

# **Power System Transient Stability Analysis Based on Evolutionary Interval Type-2 Fuzzy Logic Controller and GA System**

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**ABSTRACT:** This work aims to develop a controller based on evolutionary interval type-2 fuzzy logic to simulate an automatic voltage regulator (AVR) in transient stability power system analysis. It was simulated a one machine control to check if the evolutionary interval type-2 fuzzy logic controller (EIT2FLC) implementation was possible. After which results were compared to the results obtained with the AVR itself. The traditional type-1 Fuzzy Logic Controller (FLC) using precise type-1 fuzzy sets cannot fully handle such uncertainties. A type-2 FLC using type-2 fuzzy sets can handle such uncertainties to produce a better performance. However, manually designing the type-2 Membership Functions (MFs) for an interval type-2 FLC is a difficult task. This paper will present Genetic Algorithm (GA) based architecture to evolve the type-2 MFs of interval type-2 FLCs used for transient stability power system analysis. The GA based system converges after a small number of iterations to interval type-2 MFs which gave very good performance. The control of synchronous generator terminal voltage and reactive power has been a disturbing problem to researchers and designers of power system engineers. This paper uses the evolutionary interval type-2 fuzzy logic scheme for automatic voltage regulation of synchronous generators and observes that it is superior to convectional AVR controllers because it can tune the controller parameters and remembers what it tuned before. The simulation results obtained using evolutionary interval type-2 fuzzy logic scheme during abnormal operation of power system network shows reduction in settling time, percentage overshoot and steady state error.

**KEYWORDS:** Interval Type-2 Fuzzy Logic Controller, Transient Stability Analysis, Genetic Algorithms, Automatic Voltage Regulator, One Synchronous Machine System, 18 bus bar system.

## **I.INTRODUCTION**

From the power system point of view, the excitation system must contribute for the effective voltage control and enhancement of the system stability. It must be able to respond quickly to a disturbance enhancing the transient stability and the small signal stability. Three principal control systems directly affect a synchronous generator: the boiler, governor, and exciter controls. Assuming that the generating unit has no losses. It is a reasonable assumption when total losses of turbine and generator are compared to total output. Under this assumption all power received, as steam must leave the generator terminals as electric power. The governor controls the steam power amount admitted to the turbine. The excitation system controls the generated EMF of the generator and therefore controls not only the output voltage but the power factor and current magnitude as well. In many present-day systems the exciter is a dc generator driven by either the steam turbine (on the same shaft as the generator) or an induction motor. An increasing number are solid-state systems consisting of some form of rectifier or thyristor system supplied from the ac bus from an alternator exciter. The voltage regulator is the intelligence of the system and controls the output of the exciter so that the generated voltage and reactive power change in the desired way. In most modern systems the automatic voltage regulator (AVR) is a controller that senses the generator output voltage (and sometimes the current) then initiates corrective action by changing the exciter control in the desired direction. The speed of the AVR is of great interest in studying stability. Because of the high inductance in the generator field winding, it is difficult to make rapid changes in field current. This introduces a considerable lag in the control function and is one of the major obstacles to be overcome

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in designing a regulating system. The purpose of this work is the development of a evolutionary interval type-2 fuzzy logic controller software (EIT2FLC software) to simulate the automatic voltage regulator (AVR) behavior.

The evolutionary interval type-2 fuzzy logic is credited with being an adequate methodology for designing evolutionary interval type-2 fuzzy logic controller (EIT2FLC) that are able to deliver a satisfactory performance in applications where the inherent uncertainty makes it difficult to achieve good results using traditional methods. As a result the evolutionary interval type-2 fuzzy logic controller (EIT2FLC) has become a popular approach to power system transient stability control in recent years. There are many sources of uncertainty facing the evolutionary interval type-2 fuzzy logic controller (EIT2FLC) for a power system transient stability in changing and dynamic unstructured environments; we list some of them as follows:

- a. Uncertainties in inputs to the EIT2FLC which translate to uncertainties in the antecedent Membership Functions (MFs) as the sensor measurements are typically noisy and are affected by the conditions of observation (i.e. their characteristics are changed by the environmental conditions such as wind, sunshine, humidity, rain, etc.).
- b. Uncertainties in control outputs which translate to uncertainties in the consequent MFs of the EIT2FLC. Such uncertainties can result from the change of the actuators characteristics which can be due to wear, tear, environmental changes, etc.
- c. Linguistic uncertainties as the meaning of words that are used in the antecedent and consequent linguistic labels can be uncertain - words mean different things to different people. In addition, experts do not always agree and they often provide different consequents for the same antecedents. A survey of experts will usually lead to a histogram of possibilities for the consequent of a rule; this histogram represents the uncertainty about the consequent of a rule.
- d. Uncertainties associated with the use of noisy training data that could be used to learn, tune or optimize the EIT2FLC.

Recent work had proposed the use of neural based systems to learn the type-2 FLC parameters. However, these approaches require existing data to optimize the type-2 FLC. Thus, they are not suitable for applications where there is no or not sufficient data available to represent the various situations faced by the EIT2FLC controller. Genetic Algorithms (GAs) do not require a priori knowledge such as a model or data but perform a search through the solution space based on natural selection, using a specified fitness function. We did not evolve the interval type-2 FLC rule base as it will remain the same as the interval type-1 FLC rule base. However, the FLC antecedents and consequents will be represented by interval type-2 MFs rather than type-1 MFs.

## II.RELATED WORK

The reliability of a system can be determined on the basis of tests or the acquisition of operational data. However, due to the uncertainty and inaccuracy of this data, the estimation of precise values of probabilities is very difficult in many systems (e.g. power system, electrical machine, hardware etc., Hammer (2001), El-Hawary (2000)).

The basis for this approach is constituted by the fundamental works on fuzzy set theory of Zadeh (1978), Dubois and Prade (1980), Zimmerman (1986) and other. The theory of fuzzy reliability was proposed and development by several authors, Cai, Wen and Zhang (1991, 1993); Cai (1996); Chen, Mon (1993); Hammer (2001); El-Hawary (2000), Onisawa, Kacprzyk (1995); Utkin, Gurov (1995). The recent collection of papers by Onisawa and Kacprzyk (1995), gave 654 I.M. ALIEV, Z. KARA many different approach for fuzzy reliability. According to Cai, Wen and Zhang (1991, 1993); Cai (1996) various form of fuzzy reliability theories, including profust reliability theory Dobois, Prade (1980); Cai, Wen and Zhang (1993); Cai (1996); Chen, Mon (1993); Hammer (2001); El-Hawary (2000); Utkin, Gurov(1995), posbist reliability theory, Cai, Wen and Zhang (1991, 1993) and posfust reliability theory, can be considered by taking new assumptions, such as the possibility assumption, or the fuzzy state assumption, in place of the probability assumption or the binary state assumption. Chen [14] analyzed the fuzzy system reliability using vague set theory. The values of the membership and non-membership of an element, in a vague set, are represented by a real number in  $[0, 1]$ . Cai, Wen and Zhang (1993) presented a fuzzy set based approach to failure rate and reliability analysis, where profust failure rate is defined in the context of statistics. El-Nawary (2000) presented models for fuzzy power system reliability analysis, where the failure rate of a system is represented by a triangular fuzzy number.

The work of Jerry M.Mendel and Feilong Liu (2007) on Super-Exponential Convergence of the Karnik–Mendel Algorithms for Computing the Centroid of an Interval Type-2 Fuzzy Set is a well-recognized work in the field. Design of Interval Type-2 Fuzzy Logic Based Power System Stabilizer (Imam Robandi, and Bedy Kharisma 2008) has sufficient materials as a reference work. Juan R. Castro and Oscar Castillo (2007) worked on Interval Type-2 Fuzzy Logic for Intelligent Control Applications. Also Jerry M. Mendel and Robert I.Bob John (2002) presented, how Type-2

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Fuzzy Sets Made Simple. Mamdani (1974) developed the method to apply the fuzzy algorithm for simple control of dynamic plant. Qureshi (2003) published his work on power system reliability problems, control problems and protection problems. Qureshi (2004) in his Ph.D. thesis took the project work of Reliability of nuclear plants using fuzzy logic transformation. R.R.Yager(2000) reported a valuable information on fuzzy subsets of type-2 in decision. N.N.Karnik and J.M. Mendel worked on interval type-2 fuzzy logic systems and reported his findings in IEEE Transactions, fuzzy systems.

### III. TRANSIENT STABILITY ANALYSIS

The first demand of electrical system reliability is to keep the synchronous generators working in parallel and with adequate capacity to satisfy the load demand. If at any time, a generator loses synchronism with the rest of the system, significant voltage and current fluctuation can occur and transmission lines can be automatically removed from the system by their relays deeply affecting the system configuration. The second demand is maintaining power system integrity. The high voltage transmission system connects the generation sources to the load centers. Interruption of these nets can obstruct the power flow to the load. This usually requires the power system topology study, once almost all electrical systems are connected to each other. When a power system under normal load condition suffers a disturbance there is synchronous machine voltage angles rearrangement. If at each disturbance occurrence an unbalance is created between the system generation and load, a new operation point will be established and consequently there will be voltage angles adjustments. The system adjustment to its new operation condition is called "transient period" and the system behavior during this period is called "dynamic performance".

As a primitive definition, it can be said that the system oscillatory response during the transient period, short after a disturbance, is damped and the system goes in a definite time to a new operating condition, so the system is stable. This means that the oscillations are damped, that the system has inherent forces which tend to reduce the oscillations. The instability in a power system can be shown in different ways, according to its configuration and its mode of operation, but it can also be observed without synchronism loss.

### IV. AUTOMATIC VOLTAGE REGULATOR (AVR)

Automatic devices control generators voltages output and frequency, in order to keep them constant according to pre-established values. These automatic devices are:

1. Automatic Voltage Regulator (AVR)
2. Governor

However any governor due to its action loop, is slower than the AVR This is associated mainly to its final action in the turbine. The main objective of the automatic voltage regulator AVR is to control the terminal voltage by adjusting the generators exciter voltage. The AVR must keep track of the generator terminal voltage all the time and under any load condition, working in order to keep the voltage within pre-established limits. Based on this, it can be said that the AVR also controls the reactive power generated and the power factor of the machine once these variables are related to the generator excitation level. The AVR quality influences the voltage level during steady state operation, and also reduces the voltage oscillations during transient periods, affecting the overall system stability. Fig.1 illustrates the AVR model used in the program developed.

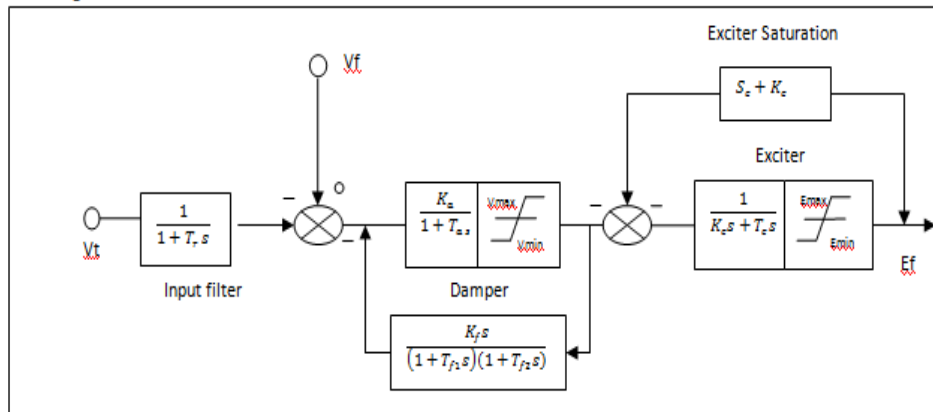


Fig.1 AVR Model

**V.THE SYNCHRONOUS GENERATOR MODEL (PLANT)**

Fig.2 below shows a functional block diagram of synchronous generator connected to bus bar through a step-up transformer. It also indicates the terminal voltage/reactive power control loop using automatic voltage regulator (AVR) and the load frequency and real power control (LFC) loop using the governor. During faulted condition, a single machine infinite bus power system shown in Fig. 4 is used.

Fig.3 above is used to study the oscillation of the synchronous generator terminal voltage under faulted condition. It has been shown that the dynamic response of (SG) in a practical power system when a fault occurs is very complicated including much nonlinearity such as the magnetic saturation. However, the classical third order dynamic generator model has been commonly used for designing the excitation controller. This third order model can be written as follows Mechanical equations

$$\delta = \omega$$

$$\omega = -\frac{D}{2H}\omega + \frac{\omega_0}{2H}(P_m - P_e) \tag{1}$$

Generator Electrical dynamic

$$E'_q = \frac{1}{T'_{do}}(E_f - E_q)$$

Electrical equations

$$E_q = \frac{x_{ds}}{x_{do}}E - \frac{x_d - x'_d}{x_{do}}V_s \cos\delta \tag{2}$$

$$P_e = \frac{V_s}{x_{ds}}E_q \sin\delta \tag{3}$$

$$I_q = \frac{V_s}{x_{ds}} \sin\delta = \frac{P_e}{x_{ds} I_f} \tag{4}$$

$$Q_e = \frac{V_s}{x_{ds}}E_q \cos\delta - \frac{V_s^2}{x_{ds}} \tag{5}$$

$$E_q = x_{ad} I_f \tag{6}$$

$$E_f = k_c U_f \tag{7}$$

$$V_t = \frac{1}{x_{ds}} [x_s^2 E_q^2 + V_s^2 x_d^2 + 2x_c x_d x_{ds} P_e \cos\delta]^{1/2} \tag{8}$$

$$x_{ds} = x_d + x_T + x_L \quad x'_{ds} = x'_d + x_T + x_L \tag{9}$$

$$X_s = X_T + X_L$$

The definition of the parameters are given below

$\delta(t)$  power angle of the generator (in radian)

$\omega(t)$  relative speed (in rad/s)

$P_m$  mechanical input power (in p.u.)

$P_e$  active power delivered to bus (in p.u.)

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$E_q'$  transient EMF in the quadrature axis (in p.u.)

$V_t$  terminal voltage of the generator (in p.u.)

By linearizing the above equations about the operating point, we have the state equation as

$$\dot{x} = A_x + B_u$$

A Fuzzy Model Reference Learning Controller for Synchronous Generator Terminal Voltage Control

$$y = cx \tag{10}$$

Where state variables  $x$  is defined as

$$x = (\Delta\delta, \Delta\omega, \Delta E_q') \tag{11}$$

and the control input and the output.

The matrices A, B, and C are given by

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{w_o v_s}{2Hx'ds} I_q \cos\delta & \frac{-D}{2H} & \frac{-w_o v_s}{2Hx'ds} \\ \frac{-E'_q - x'd'd}{V_t} \left( \frac{-x'd}{x'd_s} \right) v_s \sin\delta & 0 & \frac{-1}{T'd_o} \left( \frac{x_d - x'd}{T'd_o} \frac{1}{T'd_s} \right) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{kc}{T'd_o} \end{bmatrix} \quad C = \left[ \frac{E'_q - x'd'd}{V_t} \left( \frac{-x'd}{x'd_s} \right) v_s \sin\delta + \frac{x'd I_q}{V_t} \left( \frac{V_s}{x'd_s} \right) \cos\delta \quad 0 \quad \frac{E'_q - x'd'd}{V_t} \left( 1 - \frac{x'd}{x'd_s} \right) \right]$$

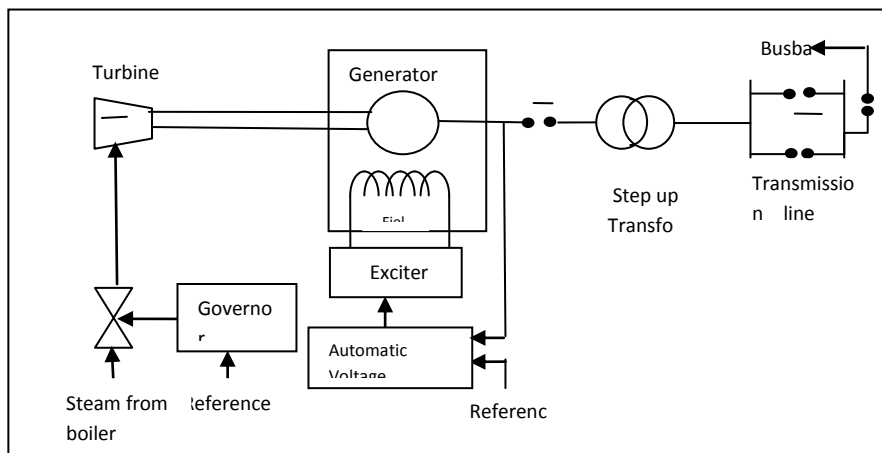


Fig. 2: Power system network showing AVR and LFC loops

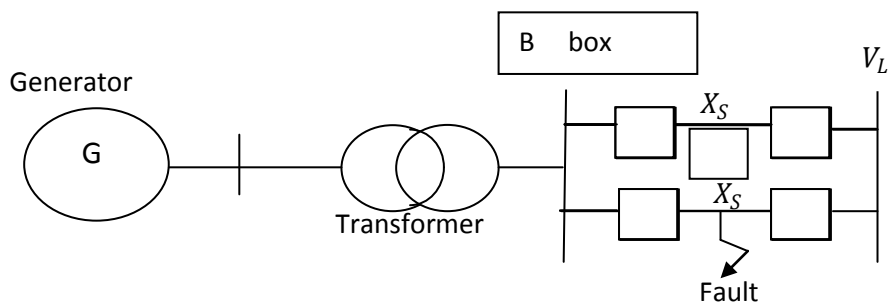


Fig.3 A single machine infinite bus power system

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## VI. INTERVAL TYPE-2 FUZZY LOGIC CONTROLLERS

The interval type-2 FLC uses interval type-2 fuzzy sets (such as those shown in Fig. 4(a) to represent the inputs and/or outputs of the FLC. In the interval type-2 fuzzy sets all the third dimension values equal to one. The use of interval type-2 FLC helps to simplify the computation (as opposed to the general type-2 FLC which is computationally intensive) which will enable the design of an interval type-2 fuzzy logic controller (IT2FLC) that operates in real time. The structure of an interval type-2 FLC is depicted in Fig.4(b), it consists of a Fuzzifier, Inference Engine, Rule Base, Type-Reducer and a Defuzzifier.

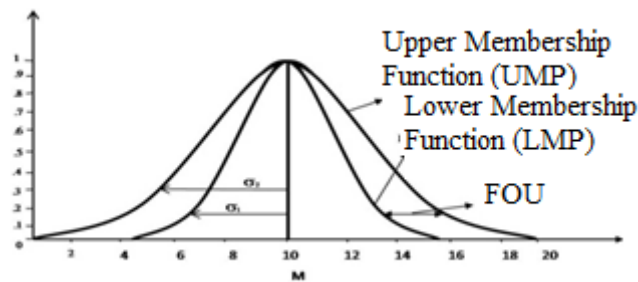


Fig.4 (a) An interval type-2 fuzzy set. (b) Structure of the interval type-2 FLC.

The interval type-2 FLC works as follows: the crisp inputs from the input sensors are first fuzzified into input type-2 fuzzy sets; singleton fuzzification is usually used in interval type-2 FLC applications due to its simplicity and suitability for embedded processors and real time applications. The input type-2 fuzzy sets then activate the inference engine and the rule base to produce output type-2 fuzzy sets. The type-2 FLC rules will remain the same as in a type-1 FLC but the antecedents and/or the consequents will be represented by interval type-2 fuzzy sets. The inference engine combines the fired rules and gives a mapping from input type-2 fuzzy sets to output type-2 fuzzy sets. The type-2 fuzzy outputs of the inference engine are then processed by the type-reducer which combines the output sets and performs a centroid calculation which leads to type-1 fuzzy sets called the type-reduced sets. There are different types of type-reduction methods. In this paper we will be using the Center of Sets type-reduction as it has reasonable computational complexity that lies between the computationally expensive centroid type-reduction and the simple height and modified height type-reductions which have problems when only one rule fires. After the type-reduction process, the type-reduced sets are defuzzified (by taking the average of the type-reduced set) to obtain crisp outputs that are sent to the actuators.

The synchronous generator which represents the plant has an input  $u(kT)$  from the fuzzy controller and terminal voltage output  $y(kT)$ . The input to the fuzzy controller is the error  $e(kT) = r(kT) - y(kT)$  and change in error  $c(kT) = \frac{e(kT) - e(kT-T)}{T}$  where  $r(kT)$  is a reference input. Membership functions for Interval type-2 Fuzzy logic controller inputs  $e(kT)$  &  $c(kT)$  are shown in Fig.5 a,b & c.

A fuzzy rules were employed as indicated below in table 1 with triangular membership functions.

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Table 1: Decision table

Change in Voltage $c(kT)$											
VOLTAGE ERROR $e(kT)$	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL	PV
NV	NV	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR
NL	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR	PS
NB	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR	PM
NM	NV	NV	NV	NL	NB	NM	NS	ZR	PS	PM	PB
NS	NV	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL
ZR	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL	PV
PS	NL	NL	NM	NS	ZR	PS	PM	PB	PL	PV	PV
PM	NL	NM	NS	ZR	PS	PM	PB	PL	PV	PV	PV
PB	NM	NS	ZR	PS	PM	PB	PL	PV	PV	PV	PV
PL	NS	ZR	PS	PM	PB	PL	PV	PV	PV	PV	PV
PV	ZR	PS	PM	PB	PL	PV	PV	PV	PV	PV	PV

In the table above, NV, NL, NB, NM, NS, ZR, PS, PM, PB, PL, PV stands for negative very large, negative large, negative big, negative medium, negative small, zero, positive small, positive medium, positive big, positive large, and positive very large

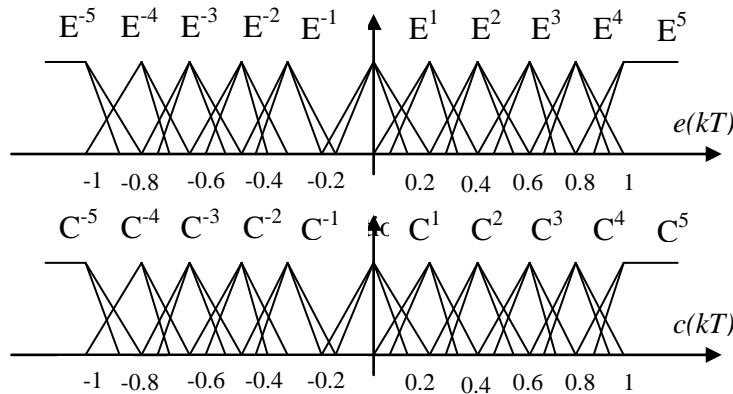


Fig. 5b: Membership functions for input change in error  $c(kT)$

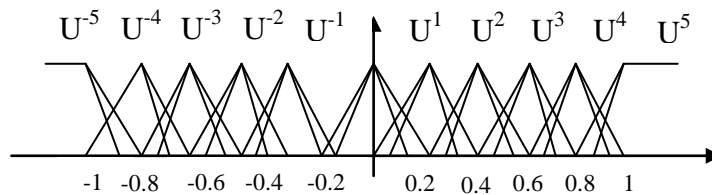


Fig. 5c: Membership functions for output  $u(kT)$

### VII. THE GA BASED EVOLUTIONARY SYSTEM

The GA chromosome includes the interval type-2 MFs parameters for both the inputs and outputs of the interval type-2 FLC. We have used the interval type-2 fuzzy set which is described by a triangular MF. The GA based system uses real value encoding to encode each gene in the chromosome. Each GA population consists of 30

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chromosomes. The GA uses an elitist selection strategy. The GA based system procedure can be summarized as follows:

**Step 1:** 30 chromosomes are generated randomly while taking into account the grammatical correctness of the chromosome). The “Chromosome Counter” is set to 1– the first chromosome. The “Generation Counter” is set to 1– the first generation.

**Step 2:** Interval Type-2 FLC is constructed using the chromosome “Chromosome Counter” and is executed on the transient stability control for 400 iterations to provide a fitness for the chromosome. After a controller has been executed for 400 iterations, a fixed controller takes over control and returns to a correct position.

**Step 3:** If “Chromosome Counter” < 30, increment “Chromosome Counter” by 1 and go to Step 2, otherwise proceed to Step 4.

**Step 4:** The best individual-so-far chromosome is preserved separately.

**Step 5:** If “Generation Counter” = 1 then store current population, copy it to a new population  $P$  and proceed to Step 6. Else, select 30 best chromosomes from population “Generation Counter” and population “Generation Counter”- 1 and create a new population  $P$ .

**Step 6:** Use roulette wheel selection on population  $P$  to populate the breeding pool.

**Step 7:** Crossover is applied to chromosomes in the breeding pool and “chromosome consistency” is checked. (\*)

**Step 8:** “Generation Counter” is incremented. If “Generation Counter” < the number of maximum generations or if the desired performance is not achieved, reset “Chromosome Counter” to 1 and go to Step 2, else go to Step 9.

**Step 9:** Chromosome with best fitness is kept and solution has been achieved; END.

(\*)The crossover operator employed computes the arithmetic average between two genes. It is used with a probability of 100% to force the GA to explore the solution space in between the previously discovered, parental solutions. With chromosome consistency we refer to the correctness of the chromosome’s genes in relation to their function in the IT2FLC. While the chromosome’s genes are rearranged to achieve this, we eliminate a chromosome from the population if it violates these criteria. The violating chromosome is replaced by a new, randomized but consistent chromosome thus introducing new genetic material into the population at the same time.

In these experiments, the interval type-2 FLC has two sonar sensors as inputs which are represented by two Triangular interval type-2 MFs (error  $e(kT)$  & change in error  $c(kT)$ ). Therefore each input interval type-2 MF is represented by three parameters (one singleton apex and two extremities). Thus, 12 genes are used to represent the interval type-2 FLC inputs (The IT2FLC has 2 input sensors, each represented by two interval type-2 MFs and each MF is represented by 3 parameters). The interval type-2 FLC has 1 output  $u(kT)$ . The IT2FLC output is represented by a triangular interval type-2 MFs. Hence as shown in Fig. 6(a), the GA chromosome for this type-2 FLC comprises 12(inputs) + 4(outputs) = 16 genes.

Through various experiments, it was found that the GA based system evolves to good interval type-2 MFs after about only 14 generations. An example of the evolutionary progress is shown in Fig. 6(b) which shows the performance of the best individual found so far against the number of generations.

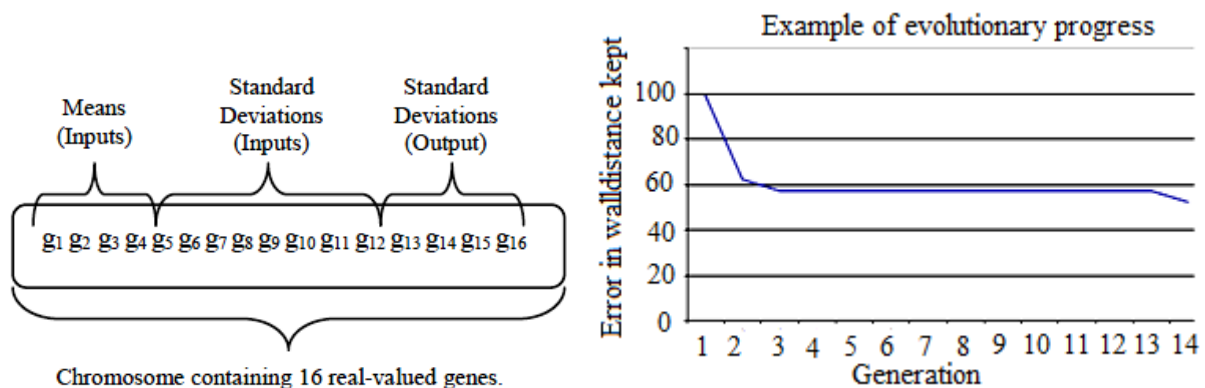


Fig.6. (a) Chromosome Structure, (b) Progress of best individual.



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## VIII.GENETIC ALGORITHM-BASED PARAMETER LEARNING

- GAs is optimization stochastic technique mimicking the natural selection, which consists of three operations, namely, reproduction, crossover, and mutation. The most general considerations about GA can be stated as follows:
- i) The searching procedure of the GA starts from multiple initial states simultaneously and proceeds in all of the parameter subspaces simultaneously.
  - ii) GA requires almost no prior knowledge of the concerned system, which enables it to deal with the completely unknown systems that other optimization methods may fail.
  - iii) GA cannot evaluate the performance of a system properly at one step. For this reason, it can generally not be used as an on-line optimization strategy and is more suitable for fuzzy modeling.

In practice, training data can be obtained by experimentation or by the establishment of an ideal model. Fig.7 shows the training process for interval type-2 fuzzy controller (IT2FLC) involved in the self-tuning system.

The following two closed-loop performance indices have been examined; the Integrated Absolute Error (IAE) and the integrated time multiplied by the absolute error (ITAE). They are defined as follows:

$$J_{IAE} = IAE = \int_0^T |e(t)| dt = \sum_{k=0}^M |r(k) - y(k)| \Delta t$$

$$J_{ITAE} = IATE = \int_0^T t |e(t)| dt = \sum_{k=0}^M k |r(k) - y(k)| \Delta t^2$$

Where  $e=r(kT) - y(kT)$  is the closed loop error,  $r(kT)$  is the reference input,  $y(kT)$  terminal voltage output and  $\Delta t$  is the time step. M is the number of training samples. Because GA endeavors to maximize the fitness function, the fitness function of each gene is calculated as follows:

$$F = \frac{1}{1+J} \tag{12}$$

Where J is the performance index and 1 is introduced at the denominator to prevent the fitness function from becoming infinitely large.

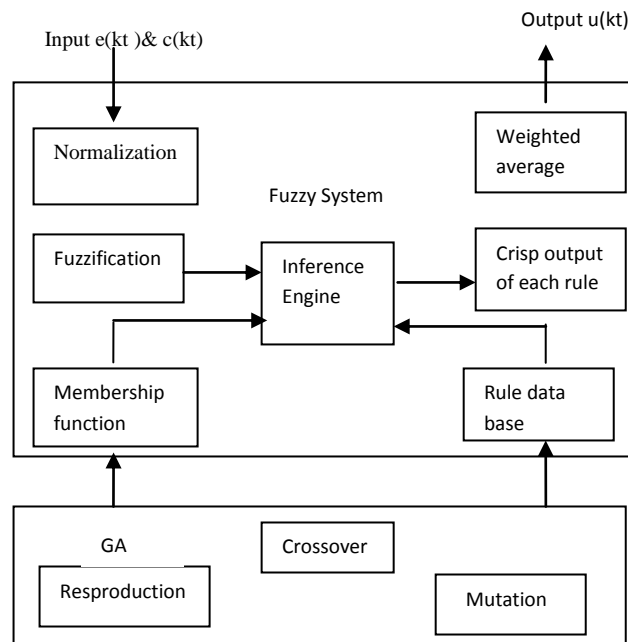


Fig.7 Genetic learning of the data-base of each module.

Coding of the parameters to be adjusted can be stated as follows:

$$c_{N1}, c_{N2}, \dots, \sigma_{N1}, \sigma_{N2}, \dots, u_{11}, u_{12}, \dots \tag{13}$$

If identical input membership is chosen, the total number of parameters is reduced to 121 i.e. parameters of the input membership functions  $c_{N1}, \sigma_{N1}, c_{Z1}, \sigma_{Z1}, c_{P1}, \sigma_{P1}$  for  $e(kT)$ ,  $c_{N2}, \sigma_{N2}, c_{Z2}, \sigma_{Z2}, c_{P2}, \sigma_{P2}$  for  $c(kT)$ ,

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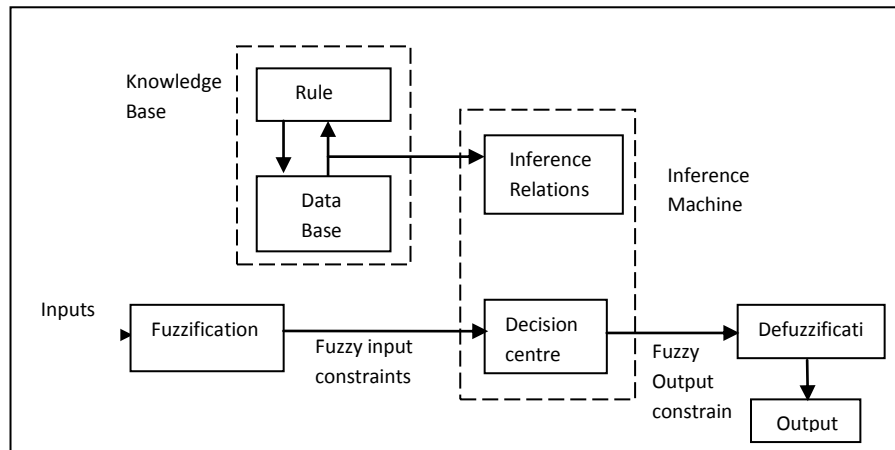
Where a certain number of each binary bits stand for each element.

## VIII.SIMULATION RESULTS

The graphs shown in the subsection below will provide the comparative performance results between the conventional control and the evolutionary interval type-2 fuzzy one. Two different situations were analyzed; the first analysis is a one synchronous machine excitation control done with the Matlab Software, the second one was done using a transient stability program called "Transufu" applied to 18 bus bar IEEE system.

Evolutionary Interval type-2 Fuzzy Logic Controller Results applied to a One Synchronous Machine System

The block diagram shown in Fig.8 shows a synchronous machine for which output the voltage is controlled by an AVR applied to its excitation system, in the MATLAB simulation. All data were taken from reference.



Next step is to replace the AVR device by an interval type-2 fuzzy logic controller in order to check its efficiency in the synchronous machine excitation voltage control. The rule-base used by EIT2FLC controller to simulate an AVR in the MATLAB program is shown in Table 2. The fuzzy controller ran with the input and output normalized universe [-1,1]. The seven linguistic variables used were generator voltage error  $e(kT)$  and generator voltage error variation  $c(kT)$ , which are: LN - large negative, MN - medium negative, SN - small negative, Z – zero, SP - small positive, MP - medium positive, LP - large positive

Table 2: The output rule base used by EIT2FLC in MATLAB program simulation.

### ERROR VARIATIONS

	MN	MN	SN	SN	Z
E	MN	SN	SN	SN	SP
R	SN	SN	Z	SP	SP
R	SN	Z	SP	SP	MP
O	Z	SP	SP	MP	MP
R	SP	SP	MP	MP	LP
	SP	MP	MP	LP	LP

Fig.9,10 & 11 show the terminal voltage, load angle and electrical torque of a synchronous machine connected to an infinite bus bar by a transmission line.

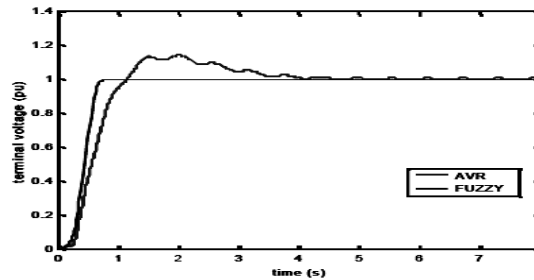


Fig.9 One machine analysis (terminal voltage Vt.) using EIT2FLC

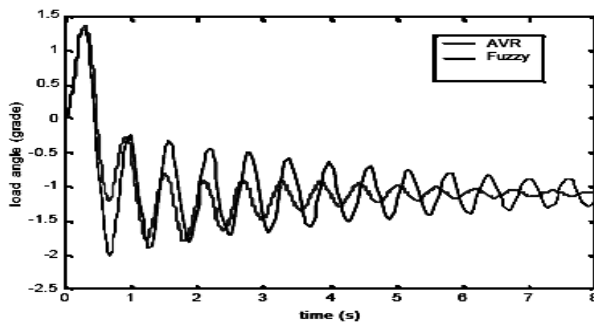


Fig.10 One machine analysis (load angle) using EIT2FLC

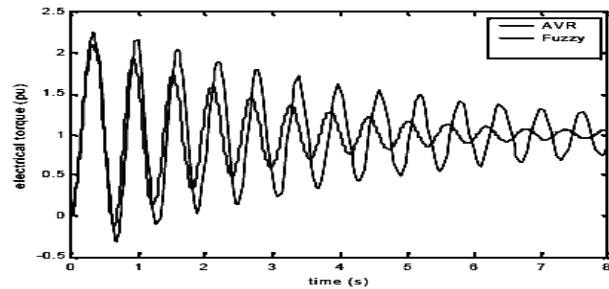


Fig.11 One machine analysis (electrical torque) using EIT2FLC

Following test cases are simulated below for Conventional Automatic Voltage Regulator (CAVR),  
A step input is applied to a normal CAVR with amplifier transfer function given by

$$\frac{KA}{1 + \tau AS} \tag{14}$$

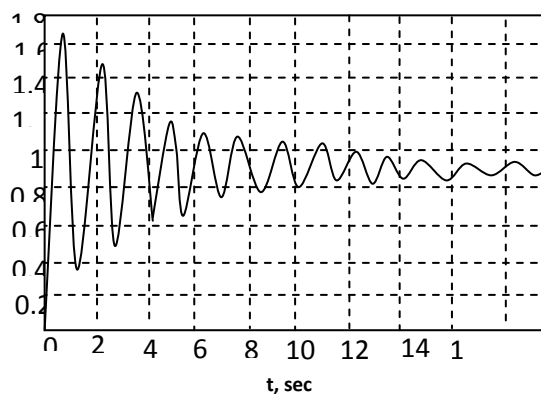
$$KA = 10, \tau G = 0.1, KE = 1, \tau E = 0.4$$

$$KG = 1, \tau G = 1, KR = 1, \tau R = 0.05$$

Below is the step response in Fig.12.

A stabilizer is connected between the exciter output and the input summer with a step input signal. The parameters above remained the same but the stabilizer has transfer function given by

$$\frac{s}{0.04s + 1}$$



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The terminal voltage step response of CAVR with stabilizer is shown in Fig.13.

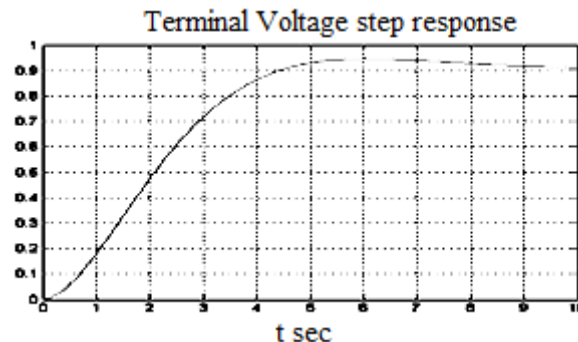


Fig.13 Terminal voltage step response of CAVR with stabilizer

## IX.CONCLUSION

This paper reviewed the various techniques employed in synchronous generator terminal voltage control. Such techniques are the CAVR, MV, GMV, PP and ordinary fuzzy controller. It identified some of the limitations of each of them, such as the steady state error presented by ordinary fuzzy controller. The application of EIT2FLC controller is the main focus of this paper. The simulation results for disturbed terminal voltage values and transmission lines faults shows a very sharp reduction in settling time, over shoot, rise time and zero steady state error. It could be observed in study using MATLAB simulation, an excellent response of the EIT2FLC controller and with no oscillation, while the AVR response presented a ripple in both studies and some oscillations before reaching the steady state operation point. It is shown that an excellent performance of the EIT2FLC control over the conventional AVR one for the excitation control of synchronous machines could be achieved. It has been shown that the genetically evolved interval type-2 FLCs can lead to superior performance in comparison to interval type-1 FLCs and the manually designed interval type-2 FLCs. The results indicate that the genetic evolution of interval type-2 MFs can provide valid and high-performance interval type-2 FLCs without relying on any a priori knowledge such as logged data or a previously existing model, making it suitable for control problems where no such a priori data is available such as in transient stability control in power system. This work will be a step towards overcoming the problem of manually specifying pseudo-optimal MFs for interval type-2 FLCs, which to date is one of the main obstacles when designing interval type-2 FLCs.

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