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Full Length Research Paper

Comparison of artificial intelligence strategies for UPFC supplementary controller design

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This paper presents the application of UPFC to enhance damping of Low Frequency Oscillations at a Single-Machine Infinite-Bus (SMIB) power system installed with UPFC. Since UPFC is considered to mitigate Low Frequency Oscillations (LFO), therefore a supplementary stabilizer controller based UPFC like power system stabilizer is designed to reach the defined purpose. Artificial intelligence methods such as Fuzzy logic schemes and Genetic Algorithms (GA) optimization are considered to design UPFC supplementary stabilizer controller. To show effectiveness and also comparing these two methods, 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 compare to GA method. Simulations are carried out in MATLAB software.

Key words: Flexible AC transmission systems, unified power flow controller, damping power system oscillations, fuzzy logic, genetic algorithms.

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 (Hingorani and Gyugyi, 2000). UPFC is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for flexible, reliable and economic operation and loading of power systems. Until recently all three parameters that affect real and reactive power flows on the line, that is, line impedance, voltage magnitudes at the terminals of the line, and power angle, were controlled separately using either mechanical or other FACTS devices. But UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time. Also, the UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations (Gyugyi, 1995, 1992; Bhowmick et al., 2008; Jiang et al., 2010; Faried and Billinton, 2009). 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. Many in the past have presented lead-Lag type UPFC stabilizer controllers (Zarghami et al., 2010; Guo and Crow, 2009; Tambey and Kothari, 2003; Wang, 1999). They are designed for a specific operating condition using linearized models. More advanced control schemes such as Particle-Swarm Optimization method(Al-Awami, 2007), Fuzzy logic (Taher et al., 2008; Eldamaty, 2005) and genetic algorithms (Taher and Hematti, 2008) offer better dynamic performances than fixed parameter controllers.

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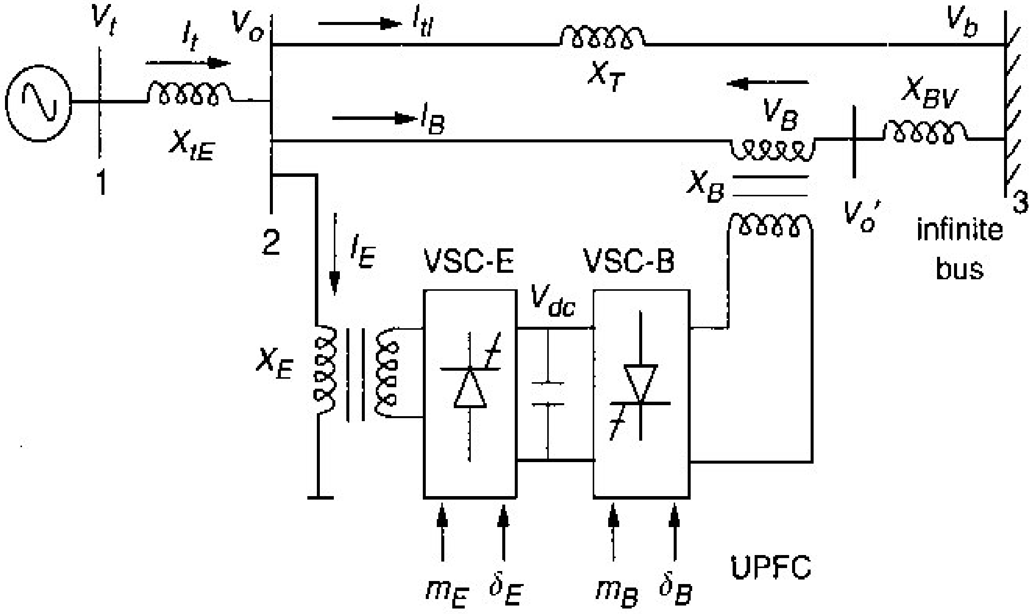

Figure 1. A Single Machine Infinite Bus (SMIB) power system installed with UPFC in one of the lines.

The objective of this paper is to investigate the ability of artificial intelligence methods such as Genetic algorithms (GA) and Fuzzy logic for UPFC supplementary damping controller design. A Sigel Machine Infinite Bus (SMIB) power system installed with a UPFC is considered as case study. In GA case, the classical damping controller like Power system stabilizer (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 UPFC damping controller design using Fuzzy logic scheme based on the Mamdani inference engine using the center of Gravity method to find the controller output is presented here. The advantages of the proposed methods are their feasibility and simplicity. Different load conditions are considered to show effectiveness of the proposed methods and also comparing the performance of these two methods. Simulation results show the validity of proposed methods in LFO damping.

SYSTEM UNDER STUDY

Figure 1 shows a SMIB power system installed with UPFC (Hingorani and Gyugyi, 2000). The UPFC is installed in one of the two parallel transmission lines. The static excitation system, model type IEEE – ST1A, has been considered. The UPFC is assumed to be based on Pulse Width Modulation (PWM) converters. The nominal system parameters are given in the appendix.

DYNAMIC MODEL OF THE SYSTEM WITH UPFC

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, transformers, transmission lines and converters), and the transients of the transmission lines and transformers of the UPFC (Nabavi-Niaki and Iravani, 1996; Wang, 2000). The nonlinear dynamic model of the system installed with UPFC is given as Equation (1).

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

The equation for real power balance between the series and shunt converters is given as (2).

$$\operatorname{Re}\left(V_B I_B^* - V_E I_E^*\right) = 0 \tag{2}$$

Linear dynamic model

A linear dynamic model is obtained by linearizing the non-linear

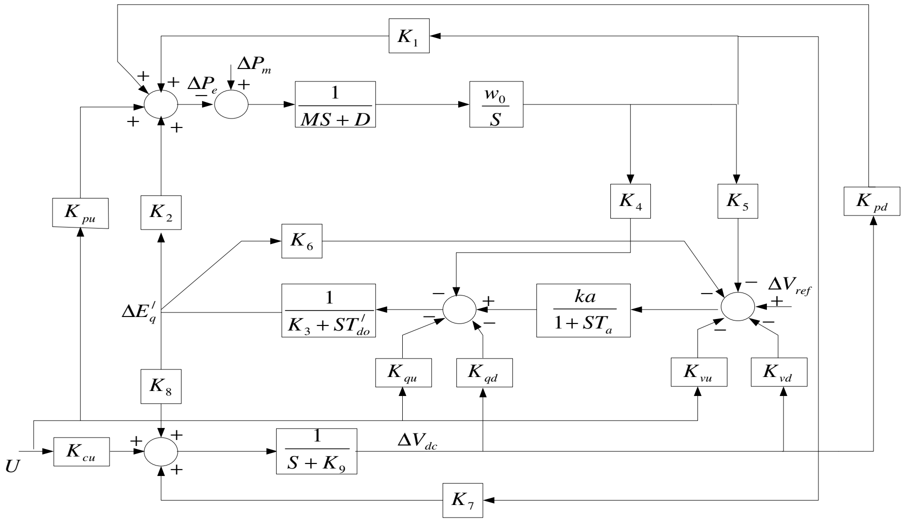

Figure 2. Transfer function model of the system including UPFC.

dynamic model around nominal operating condition. The linearised model of the system is given as Equation (3).

$$\begin{cases}\Delta\dot{\delta} = w_0\Delta w \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}_q' = (-\Delta E_q + \Delta E_{fd})/T_{do}' \\ \Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}\Delta V \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta v_{dc} + K_{ce}\Delta m_E + K_{c\delta\delta}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta\delta}\Delta\delta_B\end{cases} \tag{3}$$

Where:

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q' + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{p\delta\delta}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta\delta}\Delta\delta_B$$
$$\Delta E_q = K_4\Delta\delta + K_3\Delta E_q' + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{q\delta\delta}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta\delta}\Delta\delta_B$$
$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q' + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + K_{v\delta\delta}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta\delta}\Delta\delta_B$$

Figure 2 shows the transfer function model of the system including UPFC. The model has numerous constants denoted by K_{ij}. These constants are function of the system parameters and the initial operating condition. Also the control vector U in Figure 2 is defined as Equation (4).

$$U = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T \tag{4}$$

Where:

Δm_B: Deviation in pulse width modulation index m_B of series inverter. By controlling m_B, the magnitude of series- injected voltage can be controlled.
$\Delta\delta_B$: Deviation in phase angle of series injected voltage.
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.

The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the power input to the series converter. The fact that the DC-voltage remains constant ensures that this equality is maintained.

It should be noted that K_{pu} , K_{qu} , K_{vu} and K_{cu} in Figure 2 are the row vectors and defined as follows:

$$K_{pu} = [K_{pe} \quad K_{p\delta e} \quad K_{pb} \quad K_{p\delta b}]$$
$$K_{qu} = [K_{qe} \quad K_{q\delta e} \quad K_{qb} \quad K_{q\delta b}]$$
$$K_{vu} = [K_{ve} \quad K_{v\delta e} \quad K_{vb} \quad K_{v\delta b}]$$
$$K_{cu} = [K_{ce} \quad K_{c\delta e} \quad K_{cb} \quad K_{c\delta b}]$$

Dynamic model in state-space form

The dynamic model of the system in state-space is given as (5).

$$\begin{bmatrix}\Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_{dc}\end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T_{do}'} & 0 & -\frac{K_3}{T_{do}'} & \frac{1}{T_{do}'} & -\frac{K_{qd}}{T_{do}'} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix}\Delta\delta \\ \Delta\omega \\ \Delta E_q' \\ \Delta E_{fd} \\ \Delta V_{dc}\end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ -\frac{K_{qe}}{T_{do}'} & -\frac{K_{q\delta e}}{T_{do}'} & -\frac{K_{qb}}{T_{do}'} & -\frac{K_{q\delta b}}{T_{do}'} \\ -\frac{K_A K_{vc}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ Kce & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \times \begin{bmatrix}\Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B\end{bmatrix} \tag{5}$$

UPFC CONTROLLERS

In this research two strategies are considered for UPFC control problem:

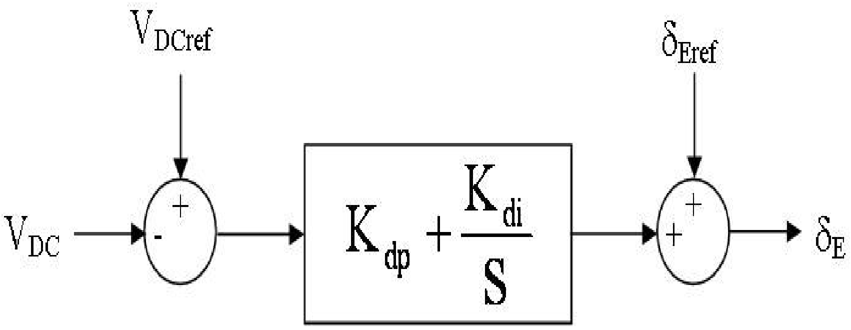

Figure 3. DC-voltage regulator.

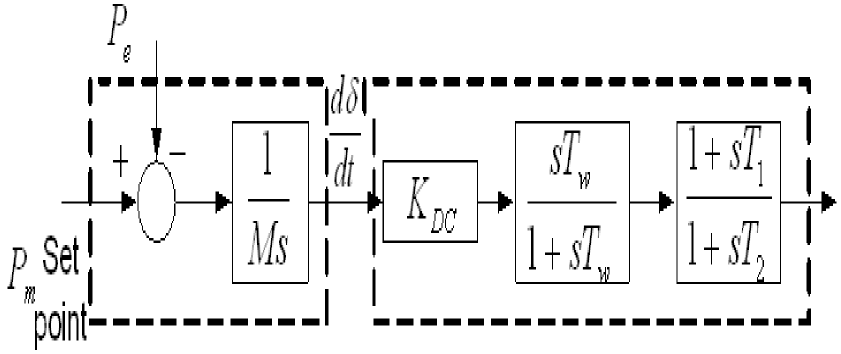

Figure 4. The structure of stabilizer controller.

Table 1. Eigen-values of the closed-loop system without stabilizer controller.

-21.5091	+0.04771 ± 2.9326i	-0.5908 ± 0.445i

1) DC-voltage regulator.
2) Power system oscillation-damping controller.

DC-voltage regulator

In UPFC, The output real power of the shunt converter must be equal to the input real power of the series converter or vice versa. In order to maintain the power balance between the two converters, a DC-voltage regulator is incorporated. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. Figure 3 shows the structure of DC-voltage regulator. In this research the parameters of DC-voltage regulator are considered as follow: K_{di}=39.5 and K_{dp}=6.54.

Stabilizer design

A stabilizer controller is provided to improve damping of power system oscillations. This stabilizer may be considered as a lead-lag compensator. However an electrical torque in phase with the speed deviation should be produced to improve damping of power system oscillations. The transfer function model of the stabilizer controller is shown in Figure 4.

ANALYSIS

For the nominal operating condition the eigenvalues of the system are obtained using state-space model of the system presented in (5) and these eigenvalues are shown in Table 1. It is clearly seen that the system is unstable and needs to power system stabilizer (damping controller) for stability.

Stabilizer controllers designs have been a topic of interest for decades, especially in form of Power System Stabilizers (PSS). But PSS can not control power transmission and also can not support power system stability under large disturbances like 3-phase fault at terminals of generator (Mahran et al., 1992). For these problems, in this paper a stabilizer controller based UPFC is provided to mitigate power system oscillations. Two methods are considered to design damping controller based UPFC. These methods are Fuzzy logic and Genetic algorithms. In the next section the stabilizer control

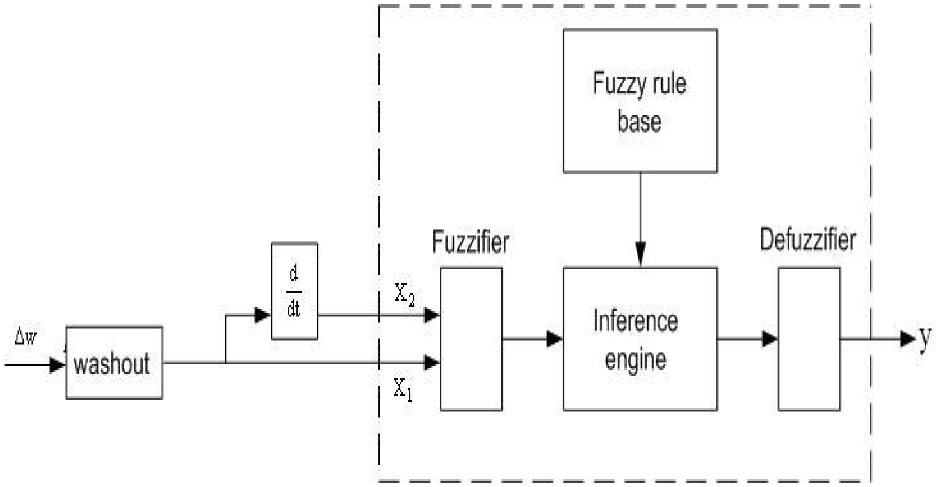

Figure 5. The structure of Fuzzy supplementary stabilizer.

Table 2. The linguistic variables for inputs and output.

Big Positive (BP)	Medium Positive (MP)	Small Positive (SP)
Big Negative (BN)	Medium Negative (MN)	Small Negative (SN)
Zero (ZE)		

design using these methods is presented.

FUZZY BASED UPFC STABILIZER CONTROLLER

Figure 5 shows the structure of Fuzzy controller block. This controller is a nonlinear PI-type Fuzzy controller with two inputs and one output. The four control parameters of the UPFC (m_E, δ_E, m_B, δ_B) can be modulated to produce the damping torque. In this paper m_E is considered as output. The speed deviation $\Delta\omega$ is considered as input to the stabilizer controller. In Figure 5 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 and 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, one of the most important blocks in the whole Fuzzy controllers should be built and it is the Knowledge Base. It consists of two more blocks namely the Data Base and the Rule Base (Rajase and Vijay, 2007).

Fuzzy controller parameters

In this paper the membership function for input variables and output variable of the fuzzy controller are considered as Table 2. Also "triangular membership functions" are used as membership functions for the input and output variables. The Figure 6 shows this in detail indicating the range of the variable. The Fuzzy rules which are used in this paper are listed in Table 3. The Defuzzification method followed in this study is the "Center of Area Method" or "Gravity method" (Rajase and Vijay, 2007).

GENETIC ALGORITHMS BASED UPFC STABILIZER CONTROLLER

Genetic Algorithms (GA) are global search techniques, based on the operations observed in natural selection and genetics (Randy and Sue, 2004). 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, for example, 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.

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

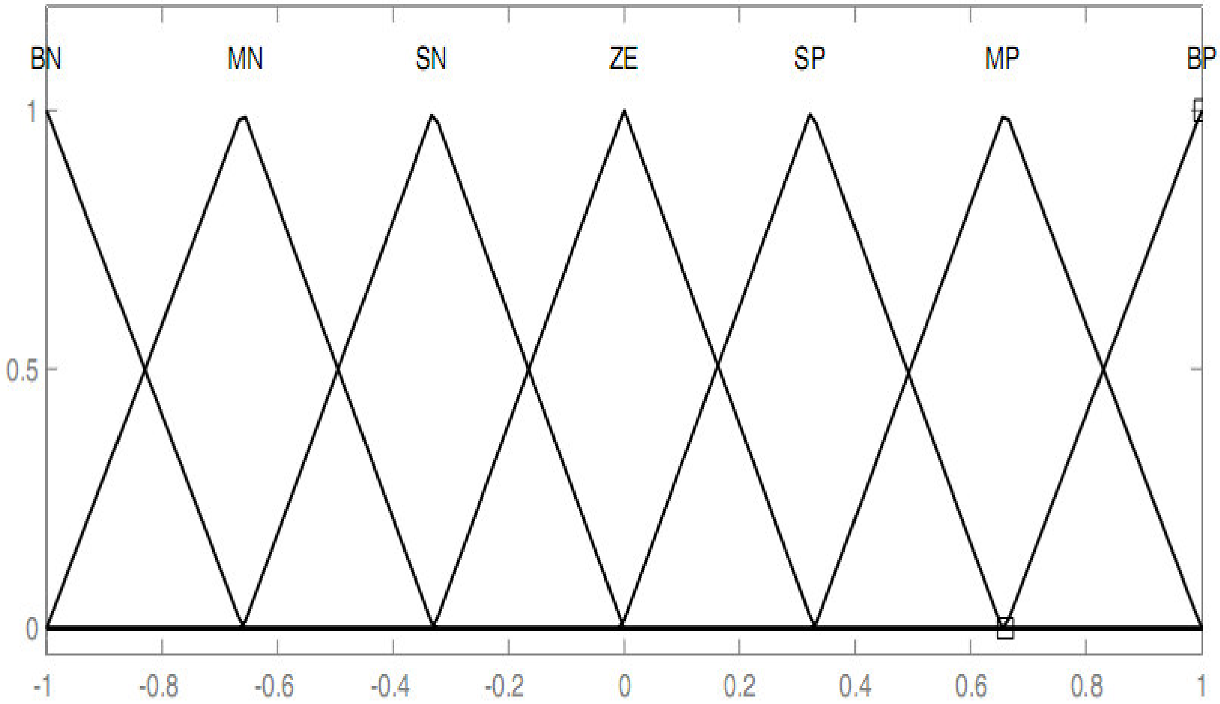

Figure 6. Membership function of inputs and output.

Table 3. Fuzzy rule bases.

$\Delta\omega$ / $d(\Delta\omega)/dt$	BN	MN	SN	ZE	SP	MP	BP
BN	BN	BN	BN	BN	MN	SN	ZE
MN	BN	MN	MN	MN	SN	ZE	SP
SN	BN	MN	SN	SN	ZE	SP	SP
ZE	MN	MN	SN	ZE	SP	MP	MP
SP	SN	SN	ZE	SP	SP	MP	BP
MP	SN	ZE	SP	MP	MP	MP	BP
BP	ZE	SP	MP	BP	BP	BP	BP

genes. Genetic operators can be divided into three main categories (Randy and Sue, 2004): Reproduction, crossover and mutation.

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

Genetic algorithms are more likely to converge to global optimal 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, will only find local optima. Genetic algorithms can also tolerate discontinuities and noisy function evaluations.

Stabilizer controller design using GA

Four control parameters of the UPFC (m_E, δ_E, m_B, δ_B) can be modulated in order to produce the damping torque. Here like Fuzzy approach, m_E is modulated to output of stabilizer controller and speed deviation $\Delta\omega$ is also considered as input of stabilizer controller. The structure of supplementary stabilizer controller is shown in Figure 4. The parameters in Figure 4 are as follow:

K_{DC}: the stabilizer controller gain
T_W: the parameter of washout block
T_1 and T_2: the parameters of compensation block

The optimum values of K_{DC}, T_1 and T_2 which minimize an array of different performance indexes are accurately computed using a Genetic Algorithms. In a typical run of the GA, an initial population is randomly generated. This initial population is referred to as the 0th

Table 4. Optimum values of K_{DC}, T_1 and T_2 for stabilizer controller.

K_{DC}	598.32
T_1	0.29
T_2	0.1

Table 5. Eigen-values of the closed-loop system after applying stabilizer controller.

-20.19, -18.309, -3.011
-0.8129 ± 0.8744i
-0.9781, -0.1129

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 genetic algorithms involves repetitively performing the following steps:

i) The calculation of the performance index for each of the individuals in the current population, to do this the system should be simulated to obtain the value of the performance index.
ii) The genetic algorithm then produces the next 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. In this study the performance index is considered as (6). In fact it is the "Integral of the Time multiplied Absolute value of the Error "or ITAE.

$$\mathrm{ITAE} = \int_0^t t|\Delta\omega|dt + \int_0^t t|\Delta V_{DC}|dt \quad (6)$$

Where, $\Delta\omega$ is the frequency deviation and ΔV_{DC} is the deviation of DC voltage. In fact this performance index is total area under the curves (output responses) and it is a suitable benchmark to compare cases with each other. The parameter "t" in performance index is the simulation time. It is clear to understand that the controller with lower performance index is better than the other controllers. 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 Algorithms. Subsequently, the optimum values of K_{DC}, T_1 and T_2 resulting from minimizing the performance index are presented. Following case for performance index is considered.

To calculate the performance index, a simulation of the system was performed over a solution time period of 50 s, 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.

1) Number of Chromosomes: 3
2) Population size: 48
3) Crossover rate: 0.5
4) Mutation rate: 0.1

A stabilizer controller like Figure 4 is considered and the optimum values of the parameters K_{DC}, T_1 and T_2 are obtained using Genetic Algorithms and summarized in the Table 4.

Also washout parameter is considered as $T\omega$=10. After applying this stabilizer controller to system the eigen-values of the system with stabilizer controller are obtained and shown in Table 5 and it is clear that the system is stable. The limits of parameters in the optimal search are considered as follows: $1<K_{DC}<1000$, $0.01<T_1<1$, $0.01<T_2<1$.

SIMULATION RESULTS

The designed Fuzzy and GA controllers are applied to the system and their responses are compared with each other. Two cases are considered as follow:

Case 1: Nominal operating condition
Case 2: Heavy operating condition

The parameters for two cases are presented in appendix. Fuzzy and GA stabilizer controllers are designed for the nominal operating condition. For case 1 the simulation results are shown in Figures 7 and 8. The simulation results show that applying the supplementary control signal greatly enhances the damping of 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 Figures 9 and 10. Under this condition, while the performance of GA supplementary controller becomes poor, the Fuzzy controller has a suitable and robust performance. It can be concluded that the Fuzzy supplementary controller have suitable parameter adaptation in comparing with the GA supplementary controller when operating condition changes. With changing system loading condition from nominal to heavy, the prominence of fuzzy stabilizer rather than GA stabilizer is obviously seen.

Conclusions

In this paper Genetic algorithms and Fuzzy logic have been successfully applied to design stabilizer controller based UPFC. A Single Machine Infinite Bus power system installed with a UPFC with various load conditions has been assumed to demonstrate the methods. Simulation results demonstrated that the designed stabilizer controllers capable to guarantee the robust stability and robust performance under a different load conditions. Also, 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 to GA method.

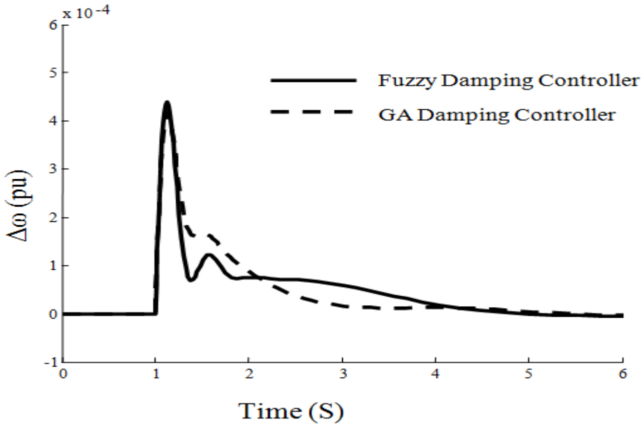

Figure 7. Dynamic response Δω for case 1.

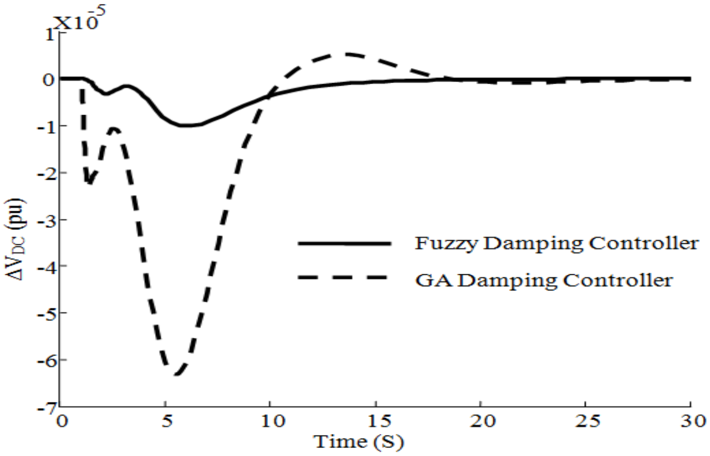

Figure 8. Dynamic response ΔV_{DC} for case 1.

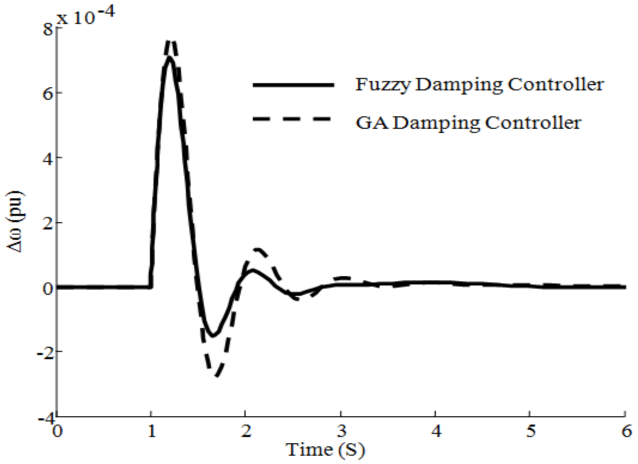

Figure 9. Dynamic response Δω for case 2.

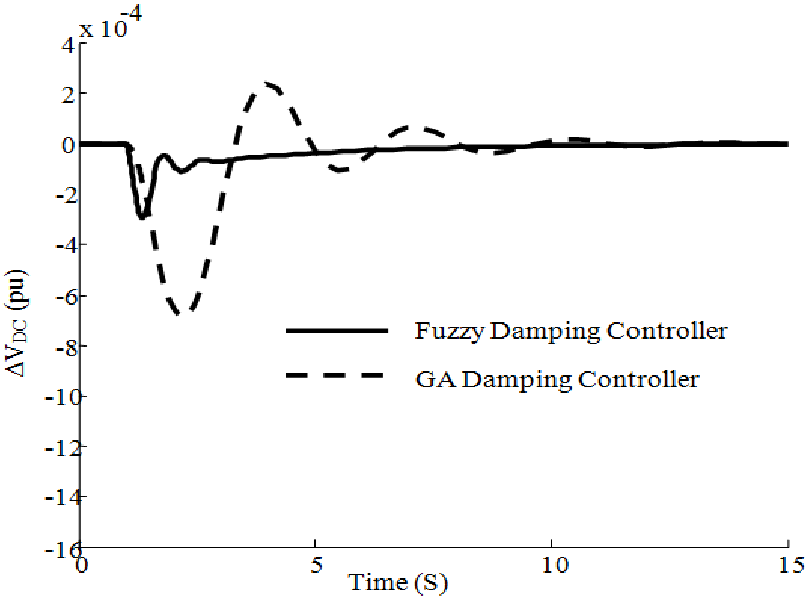

Figure 10. Dynamic response ΔV_{DC} for case 2.

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APPENDIX

The nominal parameters and nominal operating condition of the system are listed in Appendix Table 1. Also system operating conditions are defined in Appendix Table 2 (Operating condition 1 is the nominal operating condition).

Table 1. System parameters.

Generator	**$T'_{do} = 5.044$ s, $X'_d = 0.3$ p.u., $X_d = 1$ p.u., $X_q = 0.6$ p.u., M = 8 Mj/MVA**	
Excitation system	Ka = 10	Ta = 0.05 s
Transformers	$X_{te} = 0.1$ p.u.	$X_{SDT} = 0.1$ p.u.
Transmission lines	$X_{T1} = 1$ p.u.	$X_{T2} = 1.25$ p.u.
DC link parameters	$V_{DC} = 2$ p.u.	$C_{DC} = 3$ p.u.
UPFC parameters	$m_E = 1.0307$; $\delta_E = 32.57°$	$m_B = 0.1347$; $\delta_B = -8.0173°$

Table 2. System operating conditions.

Operating condition 1	P = 1 p.u.	Q = 0.2 p.u.
Operating condition	P = 1.1 p.u.	Q = 0.3 p.u.