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Looking for optimal number and placement of FACTS devices to manage the transmission congestion

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ABSTRACT

Some applications of FACTS devices show that they are proper and effective tools to control the technical parameters of power systems. However determination of optimal number, location, size and type of these devices is a difficult problem. Moreover, applying a suitable objective function for optimal placement of FACTS devices plays a very important role in economic improvement of a power market. In this paper optimal placement of parallel and series FACTS devices is studied. The STATCOM is selected as a parallel FACTS device and SSSC as a series one. The optimization problem is formulated in regard to restructured environment and a new objective function is defined so that its minimization can alleviate the congestion and provide fairer conditions for power market participants. Moreover, an index based on objective function value is presented to determine the optimal number of each FACTS device in a specific designed algorithm. The power injection models for STATCOM and SSSC are adopted by applying neural models based on the averaging technique. This model takes the converter power losses into account and produces the required PQ-phasor that is suitable for power system steady state analysis. The proposed method is applied on modified IEEE 14-bus, 30-bus and 118-bus test systems and the results are analyzed.

1. Introduction

Recently, the electric power industry is changing to be more competitive. In this new environment, optimal operation of the power system is more important. Power market participants try to transfer optimally large amounts of electric power through the transmission lines in order to gain more revenues. Thus, power systems are often operated very close to their boundary conditions and transmission lines are congested. In this situation, the expansion of transmission system is more significant due to the impact of power transfer capacity of transmission lines on power market transactions. However, today the expansion of transmission systems is restricted. Achieving acceptance to place and construct new transmission capacity is becoming more difficult due to environmental considerations, potential health effects of electric and magnetic fields and the budgetary problems. On the other hand, the use of Flexible Alternating-Current Transmission Systems (FACTS) may be a cost effective option for enhancement of power delivery of the system. FACTS devices are able to change the routes of exchanged powers through the transmission lines by changing amplitude and angle of bus voltages as well as reactance of transmission lines. Therefore, the congestion can be removed or alleviated effectively by forcing power flows to be transferred in routes which do not cause congestion problem. But selecting the optimal type, number, placement and size of these devices is a difficult problem.

According to the relevant literature about FACTS devices considering power market, reveals that researchers, in recent years, have examined the impacts of FACTS devices on improving the operation of power system, while providing the algorithms for finding the best number of each type of device has not received much attention yet. In other words, they only present different algorithms for optimal placement of a specific number of FACTS devices. Some of the reported researches about FACTS devices are reported here.

In [1], a method is presented to decide the optimal placements of Thyristor Controlled Phase Shifter (TCPS), in order to minimize active power losses of transmission lines and to augment the stability of power system. In this work, the minimization of power losses is based on the phase shifter distribution factor; moreover the selection of the placement of phase shifters is performed on the basis of the influence of each device on the active power losses of transmission lines.

In [2], Thyristor Controlled Series Capacitor (TCSC) which is modeled as variable reactance in the capacitive mode is used to maximize the Available Transfer Capacity (ATC). The number of TCSCs is limited to two devices and the amount of compensation is limited to 60%. The Genetic Algorithm (GA) is used to determine the optimal placement and compensation.

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In [3], a GA is used to determine the optimal placement of Unified Power Flow Controller (UPFC) in order to maximize the loadability of the system. Placement of UPFC is determined for different situation of active and reactive loads on the grid. The number of UPFCs is increased as long as the loadability of the system is increased considerably. Considerable increment of the objective function is not quantified by authors. Thus, it is not clear how many UPFCs are required to be applied.

In [4], a GA is used to determine the best placement of a given set of phase shifters based on the cost of production and on the return of investment of the devices. The problem of the selection of the best number of phase shifters is not taken into consideration; however the results of optimal placement of one, two and three phase shifters are compared.

The authors of [5] use a GA to seek the optimal placement of multi-type FACTS devices in a power system consist of TCSC, Static Var Compensator (SVC), TCPS and Thyristor Controlled Voltage Regulator (TCVR). The number of each FACTS device was assigned before the optimization process is solved. Optimization is performed to determine three parameters, i.e. the placement of the devices, their types and their sizes. The system loadability is employed as an index for power system performance.

In [6], TCPS and TCSC are simultaneously and individually used to maximize the Total Transfer Capacity (TTC). The optimal solution is determined using Mixed Integer Linear Programming (MILP). Only in the individual case, the number of FACTS devices increases as far as the loadability of the system is improved considerably. In this work, considerable improvement of objective function is not quantified; therefore the stop point for increasing the number of FACTS devices is not clear. In simultaneous case, the number of each device is assumed to be known.

The authors of [7] locate individually one Static Synchronous Compensator (STATCOM) and one UPFC considering the change of voltage profile of buses due to increment of the system load. The suitable bus for installing FACTS devices is the bus in which the voltage drop is more than the other buses.

In [8], one UPFC and one Interline Power Flow Controller (IPFC) are used to maximize the power transfer capacity. Linear Programming (LP) is used to determine their optimal placement and size of FACTS devices.

The authors of [9] locate individually one TCSC, four TCPS and one UPFC to alleviate the congestion. Simultaneous use of two TCPAR and two UPFC is also studied. The objective function is the sum of total generation cost and the usage cost of FACTS devices. The objective function is minimized via LP method.

The authors of [10] locate individually TCSC, TCPS and SVC to manage the congestion. The objective function is the maximization of social welfare. The optimization problem is solved by Mixed Integer Nonlinear Programming (MINP). The number of each FACTS device is increased until the objective function is improved considerably. However, the improvement of objective is not quantified.

In [11], the impacts of some combination of FACTS devices, i.e. SVC, SVC along with TCPS and SVC along with UPFC, on maximization of ATC are studied. It is assumed that the placements of FACTS devices are known.

In [12], SVC and UPFC are individually used to compensate the reactive power and to minimize the total generation cost, respectively. The placement of SVC for reactive compensation is determined considering the reduction of reactive marginal cost. The placement of UPFC was known before the optimization process is solved. The impact of UPFC on total generation cost is studied in several scenarios.

In [13], the combination of FACTS devices and the transmission rights are considered for congestion management. Two market models, i.e. bilateral contracts and multilateral contracts, are investigated. Two types of FACTS devices, i.e. one TCSC and one SVC, are applied and they are modeled as variable reactance. Two cases are investigated for TCSC. In the first case, TCSC is introduced in inductive mode for the congested lines. In the second case, TCSC in capacitive mode is introduced in the lightly loaded lines. In both cases, the optimal location of TCSC is determined by a trial and error method. SVC is introduced in different buses and its optimal location is determined by observing the rate of improvement of the objective function. The objective function is the minimization of deviations from transaction requests made by market participants.

Briefly, in previous researches several objectives such as minimizing of transmission losses, maximizing the ATC or TTC, maximizing social welfare, minimizing total generation cost and so on are considered for optimal placement of FACTS devices without present an algorithm for determining optimal number of an applied FACTS device.

This paper presents a new objective function for optimal placement of FACTS devices. In addition, an algorithm is proposed for determining the optimal number of an employed FACTS device. Two types of FACTS devices are selected, STATCOM as a parallel device and SSSC as a series device, and the optimal number of each device is determined using the presented algorithm. Due to the impact of congestion on power market transactions as well as power market efficiency, the optimization problem is formulated to alleviate the transmission congestion in a restructured environment. When transmission lines are congested, the difference of nodal prices is increased. If a congested power system is managed so that the difference of nodal prices is decreased, the congestion of transmission lines is decreased too. Moreover, it is desired to decrease the mean of nodal prices along with their differences. Therefore, the objective function is selected as the product of mean of nodal prices and their variance so that its minimization can alleviate the congestion and provide fairer condition for power market participants. It should be noted that the proposed algorithm can be used for other types of objective functions such as minimizing transmission losses, minimizing total generation cost and maximizing social welfare.

Another main subject is that, in the previous works lossless models for FACTS devices are used. In fact, power losses of FACTS devices are not included in the analysis by these models, assuming negligible energy consumption by the device itself. When the number and capacity of the employed FACTS devices increases, considerable energy losses is cancelled in power flow analysis (i.e. part of the network load is cancelled). This undermines the correctness of the process of energy pricing system by using inaccurate models for FACTS devices. In other words, the more accurate are the developed models, the fairer pricing condition is established. In fact, if equipments are modeled close to their exact operation, the energy pricing will be more precise. In particular, this would be more crucial when FACTS devices are engaged in Optimal Power Flows (OPFs) for mitigation of congestion of transmission systems. Thus, in this paper power injection models for STATCOM and SSSC is adopted by applying a neural model based on the averaging technique. This model can take the DC-link of the converter and the power losses into account and produce the required PQ-phasor that is suitable for power system steady state analysis. The case studies on modified IEEE 14-bus, 30-bus and 118-bus test systems show that the proposed method is helpful to extract the optimal number of FACTS devices as well as to create fairer condition for power market participants.

2. FACTS devices modeling

In order to demonstrate the proposed method for determining optimal number of a FACTS device in an optimization problem incorporating FACTS devices a series device, SSSC, and a parallel device, STATCOM, are selected as candidates. Power injection model is a suitable model for these devices in steady state calculations [14]. This paper uses the power injection models based on averaging technique for FACTS devices. Averaging technique presents an instantaneous time-domain model [15] and it takes all the aspects into account appropriately, including DC-link of the converter as well as the power losses. This technique is used in [16] 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. And this is quite a sophisticated process for an OPF problem (such as Security Constrained Dispatch (SCD)). To avoid this problem and link the instantaneous results to single-frequency power system analysis, it is tried to take advantage of neural networks. 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 that is suitable for power system steady state analysis. The detail of this model is described below briefly.

Average model of STATCOM is presented in [15], shown here by Fig. 1a. 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. 1b shows typical STATCOM power losses in PU against the phase shift between the converter output and the power system voltage (α) that is obtained by the average model. While the average model presents a time-dependent circuit, a PQ or PV model is essential for the power flow analysis. Hence, here adaptive analysis is performed to get 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. 1c.

Average model of Fig. 1a describes a state space model in a circuit format, and solving it leads eventually 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 amongst 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 average-neural (*AN*) model. The next step would be the selection of a suitable neural network, to identify the average model of Fig. 1a. In [17,18] several types of neural networks are applied to identify the average model of STATCOM. The Multi-layer Perceptron (MLP) identifies the average model with an acceptable error, much lower than the other considered neural network identifiers (the designed MLP identifier has eight neurons in the first two layers and one neuron for the third layer).

Similar model for SSSC can be achieved by implementing of the same procedure. Average model of SSSC is shown in Fig. 2a. Here again, L introduces the equivalent coupling inductance between the converter and the power system. The resistance R is part of the compensator losses concern with the interconnection of the converter to the power system. Similarly, a new bus is added for every SSSC as the converter AC voltage, which is located in an existing transmission line 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, a suitable *AN* model of SSSC can be obtained by testing several types of neural network identifiers. Whichever identifies the average model of SSSC with an acceptable error is selected as *AN* model of SSSC. Here, the *AN* model of SSSC is based on a MLP network which includes 12 neurons in the first two layers and one neuron for the third layer [19].

Therefore, in an OPF problem and for every operating point, the loss of STATCOM/SSSC can be extracted from the *AN* model and then incorporated in calculations.

3. Objective function

In the restructured environment, the price of electricity is not the same in all buses of the power system, due to presence of congestion and power losses in transmission lines. Generally, limits

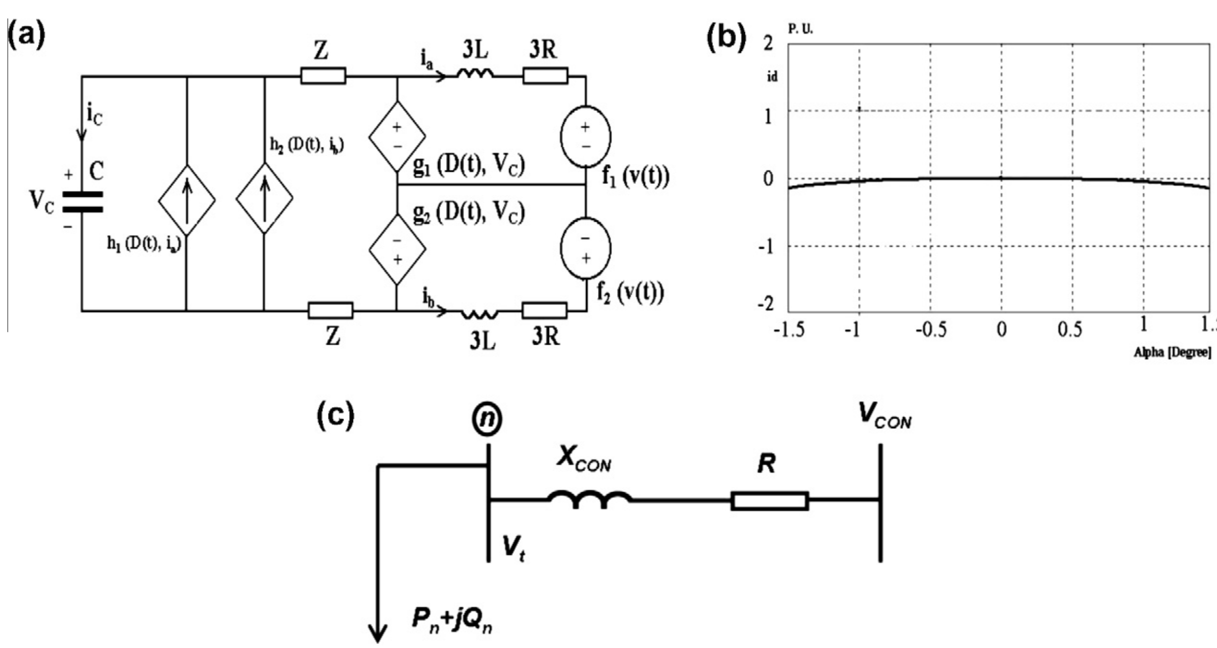

Fig. 1. (a) Average circuit model of STATCOM, (b) typical internal power losses of STATCOM obtained by the average model, (c) adaptation of the average model connected to the power system by adding a bus for STATCOM.

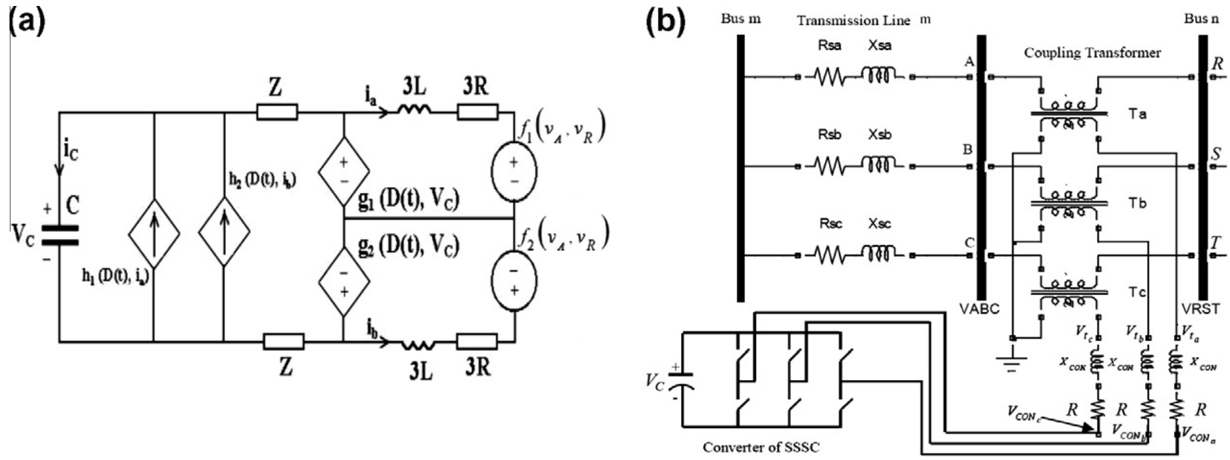

Fig. 2. (a) Average circuit model of SSSC and (b) three-phase circuit of SSSC.

caused by transmission congestion lead to undesirable effects on power market transactions as well as power market efficiency. However, by using FACTS devices, it is possible to alleviate the transmission congestion. The power transfer between two buses is given by $P = (V_1V_2/X)\sin(\delta)$, where V_1 and V_2 are voltage amplitudes at the two buses, X is the reactance of transmission line between the two buses and δ is the difference in the voltage angles at the two ends. Thus, power flow can be controlled by three parameters i.e. voltages at the two buses, reactance of transmission line and the difference in the voltage angles at the two ends. FACTS devices are able to change the routes of exchanged powers through the transmission lines by controlling one or more of the above mentioned parameters. Therefore, the congestion can be removed or alleviated effectively by guiding power flows on routes which do not cause congestion problem. However, selecting the optimal type, number, placement and size of these devices is a difficult problem.

Several objective functions have been proposed in relevant literature to locate optimally FACTS devices for congestion management of transmission lines. Some of these objective functions are reviewed in Section 1. Minimizing the power losses of transmission system, minimizing the system total generation cost and maximizing the social welfare which are considered as objective function of optimal placement of FACTS devices in some articles [1,4,9,10,12] can not show directly the situation of transmission congestion.

It should be noted that the situation of transmission congestion can be indicated by its undesirable effects on system nodal prices. When transmission lines are congested, the difference of nodal prices is increased. If a congested power system is changed so that the difference of nodal prices is decreased, the congestion of transmission lines is decreased too. In addition, decreasing the nodal prices is desired for power market consumers. Therefore, this paper offers a new objective function for optimal placement of FACTS devices to decrease the nodal prices and their differences and consequently provide a fair condition for all power market participants. The proposed objective function (*OF*) for optimal placement of FACTS devices is defined as below:

$$OF = MANP \times VANP \tag{1}$$

where

$$MANP = \frac{1}{n}\sum_{j=1}^{n} NP_j \tag{2}$$

$$VANP = \sum_{j=1}^{n}\frac{1}{n}(NP_j - MANP)^2 \tag{3}$$

where NP_j denotes the nodal price of active power at bus j, *MANP* and *VANP* are the mean and variance of power system nodal prices, respectively and n is the number of nodes.

Minimization of (1) leads to reduction of both nodal prices and their differences. Therefore, FACTS devices should be located optimally via solving an optimization problem considering generators and system constraints. This optimization problem consists of integer and real variables which should be tuned to optimize the objective function expressed by (1). In fact, this problem is a Mixed Integer Nonlinear Programming (MINP) which is needed to be solved by an effective method. Mathematical methods are not suitable for solving this type of problems, because they are model based and need to the accurate model of system for derivation. Further, their search is started from one point and the probability of capturing in local optimum is high for these types of methods. Whereas, GA is a population based, data based and free derivative method and takes advantages of genetic operators so that the chance of capturing in local optimum is less in comparison with mathematical methods. Thus, GA is used for proposing the location of FACTS devices by integer variables. Also, the real variables which are used for tuning bus voltage amplitudes and angels, active and reactive output powers of generators, injecting reactive power of FACTS devices are set optimally by Successive Quadratic Programming (SQP) technique (i.e. a SCD is solved internally). Thus, in proposed method the locations of FACTS devices are suggested by chromosomes of the GA, and then operating points of FACTS devices (placed in suggested locations) as well as system generators are set optimally using the SQP technique.

By locating FACTS devices in placements offered by the GA chromosomes, the nodal prices can be calculated by solving an SCD problem in which an objective function is minimized, subject to a number of equalities and inequalities constraints. In fact, there is another objective function which is needed for solving the SCD problem. It is noticeable that (1) is the main objective function for optimal placement of the FACTS devices. Meanwhile, the other objective function which is expressed below is used in SCD problem for tuning optimally the operating point of the power system. The objective function of SCD for calculating of nodal prices is the minimization of system total generation cost.

For an n-bus system, let $P = (p_1, \ldots, p_n)$ and $Q = (q_1, \ldots, q_n)$ as nodal active and reactive power demands. Also, suppose that the variables in power system operation to be $X = (x_1, \ldots, x_m)$. Thus, the optimal operation problem of a power system for a given load (P, Q) can be formulated as an SCD problem.

$$\text{Min} \quad f(X, P, Q) \quad \text{for } X \tag{4}$$

$$\text{s.t.} \quad G(X,P,Q) = 0 \tag{5}$$

$$H(X,P,Q) \leqslant 0 \tag{6}$$

where $f(X,P,Q)$ is the total generation cost of the power system, $G(X) = (g_1(X,P,Q),\ldots,g_{n_1}(X,P,Q))^T$ and $H(X) = (h_1(X,P,Q),\ldots,h_{n_1}(X,P,Q))^T$ have n_1 and n_2 equations, respectively and are column vectors while A^T stands for the transpose of the vector A. The $H(X, P, Q)$ includes all variables limits and function limits, such as upper and lower boundaries of transmission lines, generators outputs, stability or security limits, etc. The total generation cost of system can be expressed as:

$$f(X,P,Q) = \sum_{i=1}^{n_g} f_i(X,P,Q), \quad f_i(X,P,Q) = f_i(P_{g_i}) = A_i \cdot P_{g_i}^2 + B_i \cdot P_{g_i} + C_i \quad \$/\text{MW h}$$

where f_i is the fuel cost of the ith generator and n_g is the number of generators. In the following proposed algorithm for solving the above mentioned MINP is explained.

4. Proposed algorithm for finding the optimal number of a FACTS device

This paper proposes an algorithm for determining the optimal number of an employed FACTS device. Two types of FACTS devices are selected, STATCOM as a parallel device and SSSC as a series device, and the optimal number of each device is determined using the presented algorithm.

Optimal placements of FACTS devices are determined in the optimization problem explained in previous section. This MINP problem is solved using GA and SQP technique. In GA the placements of FACTS devices are expressed by chromosomes consisting of integer numbers. The length of each chromosome is equal to the number of FACTS devices which is determined before running the algorithm. The algorithm shown by Fig. 3 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.

According to Fig. 3, for each placement of the FACTS devices which is suggested by GA chromosomes, the SCD described by (4)–(6) is solved using SQP technique to minimize the system total generation cost (see (4)). Then the chromosomes are evaluated based on their value of objective function expressed by (1). At the next step, 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 i.e. crossover and mutation, are applied to create the new population. All above mentioned steps are repeated for new population of chromosomes until the stop criterion (no improvement in the objective function for 50 consecutive generations) is reached. Then, for the best obtained solution (i.e. the best placements and operating points of FACTS devices) the following index is calculated using the related optimal value of the objective function calculated by (1):

$$INC = \frac{\Delta OF_i}{\Delta OF_{i-1}} \tag{7}$$

$$\Delta OF_i = OF_i - OF_{i-1} \tag{8}$$

The INC is an index for finding the optimal number of a FACTS device. Subscript i denotes the number of FACTS device and OF_i is the *optimal value of objective function* when i numbers of a FACTS device are applied. The greatness of ΔOF_i shows the rate (degree) of objective function variation due to increasing the number of FACTS device from $i-1$ to i numbers. As long as the value of INC is increased the number of FACTS device should be increased. Decrement of INC due to increasing the number of FACTS device shows that the rate of objective function improvement is decreased. At this point, the effectiveness of the FACTS device for improving objective function is decreased. Therefore, the last number of FACTS device which increases the value of INC, is the best number of the FACTS device.

Consequently, the proposed algorithm continues until the value of INC is increased when the number of FACTS device is increased. It should be noted that the proposed index is designed to be applicable easily for other types of objective functions such as minimization of system losses, minimization of system total generation cost and maximization of social welfare.

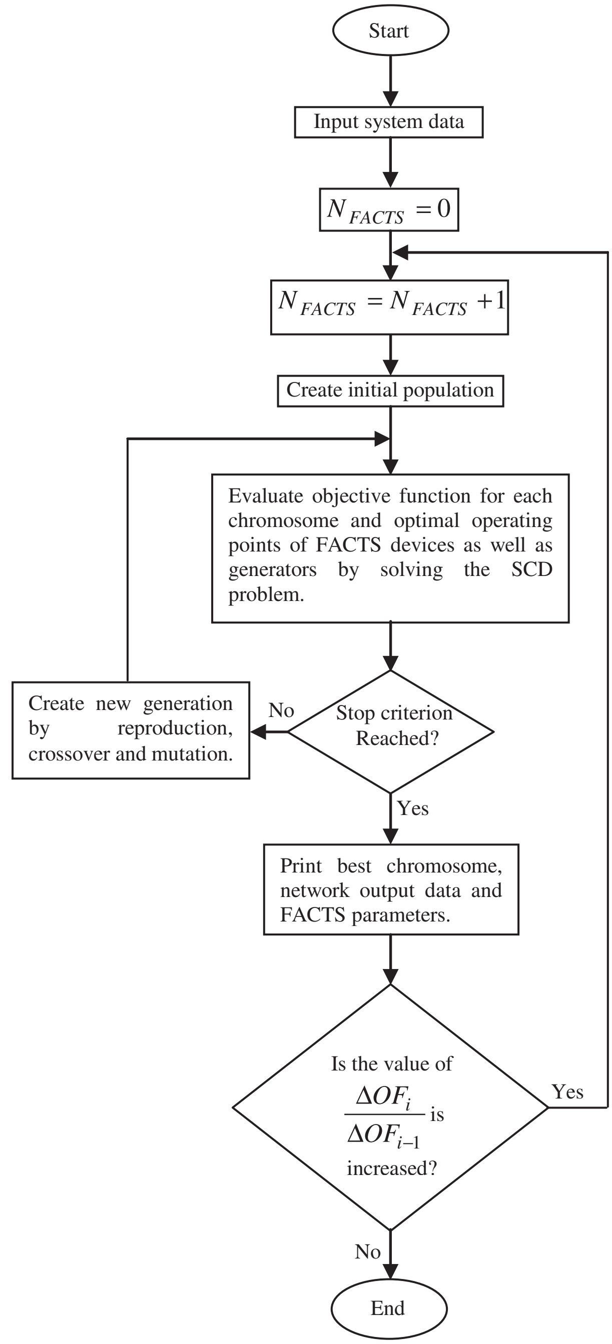

Fig. 3. Flowchart of the proposed optimization problem.

5. Numerical results

The proposed algorithm is simulated in MATLAB environment, in which some features of the methodological approach used in the power simulation package MATPOWER [20] are used. The results of applying the proposed algorithm on modified IEEE test systems are reported in following. The test systems are modified to have congestion in their transmission lines and the FACTS devices are used to alleviate the congestion.

5.1. Base case

The IEEE 14-bus and 30-bus test systems, which their data are presented in [20], are modified by removing the shunt capacitors and multiplying all loads by 1.35 in order to clearly show the effects of FACTS devices on improving the operation of power system. Moreover, the flows of transmission lines are limited to 50 MVA and 40 MVA in IEEE 14-bus and IEEE 30-bus modified systems, respectively. In addition, IEEE 118-bus test system, which its data is presented in [20], is modified multiplying all loads by 0.7 and also removing all generators with maximum output equal to 100 MW to establish the congestion condition in this system. Table 1 shows the results of SCD for modified systems without FACTS devices. The differences of nodal prices are shown by *VANP* in Table 1. These differences are caused by congestion and losses of transmission lines. In the following STATCOM and SSSC are located optimally to alleviate the transmission congestion by decreasing the difference of nodal prices. The results of applying FACTS devices with *AN* models explained in Section 2 on test systems are reported below.

5.2. Determining optimal number of STATCOMs

It is to be noted that locating STATCOMs at generator buses is not reasonable since they are considered as PV buses and they have regulators to actually control the bus voltages. Therefore, the proposed algorithm prevents the installation of STATCOMs at generator buses.

5.2.1. The modified IEEE 14-bus test system

Optimization problem described in Eqs. (1)–(6) is solved according to the algorithm of Fig. 3 to obtain the optimum value of system objective function for one to six STATCOMs and the results are presented in Table 2. As it can be seen when one STATCOM is located optimally, the best location for installation of STATCOM is bus 5 and the optimal operating point of this STATCOM is 30.02 MVar. By comparing the objective function value for one STATCOM ($OF = 187.845$) and its value in Table 1 (no FACTS device is installed, $OF = 197.148$), it is clear that the congestion is reduced a little. In addition, when number of STATCOMs is increased the value of objective function is decreased and consequently the congestion is alleviated further, so that the value of objective function decreases to 163.636 when six STATCOMs is placed optimally in buses 7, 10, 11, 12, 13 and 14. But, the improvement rate of objective function is decreased when number of STATCOMs is increased to 6.

Table 1
Modified IEEE 14-bus, 30-bus and 118-bus test SYSTEMS (SCD results).

Test system	*MANP* ($/MW h)	*VANP*	*OF*
IEEE 14-bus	42.146	4.678	197.148
IEEE 30-bus	82.26	32.03	2634.8
IEEE 118-bus	38.718	6.566	254.228

The best number of STATCOMs that can relatively alleviate the congestion of this system is calculated by applying Eqs. (7) and (8) to show the application of the proposed method. For this purpose, the value of *INC* is calculated, see Table 2, and it is observed that for up to five STATCOMs, the value of *INC* is increased and after that it is decreased. Thus, the optimal number of STATCOMs is 5. In fact, this is the decline point in improving rate of objective function when number of STATCOMs is increased. Therefore, the optimal solution is locating of five STATCOMs at buses 5, 7, 11, 12 and 13 with operating points 28.85, 18.71, 7.81, 2.25 and 11.93 MVar, respectively. It should be noted that the optimal size of STATCOMs can be selected according to the standard sizes which can cover these optimal operating points.

According to the results of Table 2, applying STATCOM is not an effective solution to alleviate the congestion of this system. This is because in this small system, five generators exist and bus voltages are in suitable range. Thus, STATCOMs cannot be helpful too much.

5.2.2. The modified IEEE 30-bus test system

Similar to case A, the optimization of system objective function is performed by optimal placement of up to eight STATCOMs in modified IEEE 30-bus system and the results are shown in Table 2. According to Table 1 due to congestion of transmission line the differences of nodal prices as well as the mean of nodal prices are very high. But, when one STATCOM is placed optimally at bus 15 with 28.75 MVar operating point, the value of objective function is decreased considerably in comparison with its value in the base case (in which no FACTS device is installed, Table 1). Reduction of transmission congestion is continued when number of STATCOMs is increased. The value of objective function by optimal installing of one STATCOM is reduced to 321.165 and it decreases further to 219.086 by optimal installing of eight STATCOMs. Thus, it is seen that the congestion of 30-bus system is alleviated relatively better than 14-bus system. In this modified system, six generators exist and most of the buses have good voltages conditions, however, some bus voltages are close to their boundary range. Therefore, the STATCOMs can relatively be helpful to improve the bus voltages of system and consequently improve the system condition for congestion management. However, the improvement rate of objective function value decreases by increasing the number of STATCOMs. According to Table 2, the value of *INC* is increased up to six STATCOMs and after that it is decreased. Thus, the optimal number of STATCOMs is 6 which should be located at buses 7, 12, 14, 15, 25 and 27. Their optimal sizes can be selected considering their optimal operating points (reported in Table 2) and the standard size of STATCOMs.

5.3. Determining optimal number of SSSCs

It is to be notice that the SSSCs shall only be located at transmission branches, thus locating of SSSCs at transformer branches is prevented by the algorithm. Moreover the maximum line compensation by SSSC is limited to 60%.

5.3.1. The modified IEEE 14-bus test system

Previous steps are repeated for a series FACTS device, SSSC, to study the impacts of this device on congestion management.

The proposed algorithm is applied for optimal locating of up to 4 SSSCs and results are shown in Table 3. By comparing results of Tables 1 and 3 it is seen that in both cases of optimal locating one and two SSSCs in the system no considerable reduction in transmission congestion is resulted. But, optimal locating of three SSSCs in lines 1, 13 and 18 is caused the objective function value reduced to 52.580 which is significant decrement in congestion of transmission lines. Also, the variance of nodal prices is reduced form 4.678 in Table 1 to 1.299 in this case. Thus, the power market is moved to

Table 2
Results of optimal placement of STATCOM for modified IEEE 14-bus and 30-bus test systems.

Test system	STATCOM parameter			*MANP* ($/MW h)	*VANP*	*OF*	$INC = \frac{\Delta OF_i}{\Delta OF_{i-1}}$
	No.	Bus no.	Operating point (MVar)				
Modified IEEE 14-bus	1	5	30.02	42.048	4.467	187.845	–
	2	5	28.76	42.057	4.299	180.783	–
		7	20.32				
	3	5	28.72	42.076	4.162	175.123	0.802
		7	20.18				
		12	4.40				
	4	5	28.51	42.102	4.038	170.015	0.903
		7	19.01				
		11	8.45				
		12	4.39				
	5	5	28.58	42.134	3.925	165.390	0.905
		7	18.71				
		11	7.81				
		12	2.25				
		13	11.93				
	6	7	21.30	42.356	3.863	163.636	0.379
		11	3.76				
		14	9.17				
		13	8.42				
		12	2.48				
		10	13.84				
Modified IEEE 30-bus	1	15	28.75	49.326	6.511	321.165	–
	2	12	32.54	46.812	5.270	246.680	–
		27	26.13				
	3	12	15.08	46.812	5.097	237.953	0.117
		15	27.15				
		27	21.80				
	4	12	12.03	46.673	5.004	233.539	0.506
		14	6.34				
		15	24.87				
		27	21.20				
	5	12	10.16	46.669	4.912	229.258	0.970
		14	6.32				
		15	22.92				
		25	12.01				
		27	13.72				
	6	7	26.12	46.629	4.821	224.817	1.037
		12	7.41				
		14	6.07				
		15	21.88				
		25	11.53				
		27	11.51				
	7	7	25.97	46.630	4.744	221.204	0.815
		12	6.80				
		14	6.11				
		15	21.90				
		25	11.24				
		27	7.98				
		29	4.48				
	8	7	25.92	46.683	4.693	219.086	0.586
		12	6.59				
		14	6.12				
		15	21.91				
		25	11.13				
		27	6.75				
		29	2.39				
		30	3.63				

work in fairer condition for power market participants. Further, the mean of nodal prices is reduced to 40.466 $/MW h which is a desirable consequence for power market consumers.

It is observed that the SSSC is being able to decrease the mean of nodal prices as well as their variance in the system, appropriately. However, improvement of objective function value is not considerable when number of SSSCs is increased to 4. This means that there is a stop point for increasing the number of SSSCs. According to Table 3, the value of *INC* is increased up to three SSSCs and after that it is decreased. Thus, the optimal number of SSSCs is 3.

By comparing results of Tables 2 and 3, it is possible to select the best type of the two FACTS devices, STATCOM and SSSC. It is

Table 3
Results of optimal placement of SSSC for modified IEEE 14-bus and 30-bus test system.

Test system	SSSC parameters				*MANP* ($/MW h)	*VANP*	*OF*	$INC = \frac{\Delta OF_i}{\Delta OF_{i-1}}$
	No.	Line no.	Operating (MVar) point	Operation mode				
Modified IEEE 14-bus	1	7	0.41	Capacitive	41.840	4.362	182.505	–
	2	6	0.01	Capacitive	41.805	4.176	174.582	–
		7	0.44	Capacitive				
	3	1	0.81	Inductive	40.466	1.299	52.580	15.399
		13	0.77	Capacitive				
		18	0.25	Capacitive				
	4	1	0.02	Capacitive	43.567	1.183	51.545	0.009
		2	0.44	Inductive				
		7	0.30	Capacitive				
		13	1.01	Capacitive				
Modified IEEE 30-bus	1	19	0.25	Capacitive	50.357	7.003	352.640	–
	2	19	0.24	Capacitive	46.180	4.939	228.077	–
		40	0.76	Capacitive				
	3	4	0.17	Capacitive	43.738	3.893	170.223	0.465
		18	0.85	Capacitive				
		40	0.75	Capacitive				
	4	7	0.02	Capacitive	42.568	1.864	79.325	1.571
		29	0.03	Capacitive				
		32	0.06	Capacitive				
		40	0.60	Capacitive				
	5	1	0.47	Inductive	38.092	1.531	58.323	0.231
		9	0.56	Capacitive				
		19	0.23	Capacitive				
		39	0.15	Capacitive				
		40	0.65	Capacitive				
	6	1	0.50	Inductive	40.337	1.491	60.148	-0.087
		4	0.26	Capacitive				
		9	0.54	Capacitive				
		17	0.49	Capacitive				
		19	0.25	Capacitive				
		27	0.35	Capacitive				

observed that the SSSC is better choice than the STATCOM for congestion alleviating in modified IEEE 14-bus test system. According to the results, the optimal number of SSSCs is three and the SSSCs should be placed in lines 1, 13 and 18 with sizes that can be selected considering their optimal operating points reported in Table 3 and the standard size of SSSCs. Fig. 4 shows the value of nodal prices in base case (without FACTS devices) and when number of SSSCs is increased to 4. In base case nodal prices have values between 26.704 and 46.208 $/MW h. This variation is caused by congestion of transmission lines. When SSSCs are located optimally the difference of nodal prices is became smaller. The best case considering the *INC* index is shown by star line.

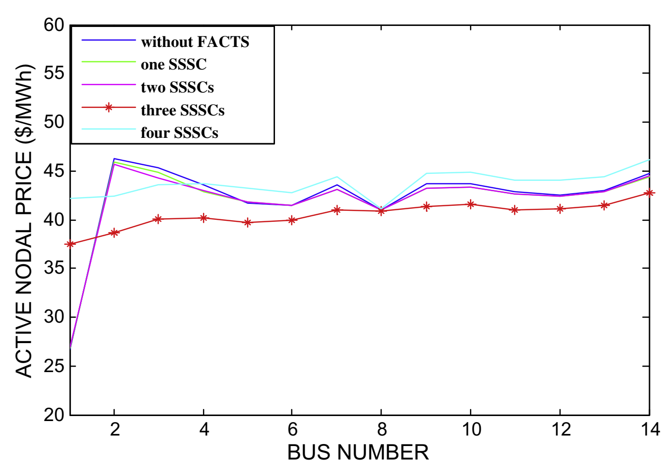

Fig. 4. Nodal prices of modified IEEE 14-bus test system with and without FACTS devices.

5.3.2. The modified IEEE 30-bus test system

Similar to case A, the problem of optimal placement of up to six SSSCs is solved for modified IEEE 30-bus test system and the results are shown in Table 3. According to the results, optimally located SSSCs are being able to manage the transmission congestion, considerably (see Tables 1 and 3). As the number of SSSCs is increased the value of objective function is decreased until the objective function is reached to value of 58.323 by installing of five SSSCs in lines 1, 9, 19, 39 and 40. But, after that by optimal installing of six SSSCs the value of objective function is not reduced. This means that increment the number of SSSCs is led to undesirable power flows in transmission lines and consequently undesirable congestion managing is obtained.

From Table 3 concluded that the value of *INC* is increased up to four SSSCs and after that it is decreased. Thus, the optimal number of SSSC is 4. The optimal locations for these SSSCs are the lines 7, 29, 32 and 40 and optimal operating points are 0.02, 0.03, 0.06 and 0.60 MVar in capacitive mode, respectively. It should be noted that the optimal size of SSSCs can be selected according to standard sizes which can cover these optimal operating points.

Comparing results of Tables 2 and 3 shows that the SSSC is a better choice for congestion management in modified IEEE 30-bus test system, as it could to reduce variance of nodal prices to 1.864 and mean of nodal prices to 42.568 $/MW h while these quantities for STATCOM at the best case are 4.821 and 46.629, respectively. Fig. 5 shows the value of nodal prices in base case and when number of SSSCs is increased to 6. The variations of nodal prices in base case show clearly the congestion of transmission lines. As SSSCs are located optimally the difference of nodal prices is decreased, considerably. The effects of installing SSSCs on congestion alleviating are well observed in Fig. 5. The best case according to the *INC* index is shown by star line. Although, the curves related to optimal installing of five and six SSSCs are located below the curve related to optimal installing four SSSCs (i.e. best case according to index *INC*), but these cases are not selected as the best case. Because, according to index *INC* improvement of objective function is not increased in these cases.

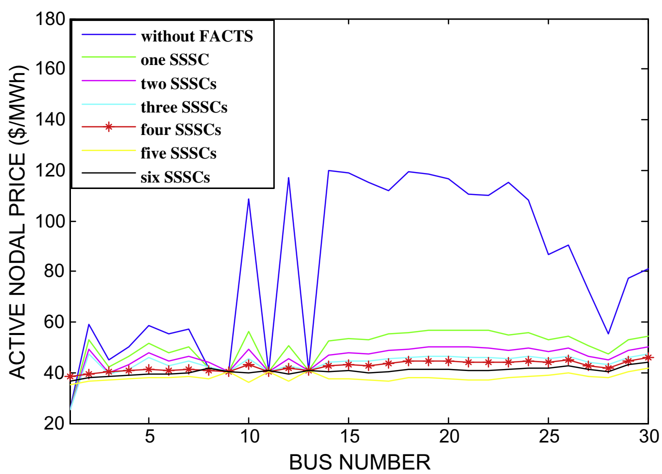

Fig. 5. Nodal prices of modified IEEE 30-bus test system with and without FACTS devices.

5.4. The modified IEEE 118-bus test system

Previous steps are repeated for 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. It is to be mentioned that the congestion assumed for IEEE 118-bus system is not very heavy (*VANP* = 6.566, see Table 1) and it is expected that by few numbers of FACTS devices the congestion be alleviated.

The results of optimal placement of STATCOM are reported in Table 4. According to Tables 1 and 4 transmission congestion of this modified system have been decreased by optimal installed STATCOMs, effectively.

When number of STATCOMs is increased from 3 to 4, a maximum for relative decrement of objective function value (*INC*) is obtained; so that the relative decrement rate of objective function is reached 1.087 and after that this rate is decreased. This means that installing of four STATCOMs at buses 35, 18, 41 and 15 with optimal operating points 9.07, 27.82, 23.80 and 29.55 MVar is the best selection. In other words, since the value of *INC* is increased up to four STATCOMs and after that it is decreased, thus, the optimal number of STATCOMs is equal to four. The optimal size of these four STATCOMs can be selected according to the standard sizes which can cover the optimal operating points.

The other FACTS device, SSSC, is located optimally and its results which are better than those obtained for STATCOM are

Table 4
Modified IEEE 118-bus test system-results of optimal placement of STATCOM and SSSC.

Type of device	FACTS device parameter				*MANP* ($/MW h)	*VANP*	*OF*	$INC = \frac{\Delta OF_i}{\Delta OF_{i-1}}$
	No.	Bus no.	Operating point (MVar)	Operation mode				
STATCOM	1	35	27.92	Capacitive	37.7885	4.2238	159.611	–
	2	35	21.95	Capacitive	37.5830	3.7269	140.069	–
		18	43.28	Capacitive				
	3	18	34.73	Capacitive	37.3778	3.2068	119.861	1.034
		35	12.10	Capacitive				
		41	25.17	Capacitive				
	4	35	9.07	Capacitive	37.1477	2.6355	97.904	1.087
		18	27.82	Capacitive				
		41	23.80	Capacitive				
		15	29.55	Capacitive				
	5	35	7.65	Capacitive	37.0526	2.3786	88.135	0.484
		18	25.12	Capacitive				
		41	23.25	Capacitive				
		15	27.41	Capacitive				
		44	13.98	Capacitive				
SSSC	1	96	8.72	Inductive	36.6181	1.6984	62.193	–
	2	96	8.72	Inductive	36.6232	1.6628	60.898	–
		170	0.65	Capacitive				
	3	25	0.14	Capacitive	36.5661	1.6021	58.583	1.854
		158	0.11	Capacitive				
		96	8.74	Inductive				
	4	54	1.08	Inductive	36.3423	1.2804	46.533	5.206
		131	0.91	Capacitive				
		12	0.35	Capacitive				
		49	0.10	Capacitive				
	5	49	0.10	Capacitive	36.3573	1.2688	46.131	0.0334
		61	0.46	Capacitive				
		23	1.43	Capacitive				
		96	8.24	Inductive				
		139	5.96	Capacitive				

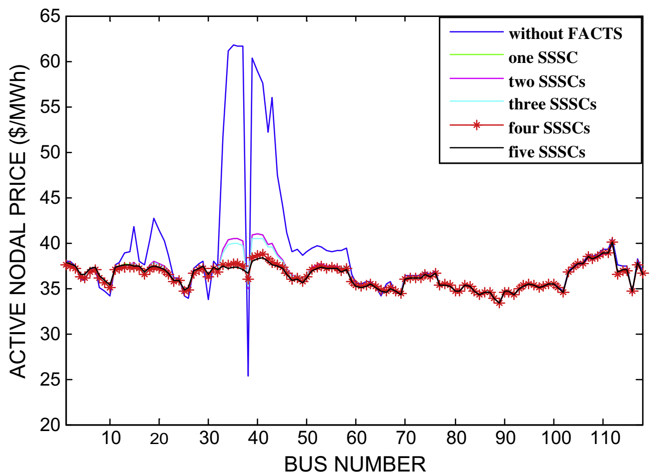

Fig. 6. Nodal prices of modified IEEE 118-bus test system with and without FACTS devices.

reported in Table 4. As it is observed, by locating one SSSC in line 96 the value of objective function decreases to 62.193 which is less than the all results obtained from optimal placement of SATATCOMs. This show that the SSSC is more effective than STATCOM in congestion managing of this modified test system. The optimal locations of four SSSCs are lines 54, 131, 12 and 49 that is the best case in accordance to *INC* index. Because, the results of Table 4 show that the value of *INC* is increased up to four SSSCs and after that it is decreased. Thus, the optimal number of SSSCs is 4. The optimal size of these four SSSCs can be selected according to the standard sizes which can cover the optimal operating points.

Fig. 6 shows the value of nodal prices in base case and when number of SSSCs is increased to 5. The minimum and maximum value of nodal prices in base case, are 25.39 $/MW h in bus 38 and 61.72 $/MW h in bus 35, respectively. These values show clearly effects of congestion of transmission lines on differing of nodal prices. As SSSCs are located optimally the variation of nodal prices is became smaller. The best case considering the *INC* index is shown by star line.

Comparing results obtained for STATCOM and SSSC show that the SSSC is a better device for alleviating the transmission congestion.

6. Conclusion

Optimal and efficient operation of a power system is achieved when the appropriate tools are employed by a suitable objective function. The use of FACTS devices as an effective option provides an opportunity to improve and optimize the operation condition of power system by alleviating the transmission congestion. Thus, in this paper optimal placement problem of parallel and series FACTS devices in the restructured environments is examined which the objective function of the problem is formulated to decrease the mean of nodal prices and their differences. The STATCOM is considered as a parallel device and the SSSC as a series one. The power injection model for these devices is adopted by applying a neural model based on the averaging technique which can take into account the power losses of the devices. Moreover, an algorithm is proposed in which an index is designed based on the value of objective function to find out the optimal number of each FACTS device. This index is defined to be applicable for other types of objective functions. The case studies on modified IEEE 14-bus, 30-bus and 118-bus test systems show that the proposed method is helpful to find the optimal number of FACTS devices and is effective to manage the congestion of transmission lines as well as to create fairer condition for power market participants.

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