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Design and Implementation of Synchronous Generator Excitation Control System Using Fuzzy Logic Controller

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Abstract: - The main advantage of the fuzzy logic controller (FLC) is that it can be applied to plants that are difficult to model mathematically, and the controller can be designed to apply heuristic rules that reflect the experience of human experts. This paper investigates the design and implementation of a fuzzy logic PID controller, then application of this fuzzy logic PID controller in synchronous generator excitation control system (AVR). It includes simulations for the justification of this design in MATLAB. This design uses the basic concepts of control system and also includes the mathematical models to represent the transfer functions of several components of automatic voltage regulator control system.

Keywords: Fuzzy Logic Control, Synchronous Generator Excitation, PID controller

I. INTRODUCTION

The main motive of this paper is to design a regulator control system in such a manner to overcome the difficulties of complex mathematical model of the plant to be controlled, and to develop an intelligent control system, so that the regulator becomes independent of the system to be controlled and it generates controlling signals on the bases of experiences it faces during the operation. Also the system should be very simple to understand, and easy to program. Regulator control systems mostly use PID controllers which are given by [1].

$$G_c(s) = \frac{M(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s$$

The PID controller has two zeros and one pole. Generally an additional pole is required to limit the high-frequency gain [2]. To develop the control law for fuzzy logic controller, which performs the function of PID control efficiently, the concept of digital PID is necessary.

In case of digital PID controllers, the multiplication, integration and differentiation are performed numerically in digital computers [2].

The transfer function of digital PID controller using numerical integration and differentiation is expressed in z-transform [3].

$$M(z) = D(z)E(z) = \left[K_P + \frac{K_I Tz}{z-1} + \frac{K_D(z-1)}{Tz}\right]E(z)$$

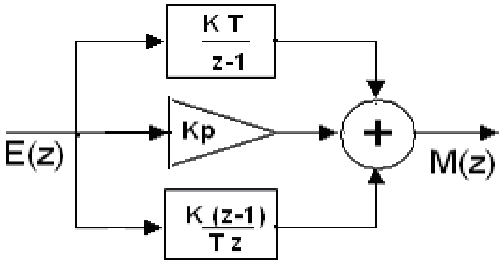


Fig 1 Digital PID controller

IMPLEMENTATION OF FUZZY LOGIC PID CONTROLLER

The basic control equation for PID is given by [2]

$$m(t) = K_P e(t) + K_I \int_0^t e(\tau)d(\tau) + K_D \frac{de(t)}{dt} \qquad (1)$$

where m(t) is the control signal and e(t) is the error signal.
Differentiating (1):

$$\frac{dm}{dt} = K_P.\frac{de}{dt} + K_I.e \qquad (2)$$

where m and e are time dependent variables. In discrete time (2) can be written as follows [4]

$$\frac{m(kT) - m[(k-1)T]}{T} = K_P.\frac{[e(kT) - e\{(k-1)T\}]}{T} + K_I.e(kT)$$

$$\frac{\Delta m}{T} = K_P.\frac{\Delta e}{T} + K_I.e$$

$$u = K_P.v + K_I.e$$

where,
T = sampling time.
u = change in output ‘m’ over one sampling time.
V = change in error signal ‘e’ over one sampling time.

Characteristics of PI controller can be represented by the phase plane diagram shown below. A diagonal line where **u=0**, divides the area where **u** is positive and **u** is negative.
In order to design a fuzzy controller based on PI control structure, the following definitions are made,
Let E be the linguistic variable for the error e,
V be the linguistic variable for the change in error over one sample time.
U be the linguistic variable for control output u over one sample time.

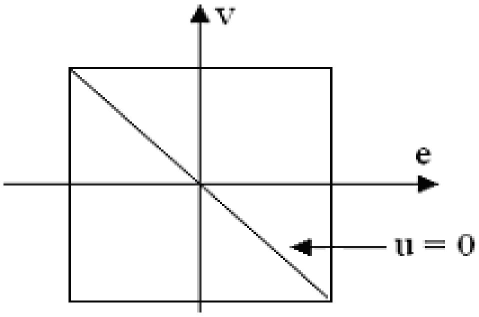


Fig 2 Characteristics of Fuzzy PI Controller

Following fuzzy sets can be defined:
LE = {NB, N, Z, P, PB}
LV = {NB, N, Z, P, PB}
LU = {NVB, NB, N, NS, Z, PS, P, PB, PVB}

Each element of a linguistic variable set is a membership function of that variable. The present design uses three types of functions, s-function, z-function, and triangle function [5].

A. Membership Functions

(1) For S-shaped

$$v(e;\alpha,\beta) = \begin{cases} 0 & e < \alpha \\ (e-\alpha)/(\beta-\alpha) & \alpha \le e \le \beta \\ 1 & e > \beta \end{cases}$$

(2) For Z-shaped

$$v(e;\alpha,\beta) = \begin{cases} 1 & e < \alpha \\ (e-\alpha)/(\beta-\alpha) & \alpha \le e \le \beta \\ 0 & e > \beta \end{cases}$$

(3) For triangular

$$v(e;\alpha,\beta,\gamma) = \begin{cases} 0 & e < \alpha \\ (e-\alpha)/(\beta-\alpha) & \alpha \le e \le \beta \\ (e-\gamma)/(\beta-\gamma) & \beta \le e \le \gamma \\ 0 & e > \gamma \end{cases}$$

The crisp values of the input variables are mapped onto the fuzzy plane using the equations given above [6, 7].

A. Fuzzy Rule Base

Each input variable can take any of the five linguistic values, therefore 5×5=25 rules are formulated. The rules have the typical fuzzy rule structure, using linguistic variables in both the antecedent, and are expressed in IF-THEN manner. The corresponding PI control law in IF-THEN rules can be represented as [8,9]:

R^k: IF E is A_1^k and V is A_2^k , THEN U is C^k

A_1^k can take any linguistic value in set LE

A_2^k can take any linguistic value in set LV

where: C^k can take any linguistic value in set LU.

To implement this design into
FLC, let:

- x1 = E
- x2 = V
- $\{B_i^1, B_i^2, B_i^3, B_i^4, B_i^5\}$ = {NB, N, Z, P, PB} for i=1, 2
- $\{D^1, D^2, D^3, D^4, D^5, D^6, D^7, D^8, D^9\}$ = {NVB, NB, N, NS, Z, PS, P, PB, PVB}.

The rule base can be represented by a fuzzy associative memory (FAM) table shown below:-

I. TABLE FUZZY ASSOCIATIVE MEMORY

x1 **x2**	**B1_1**	**B1_2**	**B1_3**	**B1_4**	**B1_5**
B2_1	C1	C2	C3	C4	C5
B2_2	C6	C7	C8	C9	C10
B2_3	C11	C12	C13	C14	C15
B2_4	C16	C17	C18	C19	C20
B2_5	C21	C22	C23	C24	C25

II. TABLE FUZZY ASSOCIATIVE MEMORY

E **V**	**NB**	**N**	**Z**	**P**	**PB**
NB	PVB	PB	P	PS	Z
N	PB	P	PS	Z	NS
Z	P	PS	Z	NS	N
P	PS	Z	NS	N	NB
PB	Z	NS	N	NB	NVB

B. Inference Engine

The FLC design in this project incorporates Mamdani's implication method of inference. Mamdani's implication for the fuzzy rules of the form [5]

$$R^k: \text{ IF } E \text{ is } A_1^k \text{ and } V \text{ is } A_2^k \text{ , THEN } U \text{ is } C^k$$

is given by

$$\mu_C(y) = \max_k [\min [\mu_{A_1^k}(x1), \mu_{A_2^k}(x2)]]$$

$$k = 1, 2, \ldots, 25$$

The first phase of Mamdani's implication involves min-operation since the antecedent pairs in the rule structure are connected by a logical 'AND'. All the rules are then aggregated using a max-operation. According to this rule, the elements of Table 1 are:

C1 = min[B1_1 , B2_1]
C2 = min[B1_2 , B2_1]
C3 = min[B1_3 , B2_1]
C4 = min[B1_4 , B2_1]

. . . .
up to so on till,
C25 = min[B1_5 , B2_5]

The max operation is used to take into account the combined effect of all the rules. The 25 output conditions are aggregated into 9 linguistic values (D1 to D9) based by the conditions set by the rules.

Colour	**Max function**
🟧	D9 = [C1]
🟦	D8 = max[C2 , C6]
🟥	D7= max[C3 , C7 , C11]
🟩	D6 = max[C4 , C8 , C12 , C16]
🟪	D5 = max[C5 , C9 , C13 , C17 , C21]
🟨	D4 = max[C10 , C14 , C18 , C22]
⬜	D3 = max[C15 , C19 , C23]
🟦	D2 = max[C20 , C24]
🟦	D1 = [C25]

III. DEFUZZIFICATION TECHNIQUE

The membership functions of the output values are intentionally made to be symmetrical, as this will simplify the defuzzification computation. In this project the **weighted average** method is used as a defuzzification technique. Due to the fact that the output functions are symmetrical in nature, the mean of fuzzy set can be used as weightings for the defuzzification process. This technique requires several multiply-by-a-constant operations and only one division process [8, 9]

Dividend = E1*D1 + E2*D2 + E3*D3 + E4*D4 + E5*D5 + E6*D6 + E7*D7 + E8*D8 + E9*D9 ;

Divisor = D1 + D2 + D3 + D4 + D5
+ D6 + D7 + D8 + D9;

Output y = Dividend / Divisor.
{Divisor should not be 0}

Linguistic Value, D	D1	D2	D3	D4	D5	D6	D7	D8	D9
Weighting Values, E	E1	E2	E3	E4	E5	E6	E7	E8	E9

A. Interfacing Blocks

The input interface makes an error signal ‘**e**’ and change in error ‘□ **e**’ by computing Vref and Vdc at the plant output. Output interface converts the output of FLC into the required value for the plant. The characteristics of interfacing blocks can be described by the following equations:

Input interface:

$e = Vref - Vdc$

$x1 = e$

$x2 = x1 - x1.z^{-1}$

output interface:

$u = y$

$w = u + w.z^{-1}$

Where z^{-1} is used to represent a delay in signal by one sampling time (according to z-transform)

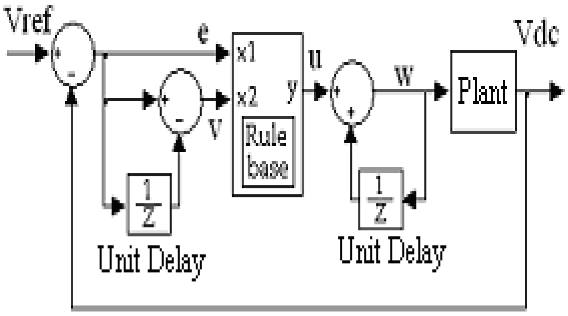


Fig.3 Block diagram of Fuzzy Control System

IV. TRANSIENT RESPONSE

The main purpose of derivative component in PID controller is to make the transient response better. Transient response is related to the rate of change of signal i.e. speed. In FLC the transient response depends on *weighting values* [10]. If weighting values in the defuzzification process are large, overcompensation will be produced due to which output oscillates. This transient response can be controlled by using appropriate weighting values in defuzzification process. It also depends on the *sampling time* of input and output interfaces or unit delay [11].

V. FUZZY LOGIC PID CONTROLLER IN SIMULINK

The Fuzzy Logic Toolbox is designed to work seamlessly with Simulink, the simulation software available from The Math Works.

Fig.4 Masked subsystem of Fuzzy Logic PID Controller designed in MATLAB

VI. APPLICATION OF FUZZY LOGIC PID CONTROLLER IN SYNCHRONOUS GENERATOR EXCITATION SYSTEM (AVR)

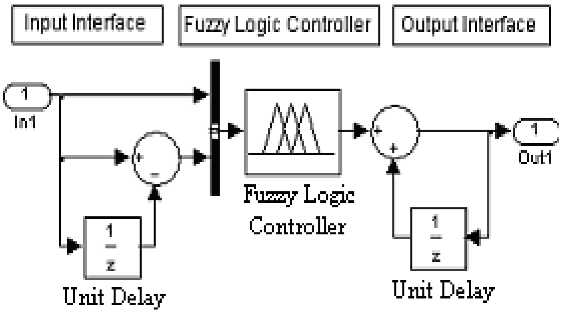


Fig 5 Looking under the mask is the block diagram of FLC

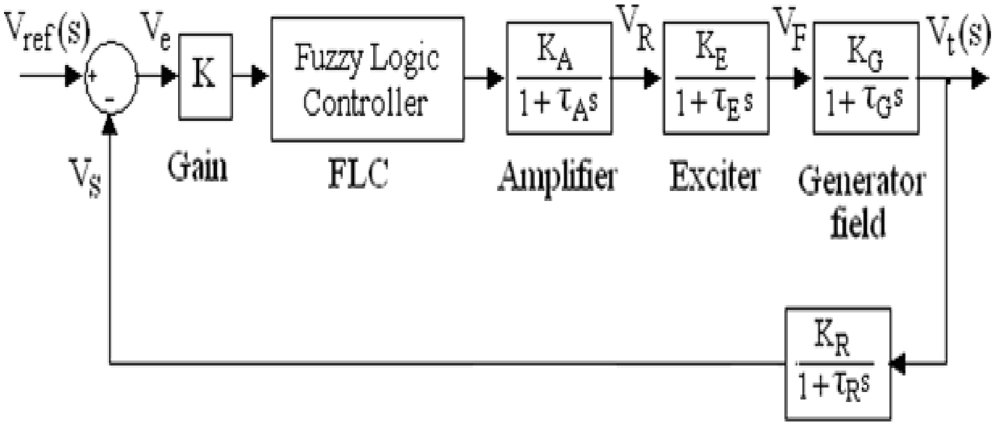


Fig 6 Block diagram of AVR in which each block represents the transfer Functional of a particular element of AVR

In the Fig (6),

- Typical values of K_A are in the range of 10 to 400.
- Typical values of τ_A are in the range of 0.02 to 0.1 seconds.
- Value of τ_E for modern exciter is very small.
- The value of gain K can be adjusted according to controller behavior.
- K_G and τ_G depend on load on the generator. Typical values of K_G are 0.7 to 1, and τ_G are between 1.0 and 2.0 seconds.
- Values of τ_R are may be assumed between 0.01 to 0.06 i.e. very small.

In block diagram, PID controller has been replaced by FLC which performs the job of PID more efficiently.

SIMULATION IN MATLAB USING SIMULINK MODEL OF A TYPICAL AVR FOR JUSTIFICATION OF FLC

Typical values for AVR given as:
$K_A = 10$, $\tau_A = 0.1$, $K_E = 1$, $\tau_E = 0.4$,
$K_G = 1$, $\tau_G = 1.0$, $K_R = 1$, $\tau_R = 0.05$,

FLC parameters are defined by Fig (7, 8 &9)

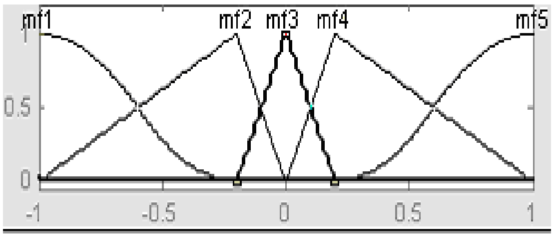


Fig 7 Membership function definition for Input 1

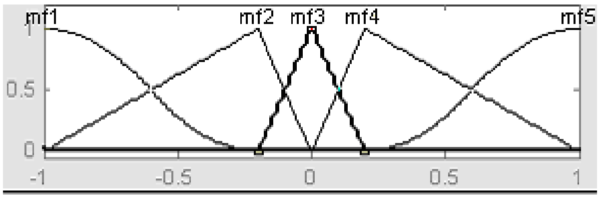


Fig 8 Membership function definition for Input 2

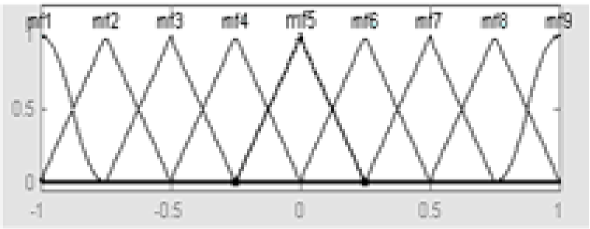
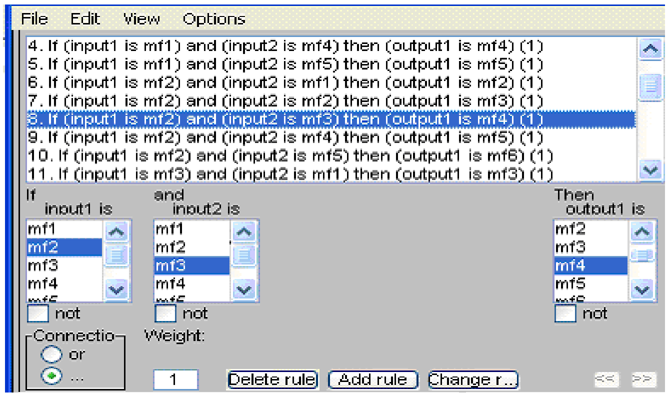


Fig 9 Membership function definition of the output



4. If (input1 is mf1) and (input2 is mf4) then (output1 is mf4) (1)
5. If (input1 is mf1) and (input2 is mf5) then (output1 is mf5) (1)
6. If (input1 is mf2) and (input2 is mf1) then (output1 is mf2) (1)
7. If (input1 is mf2) and (input2 is mf2) then (output1 is mf3) (1)
8. If (input1 is mf2) and (input2 is mf3) then (output1 is mf4) (1)
9. If (input1 is mf2) and (input2 is mf4) then (output1 is mf5) (1)
10. If (input1 is mf2) and (input2 is mf5) then (output1 is mf6) (1)
11. If (input1 is mf3) and (input2 is mf1) then (output1 is mf3) (1)

If input1 is: mf1, mf2, mf3, mf4 ☐ not
and input2 is: mf1, mf2, mf3, mf4 ☐ not
Then output1 is: mf2, mf3, mf4, mf5 ☐ not

Connectio
○ or
● ...

Weight: 1

Fig 10 Selection of input and output parameters

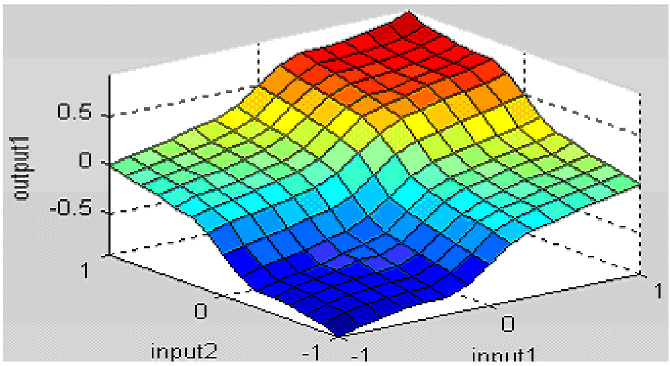


Fig 11 Surface showing input-output relationship

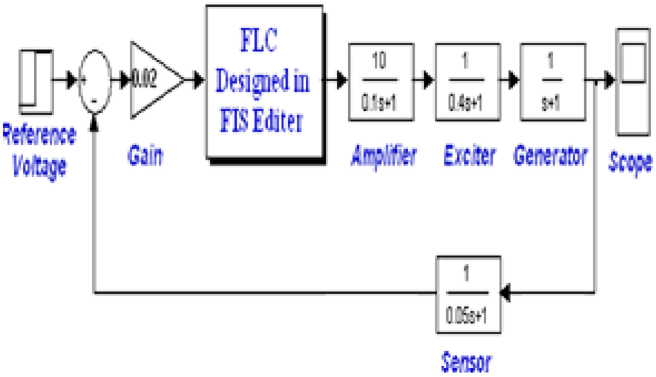


Fig 12 Simulink model for simulation

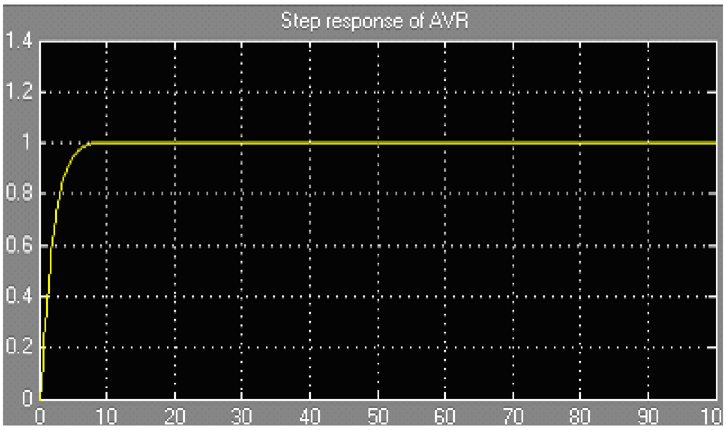


Fig 13 Simulation Results

VIII. DISCUSSION OF RESULTS

The programmed Fuzzy controller was found very quick in raising the value to the steady state as shown in Fig 13 whereas the FIS designed fuzzy controller was on the second number in response. The conventional controller using transfer function was slow in comparison to the fuzzy controllers in achieving steady state value.

The reference signal was having three levels and at the last level, reference signal gets stable and does not change its level for rest of the time. These switched levels have been produced giving a shape of square wave to check whether the controller is following the reference voltage signal or not. In response to the reference signal, the PID controller using transfer function does follow the reference signal but there are a lot of oscillations observed in switching from one level to other level.

IX. CONCLUSIONS

The performance of fuzzy logic controller is neither too fast, nor too slow, but moderate. Fuzzy logic controller is somewhat intelligent than PID, because it keeps the record of disturbances experienced by the system in FAM (Fuzzy Associate Memory). During defuzzification average area under output variable is calculated according to concept of centre of gravity. Hence the effect of disturbances which are large but for short time is diminished. Therefore overshooting and undershooting is small, and system is less oscillatory.

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