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Design of a Hierarchical Interval Type-2 Fuzzy Logic PSS for a Multi-Machine Power System Governor Control and Its Parameter Coding using GA Search Engine

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Abstract

In this paper, we introduce a novel interval type-2 Fuzzy Logic Power System (IT2FPSS). Interval type-2 FLS is used to improve the disturbance rejection of Power system which can be caused by variable nature of input parameters **(**electro-mechanical oscillations). The performance of interval type-2 fuzzy-logic power system stabilizer (IT2FPSS), which is tuned automatically as the operating conditions of power system change, is investigated by applying it to a multi-machine power system. IT2FPSS is developed using speed deviation ($\Delta\omega$) and the derivative of speed deviation ($d\Delta\omega$) as the controller inputs variables. Two scaling parameters are introduced to tune the IT2FPSS. These scaling parameters are the output of another fuzzy-logic system (IT2FPSS), which gets its inputs from the operating condition of the power system. The proposed scheme is referred to as the self tuning interval type-2 fuzzy power system stabilizer (IT2FPSS). In this paper, the GA-based strategy that was employed to tune the parameters of IT2FPSS is described. Four IT2FPSSs (IT2FPSS1, IT2FPSS 2, IT2FPSS3, and IT2FPSS4) are evolved and tested on a power system. The FPSSs have two input signals (e and $\dot{e}$ ˙). This mechanism of tuning the IT2FPSS makes it adaptive to changes in the operating condition. The response of the system with three power system stabilizers (FPSSs), namely Conventional PSS (CPSS), Fixed-parameter (FPSS) and self tuned IT2FPSS are compared. It is shown that the self tuned IT2FPSS is superior to both CPSS and Fixed-parameter FPSS. The effect of the defuzzification methods on the control signal response is also shown in this paper.

Keywords:

Conventional Power System Stabilizer (CPSS), Multi-machine system, Interval Type-2 fuzzy logic; Genetic Algorithms, Interval type-2 Fuzzy logic Power System Stabilizer (IT2FPSS)

1. Introduction

Electro-mechanical oscillation between interconnected synchronous generators is phenomena inherent to power systems. The damping of these oscillations is of vital concern and is a rerequisite for secure system operation. Power system stabilizers (PSSs) can provide supplementary control signal to the excitation system to damp these oscillations and to improve dynamic performance.

Most PSSs use in electric power systems employ the linear control theory approach based on a linear model of a fixed configuration of the power system and thus tuned at a certain operating condition. Such fixed parameter PSS, called conventional PSS (CPSS), is widely used in power systems, it often does not provide satisfactory results over a wide range of operating conditions. In recent years, fuzzy logic has emerged as a powerful tool and is starting to be used in various power system applications (Hagras H. A. 2004). Fuzzy logic can be an alternative to classical control. It allows one to design a controller using linguistic rules without knowing the mathematical model of the plant. This makes fuzzy-logic controller very attractive systems with uncertain parameters. The linguistic rule necessary for designing a fuzzy-logic controller may be obtained directly from the operator who has enough knowledge of the response of the system under various operating conditions. The inference mechanism of the fuzzy-logic controller is represented by a decision table, which is consists of linguistic IF-THEN rule. It is assumed that an exact model of the plant is not available and it is difficult to extract the exact parameters of the power plant. Therefore, the design procedure cannot be based on an exact model. However the fuzzy logic approach makes the design of a controller possible (Mendel J.M. 2000), without knowing the mathematical (exact) model of the plant.

The fuzzy logic implementation of power system stabilizer (PSS) has been reported in a number of publications. As with conventional power system stabilizer (CPSSs), the performance of FPSSs depends on the operating conditions of the system however, they are less sensitive to changing operating conditions than CPSSs. Further improvement can be achieved by the IT2FPSS as the operating conditions of the power system changed.

In this paper a rule-based IT2FPSS is designed. Its parameters are tuned by another fuzzy logic system, making it adaptable to changes in operating conditions. It is then used to stabilize a synchronous machine, which is part of a multi-machine power system (Goldberg D. E. 1989). The power system stabilizers (PSSs) are implementation at each machine. Response of the machines subjected to three-phase to ground fault are studied. System responses with tuned interval type-2 fuzzy-logic power system stabilizer (IT2FPSS) for different operating conditions are then compared with a CPSS and fixed parameter FPSS.

Interval Type-2 fuzzy sets, characterized by membership grades that are themselves fuzzy, were introduced by Zadeh in 1975 to better handle uncertainties. As illustrated in Fig.1, the membership function (MF) of a type-2 set has a footprint of uncertainty (FOU), which represents the uncertainties in the shape and position of the type-1 fuzzy set. The FOU is bounded by an upper MF and a lower MF, both of which are type-1 MFs. Fuzzy logic systems constructed using rule bases that utilize at least one interval type-2 fuzzy sets are called interval type-2 FLSs. Since the

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FOU of a type-2 fuzzy set provides an extra mathematical dimension, type-2 FLSs can better handle system uncertainties and have the potential to outperform their type-1 counterparts.

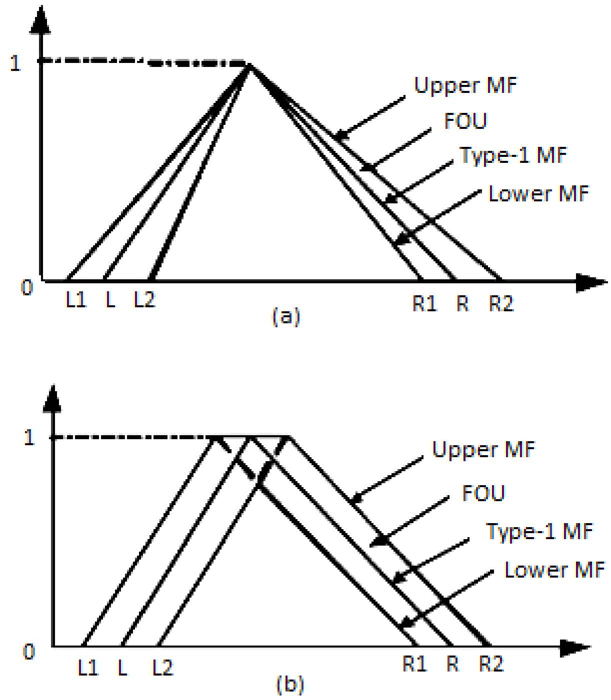

Fig.1. Interval type-2 fuzzy sets (a) Triangular MF, (b) Trapezoidal MF.

(a) A type-2 fuzzy set obtained by blurring the width of a triangular type-1 fuzzy set and

(b) A type-2 fuzzy set obtained by blurring the apex of a triangular type-1 fuzzy set, thus trapezoidal fuzzy set is obtained.

Interval Type2 Fuzzy Logic Systems (IT2FLS)

Fuzzy Logic Systems (FLS) are known as the universal-approximators and have various applications in identification and control designs. A type-1 fuzzy system consists of four major parts: fuzzifier, rule base, inference engine and defuzzifier. A type-2 fuzzy system has a similar structure, but one of the major differences can be seen in the rule base part, where a type-2 rule base has antecedents and consequents using Type-2 Fuzzy Sets (T2FS). In a T2FS, we consider a Gaussian function with a known standard deviation, while the mean (m) varies between m1 and m2. Therefore, a uniform weighting is assumed to represent a footprint of uncertainty as shaded in Fig.2. Because of using such a uniform weighting, we name the T2FS as an Interval Type-2 Fuzzy Set (IT2FS). Utilizing a rule base which consists of IT2FSs, the output of the inference engine will also be a T2FS and hence we need a type-reducer to convert it to a type-1 fuzzy set before defuzzification can be carried out. Fig.3 shows the main structure of type-2 FLS.

By using singleton fuzzification, the singleton inputs are fed into the inference engine. Combining the fuzzy if-then rules, the inference engine maps the singleton input $x = [x_1, x_2, \ldots x_3]$ into a type-2 fuzzy set as the output. A typical form of an if-then rule can be written as:

$$R_i = if\ x_1\ is\ \tilde{F}_1^i\ and\ x_2\ is\ \tilde{F}_2^i\ and\ \ldots\ldots and\ x_k\ is\ \tilde{F}_k^i\ then\ \tilde{G}^i \qquad (1)$$

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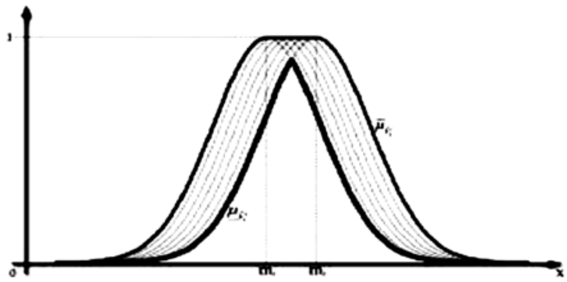


Fig. 2: Interval type 2 fuzzy set (IT2FS)

Where F_k are the antecedents (k = 1,2,…,n) and G^i is the consequent of the i^{th} rule. We use sup-star method as one of the various inference methods. The first step is to evaluate the firing set for i^{th} rule as following:

$$F^i(\underline{x}) = \prod_{i=1}^{n} \mu_{\widetilde{F_1}}(x_1) \qquad (2)$$

As all of the F_k^s are IT2FSs, so $F^i(\underline{x})$ can be written as $F^i(\underline{x}) = \left[\underline{f}^i(\underline{x})\ \overline{f}^i(\underline{x})\right]$

Where:

$$\underline{f}^i(\underline{x}) = \prod_{i=1}^{n} \underline{\mu}_{\tilde{F}_i}(x_i) \qquad (3)$$

$$\overline{f}^i(\underline{x}) = \prod_{i=1}^{n} \overline{\mu}_{\tilde{F}_i}(x_i) \qquad (4)$$

The terms $\underline{\mu}_{\tilde{F}_i}$ and $\overline{\mu}_{\tilde{F}_i}$ are the lower and upper membership functions, respectively (Fig.2). In the next step, the firing set $F_i(x)$ is combined with the i^{th} consequent using the product t-norm to produce the type-2 output fuzzy set. The type-2 output fuzzy sets are then fed into the type reduction part. The structure of type reducing part is combined with the defuzzification procedure, which uses Center of Sets (COS) method. First, the left and right centroids of each rule consequent are computed using Karnik-Mendel (KM) algorithm. Let's call them y_l and y_r respectively.

The firing sets $F^i(\underline{x}) = \left[\underline{f}^i(\underline{x})\ \overline{f}^i(\underline{x})\right]$ computed in the inference engine are combined with the left and right centroid of consequents and then the defuzzified output is evaluated by finding the solutions of following optimization problems:

$$y_l(\underline{x}) = \min_{\forall f^k \in \{\underline{f}^k, \overline{f}^k\}} \left(\sum_{i=1}^{M} y_l^i f^i(\underline{x}) \,/\, \sum_{i=1}^{M} f^i(\underline{x})\right) \qquad (5)$$

$$y_r(\underline{x}) = max_{\forall f^k \in \{\underline{f}^k, \overline{f}^k\}} \left(\sum_{i=1}^{M} y_r^i f^i(\underline{x}) \,/\, \sum_{i=1}^{M} f^i(\underline{x})\right) \qquad (6)$$

Define $f_l^k(\underline{x})$ and $f_r^k(\underline{x})$ as a functions which are used to solve (5) and (6) respectively and

let $\quad \xi_1^i(\underline{x}) = f_1^i(\underline{x}) / \sum_{i=1}^{M} f_1^i(\underline{x})$

And $\quad \xi_r^i(\underline{x}) = f_1^i(\underline{x}) / \sum_{i=1}^{M} f_r^i(\underline{x})$

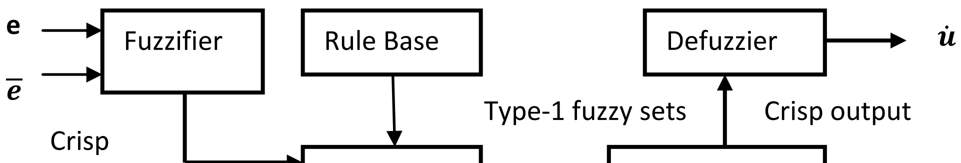


Fig.3: Main structure of interval type-2 FLS

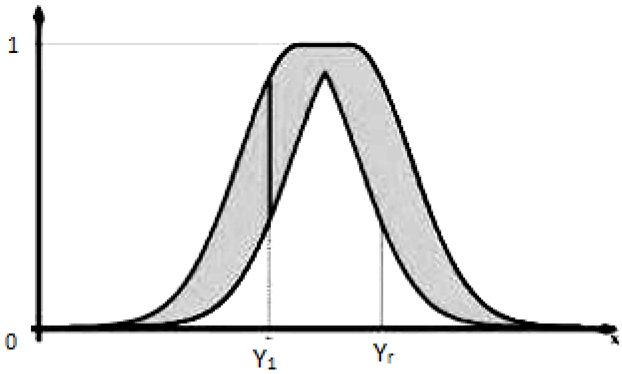


Fig.4: Computing right and left centroids for an IT2FS

Then we can write (5) and (6) as:

$$y_l(\underline{x}) = \frac{\sum_{i=1}^{M} y_1^i f_1^i(\underline{x})}{\sum_{i=1}^{M} f_1^i(\underline{x})} = \sum_{i=1}^{M} y_1^i\, \xi_1^i(\underline{x}) = \theta_1{}^T \xi_l(\underline{x}) \quad (7)$$

$$y_r(\underline{x}) = \frac{\sum_{i=1}^{M} y_r^i f_r^i(\underline{x})}{\sum_{i=1}^{M} f_r^i(\underline{x})} = \sum_{i=1}^{M} y_r^i\, \xi_r^i(\underline{x}) = \theta_r{}^T \xi_r(\underline{x}) \quad (8)$$

Where

$\xi_l(\underline{x}) = [\xi_l^1(\underline{x})\ \xi_l^2(\underline{x}) \ldots\ldots \xi_l^M(\underline{x})]$

And $\xi_r(\underline{x}) = [\xi_r^1(\underline{x})\ \xi_r^2(\underline{x}) \ldots\ldots \xi_r^M(\underline{x})]$ are the fuzzy basis functions and

$\theta_l(\underline{x}) = [y_l^1(\underline{x})\ y_l^2(\underline{x}) \ldots\ldots y_l^M(\underline{x})]$

And $\theta_r(\underline{x}) = [y_r^1(\underline{x})\ y_r^2(\underline{x}) \ldots\ldots y_r^M(\underline{x})]$ are the adjustable parameters.

Finally, the crisp value is obtained by the defuzzification procedure as follows:

$$y(\underline{x}) = \frac{1}{2}[y_l(\underline{x}) + y_r(\underline{x})] = \frac{1}{2}[\theta_l^T \xi_l(\underline{x}) + \theta_r^T \xi_r(\underline{x})] = \frac{1}{2}\theta^T \xi(\underline{x}) \quad (9)$$

Where

$\theta = [\theta_l^T \theta_r^T]^T$ and $\xi = [\xi_l^T \xi_r^T]^T$

2. Power System Stabilizer Design

First to design an Interval Type-2 Fuzzy power system stabilizer (IT2FPSS), for power system control, two crisp inputs i.e. speed deviation Δω, derivative of speed deviation (dΔω), stabilizing factor K_{STAB} and one output of IT2FPSS ‘u’ will be introduced. The working procedure of proposed IT2FPSS is as following:

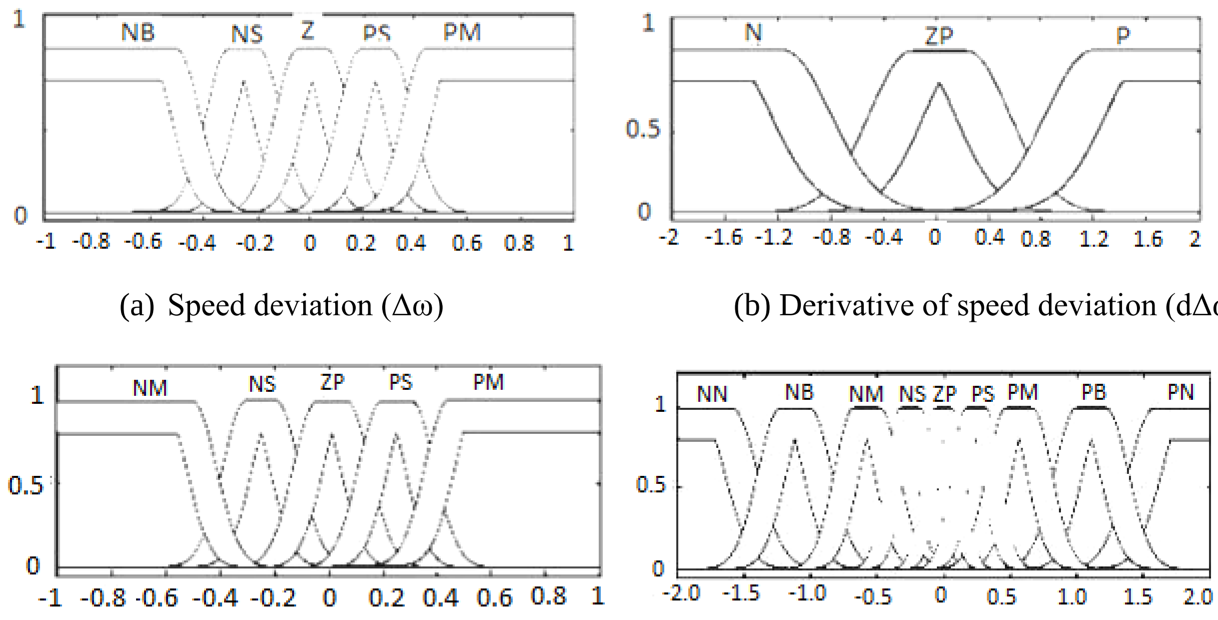
(a) In the fuzzification stage the crisp inputs are transformed to interval type-2 fuzzy sets.

(b) These sets are processed by inference machine in relation with interval type-2 rule base. Result of this procedure is a group of interval type-2 fuzzy output sets.

(c) Difuzzifacation stage integrated with type reducer block convert interval type-2 fuzzy output sets to crisp output values that are fed into control system.

This procedure is illustrated in block diagram of Fig.3. As mentioned before in power system we have four variables, Membership Functions (MFs) of these variables are chosen as interval type-2 Gaussian functions. These MFs are shown in Fig.4. It should be mentioned that the interval type-2 fuzzy sets are designed in order to minimize the effect of rule and data uncertainties. In addition, the rule base which is used in IT2PSS design is similar to the rule base proposed in Table 2. Power system needs a crisp control value so defuzzification stage is necessary; we use “center of gravity method” to defuzzify our type-2 fuzzy output sets, by using this method the output u is computed using equations (7), (8) and (9).

The overall block diagram, of the proposed IT2PSS method is shown in Fig. 7.



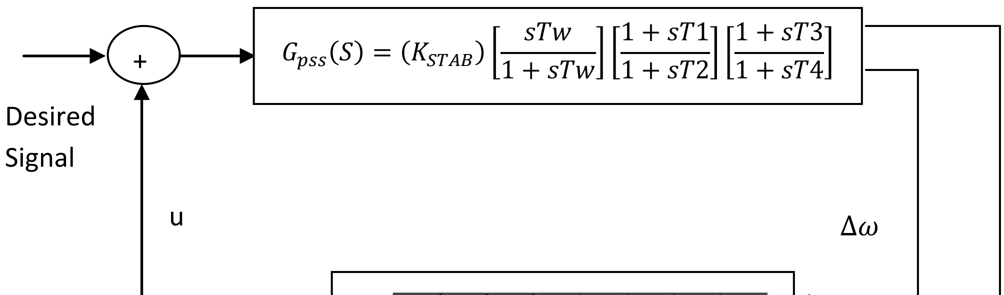
(a) Speed deviation (Δω)

(b) Derivative of speed deviation (dΔω)

(c) Controller Gain K_{STAB}

(d) output of IT2FPSS ‘u’

Fig. 5: Input/output membership functions



3. Tuner Design for IT2FPSS using Separate IT2FLS

In order to tune the IT2FPSS, two scaling factors are used to adjust the range of inputs as the operating conditions of the system change, the speed deviation is scaled with Δω and the derivative of speed deviation is scaled with dΔω Also, the output of the IT2FPSS (u) is scaled with a fixed scaling factor, which is chosen by the designer based on the system requirement. For the system under study this scaling factor is chosen to be equal to 6.5. The IT2FPSS is tuned by computing optimum input scaling factors, using separate IT2FLS. The electrical active power and reactive power of each generator are selected for input signals to represent the operating conditions of each machine. The IT2FLS with two inputs (Pe, Qe) and two outputs (scaling factors) designed this way is referred to as the tuner as shown in Fig.7.

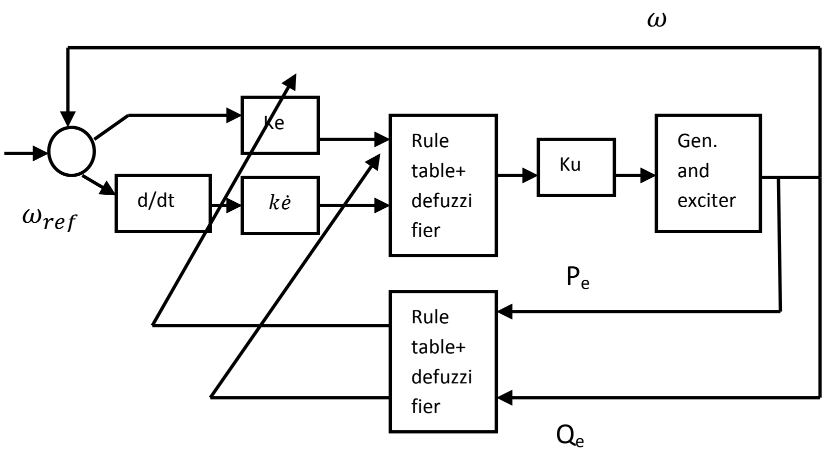


Fig. 7: Tuner for IT2FPSS using separate IT2FLS

For brevity only one rule base from four rule bases for (IT2FLS) are shown bellow:

1. If (input1 is PB1) and (input2 is PB2) then (output1 is PV3) (output2 is PV4)
2. If (input1 is PS1) and (input2 is PM2) then (output1 is PB3) (output2 is PB4)
3. If (input1 is PS1) and (input2 is PS2) then (output1 is PM3) (output2 is PM4)
4. If (input1 is PB1) and (input2 is PM2) then (output1 is PV3) (output2 is PS4)
5. If (input1 is PB1) and (input2 is PS2) then (output1 is PB3) (output2 is PV4)

For the inputs, interval type-2 trapezoidal membership functions are used and for the outputs, interval type-2 triangle membership functions are used. By nonlinear simulation with three phases to ground fault, the optimum scaling factors are chosen. The rule base for the IT2FLS is derived from the operating conditions of the generators on line (as the machine are operating) and calculates the scaling factors for the IT2FPSS. The whole stabilizer obtained is referred to as the tuner fuzzy power system stabilizer (Tuned IT2FPSS). The block diagram for IT2FPSS is shown in Fig.7 & Fig.8.

An example of the i^{th} rule is:

If Δω is SN and Δώ is MP then u is SP

In this paper, the proposed IT2PSS is designed. The Interval type-2 method proposed uses three crisp inputs (i.e. speed deviation ($\Delta\omega$), derivative of speed deviation ($d\Delta\omega$), Controller Gain K_{STAB} and one fuzzy output (i.e. output of IT2FPSS 'u'). The rule-base of type-2 fuzzy controller proposed is shown in Table 4. In this table all abbreviations are the same as Table1.

Table 1: Abbreviations

NV	Negative very big	ZE	Zero
NB	Negative big	PS	Positive small
NM	Negative medium	PM	Positive medium
NS	Negative small	PB	Positive big

Table 2: The rule-base of type-2 fuzzy controller

$\Delta\omega$	$d\Delta\omega$	K_{STAB}	u	$\Delta\omega$	$d\Delta\omega$	K_{STAB}	u	$\Delta\omega$	$d\Delta\omega$	K_{STAB}	u
NB	NB	N	PV	P	NB	-	ZE	NB	Z	P	PS
NB	N	N	PB	P	N	-	NS	NB	P	Z	ZE
NB	Z	N	PM	P	Z	-	NM	NB	P	P	NS
NB	P	N	PS	P	P	-	NV	NB	PB	Z	NS
NB	PB	N	ZE	P	PB	-	NB	NB	PB	P	NM
N	NB	-	PV	PB	NB	N	PS	PB	NB	Z	ZE
N	N	-	PM	PB	N	N	ZE	PB	NB	P	ZE
N	Z	-	PM	PB	Z	N	NS	PB	N	Z	NS
N	P	-	PS	PB	P	N	NM	PB	N	P	NS
N	PB	-	NS	PB	PB	N	NB	PB	Z	Z	NB
Z	NB	-	PM	NB	NB	Z	PB	PB	Z	P	NB
Z	N	-	PS	NB	NB	P	PM	PB	P	Z	NV
Z	Z	-	ZE	NB	N	Z	PM	PB	P	P	NV
Z	P	-	NS	NB	N	P	PM	PB	PB	Z	NV

Z	PB	-	NM	NB	Z	Z	PS	PB	PB	P	NV

Four Machines Two Area System

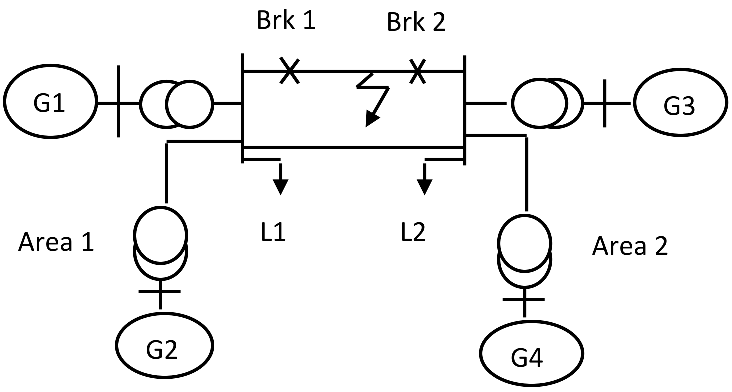


Fig. 8 Multi-machine power system for Stability study

The test system present in MATLAB 7 consists of two fully symmetrical areas linked together by two tie 230 KV lines of 220 Km length as shown in Fig.8. It was specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. Despite its small size, it mimics very closely the behavior of typical system in actual operation. Each area is equipped with two identical round rotor generators rated 20 KV/900 MVA. The synchronous machines have identical parameters except for the inertias which are H = 6.5s in area 1 and H is = 6.175s in area 2. Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciter with a 200 gain. The load is represented as constant impedance and spilt between the areas.

4. GA coding scheme and parameters

The structure of a typical type-2 FLS is shown in Fig.3. Input signals are the feedback error (speed deviation) $e = \Delta\omega$ and the change of error (derivative of speed deviation) $\dot{e} = d\Delta\omega$, and the output is the change of control signal u = IT2FPSS. Compared with their type-1 counterparts, IT2FPSSs are better suited to eliminate persistent oscillations.

In this paper, the GA-based strategy that was employed to tune the parameters of IT2FPSS is described. Four IT2FPSSs (IT2FPSS1, IT2FPSS2, IT2FPSS3, and IT2FPSS4) are evolved and tested on a power system. The FPSSs have two input signals (e and $\dot{e}$)

Structure of the FLCs

The four IT2FPSSs that were designed, three IT2FPSSs (IT2FPSS1, IT2FPSS3, and IT2FPSS3) have essentially the same architecture. The only difference is that the input domains of

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IT2FPSS1 (e and $\dot{e}$) are partitioned by type-1 sets, while that of the IT2FPSSs are partitioned by at least one interval type-2 set.

Each input domain is partitioned by three fuzzy MFs that are labeled as N, Z, and P (see Fig.9). The output space ($\dot{u}$) has five MFs labeled as NB, NS, Z, PS, and PB. As illustrated in Fig.1, a type-2 fuzzy set can be obtained by blurring the MF of a base line type-1 set. For a triangular type-1 MF, there are at least two ways of blurring to obtain a type-2 MF.

The first is to keep the apex fixed while blurring the width of the triangle, as shown in Fig.1(a).The other way is to keep the width of the triangle fixed while blurring the apex, as shown in Fig.1(b). Since each type-2 set provides an extra mathematical dimension, the IT2FPSSs have more degrees of freedom than IT2FPSS1. It is generally known that an IT2FPSS with more parameters tends to provide better performance. In order to investigate whether the simplified IT2FPSS is able to outperform a type-1 FPSS with a similar number of design parameters, another type-2 FPSS (IT2FPSS2) is included in the comparative study. It has five MFs in each input domain and the rule base is shown in Table 3.

The parameters of the four IT2FPSSs used in this study are evolved by GA, a general-purpose search algorithm that is based on the mechanics of natural selection and genetics. GAs are theoretically and empirically proven to be a robust search engine in complex spaces, thereby offering a valid approach to problems requiring efficient and effective searches.

Table 3: Rule base of IT2FPSS2

$e/\dot{e}$	$\dot{e}_1$	$\dot{e}_2$	$\dot{e}_3$	$\dot{e}_4$	$\dot{e}_5$
e_1	$\dot{u}_1$	$\dot{u}_2$	$\dot{u}_3$	$\dot{u}_4$	$\dot{u}_5$
e_2	$\dot{u}_2$	$\dot{u}_3$	$\dot{u}_4$	$\dot{u}_5$	$\dot{u}_6$
e_3	$\dot{u}_3$	$\dot{u}_4$	$\dot{u}_5$	$\dot{u}_6$	$\dot{u}_7$
e_4	$\dot{u}_4$	$\dot{u}_5$	$\dot{u}_6$	$\dot{u}_7$	$\dot{u}_8$
e_5	$\dot{u}_5$	$\dot{u}_6$	$\dot{u}_7$	$\dot{u}_8$	$\dot{u}_9$

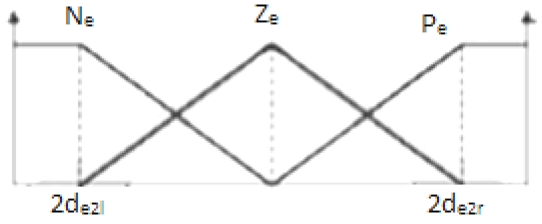

Fig. 9. Example MFs of e.

The key idea behind the search process is inspired by the natural evolution of biological creatures, where the fittest among a group of artificial entities survive to form a new generation together with those that are produced through gene exchange. Although the GA is increasingly used

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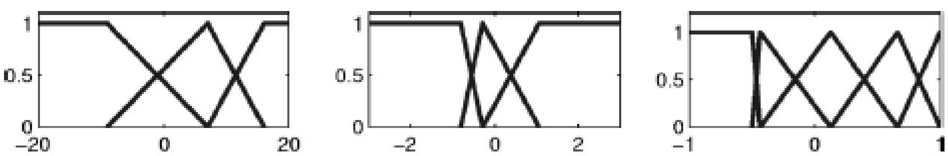
to facilitate FPSSs design, most existing works only touch on the design of type-1 systems. In this paper, GAs are used to tune both type-1 and type-2 FPSSs. First, the chromosome coding scheme is described. Since the input domain of IT2FPSS1 is partitioned by three MFs, three points are needed to determine the MFs of each input. The three points for the e domain are Ne, Ze, and Pe, as illustrated in Fig.9. Similarly, the three points that define the three sets for the $\dot{e}$ domain are $N\dot{e}$, $Z\dot{e}$ and $P\dot{e}$. Another five points are needed to determine the MFs of the output domain $\dot{u}$. Consequently, there are a total of 11 parameters which need to be optimized by the GA. Fig.10 shows the chromosome used by the GA, where the first 11 genes are parameters of IT2FPSS1. The next two genes in the chromosome determine the FOU of the only type-2 set used to partition the $\dot{e}$ domain of IT2FPSS3. They define the amount by which the type-1 set is shifted ($d\dot{e}_{2l}$ and $d\dot{e}_{2r}$) to generate the FOU of the type-2 fuzzy set. In the case of IT2FPSS4, the input domains are partitioned by six type-2 sets so the chromosome has 19 genes, as shown in Fig.10. Finally for IT2FPSS2, five parameters are needed to determine the MFs for each input and nine parameters for the consequents. Thus, each chromosome consists of 5x2 +9=19 genes, the same as that of IT2FPSS4. The fitness of each chromosome in the GA population is assessed by subjecting the simulation model of the liquid level process to step inputs. The integral of time absolute error (ITAE) obtained for each of the four machines are added together [see eq. (10)] and used to evaluate the fitness of the IT2FPSSs

$$F = \sum_{i=1}^{4} \alpha_i \left[\sum_{j=1}^{N_i} j * |e_i(j)| \right] \tag{10}$$

Where i is the weight corresponding to the ITAE of the i^{th} plant, and Ni =150 is the number of sampling instants. There is a need to introduce i because the ITAE of the second plant is usually several times bigger than that of other plants. To ensure that the ITAE of the four plants can be reduced with equal emphasis, 2 is defined as 1/3 while the other weights are unity.

1	2	3	4	5	6	7	8	9	1 0	1 1	12	13	14	15	16	17	18	19
N e	Z e	P e	N $\dot{e}$	Z $\dot{e}$	P $\dot{e}$	N B	N S	Z	P S	P B	$d_{\dot{e}2l}$	$d_{\dot{e}2r}$	d_{e2l}	d_{e2r}	$d_{\dot{e}lr}$	$d_{\dot{e}3l}$	d_{elr}	d_{e3l}
Sub-chromosome of e			Sub-chromosome of $\dot{e}$			Sub-chromosome of $\dot{u}$												

Fig.10. GA coding scheme of the IT2FPSSs



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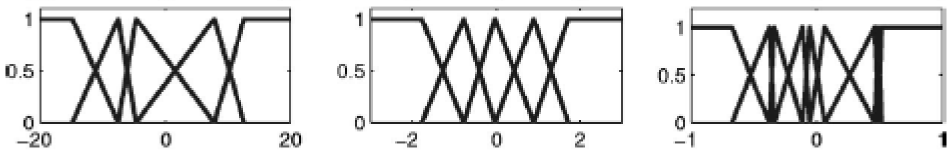
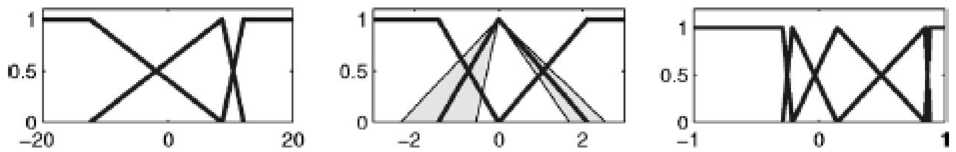
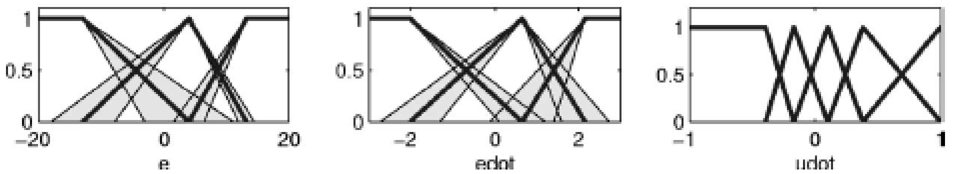
MFs of the four IT2FPSS1



MFs of the four IT2FPSS2



MFs of the four IT2FPSS3



e $\dot{e}$ $\dot{e}$

MFs of the four IT2FPSS4

Fig.11 MFs of the four IT2FPSSs

The GA consisted of 250 chromosomes in each generation and terminated after 150 generations. The crossover rate was 0.78 and the mutation rate was 0.1. The MFs of IT2FPSS1, IT2FPSS2, IT2FPSS3 and IT2FPSS4 evolved by GA are shown in Fig.11.

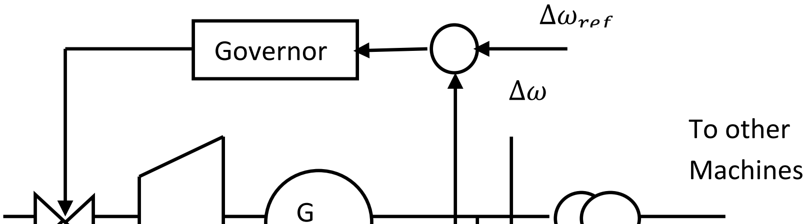
5. Simulation Studies

The performance of the IT2FPSS was evaluated by applying a large disturbance caused by three-phase fault applied at the middle of one tie line at 0.2 sec. and cleared after 0.133 sec by opening the breakers, with one tie-line the system can reach a stable operating point in steady state. A schematic diagram representation of one generator is shown in Fig.12. For comparison purpose, the system is configured to switch between different controls techniques, In order to show the improvement of the proposed IT2FPSS over fixed parameter FPSS and CPSS. The optimality is checked by the performance index:

$$J_p = \sum \Delta\omega^2$$

A CPSS that is used for comparison with this transfer function is:

$$G_{pss}(S) = (K_{STAB}) \left[\frac{sTw}{1 + sTw}\right] \left[\frac{1 + sT1}{1 + sT2}\right] \left[\frac{1 + sT3}{1 + sT4}\right]$$



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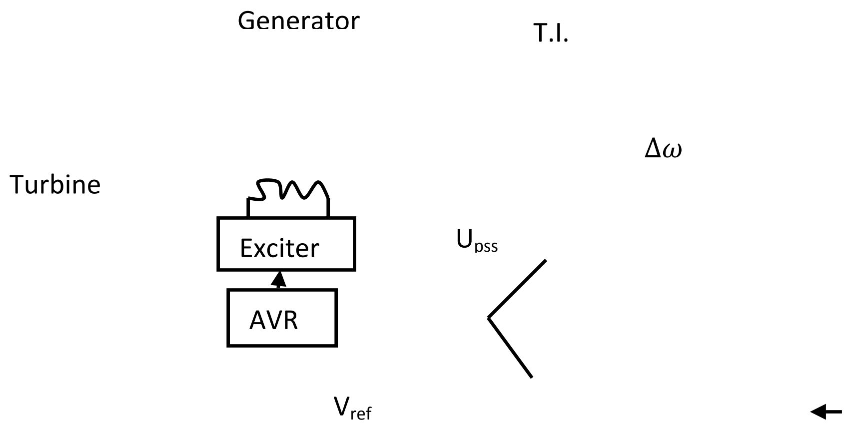

It consists of a lag-lead controller with a high pass filter that prevents steady change in speed from modifying the field voltage. The value of the washout time constant Tw should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. A high value of K_{STAB} is desirable from the viewpoint of transient stability. For the plant with three types i.e CPSS, fixed parameter FPSS and IT2FPSS, the system response for various operating conditions have been investigated, for brevity only two cases are shown here.

A. Operating condition 1

Table 4: Operating condition 1

Generator	1	2	3	4
Real Power	0.96 PU	0.59 PU	0.8 PU	0.78 PU
Reactive Power	0.17 PU	0.15 PU	0.09 PU	0.1 PU

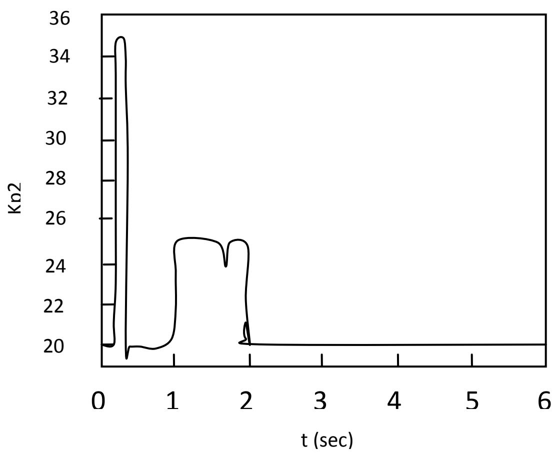

Fig. 13: IT2FPSS scaling factor setting (Kp) Machine 2

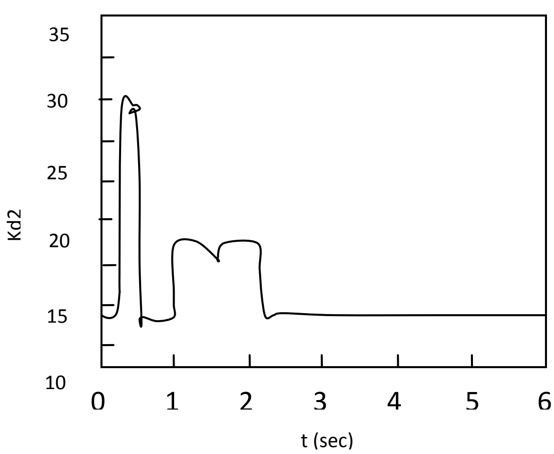

Fig.14 IT2FPSS scaling factor setting (Kd) Machine 2

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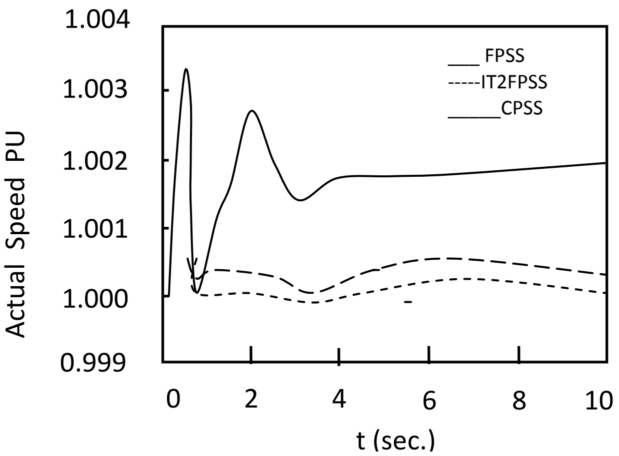

Fig. 15: Response for GEN # 1 for operating condition 1

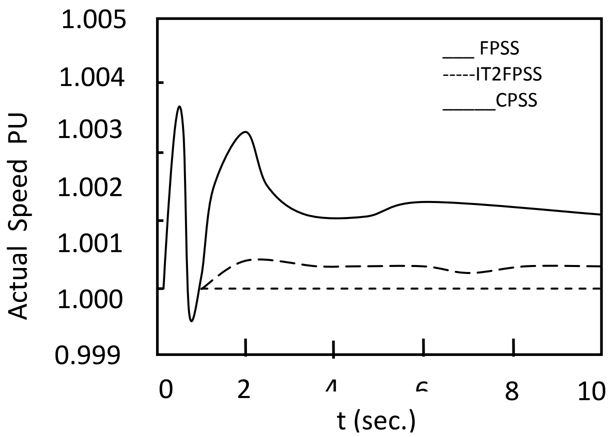

Fig. 16: Response for GEN #2 for operating condition 1

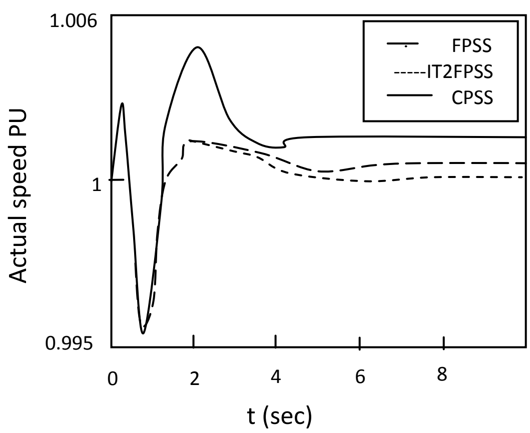

Fig. 17: Response for GEN# 3 for operating condition 1

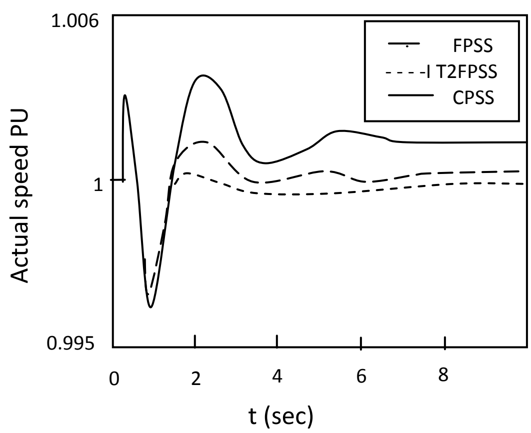

Fig. 18: Response for GEN# 4 for operating condition 1

Table 5: Comparing the performance index of operating condition of 1

Operating Condition 1	J_p		
	CPSS	FPSS	IT2FPSS
Gen. 1	213	72	18.5
Gen. 2	218	79.4	23.8
Gen. 3	366	175	91.8
Gen. 4	350	164	85

B . Operating condition 2

Table 6: Operating condition 2

Generator	1	2	3	4
Real Power	0.56 PU	0.92 PU	0.56 PU	0.61 PU

Reactive Power	0.01 PU	0.04 PU	-0.04 PU	-0.13 PU

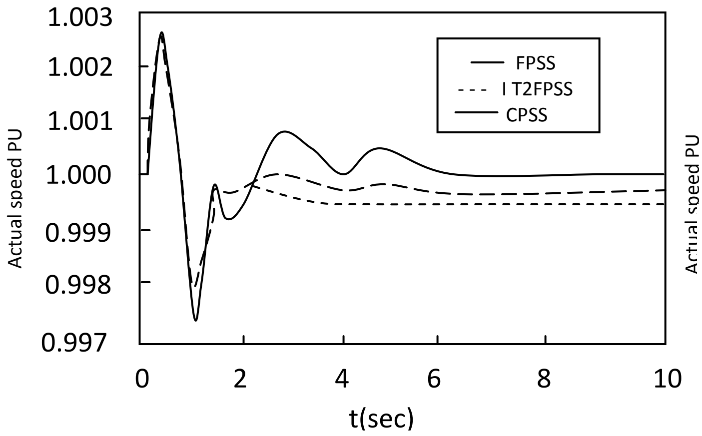

Fig. 19: Response for GEN # 1 for operating condition 2

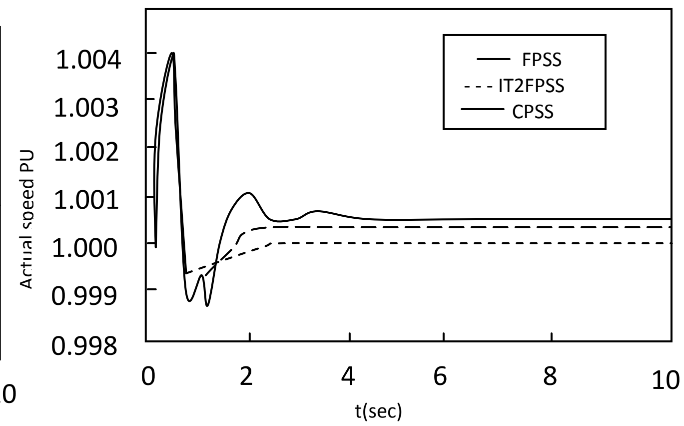

Fig. 20: Response for GEN # 2 for operating condition

Table7: Comparing the performance index of operating condition 2

Operating Condition 1	J_p		
	CPSS	FPSS	IT2FPSS
Gen. 1	76.4	42.7	31
Gen. 2	66.6	39.5	28
Gen. 3	155	121	97.5
Gen. 4	135	103	80

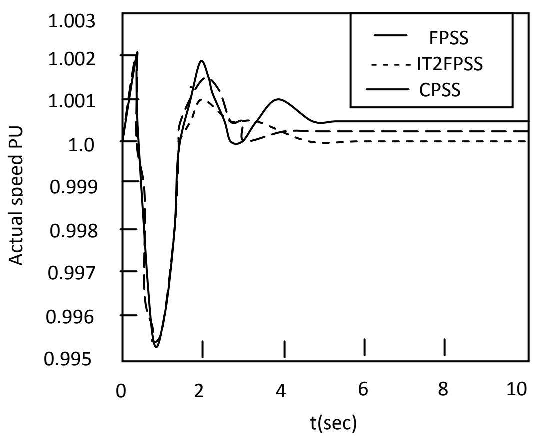

Fig. 21: Response for GEN # 3 for operating condition 2

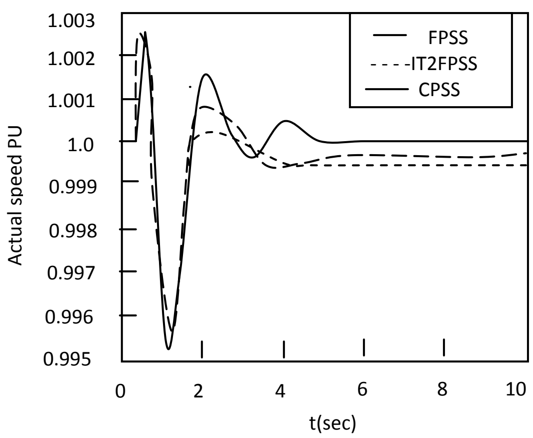

Fig. 22: Response for GEN # 4 for operating condition 2

From this two operating conditions it's observed that. The proposed IT2FPSS and fixed parameter FPSS has better response in transient condition and steady state error than CPSS. The steady state error is removed when used the proposed IT2FPSS.

6. Discussion

This section presents results from the simulation and experimental study that was conducted to assess the performance of the type-1 and type-2 FPSSs evolved by the GA. Besides, the data read by the sensor are noisy. These characteristics are not accurately captured by the model used by the GA to optimize the fuzzy controller (IT2FPSS) parameters. Hence, the ability of the four IT2FPSSs to handle modeling uncertainties can be ascertained by examining control performances of the IT2FPSSs. Using a sampling period of 1s, step responses were obtained using the four IT2FPSSs. Two operating conditions are applied here as shown in table 4 and table 6. For operating condition 1 the IT2FPSS scaling factor setting (Kp) and IT2FPSS scaling factor setting (Kd) for Machine 2 are shown in Fig.13 & Fig.14 respectively. The response for GEN # 1, GEN # 2 , GEN # 3, GEN # 4 for operating condition 1 are shown in Fig.15, Fig.16, Fig.17 and Fig.18 respectively.

Similarly, the response for GEN # 1, GEN # 2 , GEN # 3, GEN # 4 for operating condition 2 are shown in Fig.19, Fig.20, Fig.21 and Fig.22 respectively. The performance index of operating condition 1 and operating condition 2 is compared for the proposed IT2FPSS over fixed parameter FPSS and CPSS in table 5 and table 7 respectively.

From this two operating conditions it's observed that. The proposed IT2FPSS and fixed parameter FPSS has better response in transient condition and steady state error than CPSS. The steady state error is removed when used the proposed IT2FPSS.

7. Conclusions

In this paper, a simplified IT2FPSS that is more suitable for real-time control is proposed. A IT2FPSSs with simplified structure are designed for power system governing control. Its performance is compared with two type-1 FPSSs and a traditional IT2FPSS. Experimental results show that the simplified IT2FPSS outperforms the type-1 FPSSs and has similar performance as the traditional IT2FPSS. Analysis also indicates there will be at least 50% reduction in computational cost if the simplified IT2FPSS is used in place of a traditional IT2FPSS. It may, therefore, be concluded that the simplified IT2FPSS is able to bring about computational savings without sacrificing the ability to handle modeling uncertainties.

A comparison between the IT2FPSS, fixed parameters FPSS and CPSS shows that the fixed parameters FPSS has a better performance over a wide of operating conditions than the CPSS, and is less sensitive to change in operating conditions than CPSS, the fixed parameters FPSS provides good transient and damping response even when the operating conditions changes. A Supervisory fuzzy-logic system has been proposed to tune a fuzzy power system stabilizer on line. It is shown that by tuning the IT2FPSS, better response of the system can be achieved in a wide range of operating condition compared to fixed parameters FPSS and CPSS. The FPSS has a better performance than the CPSS and the proposed IT2FPSS has improvement the dynamic response.

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