World Applied Sciences Journal 7 (11): 1428-1438, 2009
ISSN 1818-4952

Comparison of Artificial Intelligence Strategies for STATCOM Supplementary Controller Design

Shoorangiz S.S. Farahani, Reza Hemati and Mehdi Nikzad

Department of Electrical Engineering, Islamic Azad University, Islamshahr Branch, Tehran, Iran

Abstract: This paper presents the application of STATCOM to enhance damping of Low Frequency Oscillations at a single-machine infinite-bus power system installed with a STATCOM as cast study. Since STATCOM has been considered to damping of Low Frequency Oscillations, therefore the supplementary damping controller based STATCOM like power system stabilizer is designed to reach defined purpose. Artificial intelligence methods like Fuzzy Logic schemes and Genetic Algorithms optimization are considered to design STATCOM supplementary damping controller. To show effectiveness and also comparing these two methods in damping of power system oscillations based STATCOM, the proposed methods are applied and simulated. Several linear time-domain simulation tests visibly show the validity of proposed methods in damping of power system oscillations. Also Simulation results emphasis on the better performance of Fuzzy method in compare with GA method. Simulations are carried out in MATLAB.

Key words: Static synchronous compensator . damping power system oscillations . fuzzy logic . genetic algorithms . flexible AC transmission systems

INTRODUCTION

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. FACTS devices have been shown to be effective in controlling power flow and damping power system oscillations. In recent years, new types of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems [1]. The static synchronous compensator (STATCOM) is one of the most important FACTS devices and it is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. The STATCOM is one of the important 'FACTS' devices and can be used for dynamic compensation of power systems to provide voltage support and stability improvement [2-10]. In [11] a unified Phillips-Heffron model [I2] of power systems installed with a STATCOM is established. STATCOM has developed from a switch mode voltage-source converter configuration with an energy-storage device (DC capacitor). Also, the STATCOM can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations. Low frequency oscillations (LFO) in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit. These oscillations need to be controlled to maintain system stability. In past decays power system stabilizer or PSS was applied for damping power system oscillations. Recently new power system controllers like as FACTS devices are presented as power system stabilizer. Many in the past have presented lead-Lag type UPFC damping controllers [13]. They are designed for a specific operating condition using linearized models. More advanced control schemes such as self-tuning control [14], Particle-Swarm method [15] and fuzzy logic control [16,17] offer better dynamic performances than fixed parameter controllers. Fuzzy control design is attractive because it does not require a mathematical model of the system under study and it can cover a wide range of operating conditions and is simple to implement.

The objective of this paper is to investigate the ability of artificial intelligence methods such as Genetic Algorithms (GA) and Fuzzy Logic methods to STATCOM supplementary damping controller design. A Sigel machine infinite bus (SMIB) power system installed with a STATCOM has been considered as test system. In GA case, classical damping controller like PSS is considered and an optimal control scheme based Genetic Algorithms method is used for tuning the parameters of this controller. In Fuzzy logic case, a STATCOM damping controller design using a fuzzy

Corresponding Author: Mehdi Nikzad, Department of Electrical Engineering, Islamic Azad University, Islamshahr Branch, P.O. Box: 33135-369, Tehran, Iran

logic scheme based on the Mamdani inference engine using the center of Gravity method to find the controller output is presented here. The proposed controllers are simulated in a Sigel Machine Infinite Bus (SMIB) power system installed with a STATCOM which has been considered as case study. The advantages of the proposed methods are their feasibility and simplicity. To show effectiveness of the proposed methods and also comparing the performance of these two methods, several load conditions like nominal operating condition and heavy operating condition are considered. Simulation results show the validity of proposed methods in LFO damping but the Fuzzy controller guarantee the better performance than GA controller for various load conditions.

SYSTEM UNDER STUDY

Figure 1 shows a Single Machine Infinite Bus (SMIB) power system with STATCOM installed. The static excitation system, model type IEEE-ST1A, has been considered. The STATCOM is assumed to be based on pulse width modulation (PWM) converters.

DYNAMIC MODEL OF THE SYSTEM

Non-linear dynamic model: A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformer, transmission line and shunt converter transformer) and the transients of the transmission lines and transformer of the STATCOM. The nonlinear dynamic model is given as below (1) [11].

$$\begin{cases} \dot{\omega} = \left(P_m - P_e - D\omega\right)/M \\ \dot{d} = \omega_0\left(\omega - 1\right) \\ \dot{E}'_q = \left(-E_q + E_{fd}\right)/T'_{do} \\ \dot{E}_{fd} = \left(-E_{fd} + K_a\left(V_{ref} - V_t\right)\right)/T_a \\ \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin\left(d_E\right)I_{Ed} + \cos\left(d_E\right)I_{Eq}\right) \end{cases} \quad (1)$$

Linear dynamic model: A linear dynamic model is obtained by linearising the non-linear model around nominal operating condition. The linearised model is given as (2).

$$\begin{cases} \Delta\dot{d} = w_0\Delta w \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}_{fd} = -\left(1/T_A\right)\Delta E_{fd} - \left(K_A/T_A\right)\Delta V_t \\ \Delta\dot{v}_{dc} = K_7\Delta d + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + K_{cde}\Delta d_E \end{cases} \quad (2)$$

Where

$$\Delta P_e = K_1\Delta d + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{pdE}\Delta d_E$$
$$\Delta E_q = K_4\Delta d + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{qdE}\Delta d_E$$
$$\Delta V_t = K_5\Delta d + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + K_{vdE}\Delta d_E$$

Figure 2 shows the transfer function model of the system including STATCOM. The model has constant parameters which are denoted by K_{ij}. These constant parameters are function of the system parameters and the initial operating condition. The control vector U in Fig. 2 is defined as (3).

$$U = [\Delta m_E \quad \Delta\delta_E]^T \quad (3)$$

Where; Δm_E: Deviation in pulse width modulation index m_E of shunt inverter. By controlling m_E, the output voltage of the shunt converter is controlled.

$\Delta\delta_E$: Deviation in phase angle of the shunt inverter voltage. By controlling δ_E, exchanging active power between the STATCOM and the power system is controlled.

It may be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig. 2 are the row vectors and defined as below:

$$K_{pu} = [K_{pe} \quad K_{pde}]; K_{qu} = [K_{qe} \quad K_{qde}];$$
$$K_{vu} = [K_{ve} \quad K_{vde}]; K_{cu} = [K_{ce} \quad K_{cde}]$$

Dynamic model in state-space form: The dynamic model of the system in state-space form is obtained as (4).

$$\begin{bmatrix} \Delta\dot{d} \\ \Delta\dot{w} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\dfrac{K_1}{M} & 0 & -\dfrac{K_2}{M} & 0 & -\dfrac{K_{pd}}{M} \\ -\dfrac{K_4}{T'_{do}} & 0 & -\dfrac{K_3}{T'_{do}} & \dfrac{1}{T'_{do}} & -\dfrac{K_{qd}}{T'_{do}} \\ -\dfrac{K_AK_5}{T_A} & 0 & -\dfrac{K_AK_6}{T_A} & -\dfrac{1}{T_A} & -\dfrac{K_AK_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta w \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\dfrac{K_{pe}}{M} & -\dfrac{K_{p\delta e}}{M} \\ -\dfrac{K_{qe}}{T'_{do}} & -\dfrac{K_{q\delta e}}{T'_{do}} \\ -\dfrac{K_AK_{ve}}{T_A} & -\dfrac{K_AK_{v\delta e}}{T_A} \\ Kce & K_{c\delta e} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \end{bmatrix} \quad (4)$$

The typical values of system parameters for nominal operating condition are given in appendix.

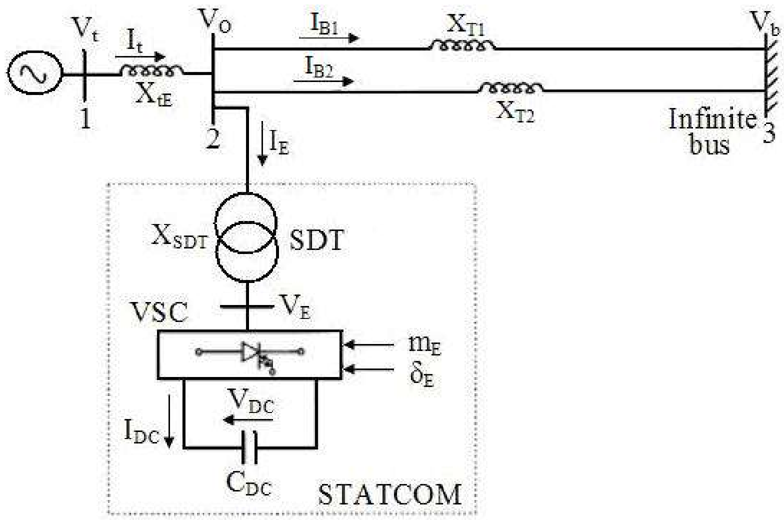

Fig. 1: A single-machine infinite-bus power system installed with STATCOM

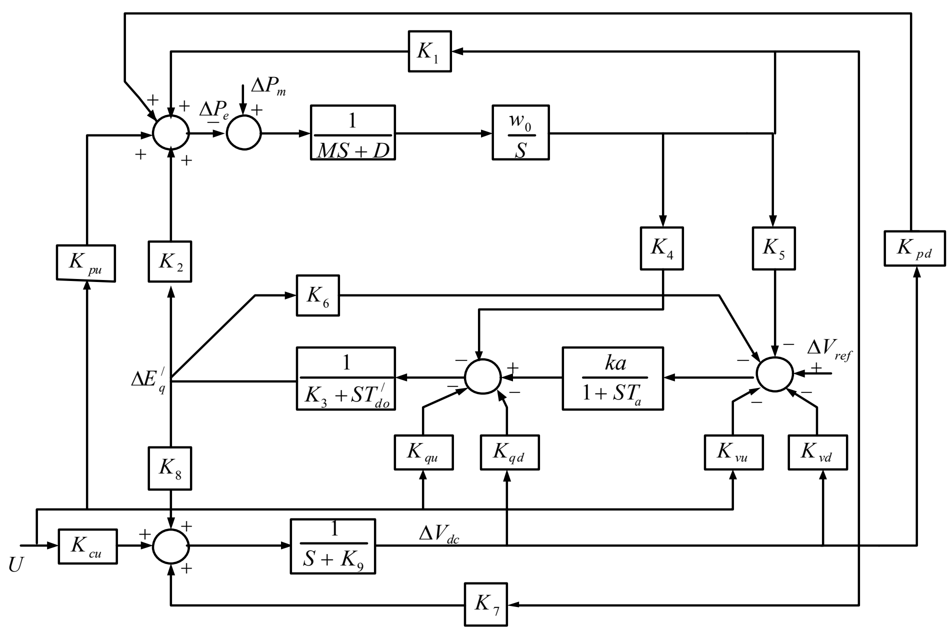

Fig. 2: Transfer function model of the system including STATCOM

STATCOM CONTROLLERS

The STATCOM control system comprises two controllers:

- DC-voltage regulator
- Power system oscillation-damping controller

DC-voltage regulator: The STATCOM need to a DC voltage regulator to regulate DC-link voltage. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. Figure 3 shows the structure of the DC-voltage regulator. A P-I type controller is considered as voltage regulator here. The parameters of DC-voltage regulator are considered as follow for this research.

$$K_{di} = 0.398 \qquad K_{dp} = 0.5778$$

Power system oscillation-damping controller: A damping controller is provided to improve power system oscillations damping. This controller may be considered as a lead-lag compensator or a fuzzy controller block or the other methods. However an

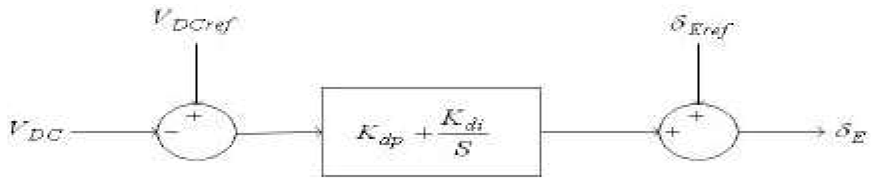

Fig. 3: DC-voltage regulator

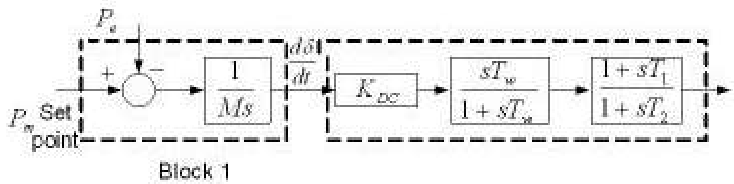

Fig. 4: The Structure of classical damping controller

electrical torque in phase with the speed deviation must be produced in order to improve the damping of the system oscillation. The transfer function block diagram of the damping controller is shown in Fig. 4.

ANALYSIS

For nominal operating condition, the eigen-values of the system are obtained (Table 1) using state-space form from transfer-function model of system in (4) and it is clearly seen that the system is unstable. Thus the system need to supplementary damping controller for stability.

DAMPING CONTROLLER

A damping controller is provided to improve the damping of power system oscillations. Through damping controller an electrical torque in phase with the speed deviation is to be produced in order to improve the damping of the system oscillation. Damping controllers design themselves have been a topic of interest for decades, especially in form of Power System Stabilizers (PSS) and Static VAR Compensators (SVC) [18-22]. Different methods were used for design of damping controllers based these devices, e.g., pole-placement using lead-lag type of damping controllers, or even fuzzy logic has been used to improve transient stability. But PSS can not control of power transmission and also can not support of power system stability under large disturbances like 3-phase fault at terminals of generator [23]. For these problems, in this paper a damping control based STATCOM is provided for damping power system oscillation. Two methods are considered to design of damping controller based STATCOM. These methods are Fuzzy Logic sachems and Genetic Algorithms optimization. In the next parts the process of design damping control using foregoing methods are presented.

Table 1: Eigen-values of the closed-loop system without damping controller

-19.2516
0.0308±2.8557i
-0.6695±0.5120i

Fuzzy logic based STATCOM damping controller: Here the proposed fuzzy supplementary controller block diagram is given in Fig. 5. In fact, this is a nonlinear PI-type fuzzy logic controller with two inputs and one output. The two control parameters of the STATCOM (m_E, d_E) can be modulated in order to produce the damping torque. In this paper m_E is modulated in order to output of damping controller. The speed deviation $\Delta\omega$ is considered as the input to the damping controller. The structure of fuzzy supplementary controller is shown in Fig. 5. Where, the inputs are the frequency deviation (X_1) and its rate of changes (X_2), which are filtered by washout blocks to eliminate the dc component. The output (y) is sent to the main controller for magnitude of shunt-injected voltage modulation.

Though the fuzzy controller accepts these inputs, it has to convert them into fuzzified inputs before the rules can be evaluated and fired. To accomplish this we have to build one of the most important and critical blocks in the whole fuzzy controllers, The Knowledge Base. It consists of tow more blocks namely the Data Base and the Rule Base [24].

Data base: It consists of the membership function for input variables (X_1) and (X_2) described by the following linguistic variables:

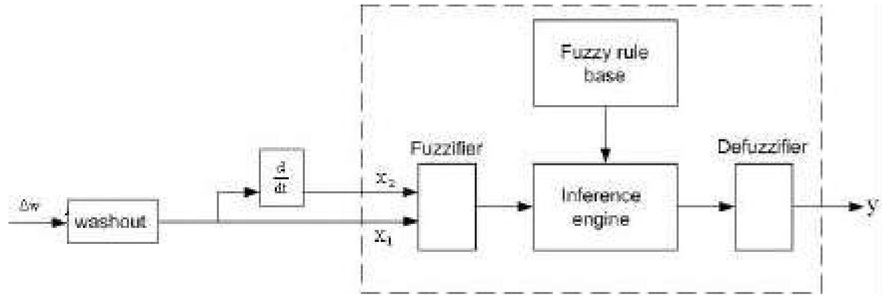

Fig. 5: Fuzzy supplementary controller

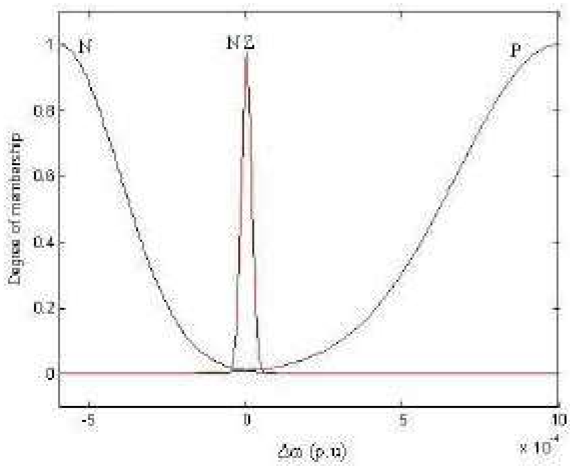

Fig. 6: Membership function of input 1 (X_1)

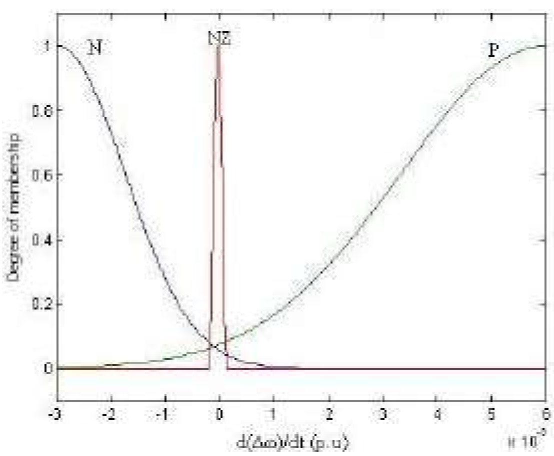

Fig. 7: Membership function of input 2 (X_2)

For (X_1):

- Positive (P)
- Negative (N)

For(X_2):

- Negative (N)
- Near Zero (NZ)
- Positive (P)

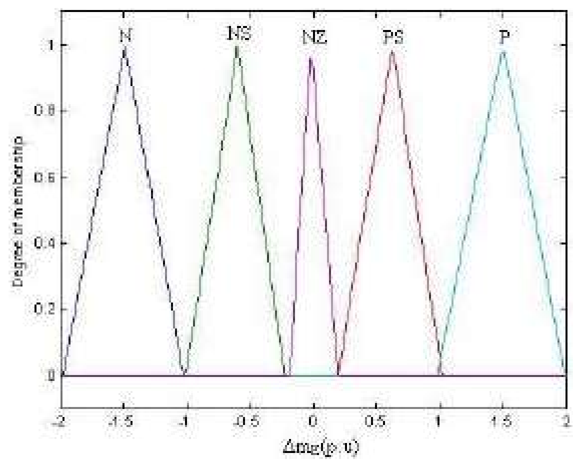

Fig. 8: Member ship function of output

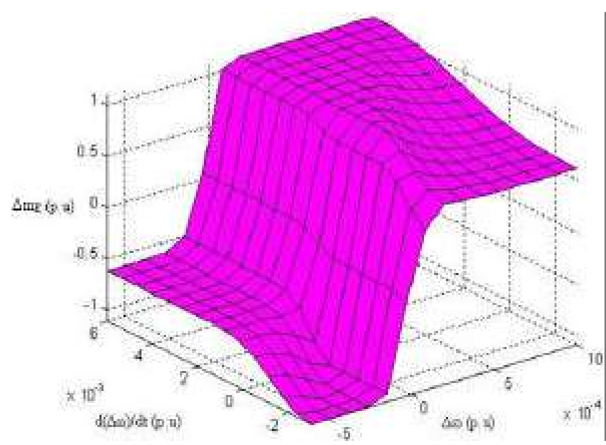

Fig. 9: The output coefficients versus two inputs

For output variable (Damping signal) described by the following linguistic variables:

- Positive (P)
- Positive Small (PS)
- Near Zero (NZ)
- Negative Small (NS)
- Negative (N)

The "Gaussian membership functions" are used as membership functions for the input variables and "Triangular membership functions" for output variable [24]. The Figs. 6-8 illustrate these in detail, indicating the range of all the variables.

Rule base: The other half of the knowledge base is the Rule Base, which consists of, all the rules formulated by the experts. It also consists of weights, which indicate the relative importance of the rules among themselves and indicates the influence of a particular rule over the net fuzzified output. The fuzzy rules used in our scheme are as mentioned in the Table 2. The next section specifies the method adopted by the Inference Engine, especially the way it uses the Knowledge Base consisting of the described Data Base and Rules Base [24]. Plotting of inputs versus output, based rules base, is shown in Fig. 9.

Methodologies adopted in fuzzy inference engine: Though many methodologies have been mentioned in evaluating the various expressions like Fuzzy Union (OR operation), Fuzzy Intersection (AND operation), etc, with varying degree of complexity, we in our fuzzy scheme use the most widely used methods for evaluating such expressions. The function used for evaluating OR is "MAX", which is nothing but the maximum of the two operands i.e.

$$MAX(X1, X2) = X1 \text{ if } X1 > X2 = X2 \text{ if } X1 < X2$$

Similarly the AND is evaluated using "MIN" function which is defined as the minimum of the two operands i.e.

$$MIN(X1, X2) = X1 \text{ if } X1 < X2 = X2 \text{ if } X1 > X2$$

It must be note that in the present research paper, the equal importances have been assigned to all the rules in the Rules Base i.e. all the weights are equal and this is indicated in the Fuzzy Rules Table 2 in the brackets against each rule [24].

De-fuzzification method: The De-fuzzification method followed in this study is the "Center of Area Method" or "Gravity method". This method is discussed in [24].

Genetic algorithms based STATCOM damping controller: Genetic algorithms (GA) are global search techniques, based on the operations observed in natural selection and genetics [24, 25]. They operate on a population of current approximations-the individuals-initially drawn at random, from which improvement is sought. Individuals are encoded as strings (Chromosomes) constructed over some Particular alphabet, e.g., the binary alphabet {0.1}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution. At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance.

Table 2: Fuzzy rules

Rule 1: If (X_2) is NZ then (y) is NZ [1]
Rule 2: If (X_2) is P then (y) is P [1]
Rule 3: If (X_2) is N then (y) is N [1]
Rule 4: If (X_2) is NZ and (X_1) is P then (y) is NS [1]
Rule 5: If (X_2) is NZ and (X_1) is N then (y) is PS [1]

The selected individuals are then modified through the application of genetic operators. In order to obtain the next generation Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories [24, 25]: Reproduction, crossover and mutation.

- Reproduction: selects the fittest individuals in the current population to be used in generating the next population.
- Cross-over: Causes pairs, or larger groups of individuals to exchange genetic information with one another
- Mutation: causes individual genetic representations to be changed according to some probabilistic rule.

Genetic algorithms are more likely to converge to global optima than conventional optimization Techniques, since they search from a population of points and are based on probabilistic transition rules. Conventional optimization techniques are ordinarily based on deterministic hill-climbing methods, which, by definition, wi11 only find local optima. Genetic algorithms can also tolerate discontinuities and noisy function evaluations.

Design damping controller using GA: The two control parameters of the STATCOM (d_E, m_E) can be modulated in order to produce the damping torque. Here like Fuzzy approach, m_E is modulated in order to output of damping controller. The speed deviation $\Delta\omega$ is also considered as the input of damping controller. The goals are stability of system with suitable oscillations damping and also obtaining a good performance. The structure of supplementary damping controller is shown in Fig. 4. Where K_{DC} is the gain of damping controller and T_W is the parameter of washout block and T_1 and T_2 are the parameters of compensation block. In this study, the optimum values of K_{DC}, T_1 and T_2 which minimize an array of different performance indexes are easily and accurately computed using a Genetic Algorithm. In a typical run of the GA, an initial population is randomly generated. This initial population is referred to as the 0^{th} generation. Each individual in the initial population has an associated performance index value. Using the performance index information, the GA then produces a new population. The application of a genetic algorithm involves repetitively performing two steps.

The calculation of the performance index for each of the individuals in the current population: To do this, the system must be simulated to obtain the value of the performance index. The genetic algorithm then produces the nest generation of individuals using the reproduction crossover and mutation operators.

These two steps are repeated from generation to generation until the population has converged, producing the optimum parameters.

The performance index which has considered in this study is as following form:

$$per\_ind = a\int t\left|\Delta\omega\right|dt + ß\int t\left|\Delta V_{DC}\right|dt$$

Where $\Delta\omega$ is the frequency deviation and ΔV_{DC} is the deviation of DC voltage. To compute the optimum parameter values, a 0.1 step change in mechanical torque (ΔTm) is assumed and the performance index is minimized using Genetic Algorithm. In the next section, the optimum values of the K_{DC}, T_1 and T_2 for damping controller, resulting from minimizing the performance index are presented. Following case for performance index is considered:

Case 1: $\alpha = 1$, $\beta = 1$ (frequency deviations and DC voltage deviation are equally penalized). It should be note that the α, β and λ (weighting coefficients) are chosen by the designer.

To calculate the performance index, a simulation of the system was performed over a solution time period of 100 seconds, for each of the individuals of the current population. The values of the performance index obtained were fed to the genetic algorithm in order to produce the next generation of individuals. The procedure is repeated until the population has converged to some minimum value of the performance index producing near optimal parameters set. The genetic algorithm used here utilizes direct manipulation of the parameters. The following genetic algorithm parameters have been used in present research.

Table 3: Optimum values of K_{DC}, T_1 and T_2 for damping controller

K_{DC}	631.6
T_1	0.25
T_2	0.1
Performance index	0.67239

Table 4: Eigen-values of the closed-loop system with damping controller

-19.3328,-16.4275,-2.8609
-0.9251±0.9653i
-0.8814,-0.1067

Number of Chromosomes: 2; Population size: 48; Crossover rate: 0.5; Mutation rate: 0.1.

In this part of the study a damping controller like Fig. 4 is considered. The optimum value of the parameters K_{DC}, T_1 and T_2 for performance index as obtained using Genetic Algorithms is summarized in the Table 3.

Also washout parameter is considered as $T\omega$=10. After employing this damping controller to system, the eigen-values of the system with damping controller are obtained (Table 4) and it is clearly seen that the system is stable.

In next part of the study, Fuzzy logic controller designed in previous section and GA based controller designed in this section are applied to STSTCOM.

ANALYSIS AND SIMULATION RESULTS

The Fuzzy control design approach which was presented in previous part is now applied to design of damping controller in test system. Also GA damping controller which was designed in pervious part is applied to system. The fuzzy damping controller results are compared with GA damping controller results. Two cases are simulated: case 1: nominal operating condition and case 2: heavy operating condition. The parameters for two cases are presented in appendix. Both, fuzzy and GA damping controllers were designed for the nominal operating condition. For case 1 the simulation results are depicted in Fig. 10 and 11. The simulation results show that adding the supplementary control signal greatly enhances the damping of

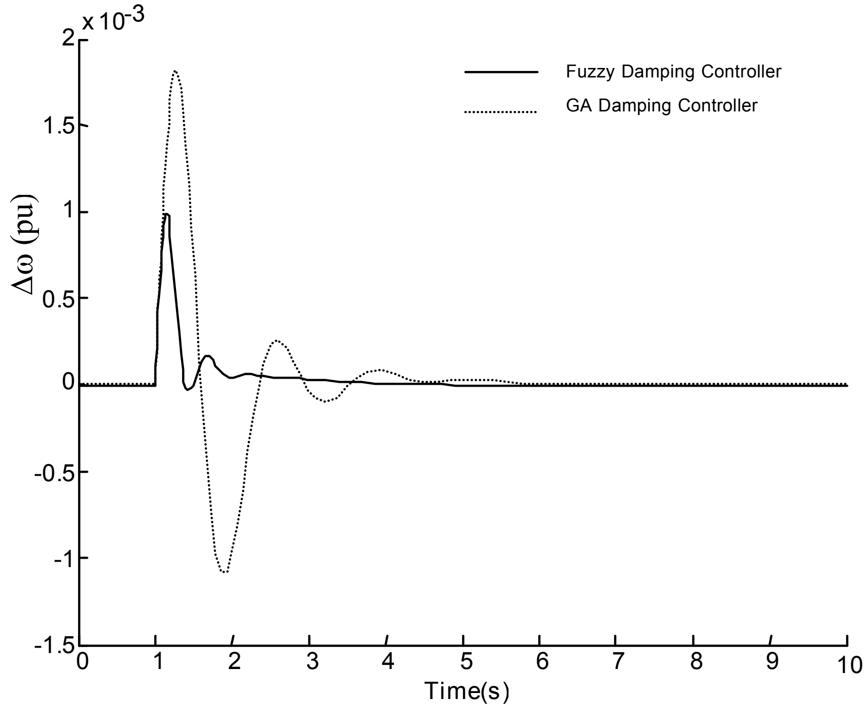

Fig. 10: Frequency deviation for case 1

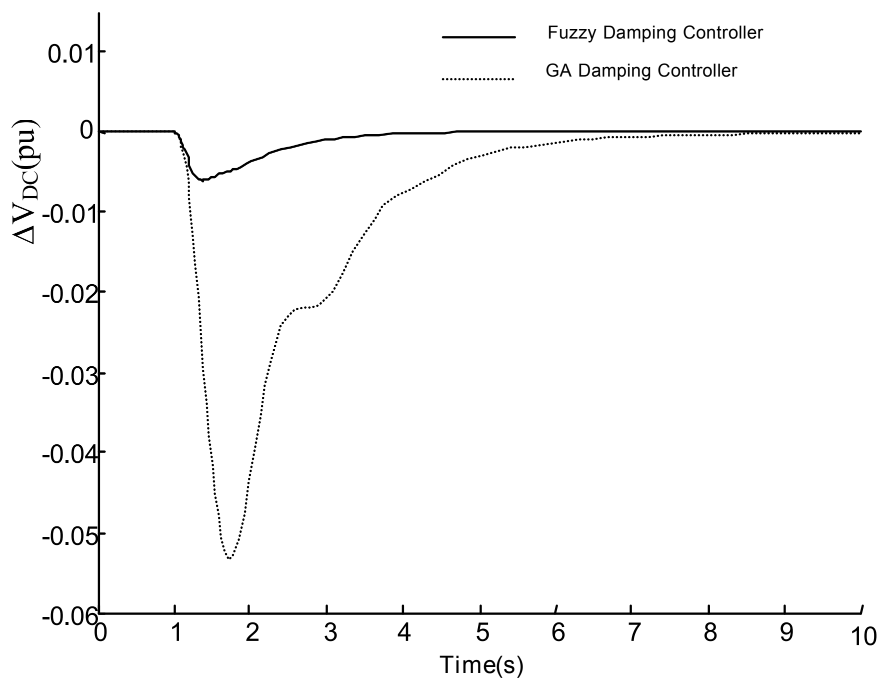

Fig. 11: Dynamic response of ΔV_{DC} for case 1

the generator angle oscillations and therefore the system becomes more stable. The fuzzy controller performs better than the GA controller. For case 2, the simulation results are shown in Fig. 12 and 13. Under this condition, while the performance of GA supplementary controller becomes poor, the fuzzy controller has a good and robust performance. It can be concluded that the fuzzy supplementary controller have good parameter adaptation in comparison with the GA supplementary controller when operating condition changes. Simulations are carried out in MATLAB [26].

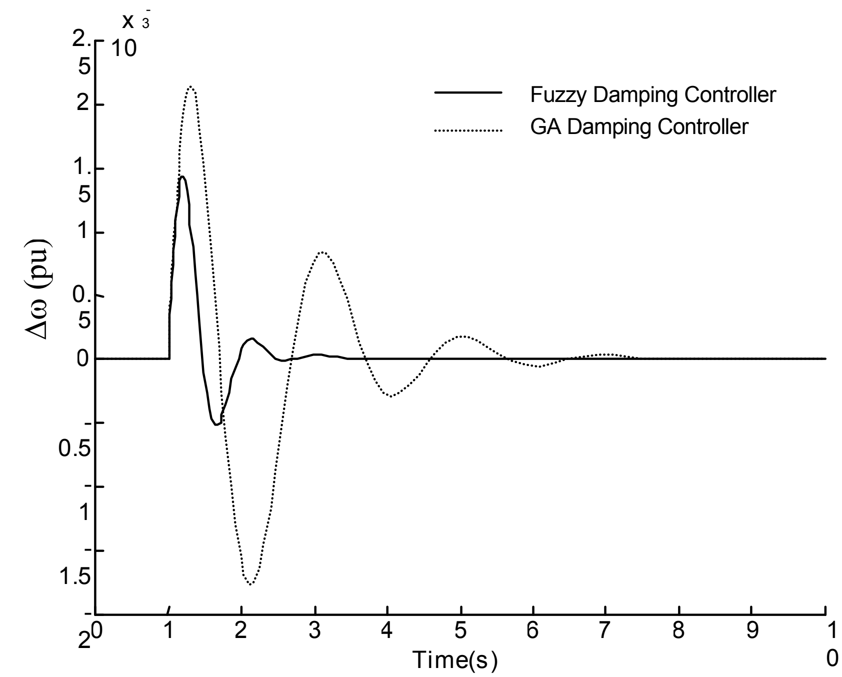

Fig. 12: Frequency deviation for case 2

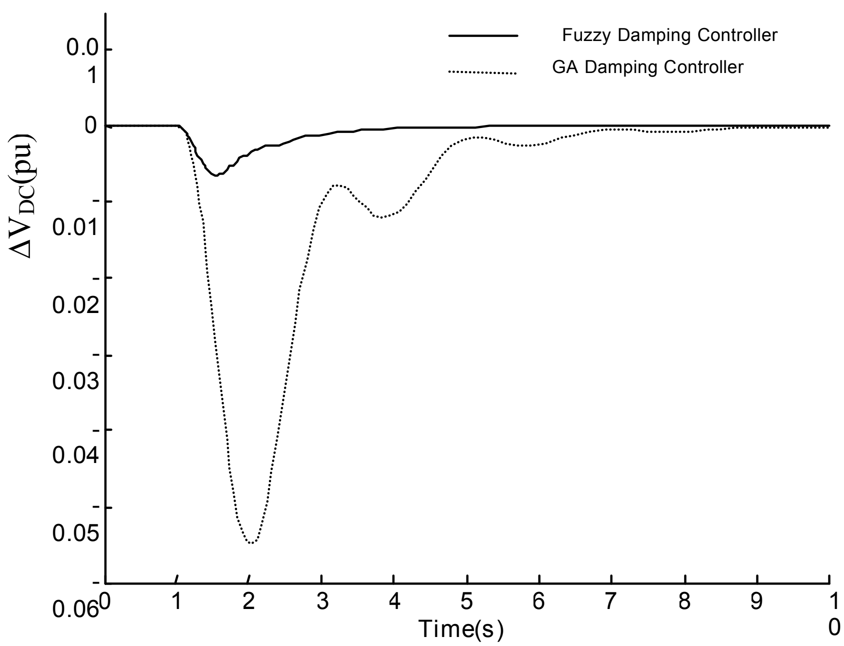

Fig. 13: Dynamic response of ΔV_{DC} for case 2

CONCLUSION

In this paper Genetic Algorithms and Fuzzy logic have been successfully applied to design of damping controller for STATCOM. A single machine infinite bus power system installed with a STATCOM with various load conditions has been assumed to demonstrate the methods. Design strategies include enough flexibility to setting the desired level of stability and performance and considering the practical constraint by introducing appropriate uncertainties. Simulation results demonstrated that the designed

Appendix: The nominal parameters and operating conditions of the system are given below:

Generator	M = 8 Mj/MVA	T'_{do} = 5.044s	X_d = 1_{pu}
	X_q = 0.6p.u	X'_d = 0.3_{pu}	D = 0
Excitation system		K_a = 10	T_a = 0.05s
Transformers		X_{tE} = 0.1_{pu}	X_{SDT} = 0.1_{pu}
Transmission line		X_{T1} = 1_{pu}	X_{T2} = 1.3_{pu}
Operating condition		P = 0.8_{pu}	Q = 0.15_{pu}
		V_t = 1.03_{pu}	
DC link parameter		V_{Dc} = 2_{pu}	C_{DC} = 3_{pu}
STATCOM parameters		δ_E = 26.9°	m_E = 1.0233

controllers capable to guarantee the robust stability and robust performance under a various load conditions. Also, linear simulation results show that the Fuzzy method has an excellent capability in power system oscillations damping and power system stability enhancement under small disturbances in compare with GA method.

The parameter for operating conditions: (The operating condition 1 is nominal operating condition)

Operating condition 1	P = 0.8	Q = 0.15	Vt = 1.032
Operating condition 2	P = 1.0	Q = 0.20	Vt = 1.032

REFERENCES

1. Hingorani, N.G. and L. Gyugyi, 2000. Understanding FACTS. IEEE Press, New York.
2. Gyugyi, L., N.G. Hingorani, P.R. Nannery and T. Tai, 1990. Advanced Static Var compensator using Gate turn-off Thyristors for Utility Applications. In the Proceedings of the 1990 CIGRE Conference, pp: 23-203.
3. Gyugyi, L., 1979. Reactive Power Generation and Control by Thyristor Circuits. IEEE Trans., IA-15 (5): 521-532.
4. Schauder, C. and A.H. Mehta, 1993. Vector Analysis and Control of Advanced Static VAR Compensator. In the Proceedings of the 1993 IEE conference, pp: 299-306.
5. SchauderS, C., M. Gernhardt, E. Stacey, T.W. Cease and A. Edrise, 1995. Development of a ±100 MVAR Static Condenser for Voltage Control of Transmission Systems. IEEE Trans on Power Delivery, 10 (3): 1486-1496.
6. Ekanayake, J.B., N. Jenkins and C.B. Cooper, 1995. Experimental Investigation of an Advanced Static Var Compensator. IEE Proc. Generation, Trans. and Distribution, 142 (2): 202-210.
7. Saad-Saoud, Z., M.L. Lisboa, J.B.E. Kanayake, N. Jenkins and G. Strbac, 1998. Application of STATCOMs to wind Farms. IEE Proc. Generation, Trans. and Distribution, 145 (5): 511-516.
8. Trainner, D.R., S.B. Tennakoon and R.E. Morrison, 1994. Analysis of GTO-Based Static VAR Compensators. IEE Proc. Generation, Trans. and Distribution, 141 (6): 293-302.
9. Ainsworth, J.D., M. Davies, J.P. Fitz, K.E. Owen and D.R. Trainer, 1998. Static Var Compensator (STATCOM) Based on single-Phase Chain Circuit Converters. IEE Proc. Generation, Trans. and Distribution, 145 (4): 381-386.
10. Mori, S., K. Matsuno, M. Takeda and M. Seto, 1993. Development of a Large Static Var Generator Using Self-commutated Inverters for Improving Power System Stability. IEEE Trans. Power System.
11. Wang, H.F., 1999. Phillips-Heffron model of power systems installed with STATCOM and applications. IEE Proc. Generation, Trans. and Distribution, 146 (5): 521-527.
12. Heffron, W.G. and R.A. Phillips, 1952. Effect of a modem amplidyne voltage regulator on under excited operation of large turbine generator. AIEE Trans, pp: 71.
13. Tambey, N. and M.L. Kothari, 2003. Damping of Power System Oscillation with Unified Power Flow Controller (UPFC). IEE Proc. Generation, Trans. and Distribution, 150 (2): 129-140.
14. Cheng, S., O.P. Malik and S.G. Hope, 1986. Self-Tuning Stabilizers for a Multi-Machine Power System. IEE Proceedings, Part C (4):176-185.
15. Al-Awami A.T. *et al*., 2007. A Particle-Swarm-Based Approach of Power System Stability Enhancement with UPFC. Electrical Power and Energy Systems, 29: 251-259.
16. Mishra, S., P.K. Dash and G. Panda, 2000. TS-Fuzzy Controller for UPFC in a Multi-Machine Power System. IEE Proceedings on Generation, Transmission and Distribution, 147 (1): 15-22.
17. Eldamaty, A.A., S.O. Faried and S. Aboreshaid, 2005. Damping Power System Oscillation Using a Fuzzy Logic Based Unified Power Flow Controller. IEEE CCECE/CCGEI, 1: 1950-1953.
18. Liou, L. and Y.Y. Hsu, 1986. Damping of Generator Oscillation Using Static VAR Compensator. IEEE Trans. Aero. Electron System, 22 (5): 605-617.
19. Liou, K.L. and Y.Y. Hsu, 1992.Damping of Generator Oscillation Using an Adaptive Static VAR Compensator. IEEE Trans. Power System, 7 (2): 718-725.
20. Smith, J.R. *et al*., 1989. An Enhanced LQ Adaptive VAR Unit Controller for Power System Damping. IEEE Trans. Power System, pp: 443-451.

21. Zhao, Q. and J. Jiang, 1995. Robust SVC Controller Design for Improving Power System Damping. IEEE Trans. Power System, 10 (4): 1927-1932.
22. Parniani, M. and M.R. Iravani, 1998. Optimal Robust Control Design of Static VAR Compensators. IEE Proc., Gen. Trans. Dist, 145 (3): 301-307.
23. Mahran, A.R., B.W. Hogg and M.L. El-sayed, 1992. Co-ordinate Control of Synchronous Generator Excitation and Static Var Compensator. IEEE Trans. Energy Conversion, 7 (4): 615-622.
24. Rajasekaran, S. and G.A. Vijayalakshmi, 2007. Neural Networks, Fuzzy Logic and Genetic Algorithms, Synthesis and Applications. Prentice Hall of India, Seventh Edition.
25. Randy, L.H. and E.H. Sue, 2004. Practical Genetic Algorithms. John Wiley & Sons, Second Edition.
26. Matlab Software, 2006. Fuzzy Logic Toolbox, the Mathworks, Inc.