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Optimal Supplementary Controller Design Using GA for UPFC in Order to LFO Damping

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Abstract: This study presents a study of the application of a Unified Power Flow Controller (UPFC) to enhance the damping of Low Frequency Oscillation (LFO) in Single-machine Infinite-bus (SMIB) power system. In practice systems use simple traditional UPFC supplementary damping controller (like lead-lag) for LFO damping. However, since the traditional supplementary damping controller parameters are usually tuned based on classical or trial-and-error approaches, they are incapable of obtaining good dynamic performance for various load conditions and disturbances in power system. For this problem, in this study, a UPFC supplementary damping controller design using a Genetic Algorithms (GA) schemes is considered to enhance damping and performance. In this approach the parameters of damping controller are tuned based on GA method. Because GA is an optimization method, therefore, obtained damping controller is an optimal controller. The advantages of the proposed method are their feasibility and simplicity. To show effectiveness of GA approach in damping power system oscillation, the proposed method is compared with a conventional method (lead-lag compensator). Several non-linear time-domain simulation tests visibly show the validity of proposed method in compare to traditional method.

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

INTRODUCTION

The Flexible AC Transmission Systems (FACTS) based on power electronics offer an opportunity to enhance controllability, stability and power transfer capability of AC transmission systems (Hingorani and Gyugyi, 2000). The 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 3 parameters that affect real and reactive power flows on the line, i.e., line impedance, voltage magnitudes at the terminals of the line and power angle, were controlled separately using either mechanical or other FACTS devices such as static VAR compensators (SVC), Thyristor Controlled Series Capacitors (TCSC), etc (Hingorani and Gyugyi, 2000; Gyugyi *et al*., 1995; Gyugyi, 1992; Li *et al*., 2000; Gholipou and Saadat, 2005; Wang, 1999). However, the UPFC allows simultaneous or independent control of all these 3 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 (Wang, 2000). 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 s tability. Many in the past have presented lead-lag type UPFC damping controllers (Tambey and Kothari, 2003). They are designed for a specific operating condition using linearized models. More advanced control schemes such as self-tuning control (Cheng *et al*., 1986), particle-swarm method (Al-Awami *et al*., 2007) and fuzzy logic control (Mishra *et al*., 2000; Eldamaty *et al*., 2005) offer better dynamic performances than fixed parameter controllers.

In this study, a optimal controller, based on the GA approach is proposed for the design of damping controller of UPFC in SMIB power system. UPFC supplementary damping controller is considered to LFO damping. An optimal control scheme based GA method is used for tuning the parameters of supplementary damping controller. To show effectiveness of proposed method and also compare the performance, proposed method is compared with a conventional method (lead-lag). Results of non-linear simulation show the GA controllers guarantee the good performance for various load conditions and large disturbances.

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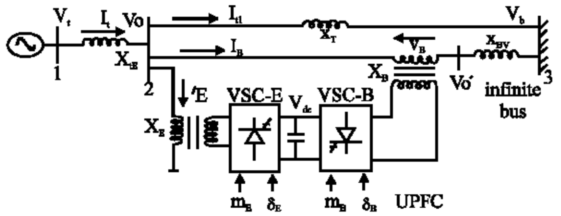

Fig. 1: A SMIB power system installed with an UPFC in one of the lines

Appendix 1: The nominal parameters and operating conditions of the system

Generator M = MJ/MVA	T'_{do} = 5.044 s	X_d = 1pu
X_q= =0.6 p.u.	X'_d = 0.3 pu	D = 0
Excitation system	K_A = 10	T_a = 0.05 s
	X_{tE} = 0.1pu	X_E = 0.1 pu
Transformers	X_B = 0.1 pu	
Transmission line	X_{T1} = 1 pu	X_{T2} = 1.3 pu
	P = 0.8 pu	Q = 0.15 pu
Operating condition	V_t = 1.032 pu	
DC link parameter	V'_{Dc} = 2 pu	C_{DC} = 3 pu
	m_B = 1.104	δ_B = -55.87°
UPFC parameters	δ_E = 26.9°	m_E = 1.0233

The parameter for operating conditions: (The operating condition 1 is nominal operating condition); Operating condition 1: P= 0.8, Q = 0.15, Yt = 1.032; Operating condition 2: P= 1.1, Q = 0.28, Yt = 1.032

SYSTEM UNDER STUDY

Figure 1 shows a SMIB power system with UPFC installed (Hingorani and Gyugyi, 2000). The UPFC is installed in one of the 2 parallel transmission lines. This configuration, comprising 2 parallel transmission lines, permits the control of real and reactive power flow through a line.

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 loading condition and system parameters are given in Appendix I.

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, transformer, transmission lines and shunt and series converter transformers) and the transients of the transmission lines and transformers of the UPFC. The nonlinear dynamic model of the system using UPFC is given as (Tambey and Kothari, 2003):

$$\begin{cases} \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin(\delta_E) I_{Ed} + \cos(\delta_E) I_{Eq}\right) \\ + \dfrac{3m_B}{4C_{dc}}\left(\sin(\delta_B) I_{Bd} + \cos(\delta_B) I_{Bq}\right) \end{cases}$$

$$\begin{cases} \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin(\delta_E) I_{Ed} + \cos(\delta_E) I_{Eq}\right) \\ + \dfrac{3m_B}{4C_{dc}}\left(\sin(\delta_B) I_{Bd} + \cos(\delta_B) I_{Bq}\right) \end{cases} \tag{1}$$

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

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

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

$$\begin{cases} \Delta\dot{\delta} = \omega_0 \Delta\omega \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}_{fd} = -\dfrac{1}{T_A}\Delta E_{fd} - \dfrac{K_A}{T_A}\Delta V \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + \\ K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \end{cases} \tag{3}$$

where,

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

Figure 2 shows the transfer function model of the system including UPFC. The model has 28 constants denoted by K. These constants are functions of the system parameters and the initial operating condition. The control vector u is defined as follows:

$$u = [\Delta M_E \ \ \Delta\delta_E \ \ \Delta m_B \ \ \Delta\delta_B]^T \tag{4}$$

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 injected voltage.
- ΔM_E : Deviation in pulse width modulation index m_B 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 may be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig. 2 are the row vectors defined as:

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

and $u = [\Delta M_E\ \ \Delta\delta_E\ \ \Delta m_B\ \ \Delta\delta_B]^T$.

Dynamic model in state-space form: The dynamic model of the system in state-space from transfer-function model is as Eq. (5):

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E'_q} \\ \dot{\Delta E_{fd}} \\ \dot{\Delta v_{dc}} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qd}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{pde}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{pdb}}{M} \\ -\frac{K_{qe}}{T'_{do}} & -\frac{K_{qde}}{T'_{do}} & -\frac{K_{qb}}{T'_{do}} & -\frac{K_{qdb}}{T'_{do}} \\ -\frac{K_A K_{vc}}{T_A} & -\frac{K_A K_{vde}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{vdb}}{T_A} \\ Kce & K_{cde} & K_{cb} & K_{cdb} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta d_B \end{bmatrix} \quad (5)$$

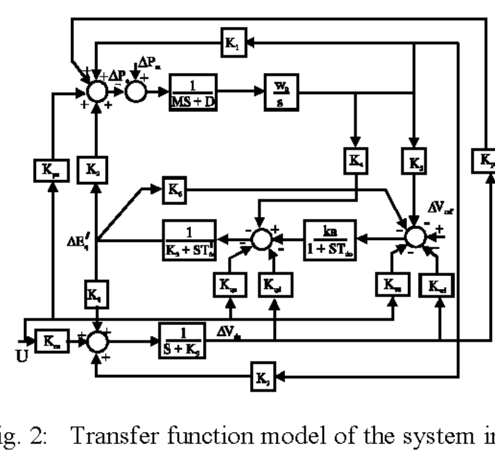

Fig. 2: Transfer function model of the system including UPFC

The typical values of system parameters for nominal operation condition are given in Appendix I. The system parametric uncertainties are obtained by changing load (active and reactive power) from their typical values. Based this uncertainty, operation condition 2 is defined and shown in Appendix 1.

UPFC CONTROLLERS

The UPFC control system comprises 2 controllers:

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

DC-voltage regulator: The UPFC is installed in one of the 2 lines of the SMIB system. The real power output of the shunt converter must be equal to the real power input of the series converter or vice versa. In order to maintain the power balance between the 2 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 the DC-voltage regulator. The parameters of this controller are given in Appendix 2.

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

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 parameters of compensation block.

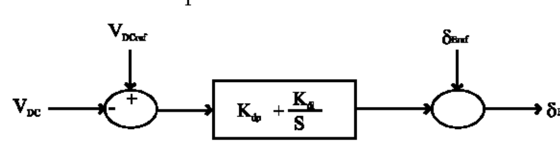

Fig. 3: DC-voltage regulator

Appendix 2: The parameters of DC-voltage regulator are considered as follow for this research

$K_{di} = 46.7$	$K_{dp} = 7.1$

The limited of m_B signal is as follow: $0 \le m_B \le 2$

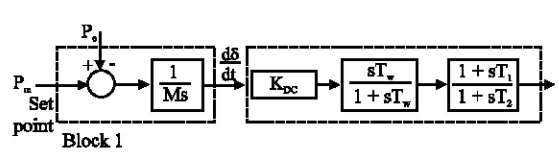

Fig. 4: Structure of damping controller

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

-19.2516
0.0308±2.8557i
-0.6695±0.5120i

ANALYSIS

For nominal operating condition, the eigen-values of the system are obtained (Table 1) usage state-space form transfer-function model of system in Eq. (5) and it is clearly seen that the system is unstable. Thus, the system need to supplementary damping controller for stability.

DAMPING CONTROLLER

In order to improve the damping of power system oscillations, a damping controller is provided. 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) (Liou and Hsu, 1986; Liou and Hsu, 1992; Smith *et al*., 1989; Zhao and Jiang, 1995; Parniani and Iravani, 1998). 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 (Mahran *et al*., 1992). For these problems, in this study, a damping control based UPFC is provided for damping power system oscillation.

Also, the conventional damping controllers (like lead-lag controllers) are based on the linear control theory and they are usually tuned based on classical or trial-and-error approaches. Therefore, conventional damping controllers can not provide appropriate stabilization signal over a wide range of operation conditions. In turn, in this work a GA schemes is considered for design of damping controller based UPFC. A schematic control diagram of a conventional lead-lag controller is as shown in Fig. 4. It consists of gain, signal washout and phase compensator blocks. Before beginning of design process it is necessary to introduction with GA. In the next section a brief description about GA optimization is developed.

GENETIC ALGORITHM

GA are global search techniques, based on the operations observed in natural selection and genetics (Randy and Sue, 2004; Rajasekaran and Vijayalakshmi, 2007). 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.

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 3 main categories (Randy and Sue, 2004; Rajasekaran and Vijayalakshmi, 2007): 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, will only find local optima. G can also tolerate discontinuities and noisy function evaluations.

GA BASED UPFC DAMPING CONTROLLER

The 4 control parameters of the UPFC (m_B, m_E, δ_B and δ_E) can be modulated in order to produce the damping torque. In this study, m_B is modulated in order to output of damping controller. The speed deviation $\Delta\omega$ is also considered as the input to the damping controller.

In this study, supplementary optimal damping controller designed for improving of LFO damping and stability using GA. The goals are stability of system with good damping of oscillation, also obtain a good performance. The structure of supplementary damping controller is show in Fig. 4.

In this study, the optimum values of K_{DC}, T_1 and T_2 which minimize an array of different performance indices are easily and accurately computed using a GA. 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 GA involves repetitively performing 2 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 2 steps are repeated from generation to generation until the population has converged, producing the optimum parameters.

The nominal system parameters are given in Appendix 1.

The performance index considered in this study, is of the form:

$$Per\_Ind = \alpha\int_0^\infty t|\Delta\omega|dt + \beta\int_0^\infty t|\Delta V_{DC}|dt \qquad (6)$$

Where,

$\Delta\omega$: Is frequency deviation.

ΔV_{DC} : Is 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 a GA. In the next section, the optimum values of the parameters.

K_{DC}, $T_1$and T_2 : For damping controller, resulting from minimizing the performance index are presented. This case for performance index was considered:

Case 1: $\alpha = 1$, $1 = \beta$ (frequency deviations and DC voltage deviation are equally penalized).

It should be noted that the α and β are weighting coefficients, which chosen by the designer.

Design of optimal damping controller: To calculate the performance index, a digital simulation of the system was performed over a solution time period of 100 sec, for each of the individuals of the current population. The values of the performance index thus obtained were fed to the GA 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 GA used here utilizes direct manipulation of the parameters.

The following GA parameters were used in present research:

- Number of Chromosomes: 3
- 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 2.

Also washout parameter is considered as $T_w = 10$. After employ this damping controller to system, the eigen-values of the system with damping controller are obtained (Table 3) and it is clearly seen that the system is stable.

To show effectiveness of GA method, a classic lead-lag damping controller is designed. The parameters of the classic damping controller are obtained using the phase compensation technique. The detailed step-by-step procedure for computing the parameters of the damping controllers using phase compensation technique is presented in (Yu, 1983; Wang *et al.*, 1997). The parameters of classic damping controllers were designed and obtained as Table 4. Wash-out block is considered and also damping ratio is considered as 0.5 in this design.

Table 2: 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 3: Eigen - values of the closed-loop system with damping controller

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

Table 4: Classical damping controller parameters

K_{DC}	570.02
T_1	0.029
T_2	0.1
$T\omega$	10

RESULTS

The GA damping controller presented in previous section is now applied to produce damping in test system.

The results obtained with the GA damping controller are compared to those obtained with the lead-lag controller applied to the series converter side. For evaluation of proposed method, 2 cases were simulated. case 1: nominal operation condition (operating point 1) and case 2: heavy operation condition (operation point 2). Both, GA and lead-lag damping controllers were designed for the nominal operating condition.

The linear model and linear simulations are suitable for study of small disturbance in power system like step change in mechanical torque or so on. But a detailed non-linear simulation is required to prove the robustness of the designed controllers. Therefore, nonlinear simulations are presented here for study of large disturbance such as short circuit and small disturbances such as step change in power system. However, in this study the nonlinear simulation results to 3-phase short circuit in generator terminals and step change in mechanical torque are presented.

The performance of the designed damping controllers after 0.1 step change in mechanical torque, were compared and shown in Fig. 5 for case 1. Figure 5 shows that adding the supplementary control signal greatly enhances the damping of the generator angle oscillations and therefore, the system becomes more stable. The GA damping controller performs better than the conventional controller.

To study the effectiveness of proposed GA controller for large disturbance, the performance of the designed GA damping and classic damping controllers after 3-phase short circuit in generator terminals, were compared and shown in Fig. 6 for case 1. Figure 6 shows that the proposed GA damping controller compared to classic damping which have the best ability to control power system under large disturbance faults.

Also to study of system operation under heavy load, both damping controllers were applied for case 2. The simulation results are shown in Fig. 7. Under this condition, while the performance of classic supplementary controller becomes poor, the GA controller has a good and robust performance. We can conclude the GA

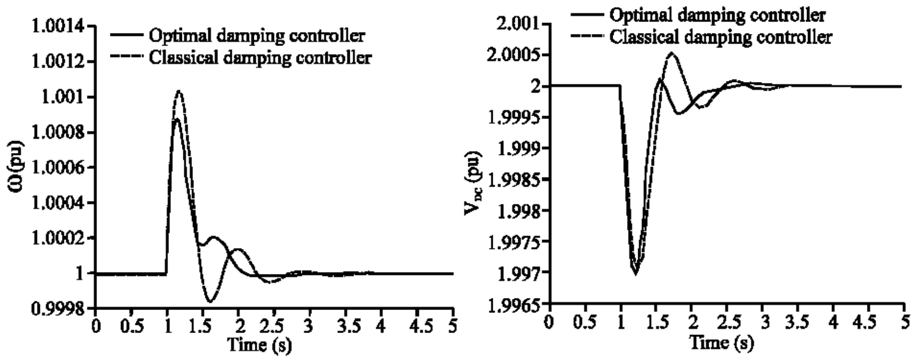

Fig. 5: Dynamic responses at nominal load (operating condition 1), following 0.1 step in mechanical torque (Δtm); a: Speed variation, b: DC-voltage variation

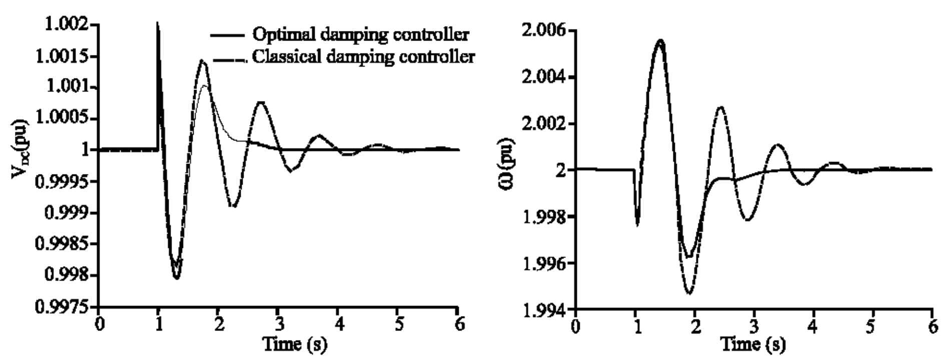

Fig. 6: Dynamic responses with considering 17 ms transitory 3-phase fault at the generator terminals at nominal load (operation condition 1); a: Speed variation, b: DC-voltage variation

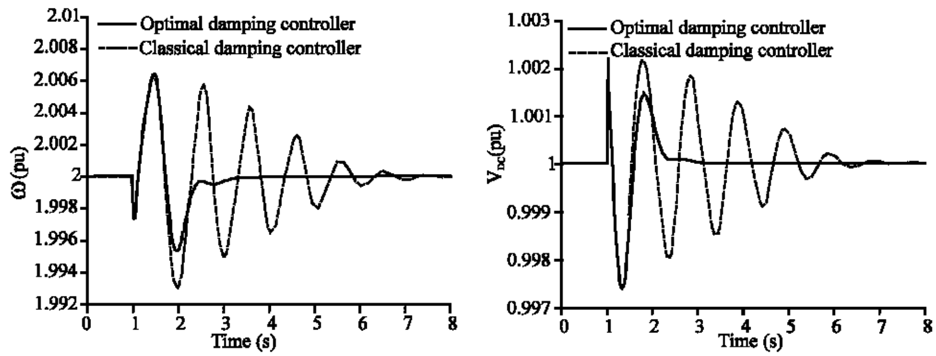

Fig. 7: Dynamic responses with considering 17 ms transitory 3-phase fault at the generator terminals at heavy load (operation condition 2); a: Speed variation, b: DC-voltage variation

supplementary controller have good parameter adaptation in comparison with the classic supplementary controller when operation condition changes. Also, simulations are carried out in Matlab (2006).

CONCLUSION

In this study, Genetic Algorithms have been successfully applied to tune the parameters of supplementary damping controller for UPFC. Design strategy includes enough flexibility to setting the desired level of stability and performance and considering the practical constraint by introducing appropriate uncertainties.

The proposed method was applied to a typical SIMB power system installed with an UPFC with various loads conditions. Simulation results demonstrated that the designed controller capable to guarantee the robust stability and robust performance under a various load conditions and large disturbances. Also, non-linear simulation results show that the proposed method has an excellent capability in damping of power system oscillations and enhance of power system stability under large disturbances in compare to classical method.

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