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Swarm Intelligence based Approach for the Loss Minimum and Cost Minimum Configuration of an Interconnected Power System

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This paper presents particle swarm optimization (PSO) based approach for the allocation and coordinated operation of multiple FACTS (Flexible AC Transmission System) devices for the economic operation as well as to increase power transfer capacity of an interconnected power system under different loading condition. The PSO based approach is applied on IEEE 30-bus system. The system is reactively loaded starting from base to 200 % of base load. FACTS devices are installed in the different locations of the power system and system performance is noticed with and without FACTS devices. First, the locations, where the FACTS devices to be placed is determined by calculating active and reactive power flows in the lines. A PSO based algorithm is then applied to find the amount of magnitudes of the FACTS devices. This PSO based approach for the placement of FACTS devices yields promising result both in terms of performance and economy which is clearly observed from the results obtained.

Keywords: *FACTS Devices, Line power flow, Optimal location of FACTS devices and PSO.*

1.0 INTRODUCTION

With the worldwide restructuring and deregulation of Power Systems, sufficient transmission capacity and reliable operation have become more valuable to both power system planners and operators. Hence it becomes necessary to explore new ways of maximizing power transfer capability with the existing transmission facilities and maintaining the acceptable levels of network reliability and stability. Proper use of flexible AC transmission system (FACTS) technology can yield promising solution in this aspect. FACTS can provide benefits in increasing system transmission capacity, flexible power flow control and rapidity. It is known that the power flow through an AC transmission line is a function of line impedance, the magnitude and the phase angle between the sending end and the receiving end voltages. By proper coordination of TCSC (Thyristor Controlled Series Capacitor) and SVC (Static Var Compensator) in the power system network, both the active and reactive power flow in the lines can be controlled. Tighter control of power flow and the increased use of transmission capacity by FACTS devices are discussed in [1].

A scheme of power flow control in lines is discussed in [2]. Use of static phase shifters and FACTS controllers for the purpose of increasing power transfer capacity in the transmission line is described in [3–4]. In [5] authors have discussed about the power flow control in transmission network. About the modeling and selection of possible locations for the installation of FACTS devices have been discussed in [6]. Assessment and impact on power networks by the use of FACTS devices have been discussed

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in [7] through the concept of steady state security regions. Allocation of variable series capacitor and static phase shifters in transmission lines was the main objective in [8] for the optimal power flow. A hybrid Genetic Algorithmic approach with FACTS devices for optimal power flow is dealt in [9]. In a congested power system, first the locations of the FACTS devices were decided based on the sensitivity factors and then dispatch problem was solved in [10]. How the unified power flow controllers can be used in a congested power system is discussed in [11].

A GA based separate and simultaneous use of thyristor controlled series capacitor (TCSC), unified power flow controller (UPFC), thyristor controlled voltage regulator (TCVR), and static Var compensator (SVC) were studied in [12] for increased power flow. The objective of this present work is the optimal allocation of FACTS devices in the transmission network so the transmission loss becomes minimized and also for the simultaneous increase of power transfer capacity of the transmission network that ultimately yields minimum operating cost under various loading conditions. Minimization of transmission loss is a problem of reactive power optimization and can be done by controlling reactive generations of the generators, controlling transformer tap positions and adding shunt capacitors in the weak buses [13] but the active power flow pattern can't be controlled. GA based optimization technique [14] is discussed for the placement of FACTS devices in some Test systems. Power flow control with different FACTS devices were discussed in [15]. In the proposed work, first the locations of the FACTS devices are identified by calculating different line flows. TCSC's are placed in lines where reactive power flows are very high and the SVC's are connected at the receiving end buses of the other lines carrying significant amount of reactive power.

In this proposed work, a PSO based approach considering the simultaneous effect of two types of the FACTS devises are presented and the effectiveness of this technique is clearly evident from the result shown.

2.0 FACTS DEVICES

A. Modelling of FACTS Devices and cost functions

Mathematical modeling of FACTS devices are required for the steady state analysis. Here the FACTS devices used in the transmission network are TCSC and SVC.

TCSC

By modifying the line reactance TCSC acts as either inductive or capacitive compensator. The maximum value of the capacitance is fixed at -0.8 X_{Line} and 0.2X_{Line} is the maximum value of the inductance. Transmission line admittance in which TCSC is connected can be written as

$$G_{tcsc}+jB_{tcsc} = \frac{1}{R + j(X_{Line} + X_{tcsc})} \quad .... (1)$$

where R and X_{Line} are the resistance and reactance of the line without TCSC.

SVC

The SVC can be operated as either inductive or capacitive compensation. It can be modeled as a fixed capacitor and a thyristor controlled reactor. So function of the SVC is either to inject reactive power to bus or to absorb reactive power from the bus where it is connected. The SVC's effective reactance X_{SVC} is determined by parallel combination of X_C and X_L and is given by

$$X_{SVC} = \frac{\pi X_C X_L}{X_C[2(\pi-\alpha) + 2\sin\alpha] - \pi X_L} \quad .... (2)$$

where α is the firing angle.

B. FACTS Devices cost Functions

According to [13], cost functions for SVC, and TCSC are given below :

TCSC:

$$C_{TCSC} = 0.0015(OR)^2 - 0.7130(OR) + 127.38 (US/kVAr) \quad .... (3)$$

SVC:

$$C_{SVC} = 0.0003(OR)^2 - 0.2691(OR) + 188.22 (\text{US \$/kVAr}) \quad .... (4)$$

Here, (OR) is the operating range of the FACTS Devices.

3.0 OPTIMAL PLACEMENT OF FACTS DEVICES

Here the main objective is to minimize the total operational cost under different loading situation by incorporating FACTS devices at suitable locations of the transmission network. There are three main issues that are to be considered: types of device, its capacity and location. The decision where they are to be placed is largely dependent on the desired effect and the characteristics of the specific system. SVCs are mostly suitable when reactive power flow or voltage support is necessary. TCSC devices are not suitable in lines with high Reactive Power flow. Inclusion of FACTS controllers also increase the system cost.

So, optimal placements of FACTS devices are required such that the gain obtained by reducing the transmission loss is significant even after the placement of costly FACTS devices. Installation costs of various FACTS devices and the cost of system operation, namely, energy loss cost are combined to form the objective function to be minimized. Besides FACTS devices, transmission loss can be minimized by optimization of reactive power, which is possible by controlling reactive generations of the generator's, controlling transformer tap settings, and by the addition of shunt capacitors at weak buses. But with FACTS devices both the active and reactive power flow pattern can be changed and results significant changes in the system performance. The optimal allocation of FACTS Devices can be formulated as:

$$C_{TOTAL} = C_1(E) + C_2(F) \quad .... (5)$$

where $C_1(E)$ is the cost due to energy loss and $C_2(F)$ is the total investment cost of the FACTS Devices.

Subject to the nodal active and reactive power balance

$$P_{ni}^{min} \le P_{ni} \le P_{ni}^{max}$$

$$Q_{ni}^{min} \le Q_{ni} \le Q_{ni}^{max}$$

voltage magnitude constraints: $V_i^{min} \le V_i \le V_i^{max}$ and the existing nodal reactive capacity constraints:

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}$$

A. PSO approach in brief:

The basic approach for the optimization of nonlinear functions using particle swarm optimization technique is introduced in [16]. The formulae on which PSO works is given as

$$\upsilon_i^{k+1} = \omega_i \upsilon_i^k + C_1 \text{ rand } \times \left(P_{best_i} - S_i^k\right) + C_2 \text{ rand } \times \left(g_{best} - S_i^k\right)$$

Where,

υ_i^k → current velocity of agent *i* at iteration *k*,

$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \times iter$ → is the modified velocity of the ith agent

rand → is the random number between 0–1,

S_i^k → current position of agent *i* at iteration *k*,

C_i → weight coefficient for each term,

P_{best_i} → P_{best} of agent *i*,

g_{best} → g_{best} of the group,

ω_i → weight function for velocity of agent *i*.

Where ω is updated by the following equation at each iteration

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \times iter$$

Here ω_{max} = 0.9, ω_{min} = 0.4, $iter_{max}$ = 500 and iter = current iteration, C_1 and C_2 are set to 2.0.

PSO is used after the solution obtained by the Fuzzy approach for optimal setting of transformer tap positions, Generator's reactive generations. Here the control variables are represented within a string. Initially strings are generated randomly and each string may be a potential solution. In PSO, each potential solution, called particles is assigned a velocity. The particles of the population always adjust their velocity depending upon their position with respect to the position of the p_{best} (the particle having the best fitness in the current generation) and the g_{best} (the particle having the best fitness upto the present generation). While adjusting their velocities and positions, particles adjust their fitness value as well. The particle having the best fitness among all is selected as the p_{best} for the current generation, and if this p_{best} has better fitness than the g_{best}, it takes the position of the g_{best} as well. In PSO, therefore, the g_{best} particle always improves its position and finds the optimum solution and the rest of the population follows it. The string length depends upon the problem and the control variables within the string are shown in Figure 1.

TCSC elements (4 nos)				**Shunt elements (4 nos)**				**Transfer tap (4 nos)**				**Reactive generations (5 nos)**				
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	5

FIG. 1 STRING REPRESENTING THE CONTROL VARIABLES

4.0 TEST RESULTS

The proposed for the placement of FACTS devices is applied on IEEE 30-bus system. The power system is loaded (reactive loading is considered) and accordingly FACTS devices are placed at different locations of the power system. The power system is loaded up to the limit of 200% of base reactive load and accordingly the system performance is observed with and without FACTS devices. Table 1 shows the locations of different FACTS devices in the transmission network. A comparative study of the operating cost of the system with and without FACTS devices using PSO is given in Table 2. The magnitude and phase angle of the bus voltages with and without FACTS devices for highest reactive loading i.e. for 200% is shown in Table 3. Phase angles are given in radian. It is observed from Table 1, that SVC's are connected at the buses 21, 7, 17 and 15 those are at the finishing ends of the lines 27, 26, 9 and 18 respectively because these are the four lines carrying highest, second highest, third and fourth highest reactive power respectively, as found by calculating reactive power flow in different lines. After connecting SVC's at theses buses, voltage profile at these buses are improved, also reactive power flow reduces greatly in the lines 27, 26, 9 and 18 in each case of loading. TCSC's are placed in the lines 25, 41, 28 and 5 as these are the next four highest reactive power carriers.

TABLE 1

LOCATIONS OF DIFFERENT FACTS DEVICES IN THE TRANSMISSION NETWORK

TCSC in lines	**SVC in buses**
25, 41, 28, 5	21, 7, 17, 15

TABLE 2

COMPARATIVE ANALYSIS OF ACTIVE POWER LOSS AND OPERATING COST USING PSO

Reactive loading	**Active power loss without FACTS (p.u.)**	**Operating cost due to the energy loss (in \$) (A)**	**Active power loss with FACTS using PSO (p.u.)**	**Cost due to energy loss with FACTS (in \$)**	**Operating cost with FACTS devices (in \$) (B)**	**Cost of FACTS devices (in \$)**	**Net saving (in \$) (A-B)**
100%	0.0711	3737016	0.0445	2338920	2.4052×10^{6}	66280	1331816
150%	0.0742	3899952	0.0478	2512368	2.6080×10^{6}	95632	1291952
175%	0.0765	4020840	0.0497	2612232	2.7693×10^{6}	157068	1251540
200%	0.0795	4178520	0.0637	3.3481×10^{6}	3.4460×10^{6}	97900	732520

TABLE 3

BUS VOLTAGES AND PHASE ANGLES WITH AND WITHOUT FACTS DEVICES FOR 200% REACTIVE LOADING USING PSO

Bus No.	**Bus voltage without FACTS**	**Bus voltages with FACTS using PSO**	**Bus angle without FACTS**	**Bus angle with FACTS using PSO**
1	1.0500	1.0500	0.0000	0
2	1.0338	1.0338	–0.0481	–0.0483
3	1.0284	1.0215	–0.0813	–0.0793
4	1.0231	1.0149	–0.0975	–0.0951
5	1.0058	1.0058	–0.1579	–0.1591
6	1.0182	1.0100	–0.1127	–0.1112
7	1.0014	0.9952	–0.1391	–0.1383
8	1.0230	1.0230	–0.1137	–0.1146
9	1.0302	1.0933	–0.1415	–0.1380
10	1.0135	1.0801	–0.1755	–0.1694
11	1.0913	1.0913	–0.1083	–0.1067
12	1.0295	1.0674	–0.1644	–0.1511
13	1.0883	1.0883	–0.1432	–0.1307
14	1.0096	1.0558	–0.1789	–0.1658
15	1.0036	1.0574	–0.1795	–0.1711
16	1.0122	1.0618	–0.1728	–0.1622
17	1.0050	1.0662	–0.1775	–0.1696
18	0.9906	1.0487	–0.1893	–0.1800
19	0.9871	1.0477	–0.1920	–0.1825
20	0.9926	1.0547	–0.1888	–0.1801
21	0.9956	1.0684	–0.1816	–0.1773
22	0.9965	1.0678	–0.1816	–0.1767
23	0.9892	1.0476	–0.1851	–0.1763
24	0.9819	1.0469	–0.1877	–0.1794
25	0.9901	1.0527	–0.1885	–0.1794
26	0.9651	1.0271	–0.1917	–0.1809
27	1.0079	1.0694	–0.1859	–0.1773
28	1.0121	1.0055	–0.1195	–0.1184
29	0.9832	1.0448	–0.2057	–0.1942
30	0.9696	1.0315	–0.2208	–0.2072

From Table 2, we observe that transmission loss as well as operational cost reduced significantly in all cases of loading with FACTS devices as compared to without such devices. Significant economic gain is obtained even at a loading of 200% of base reactive loading which is also evident from Table 2. The economic gain obtained is much higher than the installation cost of FACTS devices in every cases of loading.

Here, energy cost is taken as 0.06$/kWh.

Figure 1 shows the different FACTS devices to be installed in the system within a string, PSO is used to optimize these parameters. Figures 2–5 shows the reactive power flow in the selected lines without and with FACTS devices for different loading cases. It is clear from the figure that reactive power has been reduced after installation of FACTS devices. Figures 6–9 shows the variation of operating cost with generation from base to 200% of reactive loading of the system with PSO based methods.

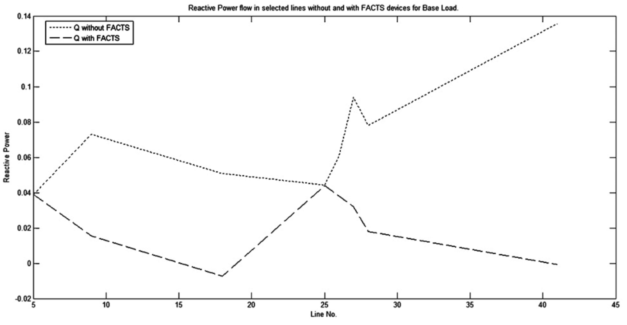

FIG. 2 REACTIVE POWER FLOW IN LINES WITHOUT AND WITH FACTS DEVICES FOR BASE LOAD.

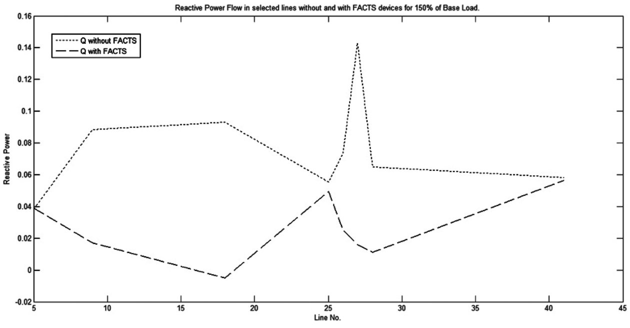

FIG. 3 REACTIVE POWER FLOW IN LINES WITHOUT AND WITH FACTS DEVICES FOR 150% OF BASE LOAD.

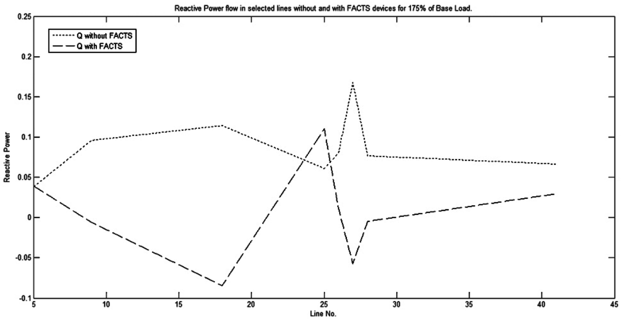

FIG. 4 REACTIVE POWER FLOW IN LINES WITHOUT AND WITH FACTS DEVICES FOR 175% OF BASE LOAD.

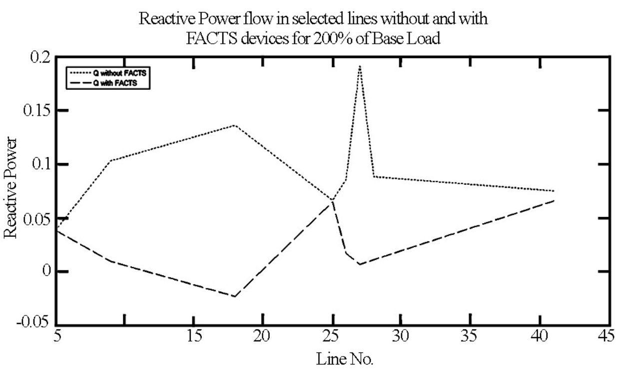

FIG. 5 REACTIVE POWER FLOW IN LINES WITHOUT AND WITH FACTS DEVICES FOR 200% OF BASE LOAD.

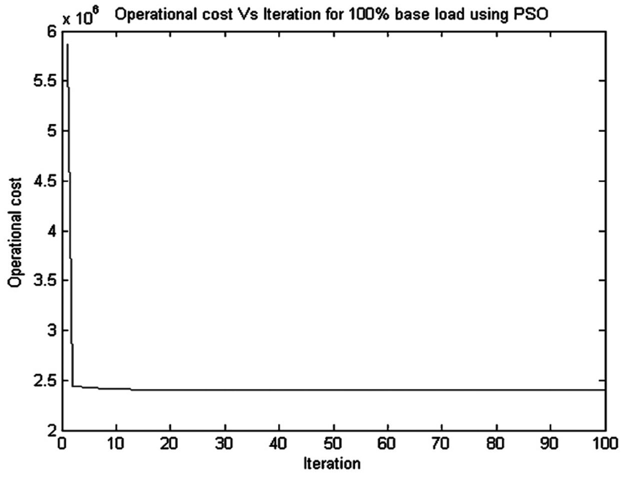

FIG.6 VARIATION OF OPERATING COST WITH GENERATION FOR BASE REACTIVE LOADING USING PSO.

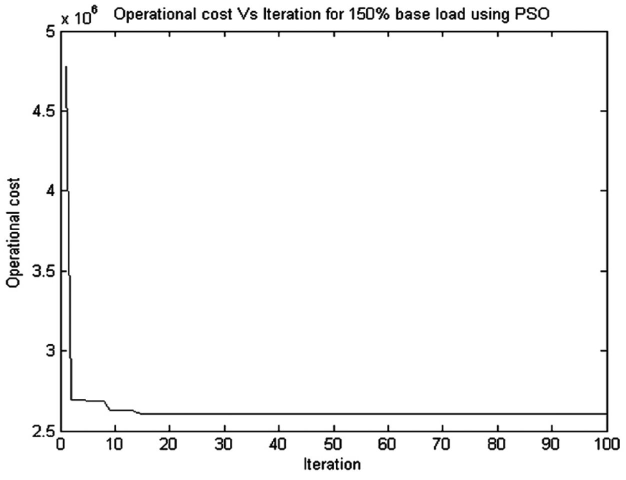

FIG. 7 VARIATION OF OPERATING COST WITH GENERATION FOR 150% OF BASE REACTIVE LOADING USING PSO.

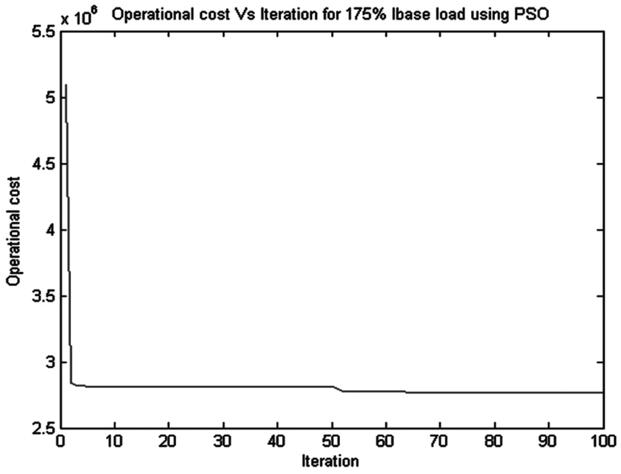

FIG. 8 VARIATION OF OPERATING COST WITH GENERATION FOR 175% OF BASE REACTIVE LOADING USING PSO.

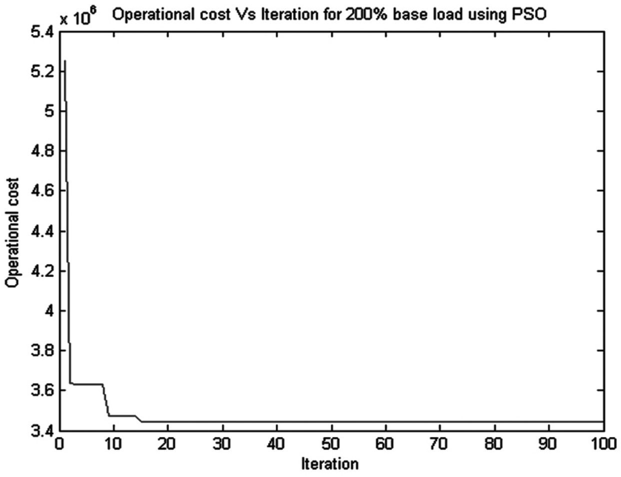

FIG. 9 VARIATION OF OPERATING COST WITH GENERATION FOR 200% OF BASE REACTIVE LOADING USING PSO.

5.0 CONCLUSIONS

In this approach, PSO based optimal placement of FACTS devices in a transmission network is done for the increased load ability of the power system as well as to minimize the total operating cost. Cost of FACTS devices are very less compared to the benefits in terms of the system operating cost for each cases of loadings are clearly observed. Two different types of FACTS devices are considered. It is clearly evident from the results that effective placement of FACTS devices using proper in proper locations by using suitable optimization technique can significantly improve system performance. Hence, this PSO based approach could be a new technique for the installation of FACTS devices in the transmission system.

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