A NEW METHOD TO INCORPORATE FACTS DEVICES IN OPTIMAL POWER FLOW USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

In this work, Particle Swarm Optimization (PSO) for the solution of the optimal power flow (OPF) with use of controllable FACTS devices is studied. Two types of FACTS devices, thyristor controlled series compensator (TCSC) and thyristor-controlled phase shifters (TCPS) are considered in this method. The specified power flow control constraints due to the use of FACTS devices are included in the OPF problem in addition to normal conventional constraints. The sensitivity analysis is carried out for the location of FACTS devices. This method provides an enhanced economic solution with the use of controllable FACTS devices. IEEE standard 30-bus system is taken and results have been compared with GA to show the feasibility and potential of this PSO approach.

Keywords: *Thyristor Controlled Series Compensator (TCSC) and Thyristor-Controlled Phase Shifters (TCPS), Particle Swarm Optimization (PSO), optimal power flow (OPF).*

1. INTRODUCTION

Deregulation of the electricity supply system becomes an important issue in many countries. Flexible AC Transmission System (FACTS) devices become more commonly used as the power market becomes more competitive. They may be used to improve the transient responses of power system and can also control the power flow (both active and reactive power). The main advantages of FACTS are the ability in enhancing system flexibility and increasing the loadability [1].

In steady state operation of power system, unwanted loop flow and parallel power flow between utilities are problems in heavily loaded interconnected power systems. These two power flow problems are sometimes beyond the control of generators or it may cost too much with generator regulations. However, with the FACTS controllers, the unwanted power flow can be easily regulated [2][3].

In OPF the main objective is to minimize the costs of meeting the load demand for the power system while satisfying all the security constraints [4]. Since OPF is a non-linear problem, decouple of the control parameter of the FACTS device is a highly nonlinear problem [5] so that PSO is used as a methodology to solve. In this context, more control facilities may complicate the system operation. As control facilities influence each other, a good coordination is required in order to bring all devices to work together, without interfering with each other. Therefore, it becomes necessary to extend available system analysis tools, such as optimal power flow to represent FACTS controls. It has also been noted that the OPF problem with series compensation may be a non-convex and non-linear problem, which will lead the conventional optimization method stuck into local minimum.

Population based co-operative and competitive stochastic search algorithms are very popular in the recent years in the research area of computational intelligence. Some well established search algorithm such as GA[6] and evolutionary programming[7] are successfully implemented to solve the complex problems. The PSO algorithm was introduced by kennedy and Eberhart[8],[9] and further modifications in PSO algorithm were carried in [10].PSO is applied for solving various optimization problem in electrical engineering[11],[12].

In this work, the conventional OPF problem is solved with GA and PSO approaches along with two powers flow constraints. The approach minimize total cost as well as iteratively evaluates the control settings of TCSC and TCPS that are needed to maintain specified line flows. The sensitivity analysis is carried to position the TCSC and TCPS in test system [13][14]. The results obtained shows that PSO is superior in convergence compared to GA. The PSO is used to obtain Economic dispatch of generators such that these generations give minimum cost as well as does not result in line flow violation.

2. STATIC MODELING OF FACTS DEVICES

For Injected-power model, static modelling is a good model for FACTS devices because it will handle well in load flow computation and OPF analysis [2]. About load-equivalent method, actually it is only used when the control objectives of FACTS devices are known. In fact, the injected-power model is convenient and enough for power systems with FACTS devices.

2.1.Thyristor Controlled Series Compensator

The effect of TCSC on the network can be seen as a controllable reactance inserted in the related transmission line. The model of the network with TCSC is shown in Fig 2.1. The controllable reactance, x_c, is directly used as the control variable to be implemented in the power flow equation.

The power flow equations of the branch can be derived as follows:

$$P_{ij} = U_i^2 g_{ij} - U_i U_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) \quad (1)$$

$$Q_{ij} = -U_i^2 b_{ij} - U_i U_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \quad (2)$$

Where $g_{ij} = \dfrac{r_{ij}}{r_{ij} + (x_{ij} - x_c)^2}$

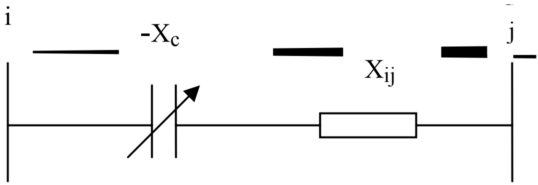

Fig. 2.1 Equivalent circuit of TCSC

Here, the only difference between normal line power flow equation and the TCSC line power flow equation is the controllable reactance x_c

2.2. Thyristor Controlled Phase Shifter

A series inserted voltage source U_I and a tapped current I_T can model the effect of TCPS on a network. Its equivalent circuit is shown in Fig.2.2. The additional voltage source changes the bus voltage from U_i to U_j corresponding to the shifting of the bus voltage U_I by an angle Φ.

$$\frac{U'_i}{U_i} = \frac{e^{j\theta}}{K}$$

Where, K=cosΦ is the transformation co efficient of the voltage magnitude. We can derive the power flow equation of TCPS branch as follow:

$$P_{ij} = U_i^2 g_{ij} / K^2 - U_i U_j [g_{ij} \cos(\delta_{ij} + \phi) + b_{ij} \sin(\delta_{ij} + \phi)] / K \quad (4)$$

$$Q_{ij} = -U_i^2 b_{ij} / K^2 - U_i U_j [g_{ij} \sin(\delta_{ij} + \phi) - b_{ij} \cos(\delta_{ij} + \phi)] / K \quad (5)$$

$$P_{ji} = U_i^2 g_{ij} - U_i U_j [g_{ij} * \cos(\delta_{ij} + \phi) - b_{ij} \sin(\delta_{ij} + \phi)] / K \quad (6)$$

$$Q_{ji} = U_i^2 b_{ij} - U_i U_j [g_{ij} * \sin(\delta_{ij} + \phi) - b_{ij} \cos(\delta_{ij} + \phi)] / K \quad (7)$$

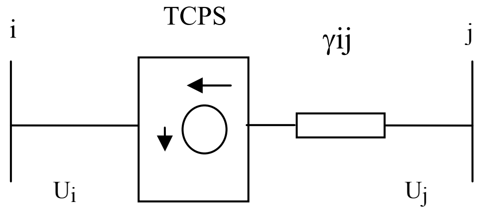

Fig 2.2. Equivalent circuit of TCPS

Where
T=tanΦ.

3. PROBLEM FORMULATION

In this study, the optimal power flow problem has the objective of minimizing the total cost of operating the spatially separated generating units subject to the set of equations that characterize the flow of power through the system and all operational and security constraints [6]. The TCSC reactance and TCPS phase shift parameters constraints are included in the OPF problem. The optimal power flow problem in flexible AC transmission systems is therefore expressed as follows:

Objective function

$$= \min \sum_{i \in NG} (a_i P_{gi}{}^2 + b_i P_{gi} + c_i) \quad (8)$$

$$st P_{g_i} + P_{is}(\phi) - P_d - \sum \begin{matrix} ViVjYij(xc)* \\ \cos(\theta ij + \delta i - \delta j) = 0 \forall i = N \end{matrix} \quad (9)$$

$$st Q_{g_i} + Q_{is}(\phi) - Q_d - \sum \begin{matrix} ViVjYij(xc)* \\ Sin(\theta ij + \delta i - \delta j) = 0 \forall i = N \end{matrix}$$

(14)

$$P_{gi}{}^{\min} \le P_{gi} \le P_{gi}{}^{\max} \qquad \forall \text{ i} \in \text{NG} \quad (10)$$

$$Q_{gi}{}^{\min} \le Q_{gi} \le Q_{gi}{}^{\max} \qquad \forall \text{ i} \in \text{NG} \quad (11)$$

$$T_{gi}{}^{\min} \le T_{gi} \le T_{gi}{}^{\max} \qquad \forall \text{ i} \in \text{NT} \quad (12)$$

$$F_{ij}{}^{\min} \le F_{ij} \le F_{ij}{}^{\max} \qquad \forall \text{ i} \in \text{NB} \quad (13)$$

$$X_{ci}{}^{\min} \le X_i \le X_{ci}{}^{\max} \qquad \forall \text{ i} \in \text{NP} \quad (14)$$

$$\theta_i^{\min} \le \theta_i \le \theta_i^{\max} \qquad \forall \text{ i} \in \text{NS} \quad (15)$$

4. IMPLEMENTATION OF PSO

PSO is initialized with a group of random particles and the searches for optima by updating generations. In every iteration each particle is updated by following "two best" values. The first one is the best solution (fitness value) it has achieved so far. This value is called Pbest. Another best value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is the global best called Gbest. After finding the best values the particles update its velocity and position with the following equation:

$$Vi^{k+1} = W * V_i^k + C1 * rand1 * (Pbesti - S_i{}^k) + c2 * rand2 * (Gbesti - S_i{}^k) \quad (16)$$

$$S_i{}^{k+1} = S_i{}^k + V_i{}^{k+1} \quad (17)$$

$$W = W_{\max} - (\frac{W_{\max} - W_{\min}}{iter \max}) * iter \quad (18)$$

where

V_i^k = Velocity of agent i at kth iteration k +1

V_i^{k+1} = Velocity of agent i at (k +1)th iteration

W = The inertia weight

$C_1 = C_2$ = Weighting Factor (0 to 4)

S_i^K= Current position of agent i at kth iteration

S_i^{K+1} = Current Position of agent i at (k+1)th iteration

iter max = Maximum iteration number

iter = Current iteration number

P_{besti} = P of agent i best

G_{besti} = G of the group best

$W_{\max}$ = Initial value of inertia weight = 0.9

$W_{\min}$ = Final value of inertia weight = 0.2

The velocity of the particle is modified by using (16) and the position is modified by using (17). The inertia weight factor is modified according to (18) to enable quick convergence.

Implementation of an optimization problem of GA is realized within the evolutionary process of a fitness function. The fitness function adopted is given as:

$$\text{Fitness function} = \frac{1}{objective + penality} \quad (19)$$

where objective function is the generation cost and the penalty is the bus voltage angle. Penalty cost has been added to discourage solutions which violate the binding constraints. Finally, the penalty factor is tended to zero.

The PSO algorithm to solve the optimal power flow with FACTS devices can be summarized as follows:

Step 1. Initialize the population of individuals is created in normalized form so as to satisfy the generation constraints and FACTS devices constraints.

Step 2. for each individual in the population, the fitness function is evaluated by using (19) in denormalized form.
Step 3. The velocity is updated by using (16) and new population is created by using (17)
Step 4. If maximum iteration number is reached, then go to next step else go to step 2.
Step 6. Print the best individual's settings.

4. OPTIMAL LOCATION OF TCSC AND TCPS

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index [8], as given below in equation (20).

$$PI = \sum_{m=1}^{N_l} \frac{W_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right) \qquad (20)$$

where P_{lm}, is the real power flow and $P_{lm}^{\max}$ is the rated capacity of line-m, n is the exponent and W_m a real nonnegative weighting coefficient which may be used to reflect the importance of lines. PI will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for a given state of the power system. In this study, the value of exponent has been taken as 2 and W_i=1.

The real power flow PI sensitivity factors with respect to the parameters of TCSC and TCPS placed in line-k, one at a time, are defined as

$$a_k^{\,c} = \frac{\partial PI}{\partial x_{ck}} \qquad (21)$$

$$a_k^{\,s} = \frac{\partial PI}{\partial \phi_k} \qquad (22)$$

Using (l), the sensitivity of PI with respect to FACTS device parameter X, ***(*** x_{ck} for TCSC and ϕ_k for TCPS) connected between bus-i and bus-j for the case *n* =2**,** can be written as

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{N_l} W_m P_{lm}^{\;3} \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{\partial P_{lm}}{X_k} \qquad (23)$$

The real power flow in a line-m PI can be represented in terms of real power injections using DC power flow equations [7] where s is slack bus, as $P_{lm} = \sum_{m=1}^{N_l} S_{mn} P_m$ for m≠k

$$P_{lm} = \sum_{m=1}^{N_l} S_{mn} P_m + P_j \qquad \text{for m=k} \qquad (24)$$

where S_{mn} is the mnth element of matrix [S] which relates line flow with power injections at the buses without FACTS devices and N is the number of buses in the system.

Using (25), the following relationship can be derived,

$$\frac{\partial P_{lm}}{\partial X_k} = S_{mi} \frac{\partial P_i}{\partial X_k} + S_{mj} \frac{\partial P_j}{\partial X_k} \qquad \text{for m≠k}$$

$$\frac{\partial P_{lm}}{\partial X_k} = \left(S_{mi} \frac{\partial P_i}{\partial X_k} + S_{mj} \frac{\partial P_j}{\partial X_k} \right) + \frac{\partial P_j}{\partial X_k}$$

for m=k (2925)

the term $\left.\frac{\partial P_i}{\partial X_k}\right|_{X_{ck}=0}$, $\left.\frac{\partial P_j}{\partial X_k}\right|_{X_{ck}=0}$, $\left.\frac{\partial P_j}{\partial \phi_k}\right|_{\phi_k=0}$ and $\left.\frac{\partial P_j}{\partial \phi_k}\right|_{\phi_k=0}$ can be obtained using equation (22-25)and are given below:

$$\frac{\partial Pi}{\partial X_k} = \frac{\partial P_{ik}}{\partial X_{ck}} = 2V^2 - ViVj \cos \delta ij * B_{ij}^{\;2} - G_{ij}^{\;2} -$$

$$\frac{\partial Pi}{\partial X_k} ViVj \sin \delta_{ij} (B_{ij}^{\;2} - G_{ij}^{\;2})$$

$$\frac{\partial P_j}{\partial X_k} = \frac{\partial P_{jk}}{\partial X_{ck}} = 2V^2 - ViVj \cos \delta ij * (B_{ij}^{\;2} * G_{ij}^{\;2}) -$$

$$\frac{\partial Pj}{\partial X_k} ViVj \sin \delta_{ij} (B_{ij}^{\;2} - G_{ij}^{\;2})$$

$$\left.\frac{\partial P_j}{\partial \phi_k}\right|_{\phi_k=0} = \left.\frac{\partial P_{js}}{\partial \phi_k}\right|_{\phi_k=0} = V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$$

$$\left.\frac{\partial P_j}{\partial \phi_k}\right|_{\phi_k=0} = \left.\frac{\partial P_{js}}{\partial \phi_k}\right|_{\phi_k=0} = -V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij})$$

(26-29)

Line-k		TCSC (a_k^c)	TCPS (a_k^s)
No:	i-j		
1	1-2	2.8637	-20.5548
2	1-3	-0.0451	0.3140
3	2-4	-2.9016	-11.5733
4	3-4	-0.0784	1.0419
5	2-5	-3.4293	11.2810
6	2-6	***-6.6653***	-37.0595
7	4-6	0.2635	4.5995
8	5-7	0.1448	1.8885
9	6-7	-0.1602	1.5212
10	6-8	-2.1366	22.2651
11	6-9	0.0117	0.0820
12	6-10	-0.1726	4.4295
13	9-11	1.0316	-7.3835
14	9-10	-0.9427	6.6450
15	4-12	-0.2079	8.2213
16	12-13	2.8972	2.0427
17	12-14	0.2692	6.3608
18	12-15	0.8510	36.3020
19	12-16	0.8397	11.1163
20	14-15	-0.0395	2.2285
21	16-17	-1.0072	16.6773
22	17-18	0	0
23	18-19	-0.7089	10.3708
24	19-20	0.0813	0.9027
25	10-20	0.1181	1.8124
26	10-17	-0.0069	0.2409
27	10-21	-0.8743	12.5895
28	10-22	5.8480	***41.0594***
29	21-22	0.0195	0.1358
30	15-23	0.5250	8.2576
31	22-24	-2.2810	16.2996
32	23-24	-0.6831	10.7628
33	24-25	0.0300	0.2109
34	25-26	-0.2798	1.9994
35	25-27	0.0004	-0.0083
36	26-27	0	0
37	27-29	-0.6531	4.6597
38	27-30	-2.7140	19.4252
39	29-30	-0.4436	5.0815
40	8-28	0.0925	0.6493
41	6-28	0.9000	6.3184

The sensitivity factors ak^c and ak^s can now be found by substituting equations (26-29) in equation (25)(21)(22).

4.1 CRITERIA FOR OPTIMAL LOCATION

The FACTS device should be placed on the most sensitive lines. With the sensitive indices computed for each type of FACTS device, TCPS should be placed in a line (k) having largest absolute value of the sensitivity factor. However, TCSC should be placed in a line (k) having largest negative value of the sensitivity factor.

It is found that the real power flows in lines are within the rating limit. Sensitivities are calculated for FACTS devices (TCSC and TCPS) placed in every line both at a time for this operating condition. The sensitivities of real power performance index with respect to TCSC and TCPS are presented in Table 4.1. The highest negative sensitivities in case-of TCSC and the highest absolute value of sensitivities in case of TCPS are presented in bold italic type.

Table4.1 SENSITIVITY FACTOR

5. CASE STUDIES

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 TCPS constraints.

The reactance of the TCSC is between 0 and 0.20 (p.u), while the voltage shift angle limit of TCPS are between 0 and 0.07 (radian).

Three cases have been studied; Case 1 is the conventional OPF without FACTS devices and (N-I) security constraints using GA. Case 2 is the conventional OPF with FACTS devices using GA. Case 3 is the conventional OPF with FACTS devices using PSO. The main optimization results are listed in Table 5.1.

Table 5.1. IEEE 30-bus system case study results

P_{Gi} (MW)	Case 1	Case 2	Case 3
P_{G1} (MW)	183.1800	192.5400	189.8200
P_{G2} (MW)	43.9700	48.6200	47.4100
P_{G5} (MW)	18.4400	19.5200	20.6200
P_{G8} (MW)	25.6200	11.7500	12.5500
P_{G11} (MW)	10.4300	10.2000	11.7400
P_{G13} (MW)	12.0000	12.1100	12.2100
$\sum P_{Gi}$(MW)	293.6400	294.7400	294.3500
∑cost($/hr)	805.0132	807.2548	805.3789

Without FACTS devices the cost of OPF is 805.0132 and Cost of OPF with FACTS using GA and PSO is 807.2548 and 805.3789 respectively. The results show that the generation cost of the has been reduced in PSO when compare to that of GA, and system the system loss also reduced. This shows the potential of the PSO algorithm.

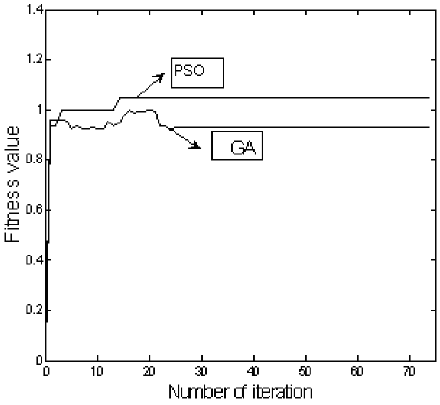

Fig.5.1. FF comparison for IEEE 30-bus system.

Two set of test runs are performed, the first (GA) with only the basic GA operators and the second (PSO). The FF evolution of the best of these runs is shown in Fig.5.1. The operating costs of the GA and PSO solutions are 807.2548 $/h and 805.3789 $/h, respectively. The operating cost of all PSO -OPF solutions is slightly less than the GA. Fig. 5.1 demonstrates the improvement achieved with the PSO algorithm.

Sensitivity factor of TCSC for line-6 is the most negative than the other lines and hence the most suitable for the TCSC placement. A branch 28 is the most sensitive for TCPS placement.The specified branches flow constraint values are listed in Table 5.2.

Table 5.2. IEEE 30-bus system specified line flow data

Line flows	F6	F28
Solution	0.4854	0.0749
Specified flow	0.3300	0.1800

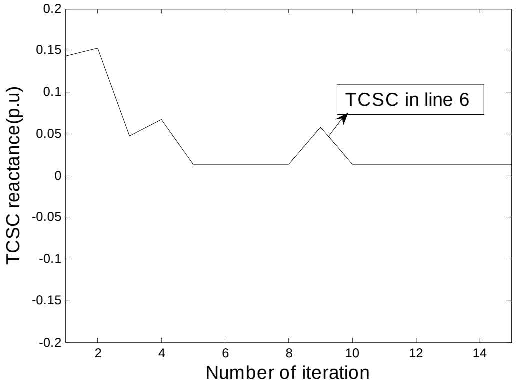

Fig.5.2.Modified IEEE 30 bus system with TCSC value in case 2

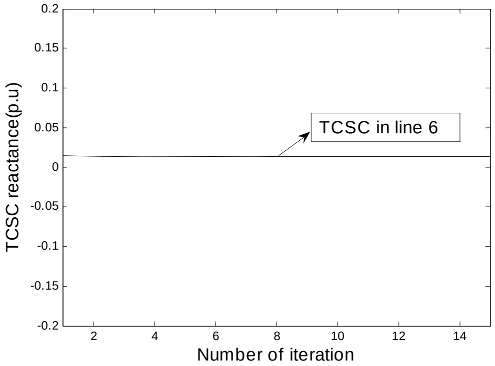

Fig.5.3.Modified IEEE 30 bus system with TCSC value in case 3

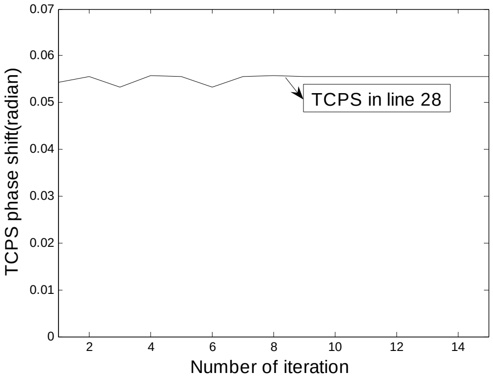

Fig.5.4.Modified IEEE 30 bus system with TCPS value in case 2

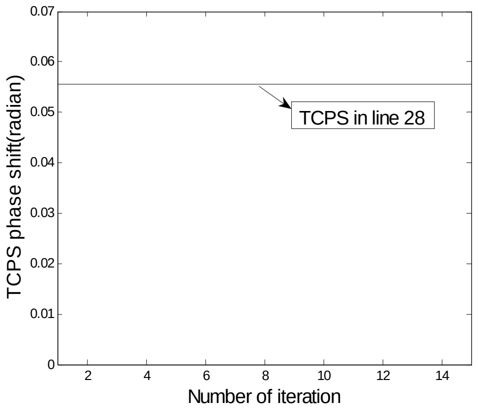

Fig.5.5.Modified IEEE 30 bus system with TCPS value in case 3

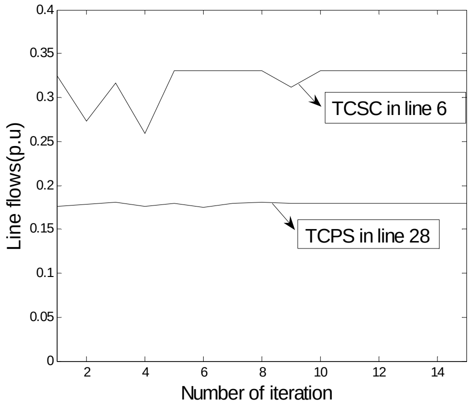

Fig.5.6.Modified IEEE 30 bus system with specified line flows in case 2

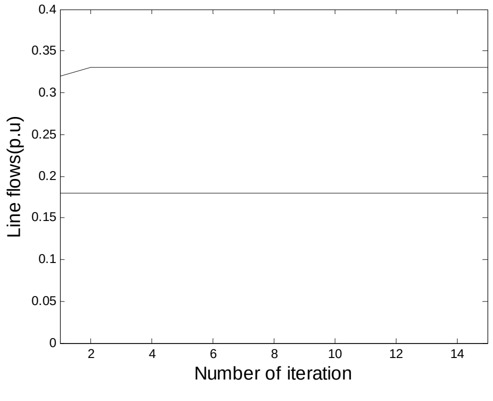

Fig.5.7.Modified IEEE 30 bus system with specified line flows in case 3

Along with the conventional OPF, the power through line numbers 6 and 28 has been taken as additional constraints. The specified values of power are to be achieved by placing TCSC in line 6 and TCPS in line 28. Now the next step is to find the value of TCSC reactance and TCPS phase shift that are needed to maintain the specified power flow.

Along with the conventional OPF, the power through line numbers 6 and 28 has been taken as additional constraints. The specified values of power are to be achieved by placing TCSC in line 6 and TCPS in line 28. Now the next step is to find the value of TCSC reactance and TCPS phase shift that are needed to maintain the specified power flow.

These values are found by GA and PSO method, with their convergence is shown in Fig. 5.2 through Fig 5.5. The corresponding power flows found iteratively for GA and PSO have been shown on Fig 5.6 and Fig 5.7 respectively.

With the GA being optimization method used the power flow through line 6 converge to the required value of 0.33 p.u approximately after 11 iterations, where as the power flow through line 28 converge to the required value of 0.18 p.u approximately after 8 iterations. With the PSO being optimization method used, the power in the line 6 and 28 are converge after second iteration. PSO converged very fast than GA.

If the power flow control constraints are not some specified values but some ranges, it is possible to use the appropriate convergent threshold to achieve this. For example, suppose the power flow control value of one branch is between 0.5 to 0.6 p.u, it can be set the specified branch flow at 0.55 and set the convergent threshold at 0.05 p.u. Thus, when the problem converges, this branch power flow is between 0.5 to 0.6 p.u using this method, and fulfills different power flow control needs.

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6. CONCLUSION

A PSO algorithm method was presented to solve the optimal power flow problem of power system with flexible AC transmission systems (FACTS) devices. The proposed method introduces the injected power model of FACTS devices into a conventional AC optimal power flow problem to exploit the new characteristic of FACTS devices. Case studies on modified IEEE test system show the potential for application of PSO to determine the control parameter of the power flow controls with FACTS. It can be shown that the FACTS device cannot reduce the generation cost (i.e. it is not a cost saving device) compared with normal system OPF. However, it can increase the controllability and feasibility of the system and provide wider operating margin and higher voltage stability with higher reserve capacity.

In this method, PSO effectively finds the optimal setting of the control parameters by using the conventional OPF method. It also shows that the PSO was suitable to deal with non-smooth, non-continuous, non-differentiable and non-convex problem, such as the optimal power flow problem with FACTS.

Nomenclature

N = set of bus indices.
NG= set of generation bus indices.
NT = set of transformer indices.
NB = set of transmission line indices.
NP = set of TCPS indices.
NS = set of TCSC indices.
Y_{ij} and θ_{ij} = magnitude and phase angle of element in admittance matrix.
P_{Gi} and $Q_{Gi=}$ active and reactive power generations at bus i.
P_{di} and Q_{di} = active and reactive power demands at bus i.
P_{is} and Q_{is} = injected active and reactive powers at bus i due to TCPS.
V_i and δ_i = voltage magnitude and angle at bus i.
T_i = tapping ratio at transformer i.
I_i = current magnitude at transmission line i.
ϕ_i = voltage shift angle of TCPS i.
x_{ci} = reactance of TCSC i.
a_k^c = PI sensitivity factors for TCSC.
a_k^s = PI sensitivity factors for TCPS.

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