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Application of Gravitational Search Algorithm to Improve Power System Security by Optimal Placement of FACTS Devices

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In deregulated power industry, system parameters such as bus voltages and line power flows are operated near the limit values to meet the demanded load. However, this is a very dangerous situation for the secure operation of power systems. In order to preserve the power system security, it is necessary to use compensating devices for altering the line power flows and bus voltage regulation. In this matter, FACTS devices are the best compensating devices employed so far, for efficient performance of the power flows. On the contrary, poor location of FACTS devices can cause unnecessary power flows and disturb the bus profile which lead to security issues. In the paper, bus voltage deviation and line power flow factor to the maximum limit are considered as security indexes. These indexes are used as objectives for security problem and are compensated by optimally placing the FACTS devices. Here, the FACTS devices used are Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC) and Unified power flow controller (UPFC). These FACTS devices are needed to be placed optimally in the power system to improve the security margins. The proposed algorithm for this purpose is Gravitational Search Algorithm (GSA). Additionally, installation costs of FACTS devices and power system losses are also included in the objective function for economic operation of FACTS installations. The proposed GSA method is validated on IEEE 30, IEEE 57 bus test systems for optimal allocation of FACTS devices. The performance of the proposed GSA is analyzed and compared with existing techniques.

Keywords: GSA, power system security, FACTS, TCSC, SVC, UPFC and optimal location.

1. Introduction

Due to the deregulated policy in power industry, security margin is the main concern of Independent Power System Operator (IPSO). Its assessment deals with determining whether or not the system operating in a normal state can withstand contingencies such as outage of transmission lines without any system parameters limit violation. If the present operating state is found to be insecure, action must be taken to prevent it [1]. Security enhancement measures deal with the task of taking remedial action against possible network overloads in the system following the occurrence of contingencies. Here, most of the contingency burden is imposed on transmission lines. In this scenario, to meet the load demand, either the existing transmission lines must be utilized more efficiently, or new line(s) should be added to the system. The latter is often impractical due to the reason of time consuming process and sometimes an impossible task [2]. Therefore, the first option is the preferred one than building new line. In the efficient usage of existing lines, the overload can be alleviated by rerouting power flows in the system. A change in line flow can be caused by an appropriate change in phase angles and magnitude of bus voltages. In

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these situations, FACTS device controllers have played a major role in power system security measures.

Generally, FACTS devices are the solid state converters that have the capability of control of various electrical parameters in transmission circuits to influence power flows and voltages to different degrees depending on the type of the device [3]. The type of FACTS devices include the following devices; TCSC, Thyristor controlled phase angle regulator (TCPST), SVC, Static Synchronous series compensator (SSSC), Static compensator (STATCOM), UPFC etc. The purpose of mentioned FACTS devices;

- ✓ TCSC is connected in series with the line conductors to compensate for the inductive reactance of the line [4].
- ✓ SSSC can directly control the current, and indirectly the power flowing through the line by controlling the reactive power exchange between the SSSC and the AC system [5].
- ✓ SVC helps to maintain a bus voltage at a desired value during load variations by controlling the reactive power injection at the location [6].
- ✓ DSATCOM can compensate the reactive power requirement in the distribution systems. UPFC allows the independent influence of active and reactive power flows as well as a control of the voltage profile at the same time [7].

The increased interest in these devices is essentially due to two reasons; cost effective and increased loading of power systems [8]. It is important to ascertain the location for placement of these devices because of their considerable costs and for avoiding of unnecessary power flows which increases the system power losses [9].

The increased interest in optimal placement of FACTS devices in power systems is studied by many authors. In [10], extended voltage phasors approach (EVPA) is presented for identifying the critical paths (critical buses/line segments) from the voltage stability viewpoint. And for improving the system load-ability; Genetic Algorithm (GA) in [11], Particle Swarm Intelligence (PSO) in [12] and Modified PSO in [13] are employed. Similarly, such optimization algorithms are employed for optimizing the locations and sizes of FACTS devices in security point of view. In such kind of attempts on secure operation of the power system, the formulation of reactive power (VAR) planning problem and optimal power flow problem are performed in [14][15][16][17][18]. In the mentioned papers, presented algorithms such as PSO, GA, etc. are having trouble in determining the better locations for FACTS devices. It is due to their inability to find the global optimum locations because of regular updating of algorithm parameters. These drawbacks might deteriorate the power system security assessment.

In this paper, we have used recently developed algorithm for improving the power system security index. The proposed algorithm is gravitational search algorithm (GSA) which is previously applied in power system analysis for optimal reactive power dispatch, voltage control, optimal power flow, distributed generation planning, distribution feeder reconfiguration, etc. Here, power system security assessment is performed by optimally placing the FACTS devices which is assisted by GSA. Along with the security indexes, the economic installations of FACTS and power loss index are included in the fitness function of GSA. The detailed version of GSA and its application for proposed purpose are explained in section 4 and 5 respectively. Prior to that, the power system security assessment is formulated in section 3 and employed FACTS devices are modelled in section 2. At the end, paper is concluded.

2. FACTS modelling

In this section, the modeling of considered three different FACTS devices has been presented. Those FACTS devices are TCSC, SVC & UPFC. The circuit diagrams with equivalent models of a single transmission line, TCSC, SVC and UPFC are shown in Fig 1.

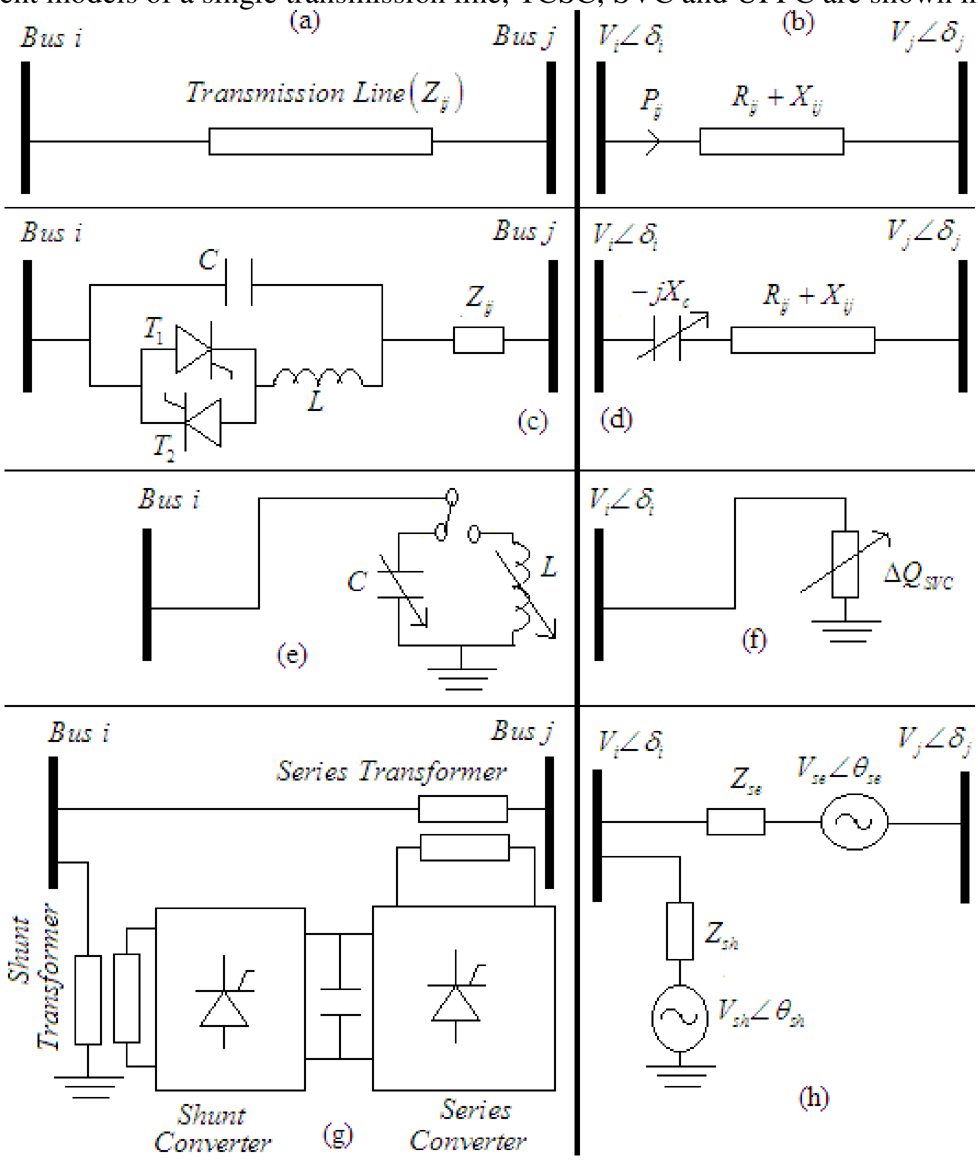

Figure 1: FACTS devices; (a) & (b) A simple Transmission line between i^{th} and j^{th} buses, (c) & (d) TCSC, (e) & (f) SVC and (g) & (h) UPFC

In figure 1, the circuit diagram and equivalent model of three FACTS devices is presented with actual transmission line model without any FACTS device connection to it. From figure 1(b), power flow (P_{ij}) through the transmission line depends on the line reactance (X_{ij}), the bus voltage magnitudes (V_i, V_j) and phase angles (δ_i, δ_j). It is given as [11],

$$P_{ij} = \frac{V_i V_j \sin\left(\delta_i - \delta_j\right)}{X_{ij}} \qquad (1)$$

As the power flow (P_{ij}) depends on the mentioned parameters of the transmission line. The power flow can be altered as per the requirement to optimal real and reactive power planning and congestion relief and improvement system security. Now, the changes in transmission line parameters due to the introduction of these FACTS devices is presented here.

2.1. TCSC

TCSC compensates the reactance of the transmission line. This changes the line flow due to change in series reactance. From figure 1(c & d), TCSC is modelled as follows [4]:

$$X_{ij} = X_{line} + X_{TCSC} \qquad (2)$$

With $X_{TCSC} = r_{TCSC} . X_{line}$

Where, X_{line} is the reactance of the transmission line and r_{TCSC} is the compensation factor of TCSC. The rating of TCSC depends on transmission line.

2.2. SVC

SVC can be used for both inductive and capacitive compensation. From figure 1(e & f), SVC is modelled as an ideal reactive power injection at i^{th} bus. It is given as [6],

$$\Delta Q_i = Q_{SVC} \qquad (3)$$

2.3. UPFC

UPFC control power flow in the transmission line by injecting through series converter and absorbs from shunt converter. From figure 1(g & h), UPFC is modelled through an effective reactance of the transmission line. It is given as [19],

$$X_{ij} = X_{line} + X_{UPFC} \qquad (4)$$

$$X_{UPFC} = X_{se} . r_{\max}^2 \left(\frac{P_{base}}{S_{se}} \right) \qquad (5)$$

Where, X_{se} is the series transformer reactance, $r_{\max}$ is the maximum per unit value of injected voltage magnitude, P_{base} is the system base power and S_{se} nominal rating power of the series converter.

3. Power System Security Index

The goal of the power system security is to maintain the flat voltage profile and no violation of any transmission line power flow. This two security objectives are modelled using voltage security index (VSI) and line security index (LSI) respectively. Both of the security indexes are given as [1] [20],

$$VSI = \sum_{i} w_i \left| V_i - V_{i,ref} \right|^2 \qquad (6)$$

$$LSI = \sum_{j} w_j \left(\frac{S_j}{S_{j,\max}} \right)^2 \qquad (7)$$

With

$$\left. \begin{array}{l} V_i^{\min} \le V_i \le V_i^{\max} \\ S_j \le S_j^{\max} \end{array} \right\} \qquad (8)$$

Where

V_i, w_i and $V_{i,ref}$ are voltage amplitude, associated weighting factor and nominal voltage magnitude for i^{th} bus respectively. S_j, w_j and $S_{j,\max}$ are apparent power, associated weighting factor and the nominal apparent power of j^{th} line respectively. Equation (8) shows the tolerance of bus voltage and line power flow limit respectively.

In equations (6) and (7); they show how much the bus voltage is close to the reference voltage and even distribution of the total active flow respectively. If the bus voltages are far away from their reference values then VSI value increases. Similarly, if the number of overloaded lines increases then the LSI value also increases. Therefore, it is necessary to take actions for minimizing both indexes for secure operation of power system.

In the proposed work, we have also considered the economic operation of FACTS devices with reduction of total power loss of the power system. Economic operation of FACTS devices determines possible minimum size of FACTS devices which minimizes the total installation cost. And reduced power loss in the system avoids the overheating of transmission lines which improves the efficient usage of transmission lines for longer services. For this purpose, the installation cost index (ICI) of the FACTS devices and power loss index (PLI) are modelled. They are given as follows,
The cost function for SVC, TCSC and UPFC are given as follows [19]:

$$\left.\begin{aligned} C_{TCSC} &= 0.0015s^2 - 0.7130s + 153.75 \\ C_{SVC} &= 0.0003s^2 - 0.3051s + 127.38 \\ C_{UPFC} &= 0.0003s^2 - 0.2691s + 188.22 \end{aligned}\right\} \quad (9)$$

Where s is the operating range of the FACTS devices in MVAR and C_{TCSC}, C_{SVC} and C_{UPFC} are in US$/KVAR. Therefore, the total installation cost index (ICI) for mentioned three FACTS devices is given as,

$$ICI = C_{TCSC} + C_{SVC} + C_{UPFC} \quad (10)$$

The total power loss in the power system is a nonlinear function of bus voltages and phase angles. It is given as [21],

$$PLI = \sum_{k=1}^{NL} g_k \left[V_i^2 + V_j^2 - 2V_iV_j \cos\left(\delta_i - \delta_j\right) \right] \quad (11)$$

Where, NL is the number of lines, g_k is the conductance of k^{th} line between i^{th} and j^{th} buses.

The goal of the proposed work is to optimally place the FACTS devices in the power system to enhance power system security levels (VSI and LSI) and economic operation of FACTS devices (ICI) with the reduced total power losses (PLI). Therefore, the single objective function determined for the above purposes is given as,

$$SOF = \min\left\{ a_1\left(LSI\right) + a_2\left(VSI\right) + a_3\left(ICI\right) + a_4\left(PLI\right) \right\} \quad (12)$$

Where, the coefficients $\{a_1, a_2, a_3, a_4\}$ are constant values and determined by trial and error method. Now, equation (12) is considered as a single objective minimization problem (fitness function) to be optimized for the placements and sizes of TCSC, SVC and UPFC devices. It indicates the security indexes and economic operation of FACTS devices with reduced power losses. In the following sections, the proposed GSA method is detailed for above purpose only.

4. Original GSA

GSA is a newly developed evolutionary algorithm which is motivated Newtonian gravitational law and law of motion by Rashedi *et al.* in 2009 [22] [23] [24]. Since 2009, its application in engineering field is rapidly increased day-by-day and its research fields are extended to microwaves, antennas & propagation, clustering, servo systems, design of digital & analogue circuits, designing of optical networks, magnetic, etc. It is best known for its searcher agents called as collection of masses. In physics, gravitation is a tendency by which objects with mass accelerate toward each other. In the Newton gravitational law, each particle attracts other particles with a force known as the gravitational force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them [22]. Based on the mentioned laws, the GSA algorithm is developed. The summary of the GSA is defined as follows.

GSA can be considered as a collection of agents (candidate solutions) whose masses are proportional to their value of fitness function and interact with each other using laws of gravity and motion of Newton. During generations (iterations), all masses attract each other by the gravity forces between them and this force causes a global movement of all objects towards the objects with heavier masses. A heavier mass has the bigger attraction force. Therefore, the heavier masses which are probably close to the global optimum attract the other masses proportional to their distances. Hence, masses cooperate using a direct form of communication, through gravitational force. The heavy masses correspond to good solutions and move more slowly and conversely light masses correspond to poor solutions and move towards heavy masses much faster. This guarantees the exploitation step of the algorithm. Velocity of each agent is updated after calculating acceleration of each agent, using Newton's law of motion. Consequently, position of each agent is updated using the modified velocity. The position of the mass corresponds to a solution of the optimisation problem, and its mass represents fitness function [23] [24].

For describing the proposed algorithm, we suppose a system with N agents. The algorithm starts with randomly placing all agents in search space and starts optimizing. The procedure of the GSA algorithm is as follows.

Step 1: Initialize the parameters to be optimized.

Step 2: Generate the candidate agent's initial position and their velocity using equation (13)

$$\left.\begin{aligned} x_i^d &= x_i^{d-\min} + rand_1\left(x_i^{d-\max} - x_i^{d-\min}\right) \\ v_i^d &= v_i^{d-\min} + rand_1\left(v_i^{d-\max} - v_i^{d-\min}\right) \end{aligned}\right\} \tag{13}$$

With

$i = 1, 2, ..., N$, $d = 1, 2, ..., D$ and $0 \le rand_1 \le 1$

Where,

x_i^d is the d^{th} dimension in i^{th} candidate agent, $x_i^{d-\min}$ and $x_i^{d-\max}$ are the minimum and maximum values of d^{th} dimension in i^{th} candidate agent, and is similar for velocity too.

Step 3: Compute the fitness function {fit=SOF} of all agents using equation (12). And, using the fitness value, update the gravitational constant, worst fitness, best fitness and mass of all agents as follows,

$$\left.\begin{aligned} &G(t) = G_0.e^{-\alpha t/T} \\ &best(t) = \min_{j\in\{1,2,\ldots,N\}}\left(fit_j(t)\right) \\ &worst(t) = \max_{j\in\{1,2,\ldots,N\}}\left(fit_j(t)\right) \\ &M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)}; m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \end{aligned}\right\} \quad (14)$$

Step 4: Compute the force acting upon the i^{th} candidate agent due to all N-1 masses of other agents,

$$F_i^d(t) = \sum_{j=1, j\neq i}^{N} rand_2 F_{i,j}^d(t) \quad (15)$$

With,

$$\left.\begin{aligned} &0 \leq rand_2 \leq 1 \\ &F_{i,j}^d(t) = G(t)\frac{M_i(t)M_j(t)}{R_{i,j}(t) + \in}\left(x_j^d(t) - x_i^d(t)\right) \\ &R_{i,j}(t) = \left\|x_i(t), x_j(t)\right\|^2 \end{aligned}\right\} \quad (16)$$

Where,

$F_{i,j}^d(t)$ is the force of attraction between the masses of candidate agents i and j,

$G(t)$, $R_{i,j}(t)$ and $\in$ are the gravitational constant, Euclidian distance between two agents and constant term whose magnitude is very small at iteration t.

Step 5: Compute the acceleration of i^{th} candidate agent using equation (17),

$$a_i^d(t) = \frac{F_i^d(t)}{M_i^d(t)} \quad (17)$$

Step 6: Update the velocity of the i^{th} agent and find next of it.

$$\left.\begin{aligned} &v_i^d(t+1) = v_i^d(t).rand_3 + a_i^d(t) \\ &x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \end{aligned}\right\} \quad (18)$$

Step 7: Check for stopping criteria using below equation

$$t > T\,? \tag{19}$$

If above equation is satisfied, stop the algorithm and give the best results or otherwise, repeat the steps from 3 to 7.

This is the procedure for GSA algorithm for optimization. Here, it is applied for optimal placement and size of FACTS devices. The purpose of GSA is given in the following section.

5. Application of GSA for enhancing the power system security

In this section, GSA is applied to optimally place the FACTS devices are presented. Here, optimization means to minimize the fitness function i.e., equation (12). The procedure of GSA in optimal locating and sizing of FACTS devices is as follows.

Step 1: Define the input data,
In this step, the input data including the location of FACTS devices, range of FACTS devices are defined.

Step 2: Generate an initial population and an initial velocity and set iteration t=0.
In this step, population in the sense, it is the position of an agent in search space. It consists of FACTS locations and capacities.

Step 3: Select the i^{th} agent in the population.

Step 4: Compute the fitness function
In this step, load flow of the system is studied for that FACTS locations and capacities. From that, bus voltages and line power flows are determined. Using the bus voltages, line powers, power losses, installation costs; fitness function is computed using equation (12)

Step 5: Update the gravitational constant, best fitness, worst fitness and mass of the agent
In this step, using equation (14), mentioned parameters are updated.

Step 6: Compute the force of attraction of all agent's masses
In this step, the force of attraction on each agent due to other agent attractions is computed using equation (15).

Step 7: Compute the acceleration of each agent
In this step, the acceleration of each agent is computed using equation (17) based on the force of attraction on it and self mass of the agent.

Step 8: Update the velocity of the each agent new position
In this step, each agent position is updated using equation (18). Here, first, the velocity of the each is updated and using that next position of the agent is determined.

Step 9: If all agents are selected, go to the next step. Otherwise iteration counts (t=t+1) and go back to Step 3.

Step 10: Check the stopping criteria.
If the stopping criteria satisfied finish the algorithm and provide the optimal placement & size of FACTS devices, else go to Step 3 until convergence criteria met.

Now, the flow chart of the GSA for FACTS devices is given in figure 2.

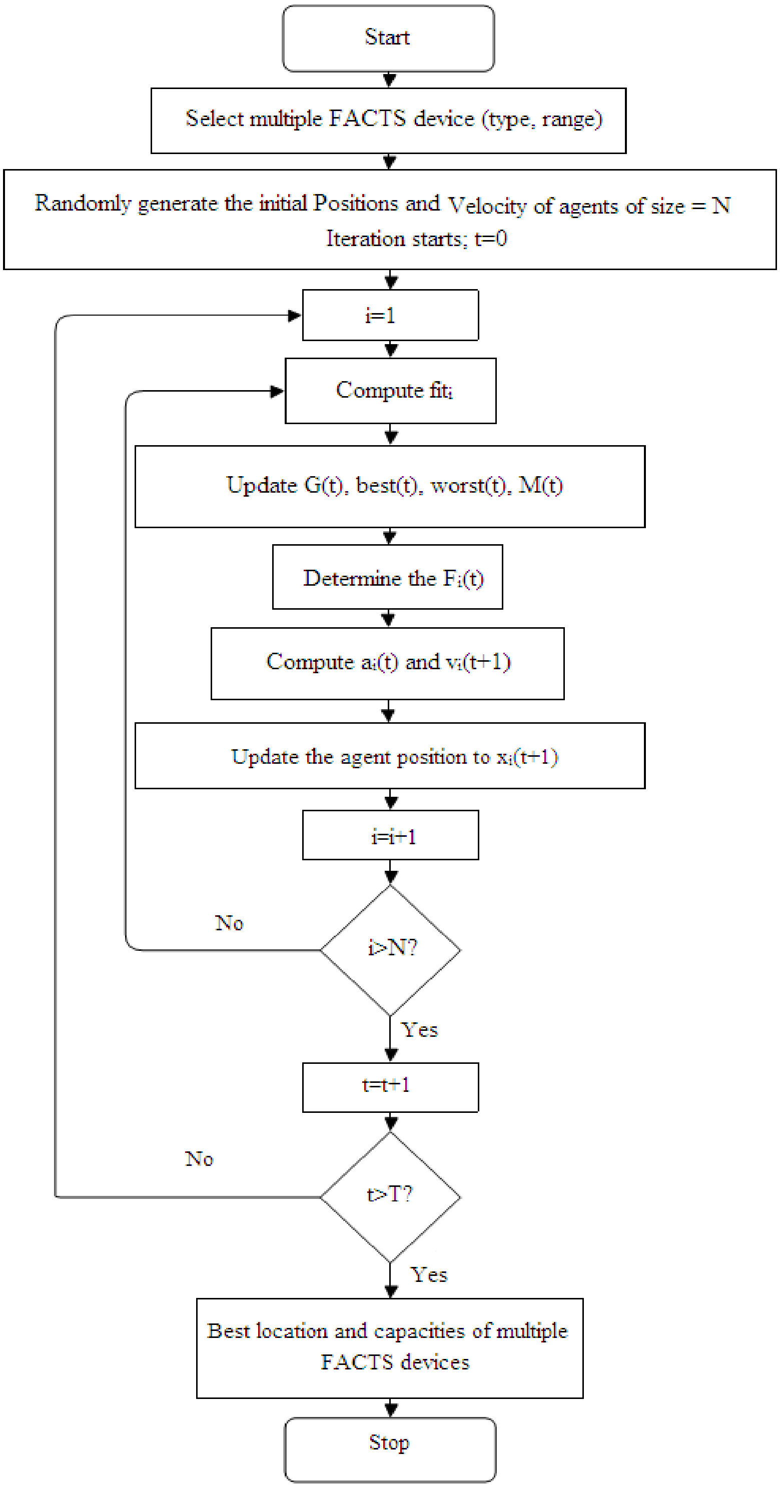

Figure 2: The flow chart of proposed GSA for optimizing the locations of FACTS devices

Once, the determination of optimal locations and sizes of FACTS devices is performed by proposed GSA. They are placed in the determined locations and check for power system security indexes whether the power system is secure or not. In the following section, validation of the proposed work is presented.

6. Simulation results and discussions

The proposed GSA technique for optimal allocation and sizing of FACTS devices is implemented in the MATLAB platform. Initially, it generates a random numbers of locations for placing the FACTS devices with different size values. Then, for generated each combination of locations and sizes of FACTS devices; power flow studies of the power system is performed. From the power studies, bus voltages, line flows, total power losses are determined. From these determinations, fitness function of each combination is computed. Based on the fitness values of each combination, GSA proceeds for optimizing and determines the optimum locations and sizes for FACTS devices.

The performance of the proposed GSA method for optimal allocation of FACTS devices is analyzed with IEEE 30, IEEE 57 bus test systems. For doing so, following details are assumed.

1. The type of FACTS devices to be placed are selected first,
2. The range of each FACTS device (for each type) must be given before.

The validation of the proposed work is carried in 5 different scenarios. They are;

- Case 1: Power system normal operation (without FACTS devices installation),
- Case 2: Only one TCSC is installed,
- Case 3: Only one SVC is installed,
- Case 4: Only one UPFC is installed

Here, case 1 is the normal operation of network without connecting any type of FACTS device in the system. Other cases are based on the type of FACTS device considered for improving the power system security. For mentioned three FACTS device allocation cases, the optimal location is determined by GSA algorithm. The performance of the GSA is analyzed as follows. The cost graphs, performance index evolution of implemented methods are shown in Fig. 3 to Fig. 14. Tables 2 to 5 show optimal location of devices, sizes and security indices for different cases. These results show the installation of FACTS device in network could improve security of power system and reduction in power system losses simultaneously. FACTS devices should be placed in optimal location to improve security margins and reduce losses in the network.

Table 1: GSA parameters

NP	G_o	Iterations
50	100	100

Table 2: FACTS allocation and sizes for IEEE 30 bus test system

Device type	UPFC		TCSC		SVC	
Size/location	Size (MVA)	Location (Bus no-Bus no)	Size (MVA)	Location (Bus no-Bus no)	Size (MVA)	Location (Bus no)
TCSC	-	-	135	2-6	-	-
SVC	-	-	-	-	11	2
UPFC	92	5-7	-	-	-	-

Table 3: Performance of GSA in terms of VSI and LSI for IEEE 30 bus test system

Scenario	LSI	VSI	ICI ($)	PLI (MVA)
1	18.400	4.340	-	12.4964
2	16.8013	3.8608	1342846	10.8870
3	14.426	3,4627	1208374	9.08000
4	15.7825	2.6288	1871550	11.1100

Table 4: FACTS allocation and sizes for IEEE 57 bus test system

Device type	UPFC		TCSC		SVC	
Size/location	Size (MVA)	Location (Bus no-Bus no)	Size (MVA)	Location (Bus no-Bus no)	Size (MVA)	Location (Bus no)
TCSC	-	-	81	8-9	-	-
SVC	-	-	-	-	59	8
UPFC	98	13-14	-	-	-	-

Table 5: Performance of GSA in terms of VSI and LSI for IEEE 57 bus test system

Scenario	LSI	VSI	ICI ($)	PLI (MVA)
1	24.300	4.30	-	22.4000
2	21.810	3.62	1432846	20.4250
3	16.426	3.45	1304344	19.2340
4	15.213	2.93	1961560	18.2654

The cost graphs, performance index evolution figures from fig. 3 to 8 are corresponding to IEEE 30 bus test system.

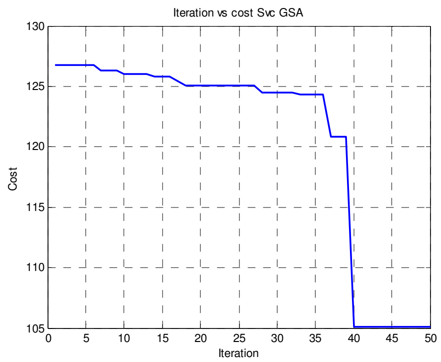

Figure 3: Cost vs. iteration using SVC

Figure 4: Performance index evolution with SVC

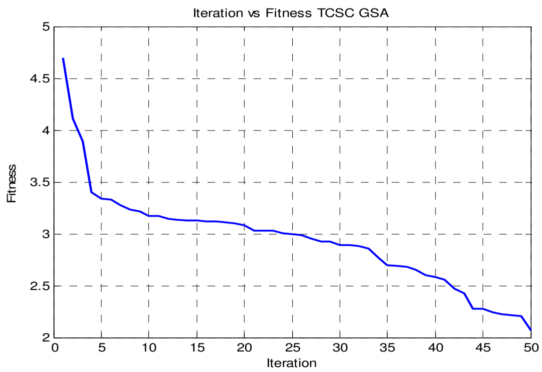

Figure 5: Performance index evolution with TCSC

Figure 6: Cost vs. iteration using TCSC

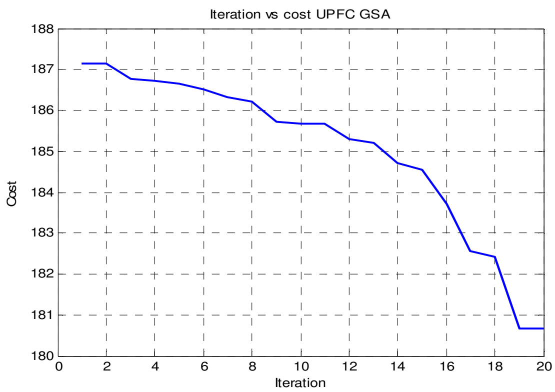

Figure 7: Cost vs. iteration using UPFC

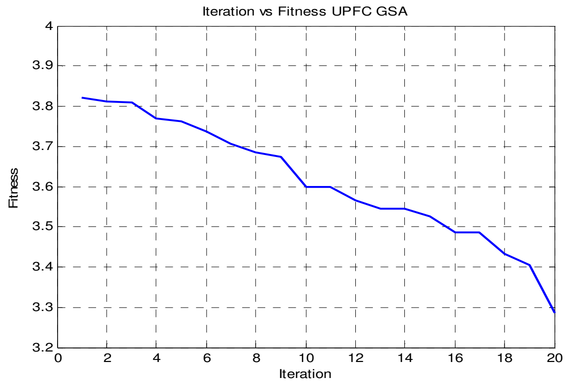

Figure 8: Performance index evolution with UPFC

The cost graphs, performance index evolution figures from fig. 9 to 14 are corresponding to IEEE 57bus test system.

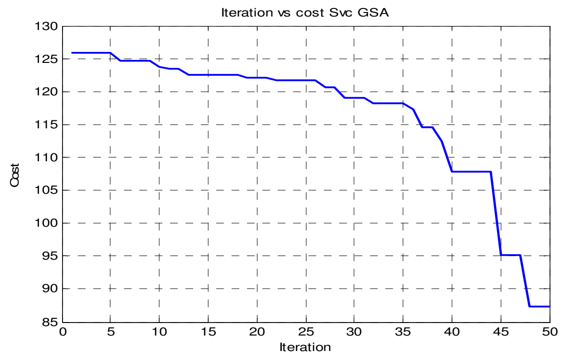

Figure 9: Cost vs. iteration using SVC

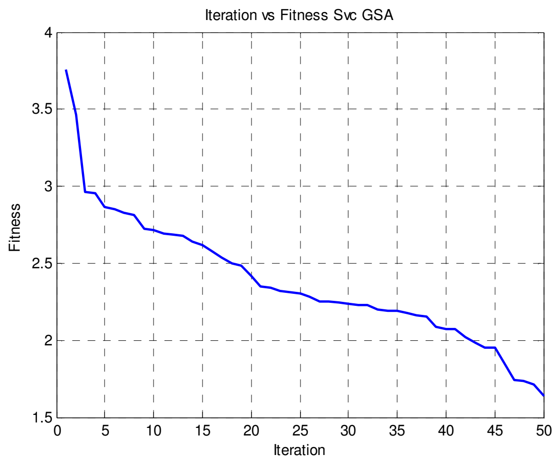

Figure 10: Performance index evolution with SVC

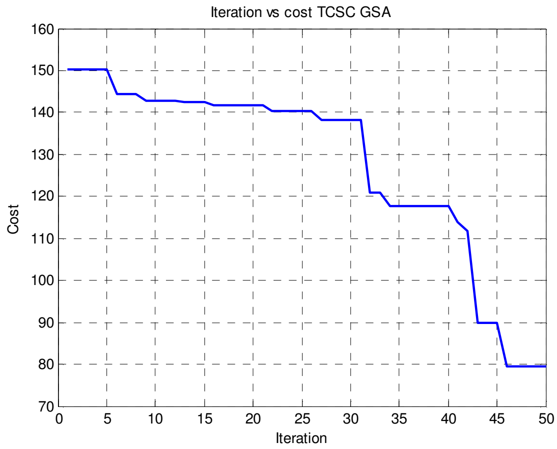

Figure 11: Cost vs. iteration using TCSC

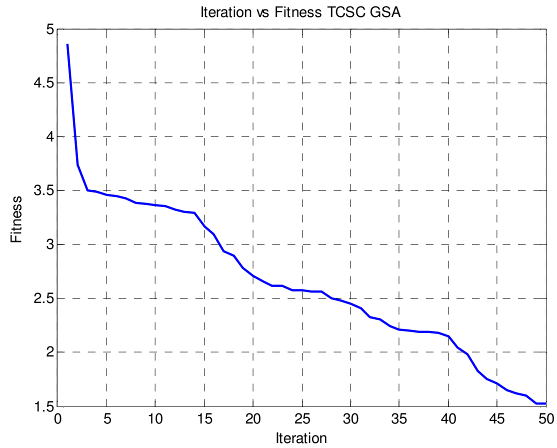

Figure 12: Performance index evolution with TCSC

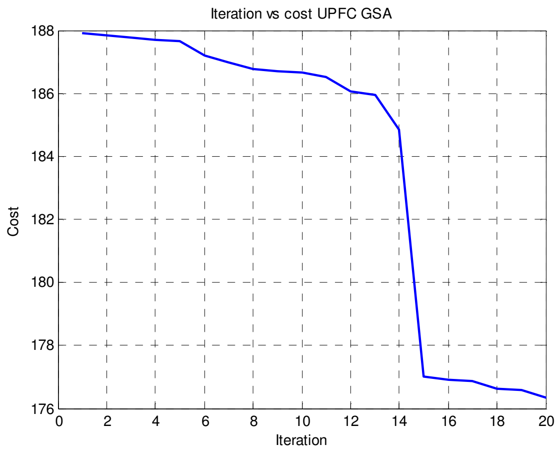

Figure 13: Cost vs. iteration using UPFC

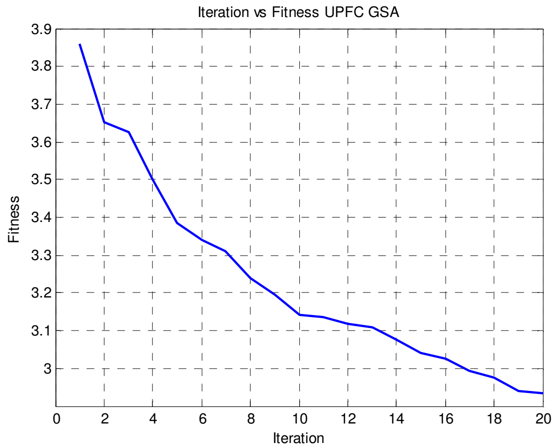

Figure 14: Performance index evolution with UPFC

7. Conclusions

In this paper, a GSA algorithm was presented for the optimal placement of FACTS devices (TCSC, SVC and UPFC). The optimization of these devices was performed based on the security indexes (voltage stability and limited line power flow) and reduction of power losses with economic operation and cost of the device. The validation of the proposed GSA method was performed on IEEE 30, IEEE 57 bus test systems. From the simulations, it was shown that the proposed GSA method had placed the FACTS devices in optimal locations which improved the security indexes and hence the power system security is enhanced.

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