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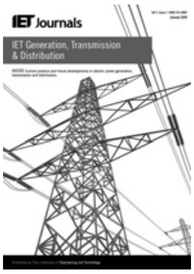

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Simultaneous application of multi-type FACTS devices to the restructured environment: achieving both optimal number and location

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Abstract: A novel method based on genetic algorithm is proposed to find the location, the operating point as well as the number of multi-type FACTS devices in the restructured environments simultaneously and optimally. This method comprises two separate algorithms and takes the advantages of a proposed heuristic search manner, which can decrease considerably the feasible search space. A desirability criterion is proposed to evaluate the suitability of the results. The objective function of the combinatorial optimisation problem is designed such that the nodal prices along with their standard deviation are decreased effectively. A new model, average-neural lossy model is used for FACTS devices, STATCOM and SSSC, which takes the converter power losses into account and thus produces the required PQ-phasor to evaluate STATCOM and SSSC in steady-state situation. The proposed method is appropriate for medium and large-scale systems and its effectiveness is demonstrated by the test results.

1 Introduction

High flexibility in management and control of power system can be achieved by using FACTS devices, as they are being widely used to alleviate the congestion in the transmission systems of restructured environments. However, the effects of these devices are severely dependent on their type, size, number and locations in the transmission systems. Therefore elaborate studies were done on the subject of placement of these devices for optimal improvement of power system operation. The studies made can be divided into two categories, as below:

1. A specific device is studied which belongs to one of the three groups of FACTS devices, that is, parallel, series and/or parallel–series devices [1–12].

2. Multi-type power electronic devices are considered, which may belong to one or more groups of FACTS devices [13–19]. Multi-type FACTS devices refer to employment of two or more types of FACTS controllers (e.g. ‘series and shunt’ or ‘shunt and combined’) in the analysis throughout this paper. Although combinations of various types of FACTS controllers can be studied, here two controllers of two different types are modelled and applied to the proposed algorithm. It should be emphasised that every employed FACTS controller needs to be analytically modelled before applying to the optimal power flow (OPF).

This later can be subdivided into four categories as below:

2.1 Each type is studied individually to compare the effects of different types of FACTS devices on the power system operation [13, 15–17]. This subcategory is similar to the first category.

2.2 The number and location of each device type are already known, where an optimisation problem is solved to find the optimal operating point of each FACTS controller simultaneously [14, 19].

2.3 The number of each device type is already known and an optimisation problem is solved to find simultaneously the optimal location and operating point of all devices [15].

2.4 An optimisation problem is solved to find the optimal number (limited to the number of device types) and location as well as operating points of all the devices simultaneously [18].

It should be noted, however, that the capabilities of all three groups of FACTS devices cannot be covered fully through using a single group only. Even if parallel–series devices are used, it is possible that the behaviour of parallel part of the device be optimised while the series behaviour cannot. This holds when the situation is the other way round. Therefore categories 1 and 2.1 are not suitable choices. Moreover, categories 2.2 and 2.3 in which the location and/or the number of FACTS devices are not determined optimally do not yield the desired optimal results. If category 2.4 is developed properly with suitable numbers and combinations of FACTS devices, the operation of power systems can be improved extensively. A useful combination is to use both series and parallel devices concurrently. This combination can include all the characteristics of the three groups of FACTS devices.

In addition to finding the optimal location of each device, determining the optimal number of multi-type FACTS devices is a very important and complex matter, for which a proper method is not proposed as yet. In [12], one unified power flow controller (UPFC) is installed between buses 4 and 9 close to bus 9 of the IEEE 9-bus test system, calculating the effects of this installation. Also, a research in [13] works on lowering the congestion using static VAr compensator (SVC) and thyristor-controlled series capacitor (TCSC). Each device is located across the IEEE 14-bus test system using trial and error when the number of buses and lines is low. Another research in [14] examines the increase of the total transfer capability because of the installation of one UPFC along with one TCSC in the IEEE 14-bus test system. The increase of the loadability of the IEEE RTS 24-bus system using TCSC and TCPAR is studied in [15]. Three specified certain combinations of TCSC and TCPAR are studied simultaneously. Further, STATCOM and UPFC are used in [16] for a six-bus power system as well as the IEEE 14-bus (only STATCOM is used) to improve the voltage stability.

According to these relevant literatures, two methods are presented to find the optimal number of FACTS devices and for each method a single type of device is used. In the first method, the number of single-type FACTS devices is incremented up to achieving a certain satisfactory level for the objective function [15]. Clearly, this method cannot be used to find the optimal number of multi-types FACTS devices. In the second method, which is normally based on genetic algorithm (GA), the binary coding system is used. That is to say that certain types of strings are used, whose number of bits equals to the locations where the FACTS devices can be installed [20]. Based on the results of optimisation problem, the optimal numbers of devices are equal to the number of bits valued as ‘1’. This method is not efficient for medium and large-scale power systems due to the fact that searching in a very large feasible solution space is a tedious task. Moreover, developing this method for cases in which the size of feasible space is naturally large, like in using combination of multi-type FACTS devices, is not acceptable.

Furthermore, a GA-based method is proposed in [18] to place multi-type FACTS devices simultaneously and optimally. However, the method is capable of seeking one device per type out of the multi-type number of FACTS controllers. For example, three different types of FACTS devices are considered, and the locations of these three FACTS controllers are searched simultaneously and optimally. Thus, the method cannot cover working on combinations like four FACTS devices of three different types.

This paper proposes simultaneous use of parallel and series FACTS devices to include the characteristics of three groups of FACTS devices. While the suggested algorithm is developed for multi-type FACTS controllers, here a shunt-type controller (STATCOM) along with a series type (SSSC) are analytically modelled using average-neural (AN) technique. This combination can provide appropriate tools to control both active and reactive power flows throughout the system. A novel method containing two separate algorithms is proposed to find the location and the operating point as well as the number of each type of FACTS devices simultaneously and optimally. In the first algorithm, the maximum number of each device is determined individually. Then, the best combination of multi-type FACTS devices are searched for, taking the maximum number of each device into account. This heuristic method decreases the search space significantly, which is normally known as the number of nodes for parallel devices and number of lines for series ones. This advantage makes the proposed method suitable for medium and large-scale power systems. Furthermore, a desirability criterion is suggested to evaluate the suitability of the results. The problem is formulated, regarding the power market. The power injection model for STATCOM and SSSC is adopted by applying a neural model based on the averaging technique. This model can take the converter power losses into account and produce the required PQ-phasor that is suitable for power system in steady states. Applying the algorithm to the modified IEEE 14-bus, 30-bus and 118-bus test systems, the results show that the proposed method is an effective method for finding the optimum number of multi-type FACTS devices.

2 Problem formulation

A series device, SSSC, and a parallel device, STATCOM, are selected as possible options in order to control both active and reactive power flow using FACTS devices.

2.1 Description of possible models

Power injection model is a suitable model for these devices in steady-state calculations [21]. This paper uses the power injection models based on averaging technique for FACTS devices. Averaging technique presents an instantaneous time-domain model [22] and it takes all the aspects into account appropriately, including the DC-link of the converter as well as the power losses. This technique is used in [23] to model the STATCOM in an optimal placement problem for a power system. However, the problem with this model is that it necessitates solving a set of differential equations for every operation condition. This is quite a sophisticated process for an OPF problem. To avoid this problem and link the instantaneous results to single-frequency power system analysis, the advantage of neural networks is taken. In other words, a neural model based on the averaging technique is used to extract the power injection model for STATCOM and SSSC. The resultant model produces the required PQ-phasor, which is suitable for power system in steady states.

2.2 AN lossy model of STATCOM and SSSC

In brief, while average model of STATCOM is presented in [22], resultant model is shown by Fig. 1*a*. In this model, L introduces the equivalent coupling inductance between the converter and the power system. The resistance R is part of the compensator losses concerned with the interconnection of the converter to the power system. The other part of the power losses corresponds to the converter losses that are absorbed by the proper modulation of the converter switches. Fig. 1*b* shows typical STATCOM power losses in P.U. against the phase shift between the converter output and the power system voltage (α) that is obtained by the average model. Although the average model presents a time-dependent circuit, a PQ or PV model is essential for the power flow analysis. Hence, adaptive analysis is performed here to obtain the supplied active and reactive powers of STATCOM (P_{CON} and Q_{CON}). A new bus is added for every STATCOM as the converter AC voltage, which is connected to an existing bus n through the commutation reactance (X_{CON}) and the AC resistance (R); see Fig. 1*c*.

Average model of Fig. 1*a* describes a state space-model in a circuit format, and solving it eventually leads to fundamentals of AC voltages and currents as the steady-state solution. Meanwhile, moving from one steady state to another takes time to complete the transient regime that is not suitable for the OPF to struggle with. An OPF program needs to seek among all feasible operating points, where high-speed analysis is essentially needed to boost its performance. A solution to overcome this issue could be identification of the average model of STATCOM by neural network using the average model as a reference to generate required training data for the AN model. Furthermore, a multi-layer perceptron (MLP) identifies the average model with an acceptable error [24].

Similar model for SSSC can be achieved by implementing the same procedure. Average model of SSSC is shown in Fig. 2*a*. Here again, L introduces the equivalent coupling inductance between the converter and the power system. The resistance R is part of the compensator losses concerned with the interconnection of the converter to the power system. Similarly, a new bus is added for every

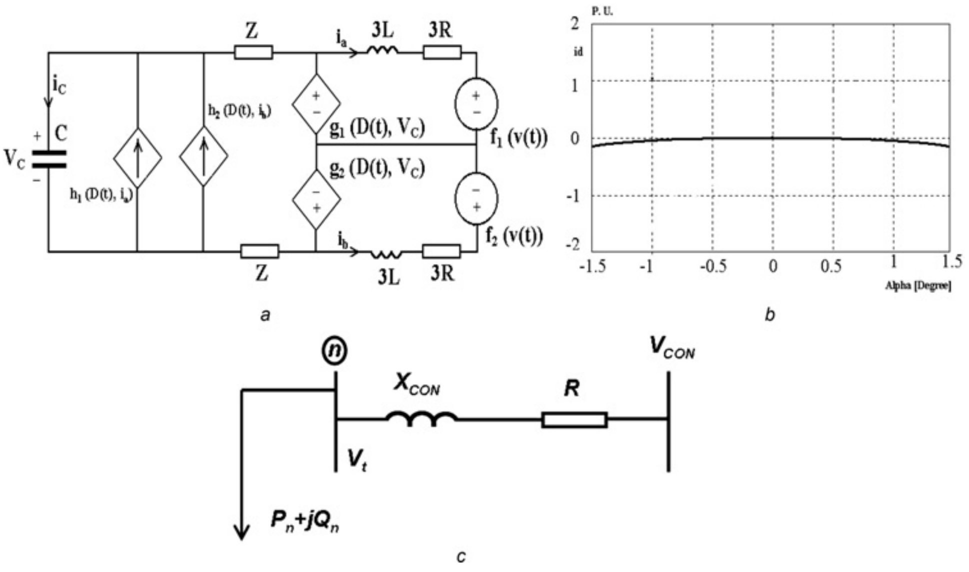

Figure 1 *The employed lossy model for the shunt compensator*

a Average circuit model of STATCOM
b Typical internal power losses of STATCOM obtained by the average model
c Adaptation of the average model connected to the power system by adding a bus for STATCOM

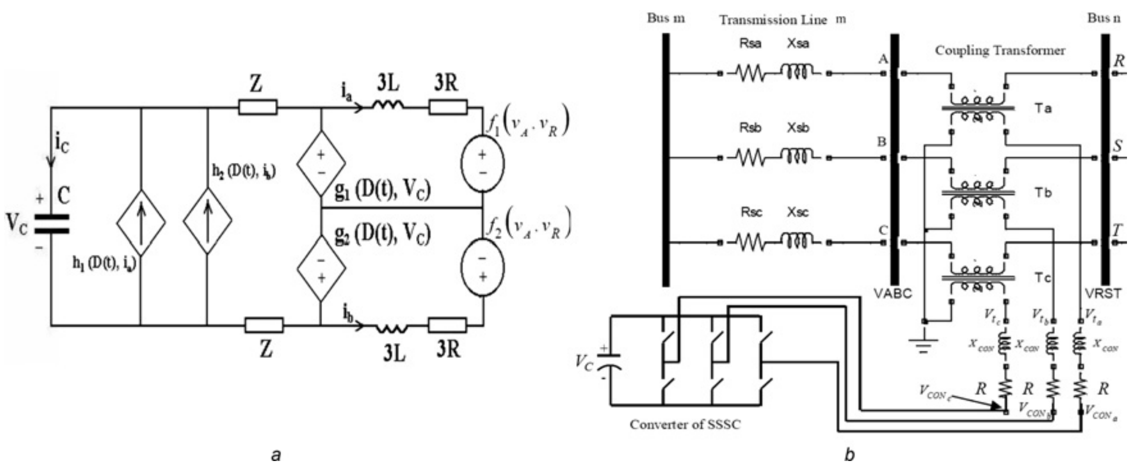

Figure 2 *The employed lossy model for the series compensator*

a Average circuit model of the SSSC
b Three-phase circuit model of the SSSC

SSSC as the converter AC voltage, which is located in an existing transmission line (numbered as m) through the communication reactance (X_{CON}) and the AC resistance (R), see Fig. 2. By using the average model as a reference to generate required training data for AN model, training data can be produced. Here, the AN model of SSSC is based on an MLP network.

2.3 Combinatorial problem formulation

In the restructured environment, occurrence of transmission congestion leads to an unfair energy pricing procedure in the network. The price of electricity may significantly differ in both sides of a congested line. As the congestion in transmission system is increased, the differences in nodal prices get wider. Therefore alleviating the congestion can provide fair pricing conditions for power market participants. By using FACTS devices, it is possible to rectify the congestion. In this respect, applying a suitable objective function for optimal placement of FACTS devices plays a very important role. This paper offers a solution to decrease the nodal prices and price differences by adopting a proper objective function for optimal placement of FACTS devices. The objective function Z can be defined as below

$$Z = \text{MANP} \times \text{VANP}, \text{ where}$$
$$\begin{cases} \text{MANP} = \dfrac{1}{n}\displaystyle\sum_{j=1}^{n} \text{NP}_j \\ \text{VANP} = \sqrt{\dfrac{1}{n}\displaystyle\sum_{j=1}^{n} (\text{NP}_j - \text{MANP})^2} \end{cases} \tag{1}$$

Nodal price of active power at bus j is shown by NP_j and n denotes the number of nodes. Minimisation of (1) leads to reduction of both nodal prices and the difference between one another. For each arrangement of FACTS devices the nodal prices can be calculated by solving an OPF problem in which an objective function is minimised, subjected to a number of equality and inequality constraints. Let us define vectors $\boldsymbol{P} \triangleq (p_1, p_2, \ldots, p_n)$ and $\boldsymbol{Q} \triangleq (q_1, q_2, \ldots, q_n)$ for an n-bus power system, where p_i and q_i represent active and reactive power demand of the ith bus, respectively. Also, assume the state variables in power system operation to be $\boldsymbol{X} = (x_1, x_2, \ldots, x_m)$, such as real and imaginary parts of each bus voltage (or voltage value and its angle), active and reactive outputs of generators etc. Therefore the operation problem of a power system for the given loads (stated by ($\boldsymbol{P}$, $\boldsymbol{Q}$)) can be formulated as an OPF problem

$$\begin{aligned} &\text{Minimise} f(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}) \\ &\text{Subjected to:} \\ &\begin{cases} \boldsymbol{G}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}) = 0 \\ \boldsymbol{H}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}) \le 0 \\ \boldsymbol{X}_{\min} \le \boldsymbol{X} \le \boldsymbol{X}_{\max} \end{cases} \end{aligned} \tag{2}$$

where $f(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q})$ is an scalar short-term operation cost (for fuel cost in here), n_1 equality constraints is represented by $\boldsymbol{G}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}) = (g_1(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}), g_2(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}), \ldots, g_{n1}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}))^{\mathrm{T}}$ (such as power flow balance (Kirchoff's laws)) and $\boldsymbol{H}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}) = (h_1(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}), h_2(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}), \ldots, h_{n2}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q}))^{\mathrm{T}}$ shows vector of n_2 inequality constraints (the superscript T stands for the transposition of a matrix). It is noticeable that $\boldsymbol{H}(\boldsymbol{X}, \boldsymbol{P}, \boldsymbol{Q})$ includes all variables limits and function limits, such as upper and lower boundaries of transmission lines, generation outputs, stability or security limits etc.

It should be mentioned, however, that the placement of FACTS devices, that is, system buses for STATCOMs and transmission lines for SSSCs, are defined by integer variables in optimisation problem. Therefore the problem

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of optimal placement of FACTS devices can be formulated as a mixed integer nonlinear programming (MINP). This problem should be solved by a suitable tool that is able to search for the optimum values of integer variables as well as the optimum of real ones.

3 Proposed method for optimal number and placement of multi-type FACTS devices

In the first step, one proposal is raised for multi-type FACTS controllers, suggesting a solution to seek their individual optimal numbers. Furthermore, in the second step, their optimal placement and operating points are investigated using the results of the first step by embedding both steps into the GA and Lagrangian optimisation method (see (1)–(2)).

First, an algorithm is proposed in order to determine the optimal number of each device individually by solving an optimisation problem repeatedly. The optimal number of each device, obtained in the first step, is considered as the maximum number in the second step in which multi-type FACTS devices are located simultaneously. In other words, for each device, its optimal number in the simultaneous case is equal or less than its optimal number in every individual case. This is due to the fact that the FACTS devices effects, when used simultaneously, are more than the case when used severally in improving the objective function. In the second step, an algorithmic search provides the best response between all the possible combinations of multi-type FACTS devices. Each combination could include any number and type of devices; from zero up to the maximum number.

3.1 Setting an upper-limit to the number of multi-type FACTS devices

The first proposed algorithm for individual placement of each type of FACTS devices is performed as the first step. These placements are expressed by strings consisting of integer numbers. The length of each string is equal to the number of FACTS devices, which is determined before running the algorithm. The algorithm is started for one device and having found the optimal solution it is restarted for two individual numbers of the same device and so on. The number of devices is increased one by one and the following indexes are calculated using the optimal value of objective function

$$\mathrm{INC} = \frac{\Delta Z_i}{\Delta Z_{i-1}} \tag{3}$$

$$\mathrm{CIM} = \frac{|\Delta Z_i|}{Z_i} \tag{4}$$

$$|\Delta Z_i| = |Z_i - Z_{i-1}| \tag{5}$$

where INC is an index to check out the stopping condition for increasing the number of FACTS devices, subscript i denotes the number of FACTS devices and Z_i is the optimal value of the objective function when applying i FACTS devices. Also, ΔZ_i shows the variation of the objective function when the number of FACTS devices is increased from $i-1$ to i. The number of FACTS devices is increased as long as ΔZ_i is ascending; otherwise, stopping condition is satisfied. Although the optimal number of FACTS devices is obtained using the stopping criteria in (3), CIM in (4) is proposed as an extra optional index in order to assess the relative variations of the objective function from $i-1$ to i. Whenever CIM is maximised for a certain number of FACTS devices, the maximum improvement for the objective function is achieved. A designer might think that any further improvement is negligible. It is noticeable that CIM gives smaller number of devices compared to that of INC. At this point, the number of related devices is termed as the maximum number of the same. Resultant maximum number of devices is used in the second algorithm.

According to the first algorithm, for each chromosome in the initial population, the objective fitness function and optimal operating point of FACTS devices as well as the generators are all evaluated by solving the OPF problem. The GA proposes the placements of FACTS devices. Furthermore, the optimum operating point of FACTS devices and generators are determined by solving the Lagrangian function. At each generation of GA, a new set of better chromosomes are created through selection of the chromosomes according to their fitness: survival of the fittest. After the candidate parents are selected, genetic operators that is, crossover and mutation, are applied to create the new population. The iteration process continues until stop criterion, implying that an assigned maximum number of generations are reached. Thus, the first algorithm can be summarised as follows:

1. Read the power system parameters and specifications.

2. Set the number of FACTS device to zero ($N_{\mathrm{FACTS}} = 0$).

3. Set $N_{\mathrm{FACTS}} = N_{\mathrm{FACTS}} + 1$.

4. Create an initial population of the chromosomes based on the proposed placement(s) of the FACTS device (bus/line numbers).

5. Solve the OPF problem defined by (2) for one chromosome.

6. Obtain the value of objective function defined by (1) using step 5.

7. Repeat steps 5 and 6 for all chromosome of the population.

8. Select a set of better chromosomes as candidate parents according to their fitness values.

9. Apply genetic operators (crossover and mutation) to the candidate parents for creating a new population.

10. Repeat steps 5–9 as long as the stopping condition is unfulfilled.

11. Save the best chromosome and its related objective function defined by (1).

12. Repeat steps 3–11 as long as INC (defined by (3)) is increasing.

13. Print the OPF results of the best chromosome, the maximum number of the FACTS device under study (for STATCOM: $N_{\mathrm{STATCOM}}^{\max}$, for SSSC: $N_{\mathrm{SSSC}}^{\max}$), optimal locations, operating points of FACTS devices as well as the value of the objective function (1).

14. Stop.

3.2 Optimal number of multi-type FACTS devices

In the second algorithm, the chromosomes of fixed length structures are designed to contain several combinations of multi-type FACTS devices. To elaborate more, suppose that the optimal number of STATCOMs and SSSCs obtained individually in the first algorithm to be 3 and 2 devices, respectively. Then the second algorithm looks for all the combinations of STATCOMs and SSSCs wherein the number of STATCOMs and SSSCs are equal or less than 3 and 2 devices, respectively. Table 1 represents all combination of FACTS devices that are considered in the second algorithm in this case.

A typical structure of each chromosome for the above cited example is shown in Fig. 3. It can be seen from Fig. 3 that the three first genes represent the locations of STATCOMs. The three last genes are randomly filled by binary values and the bits whose values are equal to one, showing the STATCOMs that are to be considered. More so, the zero values show that the related STATCOMs should be omitted. The similar description holds for SSSC. It should be noted that the genetic crossover and mutation operators are applied on the encoded chromosomes.

The second proposed algorithm is designed for simultaneous placement of multi-type FACTS devices.

Table 1 Twelve possible combinations of using three STATCOMs and two SSSCs

FACTS device	Number of devices											
STATCOM	0	0	0	1	1	1	2	2	2	3	3	3
SSSC	0	1	2	0	1	2	0	1	2	0	1	2

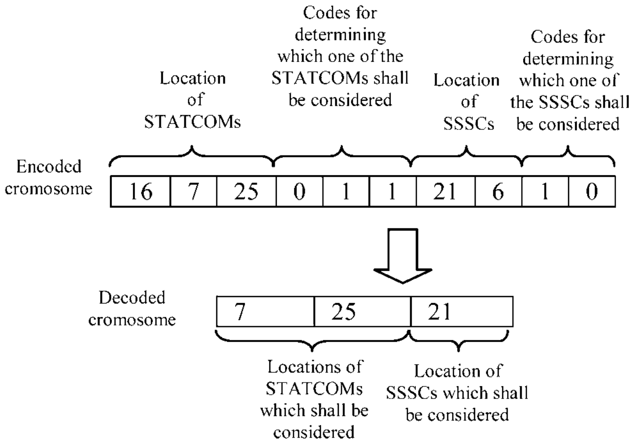

Figure 3 *Typical structure of chromosomes that is used for simultaneous optimal placement of FACTS devices*

Compared to the first proposed algorithm, the multi-type FACTS devices here are considered simultaneously. The output of this algorithm determines the optimal location, combination, number and operating point of FACTS devices as well as generators. The second proposed algorithm is described as follows:

1. Use the parameters and specifications of the power system under study as well as the maximum numbers of STATCOM ($N_{\mathrm{STATCOM}}^{\max}$) and SSSC ($N_{\mathrm{SSSC}}^{\max}$) obtained from the first algorithm.

2. Create an initial population wherein each encoded chromosome contains $2 \times N_{\mathrm{STATCOM}}^{\max} + 2 \times N_{\mathrm{SSSC}}^{\max}$ genes according to Fig. 3.

3. Decode a chromosome and determine the candidate placements (bus and line numbers) for STATCOM and SSSC installation. Note that each decoded chromosome proposes one combination among all possible combinations of numbers of STATCOMs and SSSCs that can vary up to $N_{\mathrm{STATCOM}}^{\max}$ STATCOMs and $N_{\mathrm{SSSC}}^{\max}$ SSSCs.

4. Solve the OPF problem defined by (2) for one chromosome.

5. Work out the value of objective function defined by (1) using the results of step 4.

6. Repeat steps 3–5 for all chromosomes of the population.

7. Select a set of better chromosomes as candidate parents according to their fitness values.

8. Apply genetic operators (crossover and mutation) to the candidate parents for creating a new population. Note that genetic operators are applied to the encoded chromosomes in order to create new combination of multi-type FACTS devices.

9. Repeat steps 3–8 while the stopping condition of the GA is unsatisfied.

10. Print the OPF results of the best chromosome and the optimal value of objective function as well as the optimal numbers of STATCOMs and SSSCs, their locations and operating points.

11. Stop.

3.3 Proposed criterion for evaluating the results of optimal placement

The optimal number of multi-type FACTS devices as well as their best locations were suggested, which are based on alleviating the congestion of transmission lines as the objective function. Also, application of multi-type FACTS devices is led to the reduction in the nodal prices as well as their differences. These two parameters are treated by the combinatorial optimisation problem when the mean of the nodal prices as well as their variance are minimised.

To find out about the suitability of the optimised solution, this paper proposes a desirability criterion. Assume all power flow limits are neglected in an OPF problem. It is further supposed that no FACTS devices are installed for the power system. Thus, it is expected that the transmission congestion is removed. The OPF can be solved under this circumstance, where the resultant values of the nodal prices and their differences as well as the value of the objective function are called as desirable values in this paper. Therefore the suitability of the final solutions resulting from various IEEE benchmarks can now be evaluated by comparing them with their corresponding desirable values.

4 Numerical results

The proposed method is simulated by a tool implemented in MATLAB environment, which uses some features of the methodological approach used in the power simulation package MATPOWER [25]. Modified IEEE 14-bus test system and modified IEEE 30-bus test system in which all loads are multiplied by 1.35 are used to evaluate the effectiveness of the proposed method. Additionally, the modified IEEE 118-bus test system is used in which all loads are multiplied by 0.7, removing all 100 MW generators. Two types of FACTS devices, STATCOM as a parallel device and SSSC as a series device, are selected to alleviate the transmission congestion of both test systems. Simulation results are provided below.

4.1 Modified IEEE 14-bus system

The IEEE-14 bus system is used to examine the proposed method as follows:

4.1.1 Desirable values: The OPF problem is solved by neglecting the power flow limits of transmission lines. The resultant nodal prices and their differences are presented in Table 2 as desirable values. Under this condition, the value of the desirable objective function is treated as a measure for evaluation of the effectiveness associated with the proposed method.

4.1.2 Base case: Assume the flow of transmission lines is limited to 50 MVA for the base case. Moreover, the shunt capacitors are removed to show clearly the effects of FACTS devices on alleviating the transmission congestion. The OPF results of the base case are shown in Table 2, which indicate significant increase of the nodal prices and their variance compared to the desirable case. This also shows occurrence of transmission congestion.

4.1.3 Setting an upper-limit on the maximum number of STATCOMs (individual placement): Optimisation problem is solved repeatedly for placing up to five STATCOMs individually in the IEEE-14 bus network. The obtained results including the operating points and locations of STATCOMs are listed in Table 3. The value of INC is increased up to five STATCOMs, decreasing afterward. Thus, the stopping condition using (3) is satisfied for five STATCOMs. Nevertheless, the optional index CIM, defined by (4), gives two STATCOMs for the maximum relative improvement in objective function. It should also be noted that locating STATCOMs at generator buses is not usual, since voltages of generator buses are regulated (normally considered as PV buses). Thus, the proposed algorithm prevents the installation of STATCOMs at generating buses.

4.1.4 Setting an upper-limit on the maximum number of SSSCs (individual placement): Similarly, the optimal placement of SSSC is performed individually for up to four devices. Table 3 shows the pertinent results. The value of INC is increased up to three SSSCs, decreasing afterward. Thus, the stopping condition using (3) is satisfied for three SSSCs. Nevertheless, the optional index CIM, defined by (4), gives three SSSCs for the

Table 2 OPF simulations of the modified IEEE 14-bus test system for the desirable and base cases

Description	Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z
desirable case	11 767.65	10.061	40.619	1.219	49.495
base case	12 656.43	3.729	42.146	4.678	197.148

Table 3 Simulations of optimal placement of STATCOM and SSSC (individually) for the modified IEEE 14-bus test system

Type of device	FACTS device parameter				Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z	$\|\Delta Z\|/Z$	$\Delta Z_i/\Delta Z_{i-1}$
	No.	Bus/line no.	Operating point, MVar	Operation mode							
STATCOM	1	5	30.02	capacitive	12 644.53	3.669	42.048	4.467	187.845	–	–
	2	5	28.76	capacitive	12 636.36	3.517	42.057	4.299	180.783	0.0391	–
		7	20.32								
	3	5	28.72	capacitive	12 635.67	3.500	42.076	4.162	175.123	0.0323	0.802
		7	20.18								
		12	4.40								
	4	5	28.51	capacitive	12 633.99	3.456	42.102	4.038	170.015	0.0300	0.903
		7	19.01								
		11	8.45								
		12	4.39								
	5	5	28.58	capacitive	12 631.21	3.385	42.134	3.925	165.390	0.0280	0.905
		7	18.71								
		11	7.81								
		12	2.25								
		13	11.93								
	6	7	21.30	capacitive	12 631.6	3.370	42.3564	3.8633	163.636	0.0107	0.379
		11	3.76								
		14	9.17								
		13	8.42								
		12	2.48								
		10	13.84								
SSSC	1	7	0.41	capacitive	12 616.45	3.584	41.840	4.362	182.505	–	–
	2	6	0.01	capacitive	12 615.05	3.666	41.805	4.176	174.582	0.0454	–
		7	0.44	capacitive							
	3	1	0.81	inductive	12 561.85	3.843	40.466	1.299	52.580	2.3203	15.399
		13	0.77	capacitive							
		18	0.25	capacitive							
	4	1	0.02	capacitive	14 145.84	3.673	43.567	1.183	51.545	0.021	0.009
		2	0.44	inductive							
		7	0.30	capacitive							
		13	1.01	capacitive							

maximum relative improvement in objective function. It is seen that SSSC can appropriately decrease the mean of nodal prices in the test system as well as their variance. Also, the SSSCs should only be located at transmission branches, thus locating them at the transformer branches is prevented by the algorithm. Moreover, the maximum line compensation by the SSSC is limited to 60%. As observed in Table 3, use of only one type of FACTS devices could

Table 4 Simulations of simultaneous optimal placement of SSSC and STATCOM for the modified IEEE 14-bus test system

SSSC specifications				STATCOM specifications			Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z
No.	Line no.	Operating point, MVar	Operation mode	No.	Bus no.	Operating point, MVar					
2	11	0.30	inductive	1	7	26.07	12 641.5	3.575	39.994	1.183	47.3
	18	0.24	capacitive								

not give a better result than the desirable case, presented in Table 2.

4.1.5 *Simultaneous multi-type FACTS devices: optimal numbers and placements:*

The maximum numbers of STATCOMs and SSSCs are set to be two and three, respectively. Therefore the space of all combinations of up to two STATCOMs and three SSSCs are searched by the second algorithm simultaneously for optimal placement of multi-type FACTS devices. In other words, the optimisation problem is solved for various combinations by GA and the best result is obtained. Thus, the numbers, the locations as well as the operating points are listed in Table 4 related to each type of FACTS devices.

Considering the summarised simulations in Table 4, the best solution is obtained by the use of one STATCOM connected across bus number 7 and two SSSCs located in line numbers 11 and 18. Comparing Tables 3 and 4 indicates that simultaneous optimal placement of multi-type FACTS devices provide better values for the objective function compared to the individual cases. This is due to provision of the complementary characteristics of parallel and series devices, which appears in simultaneous cases.

Moreover, the best value of objective function in simultaneous case in Table 4 is smaller than the desirable value given in Table 2. This shows clearly the effectiveness of the proposed method for finding the optimal placement of multi-type FACTS devices. It can now be emphasised that the proposed method, using multi-type FACTS devices with certain congestion limitations, is capable of introducing better results than those of the desirable case with no congestion limitations. In fact, even if no transmission congestion exists, it is suggested to use multi-type FACTS devices for more appropriate operating conditions.

4.2 Modified IEEE 30-bus test system

Assume that the power flow in transmission lines of the IEEE 30-bus test system is bounded to 40 MVA. Then, this modified network is studied like that of the IEEE 14-bus power system. Both the desirable and the base cases are shown in Table 5. First, the optimisation problem is run to find the best number of STATCOMs in an individual case study. The value of INC is increased up to six STATCOMs, decreasing afterwards. Thus, the stopping condition using (3) is satisfied for six STATCOMs. Nevertheless, the optional index CIM gives two STATCOMs for the maximum relative improvement in objective function. Further, the stopping condition using (3) is satisfied for four SSSCs according to Table 6. Nevertheless, the optional index CIM gives four SSSCs for the maximum relative improvement in objective function.

Then, all possible combinations of multi-type usage of the SSSC (up to five) and the STATCOM (up to two) are considered and the proposed algorithm is applied to each combination. The best solution for the optimal number and placement of multi-type FACTS controllers (STATCOM and SSSC) are listed in Table 7. The optimal solution suggests applying one STATCOM located across bus number 4 and two SSSCs located in transmission lines 1 and 37.

Comparing the results listed in Tables 5–7 shows that, when multi-type FACTS devices are used simultaneously, using less number of devices gains better value of the objective function. Moreover, the best value of objective function in simultaneous multi-type case (41.8) is less than desirability criterion (56.581), which verifies the efficiency of the proposed method. It should be noted, however, that the optimal number of SSSCs and STATCOMs given in Tables 4 and 7 differ from those of individually optimised cases. This implies

Table 5 OPF simulations of the modified IEEE 30-bus test system for the desirable and base cases

Description	Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z
desirable case	12 966.30	13.283	41.094	1.377	56.581
base case	14 444.88	5.925	82.262	32.030	2634.822

Table 6 Simulations of optimal placement of STATCOM and SSSC (individually) for the modified IEEE 30-bus test system

Type of Device	FACTS device parameter				Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z	$\|\Delta Z\|/Z$	$\Delta Z_i/\Delta Z_{i-1}$
	No.	Bus no.	Operating point, MVar	Operation mode							
STATCOM	1	15	28.75	capacitive	14 278.6	5.470	49.326	6.511	321.165	–	–
	2	12	32.54	capacitive	14 253.2	5.603	46.812	5.270	246.680	0.3019	–
		27	26.13								
	3	12	15.08	capacitive	14 234.2	5.231	46.812	5.097	237.953	0.0367	0.117
		15	27.15								
		27	21.80								
	4	12	12.03	capacitive	14 232.0	5.206	46.673	5.004	233.539	0.0189	0.506
		14	6.34								
		15	24.87								
		27	21.20								
	5	12	10.16	capacitive	14 225.5	5.064	46.669	4.912	229.258	0.0187	0.970
		14	6.32								
		15	22.92								
		25	12.01								
		27	13.72								
	6	27	11.51	capacitive	14 218.6	4.928	46.629	4.822	224.820	0.0197	1.037
		12	7.41								
		15	21.88								
		14	6.07								
		7	26.12								
		25	11.53								
	7	25	11.24	capacitive	14 216.9	4.896	46.630	4.744	221.204	0.0163	0.815
		7	25.97								
		14	6.11								
		12	6.80								
		15	21.90								
		27	7.98								
		29	4.48								
SSSC	1	19	0.25	capacitive	14 284.9	5.457	50.357	7.003	352.640	–	–
	2	19	0.24	capacitive	14 228.9	5.093	46.180	4.939	228.077	0.546	–
		40	0.76	capacitive							
	3	4	0.17	capacitive	14 158.2	5.000	43.738	3.893	170.223	0.34	0.465
		18	0.85	capacitive							
		40	0.75	capacitive							

Continued

Table 6 *Continued*

Type of Device	FACTS device parameter				Fuel cost, $/h	Active power losses, MW	MANP, $/MWh	VANP	Z	$\lvert\Delta Z\rvert/Z$	$\Delta Z_i/\Delta Z_{i-1}$
	No.	Bus no.	Operating point, MVar	Operation mode							
	4	7	0.02	capacitive	14 451.6	5.218	42.568	1.864	79.325	1.146	1.571
		29	0.03	capacitive							
		32	0.06	capacitive							
		40	0.60	capacitive							
	5	1	0.47	inductive	14 153.2	5.255	38.092	1.531	58.3226	0.360	0.231
		9	0.56	capacitive							
		19	0.23	capacitive							
		39	0.15	capacitive							
		40	0.65	capacitive							
	6	1	0.50	inductive	14 102.8	5.422	40.337	1.491	60.148	0.03	−0.087
		4	0.26	capacitive							
		9	0.54	capacitive							
		17	0.49	capacitive							
		19	0.25	capacitive							
		27	0.35	capacitive							

that setting the number of devices based on consecutive single-type optimisation could be unhelpful.

4.3 Modified IEEE 118-bus test system

The five steps described in Section 4.1 are repeated for the modified IEEE 118-bus test system in which the limit of flow in transmission lines is assumed to be 400 MVA for lines 1–37 and 185 MVA for other lines (this simply shows an example that can be changed accordingly). The value of INC is increased up to four STATCOM and then starts decreasing afterward. Thus, the stopping point (see (3)) of increasing the number of STATCOMs is four based on the considered limits. Using the second algorithm, all combinations of up to four STATCOMs and four SSSCs are searched and assessed for the best combination, namely

Table 7 Simulations of simultaneous optimal placement of SSSC and STATCOM for the modified IEEE 30-bus test system

SSSC specifications				STATCOM specifications			Fuel cost, $/h	Active power losses, MW	MANP, $/MWh	VANP	Z
No.	Line no.	Operating point, MVar	Operation mode	No.	Bus no.	Operating point, MVar					
2	1	0.48	capacitive	1	4	39.96	15 015.1	6.655	44.538	0.939	41.8
	37	0.55	capacitive								

Table 8 Modified IEEE 118-bus test system; the OPF results for the desirable and base cases

Description	Fuel cost, $/h	Active power losses, MW	MANP, $/MWh	VANP	Z
desirable case	83 027.60	66.430	36.2624	1.1876	43.0658
base case	83 311.63	71.684	38.7176	6.5662	254.2280

Table 9 Modified IEEE 118-bus test system; Individual optimal placement of STATCOM and SSSC

Type of device	FACTS device parameter				Fuel cost, \$/h	Active power losses, MW	MANP, \$/MWh	VANP	Z	$\|\Delta Z\|/Z$	$\Delta Z_i/\Delta Z_{i-1}$
	No.	Bus no.	Operating point, MVar	Operation mode							
STATCOM	1	35	27.92	capacitive	83 189.6	69.827	37.7885	4.2238	159.611	–	–
	2	35	21.95	capacitive	83 167.1	69.353	37.5830	3.7269	140.069	0.1395	–
		18	43.28	capacitive							
	3	18	34.73	capacitive	83 124.2	68.385	37.3778	3.2068	119.861	0.1686	1.034
		35	12.10	capacitive							
		41	25.17	capacitive							
	4	35	9.07	capacitive	83 117.2	68.348	37.1477	2.6355	97.904	0.2243	1.087
		18	27.82	capacitive							
		41	23.80	capacitive							
		15	29.55	capacitive							
	5	35	7.65	capacitive	83 112.0	68.272	37.0526	2.3786	88.135	0.1218	0.484
		18	25.12	capacitive							
		41	23.25	capacitive							
		15	27.41	capacitive							
		44	13.98	capacitive							
SSSC	1	96	8.72	inductive	83 133.7	69.314	36.6181	1.6984	62.193	–	–
	2	96	8.72	inductive	83 122.0	68.977	36.6232	1.6628	60.898	0.0213	–
		170	0.65	capacitive							
	3	25	0.14	capacitive	83 126.5	69.121	36.5661	1.6021	58.583	0.0395	1.854
		158	0.11	capacitive							
		96	8.74	inductive							
	4	54	1.08	inductive	83 057.5	67.231	36.3423	1.2804	46.533	0.2590	5.206
		131	0.91	capacitive							
		12	0.35	capacitive							
		49	0.10	capacitive							
	5	49	0.10	capacitive	83 131.4	69.265	36.3573	1.2688	46.131	0.0087	0.0334
		61	0.46	capacitive							
		23	1.43	capacitive							
		96	8.24	inductive							
		139	5.96	capacitive							

three STATCOMs and three SSSCs. The optimal placements for STATCOMs are obtained at bus numbers 6, 42 and 104; and three SSSCs are placed in lines 45, 54 and 177. The results are presented in Tables 8–10. Comparing results given in Tables 8–10 shows better values for the objective function under simultaneous optimal placement of multi-type FACTS devices. The best value of objective function in simultaneous case (42.954) is less than that of the desirability criterion (43.066), verifying the efficiency of the proposed algorithm.

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Table 10 Modified IEEE 118-bus test system; simultaneous optimal placement of SSSC and STATCOM

SSSC specifications				STATCOM specifications			Fuel cost, $/h	Active power losses, MW	MANP, $/MWh	VANP	Z
No.	Line no.	Operating point, MVar	Operation mode	NO.	Bus no.	Operating point, MVar					
3	54	0.87	inductive	3	6	20.03	83 021	66.105	36.2969	1.1834	42.954
	177	0.91	capacitive		104	31.88					
	45	0.02	capacitive		42	23.32					

5 Conclusion

A method is proposed for employing multi-type FACTS devices in a restructured environment. In brief, the proposal focuses on achieving the optimal number of multi-type FACTS devices and their best locations. The objective function of the optimal placement problem is organised to reduce both the nodal prices and their differences efficiently. The method uses an AN lossy model for STATCOM and SSSC in order to provide the required power injection model of FACTS devices in steady-state operation by taking the converter power losses into account. Furthermore, two genetic-based algorithms are proposed to tackle the complexities and difficulties to determine the optimal numbers of multi-type FACTS devices. Application of these two algorithms leads to a significant reduction in the problem search space. To validate the proposals, a desirability criterion is suggested to evaluate the efficiency of the proposed method. The suitability of the method is shown by applying the multi-type FACTS devices proposal to the modified IEEE 14-bus, IEEE 30-bus and IEEE 118-bus benchmarks. The results show better operating conditions for power system when multi-type FACTS devices are applied simultaneously compared to those of the individual cases. Moreover, the number of each type of FACTS devices in the best combination of multi-type FACTS devices differs from the number of that type in the best individual combination. This implies that holding one type of FACTS devices in its optimal number and then adding other types of FACTS devices one by one may distance from the best combination.

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