Improved Particle Swarm Optimization Method for Optimal Power Flow with Facts Devices

Dinh Luong Le, Dac Loc Ho and Ngoc Dieu Vo

Abstract— *This paper proposes an Improved Particle Swarm Optimization (IPSO) algorithm for solving optimal power flow with Facts devices problem. Two main types of FACTS devices, namely Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC) are applied to the OPF problem. In the new improved method, the conventional IPSO algorithm is used with the variance coefficients to speed up the convergence to the global solution in a fast manner regardless of the shape of the cost function. The proposed IPSO has been tested on various systems with FACTS devices to minimize the total generation fuel cost, investment costs of FACTS devices and keep the power flow within their security limits. The obtained numerical results have shown that the IPSO method is more efficient and faster than many other methods reported in the literature for finding the optimal solution of optimal power flow with Facts devices. Therefore, the proposed IPSO method can be a promising method for solving the practical optimal power flow with Facts devices problems.*

Keywords— **Facts devices; Particle Swarm Optimization; Optimal Power Flow; SVC; TCSC.**

1. INTRODUCTION

Most of the power supply system in the world is linked together broadly to address technical and economic problems. Although the building electrical system based on the load forecast but not always ensure balance between supply and demand. So the power system operating status will have some line-load lines carry some heavy loads. Transmission lines are presented limited by the temperature factor, capacitance and stability. So if not adjusted appropriate transmission lines will not make full use of its power transmission capabilities. Furthermore, because of environmental conditions, line corridor should not easily build new grid system arbitrarily renovate and replace the old system with ease.

Thereby need to reconsider traditional phone systems and implement measures for power distribution to control the power system operation more flexible and reliable. One of the control device is now the world's attention system FACTS Flexible AC [1], it can control the voltage, current, impedance phase angle of the power system, which helps improve stability too high (due to control power flow on effects, resistance, voltage and current level of short-circuit) or the phenomenon of resonance oscillation frequency below).

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be used to control power flow and enhance system stability. There is an increasing interest in using FACTS devices in the operation and control of power systems. However, their coordination with the conventional damping controllers in aiding of power system oscillation damping is still an open problem. Therefore, it is essential to investigate the coordinated control of FACTS devices and traditional power system controllers in large power systems.

Recently, appeared PSO algorithm, this algorithm has several advantages compared to other methods of computational time faster and stable convergence [2]. Scientists have applied PSO algorithm in many different areas of power system analysis such as system stability, coordination capacity… and has produced good results than other methods.

The purpose of this paper is to apply the improved particle swarm optimization algorithm to solve the optimal power flow problem with FACTS devices. Advanced IPSO method is tested and confirmed by comparing results with other methods such as Genetic Algorithm (GA), Simulated Annealing and Tabu Search (TS/SA), Evolutionary programming (EP).

2. FACTS MODELING FOR POWER FLOW STUDIES

2.1 Static VAR Compensator (SVC)

The simplest form of SVC consists of a TCR in parallel with a capacitor array as Figure 1. SVC is a variable reactance shunt connection, which is either generated or collected in reactive power to control voltage at the point of connection to the AC network [3]. It is widely used to provide fast reactive power for voltage regulation described in Figure 2. The stimulus angle control thyristor SVC allows almost instantaneous response.

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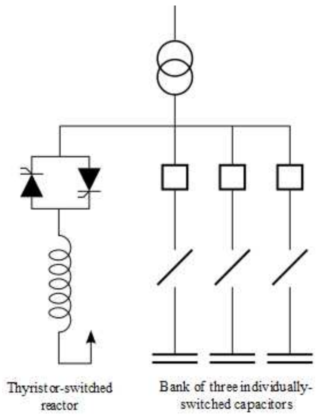

Fig. 1. Structural diagram of SVC.

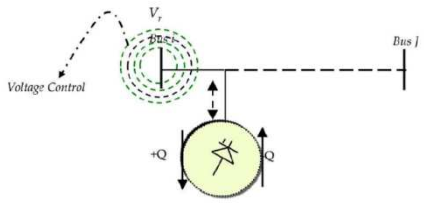

Fig. 2. Principle of voltage controlled shunt compensation devices FACTS.

Model of static compensators (SVC) is the VAr generator is presented Figure 3 that can pump or suction reactive power in the system is represented by Q_{SVC} [4].

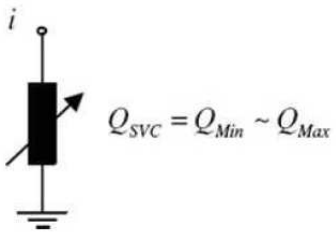

Figure 3. SVC model in power distribution [5].

2.2 Thyristor Controlled Series Capacitor (TCSC)

TCSC can change the electrical length of transmission lines. This feature enables the TCSC is used to quickly adjust power flow effects. It also increases the stability margin of the system and has proven very effective in reducing power oscillations [6]. Figure 4 describes the common structure of TCSC and Figure 5 describes the principles of the TCSC controller.

TCSC is integrated in the OPF problem by modifying the parameters of the road cord [7]. A new electric resistance (X_{new}) is as follows:

$$X_{new} = X_{ij} - X_C \tag{1}$$

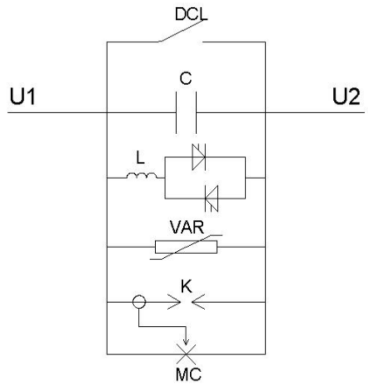

Fig. 4. Structural diagram of TCSC.

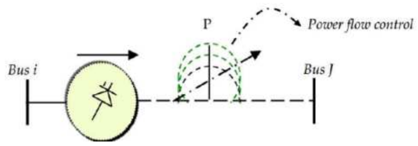

Fig. 5. The principle of power flow control serial devices FACTS.

3. OPF FORMULATION WITH FACTS DEVICES

In the OPF problem, the considered variables including control variables and state variables. The control variables include generating capacity of buttons except power balance, power pressure in the transmitter button, adjust the parameters of transformers and reactive power compensation capacitor rigs, FACTS parameters. The state variables include the transmit power of node balancing, load voltage, reactive power output of the generator, power flows on transmission lines. In addition, the OPF problem includes equality constraints are the power balance equations and inequalities bound the limits of the control variables and state variables. Generally, the OPF problem can be constructed as follows:

$$\text{Min } f(x,u) \tag{2}$$

subject to

$$g(x,u) = 0 \tag{3}$$

$$h(x,u) \le 0 \tag{4}$$

where $f(x,u)$ is the objective function to be minimized, $g(x,u)$ is the set of equality constraints, and $h(x,u)$ is the set of inequality constraints.

x is the state variable vector, u is the control variable vector:

$$x = \left[P_{G_1}, Q_{G_1},...,Q_{G_{NG}}.V_{L_1},...,V_{L_{NL}} S_{l_1},...,S_{Nl}\right]^T \tag{5}$$

with no FACTS devices

$$u = \left[P_{G_2},...,P_{N_G}, V_{G_1},...,V_{G_{NG}}.Q_{C_1},...,Q_{cN_c} T_1,...,T_{Nt}\right]^T \tag{6}$$

In case of FACTS devices, the control parameters of the device Q_{SVC}, Xc_{TCSC} be added to the control variables as follows:

$$u=\begin{bmatrix} P_{G_2},...,P_{N_G},V_{G_1},...,V_{G_{NG}},Q_{C_1},...,Q_{cN_c},T_1,...,T_{Nt}, \\ Q_1,..Q_{SVC},X_{C_1},...,X_{C_{NTCSC}} \end{bmatrix}^T \quad (7)$$

The fuel cost of each thermal generator is represented as a quadratic function of its power output.

$$MinF = \sum_{i=1}^{N} F_i\left(P_{Gi}\right) \quad (8)$$

F: total cost of the plant ($ / h).

F_i (P_{Gi}): fuel cost function of plant unit i ($ / h).

P_{Gi}: the capacity of plant unit i

N: total number of machines connected to the electrical system.

$$F_i\left(P_{Gi}\right) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (9)$$

where a_i, b_i, c_i: Fuel cost coefficients of generating unit *i*

3.1 Real and Reactive Power Flow Equations

At each bus, the real and reactive power balance should be satisfied

a. Problem no FACTS

$$P_{Gi} - P_{di} = |V_i|\sum_{j=1}^{N_b}|V_j||Y_{ij}|\cos\left(\theta_{ij} - \delta_i + \delta_j\right); i = 1...N_b \quad (10)$$

$$Q_{Gi} + Q_{ci} - Q_{di} = |V_i|\sum_{j=1}^{N_b}|V_j||Y_{ij}|\left[\sin\left(\theta_{ij} - \delta_i + \delta_j\right)\right]; i = 1...N_b \quad (11)$$

P_{Gi}, Q_{Gi}: the active power, reactive injection at bus *i*.

P_{di}, Q_{di}: the active power, the reactive load.

Q_{ci}: the reactive power compensation of power at bus i.

$|V_i|, |V_j|$: is the voltage at bus *i* and bus *j*.

$|Y_{ij}|$: The value of component i, j of the resulting matrix.

ϕ_{ij} : is the phase angle of component *i*, *j* of the resulting matrix.

δ_i, δ_j : the voltage phase angle at bus *i* and *j*.

N_b: the total number of buses in the system.

b. Problem with FACTS

$$\begin{aligned} &P_{Gi} - P_{di} \\ &= |V_i|\sum_{j=1}^{N_b}|V_j||Y_{ij}(FACTS)|\cos\left(\theta_{ij}(FACTS) - \delta_i + \delta_j\right); \\ &i = 1...N_b \end{aligned} \quad (12)$$

$$\begin{aligned} &Q_{Gi} + Q_{ci} + Q_i(FACTS) - Q_{di} \\ &= |V_i|\sum_{j=1}^{N_b}|V_j||Y_{ij}(FACTS)|\left[\sin\left(\theta_{ij}(FACTS) - \delta_i + \delta_j\right)\right]; \\ &i = 1...N_b \end{aligned} \quad (13)$$

$Q_i(FACTS)$: the reactive power of FACTS devices at bus i.

$|Y_{ij}(FACTS)|$: the value of component *i*, *j* of matrix can lead mention FACTS devices.

3.2 Limits at Generation Buses

The real power, reactive power, and voltage at generation buses should be within between their lower and upper bounds.

$$P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max}; i = 1...N_g \quad (14)$$

$$Q_{Gi,\min} \le Q_{Gi} \le Q_{Gi,\max}; i = 1...N_g \quad (15)$$

$$V_{Gi,\min} \le V_{Gi} \le V_{Gi,\max}; i = 1...N_g \quad (16)$$

N_g: Number of generators

3.3 Capacity Limits for Switchable Shunt Capacitor Banks

At var sources by switchable capacitors their power output should be within their lower and upper limits [5].

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max}; i = 1...N_c \quad (17)$$

N_c: number of sources to make the system.

3.4. Transformer Tap Settings Constraints

The tap settings of each transformer should be also within their lower and upper bounds.

$$T_{k,\min} \le T_k \le T_{k,\max}; k = 1...N_k \quad (18)$$

N_k: number of branches can adjust the voltage.

3.5 Security Constraints

The voltage at load buses and power flow in transmission lines should not exceed their limits.

$$V_{li,\min} \le V_{li} \le V_{li,\max}; i = 1...N_L \quad (19)$$

$$S_l \le S_{l,\max}; l = 1...N_l \quad (20)$$

N_l: number of line systems, N_L: number of nodes of the system load.

3.6 FACTS devices constraints

$$Q_{i,\min} \le Q_i \le Q_{i,\max}; i = 1...N_{SVC} \quad (21)$$

$$X_{ci,\min} \le X_{ci} \le X_{ci,\max}; i = 1...N_{TCSC} \quad (22)$$

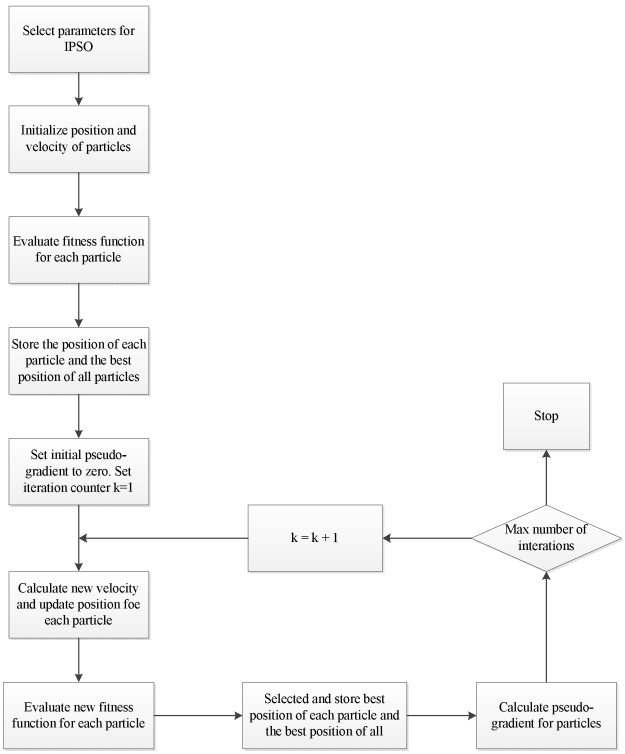

Fig. 6: Flowchart of IPSO for solving OPF problem.

4. 4. PARTICLE SWARM OPTIMIZATION

4.1. Conventional PSO

In PSO system, each individual adjusts its flying in a multi-dimensional search space according to its own flying experience and its companions flying experience. Each individual is referred to as a "particle" which represents a candidate solution to the problem. Each particle is treated as a point in a D-dimensional space [2]. The ith particle is represented as $Xi = (x_{i1}, x_{i2}, x_{i3},\ldots, x_{iD})$. The best previous position (giving the best fitness value) of any particle is recorded and represented as $P_l = (P_{i1}, P_{i2}, P_{i3},\ldots, P_{iD})$. The index of the best particle among all the particles in the population is represented by the symbol g. The rate of the position change (velocity) for particle i is represented as $V_i = (V_{i1}, V_{i2}, V_{i3},\ldots,V_{iD})$. The particles are manipulated according to the following equation:

$$V_{id} = V_{id} + c_1 r_1 (P_{id} - X_{id}) + c_2 r_2 (P_{gd} - X_{id}) \quad (23)$$

$$X_{id} = X_{id} + V_{id} \quad (24)$$

where the constants c_1 and c_2 are cognitive and social parameters, respectively and r_1 and r_2 are the random values in [0, 1].

4.2. Improved Particle Swarm Optimization

The IPSO here is the PSO with constriction factor enhanced by the pseudo-gradient for speeding up its convergence process. The purpose of the pseudo-gradient is to guide the movement of particles in positive direction so that they can quickly move to the optimization. In the PSO with constriction factor [8,9], the velocity of particles is determined in (26) and (27).

In this case, the factor φ has an effect on the convergence characteristic of the system and must be greater than 4.0 to guarantee stability. However, as the value of φ increases, the constriction C decreases producing diversification which leads to slower response. The typical value of φ is (27) (i.e. $c_1 = c_2 = 2.05$).

$$V_{id} = C.\left[V_{id} + c_1 r_1 (P_{id} - X_{id}) + c_2 r_2 (P_{gd} - X_{id})\right] \quad (25)$$

$$C = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|} \quad (26)$$

where $\varphi = c_1 + c_2, \varphi > 4$ (27)

The overall procedure of the proposed IPSO for solving the OPF problem is addressed in Figure 6.

Table 1. Result of OPF with TCSC

	No FACTS	TCSC
P_{g1} (MW)	177.9375	176.5955
P_{g2} (MW)	47.9981	47.6408
P_{g5} (MW)	21.0627	21.2075
P_{g8} (MW)	23.2693	24.0937
P_{g11} (MW)	10.0000	10.5641
P_{g13} (MW)	12.0000	12.0000
V_{g1} (pu)	1.1000	1.1000
V_{g2} (pu)	1.0844	1.0829
V_{g5} (pu)	1.0517	1.0550
V_{g8} (pu)	1.0653	1.0662
V_{g11} (pu)	1.1000	1.0839
V_{g13} (pu)	1.1000	1.1000
T_{11} (pu)	1.0000	1.0200
T_{12} (pu)	0.9100	0.9000
T_{15} (pu)	1.0300	1.0100
T_{36} (pu)	0.9500	0.9600
Q_{c10} (MVAr)	9.4000	0.0000
Q_{c24} (MVAr)	0.0000	4.3000
$TCSC_{3-4}$(pu)		0.0107
Ploss (MW)	8.8676	8.7016
Total cost ($/h)	799.9512	799.7741
Toltal Voltage deviation	1.3510	1.2481
Voltage stability index	0.1309	0.1319

5. NUMERICAL RESULTS

In this work the standard IEEE 30-bus test system has been used to test the effectiveness of the proposed method. It has a total of 8 control variables as follows:

six unit active power outputs, TCSC constraints and SVC constraints [11].

Three cases have been studied: Case 1 is the conventional OPF with TCSC devices using IPSO. Case 2 is the conventional OPF with SVC devices using IPSO. Case 3 is the conventional OPF with Multi FACTS devices using IPSO.

5.1. Optimal power flow with TCSC

In this case TCSC is considered in the OPF problem. The position of TCSC for this system according to [13] by loss sensitivity index indicates that branch 3-4 of system. In this simulation TCSC can change from 0 ~ 0.02 pu.

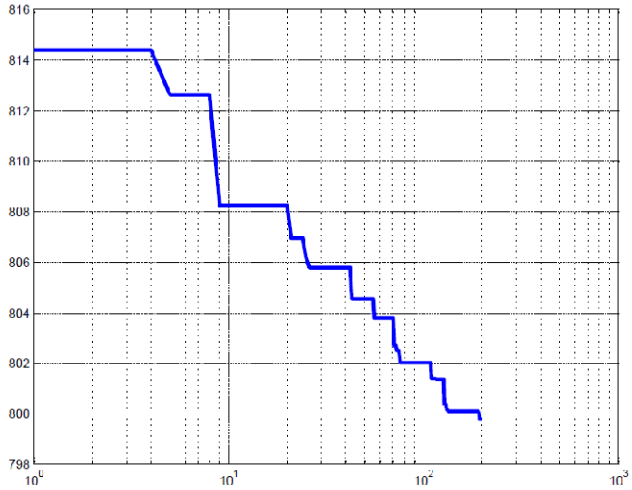

Fig. 7. Convergence characteristic of OPF with TCSC for the IEEE 30-bus system.

Table 2. Comparison of methods for OPF with TCSC

	TS/SA [12]	PSO [13]	IPSO
P_{g1} (MW)	192.6018	175.9641	176.5955
P_{g2} (MW)	48.4147	48.95	47.6408
P_{g5} (MW)	19.5561	21.526	21.2075
P_{g8} (MW)	11.6615	22.309	24.0937
P_{g11} (MW)	10	12.189	10.5641
P_{g13} (MW)	12	12	12.0000
$TCSC_{3\text{-}4}$ (pu)	0.02	0.011093	0.0107
Total cost ($/h)	804.6497	802.6552	799.7741

Results from Table 1 show that the TCSC is added to the system. Fuel costs for best solution is reduced from 799.9512 $/h in the absence of FACTS devices to 799.7741 $/h in the case with TCSC in line number 4 (line 3-4). As a result, the TCSC can lead to cost savings of 0.1771$/h or 0.022%. From the Table 2, we see IPSO can search for better solutions when compared with TS / SA [12], PSO in OPF problem with TCSC on IEEE30 bus system [13].

5.2. Optimal power flow with SVC

In this case, the SVC is considered in the OPF. SVC is placed at node 21 is the button with the reactive power demand in the highest load. SVC reactive power can be varied from 0 ~ 11.2 MVAr.

Table 3. Result of OPF with SVC

	No FACTS	SVC
P_{g1} (MW)	177.9375	177.2816
P_{g2} (MW)	47.9981	49.3202
P_{g5} (MW)	21.0627	19.5083
P_{g8} (MW)	23.2693	24.0881
P_{g11} (MW)	10.0000	10.0000
P_{g13} (MW)	12.0000	12.0000
V_{g1} (pu)	1.1000	1.1000
V_{g2} (pu)	1.0844	1.0863
V_{g5} (pu)	1.0517	1.0523
V_{g8} (pu)	1.0653	1.0565
V_{g11} (pu)	1.1000	1.1000
V_{g13} (pu)	1.1000	1.1000
T_{11} (pu)	1.0000	1.0900
T_{12} (pu)	0.9100	0.9000
T_{15} (pu)	1.0300	1.0100
T_{36} (pu)	0.9500	0.9700
Q_{c10} (MVAr)	9.4000	11.1000
Q_{c24} (MVAr)	0.0000	4.3000
SVC_{21} (MVAr)		8.2199
Ploss (MW)	8.8676	8.7982
Total cost ($/h)	799.9512	799.8193
Tolta voltage deviation	1.3510	1.2736
Voltage stability index	0.1309	0.1337

Table 4. Comparison of methods for OPF with SVC

	TS/SA [12]	PSO [13]	IPSO
P_{g1} (MW)	192.5895	176.1519	177.2816
P_{g2} (MW)	48.412	49.197	49.3202
P_{g5} (MW)	19.5554	21.533	19.5083
P_{g8} (MW)	11.6559	24.031	24.0881
P_{g11} (MW)	10	10	10.0000
P_{g13} (MW)	12	12	12.0000
SVC_{21} (MVAr)	11.196	6.4178	8.2199
Total cost ($/h)	804.5763	802.6454	799.8193

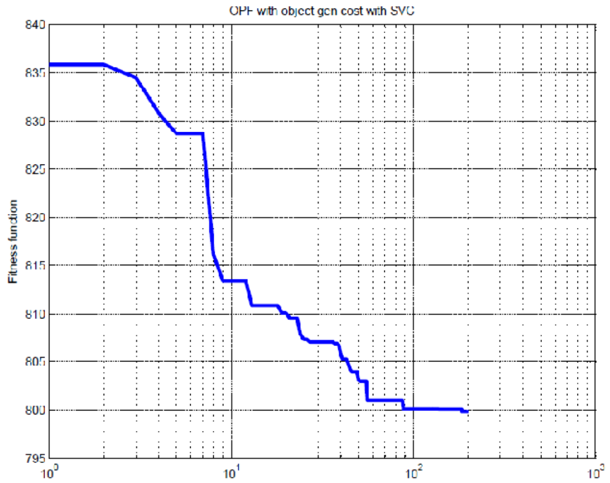

Fig. 8. Convergence characteristic of OPF with SVC for the IEEE 30-bus system

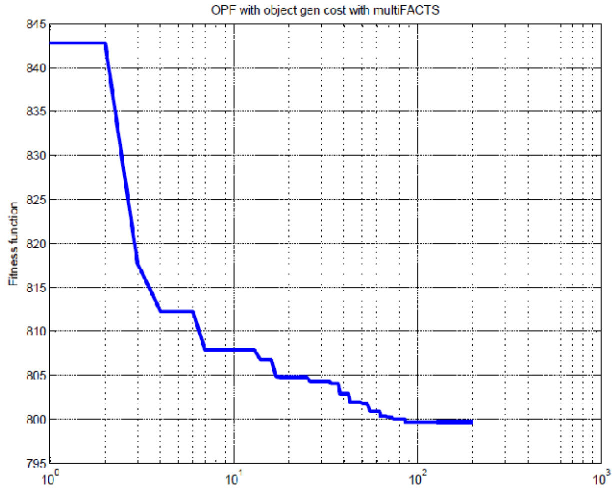

Fig. 9. Convergence characteristic of OPF with multi FACTS for the IEEE 30-bus system.

Table 5. Result of OPF with multi FACTS

	No FACTS	TCSC	SVC	Multi FACTS
P_{g1} (MW)	177.9375	176.5955	177.2816	178.8086
P_{g2} (MW)	47.9981	47.6408	49.3202	49.2240
P_{g5} (MW)	21.0627	21.2075	19.5083	21.7311
P_{g8} (MW)	23.2693	24.0937	24.0881	19.8779
P_{g11} (MW)	10.0000	10.5641	10.0000	10.6540
P_{g13} (MW)	12.0000	12.0000	12.0000	12.0000
V_{g1} (pu)	1.1000	1.1000	1.1000	1.1000
V_{g2} (pu)	1.0844	1.0829	1.0863	1.0873
V_{g5} (pu)	1.0517	1.0550	1.0523	1.0604
V_{g8} (pu)	1.0653	1.0662	1.0565	1.0693
V_{g11} (pu)	1.1000	1.0839	1.1000	1.1000
V_{g13} (pu)	1.1000	1.1000	1.1000	1.1000
T_{11} (pu)	1.0000	1.0200	1.0900	0.9700
T_{12} (pu)	0.9100	0.9000	0.9000	1.0000
T_{15} (pu)	1.0300	1.0100	1.0100	1.0000
T_{36} (pu)	0.9500	0.9600	0.9700	0.9800
Q_{c10} (MVAr)	9.4000	0.0000	11.1000	2.5000
Q_{c24} (MVAr)	0.0000	4.3000	4.3000	0.0000
SVC_{21} (MVAr)	-	-	8.2199	10.8107
TCSC (pu)	-	0.0107	-	0.0035
Ploss (MW)	8.8676	8.7016	8.7982	8.8956
Total cost ($/h)	799.9512	799.7741	799.8193	799.6030
Total voltage deiviation	1.3510	1.2481	1.2736	1.2989
Voltage stability index	0.1309	0.1319	0.1337	0.1344

Results from Table 3 show that the SVC was added to the system. Fuel costs for best solution is reduced from 799.9512 $/h in the absence of FACTS devices to 799.8193 $/h in the case of the SVC located at node 21. As a result, the SVC can lead to cost savings 0.1319 $/h or 0.017%. From the Table 4, we see IPSO can search for better solutions when compared with TS / SA, PSO in OPF with SVC problem on IEEE30 bus system.

5.3 Optimal power flow with multi FACTS

In this case TCSC and SVC are considered in the OPF problem. Table 5 shows the result of OPF with multi FACTS. Obviously, the total cost acquired by the multi Facts are all lower than that obtained by other case such as OPF with no Facts, OPF with TCSC and OPF with SVC.

6. CONCLUSION

In this paper, the improved particle swarm optimization (IPSO) algorithm has been presented to solve the optimal power flow problem considering FACTS devices. In the new improved method, the conventional IPSO algorithm is used with the variance coefficients to speed up the convergence to the global solution in a fast manner regardless of the shape of the cost function.

Calculation results show that the flexibility of PSO, IPSO in finding a global optimal solution that the other traditional algorithms can hardly be achieved. The algorithm can solve problems have complex objective function, not differentiable, have multiple discrete variables. Through comparison test shows IPSO algorithm has an advantage over PSO and TS/SA, so IPSO should be selected to solve the OPF problem with FACTS devices. A further direction for this study will be to apply other large-scale power systems with valve point effects and FACTS devices.

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