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APPLICATION OF SPEA TO OPTIMAL SETTING OF FACTS DEVICES IN LARGE POWER SYSTEMS

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Abstract- A new metaheuristic method, as the SPEA search algorithm based on the echolocation behavior of bats is proposed in this paper for optima setting of power system variables, including Flexible AC Transmission Systems (FACTS) devices. Here, two types of FACTS devices, Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are used for the optimal operation of the power system as well as in reducing congestion in transmission lines. Optimal placement of FACTS devices in the heavily loaded power system reduces transmission loss, controls reactive power flow, improves voltage profile of all nodes and also reduces operating cost. In this proposed approach, Strength Pareto Evolutionary Algorithm (SPEA) is used for the selection of weak nodes in the power system for the placement of SVC's as one of the FACTS devices while the location of TCSC's are determined by the reactive power flow in lines. The effectiveness of the proposed approach is demonstrated by comparing its performance with Particle Swarm optimization algorithm.

Keywords: SVC, TCSC, SPEA, PSO.

I. INTRODUCTION

Low frequency power oscillations are the challenging problem in interconnected power systems. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1]. Conventionally, additional damping in system is introduced by the application of PSS [2, 3]. The Power electronic controlled devices, such SVC, HVDC link have also been used for many years [4].

In [5] it has been reported the better effectiveness of a SVC than PSS in damping power system oscillations. An optimal power flow (OPF) and transmission loss minimization model with SVC has been developed in [6] to improve the system stability and security of a practical power network. The development of FACTS [7] has generated much attention of the researchers to not only improve the damping of the oscillation of the electromechanical modes but also to enhance the system power transfer capability. In [8] Unified power flow controller (UPFC), a modern FACTS device has been used to provide adequate damping in power system network with changing system conditions. Thyristor Controlled Series Compensator (TCSC), a series controlled FACTS device is increasingly applied for the purpose of improvement of damping of the electromechanical oscillations in modern power systems [9, 10]. The optimal placement of FACTS controller in power system networks has been reported in literatures based on different aspects. A method to obtain optimal location of TCSC has been suggested in [11] based on real power performance index and reduction of system VAR loss. In [12] optimal allocation of SVC using Genetic Algorithm (GA) has been introduced to achieve the optimal power flow (OPF) with lowest cost generation in power system. Particle Swarm Optimization (PSO) and Imperialist Competitive Algorithm (ICA) approach in handling FACTS devices in power system is presented in [13, 14].

In this paper two types of FACTS devices have been discussed namely TCSC (Thyristor Controlled Series Capacitor) and SVC (Static Var Compensator). The main objective of this paper is to find the optimal location of FACTS devices in the transmission network to minimize the transmission loss and also for the simultaneous increase of power transfer capacity of the transmission network that ultimately results minimum operating cost under different loading conditions. There are three main issues that are to be considered for the selection of FACTS devices, its types, its capacity and location where to be installed. Placement of FACTS devices is done on IEEE 30-bus test system in the present work. A new metaheuristic algorithm known as Strength Pareto Evolutionary Algorithm (SPEA), based on the echolocation behavior of bats, is proposed in this paper for the optimal design of FACTS devices.

II. MODELING OF FACTS DEVICE

For an interconnected congested power network FACTS devices can be modeled as power injection model. The injection model describes the FACTS as a device that injects a certain amount of real and reactive power to a node. Both TCSC and SVC devices control the power flow and voltages by adjusting the reactance of the system.

A. Thyristor Controlled Series Compensator (TCSC)

Transmission line model with a TCSC connected between bus-*i* and bus-*j* is shown in Figure 1. In steady state, the TCSC can be considered as an additional reactance $-jX_{TCSC}$. TCSC acts as either inductive or capacitive compensator by modifying transmission line reactance. By installing TCSC's in transmission line power capacity increases and also the voltage profile improves. The injection model of TCSC is shown in Figure 2. Transmission line admittance with TCSC is represented by:

$$G_{TCSC} + jB_{TCSC} = (X_{Line} - X_{TCSC}) / R_j \quad (1)$$

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

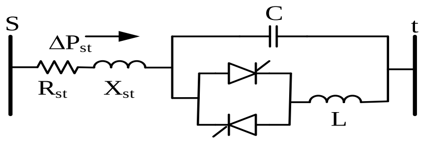

Figure 1. TCSC model

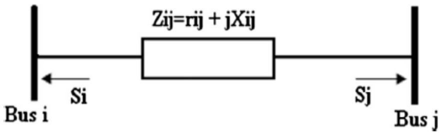

Figure 2. TCSC injection model

B. SVC Structure

The SVC can operate either in capacitive mode or in inductive mode. The function of SVC is either to inject reactive power to the bus or to absorb reactive power from the bus where it is connected. It improves the voltage in static and dynamic conditions and reduces active power loss. The variable susceptance model of SVC is shown in Figure 3. The SVC's effective reactance is determined by the parallel combination of X_C and X_L.

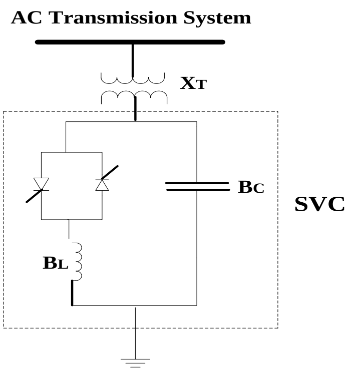

Figure 3. SVC equivalent circuit

III. COST FUNCTION AND PROBLEM FORMULATION

According to [15], cost functions for TCSC's and SVC's are given below:

$$TCSC \Rightarrow \ C_{TCSC}: 0.0015(TCSC_{Value})^2 - \\ -0.7130(TCSC_{Value}) + 153.75 \text{ (USD/Kvar)} \quad (2)$$

$$SVC \Rightarrow \ C_{SVC}: 0.0003(SVC_{Value})^2 - \\ -0.3051(TCSC_{Value}) + 127.38 \text{ (USD/Kvar)} \quad (3)$$

where, $TCSC_{value}$ and SVC_{value} are the operating values of the FACTS devices. The main objective is to find the optimal location of FACTS devices along with network constraints so as to minimize the total operational cost and relieve transmission congestion at different loading conditions. 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. The optimal allocation problem of FACTS devices can be formulated as:

$$C(T) = C_1(E) + C_2(F) \quad (4)$$

where $C_1(E)$ is the cost due to energy loss, $C_2(F)$ is the total investment cost of the FACTS devices and $C(T)$ is the operational cost of the system.

The active and reactive nodal power should be within the limits as:

$$P_{ni}^{\min} \le P_{ni} \le P_{ni}^{\max} \quad (5)$$

$$Q_{ni}^{\min} \le Q_{ni} \le Q_{ni}^{\max} \quad (6)$$

Again, these active and reactive nodal powers have to satisfy voltage magnitude constraints: $V_i^{\min} \le V_i \le V_i^{\max}$ as well as the existing nodal reactive capacity constraints:

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad (7)$$

Superscripts min, max are the minimum and maximum limits of the variables. The power flow equations between the nodes *i–j* after incorporating FACTS devices would appear as:

$$P_{ij} = V_i^2 - V_i V_j (G'_{ij} \cos\delta_{ij} + B'_{ij} \sin\delta_{ij}) \quad (8)$$

$$Q_{ij} = -V_i^2 - V_i V_j (G'_{ij} \sin\delta_{ij} - B'_{ij} \cos\delta_{ij}) \quad (9)$$

$$P_{ji} = V_i^2 - V_i V_j (G'_{ij} \cos\delta_{ij} - B'_{ij} \sin\delta_{ij}) \quad (10)$$

$$Q_{ij} = -V_i^2 - V_i V_j (G'_{ij} \sin\delta_{ij} + B'_{ij} \cos\delta_{ij}) \quad (11)$$

where G' and B' are the real and imaginary components of bus admittance matrix with the inclusion of FACTS devices such as TCSC and SVC, *G* and *B* are the real and imaginary part of Y_{bus} matrix without FACTS devices. Inclusion of TCSC in lines modifies reactance of that line and Y_{bus} matrix is modified accordingly. The real and reactive power flow will also change correspondingly in that line. The Y_{bus} matrix is modified with the new value of line reactance considering presence of TCSC in that line in the following manner:

for j = 1: n_{TCSC}
Linedata($TCSC\_pos(j)$) = Linedata($TCSC\_pos(j)$) – j* $TCSC_{value}$
end

Similarly SVC placement at a weak node corresponds to reactive power injection at that node and accordingly there will be a change in reactive power flow in the line

connected to that line. The Y_{bus} matrix will also be modified with SVC in the following way:
for j = 1: n_{SVC}
Shunt($SVC\_pos(j)$) = j * SVC_{value}
end
where n_{TCSC} and n_{SVC} are the number of TCSC and SVC elements, respectively, and $TCSC_{value}$ and SVC_{value} are the values of TCSC's and SVC's, respectively. In this way original Y_{bus} matrix is modified into:

$$Y_{bus} = G' - jB' \quad (12)$$

Then load flow is executed with this modified admittance matrix in evaluating the objective function for each individual population of generation in the cases of SPEA and PSO. The main objective of this work is the placement of FACTS devices in optimal locations of the interconnected power network. In this paper TCSC's are placed at lines carrying significantly high reactive power while the locations of SVC's are selected by calculating metaheuristic method of loss sensitivities of different buses in the standard IEEE 30-bus system. Transmission loss in an interconnected power system is given as:

$$P_{Loss} = \sum_{k=1}^{n} g_k [V_i^2 + V_j^2 - 2V_i^* V_j^* \cos(\partial_i - \partial_j)] \quad (13)$$

$$\begin{cases} \Delta P_{Loss} = [\frac{\partial P_{Loss}}{\partial V_1} \frac{\partial P_{Loss}}{\partial V_2} ... \frac{\partial P_{Loss}}{\partial V_n}][\Delta V_1 \Delta V_2 ... \Delta V_n]^T \\ \text{or} \\ \Delta P_{Loss} = C.\Delta V \end{cases} \quad (14)$$

where, $C_i = \frac{\partial P_{Loss}}{\partial V_i}$ is the loss sensitivity of each bus. SPEA and PSO Algorithms set are used to linearized objective function as:

$$F_1 = C_1.\Delta V_1$$
$$F_2 = C_2.\Delta V_2$$
$$....$$
$$F_n = C_n.\Delta V_n$$

where $C_i = \frac{\partial P_{Loss}}{\partial V_i}$ and i=1,2,…,n.

The minimization of active power loss will take place when each F_i is as negative as possible which indicates that if C_i is negative and ΔV_i will attain its maximum positive value. So more the value of F_i at a bus more will be the voltage deviation at that bus. The main objective of this paper is to minimize the overall operating cost under different condition by the installation of FACTS devices at the optimal locations in the transmission system. It is already mentioned that the determination of TCSC placement position and detection of weak nodes for SVC installation is one of the primary and important task of the proposed work. TCSC's placement locations are determined by observing reactive power flows in different lines without FACTS devices.

It is found that lines 25, 41, 28, 5 carry very high reactive power and treated as candidate lines for the TCSC placement. Similarly the weak nodes for the SVC placement are determined by BAT algorithm values of loss sensitivities at buses. We see that, buses 12, 6 and 27 are chosen as candidate buses for the placement of FACTS devices but the bus 10 and bus 3 are not selected even if of having higher values of SPEA algorithm. The reason is as:

- Bus 10 is connected with line 28 of the IEEE 30-bus system. But already a TCSC position is defined in the line 28. That is why, bus 10 is not selected.
- Bus 3 is connected to bus 1 which is considered as slack bus. That is why bus 3 is also not selected for the placement of FACTS devices.
- V_{old} is taken as 1.0 pu and V_{new} is the voltage magnitude obtained after load flow analysis in calculating active power loss.

IV. STRENGTH PARETO EVOLUTIONARY ALGORITHM

One of the most successful multi-objective optimization approaches is the SPEA [16] which is based on Pareto optimality concept. Concept of Pareto optimality can be described mathematically as below:
The vector a in the search space dominates vector b if

$$\begin{aligned} &\forall_i \in \{1,2,...,k\}: f_i(a) \geq f_i(b) \\ &\exists_j \in \{1,2,...,k\}: f_j(a) > f_j(b) \end{aligned} \quad (15)$$

If at least one vector dominates b, then b is considered dominated vector, otherwise it is called non-dominated. Each non-dominated solution is regarded optimal in the sense of Pareto or called Pareto optimal. Obviously, any Pareto optimal solution is comparatively the most optimal one in terms of at least one of the objective functions. The set of all non-dominated solutions is called Pareto Optimal Set (POS) and the set of the corresponding values of the objective functions is called Pareto Optimal Front (POF) or simply Pareto front.

The SPEA which takes benefits from many features of some other approaches is used in this paper. Figure 4, shows a flowchart of the approach which includes the following major steps [17]:

Step 1. Generate an initial population P and create the empty external non-dominated set P.
Step 2. Paste non-dominated members of P into P'.
Step 3. Remove all solutions within P' covered by any other members of P'.
Step 4. If the number of externally stored non-dominated solutions exceeds a given maximum N', prune P' by means of clustering.
Step 5. Calculate the fitness of all individuals in P and P'.
Step 6. Use binary tournament selection with replacement and select individuals from P and P' until the mating pool is filled.
Step 7. Apply crossover and mutation operators as usual.
Step 8. If the maximum number of generations is reached, then stop, else go to step 2.

Fitness evaluation is also performed in two steps. First, the individuals in the external non-dominated set P' are ranked. Then, the individuals in the population P are evaluated. For more details, refer to [17].

V. SIMULATION RESULTS

The proposed SPEA methodology is programmed in MATLAB running on an Intel w Core TM2 Duo Processor T5300 (1.73 GHz) PC with 1 GB RAM. It is applied on a multi-machine power system to demonstrate its abilities. The effect of SPEA parameters on average fitness function (among 100 trials) is investigated. The colony size (N_C) tried was 100. Hundred independent trials have been made with 100 iterations per trial. The performance of the SPEA also depends on the number of colonies. The parameters of SPEA are selected based on the average fitness function. After a number of careful experimentation, following optimum values of SPEA parameters have finally been settled as furnished in Table 1.In addition, Table 1 shows the optimum values obtained for PSO parameters.

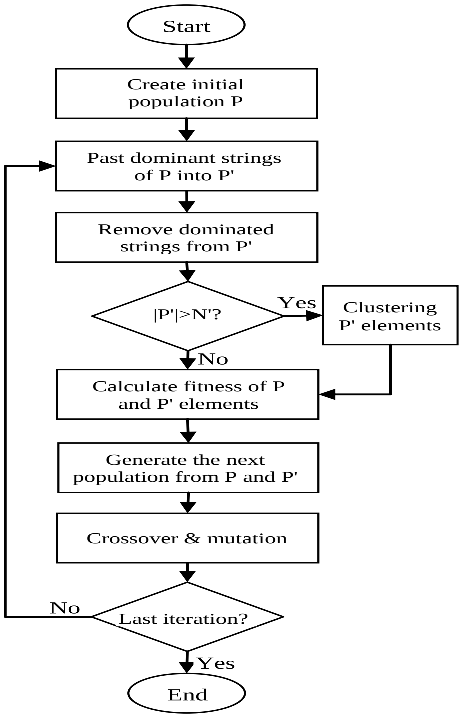

Figure 4. SPEA flowchart

Table 1. SPEA and PSO Simulation parameters

Method	Parameters
SPEA	N_C = 100; Mutation = 0.036; Length of the chromosome: 5 for each variable; Recombination: single-point crossover
PSO	Iteration=100; C_1=2, C_2=2

In this paper emphasis is given on the evolutionary algorithms over simple evolutionary optimization approach. Detection of weak nodes by standard technique of modal analysis and simultaneous use of simple evolutionary algorithms (like SPEA and PSO) active power loss and system operating cost can be reduced. In order to evaluate the performance of the SPEA and approaches, the standard IEEE 30-bus test system was used as shown in Figure 5.

The IEEE 30-bus test system's components include six genera-tors at the buses1, 2, 5, 8, 11 and 13 [18]. Significant reduction of active power loss and operating cost is noticed except in the case of SPEA. Also, the system loss and the operating cost of the system still can be reduced considerably by detecting weak nodes and parameter setting of the power system by SPEA and PSO. Difference in modal analysis and proposed method based detection results SVC placement in different buses. By modal analysis probable SVC's positions are found in 21st, 7th, 17th and 15th buses, whereas by proposed method based detection method decides 12th, 6th and 27th buses as candidate buses for the SVC's placement where as TCSC's positions are determined from reactive power flow in lines.

So TCSC positions are kept fixed both in the non-SPEA and SPEA induced environment. The existing power system variables (like generators Var generations, transformer tap positions) along with FACTS devices are represented in a string as shown Table 2 which shows the locations of FACTS devices in the transmission network using SPEA and PSO methods. Limits of FACTS devices and other controlling parameters such as transformer tap positions and reactive generation of generators is shown in Table 3.

Table 4 shows the total reactive power flow in lines without and with FACTS devices for base reactive loading and 200% of base reactive loading using different techniques. It is observed that with the combined effect of series and shunt FACTS controller, not only the reactive power flow is reduced and redistributed, the overall reactive power flow in lines reduced considerably.

Table 5 shows the magnitudes and phase angles of the bus voltages before and after placement of SVC for 200% of base reactive loading using SPEA and PSO methods. A comparative study of the operating cost of the system without and with FACTS devices under different loading conditions for all techniques are shown in Tables 6 and 7.

From the comparative study of different techniques, it is found that best result both in the basis of loss reduction and operating cost reduction is achieved using evolutionary algorithms as seen from Tables 6-7. Therefore, the SPEA technique produces a better solution when compared with PSO based technique. Finally optimal settings of parameter including FACTS devices with SPEA and PSO techniques are shown in Table 8.

Table 2. Location of FACTS devices in the transmission network

TCSC in Lines IEEE 30-bus	SVC in Buses	
	PSO	SPEA
25, 41, 28, 5	21, 7, 17, 15	12, 6, 27

Table 3. Limits of FACTS devices and other controlling parameters

TCSC (pu)		SVC (pu)		Transformer tap positions (pu)	
Min	Max	Min	Max	Min	Max
0	0.6	0	0.5	0.9	1.1

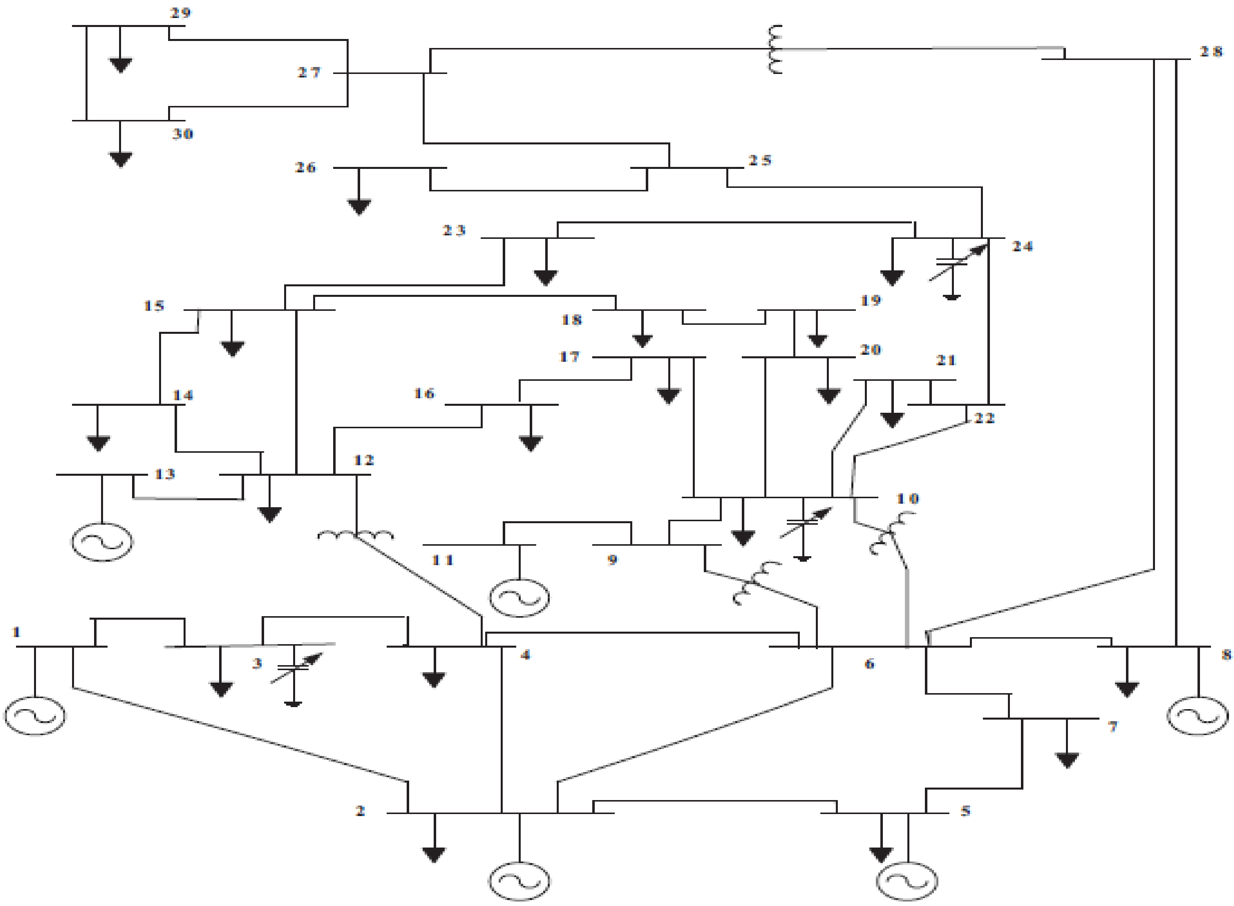

Figure 5. Single line diagram of IEEE 30-bus test system

Table 4. Limits of FACTS devices and other controlling parameters

Reactive loading (%)	Without FACTS devices $\sum linesQ$ (pu)	With FACTS devices $\sum linesQ$ (pu)	
		PSO	SPEA
100	-0.2348	-0.7564	-0.6578
200	0.4099	-0.3456	-0.02345

Table 5. Bus voltages and phase angles without and with FACTS devices for 200% of base reactive loading using SPEA and PSO approach

Number of bus	Bus voltage without FACTS (pu)	Bus voltages with FACTS using SPEA (pu)	Bus voltages with FACTS using PSO (pu)	Bus angle (in radian) without FACTS	Bus angle (in radian) with FACTS using SPEA	Bus angle (in radian) with FACTS using PSO
6	1.0178	1.0123	1.0139	-0.1347	-0.1234	-0.1098
12	1.0123	1.0379	1.0101	-0.1094	-0.1678	-0.1456
27	1.0167	1.0518	1.0899	-0.1708	-0.1789	-0.1009

Table 6. Comparative analysis of active power loss using SPEA and PSO method

Reactive loading (%)	Active power loss without FACTS (pu)	Active power loss with FACTS (pu)	
		SPEA	PSO
100	0.0876	0.0300	0.0390
150	0.0657	0.0390	0.0406
200	0.0897	0.0490	0.0401

Table 7. Comparative analysis of operating costs with and without FACTS devices using SPEA and PSO method

Reactive loading (%)	Operating cost due to the energy loss (in $)	Operating costs with FACTS devices by PSO×10^6 (in $)	Operating costs with FACTS devices by SPEA×10^6 (in $)
100	2,567,087	2.1880	2.1234
150	3,456,867	2.6785	2.2098
200	3,134,498	2.7890	2.6709

Table 8. Amount of FACTS devices and other reactive sources in the transmission network by SPEA and PSO based approach

Reactive loading (%)	SVC amount using PSO (pu)	SVC amount using SPEA (pu)	TCSC amount using PSO in lines (pu)	TCSC amount using SPEA in lines (pu)	Reactive generation Q_g using PSO (pu)	Reactive generation Q_g using SPEA (pu)	Transformer tap position using PSO (pu)	Transformer tap position using SPEA (pu)
100	0.0872	0.148	0.0001	0.0123	0.3409	0.2876	0.9099	0.9290
	0.0571	0.0048	0.0409	0.0003	0.1815	0.2764	0.9859	0.9136
	0.0328	0.0531	0.0003	0.0234	0.1911	0.0729	0.9133	0.9501
	0.0561	------------	0.0365	0.0002	0.1975	0.1865	0.9344	0.9217
200	0.2349	0.2345	0.0047	0.0004	0.1023	0.0812	0.9366	0.9010
	0.3453	0.2098	0.0048	0.0081	0.3318	0.4107	0.9880	0.9003
	0.1149	0.1456	0.0004	0.0040	0.2240	0.3469	0.9189	0.9510
	0.1255	-----------	0.0425	0.0012	0.2751	0.1843	0.9001	0.9360

VI. CONCLUSIONS

In this paper, one of the recently improved heuristic algorithms was demonstrated and successfully applied to solve optimal parameter settings along with FACTS devices. This problem was formulated as a nonlinear optimization problem with equality and inequality constraints in power systems The proposed SPEA approach was tested and investigated on the IEEE 30-bus, test system to demonstrate its effectiveness. This approach was successfully and influentially performed to find the optimal settings of the control variables of the test system. As the behavior of the power system faces challenge under increased loading conditions, the proposed approach is applied on the standard system with increased loading conditions, conditions, the system is found stable and even satisfactory loss and cost reduction observed. So, this approach can be a new technique for optimal coordination of FACTS devices along with the other existing Var generators of a power system. he comparison verifies the influentially of the proposed GSA approach over the stochastic techniques in terms of solution quality for the optimal parameter settings along with FACTS devices problem. The ability of proposed scheme compared with in other methods can be summarized as follow:

- The ability to jump out the local optima.
- Providing the correct answers with high accuracy in the initial iterations.
- Superiority in computational simplicity, success rate and solution quality.

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