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Coordinated Design of TCSC and PSS Controllers using VURPSO and Genetic Algorithms for Multi-machine Power System Stability

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Abstract: Thyristor controlled series capacitor (TCSC) can regulate line impedance and therefore increase transferred power of the system. On the other hand power system stabilizer (PSS) increases dynamic stability of generator. To enhance the stability, combination of TCSC and PSS can be applied, and in such a case coordination of TCSC and PSS is essential. This paper applies this combined controller in order to enhance the stability of multi-machine system. Parameters of these controllers are optimized by velocity update relaxation particle swarm optimization (VURPSO) algorithm and Genetic algorithm (GA). The simulation results show that the combination of VURPSO algorithm and GA leads to a better design and stability.

Keywords: Genetic algorithm, PSS, stability, TCSC, velocity update relaxation PSO.

1. INTRODUCTION

In recent decades fast development of high power and high voltage semiconductor devices improve the systems control, flexibility and continuous operation of power systems. They can be used to design appropriate compensators for power systems. These compensations are known as flexible AC transmission systems (FACTS) [1-4]. FACTS controllers can control the capacity of network very fast and this particular trait of FACTS devices can be used to improve the stability of a power system. The major features of FACTS controllers include active and reactive power control, voltage control, oscillations damping, transient and dynamic stability and voltage stability improvement and fault current limiting. In electrical power transmission lines, series capacitors improves the stability and increases the transferred power capacity [5,6]. However, this may cause sub synchronous resonance (SSR) [7]. In recent years, by the new development in power electronics devices, FACTS controllers have been widely used in power system. Thyristor controlled series capacitor (TCSC) is one of the most important and useful kind of FACTS devices. It is installed in long transmission lines and plays a major role in the system.

Time changing line impedance by TCSC has special impact on the damping of oscillations and enhancing stability of the power system. TCSC play different roles in the operation and control of power system including programming power transfer, decreasing network losses, making trustful voltage, damping power oscillations, achieving transient stability and decreasing SSR [8,9].

Power system stabilizer (PSS) is an electronics device that can improve the stability of power system. In fact, PSS is a complementary control system which is often used as a part of the excitation control system. The major role of the PSS is applying a signal to the excitation system in order to develop electric torque; this torque is then applied to the rotor while the speed is changing and it stops the external power oscillations [10-13]. To damp the oscillation and improve the stability of power system, PSS is installed in the power plant and FACTS devices are installed in the transmission line. However, the lack of coordination between these two stabilizers can result in system instability. Coordination of PSS and TCSC controllers have been conducted in [14-19]. Different methods have been so far introduced to control parameters of PSS and TCSC. In [20-23], the particle swarm optimization (PSO) algorithm, fuzzy logic and adaptive neuro-fuzzy inference system (ANFIS) have been used to estimate and regulate the parameters of the TCSC and PSS controllers. Among the disadvantage of these methods a long computaions' complexity of the design method, and high number of iterations for optimal solution are notable. Thus, it take longer computations time to estimate the parameters of controllers. PSO is a social intelligence based algorithm for optimization of a searching area or modeling social behavior [24-27]. PSO is modeled based on the social behavior of the group of birds or fishes. Application of PSO algorithm in TCSC has been described in [28,29] and applied to PSS [30,31].

In this paper, two methods of velocity update relaxation PSO (VURPSO) algorithm and GA are used to simultaneously optimize the parameters of the TCSC and PSS controllers. Taking into account non-linear characteristic of the system, low number of iterations in optim-

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ization process and lack of the required dynamics of the power system are the major features of the VURPSO and genetic algorithms. VURPSO algorithm complements PSO algorithm. This supplementary method needs less calculation and has faster response compared to that of PSO algorithm. Application of VURPSO algorithm in simultaneous SVC and PSS controllers has been described in [32].

2. THYRISTOR CONTROLLED SERIES CAPACITOR

Fig. 1 shows a simple TCSC consisting of a series reactor and two anti-parallel thyristors in parallel with a capacitor. This combined circuit can control the capacitive reactance and two anti-parallel thyristors can control the inductive reactance of the line. The controllable reactance by TCSC is calculated as follows [9,33]:

$$X_{TCSC} = B_1(X_C + B_2) - B_4 B_5 - X_C, \tag{1}$$

where B_1 to B_5 are as follows:

$$B_1 = \frac{2(\pi-\alpha) + Sin2(\pi-\alpha)}{\pi},$$

$$B_2 = \frac{X_C X_p}{X_C - X_p},$$

$$B_3 = \sqrt{\frac{X_C}{X_p}},$$

$$B_4 = B_3 \tan\left[B_3(\pi-\alpha)\right] - \tan(\pi-\alpha),$$

$$B_5 = \frac{4B_2^2 Cos^2(\pi-\alpha)}{\pi Xp},$$

where π-α is the TCSC controller conduction angle, α is the firing angle of thyristor in radian, X_C is the reactance of the capacitor, X_P is the reactance of the inductor, and B_3 is the compensation coefficient of TCSC. X_{TCSC} calculated by (1) is added to the reactance of the transmission line in order to damp the power system oscillations. This reactance value depends on the thyristors fire angle. The most usual model used for TCSC is a model-based phase lag/lead controller and it has been shown in Fig. 2 [34]. Washout filter eliminates the input signal offset from the controller response. It operates similar with a low-pass filter and time constant T_w is long enough as such that the input signal of low frequency does not change.

K_T and times constant T_{1T}, T_{2T}, T_{3T} and T_{4T} can be calculated using VURPSO algorithm and GA in order to identify a better algorithm for designing simultaneous TCSC and PSS parameters controllers.

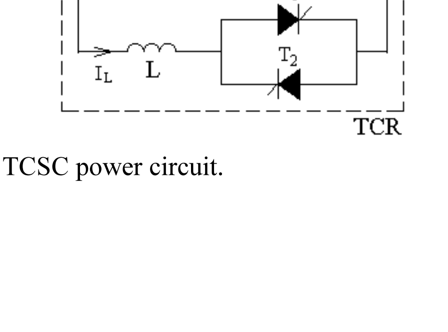
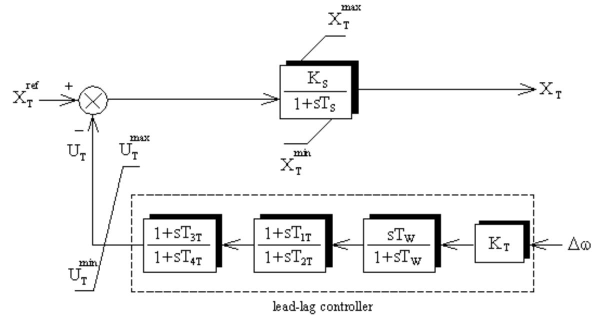


Fig. 1. TCSC power circuit.



K_T= controller gain and T_W =washout time constant

Fig. 2. TCSC with lead-lag controller.

As seen in Fig. 2, the reactance of TCSC is expressed as follows:

$$\frac{dX_T}{dt} = \frac{1}{T_S}[-X_T + K_S(X_T^{ref} - U_T)]. \tag{2}$$

3. POWER SYSTEM STABILIZER

PSS improves the dynamic operation of the power system by adding the ancillary signals to the stimulation system. The input signal of PSS is the rotor speed deviation (Δω). Considering all advantages of PSS, it is essential to regulate its parameters. The incompetent regulation of PSS is not helpful in improving the stability of the system, and in some cases it may lead to the instability. Here, VURPSO and GA are used to design parameters of PSS controller. The generator is represented by the third order model consisting of the following swing equations:

$$\frac{d\delta}{dt} = \omega_b(\omega - 1), \tag{3}$$

$$\frac{d\omega}{dt} = \frac{1}{M}[P_m - P_e - D(\omega - 1)], \tag{4}$$

where P_e and P_m are the output and input powers of the generator. ω and δ are the speed and rotor angle respectively, ω_b is the synchronous speed, D and M are the damping coefficient and inertia constant respectively.

The output power of the generator can be expressed in terms of the d-axis and q-axis components of the mature current i and terminal voltage v as follows:

$$P_e = v_d i_d + v_q i_q. \tag{5}$$

The generator internal voltage equations are as follows:

$$\frac{dE_q'}{dt} = \frac{1}{T_{d0}'}[-E_q' - (x_d - x_d')i_d + E_{fd}], \tag{6}$$

$$\frac{dE_d'}{dt} = \frac{1}{T_{q0}'}[-E_d' + (x_q - x_q')i_q], \tag{7}$$

where E_{fd} is the field voltage, T'_{do} is the open-circuit field time constant. x_d, x_q are the d-axis and q-axis reactances of the generator, x'_d, x'_q are the d-axis transient and q-axis transient reactances of the generator respectively.

IEEE type-ST1 system shown in Fig. 3 is described as follows:

$$\frac{E_{fd}}{dt} = \frac{1}{T_A}[-E_{fd} + K_A(V_{ref} - v + U_{PSS})], \tag{8}$$

where V_{ref} is the reference voltage and T_A and K_A are the time constant and gain of the excitation system respectively [34].

As shown in Fig. 3, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal U_P. The PSS input is the change in the machine speed. In Fig. 3, T_W stands for the washout time constant and K_P for their controller gain. The time constants T_{1P}, T_{2P}, T_{3P}, T_{4P} and K_P are calculated using VURPSO algorithm and GA in order to identify an appropriate algorithm for simultaneous designing of TCSC and PSS parameters controllers. It is assumed that $T_{1P} = T_{3P}$ and $T_{2P} = T_{4P}$. Voltage v in Fig. 3 is given by:

$$v = \sqrt{v_d^2 + v_q^2}, \tag{9}$$

where $v_q = E'_q - X'_d i_d$ and $v_d = E'_d + X'_q i_q$.

Fig. 4 shows the structure of the proposed system [34]. In Fig. 4, the power system consists of different areas: two synchronous generators G1 and G2 are in the first area and G3 and G4 are in the second area. All four generators are 900 MVA and 20 kV. TCSC in the second line is between bus 7 and bus 10 and PSS is installed on all four generators. The first and the second areas are connected by two 230 kV transmission lines and 220 km length. The 413 MW power of the first area is transferred to the second area.

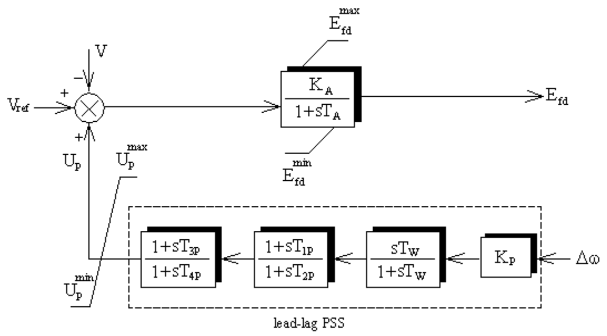


Fig. 3. IEEE type-ST1 excitation system with PSS.

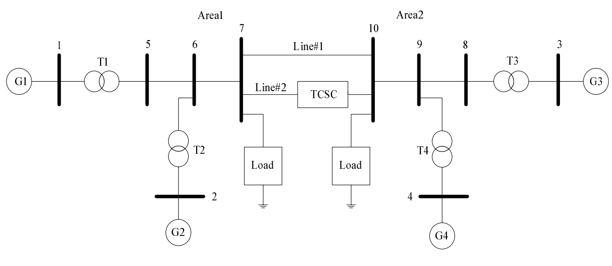


Fig. 4. Power system of two areas four-machine with TCSC.

4. OPTIMIZING PARAMETERS OF TCSC AND PSS SIMULATNEOUS CONTROLLERS

Objective function J is defined as follows:

$$J = \sum \int_0^{t_1} t\left|\Delta\omega(t, X)\right| dt, \tag{10}$$

where $\Delta\omega(t, X)$ is the speed deviation of the generator for simultaneous TCSC and PSS parameters controllers. X is the optimization parameters of this controller (K_T, T_{1T}, T_{2T}, T_{3T}, T_{4T}, K_P, T_{1P}, T_{2P}, T_{3P}, T_{4P}) and t_1 is the timeframe of the simulation.

Here, the goal is to minimize the objective function. There are the following inequalities for TCSC controller in Fig. 2:

$$K_T^{\min} \langle K_T \langle K_T^{\max}$$
$$T_{1T}^{\min} \langle T_{1T} \langle T_{1T}^{\max}$$
$$T_{2T}^{\min} \langle T_{2T} \langle T_{2T}^{\max}$$
$$T_{3T}^{\min} \langle T_{3T} \langle T_{3T}^{\max}$$
$$T_{4T}^{\min} \langle T_{4T} \langle T_{4T}^{\max}.$$

Similarly the following inequalities are held for PSS controller in Fig. 3:

$$K_P^{\min} \langle K_P \langle K_P^{\max}$$
$$T_{1P}^{\min} \langle T_{1P} \langle T_{1P}^{\max}$$
$$T_{2P}^{\min} \langle T_{2P} \langle T_{2P}^{\max}$$
$$T_{3P}^{\min} \langle T_{3P} \langle T_{3P}^{\max}$$
$$T_{4P}^{\min} \langle T_{4P} \langle T_{4P}^{\max}.$$

Here VURPSO and GA are used separately for optimization and optimal point of TCSC and PSS parameters controllers are searched.

4.1. Update relaxation PSO

VURPSO algorithm complements PSO algorithm. This supplementary method needs less calculation than PSO algorithm and finds the optimized response faster. Therefore, before explaining the VURPSO algorithm the PSO algorithm is proposed.

PSO algorithm consists of a collection of particles which makes the group. Every particle searches for the space around itself in order to find the least or the most location. PSO algorithm operates as a group of particles (as the optimization problem variables) distributing over the searching environment. It is clear that some particles are in a better position than others. According to the attacking particles behavior, other particles attempt to reach the best position level while are changing. It is noteworthy that the position of each particle changes based on the experience of the particle in the previous movements and the experience of the adjacent particles. In fact, each particle is aware of its superiority or lack of superiority over the adjacent particles and the particles of the whole group [9,11]. The equation for updating the velocity and the position of particles is as follows:

$$v_k^{t+1} = v_k^t + [c_1 \times Rand_1 \times (pbest_k - x_k^t)] + [c_2 \times Rand_2 \times (gbest - x_k^t)], \tag{11}$$

$$x_k^{t+1} = x_k^t + v_k^{t+1}, \tag{12}$$

where $pbest_k$ stands for the best position of the particle k and $gbest$ represents the best position of particles during implementation of the algorithm. $Rand_1$ and $Rand_2$ are the random numbers in the interval [0,1] and causes various kinds of answers; in this way more complete searching is done in the space. x_k^t and v_k^t are the current position and velocity of particle k at iteration t respectively, x_k^{t+1} and v_k^{t+1} are the modified position and velocity of particle k respectively. c_1 representing the parameter of individual recognition moves the particle to the best position reached by its adjacent particles. This coefficient is used as the stimulation coefficient. c_2 represents the social recognition parameter which is used as the stimulation coefficient; it causes the particle to move to the best position. c_1 causes the movement to $pbest_k$ more quickly and c_2 makes better movement to $gbest$.

Although PSO algorithm can find out the area of the optimized response quickly, the speed of its convergence decreases much extent by reaching this area. To solve this problem (11) is modified as follows:

$$v_k^{t+1} = [w_k \times v_k^t] + [c_1 \times Rand_1 \times (pbest_k - x_k^t)] + [c_2 \times Rand_2 \times (gbest - x_k^t)], \tag{13}$$

where w_k is the weight function for velocity of particle k.

In implementation of the PSO algorithm based on the following equation:

$$w_k = w_{\max} - \left[\frac{w_{\max} - w_{\min}}{iter_{\max}}\right] \times iter, \tag{14}$$

coefficient w_k decreases from 0.9 to 0.4 where $iter$ is the current iteration number and $iter_{max}$ is the maximum iteration number. To control the velocity in (14), the maximum velocity v_{max} is used. If the velocity exceeds this value, v_{max} assigned to it; if the velocity becomes less than v_{min}, v_{min} assigned to it. Therefore:

$$v_{\min} \le v_k^{t+1} \le v_{\max}. \tag{15}$$

The flowchart of PSO algorithm has been shown in Fig. 5. In Fig. 5, $P_{fitness}$ presents the value of the fitness function for each particle and $pbest_{fitness}$ is the best fitness function among the competence functions of the particles.

One of the new models of PSO algorithm which takes different procedures to improve the parameters of the systems is VURPSO algorithm.

In original PSO algorithm, the velocities of the particles are limited by [v_{min}, v_{max}] and positions of the particles are limited by [x_{min}, x_{max}]. v_{max} is equal to x_{max} and v_{min} is usually equal to x_{min}. Thus, in traditional PSO, checking the validity of the particles position and then taking some effective position restriction measure to confine or reject solutions accordingly are handled judiciously at every iteration cycle, imposing some extra computational burden. VURPSO postulates the boundary velocity validity

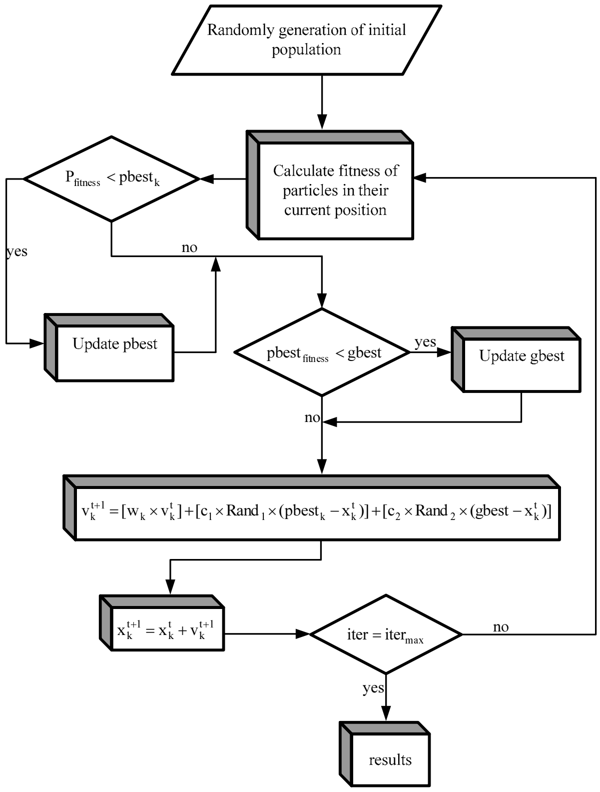


Fig. 5. Flowchart of the PSO algorithm.

checking of particles without checking the validity of positions in every iteration cycle [24]. Instead velocity-updating relaxation is adopted in every iteration cycle. In traditional PSO algorithm, the velocity is updated at every iteration cycle.

According to VURPSO, velocity of each particle is kept unchanged if its fitness at current iteration is better than that at preceding iteration; otherwise the velocity and position of particles are updated as follows:

$$v_k^{t+1} = v_k^t + [c_1 \times Rand_1 \times (pbest_k - x_k^t)] + [c_2 \times Rand_2 \times (gbest - x_k^t)], \tag{16}$$

$$x_k^{t+1} = (1 - mf)x_k^t + (mf)v_k^{t+1}, \tag{17}$$

where mf is the momentum factor between 0 and 1. In (16), $v_{max} = x_{max}$ and $v_{min} = x_{min}$. Because of mf limitations, the new position vector is the point on the line between the former position vector (x_k^t) and the new velocity vector (v_k^{t+1}).

VURPSO exhibits strong global search ability at the beginning of the run and strong local search ability near the end of the run. Some values of the parameters of VURPSO algorithm have been listed in Table 1.

Table 1. Some values for VURPSO parameters.

Number of particles	100
Number of iteration	100
$c_{1\max}$	2.05
$c_{2\max}$	2.05
Mf	0.3

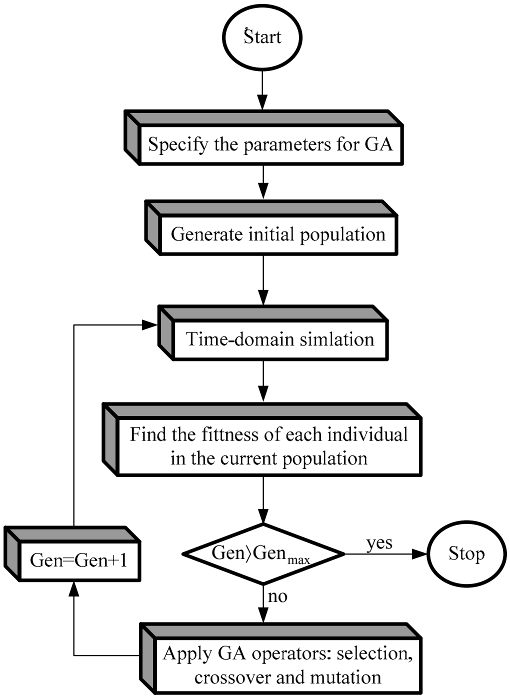


Fig. 6. Flowchart of the GA.

4.2. Genetic algorithm

GA maintains a set of candidate solutions called population and repeatedly modifies them. At each step, the GA selects individuals from the current population to be parents and uses them to generate children for the next generation. Candidate solutions are usually represented as strings of fixed length, called chromosomes. A fitness or objective function is used to reflect the goodness of each member of the population. Given a random initial population, GA operates in the cycles called generations, as follows:

- Each member of the population is evaluated using a fitness function.
- The population undergoes reproduction in a number of iterations. One or more parents are chosen stochastically, but strings with higher fitness values have higher probability of contributing an offspring.
- Genetic operators, such as crossover and mutation, are applied to parents to produce offspring.

The offspring is inserted into the population and the process is repeated. Fig. 6 presents the flowchart of GA.

5. SIMULATION RESULTS

The values for optimized parameters of simultaneous TCSC and PSS controllers with VURPSO algorithm are shown in Table 2 and for PSS in Table 3.

The convergences of the objective function for *gbest* in PSO, VURPSO algorithm and GA have been shown in Fig. 7. In Fig. 7, the objective function with GA converges to 0.0094 for *gbest* and the objective function with VURPSO algorithm converges to 0.0083 for *gbest*. As a result, VURPSO algorithm, in comparison to GA in minimizing the objective function, has done better and therefore *gbest* of the VURPSO algorithm is better.

Table 2. Value of optimized parameters of TCSC controller.

Parameters	VURPSO	GA	Range
$K_T[p.u]$	18.1387	11.205	1-50
$T_{1T}[s]$	0.4428	0.3521	0.01-1
$T_{2T}[s]$	0.2681	0.2015	0.01-1
$T_{3T}[s]$	0.4461	0.3765	0.01-1
$T_{4T}[s]$	0.3032	0.2631	0.01-1

Table 3. Value of optimized parameters of PSS controller.

Parameters	VURPSO	GA	Range
$K_{PG1}[p.u]$	29.5129	22.2653	20-60
$K_{PG2}[p.u]$	25	20.101	20-60
$K_{PG3}[p.u]$	34.226	27.3209	20-60
$K_{PG4}[p.u]$	33.0242	25.8235	20-60
$T_{1PG1}=T_{3PG1}[s]$	0.4939	0.5881	0.01-1
$T_{1PG2}=T_{3PG2}[s]$	0.5	0.5601	0.01-1
$T_{1PG3}=T_{3PG3}[s]$	0.4176	0.4936	0.01-1
$T_{1PG4}=T_{3PG4}[s]$	0.4396	0.5011	0.01-1
$T_{2PG1}=T_{4PG1}[s]$	0.3171	0.4209	0.01-1
$T_{2PG2}=T_{4PG2}[s]$	0.3812	0.4676	0.01-1
$T_{2PG3}=T_{4PG3}[s]$	0.3747	0.4536	0.01-1
$T_{2PG4}=T_{4PG4}[s]$	0.4731	0.5803	0.01-1

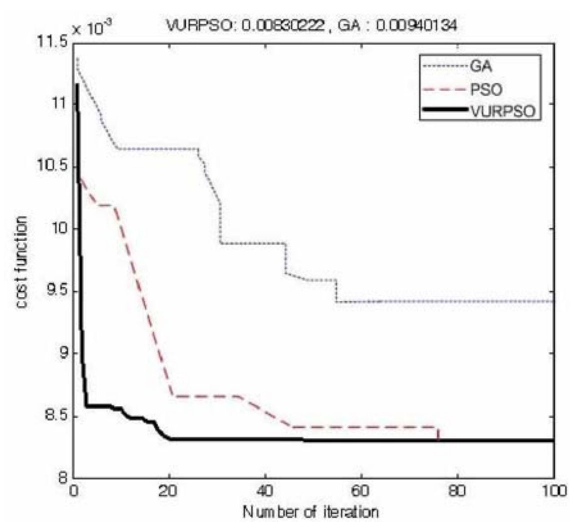


Fig. 7. Convergence of the objective function for gbest.

Also, according to Fig. 7, a VURPSO algorithm approaches 0.0083 in 23 iterations and with PSO optimization algorithm in 78 iterations, *gbest* similar to VURPSO algorithm is reached. This problem shows the preference of the VURPSO algorithm in comparison to PSO algorithm. VURPSO algorithm complements PSO algorithm. This supplementary method needs less calculation than PSO algorithm and finds the optimized response faster.

Here the worst kind fault, i.e., the three-phase short circuit fault with the ground, is studied. It is assumed that (Fig. 4), this fault has occurred in line one between bus 7 and bus 10 in 0.5 s and after 100 ms, it disappears at 0.6 s. The response of the system in the normal loading (P = 0.78 pu) and over loading case, P =1.1 pu, are considered.

5.1. Normal loading condition (P=0.78 pu)

As seen in Fig. 8, the rotor angle of generator 1 is unstable because three-phase short circuit fault with ground is damped shorter than 6 s using PSS controller and TCSC controller alone and VURPSO algorithm. Duration of damping in about 4 s and oscillations step down by the use of simultaneous TCSC and PSS controllers and VURPSO algorithm.

Regarding to Fig. 9, the rotor angle of generator 2 damps in about 3.8 s by simultaneous TCSC and PSS controllers and VURPSO algorithm.

The rotor angle of generators 1 and 2 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm have been shown in Figs. 10-11.

As seen in Fig. 11, the rotor angle of generators 1 and 2 damps in about 9 s using TCSC and PSS controllers and about 6 s if GA is applied. Duration of the damping is shorter than 4.5 s and the oscillations step down by VURPSO algorithm.

Considering Figs. 12 and 13, damping and stability of the speed of generators 2 and 4 improves by simultaneous applying TCSC and PSS controllers and VURPSO algorithm; it damps in about 3.5 s at 1pu. As it can be seen in Fig. 14, the speed of generator 4 damps in about 5 s by applying GA, duration of damping in about 3.5 s and the speed oscillations step down by VURPSO algorithm. Refereeing to Figs. 15 and 16, the speed deviation of generators 2 and 4 are damp in about 3.5 s by VURPSO algorithm.

Figs. 17 and 18 show very oscillatory output power of generators 1 and 4, but they are damped in shorter than 4.5 s at the amount before the fault using PSS controller and TCSC controller alone and VURPSO algorithm. Duration of damping is shorter than 3 s at amount before

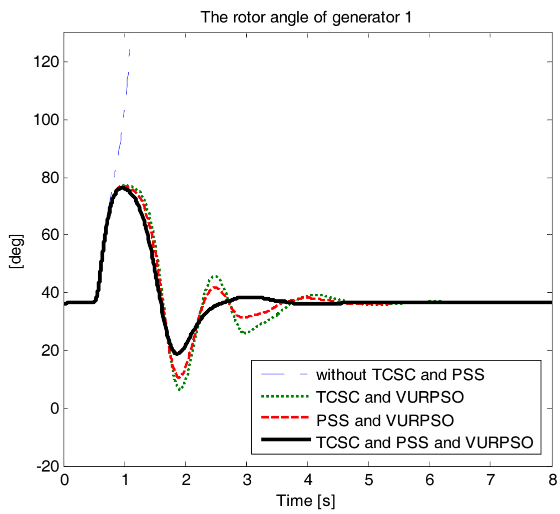


Fig. 8. Angle of rotor of Gen.1 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

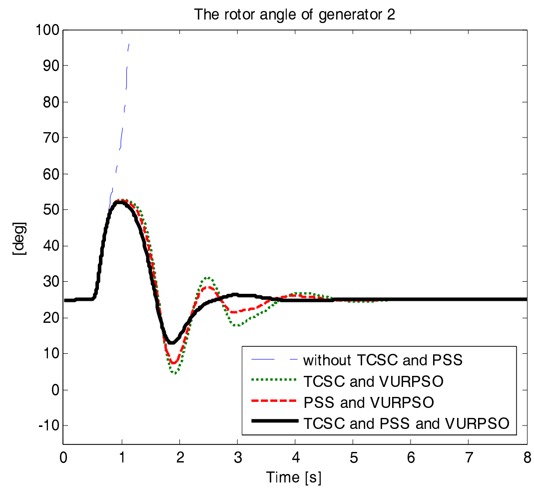


Fig. 9. Angle of rotor of Gen.2 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

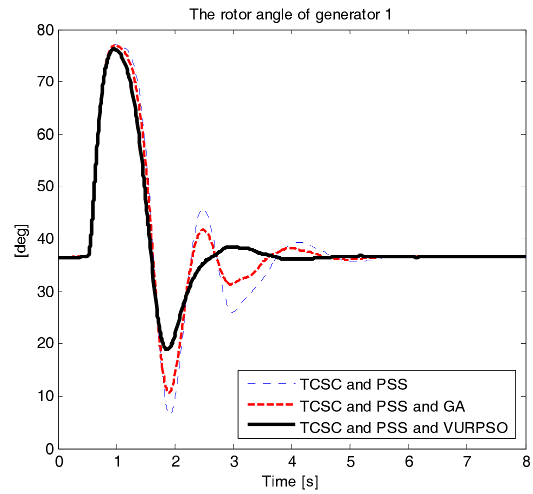


Fig. 10. Rotor angle of Gen.1 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

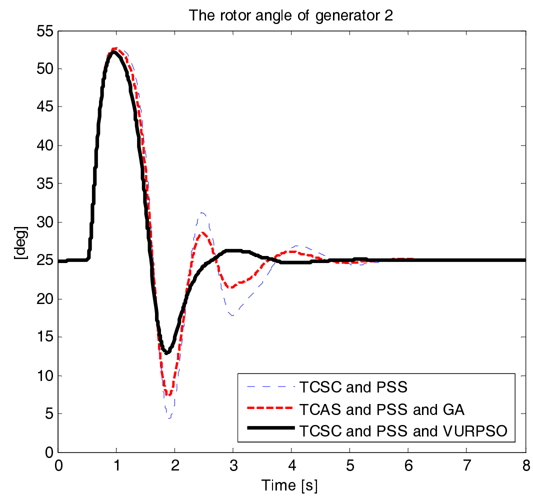


Fig. 11. Rotor angle of Gen.2 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

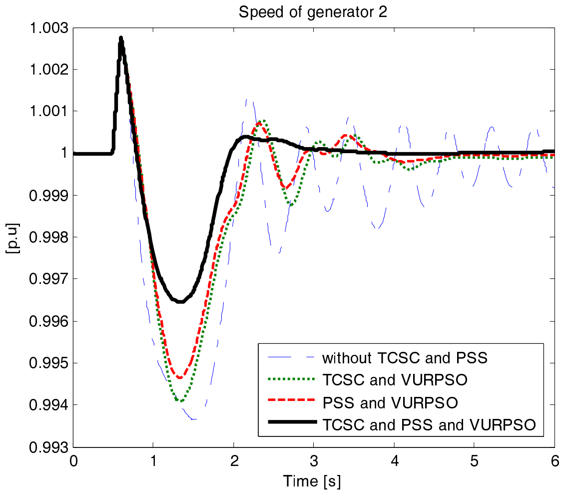


Fig. 12. Speed of Gen.2 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

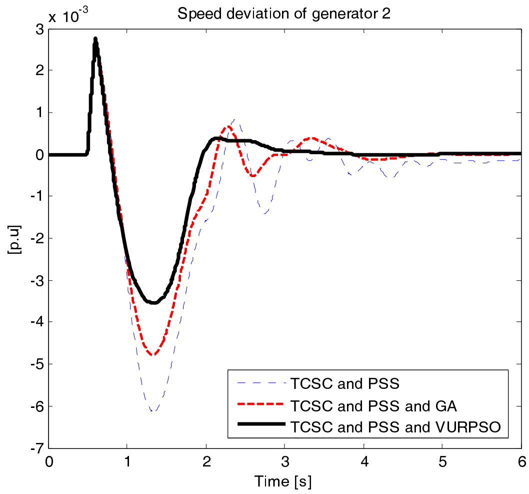


Fig. 15. Speed deviation of Gen.2 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

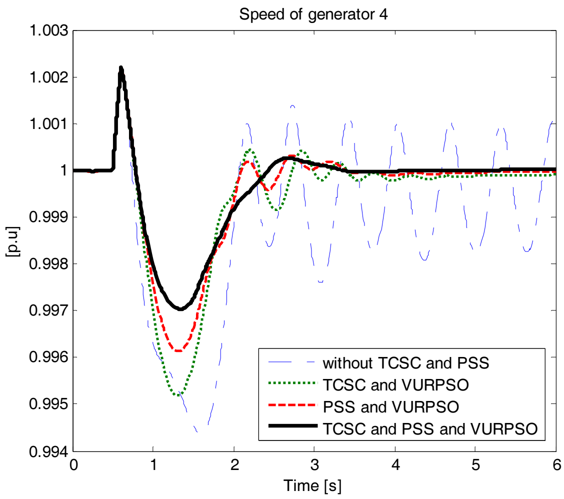


Fig. 13. Speed of Gen.4 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

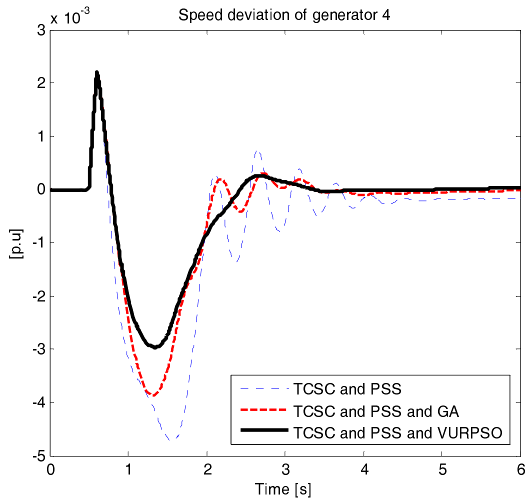


Fig. 16. Speed deviation of Gen. 4 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

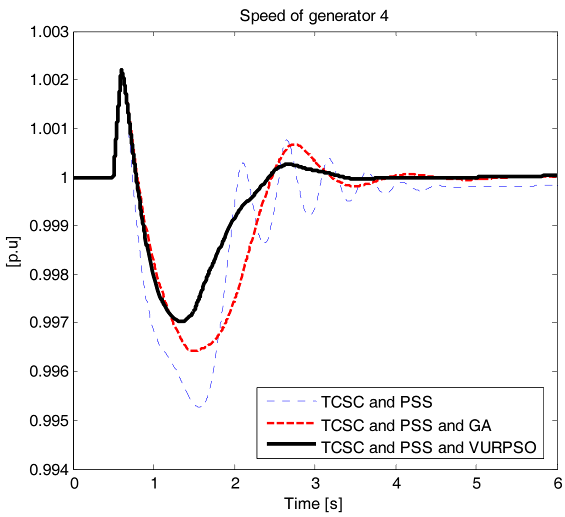


Fig. 14. Speed of Gen.4 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

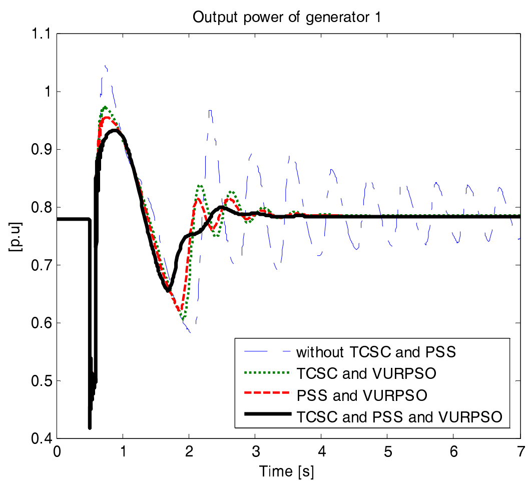


Fig. 17. Output power of Gen. 1 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

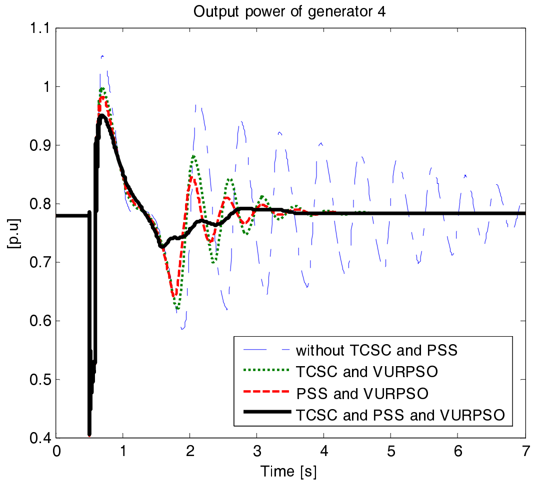


Fig. 18. Output power of Gen. 4 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

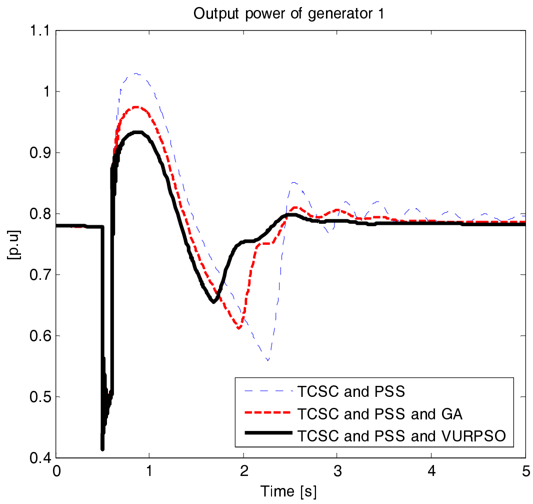


Fig. 19. Output power of Gen. 1 using simultaneous PSS and TCSC controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

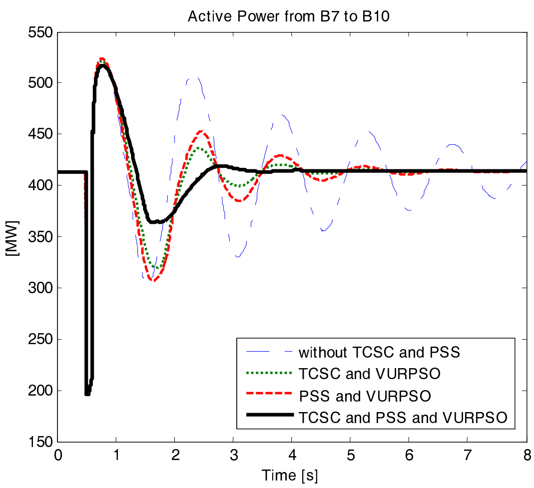


Fig. 20. Power transmission from first area to second area using simultaneous TCSC and PSS controllers and VURPSO algorithm.

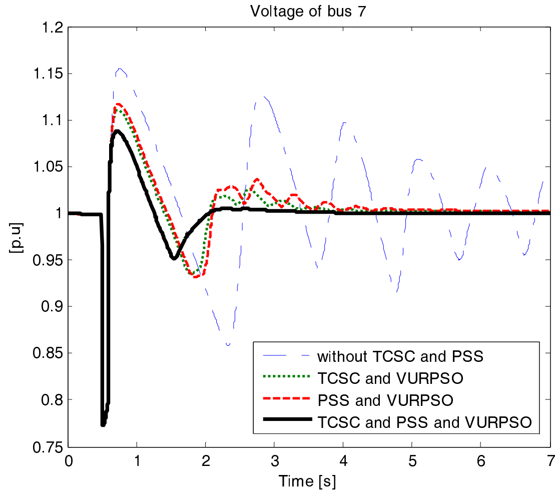


Fig. 21. Voltage of bus 7 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

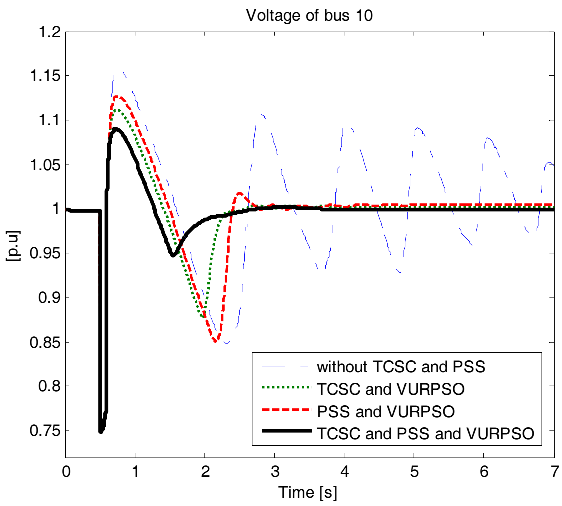


Fig. 22. Voltage of bus 10 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

the fault i.e., 0.78 pu and oscillations angle step down using simultaneous TCSC and PSS controllers and VURPSO algorithm. Referring to Fig. 19, by applying VURPSO algorithm, oscillation and time damping has been decreased compared to GA results. As shown in Fig. 20, the power transmission from the first area to the second area is damped in about 3.2 s at 413 MW (before the fault prefer) by TCSC and PSS simultaneous controllers and VURPSO algorithm.

Voltage of buses 7 and 10 (Figs. 21-22) are very oscillatory due to the three-phase short-circuit fault with the ground, and simultaneous TCSC and PSS controllers and VURPSO algorithm are damped in about 2.1s 1pu. By using VURPSO algorithm, oscillation and time damping has been decreased in comparison with that of GA (Fig. 23).

5.2. Over loading condition (P=1.1 pu)

As seen in Figs. 24 and 25, the rotor angle of generators 1 and 2 are unstable due to three-phase short-circuit fault with the ground and angles for the over loading is about 10 degrees. Duration of damping is

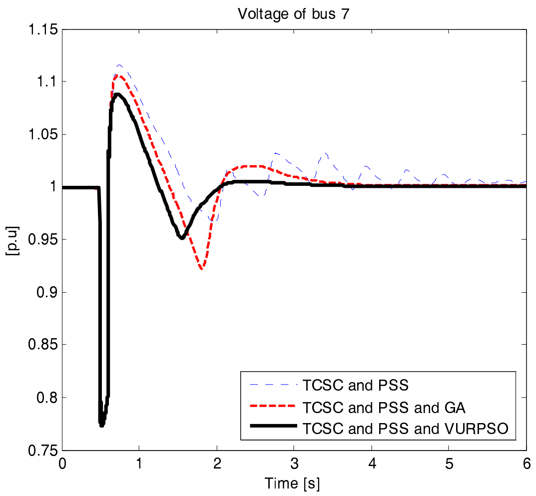


Fig. 23. Voltage of bus 7 using simultaneous TCSC and PSS controllers and GA, TCSC and PSS controllers and VURPSO algorithm.

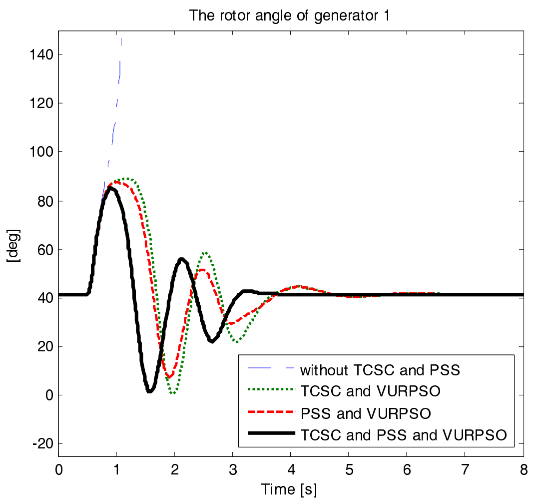


Fig. 24. Angle of rotor of Gen. 1 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

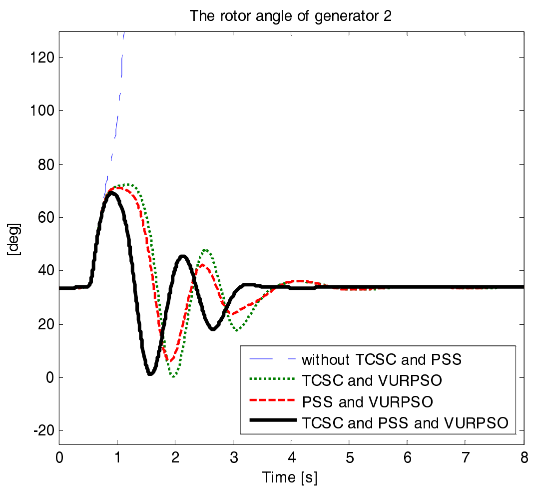


Fig. 25. Rotor angle of Gen. 2 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

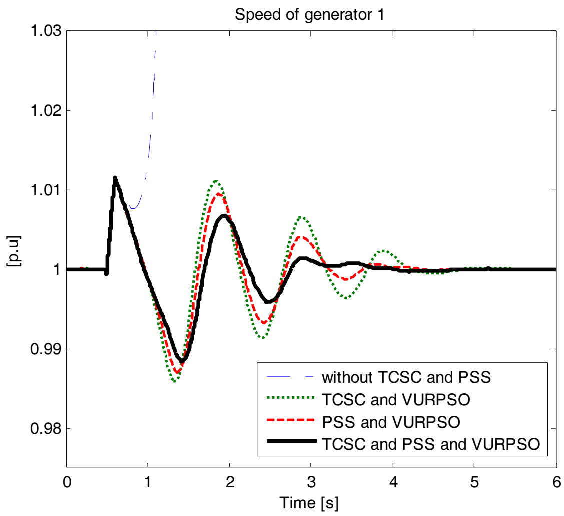


Fig. 26. Speed of Gen. 1 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

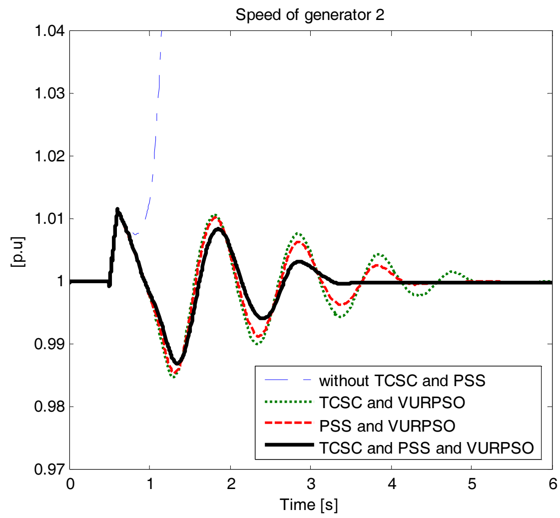


Fig. 27. Speed of Gen. 2 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

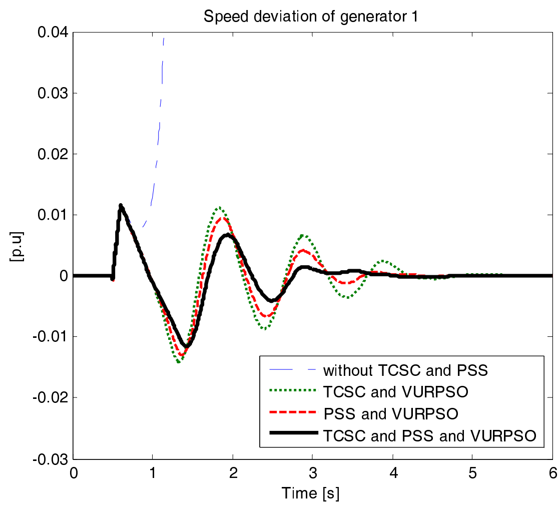


Fig. 28. Speed deviation of Gen. 1 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

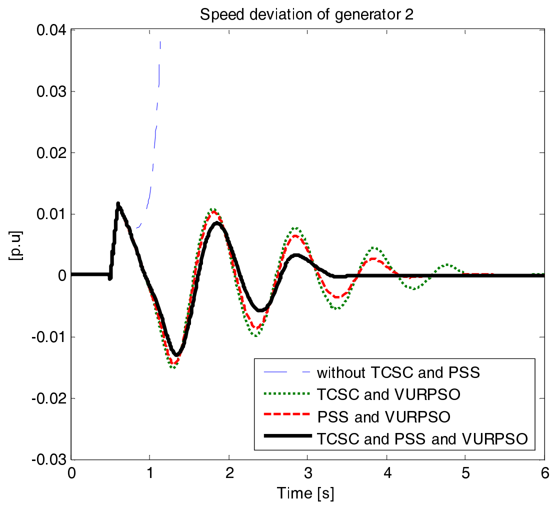


Fig. 29. Speed deviation of Gen. 2 using simultaneous TCSC and PSS controllers and VURPSO algorithm.

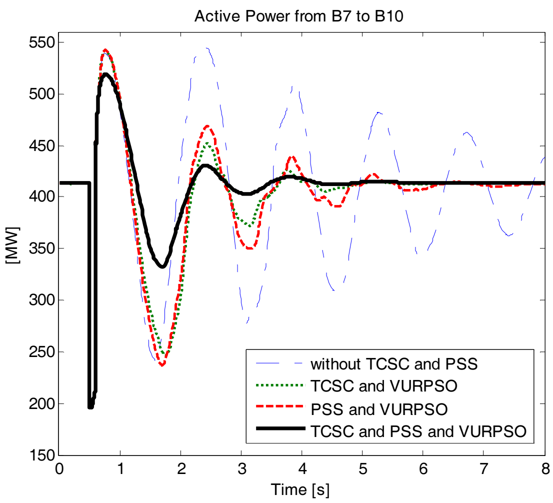


Fig. 30. Power transmission from first area to second area using simultaneous TCSC and PSS controllers and VURPSO algorithm.

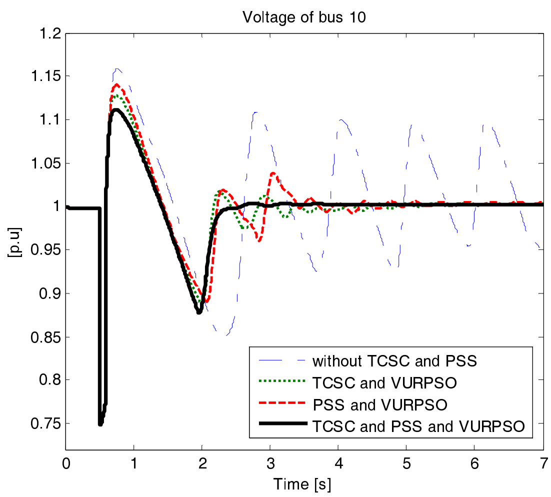


Fig. 31. Voltage of bus 10 using simultaneous PSS TCSC and controllers and VURPSO algorithm.

shorter than 4 s and the angles oscillations step down using simultaneous TCSC and PSS controllers and VURPSO algorithm.

As seen in Figs. 26 and 27, speed oscillations of generators 1 and 2 in the case of over loading are increased. In this case speed of generators 1 and 2 are damped in shorter than 4 s at 1pu by simultaneous TCSC and PSS controllers and VURPSO algorithm. As seen in Figs. 28 and 29, speed deviations oscillations of generators 1 and 2 in the case of over loading increase.

As seen in Fig. 30, oscillations of the power transmission from the first area to the second area in the case of over loading (Fig. 20) increase. Power transmission from the first area to the second area is damped in about 4.2 s at 413 MW by simultaneous TCSC and PSS controllers and VURPSO algorithm.

Referring to Fig. 31, voltage oscillations of bus 10 in the case of over-loading (Fig. 22) increase. The voltage of bus 10 is damped in about 3 s at 1 pu by simultaneous TCSC and PSS controllers and VURPSO algorithm.

6. CONCLUSION

In this paper, TCSC and PSS controllers were used simultaneously in order to increase the stability and to damp the oscillations of the non-linear four-machine system. Parameters of TCSC and PSS controllers were optimized by VURPSO algorithm or GA to improve the operation of the designed controlled for stability and oscillations damping of the power system.

The proposed system is unstable following the three-phase short-circuit fault with the ground; however, by simultaneous application of TCSC and PSS controllers, the stability of the system improves and its oscillations damp. If simultaneous TCSC and PSS controllers and VURPSO algorithm are considered, stability of the system will be enhanced and damped quickly.

This shows the excellent operation of designed controllers and also VURPSO algorithm. The results of simulation show that VURPSO algorithm and GA provide a better effect in the design of simultaneous TCSC and PSS parameters controllers and VURPSO algorithm reaches a better stability.

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