Design of an Immune-Genetic Algorithm-Based Optimal State Feedback Controller as UPFC

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***Abstract*-an optimal design of state feedback controller as an UPFC using immune genetic algorithm (IGA) is presented. The potential of the UPFC supplementary state feedback controllers to enhance the dynamic stability is evaluated. The selection of the state feedback gains for the UPFC controllers is converted to an optimization problem with the time domain-based objective function which is solved by an IGA. The effectiveness of the new controller is demonstrated through time-domain simulation studies. The results of these studies show that the designed controller has an excellent capability in damping power system oscillations.**

I. INTRODUCTION

With the increasing electric power demand, power systems can reach stressed conditions, resulting in undesirable voltage and frequency conditions. Flexible ac transmission systems devices are one of the recent propositions to alleviate such situations by controlling the power flow along transmission lines and improving power oscillations damping. In addition, interconnection between remotely located power systems gives rise to low frequency oscillations in the range of 0.5–3.0 Hz. These oscillations may keep growing in magnitude until loss of synchronism results [1, 2]. In order to damp these oscillations and increase stability, the installation of power system stabilizer (PSS) is both economical and effective. PSSs have been used years. However, PSSs suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation and losing system stability under severe disturbances [3].

Recently, FACTS technology is emerging as an interesting approach to help in alleviating several power system operating difficulties, such as inter-area oscillations and controlling voltages at critical buses. Through the modulation of bus voltage, phase shift between buses, and transmission line reactance, FACTS devices can cause a substantial increase in power transfer limits during steady-state. Among the available FACTS devices for transient stability enhancement, the unified power flow controller (UPFC) is the most versatile one [4]. The UPFC is a solid-state controller to control active and reactive power flows in a transmission line. Recently researchers have presented dynamic models of UPFC in order to design suitable controllers.

Nabavi-Niaki and Iravani [5] developed a steady-state model, a small-signal linearized dynamic model, and a state-space large-signal model of a UPFC. Wang [6] presents the establishment of the linearized Phillips–Heffron model of a power system installed with a Unified Power Flow Controller. He has not presented a systematic approach for designing the damping controllers. Further, no efforts have been made to identify the most suitable UPFC control parameter, in order to arrive at a robust damping controller. Mishra et al. [7] developed a Takagi–Sugeno fuzzy logic controller for an UPFC to damp both local and inter-area modes of oscillation for a multi-machine power system. Ref. [8] used the linear matrix inequality (LMI) formulation to approach the UPFC controller design based on H_∞ control scheme.

In this paper the stabilizers with state feedback schemes is applied to a unified power flow controller. Local and available states ($\Delta\delta$, $\Delta\omega$, $\Delta E'_q$, ΔE_{fd} and ΔV_{dc}) are used as the inputs of each controller. The design problem of controller is converted to an optimization problem and IGA is employed to solve this problem. The nonlinear simulation results have been carried out to assess the effectiveness of the proposed controllers under different loading conditions, and system configurations.

II. POWER SYSTEM MODEL

Fig. 1 shows a SMIB system equipped with a UPFC. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs), and a DC link capacitors. Parameters of the example power system are given in the Appendix. The four input control signals to the UPFC are m_E, m_B, δ_E and δ_B, where, m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle, and δ_B is the boosting phase angle.

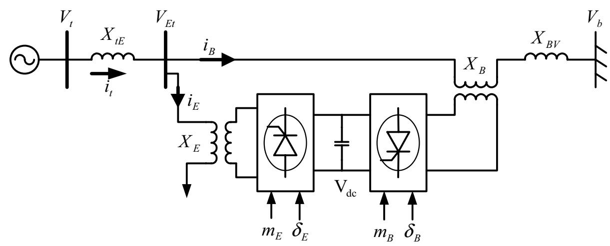


Figure 1. SMIB power system equipped with UPFC.

A. Dynamic Model of the UPFC

The dynamic model of the UPFC is required in order to study the effect of the UPFC on enhancing the small signal stability of the power system. For the study of power system oscillation stability, the resistance and transient of the transformers of the UPFC can be ignored. The dynamic equations of the UPFC can be written as [1]:

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos\delta_E v_{dc}}{2} \\ \dfrac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos\delta_B v_{dc}}{2} \\ \dfrac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \tag{2}$$

$$\begin{aligned} \dot{v}_{dc} &= \frac{3m_E}{4C_{dc}} [\cos\delta_E \quad \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} \\ &+ \frac{3m_B}{4C_{dc}} [\cos\delta_B \quad \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \end{aligned} \tag{3}$$

where v_{Et} , i_E , v_{Bt} and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage, respectively.

The non-linear model of the SMIB system shown in Fig. 1 is:

$$\dot{\delta} = \omega_0(\omega - 1) \tag{4}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{5}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{6}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \tag{7}$$

From Fig. 1 we can have:

$$\bar{v} = jx_{tE}\bar{i}_t + \bar{v}_{Et} \tag{8}$$

$$\bar{v}_{Et} = \bar{v}_{Bt} + jx_{BV}\bar{i}_B + \bar{v}_b \tag{9}$$

$$\begin{aligned} v_d + jv_q &= x_q(i_{Eq} + i_{Bq}) + j(E'_q - x'_d(i_{Ed} + i_{Bd})) \\ &= jx_{tE}(i_{Ed} + i_{Bd} + j(i_{Eq} + i_{Bq})) + v_{Ed} + jv_{Eq} \end{aligned} \tag{10}$$

where i_t and v_b, are the armature current and infinite bus voltage, respectively and v_{Et} , v_{Bt} , i_B and i_E are the ET voltage, BT voltage, BT current and ET current respectively.

B. Power System Linearized Model

The linearized model of power system shown in Fig. 1 is given as follows [1]:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{11}$$

$$\Delta\dot{\omega} = \frac{1}{M}\left(\Delta P_m - \Delta P_e - D\Delta\omega\right) \tag{12}$$

$$\Delta\dot{E}'_q = \frac{1}{T'_{d0}}\left(\Delta E_{fd} - (x_d - x'_d)\Delta i_d - \Delta E'_q\right) \tag{13}$$

$$\Delta\dot{E}'_{fd} = \frac{1}{T_A}\left(K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd}\right) \tag{14}$$

$$\begin{aligned} \Delta\dot{v}_{dc} &= K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E \\ &+ K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \end{aligned} \tag{15}$$

Where

$$\begin{aligned} \Delta P_e &= K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E \\ &+ K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \end{aligned} \tag{16}$$

$$\begin{aligned} \Delta E'_q &= K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E \\ &+ K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \end{aligned} \tag{17}$$

$$\begin{aligned} \Delta v &= K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E \\ &+ K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \end{aligned} \tag{18}$$

$K_1, K_2, \cdots, K_9$, K_{pu} , K_{qu} and K_{vu} are linearization constants. The block diagram of the linearized dynamic model of the SMIB power system with UPFC is shown in Fig. 2.

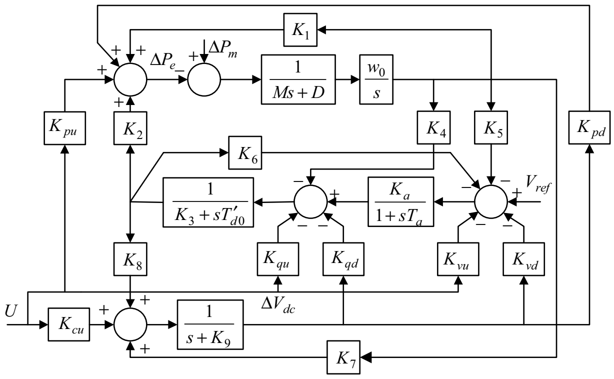


Figure 2. Modified Heffron–Phillips block diagram.

C. State Feedback Controller for UPFC

The state-space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{19}$$

Where, the state vector x is:

$$x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{dc}] \tag{20}$$

Where the input vector u is composed of the control vector U_S and disturbance vector U_d , both m×1 vectors; x is an n×1 state vector; A is an n×n plant matrix of the open-loop system and B is an n×m input matrix; n and m are the number of state variables and control signals, respectively. In this paper δ_E and m_B are modulated in order to state feedback controller design. The following control input vector is defined [9]:

$$U_s = Kx \tag{21}$$

Where, K is the feedback gain matrix with appropriate dimensions. Applying (21) to (19) we have:

$$\dot{x} = A_c x + Bu_d \tag{22}$$

$$A_c = A + BK \tag{23}$$

D. Objective Function

In this work, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. The objective function is defined as follows:

$$J = \int_0^{t_{sim}} t\,|\Delta\omega|\,dt \tag{24}$$

Where t_{sim} is the time range of simulation which the optimization is carried out. For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. In this paper the IGA is employed to solve this optimization problem and search for an optimal set of state feedback controller parameters.

III. Immune-Genetic Algorithm

A. Immune Algorithm

The vertebrate immune system is one of the most intricate bodily systems and its complexity is sometimes compared to that of the human brain. Knowledge of immune system functioning has revealed several of its main operative mechanisms. These mechanisms are very interesting not only from a biological standpoint, but also from a computational perspective. IA uses learning, memory, and associative retrieval to solve recognition relevant patterns, remember patterns that have been seen previously, and use combinatory to construct pattern detectors efficiently [10-11].

B. Immune-Genetic Algorithm

The key problem for applying genetic algorithms to constrained optimization is how to handle constraints because genetic operators used to manipulate the chromosomes often yields infeasible offspring. Owing to the fact that all chromosomes in all genetic iterations have to be checked, the feasibility checking procedure is very time-consuming. It usually causes the genetic algorithms for constrained optimization to yield lower computational efficiency. To get over the defects of GA, we introduce the immune theory into GA, and promote Immune-Genetic Algorithm (IGA).The key features of IGA may be summarized under the following terms of computation:

Step 1. Generating the first population randomly.
Step 2. Calculating the population fitness .
Step3. Generating new chromosome by RCGA algorithm.
Step 4. Replacing the new chromosome with the lowest fitness if the affinity function becomes more than threshold value [12].

The affinity fitness can be considered as Oghlidus-distance or Haming-distance and it is shown by m_{ij} . New chromosome can come in the population if the ratio of it affinity function to the total affinity function of all the population becomes more than a threshold value. It means if the formula 26 is satisfied, the chromosome can come to the population:

$$\frac{\sum_j (m_{ij} f_i)}{\sum_j m_{ij}} \geq T \tag{25}$$

$$m_{ij} = \frac{k_m}{d_{ij}} = \frac{k_m}{\sqrt{\sum (x_i - x_j)^2}} \tag{26}$$

$$T = K \frac{\sum_j f_j}{N} \tag{27}$$

The flowchart of the Immune-Genetic Algorithm is shown in Fig. 3.

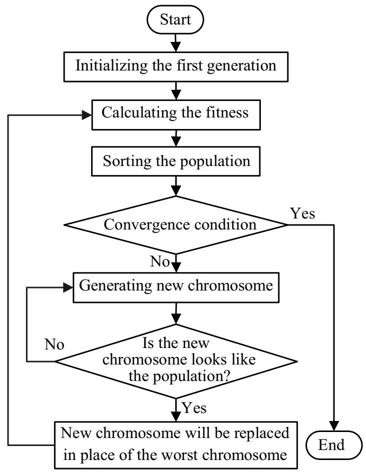


Figure 3. Flowchart of IGA Algorithm.

IV. Simulation Results

A. Design of State Feedback Controllers

The IGA has been applied to search for the optimal parameter settings of each of the supplementary controllers. In order to facilitate comparison with GA, the tuning of state feedback controller for example power system were used. The final parameter settings of the controllers are given in Table I .

TABLE I. Optimal parameters of the controllers

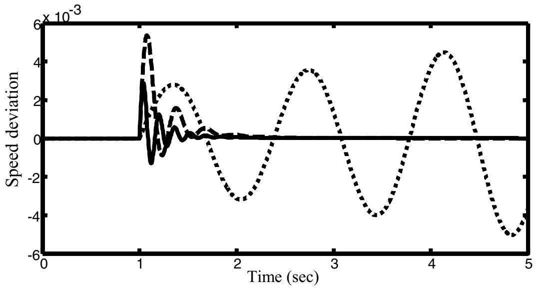
Controller parameters	δ_E		m_B	
	IGA	GA	IGA	GA
K_1	80.02	28.20	40.25	55.32
K_2	86.45	69	76.56	84.87
K_3	0.6904	0.8621	0.1412	0.3673
K_4	0.0391	0.0846	0.0481	0.0351
K_5	4.58	8.84	4.74	4.25

TABLE II. Loading conditions

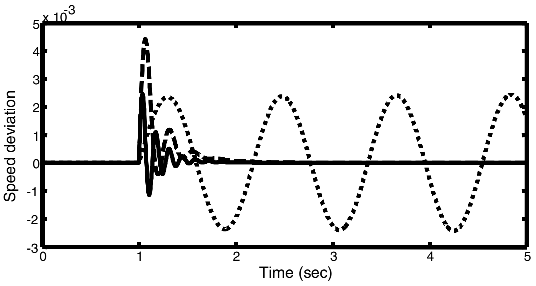
Loading condition	P_e(pu)	Q_e(pu)
nominal	0.8	0.15
light	0.2	0.01
heavy	1.2	0.4

B. Time Domain Simulation

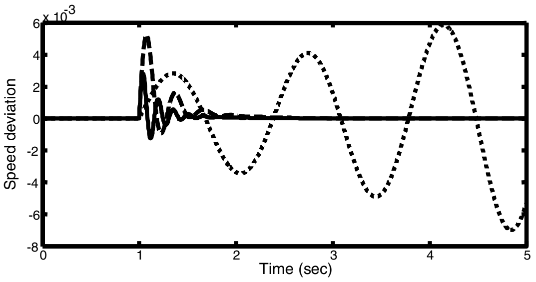
To assess the effectiveness of the proposed stabilizers, three different loading conditions are considered (Table 2). The system behavior due to the utilization of the proposed controllers under transient conditions has been tested by applying a 6-cycle 3-phase fault at the infinite bus at t = 1 s. The Dynamic responses with UPFC damping controllers for different loading conditions are shown in Figs. 4 and 5. It is clearly seen that the responses are hardly affected in terms of settling time following wide variations in loading condition. It can be seen that the IGA based controller achieves good robust performance, provides superior damping in comparison with the GA based controller and enhance greatly the dynamic stability of power systems.



(a)

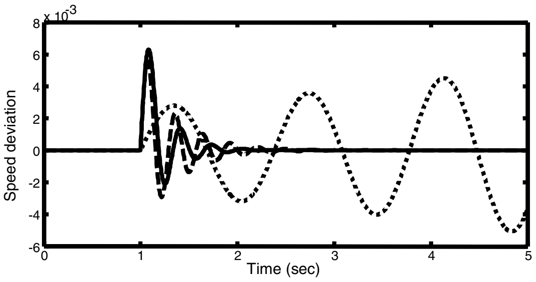


(b)

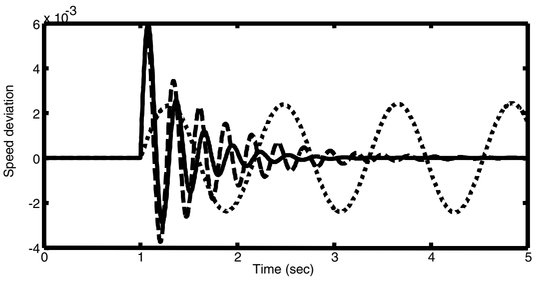


(c)

Figure 4. Dynamic responses δ_E controller at (a) nominal (b) light (c) heavy loading; Solid (IGA based controller), Dashed (GA based controller) and Dotted (Without controller).



(a)



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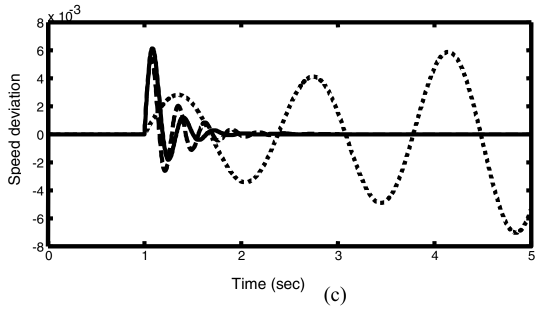

(c)

Figure 5. Dynamic responses m_B controller at (a) nominal (b) light (c) heavy loading; Solid (IGA based controller), Dashed (GA based controller) and Dotted (Without controller).

V. CONCLUSION

The immune-genetic algorithm has been successfully applied to the design of robust state feedback UPFC based damping controller. The design problem of the selecting state feedback controller parameters is converted into an optimization problem which is solved by IGA. The non-linear time domain simulation results show that the oscillations of synchronous machines can be quickly and effectively damped for power systems with the proposed controller and improves the transient stability under different operating conditions.

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