Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 1956 – 1971
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doi:10.3906/elk-1110-51

A new method based on sensitivity analysis to optimize the placement of SSSCs

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Received: 24.10.2011 • **Accepted:** 11.06.2012 • **Published Online:** 24.10.2013 • **Printed:** 18.11.2013

Abstract: The flexible altering current transmission system (FACTS) controllers such as static synchronous series compensators (SSSCs) and unified power flow controllers can strongly improve the different parameters of power systems. They can be used to improve the transient stabilities, voltage profiles, lines transmission capabilities, etc. Therefore, the optimized allocation of FACTS devices is an important issue in recent research. The optimal placements of FACTS devices can have a determinant effect on the performance of a system, too. In this paper, the proper allocation of SSSCs is proposed. Sensitivity analysis is used in order to model SSSCs' effects on the power system. The advantage of this modeling based on sensitivity analysis is to accelerate the optimization process. By using SA for modeling the SSSC, optimization needs only one load flow in the initial state. According to this method, there is no need for exact modeling of SSSCs. Due to its high speed, another advantage of this method is its ability to cover all possible input values and all candidate places for SSSCs. Additionally, the number of SSSCs is not limited and it can vary during optimization. This approach is based on the objective function including transient stability and active power transmission capacity indices. The proposed method is applied on a typical 6-bus network and the 57-bus IEEE test system. The results show the performance of this method.

Key words: Static synchronous series compensators (SSSC), optimized placement, genetic algorithm, transmission capability, transmission phase angle

1. Introduction

The voltage source convertors (VSCs) are used in several flexible alternating current transmission system (FACTS) devices. The FACTS controllers using VSCs can supply the reactive power. They can control the active and reactive power flow [1]. Static synchronous compensators (STATCOMs), static synchronous series compensators (SSSCs), unified power flow controllers (UPFCs), and interline power flow controllers (IPFCs) are the FACTS controllers that use VSCs. These devices are multiagent and they can be used under different control conditions [2]. One of these devices has been installed by the New York Power Authority. The installed controller is a changeable static compensator and is located in the Marcy Substation. It can be utilized under various conditions of system topology [1,2]. Therefore, it is desirable to analyze the FACTS devices and their performance in power systems. It is important to obtain the effects of VSCs used in FACTS devices on specified systems at large scales. Sensitivity analysis is one of the most useful methods for determining the effects of variation of one variable on the whole system. In [3,4], there were several approaches presented for sensitivity analysis related to FACTS devices. The sensitivity analysis appropriately makes direct relations between the

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control variables and the observed variables such as power flow and voltage profile in the power systems including FACTS devices [5,6]. These relations help to obtain an optimal location for FACTS devices in order to remove overloads and congestion in many applications. The above-mentioned application was used for the New York Power Authority [7].

In [3], an economical dispatching method was introduced based on nodal price calculations and there were also some FACTS devices in the system. In [3], the optimization subject of the FACTS devices' reference inputs was applied to achieve both suitable stability of the system and decreasing of the cost. The applied method in [3] was proposed by use of sensitivity analysis of the results of the transient stability simulations in the time domain and the collections of the linear limitations related to the desired inputs of active power suppliers and FACTS devices. In [7,8], sensitivity analysis was used in order to find proper locations for FACTS devices. In [7], both direct and indirect approaches were used to analyze the effects of the FACTS equipment on load flow equations, active power flow, and the voltages of different buses. There are 2 general methods to implement VSCs in system equations and analyze the effects of the equipment on a specified system. The first method is based on analytical equations and also modeling of the VSC with an injecting voltage source [9,10]. Furthermore, there is another approach that indirectly implements VSCs into system analysis as equivalent impedances [11,12]. In the direct method, transmission active power variations in different lines of the system and the proportion of different point voltages to variations of the injecting voltages of the VSCs can be calculated. Similarly, in the second method, transmission active power variations and different points' voltages in proportion to lines' impedance variations (equivalent to VSC impedance) can be considered. In both of the methods, by first-order linear extension with no need for numerous complicated calculations, the response of the system to variations of VSCs can be estimated acceptably. The indirect method has the advantage of being independent from exact modeling of the equipment in the system. This would be very useful if the existence of FACTS devices were to be analyzed at various locations [7].

One of the considered aspects of FACTS devices is finding the proper location in order to achieve the desired situations with minimum change in cost and without undesired variations in the system [13,14]. Some criteria have been proposed for the proper placement of FACTS devices in recent research. In such research, transmission capability, load flow equations, different points' voltages [7,15], voltage stabilities [13], transient stabilities and market optimization [3], consumer load variations, and variable amounts of renewable energy generation [14] are the most important factors considered in allocation of FACTS controllers. To achieve the optimum locations for FACTS devices, some evolutionary algorithms (e.g., genetic algorithm (GA), particle swarm optimization (PSO), and imperialistic competition algorithm (ICA)) have been used in different research projects. In [16–18], an allocation algorithm for FACTS devices (i.e. UPFCs) using GA and PSO analysis was introduced considering voltage stability indices, the cost function of a UPFC device, and reduction of power system losses. The same method was presented in [19] by using an ICA as the optimization algorithm.

In this paper, by equivalent impedance modeling of SSSCs based on sensitivity analysis, the proper allocation of these devices is proposed considering the lines of transmission capability and system stability. One of the most important advantages of equivalent impedance modeling of FACTS devices is fast calculations, and the problem can be solved by only one load flow calculation in the initial state. Another advantage of this method is analysis of locating FACTS controllers in all possible places with all feasible input values. Additionally, the number of SSSCs is not limited and depends on power system demands. A GA is used to solve the introduced optimization problem. Moreover, this optimization method is applied on 2 different systems to clarify its performance.

2. FACTS devices impedance modeling method

Where a FACTS device (usually as a VSC) is connected in series with a line, injected voltage of a VSC can be modeled as equivalent impedance. In this section, the equivalent impedance of a SSSC will be analyzed. In Figure 1, a SSSC is shown. The SSSC is a VSC that is connected in series to the network by an additive transformer. In Figures 2 and 3, a voltage source schematic and the equivalent impedance of a SSSC located between typical buses 1 and 2 are presented, respectively. The SSSC is not connected to the energy source or energy storage in the normal state, and so it does not inject active power to the network.

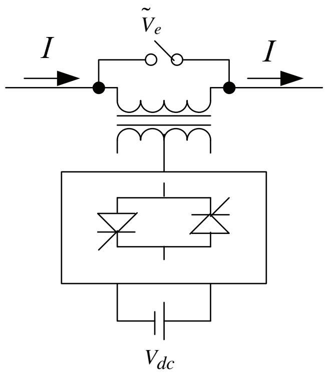

Figure 1. SSSC.

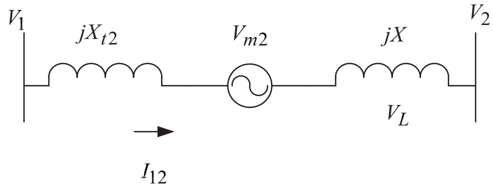

Figure 2. Voltage view of SSSC.

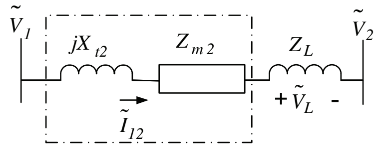

Figure 3. Equivalent impedance view of SSSC.

Eq. (1) and Eq. (2) simply represent the relation among the voltage, current, and equivalent impedance of the compensator [7]:

$$I_{12} = \frac{\vec{V}_1 - \vec{V}_2 - \vec{V}_{m2}}{jX_{t2} + Z_1}, \tag{1}$$

$$Z_{m2} = \frac{\vec{V}_{m2}}{\vec{I}_{12}}. \tag{2}$$

The series compensator cannot exchange active power with the network, so it can be concluded that the voltage of the terminals and passing current is orthogonal. In Figure 4, the voltage vectors' diagram and the SSSC current vector diagram are shown. The voltage of the VSC lags its current; therefore, it shows capacitive equivalent impedance. Furthermore, a VSC can be inductive as a series inductance with the line if its voltage leads its passing current. This state is presented in Figure 5.

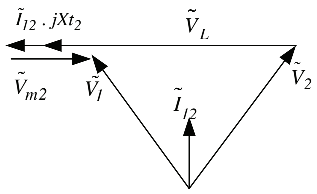

Figure 4. Vector diagram of SSSC when voltage lags from the current.

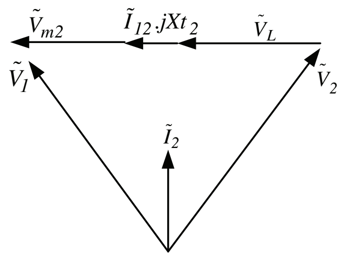

Figure 5. Vector diagram of SSSC where the current has delay from voltage.

3. Equivalent impedance estimation of SSSCs

Having related the current and voltage of a SSSC, the related equations of an equivalent impedance model can be easily calculated. However, the problem is that the current and equivalent impedance are dependent on each other. In this situation, the problem cannot be directly solved. Therefore, the iterative solutions should be used. Before the SSSC injects any voltage to the network, it has primary voltage vectors at various points. After injecting the voltage of several SSSCs, voltages of various points experience some variations. In Eq. (3), it is explained that if a SSSC operates, different points' voltages of the network will obtain an amount of voltage that is the sum of the primary voltages of those points and the variations of the SSSC addition.

$$\vec{V}_{new} = \vec{V}_{base} + \Delta\vec{V} \tag{3}$$

In a typical network with N buses, by use of the admittance matrix, the load flow equations can be written as in Eq. (4). In the case that SSSCs operate in the system, the load flow equations can be written as in Eq. (5).

$$\vec{I}_{base} = Y_{base}\vec{V}_{base} \tag{4}$$

$$\vec{I}_{new} = Y_{new}\vec{V}_{new} = (Y_{base} + \Delta Y)\left(\vec{V}_{base} + \Delta\vec{V}\right) \tag{5}$$

Calculation of the admittance matrix variations can be easily done by knowing the equivalent impedance equations of the SSSCs. In the admittance variation matrix, by superimposing SSSCs on the transmission line between buses (i) and (j), all arrays except ΔY_{ii}, ΔY_{ij}, ΔY_{ji}, and ΔY_{jj}, which take values that are nonzero, will equal zero. In Eq. (6), a mathematical expression indicates which arrays of the admittance matrix are zero.

$$\Delta Y_{ii} = 0\ ;\ k, m \neq i\ or\ j \tag{6}$$

For any FACTS device, according to its topology and the arrangement of the injecting voltage source, arrays of the admittance variation matrix would be different. In Eq. (7), the admittance variation matrix due to the operation of SSSC is expressed [14].

$$\begin{cases} \begin{bmatrix} \Delta Y_{ii}\Delta Y_{ij} \\ \Delta Y_{ji}\Delta Y_{jj} \end{bmatrix} = \begin{bmatrix} \frac{1}{jX_t+Z_m+Z_{ij}} - \frac{1}{Z_{ij}} - \frac{1}{jX_t+Z_m+Z_{ij}} + \frac{1}{Z_{ij}} \\ -\frac{1}{jX_t+Z_m+Z_{ij}} + \frac{1}{Z_{ij}} \frac{1}{jX_t+Z_m+Z_{ij}} - \frac{1}{Z_{ij}} \end{bmatrix} \\ \Delta Y_{pq} = 0\ ;\ p, q \neq i\ or\ j \end{cases} \tag{7}$$

It is possible to assume that the injection current of each SSSC is much smaller than the base current of the system. Therefore, the uncompensated and compensated currents of the lines can be considered equal.

Furthermore, by simplifying Eq. (7) as follows, it can be expressed as a relation between voltage and admittance variation matrices.

$$\begin{aligned} & a: \vec{I}_{new} = (Y_{base} + \Delta Y)\left(\vec{V}_{base} + \Delta\vec{V}\right) \\ & b: \vec{I}_{new} = Y_{base}.\vec{V}_{base} + Y_{base}.\Delta\vec{V} + \Delta Y.\vec{V}_{base} + \Delta Y.\Delta\vec{V} \\ & c: \vec{I}_{new} = \vec{I}_{base} = Y_{base}.\vec{V}_{base} \\ & d: \Delta Y.\Delta\vec{V} \simeq 0 \\ & \Rightarrow \Delta\vec{V} = -Y_{base}^{-1}.\Delta Y.\vec{V}_{base} \end{aligned} \tag{8}$$

In order to use Eq. (8), an iterative algorithm should be used. The flowchart of the required algorithm to calculate the voltage variations using the above method is illustrated in Figure 6 [7]. At first, the iterative algorithm of calculating the equivalent impedance takes load flow results for the base state, then uses Eq. (7) to find the admittance variations matrix. Finally, it calculates voltage variations by Eq. (8). If the voltage variation has a large value, voltage differential should be calculated by an updated amount of network buses' voltages. They are then compared with the voltage differential of the previous steps. In the situation that voltage variations of buses related to the compensators are approximately fixed, the algorithm will stop and the desired results will have been achieved.

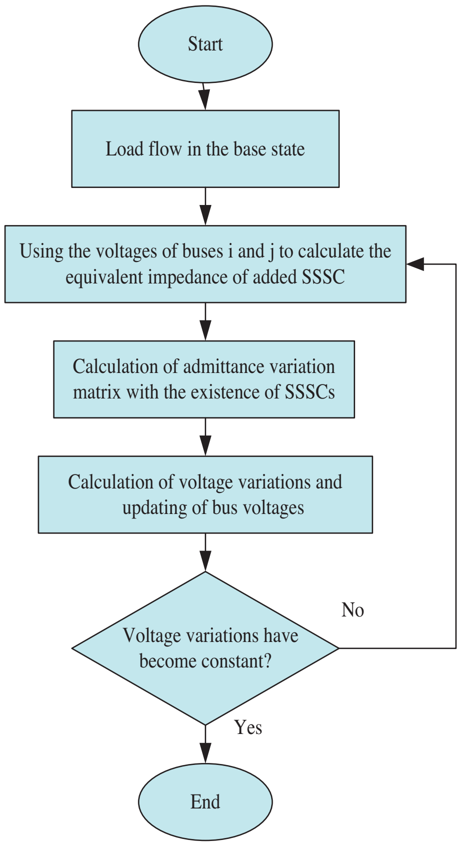

Figure 6. Flowchart of the iterative process to calculate compensated voltage matrix.

The advantage of Eq. (8) is that it determines a relation between the admittance variation and voltage variation of a SSSC. Calculations can also be done by Eq. (8) and the inverse matrix of admittance in the base state can be obtained, and there is no need to obtain the admittance inverse matrix for each possible allocation of SSSCs. This proposed method shows its performance clearly where there are several compensators in different candidate locations.

4. Objective function

Finding the proper allocation of FACTS controllers is an important subject of these controllers' design. It decreases the cost and also improves their performance. Different criteria have been implied for the allocation of FACTS devices in recent research. One of the most important objectives of using FACTS controllers is increasing the transmission lines' capability. In Eq. (9), the maximum amount of power transmission capability between buses i and j are given:

$$p_{ij,Max} = \frac{|V_i|\,|V_j|}{X_{ij}}. \tag{9}$$

Another important system parameter that affects transient stability of the system is the phase difference between voltages of network-connected buses (δ). If the δ value decreases, the stability margin of the transmission line will be increased [7]. In this paper, the maximum transmission capability and phase differential as a factor of the transient stability term are applied to obtain the objective function to allocate SSSCs.

$$O.F = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\alpha_{ij} \frac{p_{ij,\max}^{comp} - p_{ij,\max}^{uncomp}}{p_{ij,\max}^{uncomp}} + \beta_{ij} \frac{\delta_{ij}^{uncomp} - \delta_{ij}^{comp}}{\delta_{ij}^{uncomp}}\right) \tag{10}$$

In the above relation, the O.F expresses the objective function and includes the sum of the maximum transmittable power and phase shift between 2 connected buses with their own weight coefficients. $p_{ij,Max}$, δ_{ij}, α_{ij}, and β_{ij} are maximum transmittable power from the line between buses i and j, lines' transmission angles, and their weight coefficients, respectively. The coefficients α_{ij} and β_{ij} have negative values. Therefore, the best value is evaluated when the minimized value of the proposed objective function is found.

In each optimization process, the feasible area for the objective function is determined by considering some constraints. The constraints of this optimization problem are explained as follows:

$$0.9p.u \leq V_i \leq 1.2p.u, \tag{11}$$

$$-\frac{\pi}{6} \leq \delta_{ij} \leq +\frac{\pi}{6}. \tag{12}$$

In the case of using SSSCs as FACTS controllers, their installation and operation costs play a crucial role in their number in power systems. Therefore, in the above O.F relation, both the cost penalty term and a number constraint should be added in order to modify the optimization process. In this paper, it is supposed that just n SSSCs are feasible for the selected 57-bus system. Therefore, the modified objective function is:

$$O.F = \begin{cases} \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\alpha_{ij} \frac{p_{ij,\max}^{comp} - p_{ij,\max}^{uncomp}}{p_{ij,\max}^{uncomp}} + \beta_{ij} \frac{\delta_{ij}^{uncomp} - \delta_{ij}^{comp}}{\delta_{ij}^{uncomp}}\right) & \text{if} \quad n \leq n_{\max} \\ M & \text{if} \quad n > n_{\max} \end{cases}. \tag{13}$$

The optimized O.F needs several complicated calculations based on the power system characteristics to reach its optimal value. Thus, an intelligent algorithm should be used to find the optimized solutions. In this paper, a GA is used to optimize the proposed objective function.

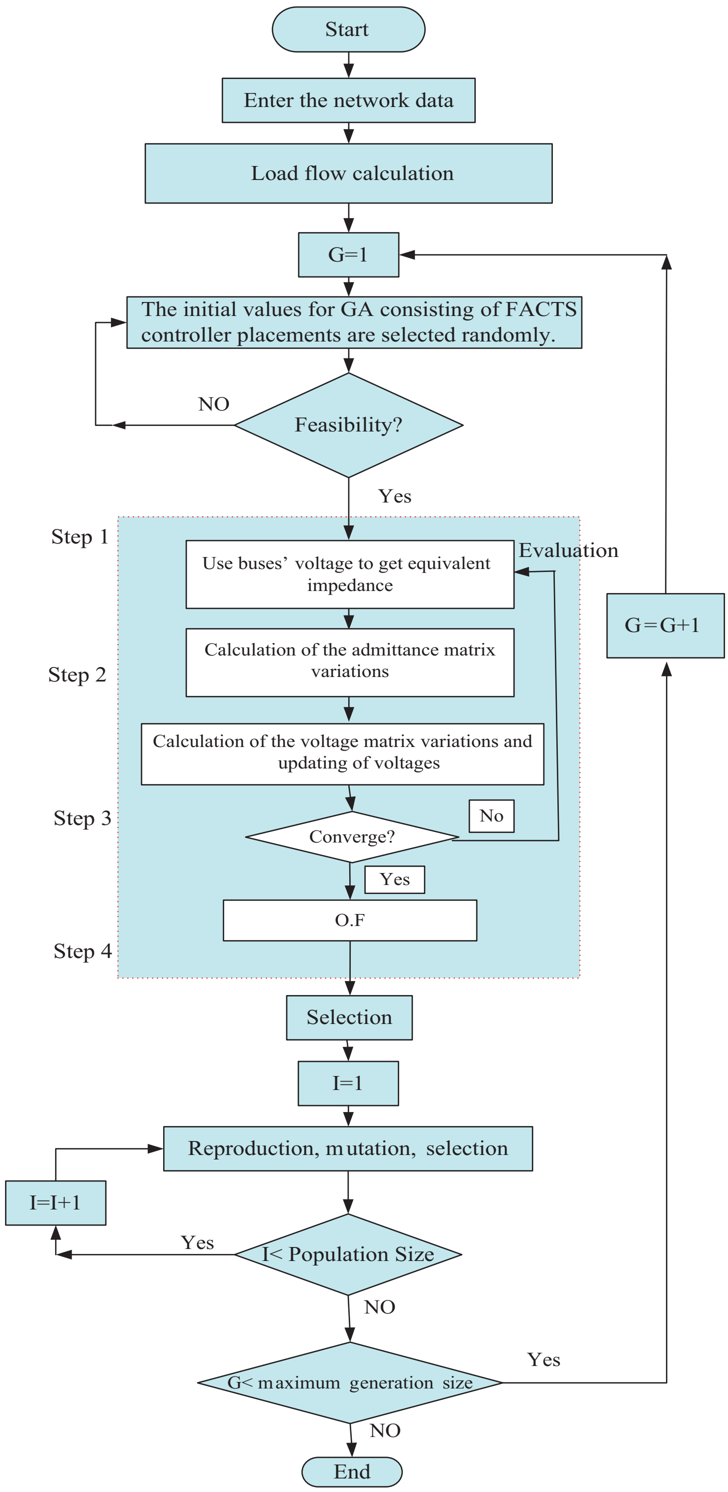

Figure 7. Flowchart of the optimization process by genetic algorithm.

In this method, each line is feasible to allocate a compensator. The optimization variables are the double vectors in the range of –0.2 p.u. and +0.2 p.u. In this paper, 2 strategies are proposed to consider optimization variables. The first strategy is the use of distinct steps with a specified step length for optimization of variables. In this approach, the voltage of each added SSSC has a discrete value between –0.2 p.u. and +0.2 p.u. for the first test system (6-bus test system) and –1 p.u. and + 1 p.u. for the second test system (57-bus IEEE test system) with a step length of 0.05 p.u. The strategy is advantageous in its simplicity and its practical application in real systems with physical devices. The other strategy is to use continuous values for optimization variables. In this method, the voltage of each added SSSC can have continuous values between –0.2 p.u. and +0.2 p.u. or –1 p.u. and +1 p.u. However, its feasibility is less than that of the former strategy.

A chromosome is defined for each variable either for the first or second strategy. A set of these chromosomes constitutes a gene, which is a set of solutions. In Figure 7, the flowchart of the proposed method is shown.

5. Test results

In this section, the proposed method is applied to typical 6-bus and 57-bus IEEE test systems. The necessary steps to implement the proposed method are clearly explained. In order to apply the proposed method to a test system, there are 4 general steps. The first step of applying the method is selection of the appropriate test system. The appropriate test system is a system that works under critical conditions (e.g., voltage profile

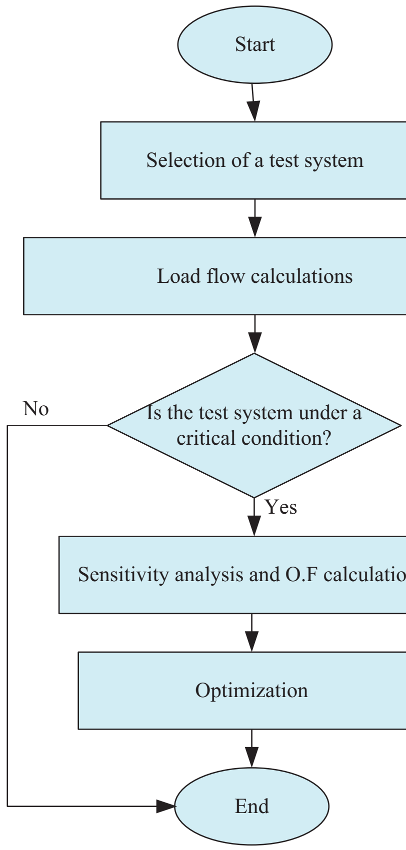

Figure 8. Flowchart of applying the proposed method.

of buses, phase angle of lines, or power congestion in lines). Since the load flow results of the test system under uncompensated conditions are required to apply the sensitivity analysis, the second step is the load flow calculations. The test system should be simulated on power software such as DIgSILENT or ETAP. In addition to use of power software for solving the load flow calculations, it is possible to code the popular methods of load flow (Gauss–Seidel or Newton–Raphson method) in programming languages (e.g., C, C++, or M-file of MATLAB). The load flow results with other test system information including the topology data and impedance of lines are imported as the input of the proposed method. In this paper, the implementation of the sensitivity analysis and objective function is coded in the M-file of MATLAB. The last step to obtain the optimum solution is solving the optimization problem. The GA toolbox is used to solve the optimization problem in this article. By solving the optimization problem, the optimum value of the objective function and the best allocation of the SSSC will be obtained. The simplified flowchart of applying the proposed method is shown in Figure 8 and it shows the general steps.

5.1. Typical 6-bus test system

The single line diagram of the selected 6-bus system is shown in Figure 9. The information about generations, loads, and network topology is presented in Tables 1 and 2.

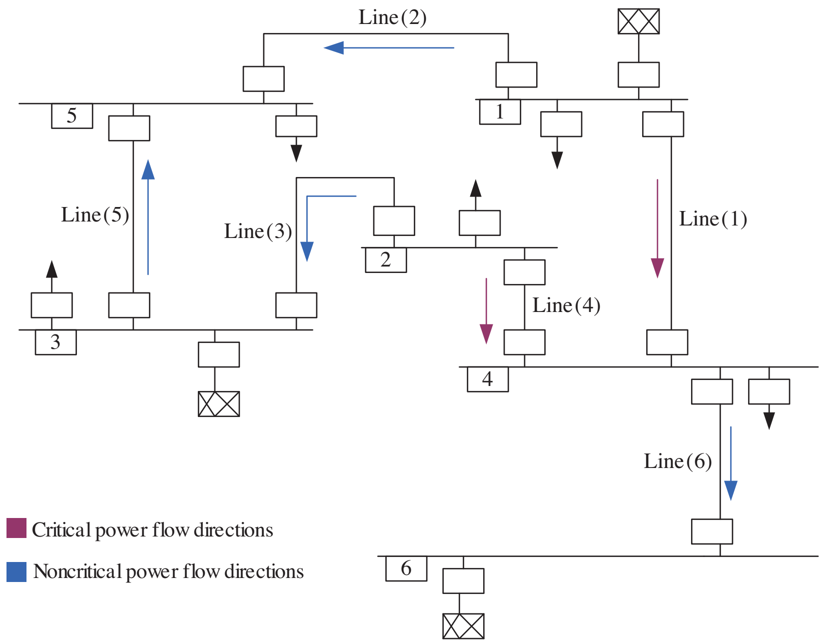

Figure 9. Single-line diagram of 6-bus system.

Table 1. Information of loads and generations.

Bus ID	Load (MVAR)	Load (MW)	Generation	Bus type
1	0	80	150	PV
2	40	240	0	PQ
3	0	40	360	PV
4	24	160	0	PQ
5	40	240	0	PQ
6	0	0	600	Slack

Table 2. Information of the network lines.

From bus	Reactance (p.u.)	Resistance (p.u.)	Length (km)	To bus
1	0.6	0.15	96.56	4
1	0.2	0.05	32.19	5
2	0.2	0.05	32.19	3
2	0.4	0.1	64.37	4
3	0.2	0.05	32.19	5
4	0.3	0.075	48.28	6

It is considered that all transmission lines are feasible to allocate a SSSC. As explained in the proposed method, it is necessary to calculate the load flow in the basic state. The DIgSILENT software is used to simulate the network and calculate the load flow. For each feasible state, the different terms of the objective function are determined by the proposed method based on the sensitivity analysis. A GA with '20' population size and '100' generation size is then used to optimize the objective function. The n_{max} and M are considered '3' and '100', respectively. The weight coefficients of power transmission capability and transmission phase angle are considered '1' and '0.2'. The best and mean values of the fitness function via generation obtained from the GA toolbox of MATLAB are shown in Figure 10. The best value of the objective function achieved is –5.0417. Moreover, the optimization results of the 6-bus test system are presented in Table. 3.

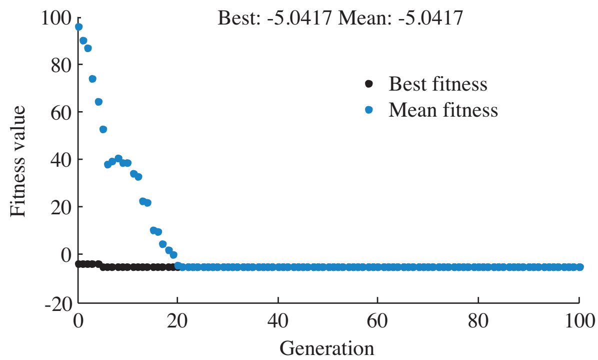

Figure 10. Convergence diagram of optimization process for 6-bus system.

Table 3. Optimization results of 6-bus system.

From bus	To bus	SSSC amplitude	$p_{ij,\max}^{uncomp}$	$p_{ij,\max}^{comp}$	δ_{ij}^{uncomp}	δ_{ij}^{comp}
1	4	0	1.583128	1.168857	0.188233	0.230559
1	5	+0.2	4.698694	1.981222	0.191067	0.007324
2	3	0	4.349051	22.38934	0.16267	0.030282
2	4	0	2.065765	4.388003	0.448056	0.711924
3	5	+0.2	4.698526	6.50329	0.093915	0.919525
4	6	0	3.324698	3.042775	0.206666	0.757447

Two SSSCs with +0.2 value of amplitude are suggested to allocate in lines 2 and 5, which are connected between buses 1 and 5 and buses 3 and 5, respectively. The power transmission capabilities of lines 3 and 5 have been improved more effectively. The greatest improvement of the transmission phase angle has occurred in line 2.

5.2. The 57-bus IEEE test system

In addition to study of the results of applying the proposed method to a 6-bus test system, this method will be applied to a 57-bus IEEE test system in order to clarify its performance. The single-line diagram of this test system is shown in Figure 11. By studying the various conditions and using the DPL code in DIgSILENT, it has been derived that the line that connects buses 35 and 36 is a special line. The outage of this line leads to critical conditions for system parameters. The test system when this line experiences an outage will be studied to find the optimum allocation of SSSCs.

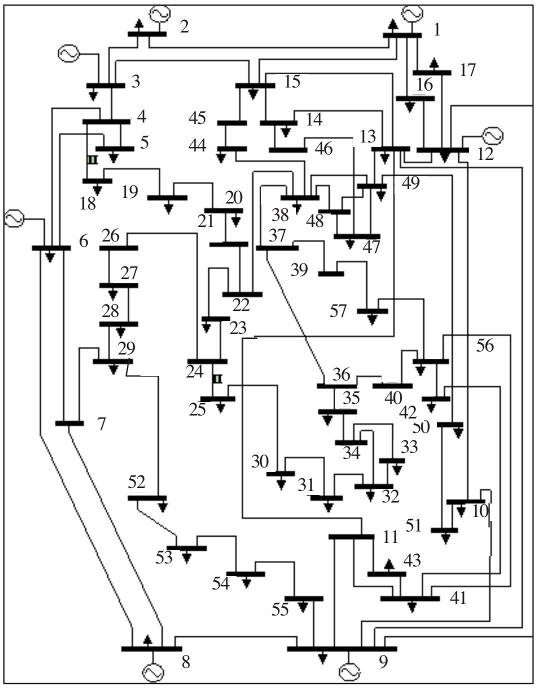

Figure 11. Single-line diagram of 57-bus IEEE test system.

The 57-bus IEEE test system when the line located between buses 35 and 36 has experienced an outage is simulated in DIgSILENT software. The load flow results of the uncompensated network simulation in DIgSILENT are imported to MATLAB as the input values for applying the proposed method.

The optimization problem is solved by a GA, similar to what was performed for a typical 6-bus test system. Since this test system has 57 buses and 80 lines, the value of GA parameters such as population and generation sizes are selected '400' and '200', respectively. Moreover, the value of $n_{\max}$ for this case study is assumed to be '5'.

The optimization results to allocate the SSSCs in this network are demonstrated in Table 4. The uncompensated and compensated values of power transmission capacities and phase angles of these test system lines are also shown in Figures 12 and 13. These figures illustrate the compensation effects while the optimum allocation of FACTS controllers is applied.

5.3. Comparison of the proposed method with available approaches

To evaluate the performance and reliability of the proposed method, it is necessary to compare this method with the results of available methods. The proposed method is simpler and faster than the previous methods that analyze the FACTS controllers with the VSC model as an injected voltage source, such as those in [9,10].

In an N-bus power system with N_g generator and n VSCs, when the approaches are computed directly, the incremental bus voltages and line flows are used and the system equations can be formulated as $N - 1$ and $N - N_g$ equations for active and reactive power bus injections/loads, respectively. Furthermore, n VSC equations are required for VSCs equations. According to the proposed method, just 1 equation per iteration is required in the iterative process shown in Figure 6 and the process is converged in less than 5 or 6 iterations; this method is much faster than direct methods. Moreover, the accuracy of the equivalent method was studied in [7] and it was shown that this method is adequately accurate. The results of [7] show that the equivalent impedance modeling includes less than 3% error in computing the equivalent impedance after only 2 iterations.

Table 4. Allocation of SSSCs for 57-bus IEEE test system.

From bus	To bus	SSSC amplitude
9	11	+1
4	18	+1
25	30	+0.8
30	31	+0.8
38	49	+1

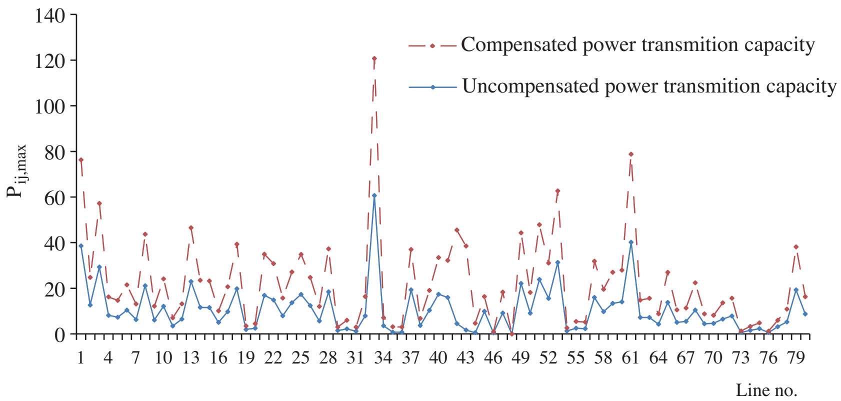

Figure 12. Compensated and uncompensated power transmission capacities of 57-bus IEEE test system.

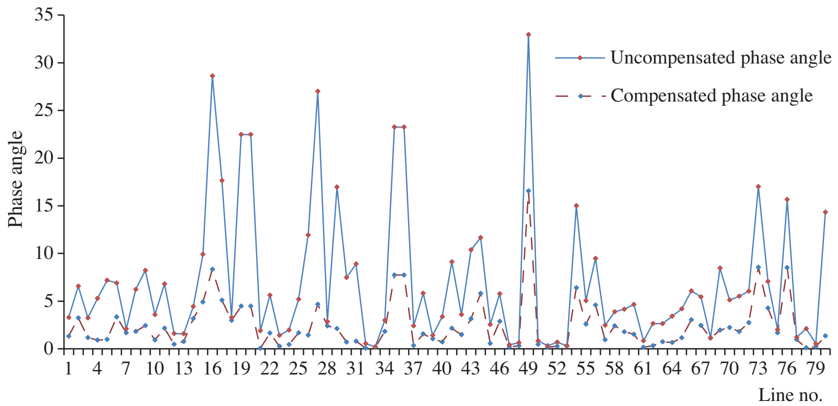

Figure 13. Compensated and uncompensated phase angles of 57-bus IEEE test system.

Since the introduced method of this paper is focused on optimization, for each iteration of the GA to solve the optimization problem of a large-scale network by direct methods, a large number of equations should be solved. The number of equations for each GA iteration can be obtained by Eq. (14). For example, in order to apply the direct methods to optimize the location of just 1 SSSC in the 57-bus test system, 4400 equations should be solved. Because of the considerably numerous calculations in the direct method, the optimization is not feasible by ordinary methods for large scale networks.

$$\text{Required equations of each GA iteration} = \text{population size} \times (N - 1 + N - N_g + m) \quad (14)$$

Furthermore, the introduced method in this paper is more useful than the available equivalent impedance models. Hence, the results of allocating 5 SSSCs in the IEEE 57-bus test system using the presented method in [7] are compared with the obtained results of the method of this paper.

Solving the optimization problem of finding the best allocation of SSSCs is not possible, because it is a nonlinear problem with a great complexity level. Therefore, in recent research, some methods have been used to find feasible solutions. Sensitivity analysis is one of the proper strategies to solve the problem. In [7], sensitivity analysis was used to allocate the FACTS controllers. Sensitivity analysis can also be more suitable to make a decision while the feasible area has been limited to special locations.

To find the optimum allocation of 5 SSSCs in a 57-bus IEEE test system, when all lines are feasible to allocate the SSSCs, firstly, the best choice to install the first SSSC should be determined. Afterwards, when the first SSSC has been located, another SSSC is located in the other line. This process continues until all SSSCs are located.

The obtained results by using the sensitivity analysis introduced in [7] to allocate the SSSCs in the 57-bus IEEE test system are presented in Table 5. As can be seen in this table, the achieved O.F value is –0.0105, while the value of O.F as optimized by the GA is –0.0425. The better value of O.F confirms that the performance of the introduced method is more appropriate than available methods. Furthermore, in Figures 14 and 15, the compensated value of power transmission capacity and the phase angle obtained according to the explained sequences of using the method of [7] are compared with the results of the introduced method of this paper. The results illustrate that although the introduced method in [7] is an appropriate approach for allocating the SSSCs, the results obtained by using a GA are more suitable than those obtained in [7].

Table 5. Results of using introduce method of [7] for allocation of SSSCs in 57-bus IEEE test system.

Step no.	From bus	To bus	SSSC amplitude	O.F value
First step	4	18	+1	–0.0045
Second step	4	18	+1	–0.0067
	10	12	+1	
Third step	4	18	+1	–0.0077
	10	12	+1	
	53	54	+1	
Fourth step	4	18	+1	–0.0094
	10	12	+1	
	53	54	+1	
	29	7	+0.2	
Fifth step	4	18	+1	–0.0105
	10	12	+1	
	53	54	+1	
	29	7	+0.2	
	9	11	+1	

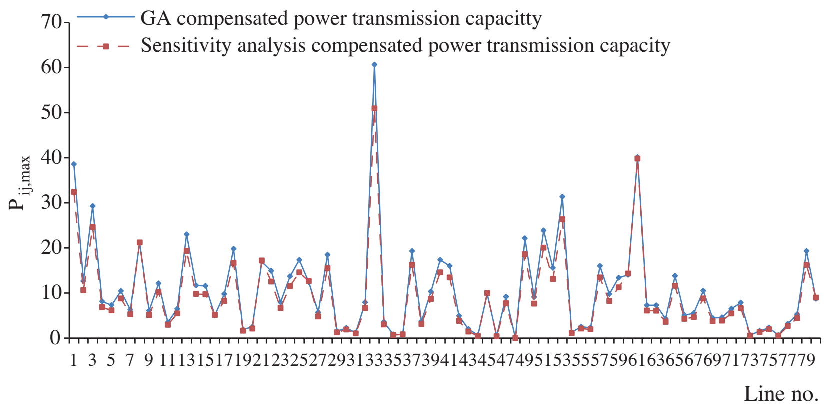

Figure 14. GA and sensitivity analysis of compensated power transmission capacity of 57-bus IEEE test system.

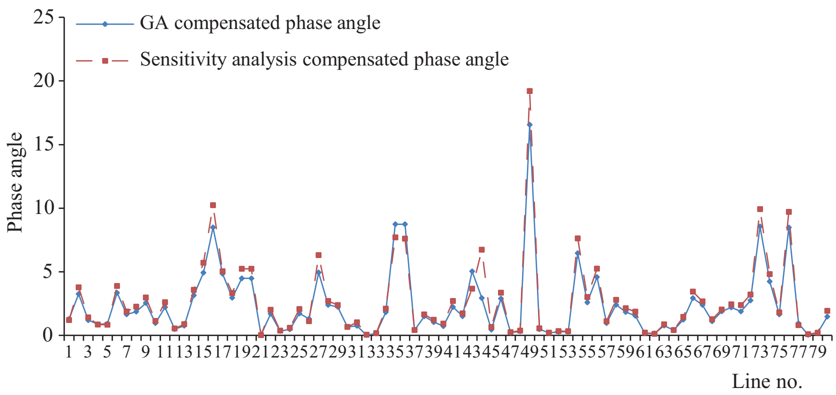

Figure 15. GA and sensitivity analysis of compensated phase angles of 57-bus IEEE test system.

6. Conclusion

The FACTS controllers have several applications in power systems. The active and reactive power flow control, increasing of the transmission capability of lines, voltage profile improvement, transient stability, etc. are some benefits of using FACTS controllers. FACTS compensators have been introduced differently based on their topology and the approach of location, including SSSCs, UPFCs, and STATCOMs. The optimized usage of FACTS controllers is one of the important subjects for power systems designers. One of the most important parameters that affect the performance of FACTS controllers is their location. Therefore, the problem of finding their optimized placement is an important issue. By considering a large amount of calculations and analysis of the effects of each device in different places, this process needs a fast method. One of the applicable methods for finding the location of devices in power systems is sensitivity analysis. In this paper, a new method to find the placement of SSSCs has been proposed based on sensitivity analysis. In this process, approximate estimation for equivalent impedance of the voltage source converter has been used to accelerate the proposed algorithm. The advantage of equivalent impedance estimation is the need of only one load flow in the base state and, in next steps, an iterative method and no need to repeat the load flow. The algorithm can be continued by exact modeling of SSSCs. The proposed method has been applied on a typical 6-bus network and 57-bus IEEE test system. The results illustrate the proper performance of the proposed method.

Nomenclature

V_c	Voltage of the SSSC
X_t	Inductance of the SSSC transformer
Z_i	Impedance of the line i
$\vec{V}_{m2}$	Voltage of the SSSC in equivalent impedance modeling
$\vec{V}_L$	Voltage drop across the line impedance
I_{ij}	Current passing the line between buses i and j
$\vec{V}_i$	Voltage of the receiving bus i
Z_{m2}	Equivalent impedance for the SSSC
$\vec{V}_{base}$	Voltage matrix in basic state obtained by the load flow
$\Delta\vec{V}$	Voltage differential matrix
$\vec{V}_{new}$	Final voltage matrix obtained by sensitivity analysis
$\vec{I}_{base}$	Current matrix in basic state
Y_{base}	Admittance matrix in basic state
ΔY	Admittance differential matrix obtained by sensitivity analysis
Y_{new}	Final admittance matrix obtained by sensitivity analysis
ΔY_{ij}	Array of ΔY matrix showing the admittance of the line between buses i and j
p_{ij}	Transmission power between buses i and j
X_{ij}	Inductance of the line between buses i and j
δ_{ij}	Phase angle of line allocated between buses i and j
δ_i	Voltage phase of bus i
$p_{ij,\max}$	Maximum amount of the transmittable power between buses i and j
α_{ij}	Weight coefficient of transmittable power term in objective function
β_{ij}	Weight coefficient of stability term in objective function
$p_{ij,\max}^{uncomp}$	Uncompensated amount of $p_{ij,\max}$
$p_{ij,\max}^{comp}$	Compensated value of$p_{ij,\max}$
δ_{ij}^{uncomp}	Uncompensated amount of δ_{ij}
δ_{ij}^{comp}	Compensated value of δ_{ij}
$P.F$	Penalty factor related to the cost in objective function
n	Number of SSSCs in the power system
$n_{\max}$	Maximum number of SSSCs that are feasible practically
M	A great amount to make objective function a large value

References

[1] N.G. Hingorani, L. Gyugyi, Understanding FACTS, Piscataway, NJ, USA, IEEE Press, 2000.

[2] X. Jiang, J.H. Chow, A.A. Edris, B. Fardanesh, E. Uzunovic, "Transfer path stability enhancement by voltage-sourced converter- based facts controllers", IEEE Transactions on Power Delivery, Vol. 25, pp. 1019–1025, 2010.

[3] T.T. Nguyen, V.L. Nguyen, A. Karimishad, "Transient stability-constrained optimal power flow for online dispatch and nodal price evaluation in power systems with flexible AC transmission system devices", IET Generation, Transmission, and Distribution, Vol. 5, pp. 332–346, 2011.

[4] T. Jibiki, E. Sakakibara, S. Iwamoto, "Line flow sensitivities of line reactances for congestion management", Proceedings of the IEEE Power Engineering Society General Meeting, pp. 1–6, 2007.

[5] W. Shao, V. Vittal, "LP-based OPF for corrective FACTS control to relieve overloads and voltage violations", IEEE Transactions on Power Systems, Vol. 21, pp. 1832–1839, 2006.

[6] A. Berizzi, M. Delfanti, P. Marannino, M.S. Pasquadibisceglie, A. Silvestri, "Enhanced security-constrained OPF with FACTS devices", IEEE Transactions on Power Systems, Vol. 20, pp. 1597–1605, 2005.

[7] X. Jiang, J.H. Chow, A.A. Edris, B. Fardanesh, E. Uzunovic, "Sensitivity methods in the dispatch and sitting of FACTS controllers", IEEE Transactions on Power Systems, Vol. 21, pp. 713–720, 2009.

[8] S. An, J. Condren, T.W. Gedra, "An ideal transformer UPFC model, OPF first-order sensitivities, and application to screening for optimal UPFC locations", IEEE Transactions on Power Systems, Vol. 22, pp. 68–75, 2007.

[9] C.R. Fuerte-Esquivel, E. Acha, "Unified power flow controller: a critical comparison of Newton-Raphson UPFC algorithms in power flow studies", IEE Proceedings on Generation, Transmission and Distribution, Vol. 144, pp. 437–444, 1997.

[10] X. Wei, J.H. Chow, B. Fardanesh, A.A. Edris, "A common modeling framework of voltage-sourced converters for load flow, sensitivity, and dispatch analysis", IEEE Transactions on Power Systems, Vol. 19, pp. 934–941, 2004.

[11] D.G. Ramey, R.J. Nelson, J. Bian, T.A. Lemak, "Use of FACTS power flow controllers to enhance operational transmission transfer limits", Proceedings of the American Power Conference, Vol. 56I, pp. 712–718, 1994.

[12] L. Gyugyi, C.D. Schauder, K.K. Sen, "Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines", IEEE Transactions on Power Delivery, Vol. 12, pp. 406–417, 1997.

[13] X. Wei, J.H. Chow, B. Fardanesh, A.A. Edris, "A dispatch strategy for a unified power-flow controller to maximize voltage-stability-limited power transfer", IEEE Transactions on Power Delivery, Vol. 20, pp. 2022–2029, 2005.

[14] X. Fang, "Rated-capacity dispatch, sensitivity analysis, and controller design of VSC-based FACTS controllers", PhD, Rensselaer Polytechnic Institute, Troy, NY, USA, 2008.

[15] S.J. Galloway, I.M. Elders, G.M. Burt, B. Sookananta, "Optimal flexible alternative current transmission system device allocation under system fluctuations due to demand and renewable generation", IET Generation, Transmission and Distribution, Vol. 4, pp. 725–735, 2010.

[16] K. Venkateswarlu, C. Sai Babu, "A new evolutionary algorithms used for optimal location of UPFC on power system", Journal of Theoretical and Applied Information Technology, Vol. 1, pp. 435–443, 2010.

[17] K. Venkateswarlu, C. Sai Babu, K.K. Kuthadi, "Improvement of voltage stability and reduce power losses by optimal placement of UPFC device by using GA and PSO", International Journal of Engineering Sciences Research-IJESR, Vol. 1, pp. 714–721, 2011.

[18] H. Chahkandi-Nejad, R. Jahani, E. Habib-Beigi, A.R. Mohammadi, "Hybrid genetic and PSO algorithm comparison and application of heuristic methods for unified power flow controllers optimal placement in power systems", American Journal of Scientific Research, Vol. 21, pp. 12–19, 2011.

[19] R. Jahani, "Optimal placement of unified power flow controller in power system using imperialist competitive algorithm", Middle-East Journal of Scientific Research, Vol. 8, pp. 999–1007, 2011.