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Design of an Interval Fuzzy Type-2- PID Controller for a Gas Turbine Power Plant

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Abstract

In this paper, an interval fuzzy type-2 PID controllers are designed for speed and Exhaust temperature in a heavy duty Gas Turbine (HDGT) power plant and the model selected is Rowen’s model to present the mechanical behavior of the gas turbine, the work is aimed to improve the system dynamic performance of speed and Exhaust temperature for a 56.6 MW, 50 HZ, simple cycle, single shaft heavy duty gas turbine, all gains for conventional PID and interval fuzzy type-2 PID are tuned using Social Spider Optimization(SSO) technique, we show the performance improvement for interval fuzzy type -2 PID controller in comparison with conventional PID via simulation.

Keywords: Interval type-2 fuzzy PID; heavy duty gas turbine power plant; Rowen’s model; Social spider optimization (SSO).

1. Introduction

The gas turbine is a power plant that produces a great amount of energy depending on its size and weight. The gas turbine has found increasing service in the past 60 years in the power industry among both utilities and merchant plants as well as the petrochemical industry throughout the world. Its compactness, low weight, and multiple fuel application make it a natural power plant for offshore platforms.

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Today there are gas turbines that run on natural gas, diesel fuel, naphtha, methane, crude, low-BTU gases, vaporized fuel oils, and biomass gases. Simplified mathematical model of simple cycle and single shaft gas turbines with inlet guide (IGV) opened suggested first by Rowen [1], and modified the models by adding the influence of axial flow compressor variable IGVs [2].Rowen used conventional lag-lead for speed, PI controller for temperature and integrator controller for acceleration, while Hannett and his colleagues [3] identified two types of controls GE Speedtronic Governor Control (PI controller) and Woodward Governor Retrofit (PID controller). J.W. Kim and S.W. Kim used incremental fuzzy PI for speed and Exhaust temperature.

In this paper, we design controllers for rotor speed, exhaust temperature using interval fuzzy type-2 PID [4-8] to overcome the limited performance of the classical PID controller. All gains of interval type -2 fuzzy PID optimized using social spider optimization (SSO) [9].

This paper is structured as follow. Section 2 gives overview of system. Section 3 present interval fuzzy type-2 PID. In section 4 the simulation results of optimized interval fuzzy type-2 controller. The conclusion is presented in Section 6.

2. Overview of System

2.1. Rowen's Model

The mathematical model of an HDGT is provided by Rowen's [1,10] and completed in [2] as shown in Figure (1). The main components of HDGT of an industrial gas turbine power plant are the compressor, combustion chambers and turbine.

Rowen's model is based on the following assumptions:

- It is a heavy duty gas turbine operated in simple cycle, generator drive only with no heat recovery steam generator (HRSG).
- Allowable speed range between 95%-107% of rated speed.
- The model operates at an ambient temperature of 15°C and ambient pressure of 101.325 kpa.
- Open Inlet guide vanes (IGV) [1].

The Rowen's model consist of sequence of blocks are: fuel demand limitation, no load consumption, valve positioner and fuel system dynamic, volume discharge delay.

Gas turbine control system includes; speed/load controller (also known as load/frequency controller), temperature controller, acceleration controller and upper and lower fuel limits [1,11].

These three control functions are all inputs to minimum value select or low value select (LVS) as shown in Figure (1).

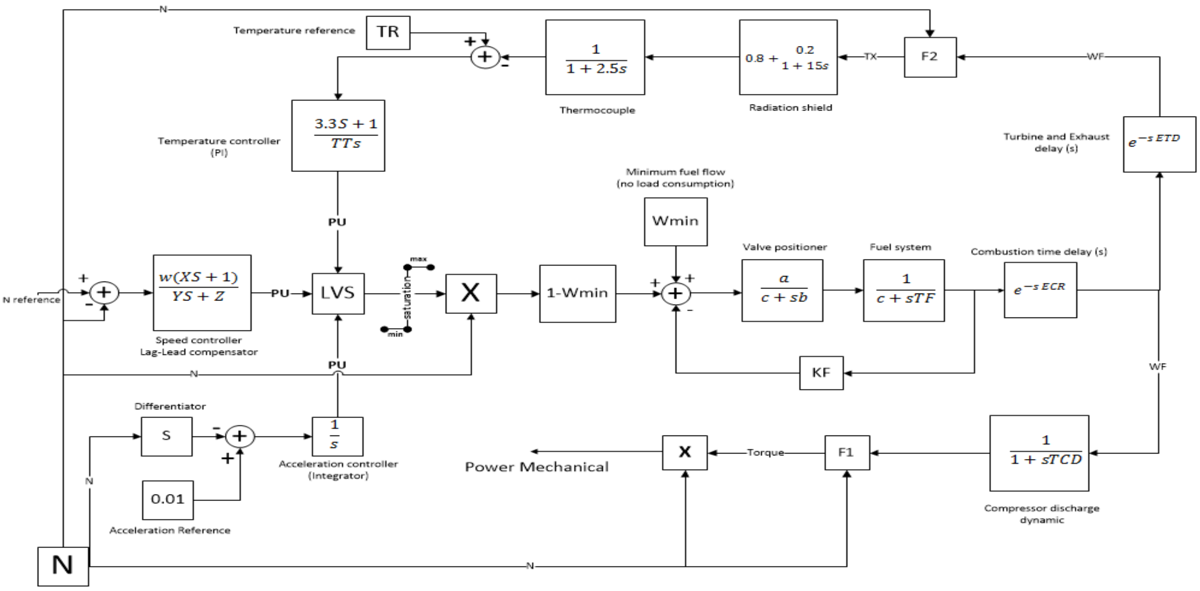

Figure 1: Simulink model of gas turbine (Rowen model) [1].

The speed control loop corresponds directly to the governor and can be operated either in the standard droop mode or in isochronous mode. The temperature control loop represents the limitation of the gas turbine output due to temperature. Exhaust temperature is measured using a series of thermocouples incorporating radiation shields as shown in the model. An acceleration control loop, in order to prevent the over-speeding of the generator in the event of a sudden loss of load, is also implemented in the model and represented by the third input into the low value select [12].

When the thermocouple output exceeds the referenced temperature, the difference becomes negative and it starts lowering the temperature control output. When the temperature control output becomes lower than the governor output, the former value will pass through the low value select to limit the CT's Mw output, and the unit is now operating on temperature control [3].

Mechanical power (PM) = T (torque)*N (speed), The function of the Rowen's model are as follow:

$$F1=1.3*(WF-0.23) + 0.5*(1-N) \tag{1}$$

$$F2=TR - 700*(1-WF) + 550*(1-N) \tag{2}$$

F1 block calculate the turbine torque and F2 block calculate the exhaust temperature.

The model parameters listed in table (1) below [13].

2.2. Electrical model

The model consists of 3-phase synchronous machine modelled in dq reference frame, stator winding are connected in wye to an internal neutral point, There is a separate block for the excitation system consisting of

V_{ref}, input voltage that voltage at the terminal of the generator and automatic voltage regulator in conjunction with the power system stabilizer block V_{stab} attached to it for better stabilization of the generated voltage. The model also consist of Three-Phase PI Section represent Line three-phase transmission line with a single PI section, one set of three phase series RLC load element and three phase source as shown in Figure(2).

Table 1

Parameter	Description	Value
W	Gain=1/Droop(pu MW/pu speed)	16.7
X	Governor lead time constant(s)	0.6
Y	Governor lag time constant(s)	1.0
Z	Governor mode(1=drop,0=isochronous)	1
Max	Demand upper limit (pu)	1.5
Min	Demand lower limit (pu)	-0.1
a	Valve positioner	1
b	Valve positioner	0.05
c	Valve positioner	1
W_{min}	Minimum fuel flow	0.23
T_f	fuel control time constant(s)	0.4
KF	Fuel system feedback	0
E_{CR}	Combustion reaction time delay(s)	0.01
E_{TD}	Turbine and exhaust delay(s)	0.04
T_{CD}	Compressor discharge volume time constant (s)	0.2
TR	Turbine rated exhaust temperature (°F)	950
T_T	Temperature controller integration rate (°F)	450
T_I	Inertia =2*H(H:inertia constant)	15.64

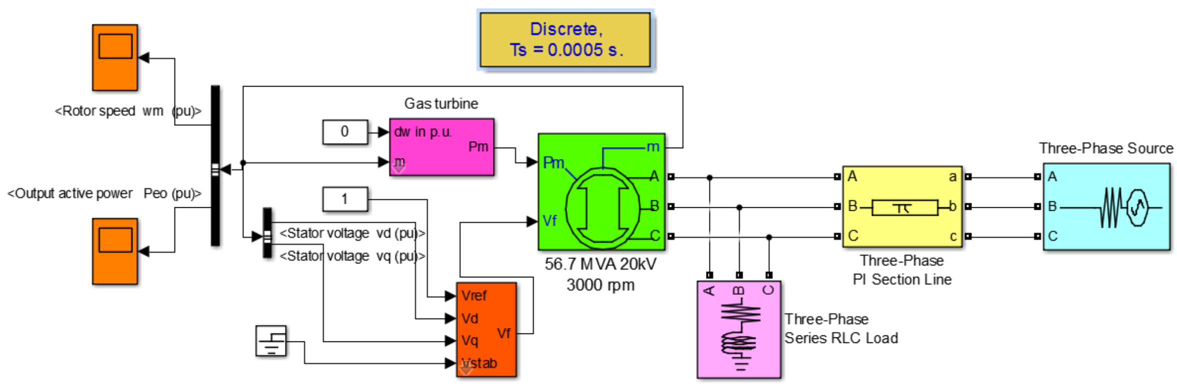

Figure 2: gas turbine with synchronous machine [13,14].

Table 2: Synchronous generator parameters

parameter	value
Nominal power	56.7mw
Line to line voltage	20 kv
Reactance(Xd,Xd',Xd",Xq,Xq',Xq" Xl)(P.U)	(1.65,0.25,0.2,1.59,0.46, 0.2,0.14)
d axis	Open circuit
q axis	Open circuit
[Tdo' Tdo" Tqo' Tqo"] (s)	[4.5, 0.04, 0.67, 0.09]
Stator resistance Rs (pu)	0.0045
Inertia coefficient H(s)	7.82
Friction factor F(pu)	0
Poles pairs p	1

3. Interval type-2 fuzzy PID controller

One aspect of the construction of conventional fuzzy logic system is the establishment of the rules. Knowledge of building these rules is uncertain which leads to antecedent or consequents of rules that are uncertain. Consequently, uncertain membership functions (MFs) arise. Thus, this type of control cannot deal with uncertainty. Type-2 fuzzy set, which was introduced by Zadeh in 1975, is a set that its membership function (MF) deals with uncertainty with three dimensions. It is the general form of conventional, which can also be called type-1, fuzzy logic. It is used when there is a difficulty to obtain an exact membership function for a set [15]. In order to give a clear idea about Type-2 fuzzy sets, the following Definition of IT2FLC [16].

3.1. Definitions

Definition 1. $\tilde{A}$ is denoted for the Type-2 fuzzy sets and is characterized by Type-2 MF$u\tilde{A}$ (x,u) ,where $x \subset X$, X is the universe of discourse and $u \in Jx \subseteq [0,\ 1]$, then:

$$\tilde{A} = \{((x,\ u)\ ,\ \mu_{\tilde{A}}(x,\ u))\ |x \in X,\ u \in J_x \subseteq [0,\ 1]\} \qquad (3)$$

In which $0 \leq u_{\tilde{A}}(x,\ u) \leq 1$. It can also be represented by:

$$\tilde{A} = \int_{x\in X}\int_{u\in J_x} \frac{\mu_{\tilde{A}}(x,u)}{(x,u)} \subseteq [0,1] \qquad (4)$$

Where denotes union over all admissible x and u

Definition 2. The 2-D plane whose axes are u and $u_{\tilde{A}}\ (x,\ u)$ is known vertical slice of $u_{\tilde{A}}\ (x,\ u)$ as follows:

$\mu_{\tilde{A}}\ (x = x_l, u) \equiv \mu_{\tilde{A}}(x_l) = \int_{u\in Jxl} \frac{f_{xl}(u)}{u}\ J_{xl} \subseteq [0,1]$(5)

where$0 \leq f_{x1}\ (u) \leq 1$ and $\mu_{\tilde{A}}\ (X1)$ is referred to as a secondary MF and secondary set. It is the Type-1 fuzzy set. J_{x1} is the primary MF of x_1. It is the domain of the secondary membership where $J_{x1} \subseteq [0, 1]$ for all $x_1\ in\ X$.

Definition 3. The second degree is defined as the amplitude of the secondary membership and the MF is named secondary grade.

Definition 4. If the secondary MF of $f_{x1}\ (u) = 1\ u \in J_{x1} \subseteq [0, 1]$, then it is the interval set. If this is true for $x_1 \in X$, and Interval Type-2 MF is obtained. The secondary MF of type-2 represents a uniform uncertainty at the primary membership of x.

Definition 5. Footprint of Uncertainty is defined as the bounded region for the uncertainty of a type-2 fuzzy set $\tilde{A}$. It represents the union of all primary membership functions, where:

$$FOU\ (\tilde{A}) = U_{x\in X} J_x. \qquad (6)$$

Definition 6. The upper MF and the lower MF of $\tilde{A}$ are two Type-1 fuzzy sets where the boundaries for ($\tilde{A}$) of Type2 fuzzy sets $\tilde{A}$ are type-1 upper and lower fuzzy sets. The upper MF is denoted by $\tilde{\mu}_{\tilde{A}}\ (x)\ x \in X$ while the lower MF is denoted by $\tilde{\mu}_{\tilde{A}}\ (x)\ x \in X$. That is:

$$\tilde{\mu}_{\tilde{A}}\ (x) = FOU\ (\tilde{A}) \qquad (7)$$

And

$$\tilde{\mu}_{\tilde{A}}\ (x) = FOU\ (\tilde{A}) \qquad (8)$$

The lower and upper MFs very often exist because the domain of the secondary MFs have been confined in [0, 1]. The type-2 membership function with its secondary memberships is shown in Fig.(3)

a) T2FLC set representing Type-1 fuzzy set with uncertain mean.

b) FOU for a sample T2FLC set.

c) The secondary membership function for T2FLC set.

d) The secondary membership function of IT2FLC [17].

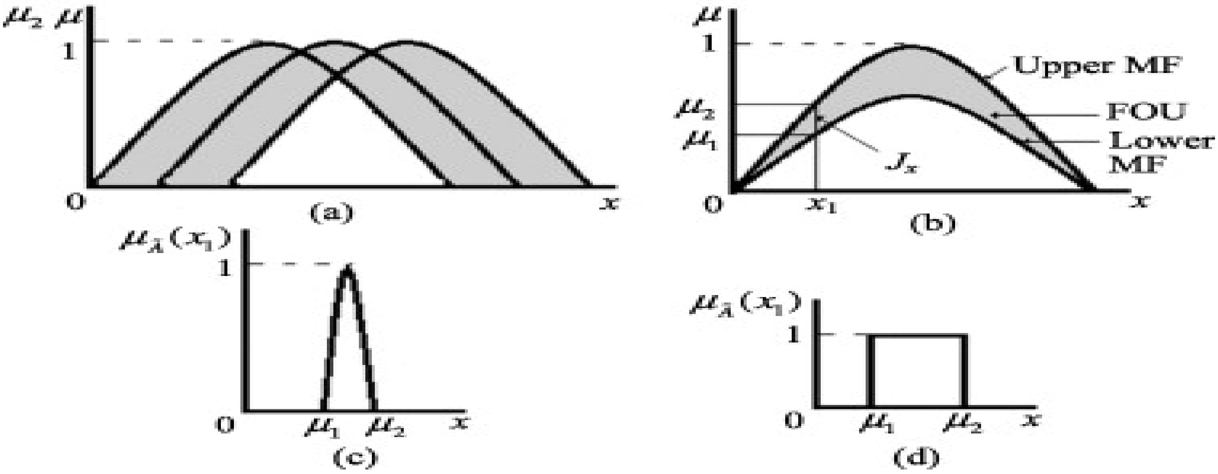

Figure 3: Type-2 membership function with its secondary membership.

3.2. Structure of IT2FLC

The structure of the T2FLC, shown in Fig. 4, is similar to Type-1 but the difference is in the nature of the membership functions and type reduction.

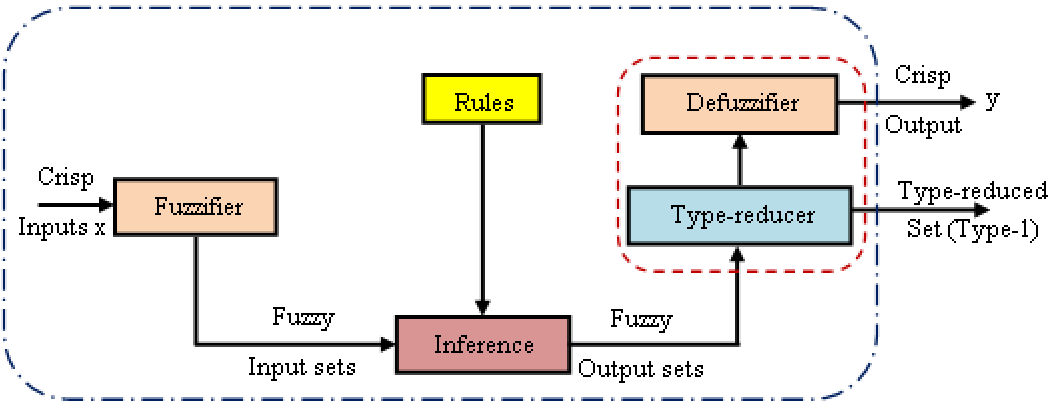

Figure 4: Structure of T2FLC [18]

a. Fuzzifier: The fuzzifier maps crisp inputs into Type-2 fuzzy sets which make the inference engine start working.

b. Rule base: The rules in the IT2FLC are similar to the rules in the T1FLC but the difference is in the antecedents and consequents which are represented by the fuzzy sets.

c. Inference engine: Inference engine block assigns fuzzy inputs to fuzzy outputs using the rules base and the operators such as the intersection and union operators.

d. Type-reduction: The type-2 fuzzy sets outputs of the inference engine are converted into type-1 fuzzy sets and they are named type reduced sets.

e. Defuzzification: The type reduction block outputs are given as inputs to the defuzzification block, defuzzification is made up of two steps: the first step is to transform the type-2 fuzzy sets into type-1 fuzzy sets (type-reduced) [24, 26]. The type reduction sets are calculated from the left and right end points, the defuzzification value is calculated by the average of the points.

3.3. IT2FLC Computations

In practice the computations in an IT2FLC can be significantly simplified. Consider the rule base of an IT2FLC consisting of N rules assuming the following form:

R^n $IF\ x_1 is\ \tilde{X}_1^n\ and\ \dots and\ x_I is\ \tilde{X}_1^n, then\ y\ is\ Y^n\ n = 1,2,\dots,N$ (9)

Where $\underline{\tilde{X}i}\ n$ (i=1 ,….,I) are IT2 fuzzy sets and Yn= [yn, yn] is an interval that can be understood the centroid, of a consequent IT2FLC , or the simplest TSK model. Each rule consequent is represented by a crisp number in many applications [19].

For an input vector X' = ($x'1$, $x'2$, ….$x'I$) , typical computations in an IT2FLC involve the following steps:

1) Compute the membership interval of $x'i$ on each X_n^i , $[\mu X_i^n(x'i), \mu X_i^n(x'i)], i = 1,2,\dots,I, n = 1,2,\dots,N$. (10)

2) Compute the firing interval of the nth rule , Fn (x′):

$$F^n(x')\left[\mu \underline{X}_i^n(x_1') \times \dots \times \mu \underline{X}_I^n(X_I') \times \dots \times \mu \overline{X}_I^n(x_I')\right] \equiv \left[\underline{f}^n, \overline{f}^n\right], \qquad n = 1,\dots,N \tag{11}$$

3) The third step is that perform type reduction, the most commonly used one is the center of sets type reducer:

$$yl = \min_{k\in[1,N-1]} \frac{\sum_{n=1}^{k} \overline{f}^n \underline{y}^n + \sum_{n=k+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{K} \overline{f}^n + \sum_{n=k+1}^{N} \underline{f}^n} \equiv \frac{\sum_{n=1}^{L} \overline{f}^n \underline{y}^n + \sum_{n=L+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{L} \overline{f}^n + \sum_{n=L+1}^{N} \underline{f}^n} \tag{12}$$

$$yr = \max_{k\in[1,N-1]} \frac{\sum_{n=1}^{k} \underline{f}^n \overline{y}^n + \sum_{n=k+1}^{N} \overline{f}^n \underline{y}^n}{\sum_{n=1}^{K} \underline{f}^n + \sum_{n=k+1}^{N} \overline{f}^n} \equiv \frac{\sum_{n=1}^{R} \underline{f}^n \overline{y}^n + \sum_{n=R+1}^{N} \overline{f}^n \underline{y}^n}{\sum_{n=1}^{R} \underline{f}^n + \sum_{n=R+1}^{N} \overline{f}^n} \tag{13}$$

In equation (12) and (13) k is a potential switch point. Fortunately, yl and yr, as shown in Figure (5), can also be calculated by the type reduction algorithm.

The type reduction used is Karnik-Mendel (KM) [20]

4) Compute the defuzzified output as:

$$y = \frac{(yl + yr)}{2}$$

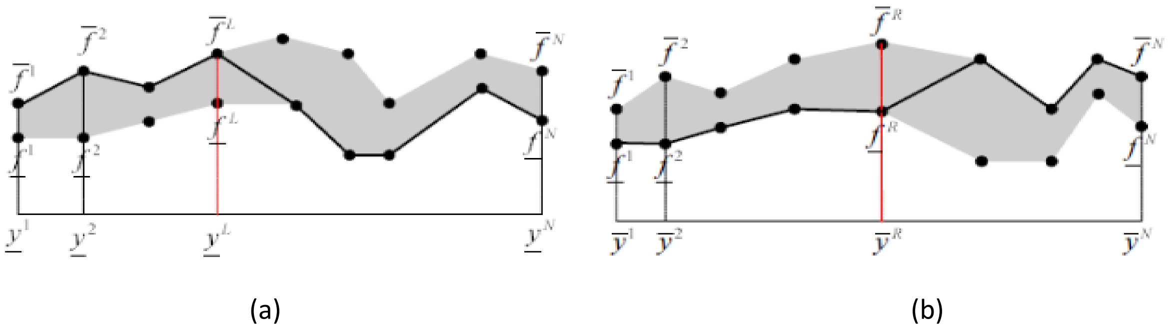

Figure 5: Switch points in computing $\boldsymbol{yl}$ and $\boldsymbol{yr}$ (a) $\boldsymbol{yl}$: switch from the upper bounds to the lower bounds; (b) $\boldsymbol{yr}$: switch from the lower bounds to the upper bounds.

KM Algorithm for computing yl and yr is given in **Table (3).**

Table 3

Step	For computing yl	For computing yr
1	Initialize $f^n = \frac{\underline{f}^n + \overline{f}^n}{2}$ n=1,2,…,N And compute $y = \frac{\sum_{n=1}^{N} \underline{y}^n f^n}{\sum_{n=1}^{N} f^n}$	Initialize $f^n = \frac{\underline{f}^n + \overline{f}^n}{2}$ n=1,2,…,N And compute $y = \frac{\sum_{n=1}^{N} \overline{y}^n f^n}{\sum_{n=1}^{N} f^n}$
2	$find\ l \in [1, N-1]\ such\ that$ $\underline{y}^l \le y \le \underline{y}^{l+1}$	$find\ r \in [1, N-1]\ such\ that$ $\overline{y}^r \le y \le \underline{y}^{r+1}$
3	Set $f^n = \begin{cases} \overline{f}^n, n \le l \\ \underline{f}^n, n > l \end{cases}$ And compute $y' = \frac{\sum_{n=1}^{N} \underline{y}^n f^n}{\sum_{n=1}^{N} f^n}$	Set $f^n = \begin{cases} \overline{f}^n, n \le r \\ \underline{\overline{f}}^n, n > r \end{cases}$ And compute $y' = \frac{\sum_{n=1}^{N} \underline{y}^n f^n}{\sum_{n=1}^{N} f^n}$
4	If y'= y, stop and set yl= y and L= l , Otherwise, set y = y' and go to step 2.	If y'= y, stop and set yr= y and R= r ; Otherwise, set y = y' and go to step 2.

The main idea is to find the switch points for yl and yr, $y\ n$ increases along the horizontal axis from the left to the right. For computing yl, switch from the upper firing level to the lower firing level, and switch from the lower firing level to the upper firing level for computing yr, as shown in Fig.(5).

However, seven triangular MFs with normalized universe of discourse (-1, 1) for both two inputs (e and$\dot{e}$) and the output (u) are shown in Figure (6). The defuzzification technique is selected as Centroid method. The sampling time is $5 \times 10^{-4}\ s$. Mamdani-type is used to perform fuzzy inference of the controller. Product t-norm, Karnik Mendel algorithm are used to implement the type reduction method of the IT2FLC.

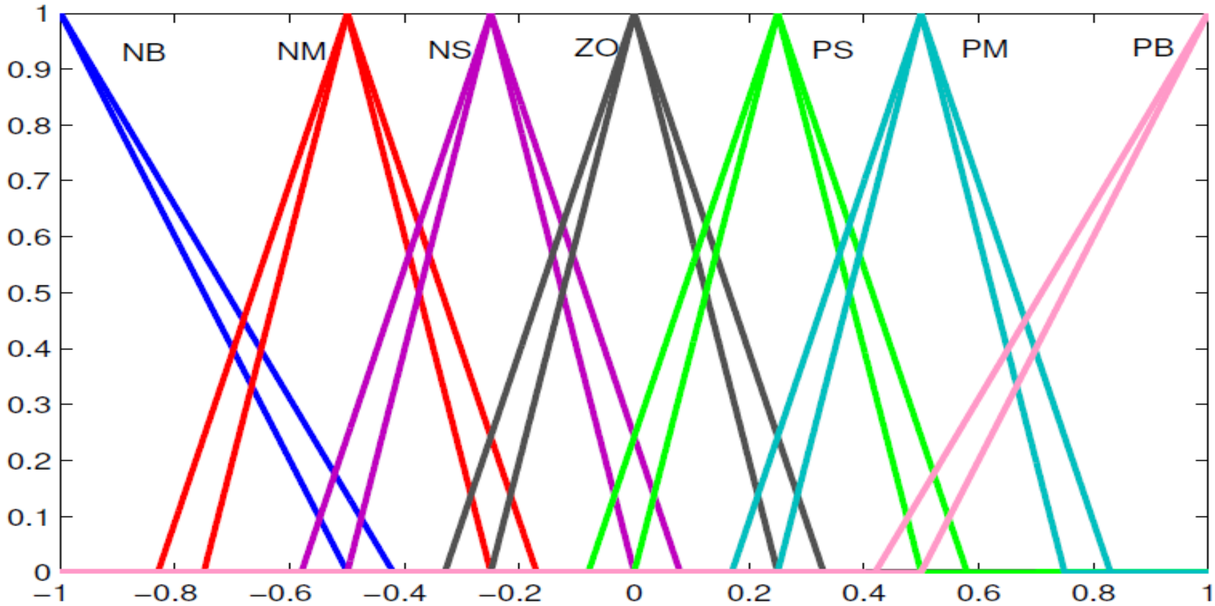

Figure 6: Membership function for $e, \dot{e}$ *and* U

Table 4: IT2FS rule base table

$E\backslash\dot{E}$	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZO
NB	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

The IT2- FPID controller is constructed by choosing the inputs as error signal (e), change of the error signal ($\dot{e}$) and the output as control signal (U) as shown in Figure 7 [21]. Here, kp and kd are the input gains and ki, kv are output gains.

The control signal of IT2-FPID control signal as follows:

U=upd+upi

U= Ki u+ kv ∫ u dt

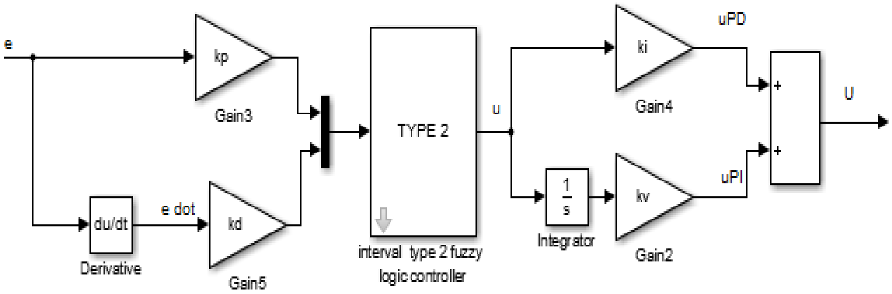

Figure 7: Structure of IT2FLC-PID

4. Simulation results

The configuration of SSO [9] for tuning the gains are summarized in the following:

- Spiders number :50
- Iteration:10
- Dimensions:5
- Fitness function : $F = \int t.|(e)| \; dt$

Table 5: The optimized gains for speed and Exhaust temperature controllers

Controller type	Optimized gains				
Conventional PID	KP = 4.881221	KI = 0.836034	KD = 7.970507	Fractional order =0.014003	
IT2FLC	KP=4.921698	KD=4.745647	KI=4.100953	KV=4.510562	Fractional order=0.954436

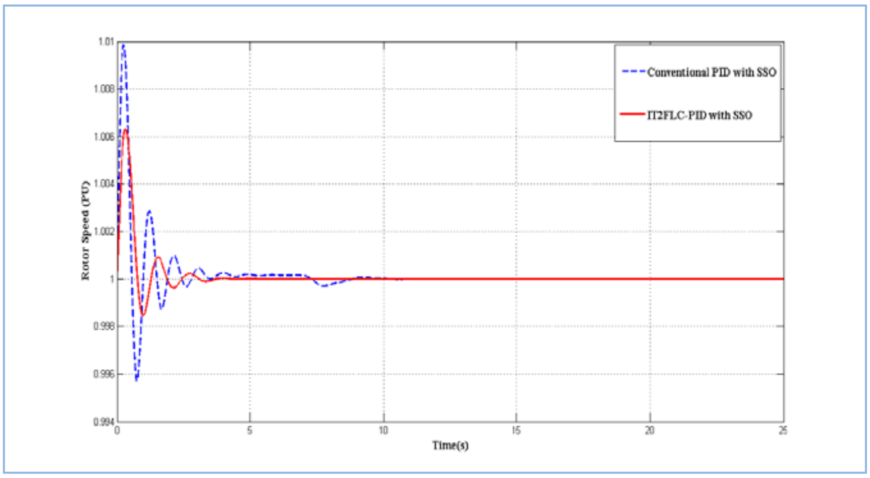

Figure 8: Rotor Speed

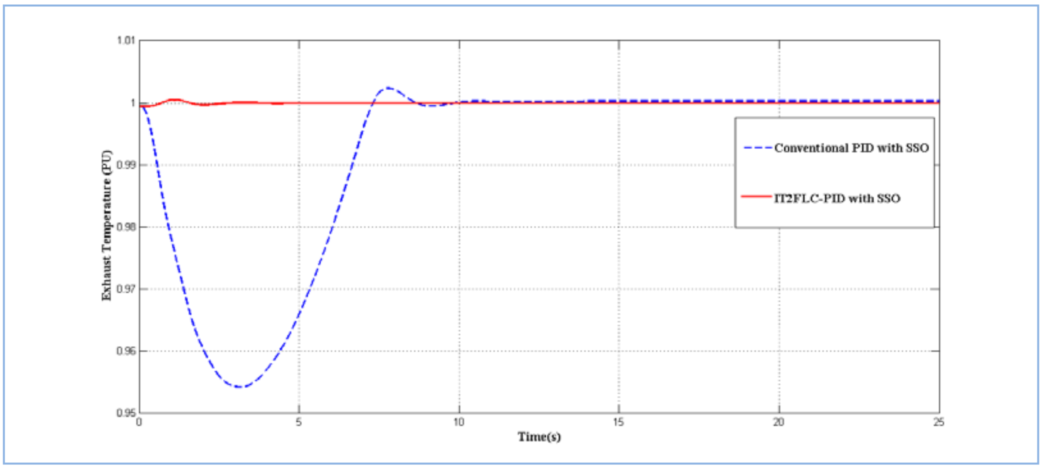

Figure 9: Exhaust temperature

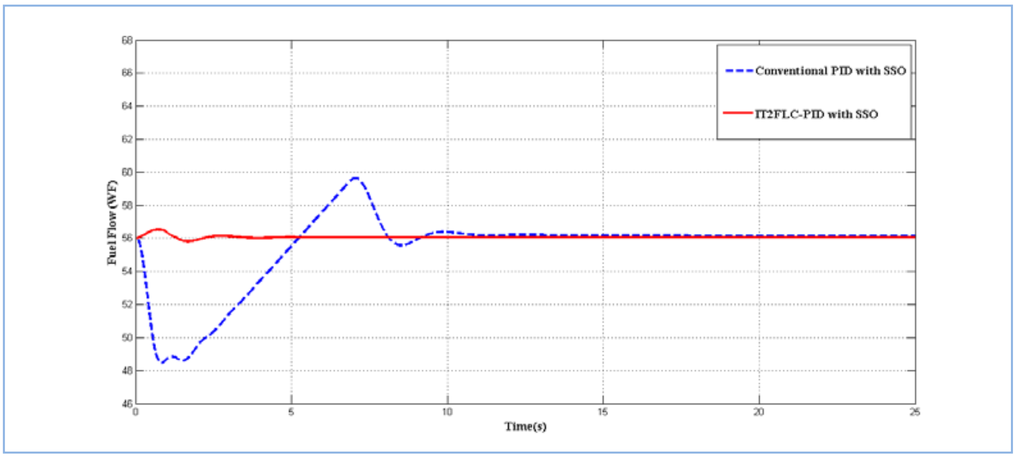

Figure 10: Fuel flow (WF)

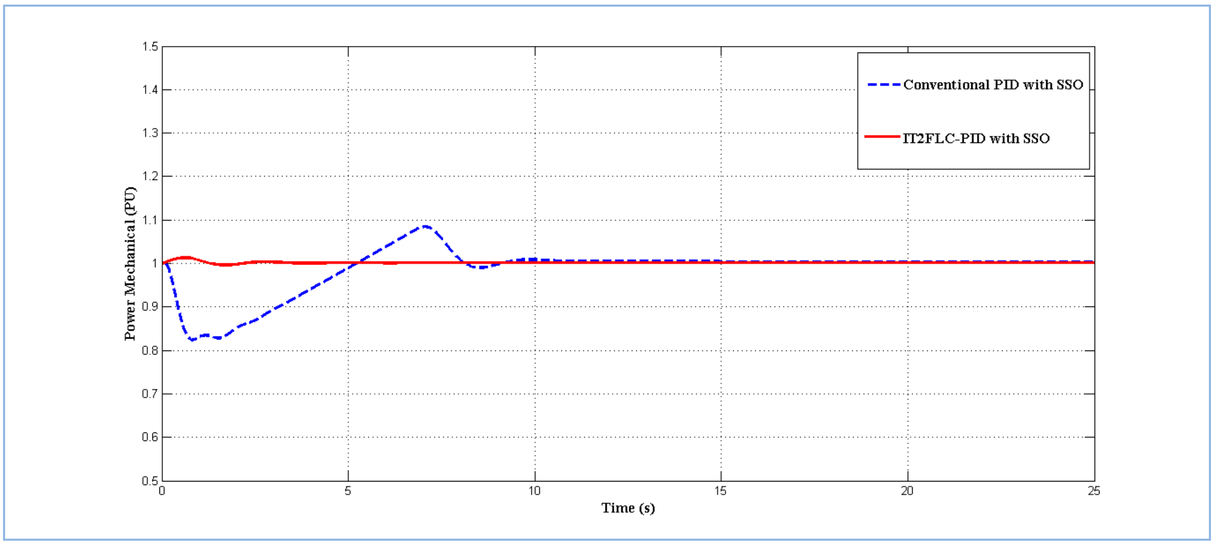

Figure 11: Power mechanical

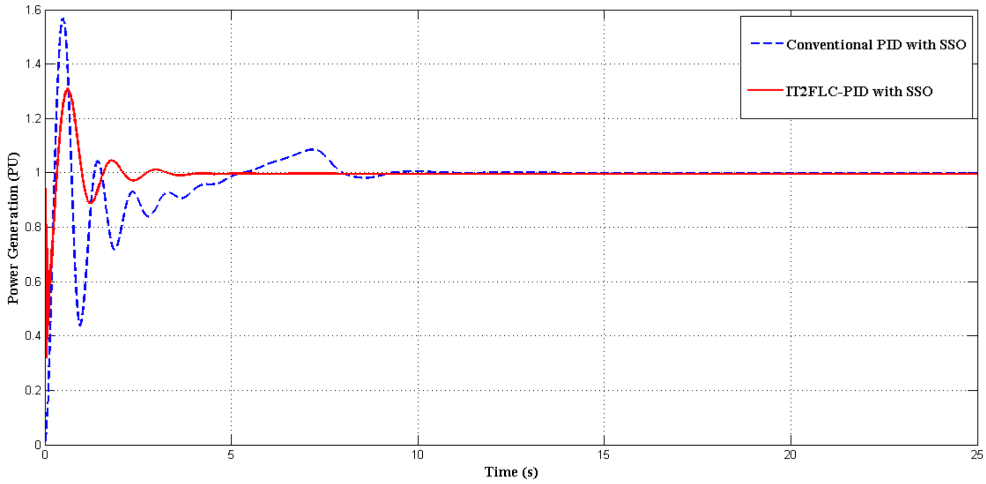

Figure 12: power generation

Table 6: comparison of performance

	Controller Type	ITAE	Overshoot (%)	Settling Time(S)
Speed	Conventional PID	21	1	9
	IT2FLC-PID	11.35	0.6	4
Exhaust Temp.	Conventional PID	1648	0.3	11.6
	IT2FLC-PID	2.244	0.05	4.1

6. Conclusion

In this paper conventional PID and IT2FLC-PID is proposed and used to regulate the exhaust temperature and rotor speed for a gas turbine power plant to improve the performance of single shaft gas turbine with fixed inlet guide vane (IGV) under normal conditions (TA=15 C°, PA=15 Kpa). The simulation results between two controllers have been obtained and compared. It was indicated that the IT2FLC-PID improve the dynamic performance of gas turbine with minimum overshoot and settling time. As future work, we plan to design IT2FLC for a combine cycle power plant to improve the dynamic behavior of system.

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