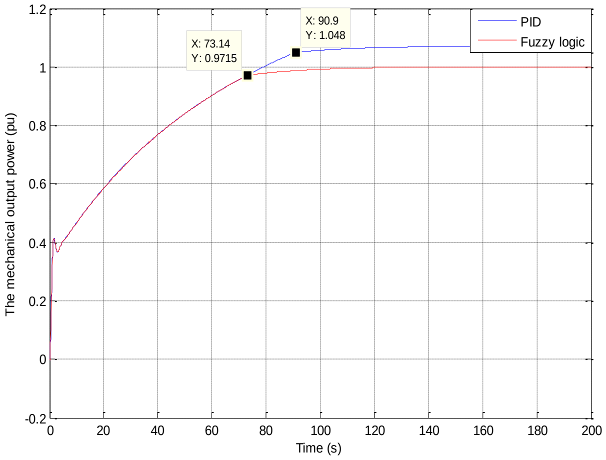
The simulation deals with two cases, the first one with PID controller and then the Fuzzy logic controller. The controllers were implemented in the speed governing control system in order to improve its performances.



5. Simulation model of the CCGT plant using fuzzy logic controller.

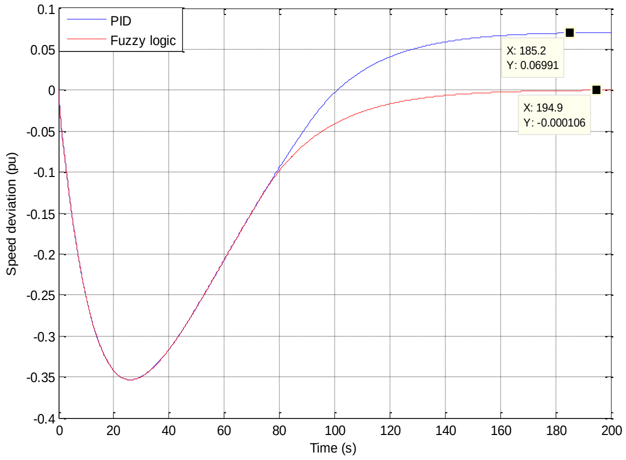
A. Simulation results for a set point load

The simulation results for a set point power load are represented in figures 6, 7 and 8.

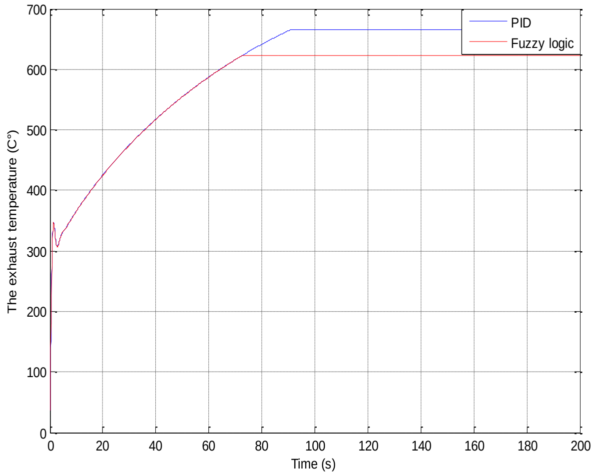


6. Mechanical output power (pu)

As illustrated in Fig. 6, the mechanical output power is represented for a PID controller and a fuzzy logic controller. It is clear that the response of the fuzzy logic is better than the response of PID controller in terms of tuning of settling time and the consistent responses. The same thing can be noted for the speed deviation illustrated in Fig. 7, and the exhaust temperature shown in Fig. 8.



7. Speed deviation (pu)

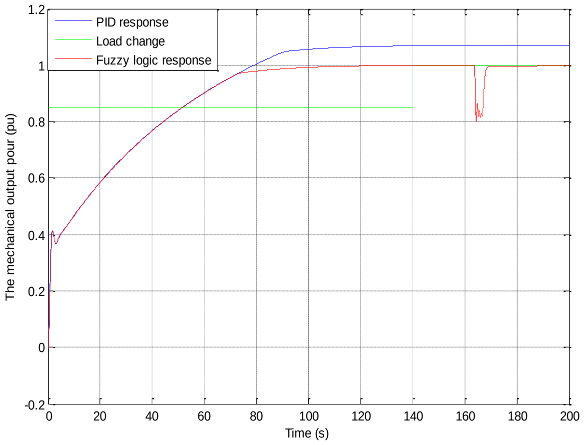


8. Exhaust temperature (C°)

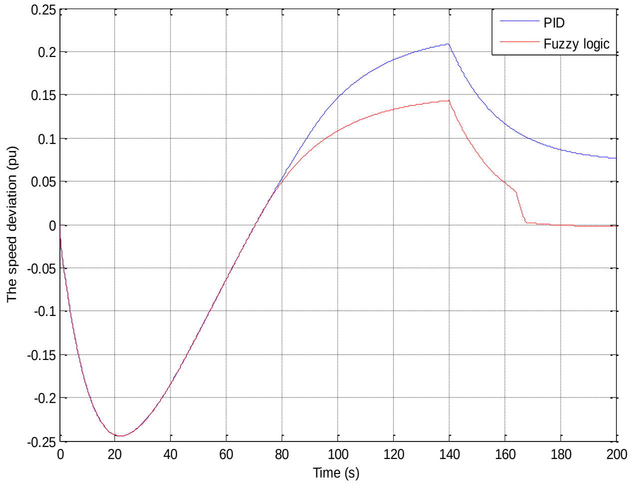
B. Simulation results for a sudden change in load

In this stage, a sudden change in power load is applied in the steady state, at t=140 (s), where the load power balanced from 0.85 (pu) to 1 (pu). The dynamic responses to a sudden load change are presented in figures 9, 10 and 11.

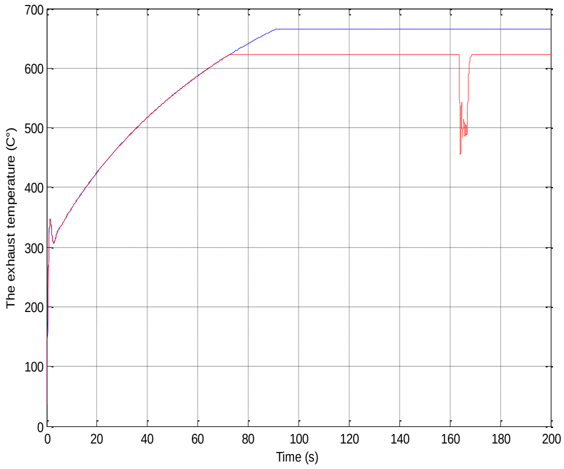
The fuzzy logic controller is more sensitive for the applied load change compared to the Zeigler Nichols PID controller. The response to this change is noted around t=165 (s) while the change is applied at t=140 (s), because of the slow dynamic of the system. This can be noted in Figs. 9, 10 and 11, which represent respectively mechanical output power, the speed variation, and the exhaust temperature



9. Mechanical output power (pu), for a sudden change in load power at t=140s



10. Speed deviation (pu), for a sudden change in load power at t=140s.



11. Exhaust temperature (C°), for a sudden change in load power at t=140s.

CONCLUSION

In a CCGTP, a significant loss in the power without an appropriate control system can lead to disagreeable operating system and frequency disturbances in the power grid. Therefore, it is important to improve the control system in these power plants by the exploitation of more advanced control strategies. In this study, the fuzzy logic controller has been implemented in the governing system in order to get better performance. The simulation results compared to the traditional PID Ziegler Nichols controller, indicate suitable dynamic responses in terms of the sensitivity to the load disturbance, fast response, reduction of settling time and a notable elimination of the whole overshoot from the output responses.

APPENDIX

PARAMETERS SIMULATION USED IN THIS STUDY [14].

Symbol	Description	Value
t_i	Compressor inlet temperature	30°C
t_{d0}	Compressor discharge temperature	390°C
t_{f0}	Gas turbine inlet temperature	1085°C
t_{e0}	Gas turbine exhaust temperature	535 °C
P_{r0}	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 con-stant	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 nstantaneous)	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	Time constant heat capacitance of aste heat recovery boiler	5
T_b	Boiler storage time constant	20
T_i	Turbine rotor time constant	18.5

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