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TRANSIENT ENHANCEMENT OF NIGERIAN GRID SYSTEM USING OPTIMALLY TUNED UPFC BASED ON SMALL POPULATION PARTICLE SWARM OPTIMIZATION

G. A. Bakare [1], U. O. Aliyu [1], Y. S. Haruna[1], U. A. Abu[2]

[1]Electrical and Electronics Engineering Programme, ATBU Bauchi.
[2]Electrical and Electronics Engineering Department,
Federal Polytechnic Idah, Kogi State.
NIGERIA.
bakare_03@yahoo.com,

ABSTRACT

Transient and dynamic stability considerations are among the most important issues in the reliable and efficient operation of power systems. Flexible AC Transmission Systems (FACTS) devices produced more flexibility in power system operation and control, thus improving the usage of the existing transmission systems. A unified power flow controller (UPFC) has the ability to adjust the three control parameters, viz. the bus voltage, transmission line reactance, and phases angle between two buses either simultaneously or independently. In this paper, a small population based particle swam optimization (SPPSO) is used to optimally tune three parameters of UPFC in a multi-machine power system, providing faster convergence and less computation time. Simulation results on Nigerian grid system modeled in PSAT environment with and without UPFC installed were presented. The results revealed appreciable enhancement of the voltage profile, power flow along the lines and damping of power system oscillations.

Keywords: FACTS Devices, UPFC, SPPSO, PSAT

INTRODUCTION

Power system is a complex network comprising of numerous generators, transmission lines, variety of loads, switches, active or passive compensators and transformers. Such a network is non-linear and non-stationary, and in practice it is prone to several faults and disturbances. With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a transmission limiting factor. Transient stability of a system refers to the stability when subjected to large disturbances such as faults and switching of lines. The resulting system response involves large excursions of generator rotor angles and is influenced by the non-linear power angle relationship. Stability depends upon both the initial operating conditions of the system and the severity of the disturbance (Seo, et al 2001).

Reinforcing a power system can be done by increasing the voltage level or adding transmission lines. However, these solutions require consideration investment which is difficult to recover Bakare, et al 2005, Nwohu 2007, Abe and Doi 1983). Power system can be effectively improved by the use of FACTS devices. A unified power flow controller (UPFC) is the most promising device in the FACTS concept. It has the ability to adjust the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently. UPFC performs this through the control of the in-phase voltage, quadrature voltage and shunt compensation, (Dizdarevic et al 1998, Chang and Hsu 2005, Hingorani and Gyugyi 1999, Huang et al 2000).

Particle swarm optimization (PSO) has been recently developed as a promising member in the family of those meta-heuristics which are inspired by natural processes that do take place for ages. The heuristic approach that is implemented here is a modified particle swarm optimization (PSO) algorithm with a small population for the design of optimal tuning of UPFC (Cai and Erlich 2003, Gerbex et al 2001, Kothari and Tambey 2003, LimyingCharoen et al 1998). The small population based PSO (SPPSO) is used to determine the optimal parameters of UPFC in a multi-machine power system. Finally, a multi-machine system with the FACTS device installed is simulated using MATLAB and PSAT software to analyze the performance of UPFC.

PROBLEM STATEMENT

Transmission lines in congested areas are often driven close to or even beyond their limits in order to satisfy the increased demand. Thus, secure operations and reliable supply is endangered by the higher risks for faulted lines. But the construction of additional power lines is often difficult for environmental, economic and political reasons. This is where the technology of FACTS provides a significant opportunity.

In interconnected power systems, it is important to have control over power transfer. In order to have a better use of the transmission capabilities of the transmission lines, different types of FACTS devices were studied. Among them is a unified power follow controller (UPFC), which is a power electronic-based system considered as the most powerful. It can provide full dynamic control of the parameters of a transmission line, bus voltage, line impendence and phase angle (Mihalic et al 1996, Huang et al 2000, Kothari and Tambey 2003).

The main concern of this paper is to apply a heuristic technique, the small population particle swarm optimization SPPSO to optimally tune the parameters of the UPFC that will provide optimal transient enhancement characteristics on the Nigerian Power System.

LITERATURE REVIEW

Flexible AC transmission system (FACTS) is an evolving technology based solution to help electric utilities fully utilize their transmission assets. Its first concept was introduced by Hingorani in 1988, since then different kinds of FACTS devices have been proposed. Among them the UPFC is the most versatile and effective device which was introduced in 1991. The UPFC consists of voltage source convertors, one connected in series and other in shunt and both are connected back to back through a dc capacitor. In order to investigate the impact of UPFC on power systems effective, it is essential to formulate their correct and appropriate model.

According to Seo et al 2001, Mihalic et al 1996 and Huang et al 2000, some of the areas of application of UPFC includes; power system stabilization and control, steady state and transient studies, fixed parameter lead-lag controller, shunt compensation etc.

Concept of Particle Swarm Optimization Technique

An optimization problem is a mathematical model where main objective is to minimize undesirable things, maximize desirable things or assign/distribute optimally (generation, FACTS devices etc.) subject to some constraints. The main advantage of algorithmic methods is optimality which is mathematically rigorous in some algorithms.

Particle swarm optimization (PSO) has been recently developed as promising members in the family of those meta-heuristics which are inspired by natural processes that do take place for ages as described by Yoshida et al in 1999, and Fan and Shi in 2001. In PSO, a population of particles is flown in multidimensional space in quest for a position which can give the optimum solution. The concept of PSO were described fully by Yoshida et al, in 1999, Fah and Sha in 2001 and Abido in 2002.

Small population particle swarm optimization

The difference between small population PSO and the conventional PSO is the concept of particle regeneration that gives the particles ability to keep carrying out the search despite a small population. The particles are regenerated after every N number of iterations, retaining their previous *gbest* and *pbest* fitness values and positions.

The selection of the value N is very crucial in realizing an efficient SPPSO algorithm. If the value of N is low, the new particles may be regenerated too quickly and, in turn, disturb the search process. Randomizing the positions and velocities of the particles every N-iteration aids the particles in avoiding local minima and finding the global minimum. The regeneration concept drastically reduces the number of evaluations required to find the best solution, and each evaluation is less computationally intensive compared to the classical PSO algorithm. This informs the choice of SPPSO for this study.

Unified Power Flow Controller (UPFC)

The UPFC consists of two ac/dc voltage supports for the converter operation and functions as energy storage. The ac side of the booster inserts a synchronous ac voltage of controllable magnitude and phase angle in series with the transmission line through a series booster transformer. The ac side of the exciter is connected in parallel to the transmission line through a transformer where a current of controllable magnitude and power factor angle is injected to or absorbed from the power system.

The UPFC has several operating modes. Two control modes are possible for the shunt control (Menniti et al 2001):

- VAR control mode: the reference input is an inductive or capacitive Var request.
- Automatic voltage control mode: the goal is to maintain the transmission line voltage at the connection point to a reference value.

By the control of series voltage, UPFC can be operated also in four different ways:

- Direct voltage injection mode: the reference inputs are directly the magnitude and phase angle of the series voltage.
- Phase angle shifter emulation mode: the reference input is phase displacement between the sending and the receiving end voltage.
- Line impendence emulation mode: the reference input is an impendence value to insert in series with the line impendence.
- Automatic power flow control mode: the reference inputs are values of P and Q to maintain on the transmission line despite system changes.

Generally, for damping of power system oscillations, UPFC will be operated in the direct voltage injection mode.

PROBLEM FORMULATION

The mathematical model for the optimal tuning of the UPFC parameter is:

$$Min \quad J = \int_0^t (\alpha \cdot \Delta f^2 + \beta \cdot \Delta V^2) dt \tag{1}$$

Subject to the following constraints

- Percentage series compensation constraints: $C_{p_i}^{\min} \leq C_{p_i} \leq C_{pi}^{\max}$
- Regulator gain constraints: $K_i^{\min} \leq K_R \leq K_i^{\max}$
- Regulator time constant: $T_i^{\min} \leq T_R \leq T_i^{\max}$

Where

J : the performance index of the integral of the square of errors (ISE)

α and β : weight factors, the values of which determine the relative importance attached to the various errors. The appropriate values will be determined for this problem.

Δf : frequency deviation

ΔV : voltage deviation

Modeling of UPFC and System Losses

In order to investigate the impacts of FACTS devices on power systems effectively, appropriate models of FACTS devices are very important. In this section, the FACTS device of interest is the Unified Power Flow Controller (UPFC). Good mathematical modeling of UPFC will be adequately handled in the load flow computation problems without affecting the existing impedance matrix. However, in this paper, UPFC current injection model is proposed (Nabavi-Niaka and Iravani 1996, Menniti and Pannarelli 2001, Chang and Shu 2005).

Generally, the relationship between power flow P_{ij}, the voltage magnitude V_i, V_j and phase angle between the sending and receiving end voltages δ_i and δ_j is given by equation (2).

$$P_{ij} = \frac{V_i V_j}{x_{ij}} . \sin(\delta_i - \delta_j) \tag{2}$$

FACTS device can be applied to control the power flow and hence, the system losses by adjusting the variables contained in eqn. (2). Since FACTS device can regulate these variables in a very fast and effective way, then they are considered suitable for power system dynamic controls.

The UPFC voltage source is assumed to be connected between buses i and j in a transmission line of a power system. The series voltage source converter can be modeled as an ideal series voltage V_s in series with a reactance X_s whilst the shunt converter can be modeled as an ideal shunt current source $I_{shun.}$ Thus, we have the UPFC model as shown in fig. 1.

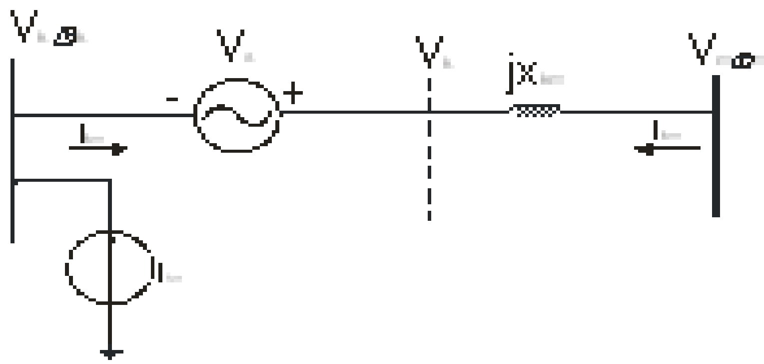

Figure 1: UPFC Circuit

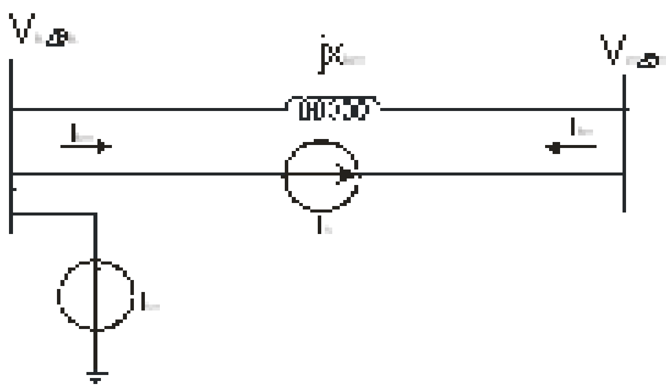

Fig 2: Replacement of a Voltage Source by a Current Source

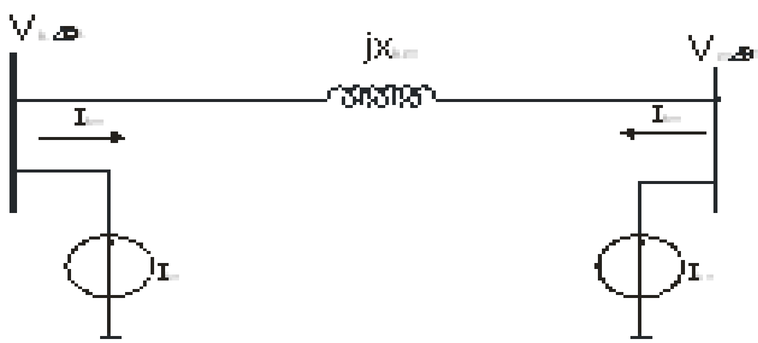

Fig. 3: Injection Current Model of UPFC

From Figure 1, $I_{shunt} = I_d + I_q$
(3)

Where,

I_d is the direct current in line and I_q is the quadrature current with

V_i, $V_s = rV_i\, e^{j(\Theta+\gamma)}$ (4)

$0 < r < r_{max}$ and $0 < \theta < 2$, $r_{max} = 0.1V_m$

V_m is the rated voltage of the transmission line where the UPFC is installed; $-180^0 < \gamma < 180^0$.

The current injection model of the UPFC is obtained by replacing the voltage source V_s by the equivalent Norton current source I_s as shown in figure 2. The shunt connected current source is used mainly to provide the active power which is injected to the network via the series connected voltage source. From figure 2, we have,

$$I_s = -jb_sV_s = -jb_srV_ie^{j(\Theta+\gamma)} \quad (5)$$

Where,

$$b_s = \frac{1}{x_s}.$$

After some modification of figure 2, we have the current injection model of UPFC as shown in figure 3.

If the excitation converter of the UPFC shunt is designated by conv1 and the boosting converter of the UPFC series part designated by conv2, assuming the losses are neglected,

$$P_{CONV1} = P_{CONV2} \quad (6)$$

The apparent power supplied by the series voltage source is obtained thus,

$$S_{CONV2} = V_s i_{IJ} = r e^{j\theta i} V_i \left[\frac{V_i + r e^{j\theta i} V_i - V_j}{jX_s} \right] \quad (7)$$

From equation 6 we have,

$$P_{CONV2} = rb_sV_iV_j \sin(\Theta_i - \Theta_j + \gamma) - rb_sV_i^2 \sin\gamma \quad (8)$$

$$Q_{CONV2} = rb_sV_iV_j \sin(\Theta_i - \Theta_j + \gamma) - rb_sV^2{}_i \cos\gamma + r^2b_sV_i^2 \quad (9)$$

The active power supplied by the shunt current source is calculated from

$$P_{CONV1} = Re\,[V_i(-I_{Shunt})^*] = -V_iI_d \quad (10)$$

Combining equations (6, 8 and 10) we obtain,

$$I_d = -rb_sV_j \sin(\Theta_i - \Theta_j + \gamma) + rb_{s+}V_i \sin\gamma \quad (11)$$

Then the shunt current is computed from

$$I_{shunt} = (I_d + jI_q)V_ie^{j\Theta i} = (-r b_s V_j \sin(\theta_i - \theta_j + \gamma) + r b_s V_i \sin\gamma + j I_q) e^{j\theta i} \quad (12)$$

Lastly, the injected current model of UPFC is deduced, thus

$$I_{SI} = I_{shunt} - I_s = -rb_sV_j \sin(\Theta_i - \Theta_j + \gamma + rb_sV_i \sin\gamma + jI_q)\, e^{j\Theta i} + jrb_sV_ie^{j(\Theta+\gamma)} \quad (13)$$

$$\overline{I_{sj}} = I_s = -jrb_sV_i\overline{e^{j(\Theta+\gamma)}} \quad (14)$$

Realization of Small Population Based Optimal Tuning of UPFC

The computational steps involved in the realization of the SPPSO based optimal tuning of UPFC are:

Step 1

Read the relevant PSO parameters such as population size, number of iteration for restart N, maximum number of generation etc. Also relevant power system data required for computational process are actualized from the data files by initializing Power System Analysis Toolbox (PSAT) software. Also the limits on three parameters of the UPFC such as percentage of series compensation, the regulator gain, and the regulator time constant are also set forth.

Step 2

Initial swarm of particles with random positions and velocities are randomly generated. Each candidate solution should be within the feasible region of the UPFC parameters of percentage of series compensation, the regulator gain, and the regulator time constant.

Step 3

For each individual comprises the population run the load flow and dynamic simulation to obtain mean square of error of voltage and frequency using PSAT. Compute the fitness value of the initial particles in the swarm using the objective function equations (1). Set the initial *pbest* to current position of each particle and the initial best evaluated value among the swarm is set to *gbest*.

Step 4

Increase the generation number and check if the iteration number is equal to N. Then perform restart operation and go to step 6 otherwise go to step5.

Step 5

Update the velocities and positions of the particles.

Step 6

Compute the fitness value of the new particles in the swarm using the objective function equation (1). Update the *pbest* with the new positions, if the particle present fitness is better than the previous ones. Also update the *gbest* with the best particle in the swarm.

Step 7

Repeat steps 3 to 5 until the preset convergence criterion: maximum number of generations is achieved. The SPPSO optimal parameter setting is shown in Table 1.

Table 1: Optimal SPPSO based UPFC tuning parameter settings

Parameters	**Setting**
Maximum generation, $iter^{max}$	30
Particle size, np	5
Objective function weighting factors **α and β**	1
Cognition constant, c_1	2
Social constant, c_2	2
Maxmum inertia weight, w^{max}	0.9
Minimum inertia weight, w^{min}	0.2
Maximum velocity resolution	6

SIMULATION RESULTS AND DISCUSSIONS

The tuning of SPPSO based UPFC was implemented using MATLAB coupled with PSAT for Nigerian 330kV grid system. The feasibility and effectiveness of the proposed approach in enhancing the transient performance of Nigerian grid system were demonstrated.

To test the effectiveness of the proposed tools, a scenario was created by applying a three phase fault at Shiroro (HT) bus 30 for 0.2 seconds. The optimal location of the UPFC has already been determined by Nwohu (2008) between Ikeja West and Egbin bus. SPPSO was used to generate optimal parameter for the UPFC and the following results were obtained.

Percentage of series compensation C_P=23.9%.

The regulator gain K_R=85.0.

The regulator time constant, T_R=0.05Secs.

The voltage and dynamic responses at some selected generator buses are compared with the UPFC optimally tuned and without UPFC installed. It can be seen that the installation of UPFC enhanced the voltage profile in area 1(West) and area 2 (East) as compared with area 3 (North) since the UPFC is electrically located far from the North.

It can also be seen that the installation of UPFC dampened the frequency of oscillation within few seconds as compared with when UPFC is not installed and the oscillation of power flow along the neighboring lines is also enhanced by the installation of UPFC.

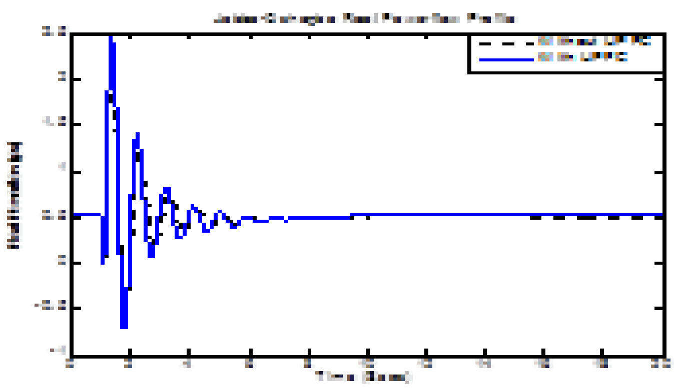

Figure 4: Real Power Flow along Jebba-Oshogbo Line

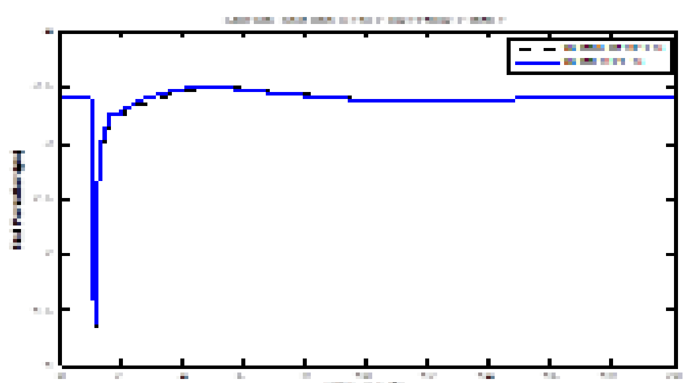

Figure 5: Real Power Flow along Shiroro-Kaduna Line (Area3)

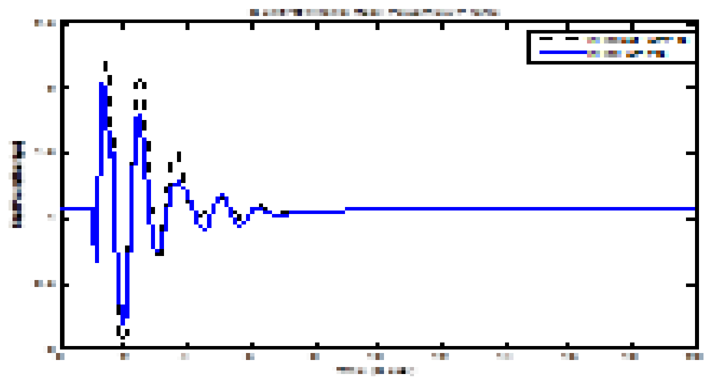

Figure 6: Real Power Flow along Benin-Onitsha Line (Area2)

Analysis of the Performance of UPFC Installed

The installation of UPFC in the South West area between Egbin (HT) and Ikeja West caused visible transient enhancement in this area, however, the effect of UPFC also manifest in other areas like the North East between Shiroro and Kaduna, where it also brought about transient enhancement, although not as conspicuous as in the South west.

Frequency Responses at Kanji Hydro-station

Transient responses and transient stability considerations are essentially discussing the frequency swings. This is glaring from the results obtained in figure 7. The transient characteristic without UPFC was more severe in terms of amplitude swings, frequency oscillation and setting time, this is shown by the dotted lines. However, when UPFC was installed, the transient characteristic was better in terms of amplitude swing, frequency of oscillation and settling time.

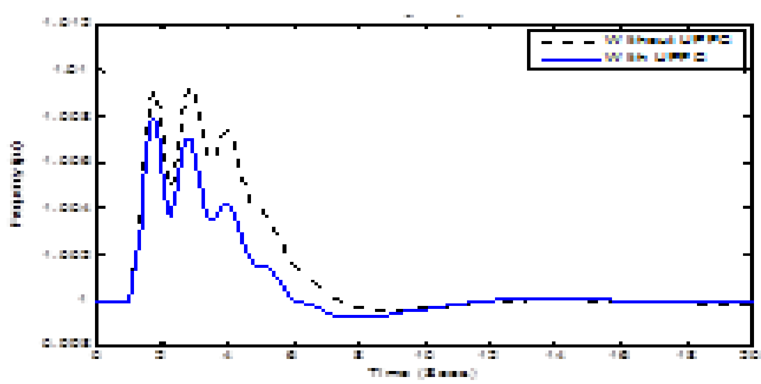

Figure 7: Frequency Response at Kainji Hydro Station (Area 3)

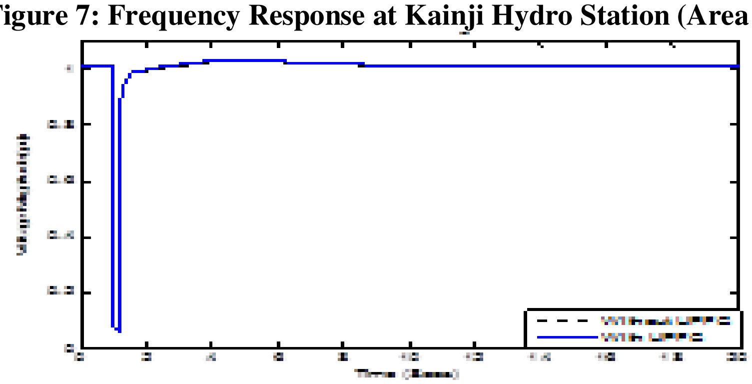

Figure 8: Voltage Profile Enhancement at Shiroro Hydro Station (Area 3)

It can be deduced from the simulation result obtained for voltage profile with and without UPFC, and with SPPSO tuned in figure 9,10 and 11, that the voltage profile improved at Buses 7, 11, 14, 16, 20, 31, 32, 37, 38, 39 respectively.

Voltage Profile at Ikeja – West Bus

The results in figure 10, showed appreciable enhancement in the transient characteristics, this brought about voltage improvement at the Ikeja-west bus i.e. in area 1, where the UPFC was installed. The effect of the UPFC was also observed at the Shiroro HT, area 3, although marginal. Even at this, there is noticeable transient enhancement.

Real Power Flow along Benin-Onitsha Transmission Line

The plot of the real power flow (p.u) and time (sec) of figure 9 shows that there is an appreciable transient enhancement along the Benin-Onitsha transmission line when UPFC was installed. The effect is however more appreciable along the Benin-Onitsha transmission line than on the Shiroro-Kaduna real power flow profile which is quite far off from the installation area of the UPFC.

Bus Voltage Profile with UPFC SPPSO Tuned

The result in figure 11 was obtained when the heuristic technique was implemented. The small population particle swarm optimization is an upgrade of the classical PSO. It handles a smaller population, faster convergence and lesser number of iterations. The optimal parameters of the UPFC namely; the percentage series compensation, the regulator gain and the regulator time constant are enabled by this technique. Appreciable voltage profile was observed at Buses: 7, 11, 14, 16, 20, 31, 32, 37, 38 and 39 respectively.

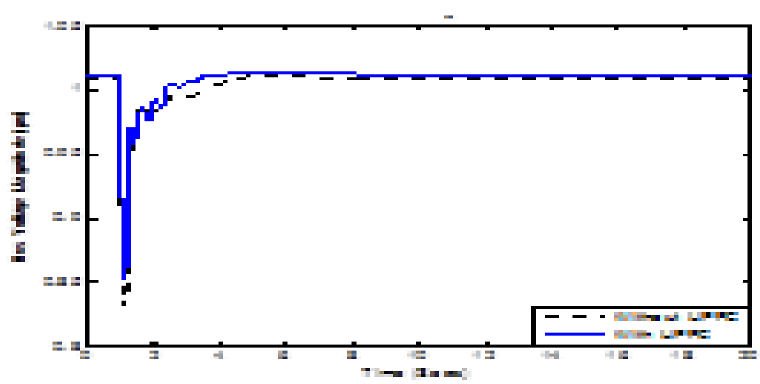

Figure 9: Voltage Profile Enhancement at Benin TS (Area 2)

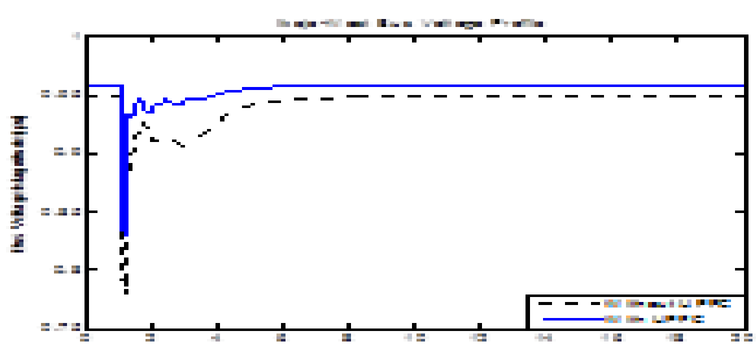

Figure 10: Voltage Profile Enhancement at Ikeja-West TS (Area 1)

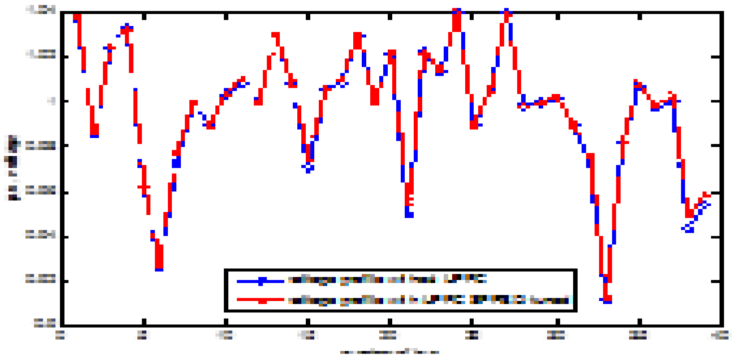

Figure 11: Transient Bus Voltage Profile Enhancement

In summary, essentially two feats have been achieved, first, UPFC has brought about transient enhancement, and second the SPPSO also enabled the optimally tuned parameters of the UPFC.

CONCLUSION

The Nigerian power system without optimally tuned UPFC exhibits minimum damping and maximum overshoot with many oscillatory modes. The overshoot and the settling time are minimized with the SPPSO optimized UPFC. Here it's clear that even for disturbances not as severe as three-phase short circuits, the SPPSO out performs the PSO. The SPPSO algorithm gave robust damping performance for various operating conditions and disturbances. The SPPSO with the regenerative concept is seen to have faster convergence with less number of fitness evaluations. The SPPSO is found to be superior to the classical PSO in term of computational complexity, convergence speed and damping performances.

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