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Application of Tabu Search to UPFC Stabilizer Adjustment at a Multi Machine Electric Power System

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Abstract: Unified Power Flow Controller (UPFC) is one of the most viable and important Flexible AC Transmission Systems (FACTS) devises. Application of UPFC in single machine and multi machine electric power systems has been investigated with different purposes such as power transfer capability, damping of Low Frequency Oscillations (LFO), voltage support and so forth. But, an important issue in UPFC applications is to find optimal parameters of UPFC controllers. This paper presents the application of Unified Power Flow Controller (UPFC) to enhance dynamic stability of a multi-machine electric power system. A supplementary stabilizer based on UPFC (like power system stabilizer) is designed to reach the defined purpose. An intelligence optimization method based on Tabu Search (TS) is considered for tuning the parameters of UPFC supplementary stabilizer. Several nonlinear time-domain simulation tests visibly show the ability of UPFC in damping of power system oscillations and consequently stability enhancement.

Key words: Low frequency oscillations, multi machine electric power system, tabu search, unified power flow controller

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, 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. But UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time (Faried and Billinton, 2009; Mehraeen *et al*., 2010; Jiang *et al*., 2010a, b; Farrag and Putrus, 2011). Also, the UPFC 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. Many in the past have presented lead-Lag type UPFC damping controllers (Wang, 1999; Tambey and Kothari, 2003; Guo and Crow, 2009; Zarghami *et al*., 2010). They are designed for a specific operating condition using linearized models. More advanced control schemes such as Particle-Swarm method, Fuzzy logic and genetic algorithms (Eldamaty *et al*., 2005; Al-Awami, 2007; Hao *et al*., 2008; Singh *et al*., 2009) offer better dynamic performances than fixed parameter controllers.

The objective of this study is to investigate the ability of UPFC for dynamic stability enhancement via damping of low frequency oscillations at a multi machine electric power system. TS is incorporated for tuning the parameters of UPFC supplementary stabilizer. The proposed method is evaluated on a multi machine power system installed with a UPFC. A classical Power System Stabilizer (PSS) is connected to UPFC and the parameters of this UPFC based stabilizer are adjusted using TS. The advantages of the proposed methods are their feasibility and simplicity. Different load conditions are considered to show effectiveness of UPFC. Simulation results show the validity of UPFC in LFO damping and stability enhancement at large electric power systems.

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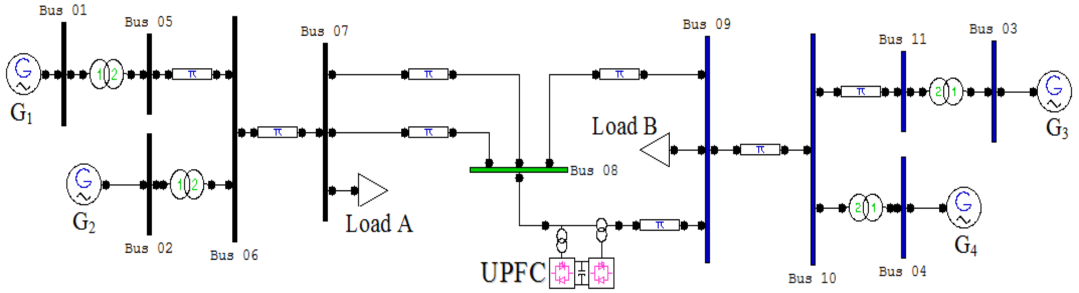

Fig. 1: Four-machine eleven-bus power system

Table 1: System loading conditions

	Light		Nominal		Heavy	
Load	P	Q	P	Q	P	Q
A	17.6258	-2.1000	18.5535	-2.625	20.4089	-2.630
B	9.64580	-0.8400	10.1535	-1.050	11.1689	-1.055

System under study: Figure 1 shows a multi machine power system installed with UPFC (Kundur, 1993). The static excitation system, model type IEEE-ST1A, has been considered. The UPFC is assumed to be based on Pulse Width Modulation (PWM) converters. Detail of the system data are given in (Kundur, 1993). To assess the effectiveness and robustness of the proposed method over a wide range of loading conditions, three different cases as nominal, light and heavy loading are considered and listed in Table 1.

Dynamic model of the system: The nonlinear dynamic model of the system installed with UPFC is given as (1). The dynamic model of the system is completely presented in (Kundur, 1993) and also dynamic model of the system installed with UPFC is presented in (Nabavi-Niaki and Iravani, 1996; Wang, 2000).

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

where,
i = 1, 2, 3, 4 (the generators 1 to 4)

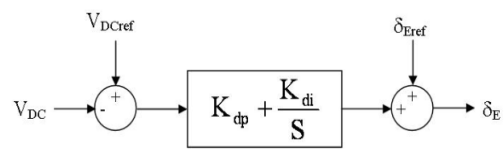

Fig. 2: DC-voltage regulator

- δ Rotor angle
- ω Rotor speed
- P_m Mechanical input power
- P_e Electrical output power
- E'_q Internal voltage behind x'_d
- E_{fd} Equivalent excitation voltage
- Te Electric torque
- T'_{do} Time constant of excitation circuit
- K_a Regulator gain
- T_a Regulator time constant
- V_{ref} Reference voltage
- V_t Terminal voltage
- m_B Pulse width modulation of series inverter. By controlling m_B, the magnitude of series- injected voltage can be controlled
- δ_B Phase angle of series injected voltage
- m_E Pulse width modulation of shunt inverter. By controlling m_E, the output voltage of the shunt converter is controlled
- δ_E 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.

UPFC controllers: In this study two control strategies are considered for UPFC:

- DC-voltage regulator
- UPFC supplementary stabilizer

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 2 shows the structure of DC-voltage regulator. In this paper the parameters of DC-voltage regulator are considered as K_{di} = 39.5 and K_{dp} = 6.54.

UPFC supplementary stabilizer: A stabilizer controller is provided to improve damping of power system oscillations. This controller is considered as a lead-lag compensator and it provides an electrical torque in phase with the speed deviation in order to improve damping of power system oscillations. The transfer function model of the classical stabilizer is as (2). Where, ω is the deviation in speed from the synchronous speed. This type of stabilizer consists of a washout filter, a dynamic compensator. The output signal is fed as a supplementary input signal to the UPFC. The washout filter, which essentially is a high pass filter, is used to reset the steady state offset in the output of the PSS. In this paper the value of the time constant (Tw) is fixed to 10 s. The dynamic compensator is made up to two lead-lag stages and an additional gain. The adjustable stabilizer parameters are the gain of the Stabilizer, K_{DC}, and the time constants, T1-T4. The lead-lag block present in the system provides phase lead compensation for the phase lag that is introduced in the circuit between the UPFC input and the electrical torque:

$$U = K\frac{ST_W}{1+ST_W}\frac{1+ST_1}{1+ST_2}\frac{1+ST_3}{1+ST_4}\Delta\omega \qquad (2)$$

Stabilizer design: Stabilizer controllers design themselves have been a topic of interest for decades, especially in form of classical Power System Stabilizers (PSS) which are connected to the excitation system of generator. But classical PSS cannot 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 on UPFC is provided to mitigate power system oscillations. An optimization method such as TS is handled for tuning stabilizer parameters. In the next section an introduction about TS is presented.

Tabu search: Tabu Search (TS) was first presented in its present form by Glover (1986). Many computational experiments have shown that TS has now become an established optimization technique which can compete with almost all known techniques and which - by its flexibility - can beat many classical procedures. Up to now, there is no formal explanation of this good behavior. Recently, theoretical aspects of TS have been investigated (Faigle and Kern, 1992).

The success with TS implies often that a serious effort of modeling be done from the beginning. In TS, iterative procedure plays an important role: for most optimization problems no procedure is known in general to get directly an "optimal" solution.

The general step of an iterative procedure consists in constructing from a current solution x_i a next solution x_j and in checking whether one should stop there or perform another step.

In other hand, a neighborhood $N(x_i)$ is defined for each feasible solution x_i and the next solution x_j is searched among the solutions in $N(x_j)$.

In this part we summarize the discrete TS algorithm in four steps. Assume that X is a total search space and x is a solution point sample and f(x) is cost function:

- Choose $x \in X$ to start the process
- Create a candidate list of non-Tabu moves in neighborhood. (x_i i = 1, 2, ..., N)
- Find $x_{winner} \in N(x)$ such that $f(x_{winner}) < f(x_i)$, $i \neq$ winner
- Check the stopping criterion. If satisfied, exit the algorithm.

If not, winner $x = x_{winner}$, update Tabu List and then go to step 2.

In order to exit from algorithm, there are several criterions that are considered in our research:

- By determining a predetermined threshold: If the value of cost function was less, algorithm would be terminated
- Determination of specific number of iterations
- If the value of the cost was remained invariable or negligible change for several iterations, algorithm would be terminated

A dedicated presentation of TS and a service of applications have been collected in (Glover *et al*., 1986).

TS based stabilizer design: In this section the parameters of the proposed stabilizer are tuned using TS. Four control parameters of the UPFC (m_E, δ_E, m_B and δ_B) can be modulated in order to produce the damping torque. The parameter m_E is modulated to output of damping controller and speed deviation Δw is also considered as input of damping controller. The optimum values of stabilizer parameters (K and T_1-T_4) which minimize an array of different performance indexes are accurately computed using TS. In optimization methods, the first

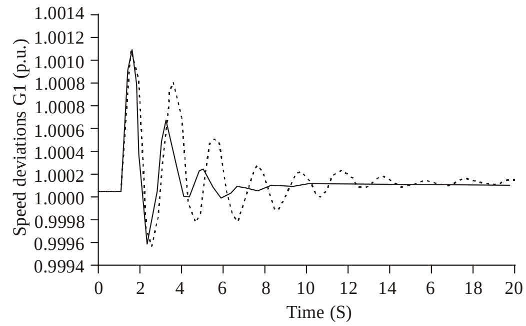

Fig. 3: Speed deviations generator 1 with nominal loading condition Solid (TS-stabilizer), Dashed (without-stabilizer)

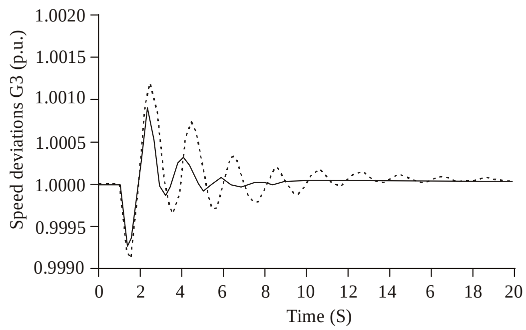

Fig. 4: Speed deviations generator 2 with nominal loading condition Solid (TS-stabilizer), Dashed (without-stabilizer)

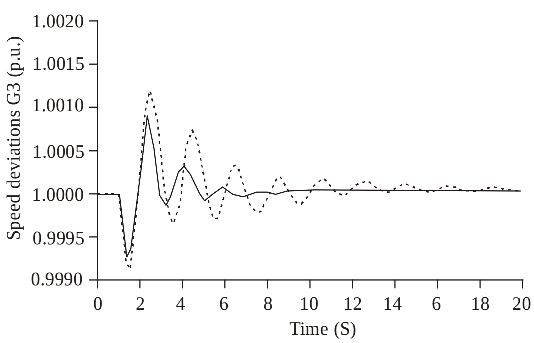

Fig. 5: Speed deviations generator 3 with nominal loading condition Solid (TS-stabilizer), Dashed (without-stabilizer)

step is to define a performance index for optimal search. In this study the performance index is considered as (3). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE).

$$ITAE = \int_0^t t\left|\Delta\omega_1\right|dt + \int_0^t t\left|\Delta\omega_2\right|dt + \int_0^t t\left|\Delta\omega_3\right|dt + \int_0^t t\left|\Delta\omega_4\right|dt \tag{3}$$

Table 2: Optimal parameters of stabilizer using TS

Parameter	K	T_1	T_2	T_3	T_4
Value	1.48	0.26	0.1921	0.889	0.214

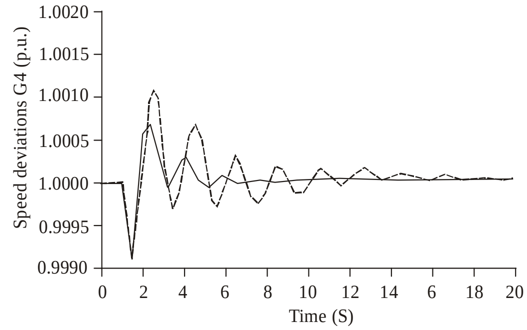

Fig. 6: Speed deviations generator 4 with nominal loading condition Solid (TS-stabilizer), Dashed (without-stabilizer)

where, Dw is the frequency deviation and parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 6 cycle three phase fault is assumed in bus 8 and the performance index is minimized using TS. The optimum values of parameters, resulting from minimizing the performance index is presented in Table 2.

RESULTS AND DISCURSION

In this section, the designed HS based stabilizer is exerted to damping LFO in the under study system. In order to study and analysis system performance, a three phase short circuit at bus 4 is considered as disturbances. The simulation results under proposed disturbance are presented in Fig. 3-6. Each figure contains two parameters as follows: TS based stabilizer (solid line) and system without stabilizer (dashed line). The simulation results show that applying the supplementary stabilizer signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. Under this disturbance, while the performance of system without stabilizer becomes poor, the TS stabilizer has a stable and robust performance. It can be concluded that the TS supplementary stabilizer have suitable parameter adaptation when operating condition changes. Also in all figures, the system responses without any supplementary stabilizer have been shown. It is clear to seen that the system without stabilizer does not have enough damping and the responses go to fluctuate after disturbance.

The results clearly show that in large electric power systems, UPFC can successfully increase damping of power system oscillations and the system with UPFC based stabilizer is more robust and stable after disturbances. In regular papers, short circuit is considered in order to study of system under disturbance but in this paper, considering different types of disturbances (disconnection of line and short circuit) helps to comprehensive study of UPFC under real world disturbances.

CONCLUSION

In this study Tabu search has been successfully exerted to design a supplementary stabilizer based on UPFC. A multi machine electric power system installed with a UPFC with various load conditions and disturbances has been assumed to demonstrate the ability of UPFC in stability enhancement via LFO damping. Considering real world type disturbances such as disconnection of line and three phase short circuit guarantee the results in order to implementation of controller in industry. Simulation results demonstrated that the designed UPFC based stabilizers capable to guarantee the robust stability and robust performance under a different load conditions and disturbances. Application to a multi machine electric power system which is near to practical systems can increase admission of the technique for real world applications.

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