

Analysis of Performance of SSSC FACTS Device Using PSO Based Optimal Power Flow Solutions

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ABSTRACT:

This paper incorporates the SSSC FACTS device in optimal power flow solutions to enhance the performance of the power systems. The particle swarm optimization is used for solving the optimal power flow problem for steady-state studies. The effectiveness of the proposed approach was tested on IEEE 14-bus and IEEE 30-bus systems with SSSC FACTS device. Results show that the proposed PSO algorithm gives better solution to enhance the system performance with SSSC device compared to without SSSC device.

KEYWORDS: Power system operation, Optimal power flow solution, Particle swarm optimization (PSO), FACTS, SSSC device.

1. INTRODUCTION

Complexity of operating modern power systems is continually increasing because of larger power transfer over longer distances, greater interdependence among interconnected systems, more complicate coordination and interaction among various system controllers and fewer power reserves. These demands have forced systems to be operated closer to their security limits, because instability has become a major threat for system operation, as evidenced by the recent state of blackouts. Voltage Stability [1] is becoming an increasing source of concern in secure operation of present day power systems. Hence it is necessary to consider the voltage stability aspects in solving the optimal power control problems.

To meet the increasing power demand with existing transmission lines, the introduction of FACTS devices becomes an alternative. FACTS can improve the stability of network, and reduce the flows in heavily loaded lines by controlling their parameters, including series impedance, current, and voltage and phase angle. Especially, FACTS [2] devices can enable a line to carry its flow close to rating capacity and consequently, can improve the power system security in contingency.

In a power system, the FACTS devices may be used to achieve several goals. In steady-state [3], for a meshed network, they can permit to operate transmission lines close to their thermal limits and to reduce the loop flows. In this respect, they act by supplying or absorbing reactive power, increasing or reducing voltage and controlling series impedance or

phase angle [2]. Different types of devices have been developed such as series controllers, shunt controllers, and combined series-shunt controllers. Inside a category, several FACTS devices exist and each one has its own properties and may be used in specific contexts. The choice of the appropriate device is important since it depends on the goals to be reached.

Recently, the success achieved by evolutionary algorithms for the solution of complex problems, and the improvement made in computation such as parallel computation have stimulated the development of new algorithms like Particle Swarm Optimization (PSO) [4] present great convergence characteristics and capability of determining global optima.

This paper examines the effect of SSSC FACTS device on the power system performance using PSO based OPF solutions. The effectiveness of the proposed method with SSSC was examined on IEEE 14-bus and IEEE 30-bus tested systems and comparison made on the performance of the other FACTS devices.

2. VOLTAGE STABILITY INDEX (L-INDEX) COMPUTATION

The voltage stability L-index is a good voltage stability indicator with its value change between zero (no load) and one (voltage collapse). Moreover, it can be used as a quantitative measure to estimate the voltage stability margin against the operating point. For a given system operating condition, using the load flow (state estimation) results, the voltage stability L -index

is computed as [1], [5].

$$L_j = \left| 1 - \sum_{i=1}^g \overline{F_{ji}} \frac{\overline{V_i}}{V_j} \right| \quad j = g + 1, \dots, n \quad (1)$$

where L_j - voltage stability L -index

$\overline{V_i}$ is voltage at bus i

V_j is voltage at bus j

All the terms within the sigma on the RHS of equation (1) are complex quantities. The values of F_{ji} are obtained from the network Y -bus matrix.

For stability, the index L_j must not be violated (maximum limit=1) for any of the nodes j (load buses). Hence, the global indicator L_j describing the stability of the complete subsystem is given by maximum of L_j for all j . An L_j -index value away from 1 and close to 0 indicates an improved system security. The advantage of this L_j -index lies in the simplicity of the numerical calculation and expressiveness of the results.

3. FACTS CONTROLLERS

FACTS controllers are able to change, in a fast and effective way, the network parameters in order to achieve better system performance. FACTS controllers[6]-[8], such as phase shifter, shunt, or series compensation and the most recent developed converter-based power electronic controllers, make it possible to control circuit impedance, voltage angle, and power flow for optimal operation performance of power systems, facilitate the development of competitive electric energy markets, stimulate the unbundling the power generation from transmission and mandate open access to transmission services, etc. The benefit brought about by FACTS includes improvement of system behavior and enhancement of system reliability. However, their main function is to control power flows.

3.1. Static Synchronous Series Compensator (SSSC)

A SSSC [9], [10] usually consists of a coupling transformer, an inverter and a capacitor. The SSSC is series connected with a transmission line through the coupling transformer.

It is assumed here that the transmission line is series connected via the SSSC bus j . The active and reactive power flows of the SSSC branch i - j entering the bus j are equal to the sending end active and reactive power flows of the transmission line, respectively. In principle, the SSSC can generate and insert a series voltage, which can be regulated to change the impedance (more precisely reactance) of the transmission line. In this way, the power flow of the transmission line or the voltage of the bus, which the

SSSC is connected with, can be controlled.

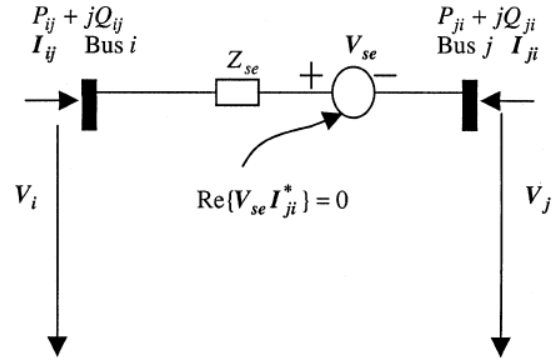


Fig. 1. Equivalent Circuit of SSSC.

The equivalent circuit of SSSC is as shown in the Figure 1. From the equivalent circuit the power flow constraints of the SSSC can be given as

$$P_{ij} = V_i^2 g_{ii} - V_i V_j (g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij}) - V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) + b_{ij} \sin(\theta_i - \theta_{se})) \quad (2)$$

$$Q_{ij} = -V_i^2 b_{ii} - V_i V_j (g_{ij} \sin \theta_{ij} - b_{ij} \cos \theta_{ij}) - V_i V_{se} (g_{ij} \sin(\theta_i - \theta_{se}) - b_{ij} \cos(\theta_i - \theta_{se})) \quad (3)$$

$$P_{ji} = V_j^2 g_{jj} - V_i V_j (g_{ij} \cos \theta_{ji} + b_{ij} \sin \theta_{ji}) + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) + b_{ij} \sin(\theta_j - \theta_{se})) \quad (4)$$

$$Q_{ji} = -V_j^2 b_{jj} - V_i V_j (g_{ij} \sin \theta_{ji} - b_{ij} \cos \theta_{ji}) + V_j V_{se} (g_{ij} \sin(\theta_j - \theta_{se}) - b_{ij} \cos(\theta_j - \theta_{se})) \quad (5)$$

where

$$g_{ij} + jb_{ij} = 1/Z_{se}, g_{ii} = g_{ij},$$

$$b_{ii} = b_{ij}, g_{jj} = g_{ij}, b_{jj} = b_{ij}$$

Operating constraint of the SSSC (active power exchange via the DC link) is as

$$PE = \text{Re}(V_{se} I_{ji}^*) = 0 \quad \text{or} \\ -V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) - b_{ij} \sin(\theta_i - \theta_{se})) + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) - b_{ij} \sin(\theta_j - \theta_{se})) = 0 \quad (6)$$

The active and reactive power flow constraints is

$$P_{ji} - P_{ji}^{specified} = 0 \quad (7)$$

$$Q_{ji} - Q_{ji}^{specified} = 0 \quad (8)$$

where $P_{ji}^{specified}$ and $Q_{ji}^{specified}$ are specified active and reactive power flows.

The equivalent voltage injection $V_{se} \angle \theta_{se}$ bound constraints are as

$$V_{se}^{\min} \leq V_{se} \leq V_{se}^{\max} \quad (9)$$

$$\theta_{se}^{\min} \leq \theta_{se} \leq \theta_{se}^{\max} \quad (10)$$

where, $V_{se}=0.04$ p.u., $V_{se}^{\min}=0.001$, $V_{se}^{\max}=0.2$

$$\theta_{se} = 87.13^0, \theta_{se}^{\min} = 90^0, \theta_{se}^{\max} = 180^0$$

3.2. Mathematical Formulation of OPF Problem

The PSO technique with SSSC FACTS device is applied to minimize the fuel cost of generation and to improve the system performance by maintaining thermal and voltage constraints. Mathematically, the OPF problem after incorporating SSSC FACTS controller can be formulated as follows [11]-[13]:

$$\text{Minimize } F = \left(\sum_{i=1}^{NG} (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \right) \quad (11)$$

The minimization problem is subjected to following equality and inequality constraints.

3.3. Constraints

The OPF problem has two categories of constraints:

3.3.1. Equality Constraints

These are the sets of nonlinear power flow equations that govern the power system, i.e,

$$P_{Gi} - P_{Di} - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (12)$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (13)$$

where P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at bus i respectively, the load demand at the same bus is represented by P_{Di} and Q_{Di} , and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij} .

3.3.2. Inequality Constraints:

These are the set of constraints that represent the system operational and security limits like the bounds on the following:

1) generators real and reactive power outputs

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, i = 1, \dots, N \quad (14)$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, i = 1, \dots, N \quad (15)$$

2) voltage magnitudes at each bus in the network

$$V_i^{\min} \leq V_i \leq V_i^{\max}, i = 1, \dots, NL \quad (16)$$

3) transformer tap settings

$$T_i^{\min} \leq T_i \leq T_i^{\max}, i = 1, \dots, NT \quad (17)$$

4) reactive power injections due to capacitor banks

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max}, i = 1, \dots, CS \quad (18)$$

5) transmission lines loading

$$S_i \leq S_i^{\max}, i = 1, \dots, nl \quad (19)$$

6) voltage stability index

$$Lj_i \leq Lj_i^{\max}, i = 1, \dots, NL \quad (20)$$

3.4. FACTS devices constraints

Static Synchronous Series Compensator (SSSC)

iii) SSSC constraints: Series voltage source magnitude and angle limits

$$V_{se}^{\min} \leq V_{se} \leq V_{se}^{\max} \quad (21)$$

$$\theta_{se}^{\min} \leq \theta_{se} \leq \theta_{se}^{\max} \quad (22)$$

The equality constraints are satisfied by running the power flow program. The generator bus terminal voltages (V_{gi}), transformer tap settings (t_k) and the reactive power generation of capacitor bank (Q_{ci}) are the control variables and they are self-restricted by the representation itself. The active power generation at the slack bus (P_{gs}), load bus voltages (V_{Li}) and reactive power generation (Q_{gi}), voltage stability (L_j)-index are state variables which are restricted through penalty function approach.

The installation of shunt reactive power sources involves the investment cost. The location of FACTS devices and its size also involves the investment cost. These issues are beyond the scope of this thesis, and are not considered in the solution of optimal power flow problems during minimization of different objective functions.

4. OVERVIEW OF PARTICLE SWARM OPTIMIZATION

Basically, the PSO was developed through simulation of birds flocking in two-dimensional space [14]. The position of each bird (called agent) is represented by a point in the X-Y coordinates, and the velocity is similarly defined. Bird flocking is assumed to optimize a certain objective function. Each agent knows its best value so far (pbest) and its current position. This information is an analogy of personal experience of an agent. Moreover, each agent knows the best value so far in the group (gbest) among pbests of all agents. This information is an analogy of an agent knowing how other agents around it have performed. Each agent tries to modify its position using the concept of velocity.

The velocity of each agent can be updated by the following equation:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 * (pbest_i - s_i^k) + c_2 rand_2 * (gbest - s_i^k) \quad (23)$$

where v_i^k is velocity of agent i at iteration k,

w is weighting function,

c_1 and c_2 are termed as cognition and social components respectively are the acceleration constants which changes the velocity of a particle towards pbest and gbest, $rand_1$ and $rand_2$ are random numbers between 0 and 1,

s_i^k is current position of agent i at iteration k,

pbest_i is the pbest of agent i, and gbest is the best value so far in the group among the pbests of all agents. The following weighting function is usually used in (23):

$$w = w_{max} - ((w_{max} - w_{min}) / (iter_{max})) * iter \quad (24)$$

where w_{max} is the final weight, w_{min} is the initial weight as these limits controls exploration and exploitation of the search space because it dynamically adjusts velocity, $iter_{max}$ is the maximum iteration number, and iter is the current iteration number. Using the previous equations, a certain velocity, which gradually brings the agents close to pbest and gbest, can be calculated. The current position (search point in the solution space) can be modified by the following equation. The flow chart [15] of PSO is given in Figure 2.

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (25)$$

5. OVERALL COMPUTATIONAL PROCEDURE FOR SOLVING THE PROBLEM

The implementation steps of the proposed PSO based algorithm [16]-[18] can be written as follows;

- Step 1: Input the system data for load flow analysis.
- Step 2: Select a SSSC FACTS device and its location in the system.
- Step 3: At the generation Gen =0; set the simulation parameters of PSO parameters and randomly initialize k individuals within respective limits and save them in the archive.
- Step 4: For each individual in the archive, run power flow under the selected network contingency to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.
- Step 5: Evaluate the penalty functions
- Step 6: Evaluate the objective function values and the corresponding fitness values for each individual.
- Step 7: Find the generation local best **xlocal** and global best **xglobal** and store them.
- Step 8: Increase the generation counter Gen = Gen+1.

- Step 9: Apply the PSO operators to generate new k Individuals.
- Step 10: For each new individual in the archive, run power flow to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.
- Step 11: Evaluate the penalty functions
- Step 12: Evaluate the objective function values and the corresponding fitness values for each new individual.
- Step 13: Apply the selection operator of PSO and update the individuals.
- Step 14: Update the generation local best **xlocal** and global best **xglobal** and store them.
- Step 15: If one of stopping criterion have not been met, repeat steps 4-14. Else go to step 16.
- Step 16: Print the results.

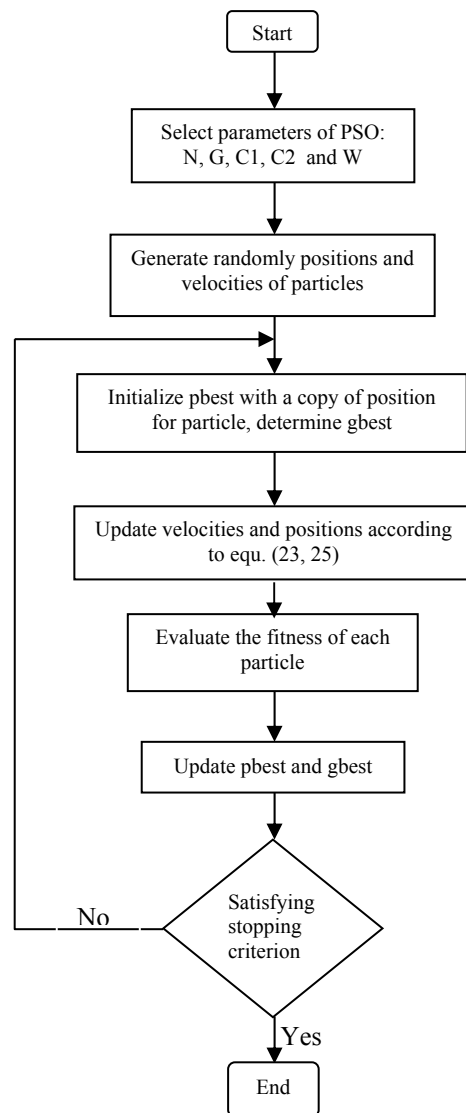


Fig. 2. Flow chart of PSO

6. SIMULATION RESULTS

The proposed PSO algorithm to solve optimal power flow problem incorporating SSSC FACTS device is tested on standard IEEE 14-bus and IEEE 30-bus test systems. The proposed algorithm are implemented using MATLAB 7.8 running on Pentium IV, 2.66GHz, and 512MB RAM personal computer. The PSO parameters used for the simulation are summarized in Table.

Table 1. Optimal parameter settings for PSO

Parameter	PSO
Population size	20
Number of iterations	150
Cognitive constant, c1	2
Social constant, c2	2
Inertia weight, W	0.3-0.95

The network and load data for this system is taken from [19]. To test the ability of the proposed PSO algorithm for solving optimal power flow problem with and without SSSC FACTS device. One objective function is considered for the minimization using the proposed PSO algorithm. In order to show the affect of power flow control capability of the SSSC FACTS device in proposed PSO OPF algorithm, two sub case studies are carried out on the IEEE 14-bus and IEEE 30-bus test systems.

Case (a): power system normal operation (without FACTS devices installation),

Case (b): one SSSC installed. SSSC installed in IEEE 14-bus and IEEE 30-bus test system at line connected between buses 12&13 and 9&10 with line real and reactive power settings of $P_{mk} = 0.025125$ & $Q_{mk} = 0.0145$ and $P_{mk} = 0.40775$ & $Q_{mk} = 0.04575$.

The first case is the normal operation of network without using FACTS device. In second case, installation of SSSC FACTS device has been considered. The device is placed in optimal location obtained from the literature and trail and error method.

The evolution of objective function during optimization by the proposed method is shown in Figure 3 and in Figure 4 under selected SSSC FACTS device. The optimal settings of control variables and SSSC FACTS device parameters during minimization of objective function are given in Tables 2 and 3 under the selected SSSC FACTS device respectively. From the Tables 2 and 3 it is noted that PSO algorithm is able to enhance the system performance while maintaining all control variables and reactive power outputs within their limits.

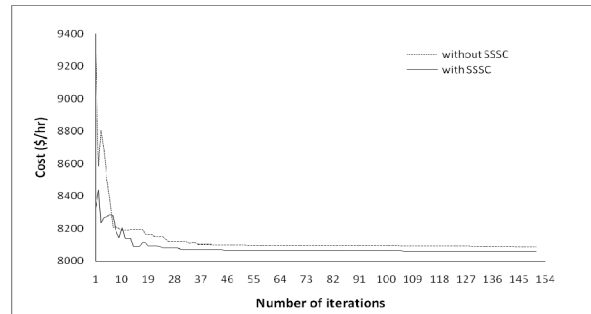


Fig. 3. Convergence of cost of generation without and with SSSC FACTS device for IEEE 14-bus system

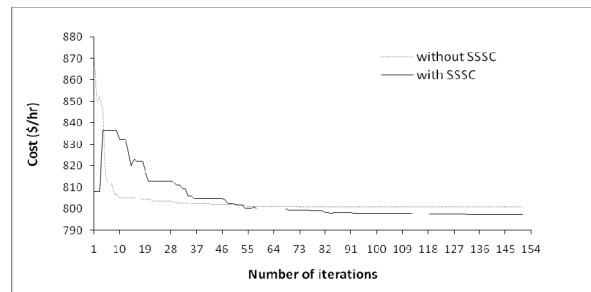


Fig. 4. Convergence of cost of generation without and with SSSC FACTS device for IEEE 30-bus system.

Table 2. Optimal settings of control variables for IEEE14-bus system.

Control Variables	Limits(p.u)		Without SSSC	With SSSC
	Min	Max		
P_{G1}	0.0	3.324	1.9447	1.9743
P_{G2}	0.0	1.400	0.3647	0.3689
P_{G3}	0.0	1.000	0.2919	0.2820
P_{G4}	0.0	1.000	0.0000	0.0000
P_{G5}	0.0	1.000	0.0830	0.0549
V_{G1}	0.95	1.10	1.0557	1.0913
V_{G2}	0.95	1.10	1.0292	1.0658
V_{G3}	0.95	1.10	1.0046	1.0422
V_{G4}	0.95	1.10	0.9961	1.0418
V_{G5}	0.95	1.10	0.9974	1.0403
Tap - 1	0.9	1.1	1.0152	1.0169
Tap - 2	0.9	1.1	0.9488	0.9640
Tap - 3	0.9	1.1	1.0539	0.9792
Q_{C6}	0.0	0.10	0.0639	0.0014
Q_{C8}	0.0	0.10	0.0357	0.1000
Q_{C14}	0.0	0.10	0.0556	0.0579
Cost (\$/h)			8087.200	8059.700
Ploss (p.u.)			0.0942	0.0901
Ljmax			0.0872	0.0749
CPU time (s)			20.0470	24.3800

Table 3. Optimal settings of control variables for IEEE 30-bus system.

Control Variables	Limits(p.u)		Without SSSC	With SSSC
	Min	Max		
P _{G1}	0.50	2.000	1.7718	1.7629
P _{G2}	0.20	0.800	0.4867	0.4901
P _{G3}	0.10	0.350	0.2109	0.1441
P _{G4}	0.10	0.300	0.1215	0.1392
P _{G5}	0.15	0.500	0.2144	0.2533
P _{G6}	0.12	0.400	0.1200	0.1200
V _{G1}	0.95	1.10	1.0868	1.0777
V _{G2}	0.95	1.10	1.0667	1.0606
V _{G3}	0.95	1.10	1.0405	1.0386
V _{G4}	0.95	1.10	1.0645	0.9937
V _{G5}	0.95	1.10	1.0348	1.0406
V _{G6}	0.95	1.10	1.0425	1.0451
Tap - 1	0.9	1.1	1.0464	1.0217
Tap - 2	0.9	1.1	0.9000	1.0210
Tap - 3	0.9	1.1	0.9568	0.9734
Tap - 4	0.9	1.1	0.9623	1.0691
QC10	0.0	0.10	0.0783	0.0000
QC12	0.0	0.10	0.0000	0.0375
QC15	0.0	0.10	0.0629	0.0294
QC17	0.0	0.10	0.0518	0.0439
QC20	0.0	0.10	0.0785	0.0086
QC21	0.0	0.10	0.0386	0.0688
QC23	0.0	0.10	0.0429	0.0581
QC24	0.0	0.10	0.0260	0.0505
QC29	0.0	0.10	0.0260	0.0468
Cost (\$/h)			800.8678	797.1873
Ploss (p.u.)			0.0913	0.0758
Ljmax			0.1381	0.1322
CPU time (s)			45.5510	90.5780

The line loadings, bus voltage profiles, bus voltage angles, and voltage stability indices with SSSC and without SSSC FACTS controller for IEEE 14 bus and IEEE30 bus systems are shown in Figures 5-12. The Figures 5-12 reveal that the proposed PSO methodology incorporating SSSC FACTS device is capable of maintaining better line loadings, load bus voltage profiles, bus voltage angles and voltage stability indices.

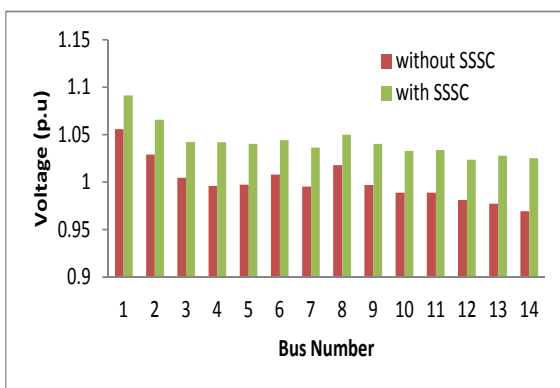


Fig. 5. Bus voltage profiles of IEEE 14-bus system with and without SSSC FACTS device.

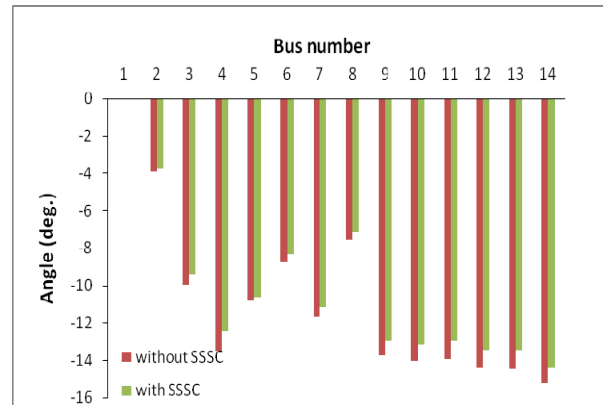


Fig. 6. Bus voltage angles of IEEE 14-bus system with and without SSSC FACTS device.

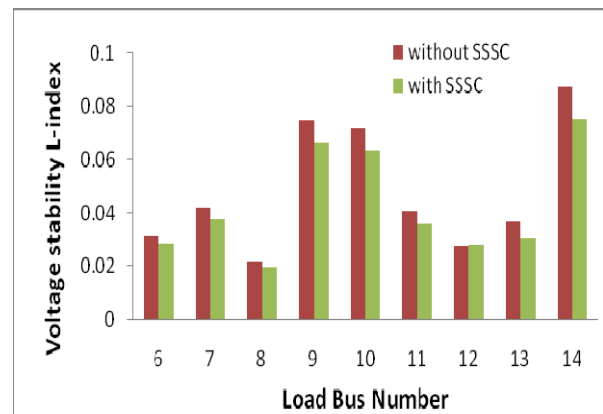


Fig. 7. Voltage stability indices of IEEE 14-bus system with and without SSSC FACTS device.

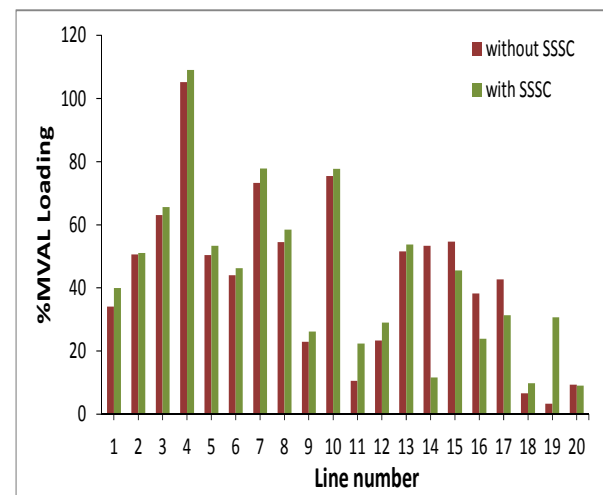


Fig. 8. Line loadings of IEEE 14-bus system with and without SSSC FACTS device .

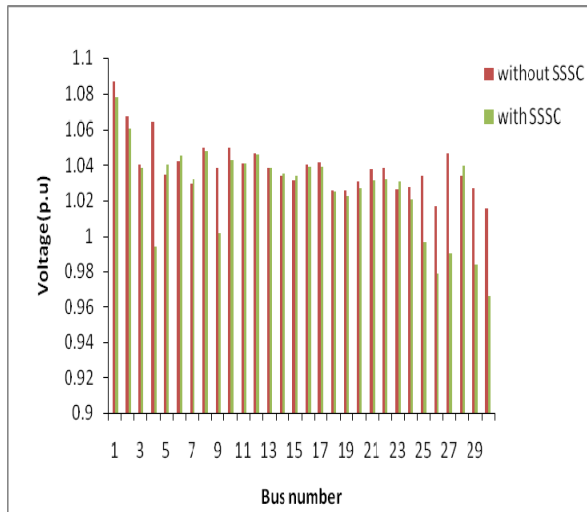


Fig. 9. Bus voltage profile of IEEE 30 bus system with and without SSSC FACTS device.

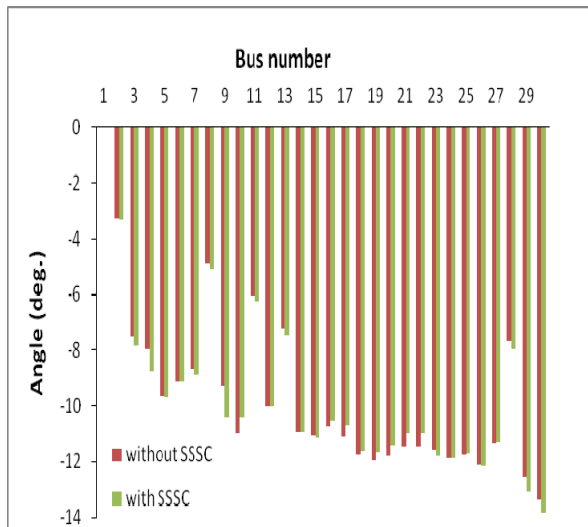


Fig. 10. Bus voltage angles of IEEE 30-bus system with and without SSSC FACTS device.

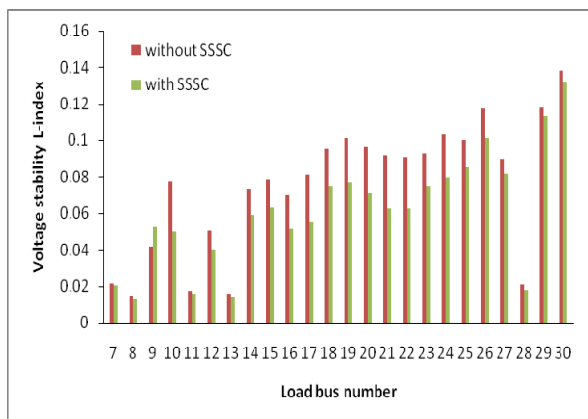


Fig. 11. Voltage stability indices of IEEE 30 bus system with and without SSSC FACTS device

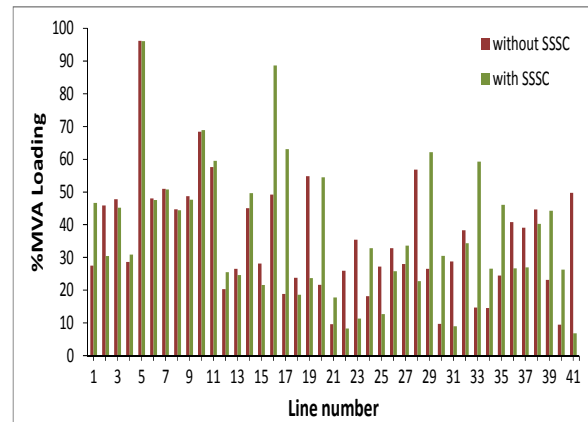


Fig. 12. Line loading of IEEE 30 bus system with and without SSSC FACTS device.

7. COMPARISON OF FUEL COST OF GENERATION WITH DIFFERENT FACTS CONTROLLERS

The comparison of fuel cost of generation of the proposed method with different FACTS controllers is reported in the literature is given in the Table 4. It is seen that PSO algorithm gives less cost of generation with SSSC device comparative to other devices.

Table 4. Comparison of fuel costs for IEEE 14 bus and IEEE 30 bus systems with different FACTS controllers.

Controllers	Cost	
	IEEE 14 bus system	IEEE 30 bus system
Without FACTS	8087.200	800.8678
PST	8086.000	800.6559
SVC	8084.600	800.5888
STATCOM	8080.000	800.5836
TCSC	8061.200	800.5671
UPFC	8061.000	800.5643
SSSC	8059.700	797.1873

8. COMPARISON OF COST OF GENERATION WITHOUT FACTS DEVICES

The comparison of fuel cost of the proposed method with other methods is given in Table 5. It can be seen from the Table 5 that the proposed PSO algorithm gives less cost of generation compared with the cost of generation obtained with other methods.

Table 5. Comparison of fuel costs for IEEE 30-bus system

Method	Fuel Cost (\$/hr)
EP [18]	802.907
TS [18]	802.502
TS/SA [18]	802.788
ITS [18]	804.556
IEP [18]	802.465
SADE ALM [20]	802.404
OPF PSO [17]	800.410
MDE-OPF [21]	802.376
Genetic Algorithm (\$/hr) [22]	803.050
Gradient method [23]	802.430
PSO (proposed)	800.8678

9. CONCLUSIONS

This paper has presented an OPF model incorporating SSSC series FACTS controller using the PSO algorithm for enhancement of system performance. This model is able to solve power networks of any size and converges with minimum number of iterations and independent of initial conditions. The IEEE 14-bus AND IEEE 30-bus systems have been used to demonstrate the proposed methods over a wide range of power flow variations in the transmission system. The results from the two tested systems showed that the proposed integrated OPF with Static Synchronous Series Compensator scheme is very effective compared to other FACTS devices in improving the security of the power system.

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