A NEW FUZZY LOGIC BASED POWER SYSTEM STABILIZER

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ABSTRACT : A new power system stabilizer based on Fuzzy logic control (NFLPSS) using speed deviation ($\Delta\omega$) and change in excitation voltage (ΔE_{fd}) as inputs is presented in this paper. Also a new method of defining the membership functions of fuzzy classes for the variables over the respective universe of discourses is also presented. Simulation studies have shown that the proposed NFLPSS provides good damping over a wide operating range and significantly improves the dynamic performance.

1. INTRODUCTION

Studies in the past have shown that the use of supplementary signal in the excitation and/or governor system of the generating unit provides extra damping for the system to damp out low frequency oscillations and improves the dynamic performance of the system. Conventional power system stabilisers (PSSs) are designed based on linear control theory. The power system model is linearised around a normal operating point , and the structure of the PSS is determined to provide optimal performance at this point. Power systems in general are nonlinear and the operating conditions can vary over a wide range. Thus the fixed parameter PSS cannot provide optimal performance over the whole operating range. It is desirable to develop a stabilizer that yields satisfactory performance over such operating ranges without necessitating any changes in parameter settings of control variables. Although alternative controllers using adaptive control and self –tuning techniques have been proposed to overcome such problems, they require intensive computations and long processing time as they involve identification of the system model. Unlike this classical approach which requires a deep understanding of the system, fuzzy logic incorporates an alternate way of thinking, allowing complex systems to be modeled from accumulated knowledge and experience.

A fuzzy logic controller (FLC) uses fuzzy logic as a design methodology which can be applied in developing linear and nonlinear systems for embedded control. The simplicity of fuzzy logic enables control system designers to realize control in less time, lower cost and better performance.

2. DESIGN OF AN FLC

The main processes in FLC are fuzzification, rule definition, rule inference and defuzzification. Fuzzification is the process of transforming the crisp control variables to corresponding fuzzy linguistic variables. The output error and its derivative are generally taken as inputs to FLC. However as the target of the application presented in this paper is to improve damping of a synchronous machine, speed deviation $\Delta\omega$ and excitation voltage deviation ΔE_{fd}, which are easily measurable, are chosen as the controller inputs.

2.1 Fuzzification and membership functions

Each of the FLC input and output signals ($Xj = \{\Delta\omega, \Delta E_{fd}, U\}$ is interpreted as a number of linguistic variables. Each linguistic variable has its membership function and it can be defined over an equal interval. However in many dynamic systems the sensitivity of the control signal to deviations in the system output is variable. For example in a PSS the control signal U needed to stabilize a system for large deviations in $\Delta\omega$ and ΔE_{fd} may not be the same as that when one of the variables is small. Thus there is a need to vary the stabilizing signal proportional to the magnitudes of $\Delta\omega$ and ΔE_{fd}. This is achieved in this paper by considering that the fuzzy classes are non-uniform. The non-uniform membership functions for the fuzzy classes are realized based on a shrinking span factor, which is usually less than or equal to one, and the non uniform fuzzy classes for a given variable are defined over its universe of discourse based on this shrinking span factor. In general fuzzy systems map input fuzzy sets to output fuzzy sets. The typical description of fuzzy membership functions for a triangular membership function and that for triangular with shrinking span factor (ssf) are given in Fig.3. The general triangular membership functions are described with an overlap of 50% and are defined as that with an ssf = 1. Fuzzy rules are the relations between input and output fuzzy sets. For a system of two variables with seven linguistic variables in each range, this leads to a 7x7 decision table as shown in Table I. Every entry in the table represents a rule. The activation of the i th rule is evaluated as the product of two rule antecedent conjunct values. The rule table has been formulated based on the action of a conventional lead lag PSS operating at a particular operating point.

2.2 Rules creation and inference

In general fuzzy systems map input fuzzy sets to output fuzzy sets. Fuzzy rules are the relations between input/output fuzzy sets. Generally fuzzy rules are of the form

If $\Delta\omega$ is NB and ΔE_{fd} is NM then U is PM

The knowledge required to generate the fuzzy rules can be derived from an offline simulation, an expert operator and/or a design engineer. Normally rule definition is based on operator's experience and the engineer's knowledge. If system dynamics are not known clearly then trial and error procedures are used to define the rules. In this paper, the steps for the development of the Fuzzy rule matrix are given below.

1. A three-phase fault is created as a disturbance at the middle of the transmission line of the study system given in Fig.1
2. The output of a Rule base program as outlined in the ref.1 is used to study the response for this disturbance and the results are tabulated.

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3. The range of values of $\Delta\omega$, ΔE_{fd} and "u" as obtained from the simulation of this disturbance are noted. (The ranges for the inputs and output of FLC are noted)
4. These ranges of values for the FLC inputs and fuzzy output are defined as the universes of discourse for the two fuzzy inputs and one fuzzy output.
5. Each of the universes of discourse of the fuzzy input variables $\Delta\omega$ and ΔE_{fd}, and the fuzzy output "u" are divided into seven fuzzy classes, defined as overlapping triangular SSMF as given in Fig.3.
6. The shrinking span factor for these three variables is taken to be 0.6.
7. At each time step the crisp values of $\Delta\omega$ and ΔE_{fd} are noted from the results based on the method given in ref.1.
8. These crisp values of inputs to the FLC are fuzzified as linguistic variables in their respective universes of discourse.
9. The output "u" obtained at this time step is also fuzzified on its universe of discourse.
10. The fuzzy combination of the inputs and the resultant fuzzy output are formulated as an IF.. THEN rule in the fuzzy relation matrix. The row of fuzzy relation matrix represents the fuzzy classes of $\Delta\omega$ and the columns of the fuzzy relation matrix represent the fuzzy classes of ΔE_{fd}. The fuzzy linguistic output is thus incorporated in the corresponding row and column of the fuzzy rule matrix.
11. This process of generating the fuzzy rules based on the results of the method proposed in ref.1 is repeated at every time step.
12. For each element of FRM, a number of possible outputs are generated. The linguistic variable which occurs the maximum number of times in the FRM is retained in the fuzzy relation matrix. Thus the elements of FRM are generated.
13. The entries of FRM are generally increasing or decreasing across a row or a column. Thus any missing elements of the FRM are filled up based on this principle.

Defuzzifying the fuzzy decision table inferred from the fired rules is then done using center of gravity method. For a discretised output universe of discourse, $Y = [y_1 \ y_2 \ y_3 \ .... \ y_p]$ which gives the discrete fuzzy centroid, the output of the FLC can be reduced to

$$u_k = \frac{\sum_{i=1}^{P} y_i w_i}{\sum_{i=1}^{p} w_i}$$

and w_i = membership function of output variable

3. SELECTION AND TUNING OF FLC PARAMETERS

The choice of ΔE_{fd} as one of the inputs is based on the following considerations.

1. ΔE_{fd} is easily measurable.
2. As the objective of a PSS is to damp out the oscillations in a power system occurring due to the mismatch between P_e and P_m. The electrical power output is very sensitive to changes in field excitation, ΔE_{fd}, and so ΔE_{fd} would be effective in damping out oscillations in the power mismatch.
3. Further the choice of $\Delta\omega$, $d\Delta\omega/dt$ as inputs to a FLC is general case, and other combinations of inputs have been tried and reported in literature. For example Malik[4] et al have used $\Delta\omega$, ΔP_e as inputs to a fuzzy logic PSS.

In order that fuzzy systems yield better system response, it is necessary to tune the FLC parameters. In the present method, the universe of discourses for U has to be defined. In order to evaluate the limits of U, a set of two quadratic performance indices were evaluated off-line. These are

$$J_1 = \sum_{k=0}^{M} \Delta\delta(k)^2$$

$$J_2 = \sum_{k=0}^{M} (t\,\Delta\omega(k))^2$$

4. THE PROPOSED METHOD

4.1 Algorithm for fuzzy PSS

1. The universes of discourse for each of the inputs and the output are defined.
2. For a given operating time a set of six differential equations as given in Appendix are evaluated.
3. The set of algebraic equations as given by eqns. 8 to 10 of Appendix are evaluated.
4. The operating point is fixed as the value of $\Delta\omega$ and ΔE_{fd} evaluated at this time step.
5. The inputs are fuzzified according to the respective universe of discourses.
6. The fuzzy rule matrix is used to find out the activation OR the firing of control rules for this combination of inputs.
7. Using the fuzzy values of output (U) as obtained from this fuzzy relation matrix and the universe of discourse defined for the output variable, the crisp value of output U is obtained by defuzzifcation using the centre of gravity method.
8. The evaluated value of U is used to evaluate the differential equations as outlined in step 1 above, at the next time step.
9. The above steps are repeated till the end of the simulation time.

4.2 Model Calculation for Fuzzy PSS

The universes of discourse and the fuzzy classes for $\Delta\omega$, ΔE_{fd}, and u are

$\Delta\omega_{max} = 2.4$ $\Delta\omega_{min} = -2.4$ ssf = 0.6 for all the three variables.

$\Delta E_{fd\,max} = 2.1$ $\Delta E_{fd\,min} = -2.1$

$U_{max} = 1.3$ $U_{min} = -1.3$

Time = 0.1 sec

$\Delta\omega = 1.97546$ $\Delta E_{fd} = -0.49975$

The fuzzy classes of $\Delta\omega$ are "PM" and "PB"

The fuzzy classes of ΔE_{fd} are "NS" and "Z"

For the above combination of fuzzy inputs four rules are activated as below:

If $\Delta\omega$ is "PM" and ΔE_{fd} is "NS" then U is "PS"

If $\Delta\omega$ is "PM" and ΔE_{fd} is "Z" then U is "Z"

If $\Delta\omega$ is "PB" and ΔE_{fd} is "NS" then U is "PS"

If $\Delta\omega$ is "PB" and ΔE_{fd} is "Z" then U is "Z"

The crisp output of U for the activation of these rules is obtained by defuzzification using the center of gravity method and is given to be 0.22905 for the given combination of $\Delta\omega$, ΔE_{fd}.

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5. SIMULATION STUDIES

A power system model consisting of a synchronous machine connected to a constant voltage bus through a transmission line as given is used in simulation studies. A schematic diagram for the model is shown in Fig.1. The supplementary stabilizing signal is fed to the excitation control loop as shown in this figure. Two types of disturbances, a three phase fault at the middle of transmission line as a large disturbance and a step change in V_{ref} as a small disturbance have been considered for the simulation studies. The results are presented in Figs.4-6. The control inputs are sampled every 20 ms and the maximum simulation time is set to 10 seconds. The control output U for NFLPSS has been fixed to be 1.1 pu.

6. RESULTS

The results of simulation studies are shown in Figs.4-6. The results indicate that the NFLPSS provides better damping for a severe disturbance as well as for a small disturbance. Thus it shows that NFLPSS can provide control action over a wide range of operating points for the system. Further the results indicate that the PSS does not need any further alterations for fine tuning the parameters of PSS .

TABLE I - FUZZY RELATION MATRIX

		ΔE_{fd}						
		NB	NM	NS	Z	PS	PM	PB
	NB	PM	PM	PS	Z	NS	NM	NB
	NM	PM	PS	Z	NS	NS	NM	NM
	NS	PM	PM	PS	Z	Z	NS	NM
$\Delta\omega$	Z	PM	PS	PS	Z	Z	NS	NM
	PS	PM	PM	PS	Z	NS	NM	NM
	PM	PB	PM	PS	Z	Z	NS	NS
	PB	PB	PM	PS	Z	NS	NS	NM

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[2] Earl Cox, Fuzzy Fundamentals, IEEE Spectrum 1992.

[3] C.C.Lee, Fuzzy logic in Control Systems - Part I & II, IEEE Tr. SMC-20, 1990.

[4] K.A.El-Metwally and O.P.Malik, Fuzzy logic based Power system stabiliser, IEE Proc. Gen., Tran., Dist., Vol. 142, No.3, May 1995

Appendix

The study generator as described by the third order model given by the following equations is used in this paper.

$$d\delta/dt = \Delta\omega \qquad (1)$$

$$d\,\Delta\omega/dt = (P_t - D.\,\Delta\omega - P_e)/((M/\omega_o) \qquad (2)$$

$$dE_q/dt = (E_{fd} - E_q' - (x_d - x_d')\,id)/T_{do}' \qquad (3)$$

$$|E_{fd}| \le E_{fdmax}$$

where $\Delta\omega = \omega - \omega_o$

$$P_t = P_{to} + \Delta P_t$$

$$E_{fd} = E_{fdo} + \Delta E_{fd}$$

The maximum excitation voltage E_{fdmax} is specified to be 7.0 pu in this study.The automatic voltage regulator (AVR) is described by

$$d\Delta E_{fd}/dt = [-K_a\,(V_t - V_r) - \Delta E_{fd})/T_a + (K_{au})/J_a \qquad (4)$$

The stabilising signal u is given by the equation

$$u = U(k) \text{ for } k\Delta T \le t \le (k+1)\,\Delta t$$

where

$$V_t = v_d^2 + v_q^2$$

$$V_r = 1.0 \text{ pu}$$

The speed governor is described by

$$d\Delta P_v/dt = (-K_v\,\Delta\omega - \Delta P_v)/T_v \qquad (5)$$

$$d\Delta P_v/dt = (\Delta P_v - \Delta P_t)/T_t \qquad (6)$$

The valve opening on closing speed is restricted by

$$|d\,\Delta P_v/dt| \le P_{vmax}$$

where P_{vmax} is specified to be 0.1 Pu/s in this paper. In the above equations, the subscript 'o' denotes the steady state values.

Exciter output voltage

$$E_{fd\phi} = E_q + (x_d - x_q)\,i_d$$

The state variables δ, $\Delta\omega$ and E_q' are calculated by solving the state equations (1) to (6) during the iterative process. Generator terminal voltage 'V_t' armature current 'I_a' and the power output of the machine 'P_e' which are continuous time are calculated at the end of each iteration as follows:

Machine armature current I_a can be given by the following two equations:

$$I_a = \frac{E_q - V_f}{j\ x q} \qquad (7)$$

Also $I_a = V_t\,(G + jB) + (V_t - V_\infty)\,(g_{12} + jb_{12})$ (8)
Equating (7) and (8) and solving for V_t we get

$$V_t = \frac{[(I_m\,I_q/x_q + V_\infty\,g_{12}) + j\,(V_\infty\,b_{12} - Re_q/x_q)]}{[G_{11} + j\,(B_{11} - 1/x_q)]} \qquad (9)$$

Now, the machine armature current I_a is calculated using

$$I_a = \left(\frac{E_q - V_t}{j\,x_q}\right) = \frac{(Re_q + jIm\,E_q) - (RV_t + jIm\,V_t)}{j\,x_q} \qquad (10)$$

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$$= \frac{(\mathrm{Im}\,E_q - \mathrm{Im}\,V_t)}{x_q} + j\,\frac{(RV_t - Re_q)}{x_q}$$

where $E_q = E_q' + (x_q - x_d')\, i_d$

$I_d = I_a \sin(\delta+\theta)$

Active power delivered by the machine is,

$P_e = R_e (V_t I_a{}^*) = R_e [(RV_t = j\mathrm{Im}V_t)(Ri_a - j\mathrm{Im}I_a)$

$= RV_t \,.\, Ri_a + \mathrm{Im}\, V_t \,.\, \mathrm{Im}\, I_a$

At the end of each sampling interval, we get the values of the state variables δ, $\Delta\omega$ and E_q. To calculate the electrical power output of the generator at the end of each time interval, we have to know the values of V_t and armature current 'I_a'. Calculation of I_a and V_t using equations (9) and (10) respectively require the value of E_q, which in turn needs the value of I_a. Hence the values of I_a V_t are calculated by an iterative procedure. In this iterative procedure, equations (8), (9) and (10) are evaluated simultaneously. The iterative procedure is continued until the difference between two successive values of 'I_d' is less than specified tolerance limit.

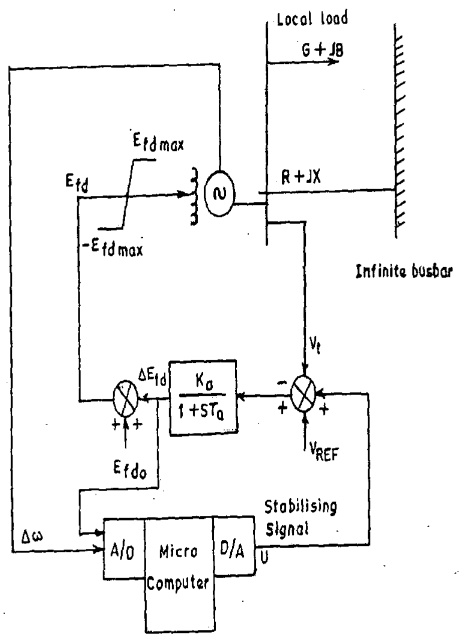


Fig. 1 Study system to simulate disturbances

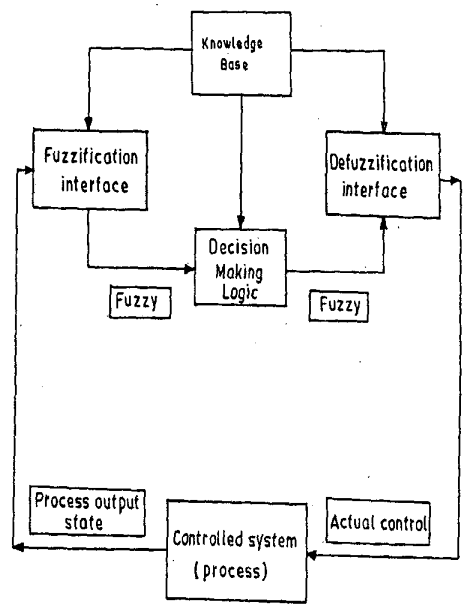
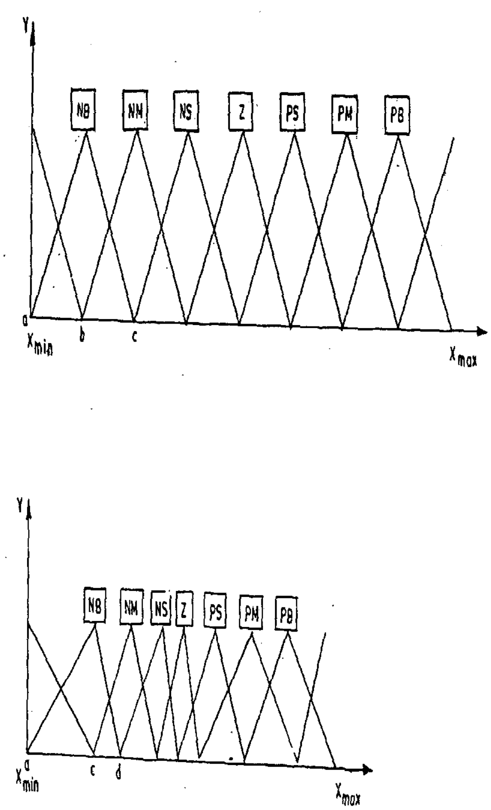


Fig 2. Block diagram of Fuzzy Logic Controller (FLC)

Fig 3. Typical fuzzy membership functions



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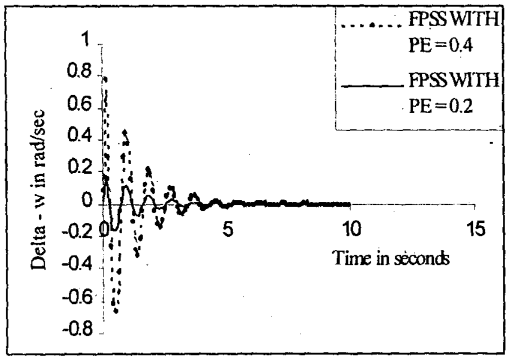

Fig 4. Variation of $\Delta\omega$ with time for 3-phase fault

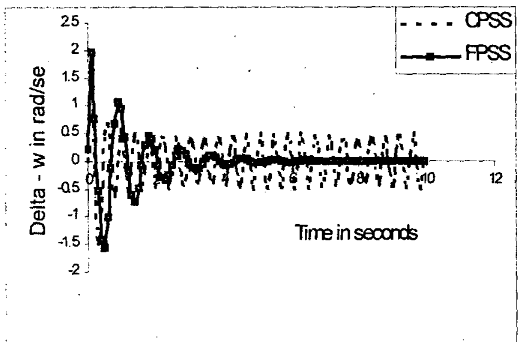

Fig 5.Variation of $\Delta\omega$ with time for 3-phase fault

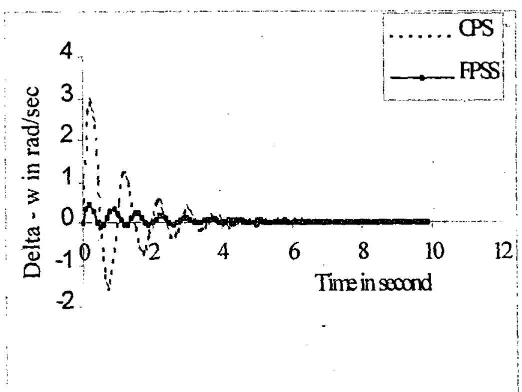

Fig 6. Variation of $\Delta\omega$ with time for step change in V_{REF}

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