Comparative between PI and Fuzzy Logic Controllers for Synchronous Generator Excitation System of Kun Hydropower Plant

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***Abstract*—This paper is focused on the simulation and implementation of simple fuzzy logic excitation control of a synchronous generator. Synchronous machine in hydro power plant could be controlled and conducted by fuzzy controller.In this work, a model of a static excitation system of an alternator connected to a network via a transformer has been built using MATLAB-SIMULINK. A Fuzzy logic controller is used to control the output terminal voltage power of the synchronous generator for static excitation system. The proposed controller consists of a single control loop for both the voltage and the damping control. A method based on step response has been proposed and verified for tuning the parameters of the controller. The simulation test results with this excitation control system model using fuzzy logic controller has found more satisfactory than without using it. The behaviour of the excitation system with fuzzy logic controller is compared with excitation system based on the PI voltage controller in this paper.**

***Keywords*—Synchronous generator, excitation control, fuzzy logic controller, voltage stability, PI**

I. INTRODUCTION

In classical regulation structure of the excitation control of a synchronous generator PI voltage controller is superior to excitation current controller. Instead PI voltage controller a simple fuzzy logic controller is used for voltage control and generator stabilization.

The static systems consist of some form of controlled rectifiers or choppers supplied by the ac bus of the alternator or from an auxiliary bus. The voltage regulator controls the output of the exciter so that the generated voltage and reactive power can be controlled. Theexcitation system must contribute to the effective voltage control and therefore enhance thesystem stability. It must be able to respond quickly to a disturbance, thereby enhancing thetransient stability as well as the small signal stability. In most modern systems the automaticvoltage regulator is a controller that senses the generator output voltage and thecurrent or reactive power then it initiates corrective action by changing the exciter control tothe desired value. The excitation system controls the generated EMF of the generator andtherefore controls not only the output voltage but the reactive power as well.The response of the automatic voltage regulator is of great interest in studying stability. It is difficult to makerapid changes in field current, because of the high inductance in the generator field winding.This introduces a considerable lag in the control function and is one of the major obstacles tobe overcome in designing a regulating system. The Voltage Regulator keep the voltage within pre-established limits. Based on this, it can be said that the Voltage Regulator also controlspower factor of the machine once these variables are related to the generator excitation level.The Voltage Regulator quality influences the voltage level during steady state operation and alsoreduces the voltage oscillations during transient periods, affecting the overall system stability. Simulation of generating system found in this paper use detailed models for the generating units with their detailed excitation system of Kun Chaung Hydro generator. Fig. 1 shows the block diagram of a excitation system of proposed machine.In this work, a static excitation system of an alternator connected to a network via a transformer has been modeled and simulated using Matlab Simulink power system block (PSB).

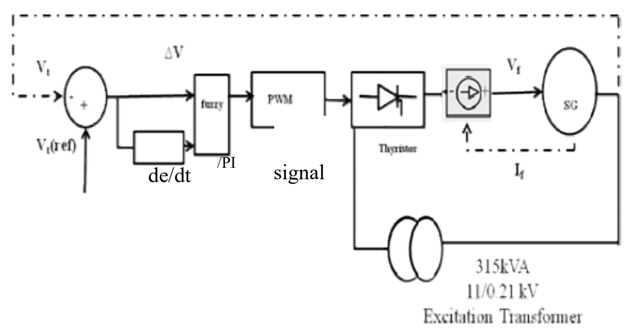


Fig.1Block Diagram of Generator with Excitation System

II. EXCITATION SYSTEM

Based on excitation power source, the excitation systems have taken many forms over theyears, namely, dynamic excitation and static excitation systems. In a dynamic excitationsystem the most parts are connected to the rotor, so that the carbonic brushes can be removed.It is sometimes called brushless excitation systems. This type uses some sort of rotatingmachines; thus their responses are poor besides the need for regular maintenance. In staticexcitation systems, on the other hand, all components are static or stationary. Static rectifier, supply the excitation current directly to the field of the synchronous generator through sliprings. The supply of the power to the rectifiers is from the main generator or via the stationauxiliary bus through a step down transformer.Voltage Regulator is the main of the excitation system. Its responsibility is to control current such that, maintain generator voltage at starting, regulating voltage andoutput terminal voltage after connecting the unit to a network. The Voltage Regulator must have high gain tokeep the operational variations within limits [3].The Voltage Regulator work on the principle of error detection. The alternator three phase outputvoltage obtained through a potential transformer is compared with a reference value. Whenthe alternator is connected to a network, and in order to control the output terminal voltage, thesignal delivered and compared are the output voltage and reference voltage. From these twovariables the output terminal voltage is determined and compared with a reference signal inorder to determine the error used to suggest the increment or decrement of field voltage.

A. Power Converter for proposed excitation system

Mostly, the power converter is a thyristor three-phase bridge. In this excitation system of Kun Chaung Hydro generator, the power converter may becontrolled by fuzzy logic controller. All excitation power is normally derived eitherfrom the synchronous machine terminals or from auxiliary source through an excitationtransformer. The voltage regulator controls the thyristor converter through a pulse-triggeringunit. The power rectifying bridges are full converter, 6 pulseinverting type and can providecurrents up to 10000 A DC and voltage up to 1400 V DC. Each rectifier bridge includes protection circuitry such as snubbers and fuses. Depending on the rating of the system, therectifier may comprise a single stack or multiple units in parallel for higher power levels.The block shown in fig. 2is implemented a bridge of selected power electronics devices. Series RC snubber circuits are connected in parallel with each switch device. For most applications the internal inductance Lon of diodes and thyristors should be set to zero. The inductance Lon is forced to 0 if the model chooses to discrete in circuit.

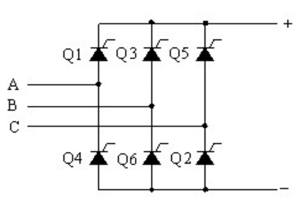


Fig.2 Commutation of Three-phase Thyristor Converter

Number of bridge arms of thyristor set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices). The voltage reference signal, as well as the measured voltage and measured excitation current signals have been made discrete using the Zero-Order Hold function.fuzzy controller is added in the forward path of the thyristor connection system of proposed model shown in Fig.3.

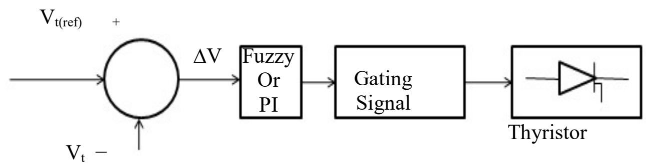


Fig. 3Thyristor Connection

B. Principle Operation of Excitation System

The field terminal voltage of the synchronous machine model is measured inside the "Field Connections" subsystem. This uses a current source driven by the DC current output of the bridge which also corresponds to the DC field current. The voltage appearing across this current source corresponds to the field voltage which must be applied to the V_f Synchronous Machine input. Voltage regulation is performed by controlling the field voltage of the exciter. This is performed by the "Voltage Regulator" block (fuzzy / PI type) which compares the measured voltage (positive sequence voltage) to a 1 p.u reference. . Finally, in order to increase the simulation speed the whole demo is discretized (T_s=1 micro sec).Fig. 4 shows the block diagram of Field connection subsystem.

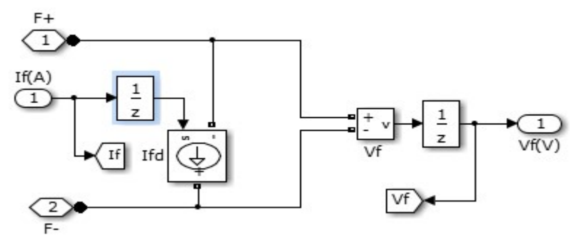


Fig. 4 Field Connection

III. SYSTEM DESCRIPTION

A schematic diagram of the proposed system with synchronous generator is shown in Fig. 5. The system consists of 20MW three phase synchronous generator is driven by respective hydro turbine. Since the input to the hydro turbine is assumed to be constant, so the output of hydro turbine is nearly constant, output power of the Synchronous generator must be held constant at all loads.

The basic function of excitation system is to provide direct current to the synchronousmachine field winding. The excitation system controls and protects essential functions of thepower system for satisfactory operation and performance. The control functions include thecontrol of the generator voltage, reactive power flow and the enhancement of system stability.The protective functions ensure that the capability limits of the synchronous machine,excitation system and other equipment are not exceeded.The proposed system used in this study consists of an alternator connected to an infinitebus via a transformer. Static excitation system is used for the generator. The proposed modelfor single line diagram of kun chaung generator is shown in Fig 5.

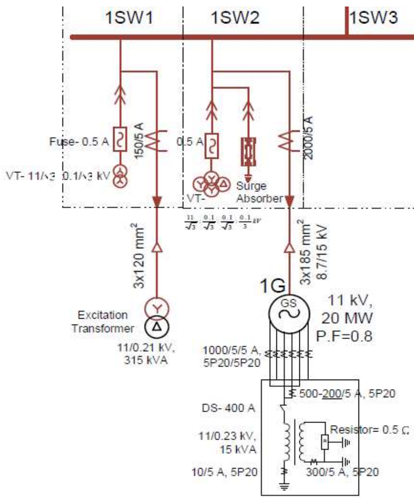


Fig. 5Single line diagram of Kun Chaung Generator

The rating of synchronous machine is 25MVA, 11kV, 50 Hz, 428.7 rpm machine driven by a hydro turbine. A 11kV / 0.21kV transformer is used to adapt the 210V output voltage of the exciter to the rectifier. The output of the rectifier bridge is connected directly to the synchronous machine field terminals. Synchronous generator nominal data of Kunchaung Hydropower plant in Kun creek of Bago region are given in Table I.

TABLE I

PARAMETERS OF SYNCHRONOUS GENERATOR OF KUN CHAUNG

Parameter	Rated
Terminal voltage	11000 V
Phase current	757 A
Frequency	50 Hz
Speed	428.6 r/min
Power factor	0.8
d-axis synchronous reactance, X_d	1.04 p.u
q-axis synchronous reactance X'_q	0.624 p.u.
d-axis transient open-circuit time constant T'_{do}	5.92 s
d-axis transient reactance X'_d	0.25 p.u.
d-axis subtransient reactance X''_d	0.181 p.u.
q-axis subtransient reactance X''_q	0.209 p.u.
Short-circuit time constant T''_d	0.043 s
Short-circuit time constant T''_q	0.047 s

IV. CONTROLLER DESCRIPTION

In order to control the generator output voltage, the field voltage must be changed in thedesired way. In this paper, methods for controlling the generator output voltage are describedusing fuzzy logic controller applied for static excitationsystem.

The fuzzy logic controller is widely used in power systems because it is closer as to human thinking and in language than conventional logical systems.A power system is highly nonlinear system. For tuning of fuzzy logic controller there is no need for exact knowledge of power system mathematical model. The fuzzy controller parameters settings are independent due to nonlinear changes in generator and transmission lines operating conditions. The detailed configuration of fuzzy logic controller is presented on the fig. 6.The fuzzy controller is the voltage control loop with the function of voltage control [3]. The voltage error signal e(t)is the difference between the voltage reference $v_{ref}$and the actual voltage v_t.The information of voltage error signal e(t)is used to get the voltage state and to determine the reference for the controller.

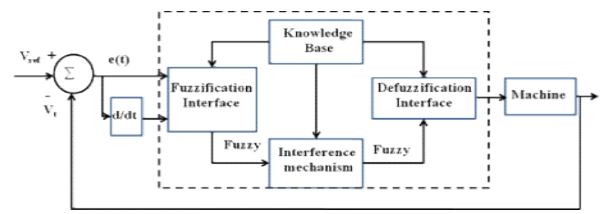


Fig .6 Schematic Diagram of Closed Loop Control with Fuzzy Controller

Generator voltage control system includes the fuzzy controller, the generation system, and the interfaces between both the controller and the generator. The fuzzy controller has been implemented in Matlab software. The generation system consists of a three-phase synchronous generator and a prime mover consisting of Hydraulic Turbine and Governor with speed control to ensure that the generator frequency is constant. The power converter is a three-phase thyristor rectifier. The operation principle of the power converter is as follows: the analog reference voltage is compared to the actual voltage field current, the error signal is then processed by a Fuzzy controller that will set up the firing angle of the thyristor bridge that leads to the excitation voltage resulting in the desired terminal voltage. The purpose of the interface between the generator and the fuzzy controller is to provide the controller with the required information from the generator, i.e., the generator terminal voltage. Instantaneous value of line-to-line voltage is measured by means of voltage sensors. Two inputs and one output Fuzzy Logic Controller has been usedin this paper. The first input is the voltage error, the second is the change in error and gatingcontrol signal for thyristor is the output.

A.Fuzzification

Fuzzy logic uses linguistic variables instead of numerical variables. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (del e)can be labeled as zero (ZE), positive (P) and negative (N).Three triangular membership for each inputs are chosen.

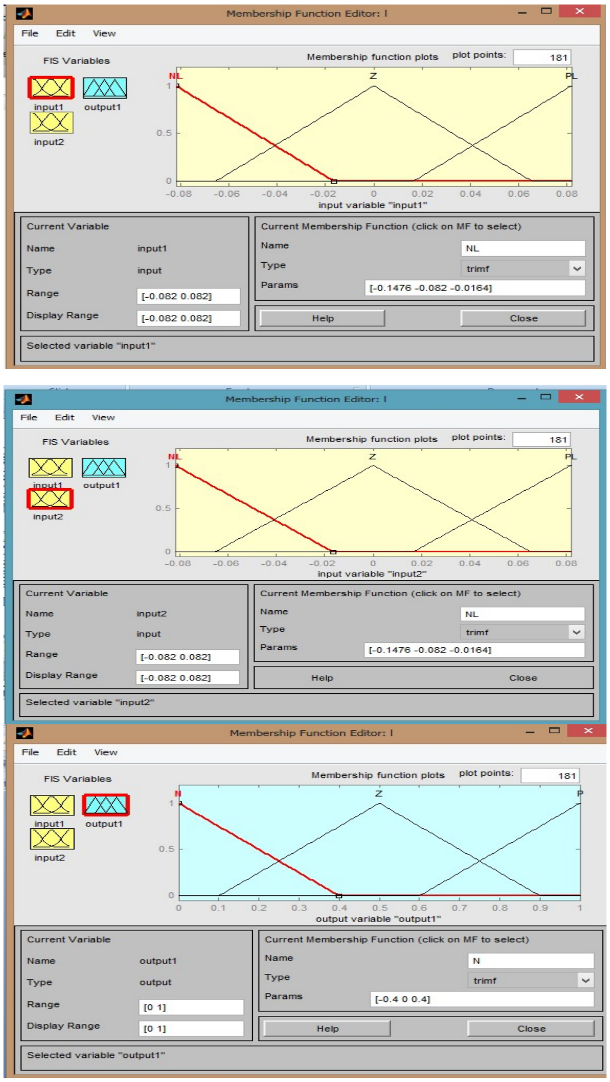


Fig .7 Membership Function of Input and Output

The input membership function for error and change of error voltage and output membership functional is shown in fig.7.Range used for the error voltageis from -910 to +910 V. Error is the difference between reference voltage 11000 and 10090 voltage record from kun chaung power plant. Table. II show the range of input for fuzzy membership functionand the range of output variable for fuzzy membership function shows in Table III. The process of converting a numerical variable (real number) into alinguistic label (fuzzy number) is called fuzzification.

TABLE II

THE RANGES OF INPUT VARIABLE FOR FUZZY MEMBERSHIP FUNCTION

Error voltage and Change of error voltage (Input MFs)			
	Start	Peak	End
Negative	-0.1476	-0.082	-0.0164
Zero	$-4.54e^{-4}$	0	$4.54e^{-4}$
Positive	$4.54e^{-4}$	0.041227	0.082

TABLE III

THE RANGES OF OUTPUT VARIABLE FOR FUZZY MEMBERSHIP FUNCTION

Control Signal			
	Low	Medium	High
Negative	-0.4	0	0.4
Zero	0.1	0.5	0.9
Positive	0.6	1	1.4

B. *Interference*

Once the membership is found for each of thelinguistic labels, an intelligent decision can be made to get desire output. This decision processis called inference.In conventional controllers, there are control laws,which are combinations of numerical values that control the reaction of the controller. In fuzzy logiccontrol, the equivalent term is rules. Rules arelinguistic in nature and allow the operator to develop acontrol decision in a more familiar human knowledge [4]. A typical rule can be written asfollows:If the “error voltage” is negative (N), AND the “rateof change of voltage error” is positive (P),then the “dcexcitation” remain unchanged. On the other handif the “voltage” is positive (P), AND the “rateof change of voltage error” is negative (N), then the “dc excitation” should be increased tokeep the output voltage to the desire one. Using these concepts, rules are built for the fuzzy controller. In this design, a minimum correlation inferencetechnique was used. This means that the logicoperation of AND will return the minimum of allinputscontroller its intelligence. It is convenient when dealingwith a large number of combinations of inputs, to putthe rules in the form of a rule table. Table IV showsthe rule table for controlling the synchronousgenerator output voltage where del volt refers to therate of change of output voltage.

TABLE IV

RULE TABLE FOR DETERMINING THE FUZZY OUTPUT

AND		Error Voltage		
		Negative	Zero	Positive
Change of error Voltage	Negative	Negative	Negative	Positive
	Zero	Negative	Zero	Positive
	Positive	Zero	Positive	Positive

After the rules are evaluated, each output membershipfunction will contain a corresponding membership.From these memberships, a numerical (crisp) valuemust be produced. This process is called defuzzification.

C. Defuzzification

Defuzzification plays a great role in a fuzzy logicbasedcontrol system. It is the process in which thefuzzy quantities defined over the output membershipfunctions are mapped into a non-fuzzy (crisp) number.It is impossible to convert a fuzzy set into a numericvalue without loosing some information. Manydifferent methods exist to accomplish defuzzification. Choosing of centroid method use as a defuzzification is shown in fig.8. when the error is (P) and the change in error is zero, that's mean the output voltage is less than the designed voltage (V_{ref}), but there is no change in the value of the output voltage, that's mean the control signal for excitation must be increased, therfore the new signal must increase by positive (P) and this signal increase output voltage. The centroid method is used as the defuzzification method. The output control signal is defined by

$$y = \frac{\sum_{j=1}^{9} w_i u(w_i)}{\sum_{j=1}^{9} u(w_i)}$$

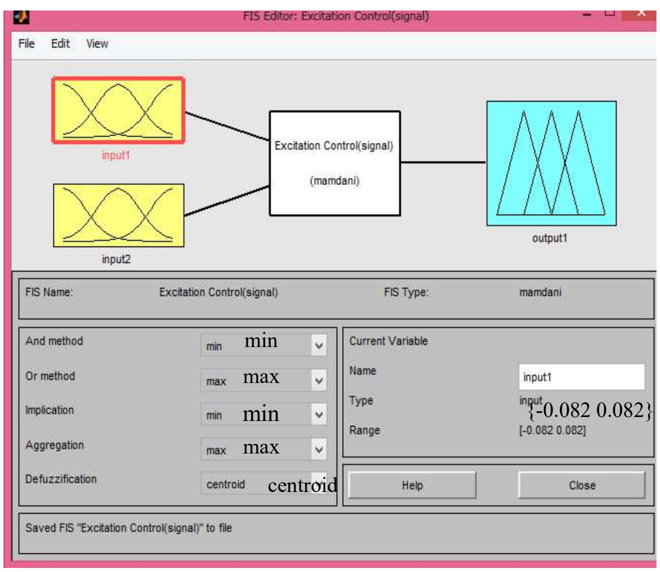
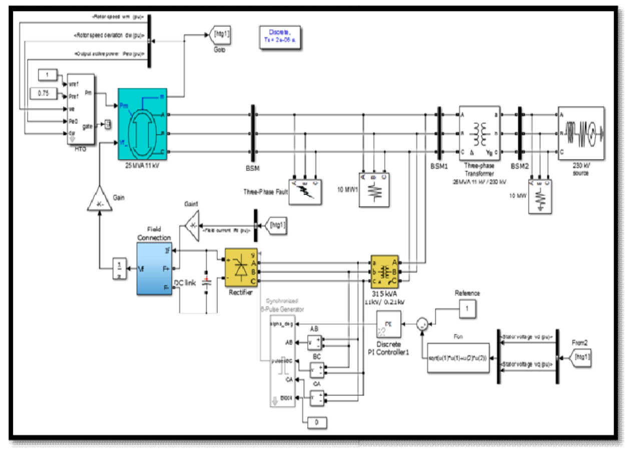


Fig.8 Deffuzification

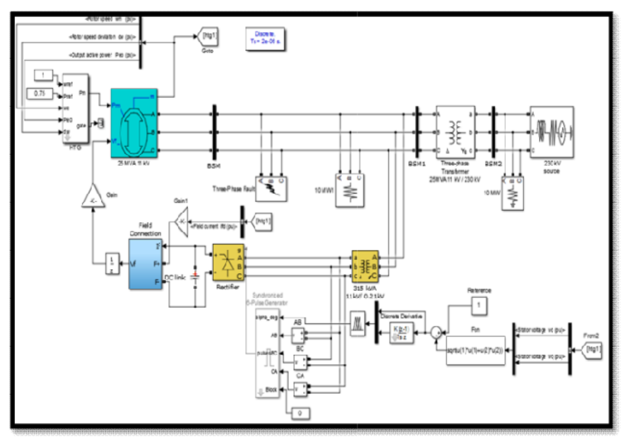
IV. SIMULATION RESULTS OF GENERATORUSING PI AND FLC CONTROLLER IN THREE PHASE FAULTCONDITION

In this part, the main fact is on whether the critical fault clearing time of the synchronous generator can be prolonged under fault conditions by using FLC or PI. A three phase fault begins at time 1.2 s and the fault condition last until time 1.3 second.

Figure9 shows the simulation model of synchronous generator associated with the hydraulic turbine and governor (HTG) and excitation system under fault condition. This model is to analyse the performance of synchronous generator under the influence of three phase fault. In this model, a three phase generator rated 25 MVA, 11 kV, 428.5 rpm is connected to a 230 kV, 100 MVA network through a Delta-Wye 25 MVA transformer. At t = 1.2 s, three phase fault occurs between generator and transformer. The fault is cleared after 5 cycles (t = 1.3 s). The responses of synchronous generator during the occurrence of three phase fault are determined by this simulation results.



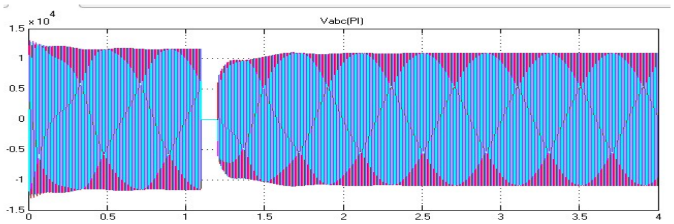
(a)



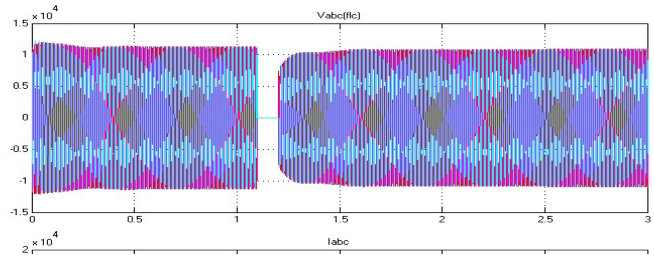
(b)

Fig 9.Simulation Model of Synchronous Generator Associated with HTG and Excitation System Under Fault Condition(a) with PI (b) with FLC

Three phase fault is not frequently found in power system. But damage of power system due to three phase fault is very large. So, the response of synchronous generator for three phase fault will be simulated in this research. In this section, the simulation for stator current, terminal voltage, excitation voltage and rotor speed under fault conditionwill be simulating. Three phase fault occurred at 1.2 sec and fault is cleared after 5 cycle at 1.3 sec. Fig12 shows the simulation results of active and reactive power of machine

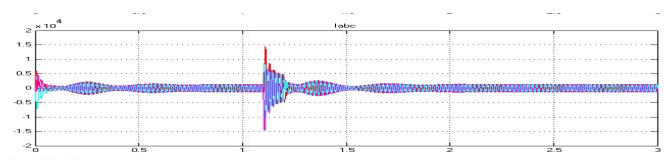


(a) with PI

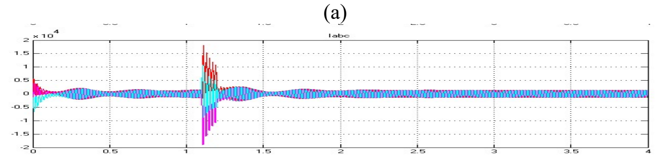


(b)with FLC

Fig10 Simulation Results of Voltage for Phase a, b ,cUsing (a) with PI (b)with FLC

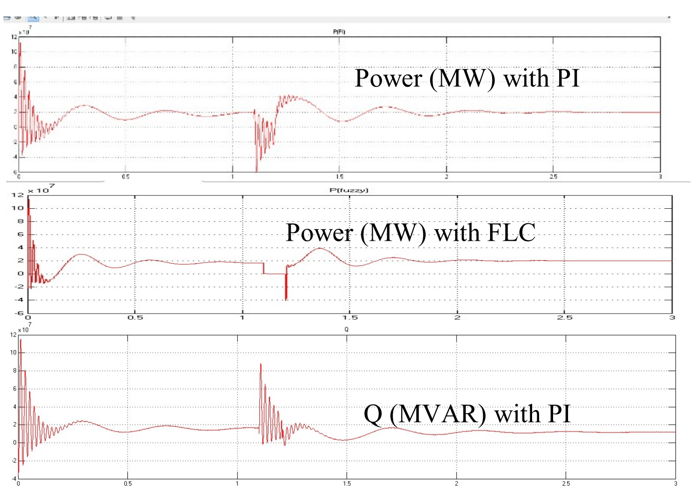


(a)



(b)

Figure 11Simulation Results of Stator Current for Phase a, b ,c Using (a)PI and (b) FLC



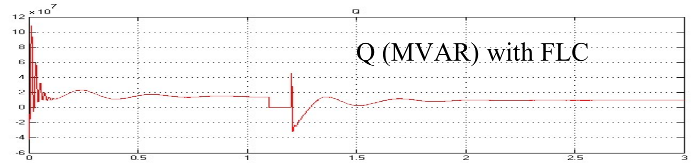


Fig 12 . Simulation Results of Active and Reactive Power of Machine Using PI andFLC

In the simulation model, fuzzy logic and PI controllers are employed for getting the stability condition. For both controllers, the inputs are error and error change rate. The output conditions of machine with excitation system using PI and fuzzy controllers for values of stator current ,voltage and active and reactive power are measured and the results are shown in Figure 10, Figure 11 and Figure 12 respectively. As shown in FiguresFigure 10, Figure 11 and Figure 12, it indicates that the generator system is stable under three phase fault condition. It does not lose synchronizing for voltage controller either with PI or FLC. It also shows that the settling time, oscillation and maximum overshoot of terminal voltage response for voltage controller with FLC are better than that for the voltage controller with PI. The reason for this is that the FLC wants to maintain the same dynamic characteristics in the generator at fault condition as in the reference model.

Control action results of rule editor can be calculated by using centroid method. In Rule5, if input 1 is zero and input 2 is zero then output is zero. In Rule 5, Input 1 = 0.00418 fuzzy weight is 0.71, Input 2= 0.0001 fuzzy weight is 0.9. so take $u(w_i) = 0.71$ $w_i = 0$ (value of center in zero membership) .

Area of membership grade,

$$u(w_i) = w(h - \frac{h^2}{2}) \qquad u(w_i) = 60(0.5 - \frac{0.5^2}{2}) = 22.5$$

So, Control action by using Centroid Method,

$$\text{Control Action} = \frac{\sum_{i=L}^{9} w_i u(w_i)}{\sum_{i=L}^{9} u(w_i)}$$

$$\text{Control Action} = \frac{(22.52 \times 30)}{22.52} = 30$$

Where,

L = number of output level

$u(w_i)$ = membership grade

w_i= amount of control action

h = height of membership function

w = Base width

Table V shows the testing of voltage control signal to control the gating pulse of thyristor for DC voltage by using centroid method of Fuzzy control and PI control method for stability condition.

$$\text{So, } V_{dc} = 1.35\ V_{ac}\ \text{Cos}\alpha = 1.35\times210\times\text{Cos } 30 = 240\ \text{V}$$

TABLE V

TESTING THE TERMINAL VOLTAGE FOR FAULT WITH CONTROLLERS

Type of fault node	Critical Fault clearing time	
	Fuzzy	PI
Three phase ground	1.5 sec	2 sec

V. CONCLUSIONS

To observe the performance of the FLC and PI controlled excitation system of machine, normal and fault operation conditions are performed. The simulation results are shown that the proposed controller is superior to conventional controller in robustness and in tracking precision for excitation control system of generator in Kun hydro-power plant. The simulation study indicates clearly the superior performance of FLC, because it is adaptive in nature. This study will be very helpful, to design a new controllers based on FLC. With use of FLC, it can reach high quality in control of nonlinear systems by seeing the simulation results.

The system operated with fuzzy logic controller achieves the desired value of active power at 1.5 seconds and 2 seconds with PI controller. This meant fuzzy logic controller achieves the settling time quickly.The performance of fuzzy logic controller is neithertoo fast, nor too slow, but moderate.This paper presents the fuzzy controller used in excitation system of synchronous generator used in Kun Chaung Hydropower Plant.

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REFERENCES

[1]. Hiyama T. *"Integratedstabilizing controller for power systems, Conference on Decision and control",* 1996.

[2]. Idzotic T. "Expanding stable operation region of the synchronous generator, Doctoral thesis, Faculty of electricalengineering and computing, University of Zagreb, 2004.

[3]. Kundur P. Power System Stability and Control, McGraw-Hill, 1993.

[4]. IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability", *IEEE Trans-actions on Power Systems*, Vol. 5, No. 2, May 2004, pp. 1387–1401.

[5]. Saadat H., Power System Analysis, McGraw-Hill Inc.Syst. 1999.

[6]. Paul M. Anderson, A. A. Fouad, *Power SystemControl and Stability*, IEEE Press, IEEE PowerSystem Engineering Series, 1994.

[7]. D. Sumina, "Fuzzy logic excitation control of synchronousgenerator", Master thesis, Faculty of electrical engineering andcomputing, 2005.

[8]. M.E.El-Hawary, "Electric Power Applications of Fuzzy Systems",*IEEE*, 1998.

[9]. Matti M.S., "Modelling and Simulation of a Static Excitation System of an Alternator Connected to a Network", Ph.D. Thesis, Mosul University 2007.

[10]. [R. C. Schaefer, "Application of static excitationsystems for rotating exciter replacement",IEEE Transaction on energy conversion 1997.

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