Optimal Based Damping Controllers of Unified Power Flow Controller using Adaptive Tabu Search

Rungnapa Taithai, and Anant Oonsivilai

***Abstract*—This paper presents optimal based damping controllers of Unified Power Flow Controller (UPFC) for improving the damping power system oscillations. The design problem of UPFC damping controller and system configurations is formulated as an optimization with time domain-based objective function by means of Adaptive Tabu Search (ATS) technique. The UPFC is installed in Single Machine Infinite Bus (SMIB) for the performance analysis of the power system and simulated using MATLAB's simulink. The simulation results of these studies showed that designed controller has an tremendous capability in damping power system oscillations.**

***Keywords*—Adaptive Tabu Search (ATS), damping controller, Single Machine Infinite Bus (SMIB), Unified Power Flow Controller (UPFC).**

I. Introduction

POWER systems are today much more loaded than before due to growing rapidly in power demand including expansion in transmission and generation is restricted. This causes the power systems to be operated next to their stability limits, power system oscillation and finally power system instabilities.

Recently development of power electronics devices introduces the use of systems Flexible AC Transmission System (FACTS) controllers in power system. FACTS devices have been effective in controlling power flow and damping power system oscillations [1]. UPFC is one of the most complex FACTS devices in a power system. It is primarily used for independent control of real and reactive power in transmission lines [2], [3]. UPFC could be applied for improvement by damping of power system oscillations [4], [5].

In the previous research have presented lead-lag controller type and output feedback controller type UPFC damping controllers [6], [7], [8]. They are designed for a specific operating condition using linear models of modified Heffron-Phillips transfer function model [9], [10]. The advanced control schemes such as Particle Swarm Optimization and Genetic algorithms [11], Chaotic Optimization [12] and Shuffled Frog Leaping Algorithm [13] offer better dynamic performances than fixed parameter controllers.

The based damping controllers of UPFC parameter were formulated as an optimization problem. By minimizing the objective function in which the influences of speed deviation are considered.

The main objective of this paper is to investigate the ability of optimization methods was ATS algorithm [14] for UPFC supplementary based damping controller design. This algorithm optimizes the total system performance by means of ATS algorithm. A modified linear Heffron-Phillips model of SMIB power system installed with UPFC is considered as case study and a UPFC based damping controller whose parameters are optimized using ATS algorithm is considered as power system oscillations. Simulation results show the validity of proposed methods in damping of power system oscillations.

II. Description of the Case Study

Fig. 1 shows a SMIB power system installed with a UPFC. The static excitation system model type IEEE-ST1A has been considered which consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSC) and a dc link capacitor. In Fig. 1, m_B, m_E and δ_B, δ_E are the amplitude modulation ratio and phase angle of the control signal of each voltage source converter, which are input control signals of UPFC parameter. The nominal loading condition and system parameters are given in Appendix.

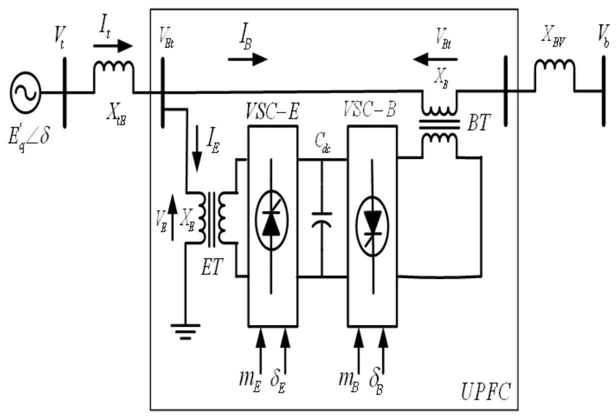

Fig. 1 A SMIB power system installed with a UPFC

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International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:6, No:12, 2012

A. Power System Nonlinear Model with UPFC

The dynamic model of UPFC is required in order to the UPFC effect study for enhancing small signal stability of power system. Park's transformation is applied and neglecting the resistance and transients of the ET and BT transformers, UPFC can be modeled as:

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

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

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

where, v_E, i_E, v_B and i_B are excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are dc link capacitance and voltage. The nonlinear model of SMIB power system shown in Fig. 1 is described by:

$$\dot{\delta} = \omega_0 \Delta\omega \tag{4}$$

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

$$\dot{E}_q' = \left(-E_q + E_{fd}\right)/T_{d0}' \tag{6}$$

$$\dot{E}_{fd} = -\frac{1}{T_a} E_{fd} + \frac{K_a}{T_a}\left(V_{t0} - V_t\right) \tag{7}$$

where

$$P_e = v_{tq} i_{tq} + v_{td} i_{td} \tag{8}$$

$$E_q = E_q' + \left(X_d - X_d'\right) i_{td} \tag{9}$$

$$v_{tq} = E_q' - X_d' i_{td} \tag{10}$$

$$v_{td} = X_q i_{tq} \tag{11}$$

$$V_t = \sqrt{\left(v_{td}^2 + v_{tq}^2\right)} \tag{12}$$

$$i_{td} = i_{Ed} + i_{Bd} \tag{13}$$

$$i_{tq} = i_{Eq} + i_{Bq} \tag{14}$$

B. Power System Linearized Model with UPFC

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system shown in Fig. 1 is given as in the following:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{15}$$

$$\Delta\dot{\omega} = \left(\Delta P_m - \Delta P_e - D\Delta\omega\right)/M \tag{16}$$

$$\Delta\dot{E}_q' = \left(-\Delta E_q + \Delta E_{fd}\right)/T_{d0}' \tag{17}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_a}\Delta E_{fd} + \frac{K_a}{T_a}\Delta V_t \tag{18}$$

$$\begin{aligned} \Delta P_e &= K_1\Delta\delta + K_2\Delta E_q' + K_{pd}\Delta V_{dc} \\ &\quad + K_{pe}\Delta m_E + K_{p\delta_e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta_b}\Delta\delta_B \end{aligned} \tag{19}$$

$$\begin{aligned} \Delta E_q' &= K_4\Delta\delta + K_3\Delta E_q' + K_{qd}\Delta V_{dc} \\ &\quad + K_{qe}\Delta m_E + K_{q\delta_e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta_b}\Delta\delta_B \end{aligned} \tag{20}$$

$$\begin{aligned} \Delta V_t &= K_5\Delta\delta + K_6\Delta E_q' + K_{vd}\Delta V_{dc} \\ &\quad + K_{ve}\Delta m_E + K_{v\delta_e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta_b}\Delta\delta_B \end{aligned} \tag{21}$$

$$\begin{aligned} \Delta\dot{V}_{dc} &= K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta V_{dc} \\ &\quad + K_{ce}\Delta m_E + K_{c\delta_e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta_b}\Delta\delta_B \end{aligned} \tag{22}$$

where, $K_1, K_2, \ldots, K_9$, K_{pu}, K_{qu}, K_{vu} and K_{cu} are linearization constants [5]. The state-space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{23}$$

where, the state vector x, control vector u, A and B are:

$$x = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E_q' & \Delta E_{fd} & \Delta V_{dc} \end{bmatrix}^T$$

$$u = \begin{bmatrix} \Delta m_E & \Delta\delta_E & \Delta m_B & \Delta\delta_B \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\dfrac{K_1}{M} & -\dfrac{D}{M} & -\dfrac{K_2}{M} & 0 & -\dfrac{K_{pd}}{M} \\ -\dfrac{K_4}{T_{d0}'} & 0 & -\dfrac{K_3}{T_{d0}'} & \dfrac{1}{T_{do}'} & -\dfrac{K_{qd}}{T_{d0}'} \\ -\dfrac{K_a K_5}{T_a} & 0 & -\dfrac{K_a K_6}{T_a} & -\dfrac{1}{T_a} & -\dfrac{K_a K_{vd}}{T_a} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$
B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\dfrac{K_{pe}}{M} & -\dfrac{K_{p\delta_e}}{M} & -\dfrac{K_{pb}}{M} & -\dfrac{K_{p\delta_b}}{M} \\ -\dfrac{K_{qe}}{T'_{d0}} & -\dfrac{K_{q\delta_e}}{T'_{d0}} & -\dfrac{K_{qb}}{T'_{d0}} & -\dfrac{K_{q\delta_b}}{T'_{d0}} \\ -\dfrac{K_a K_{ve}}{T_a} & -\dfrac{K_a K_{v\delta_e}}{T_a} & -\dfrac{K_a K_{vb}}{T_a} & -\dfrac{K_a K_{v\delta_b}}{T_a} \\ K_{ce} & K_{c\delta_e} & K_{cb} & K_{c\delta_b} \end{bmatrix}
$$

In Fig. 2 shows the block diagram of the linearized dynamic model of SMIB power system installed with UPFC.

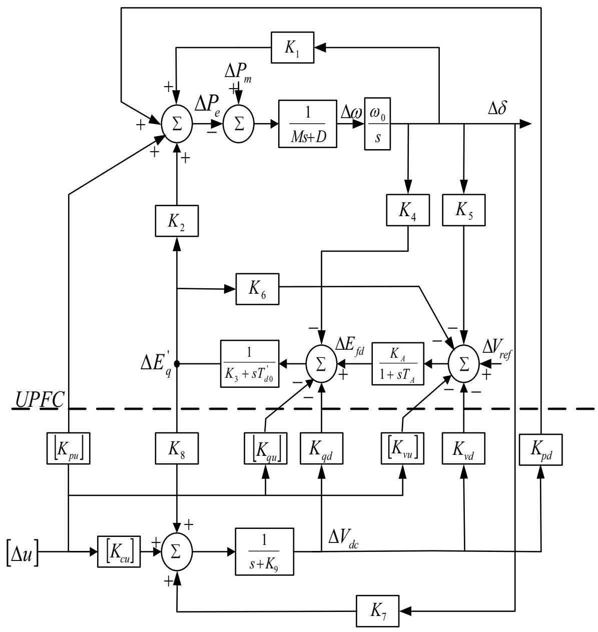

Fig. 2 Modified Heffron-Phillips transfer function model

III. Damping Controller of UPFC

The damping controllers are designed to produce an electrical torque in phase with speed deviation. The four control signal parameters of the UPFC (m_B, m_E, δ_B and δ_E) could be modulated in order to produce the damping torque. The speed deviation ($\Delta\omega$) is considered as the damping controllers input. In this paper shows two control signal parameters, m_B and δ_E, alternative are modulated and phase angle of UPFC based damping controllers in order to coordinated design.

The conventional approach is achieved by lead-lag compensator employment as shown in Fig. 3. The block consists of three blocks namely gain block, washout block and lead-lag compensator. The time constants are varied periodically to effect damping of oscillation. The change in speed deviation is fed as input and the output is fed to the UPFC parameters for stability improvement.

The block represents the lead-lag compensation where the output parameter is the controller parameter selected to achieve damping in UPFC.

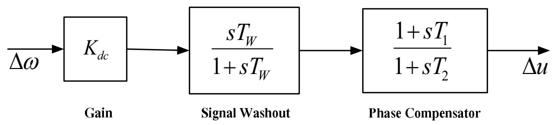

Fig. 3 Simplified UPFC damping controller block diagram

Where, K_{dc} is the controller gain, T_1 and T_2 are the time constants of compensation, T_w is the time constant of washout. The value of T_w is not critical and may be in the ranges of 1 to 20 seconds. The T_w equal to 10 seconds is chosen in the present studies [13].

IV. Objective Function

Selecting optimal values for UPFC controller parameters of a closed loop system is usually an iterative process and called parameter tuning. The ATS algorithm was applied to improve optimization synthesis and find the global optimum value of fitness function. In this work, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. Since the operating conditions in power systems are often varied, a performance index for a wide range of operating points is defined as follows:

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

where, $\Delta\omega(t)$ is the speed deviation and t_{sim} is time range of simulation.It is designed to minimize this objective function for improving system response in terms of the settling time and overshoots. The design problem could be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

$$
\begin{aligned}
&Minimize \quad J \quad subject \quad to: \\
&K_{dc}^{\min} \le K_{dc} \le K_{dc}^{\max} \\
&T_1^{\min} \le T_1 \le T_1^{\max} \\
&T_2^{\min} \le T_2 \le T_2^{\max}
\end{aligned}
$$

Typical ranges of the optimized parameters are [0.01-100] for K and [0.01-1] for T_1 and T_2 [12]. The UPFC controller parameters optimization is carried out by evaluating the cost function as given in equation (24).

V. Adaptive TABU Search Algorithm

ATS technique is the extended version of the Tabu search (TS) algorithm by adding both concepts that is back tracking and adaptive radius. These both concepts could improve the TS method performance. The TS technique normally provides local solution when the problem is complicated having many local points. Hence, the back tracking part and adaptive radius added to TS algorithm (called ATS) could escape local lock providing global solution. The more ATS details could be found in [14]. The diagram of ATS for optimization based damping controller of UPFC parameters is shown in Fig. 4 [15].

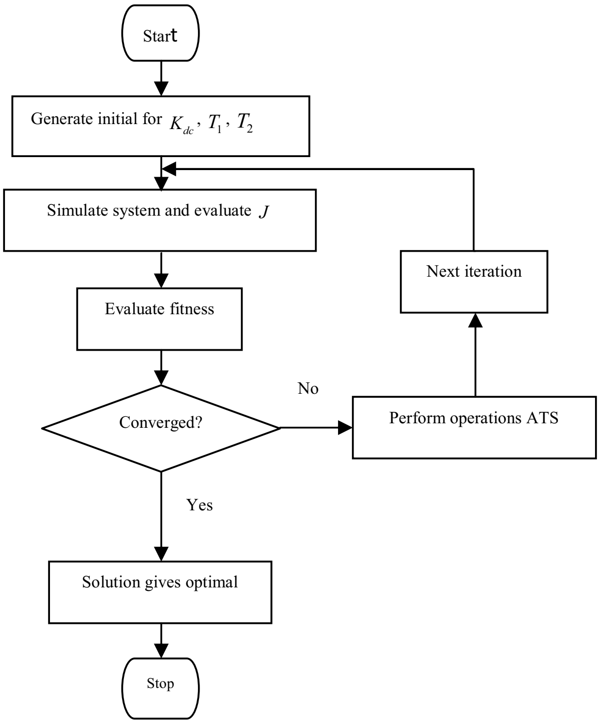

Fig. 4 Flow chart for the ATS process

VI. Simulation Results

In this section, the SMIB power system installed with UPFC was investigated. The simulation has been carried out with Modified Heffron- Phillips transfer function model in MATLAB's simulink. The simulation result of the Modified Heffron- Phillips transfer function model with four different input control signals under nominal loading conditions in mechanical power input is measured for analysis. Here, using two of input control signals are Include m_B and δ_E which is controlled by base damping controllers of UPFC parameters obtained from ATS algorithm.

Now, in order to damp the oscillations of power system will be equipped with input control signals of damping controller using ATS algorithms.

A sample step distortion has been exerted on input of system block diagram at t=0.5 sec and simulated. Fig. 5 and Fig. 6 shows the simulation result of speed deviation ($\Delta\omega$) of the power system implemented by MATLAB's simulink according to the dynamic model which using input signals m_B and δ_E are shows in Fig. 5 and Fig. 6, respectively.

In Fig. 5 and Fig. 6 the ATS algorithm on based damping controller of UPFC could noticeably damp the speed deviation $(\Delta\omega)$ and improve the dynamic response of the system.

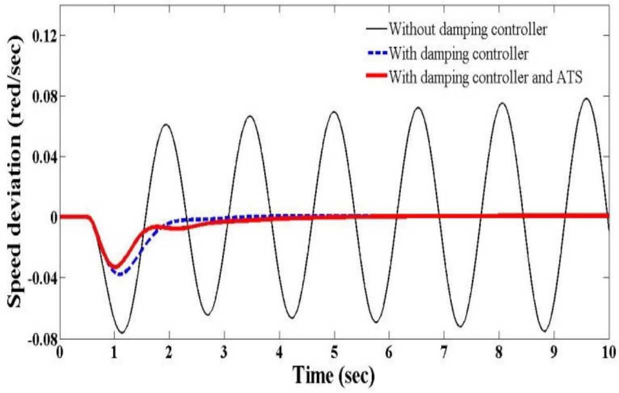

Fig. 5 Dynamic responses for $\Delta\omega$ with base damping controller (m_B)

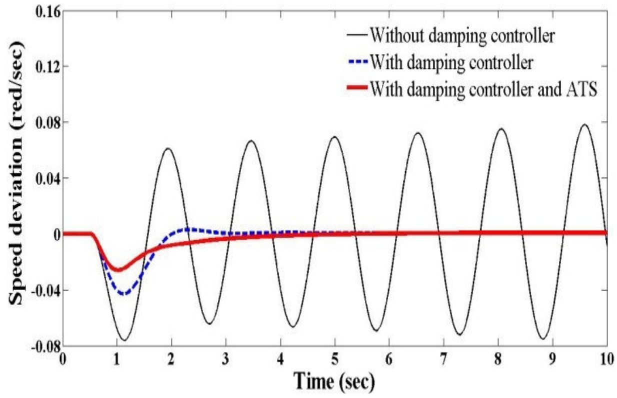

Fig. 6 Dynamic responses for $\Delta\omega$ with base damping controller (δ_E)

In addition, a sample step distortion has been exerted on the input of system block diagram at t=0.5 sec and simulated. The simulation result of electrical power variation (ΔP) of power system implemented by MATLAB's simulink according to dynamic model using input signals m_B and δ_E are shown in Fig. 7 and Fig. 8. The ATS algorithm on based damping controller of UPFC could noticeably damp the variation of electrical power (ΔP) and improve the dynamic response of the system.

ISSN: 2517-9942
Vol:6, No:12, 2012

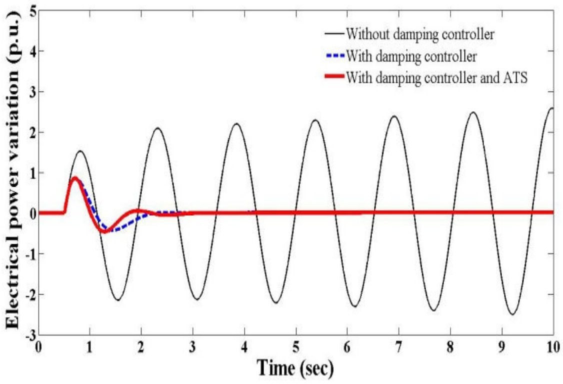

Fig. 7 Dynamic responses for ΔP with base damping controller (m_B)

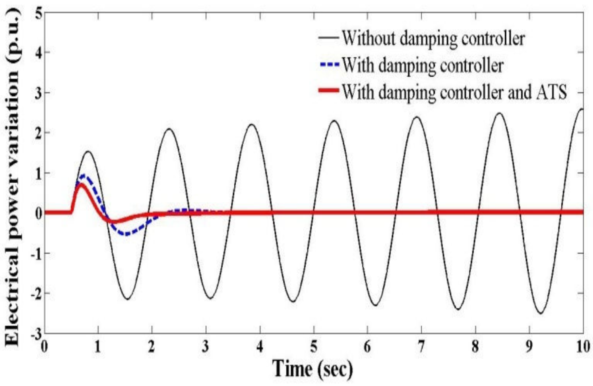

Fig. 8 Dynamic responses for ΔP with base damping Controller (δ_E)

The based damping controller parameter of UPFC could be damp the damp speed deviation ($\Delta\omega$) and variation of electrical power (ΔP) of power system when using ATS algorithm to optimization is shown in Table I.

TABLE I
THE OPTIMAL BASED DAMPING CONTROLLERS OF UPFC

controller	K_{dc}		
m_B	93.6870	0.2695	0.5740
δ_E	94.9650	0.2637	0.9895

VII. CONCLUSION

This paper presents overall model development of UPFC in SMIB power system. The model has been practical to design the optimal damping controller. The design problem of damping controller of UPFC parameters are optimization problem solved by ATS technique with time domain-based objective function. Time-domain simulations show that the oscillations of power system could be speedily and effectively. Simulation results show that the ATS algorithm has an exceptional capability in power system oscillations damping and power system stability enhancement under small disturbances.

APPENDIX

The nominal parameter and the operating condition of the system are given below:
Generator:

$$M = 2H = 0.8\, MJ/MVA \qquad D = 0.0 \qquad T'_{d0} = 5.044s$$
$$X_d = 1.0\,p.u. \;\; X_q = 0.6\,p.u. \;\; X'_d = 0.3\,p.u.$$

Excitation system:

$$K_a = 100$$
$$T_a = 0.01s$$

Transformer:

$$X_{tE} = 0.1\,p.u. \;\; X_E = X_B = 0.1\,p.u.$$

Transmission line:

$$X_{BV} = 0.3\,p.u. \;\; X_e = X_{Bv} + X_B + X_{tE} = 0.5\,p.u.$$

Operating condition:

$$P_e = 0.8\,p.u. \qquad Q = 0.167\,p.u. \qquad V_t = 1.0\,p.u.$$
$$V_b = 1.0\,p.u. \qquad f = 60Hz.$$

UPFC parameter:

$$m_E = 0.4013 \qquad m_B = 0.0789 \qquad \delta_E = -85.3478^o$$
$$\delta_B = -78.2174^o$$

Parameters of dc link:

$$V_{dc} = 2\,p.u. \;\; C_{dc} = 1\,p.u.$$

ACKNOWLEDGMENT

The authors would like to acknowledge support from School of Electrical Engineering, Institute of Engineering Suranaree University of Technology, Nakhon Ratchasima, Thailand, during a period of this work.

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