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Optimal placement of FACTS Devices to reduce Loss and improve Congestion in Transmission System using ABC Algorithm

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ABSTRACT:
In this paper, Flexible AC Transmission Systems (FACTS) devices are used as a powerful tool for controlling power flow in power system to reduce active power losses and manage transmission lines congestion which are the main factors to restrict transmitted power in the network. Optimal location and size of these devices are specified by using artificial bee colony (ABC) algorithm which is one of the most effective method for solving optimization problems with the objective of minimizing active power losses and transmission lines congestion in order to relieve the line flow of the overloaded transmission lines and increase the loadability in transmission system. The proposed method is also able to improve voltage profile in the network. The effectiveness of proposed method is tested with IEEE 30-bus system and the test results are evaluated.

KEYWORDS: Loss reduction, Congestion improvement, FACTS devices, Artificial bee colony.

1. INTRODUCTION

Nowadays privatization and restructuring of the power industry have been had significant effect on all power systems around the world. Even by increasing consumption and demand of electric power, the amounts of transactions have been increased and one or more constraints of system are violated because of flowing the power in lines more than their allowed limits. In this circumstances the system is experiencing congestion. A congested system is not able to fulfill all the demands of the electric power consumption and in case of congestion in the system, prices will be increased in some areas and reduced in other and the overall situation of market will decline and removed from its natural state. Congestion management that is one of the most important tasks of system operators, means to take actions to control the transmission system so as to improve congestion effectively, various constraints are satisfied and also system security is guaranteed.

Several methods to improve the congestion have been presented in [1]. In [2] a zonal model based on AC power flow is proposed and areas are selected based on transmission congestion distributed factors (TCDFs) and congestion is managed by rescheduling of active and reactive power of generators. In [3] rescheduling of generators method based on sensitivity analyze is used to improve congestion and reduce congestion costs using the optimal generators scheduling in form of optimal power flow and PSO algorithm is used as optimization algorithm.

On the other side, because the transmission lines are not perfect electrical conductor and resistive power losses that appears in the form of heat energy along the transmission lines is about 10% of generated power, reducing total power loss is one of the most important concerns of power system operation [4]. The power loss can be decreased using optimal power flow (OPF) with power loss as an objective function. This problem is solved by satisfying different constraints related to power flow, control variables and state variables. In OPF different objective functions can be considered such as minimization of generation costs, voltage deviations, emissions and etc [5].

Generally, relieving congested lines and safe operation of power system so that the system is operated within thermal limits is achieved by controlling power flow fast and effectively and the use of flexible alternating current transmission systems (FACTS) has been always considered as a powerful tool for this purpose. The main function of this devices is control of power flow which can be used for various purposes. These devices can control line flows without changing the overall topology and improve performance, reduce losses and increase transmission capability in the system. Due to the high cost of FACTS devices and in order to use the maximum capabilities of those, determination optimal location and size of these devices is very important [6],[7].

In this paper, the optimal placement of FACTS devices in order to reduce losses and improve congestion in the transmission system is done and TCSC and SVC are used as the most common types of these devices. Optimization process is performed by using the ABC algorithm and proposed method is tested on IEEE 30-bus test system and effectiveness of this method in congestion improvement, loss reduction and voltage profile improvement is demonstrated.

2. MODELING OF FACTS DEVICES

By developing power electronics technology, flexible alternating current transmission systems (FACTS) has been made a powerful tool for better utilization of existing power systems [8]. Main ability of FACTS devices is fast and effective control of various variables in power transmission networks. These devices have some advantages such as possibility of controlling the power flow of transmission lines, dividing power flow in parallel lines arbitrarily, bus voltage regulation and also improving transient stability and damping the oscillations in power systems [9],[10]. According to available information in [11] in terms of placement of FACTS devices in the network are divided into three categories: *a)* Series devices which are placed in series with the transmission line and usually by changing the reactance of the transmission line are able to control power flow in lines. The most common type of these devices is thyristor-controlled series compensator (TCSC). *b)* Shunt devices which are connected to a bus of system and it controls the voltage of point of connection by injecting or absorbing reactive power into or from the system. Static var compensator (SVC) is the most common type of these devices. *c)* Series-shunt devices which are combination of two previous types.

In this paper, TCSC and SVC are operated simultaneously in order to reduce active power losses and improve congestion in transmission system and the model of these devices are described in the following.

2.1. Modeling of TCSC

TCSC as shown in Fig.1 consists of TCR (a pair of thyristor series with an inductor L) in parallel with a capacitor bank C. TCSC is placed in series with line and plays the role of an inductive or capacitive compensator and changes transmission line reactance

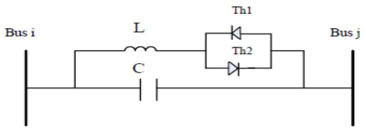

Fig. 1. Single phase model of TCSC.

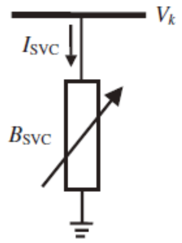

Fig. 2. Variable parallel susceptance of SVC.

In this paper TCSC has been modeled as follows:

$$X_{ij} = X_{Line} + X_{TCSC} \tag{1}$$

$$X_{TCSC} = r_{TCSC} \times X_{Line} \tag{2}$$

Where X_{Line} is reactance of transmission line and r_{TCSC} is compensation percent which will be different depended on its place in the line and can vary between -0.7 and 0.2 [12],[13].

2.2. Modeling of SVC

Like TCSC, SVC consists of a TCR in parallel with a capacitor bank and in the network controls the voltage of connected point by injecting or absorbing reactive power as a variable suscpetance. According to [14] SVC can be used as a variable parallel susceptance as shown in Fig. 2. Equations expressing the absorbed current and reactive power by SVC will be as follows:

$$I_{SVC} = jB_{SVC}V_k \tag{3}$$

$$Q_{SVC} = Q_k = -jB_{SVC}V_k^2 \tag{4}$$

Where I_{SVC} is absorbed current by SVC, B_{SVC} is susceptance of SVC, Q_{SVC} is absorbed reactive power by SVC that is equal to injected power into connective bus k and V_k is the bus voltage where SVC is connected.

3. PROBLEM FORMULATION

3.1. Objective functions

In this paper, objectives are active power loss and congestion reduction in transmission system. Objective function for minimizing the active power loss is sum of active power loss in transmission lines which can be expressed as follows:

$$f = \sum_{i=1}^{N_L} P_{LOSSi} \tag{5}$$

where P_{LOSSi} is active power loss in line i and N_L is the number of lines in the system. In this paper average percentage of lineloading has been chosen as objective function for reducing congestion which can be described in (6):

$$f = \frac{1}{N_L}\sum_{i=1}^{N_L}\left(\frac{S_{Li}}{S_{Li,\max}}\times 100\right) \qquad (6)$$

where S_{Li} is apparent power flow and $S_{Li,\max}$ is maximum limit of apparent power of i^{th} line. Objective functions expressed in (5) and (6) are minimized by satisfying various constraints related to power flow and operation systems and FACTS devices which are chosen as control variables in this paper. These constraints are classified into three types equality constraints, inequality constraints, and constraints related to the capacity of FACTS devices.

3.2. Equality constraints

Equality constraints consist of Newton-Raphson power flow typical method which are expressed in (7) and (8):

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right) = 0 \qquad (7)$$
$$, \quad i = 1, 2, ...N$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right) = 0 \qquad (8)$$
$$, \quad i = 1, 2, ...N$$

where N is the number of buses in the system, P_{Gi} and Q_{Gi} are, respectively, the active and reactive power generations at bus i; P_{Di} and Q_{Di} are the active and reactive power loads at bus i, respectively; G_{ij} and B_{ij} are the real and imaginary parts of the ij^{th} element of the bus admittance matrix, respectively; V_i and V_j are the voltage magnitudes at bus i and bus j, respectively; δ_i and δ_j are the voltage angle at bus i and bus j, respectively.

3.3. Inequality constraints

The inequality constraints are the power system operating limits which expressed as follows:

$$P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max} \qquad i = 1, ..., N_g \qquad (9)$$

$$Q_{Gi,\min} \le Q_{Gi} \le Q_{Gi,\max} \qquad i = 1, ..., N_g \qquad (10)$$

$$V_{i,\min} \le V_i \le V_{i,\max} \qquad i = 1, ..., N \qquad (11)$$

$$|S_{Li}| \le S_{Li,\max} \qquad i = 1, ..., N_L \qquad (12)$$

In (9), N_g is the number of generator units and $P_{Gi,\min}$ and $P_{Gi,\max}$ are lower and upper limits of active power generated of i^{th} unit respectively. In (10), $Q_{Gi,\min}$ and $Q_{Gi,\max}$ are lower and upper limits of reactive power generated of i^{th} unit respectively. In (11), $V_{i,\min}$ and $V_{i,\max}$ are lower and upper limits of voltage magnitude at bus i^{th} respectively and in (12) S_{Li} is apparent power flow in line i^{th} and $S_{Li,\max}$ expresses maximum thermal limit of line i^{th}.

A common way for handling the inequality constraints is the use of a penalty function. By penalizing the inequality constraints, the original constrained optimization problem is transformed to an unconstrained one.

The penalty function illustrated in (13) is used here to impose inequality constraints of active power generation of the slack bus (P_{G1}) and the constraints shown in (9), (10), (11) and (12).

$$h(x_i) = \begin{cases} (x_i - x_{i,\max})^2 & \text{if } x_i > x_{i,\max} \\ (x_{i,\min} - x_i)^2 & \text{if } x_i < x_{i,\min} \\ 0 & \text{if } x_{i,\min} \le x_i \le x_{i,\max} \end{cases} \qquad (13)$$

where $h(x_i)$ is the penalty function of variable x_i. Here, the x_i shows a dependent variable. Also, $x_{i,\max}$ and $x_{i,\min}$ are, respectively, the upper and lower limits of the variable x_i. Note that the value of penalty function grows with a quadratic form when the constraints are violated, and is 0 if the constraints are not violated.

By adding penalty functions of the active power generation of the slack bus and constraints shown in (9), (10), (11) and (12) to the objective functions expressed in (5) and (6), the extended objective function can be formulated as:

$$F = f + C_p h(P_{G1}) + C_q \sum_{i=1}^{N_g} h(Q_{Gi}) + C_v \sum_{i=1}^{N} h(\mathrm{V}_i) + C_s \sum_{i=1}^{N_L} h(S_{Li}) \qquad (14)$$

where C_p, C_q, C_v and C_s are penalty factors (weights) of active power generation of the slack bus, reactive power output of the generator buses, bus voltage magnitudes and transmission line loadings, respectively. These penalty factors are usually a large number that in this paper are considered to be 1000.

3.4. FACTS devices constraints

FACTS devices constraints are expressed as follows:

$$-0.7X_L \le X_{TCSC} \le 0.2X_L \qquad (15)$$

$$0 \le Q_{SVC} \le 100MVAR \qquad (16)$$

where in (15), X_L is reactance of line which TCSC is placed and X_{TCSC} is added reactance by TCSC to the transmission line and it can be an inductive or capacitive reactance. In (16), Q_{SVC} is injected reactive power by SVC into the bus which is connected and can vary between 0 and 100 MVAR.

4. ARTIFICIAL BEE COLONY ALGORITHM

Artificial bee colony (ABC) algorithm is a novel optimization algorithm inspired from the intelligent behavior of honeybee swarms that was proposed by Karaboga in 2005 [15]. In this algorithm, which is modeled bees foraging behavior, there are three groups of bees: *a)* Employed bees that choose food sources (possible solution) from a set of predetermined food sources and share the achieved information with other bees in the hive. *b)* Onlooker bees that choose a food source and collect amount of nectar that is in it based on obtained information from employed bees in the hive. *c)* Scout bees that find a new food source.

In the ABC algorithm, the position of a food source represents a possible solution to the optimization problem, and the nectar amount of a food source corresponds to the quality (fitness) of the solution represented by that food source. In this algorithm the first half of colony consists of employed artificial bees and the second half includes the artificial onlookers. The number of employed bees or the onlooker bees is equal to the number of solutions (SN) in the population. At the beginning of the ABC algorithm, SN numbers of initial solutions are randomly generated over the D-dimensional problem space which D is the number of optimization variables. After initializing the population of possible solution repeats the search process in MCN (Maximum Cycle Number) cycle by employed, onlooker and scout bees. At each iteration, an employed bee produces a modification on the position (solution) in her memory depending on the local information (visual information) and tests the nectar amount (fitness value) of the new source (new solution). Provided that the nectar amount of the new one is higher than that of the previous one, the bee memorizes the new position and forgets the old one. Otherwise she keeps the position of the previous one in her memory. After all employed bees complete the search process; they share the nectar information of the food sources and their position information with the onlooker bees on the dance area. An onlooker bee evaluates the nectar information taken from all employed bees and chooses a food source with a probability related to its nectar amount according to (17):

$$p_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i} \qquad (17)$$

where fit_i is the fitness value of the solution *i* which is proportional to the nectar amount of the *i*th food source. For minimization problem, fit_i can be calculated using the following expression:

$$fit_i = \begin{cases} \dfrac{1}{1+f_i} & \text{if } f_i \geq 0 \\ 1+|f_i| & \text{if } f_i < 0 \end{cases} \qquad (18)$$

where f_i is the value of the objective function.

As in the case of the employed bee, onlooker bee produces a modification on the position in her memory and checks the nectar amount of the candidate source. If the nectar amount of a food source has been exhausted or the profitability of the food source decreases under a certain level, the employed bee associated with that food source becomes a scout.

As mentioned in the initial stage, a set of food sources is chosen randomly by the bees. These food sources or initial possible solution can be expressed by (19):

$$x_{ij} = x_{\min,j} + rand[0,1] \times (x_{\max,j} - x_{\min,j}) \qquad (19)$$

where $i = \{1,2,...,SN\}$, $j = \{1,2,...,D\}$ and x_{ij} is *j*th optimization variable in *i*th possible solution of optimization problem and $x_{\min,j}$ and $x_{\max,j}$ are, respectively, the lower and upper limits of the *j*th optimization variable, and rand[0,1] denotes a uniformly distributed random number within [0,1]. Also, in order to produce a candidate food position from the old one in memory, the ABC uses the following (20):

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \qquad (20)$$

where $k = \{1,2,...,SN\}$ and $j = \{1,2,...,D\}$ are randomly chosen indices, x_{kj} is a randomly chosen solution different from x_{ij}, and v_{ij} is the new solution (food source). Also, ϕ_{ij} denotes a random number in the interval [-1,1]. It controls the production of neighbor food sources around x_{ij} and represents the comparison of two food positions visible to a bee. This can be seen from (20), as the difference between the parameters of the x_{ij} and x_{kj} decreases, the perturbation on the position x_{ij} decreases. In the ABC algorithm, three control parameters need to be selected by the user: SN (number of food sources), MCN (maximum iteration of optimization process) and Limit (maximum iteration for abandoning the food source).

5. SIMULATION RESULTS

The main objectives of this paper is to reduce active power losses and also improve congestion in the transmission system using a TCSC and SVC simultaneously. Control variables consist of continuous variable such as reactance of TCSC and injected reactive power by SVC and discrete variables such as the line number that TCSC is placed and the bus number that SVC is connected. Numerical results are represented in two cases, the objective in first case is loss minimization and in the second case is congestion improvement. Also, the effectiveness of proposed method is investigated on the voltage profile improvement in both cases and proposed algorithm has been applied to the IEEE 30-bus system with data that can be found in [16].

5.1. Case 1: Active power loss reduction

In this case, the objective is loss minimization and the objective function shown in (5) by considering penalty function related to inequality constraints introduced in section 3.3 is used that has been expressed in (14). ABC algorithm parameters is applied with SN equal to 40, Limit equal to 50 and MCN equal to 100 and optimal allocation of TCSC and SVC has been performed by this algorithm. Obtained results from 20 independent runs related to the minimum value of objective function has been reported in Table 1. After implementing the optimization algorithm, TCSC is placed in the connective line between buses 6 and 10 (line 12) with the reactance of -0.392 in p.u. and SVC is operated by injecting reactive power equal to 39.817 MVAR into bus 8. In Table 1, ''P_{LOSS1}'' and ''P_{LOSS2}'' represent active power loss before and after installing TCSC and SVC in the system, respectively, and the loss amount has been decreased from 2.4438 to 2.1031 MW. In other word, FACTS devices decrease active power loss to 13.94%. Fig.3 shows the convergence curve corresponding to the minimum loss result from the ABC approach and it is obvious that the objective function has been converged to its minimum point after 20 iteration. Also FACTS devices could improve the voltage profile so that ''V_{min1}'' and ''V_{min2}'' that show minimum value of voltage magnitude before and after installing FACTS devices respectively, has been increased from 0.9606 to 0.9679 p.u. Fig. 4 shows the voltage profile before and after installing FACTS devices.

Table 1. Location and size of FACTS in case 1.

X_{TCSC}(p.u)	Q_{SVC}(MVAR)	Line of TCSC	Bus of SVC
-0.392	39.817	12(6-10)	8
P_{LOSS1}(MW)	P_{LOSS2}(MW)	V_{min1}(p.u)	V_{min2}(p.u)
2.4438	2.1031	0.9606	0.9679

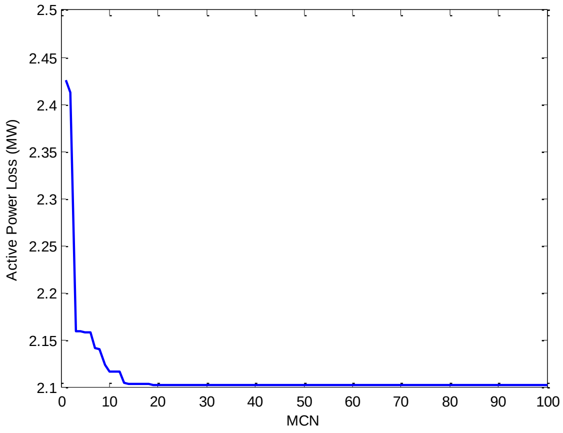

Fig. 3. Convergence of objective function in case 1.

5.2. Case 2: Congestion improvement

In this stage of the simulation the objective is relieving the lineloading in lines which are overloaded by minimizing the average of percentage of line loading of all lines in the network by considering (6) as the objective function. Like the previous case, for penalizing the violation of expressed constraints in section 3.3, the extended objective function according to (14) is considered. ABC algorithm has been applied with SN equal to 40, Limit equal to 50 and MCN equal to 100 to the test system. Obtained results from 20 independent runs related to the minimum value of objective function has been reported in Table 2. After implementing the optimization algorithm, TCSC is placed in the connective line between buses 12 and 13 (line 16) with the reactance of -0.098 in p.u. and SVC is operated by injecting reactive power equal to 35.203 MVAR into bus 8. In Table 2, ''Avg.LineLoading1'' and ''Avg.LineLoading2'' represent the objective function in this case before and after installing TCSC and SVC in the system respectively, and it has been decreased from 29.9517% to 27.4855%. Fig.5 shows the convergence curve corresponding to the minimum value of objective function and it is obvious that the objective function has been converged to its minimum

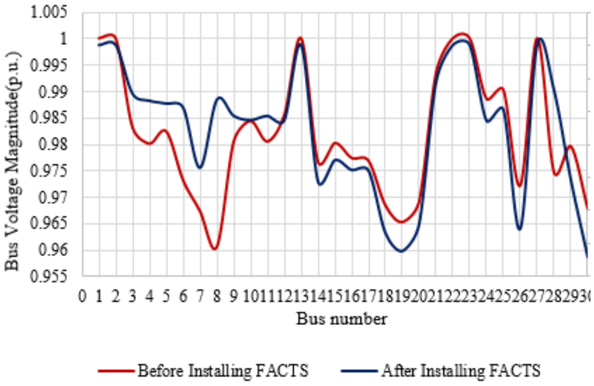

Fig. 4. Voltage profile before and after installing FACTS devices in case 1.

Table 2. Location and size of FACTS in case 2.

X_{TCSC}(p.u)	Q_{SVC}(MVAR)	Line of TCSC	Bus of SVC
-0.098	35.203	16(12-13)	8
Avg.Line Loading1(%)	Avg.Line Loading2(%)	V_{min1}(p.u)	V_{min2}(p.u)
29.9517	27.4855	0.9606	0.9679

point after 20 iteration.

Amounts of several selected line loading have been reported in Table 3. As specified in the table in bold, line 10 has a line loading percentage equal to 108.84 % and its apparent power has been violated that it has been decreased to 79.29% after installing the TCSC and SVC in the system. Also line loading and apparent power of some lines have been shown in this table and Fig. 6 shows line loading percentage of these lines before and after installing the FACTS devices. As shown in this figure, line loading of lines of 10th and 29th are under or near to congestion and are relieved after equipping the network with TCSC and SVC. Like previous case, by finding optimal location and size of FACTS devices, voltage profile has been improved so that minimum value of voltage magnitude in the test system has been increased from 0.9606 to 0.9679 p.u. as shown in Table 2. Fig. 7 shows the voltage profile before and after installing FACTS devices in this case.

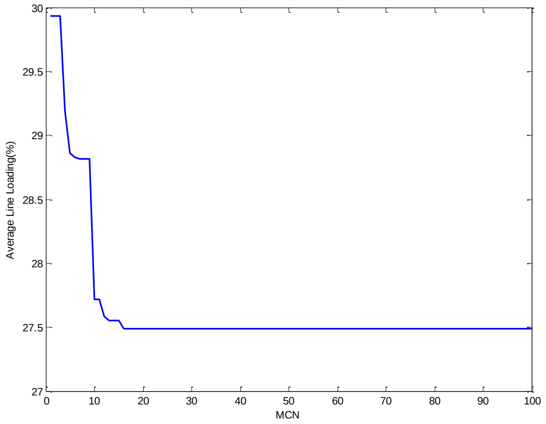

Fig. 5. Convergence of objective function in case 2.

Table 3. Line loading of several lines before and after installing FACTS devices in case 2.

Line Num.	Line Loading (%)		S_L(MVA)		$S_{L,max}$ (MVA)
	Without FACTS	With FACTS	Without FACTS	With FACTS	
3	26.51	24.64	17.23	16.02	65
6	33.41	30.86	21.72	20.06	65
10	**108.84**	**79.29**	**34.83**	**25.37**	**32**
16	59.54	60.37	38.70	39.24	65
19	28.95	29.64	9.26	9.48	32
27	37.46	23.63	11.99	7.56	32
29	95.35	84.93	30.51	27.18	32
32	44.63	45.88	7.14	7.34	16
40	25.23	16.63	8.07	5.32	32
41	8.77	13.05	2.81	4.17	32

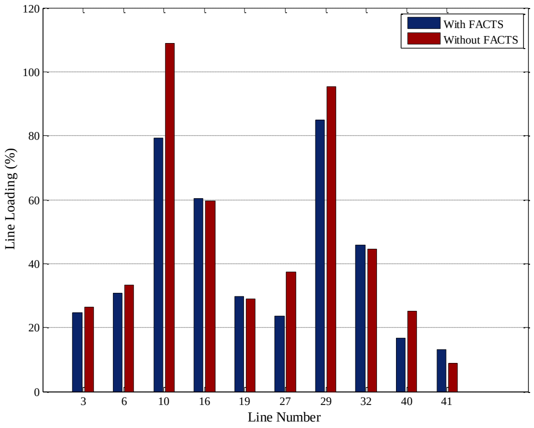

Fig. 6. Comparison line loading of several lines before and after installing FACTS devices.

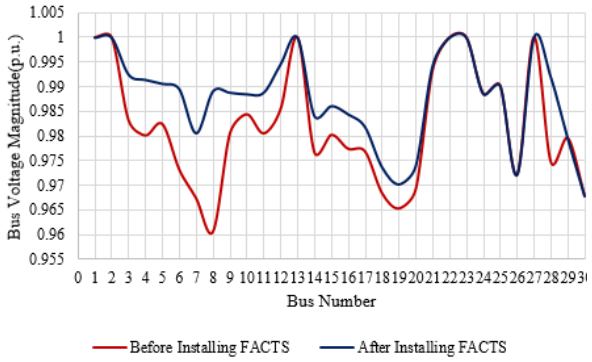

Fig. 7. Voltage profile before and after installing FACTS devices in case 2.

6. CONCLUSION

In order to operate power system effectively, in different conditions that might happen because of demanding of electric power in the deregulated environment, problems such as congestion management and loss reduction is one of the most important problems in operators point of view. In recent years, using of FACTS devices has been focused because of their ability to effectively control the power flow for relieving overloaded lines and reducing active power loss. However, due to the high install cost of these devices, finding their optimal location and size is an important problem. In this paper, TCSC and SVC have been used to reduce active power loss and congestion management in transmission system. Finding the optimal location and size of these devices have been performed by using ABC algorithm as one of the most powerful optimization approaches. Proposed method has been implemented into IEEE 30-bus test system and achieved results shows the validity and effectiveness this method in loss and congestion reduction and voltage profile improvement.

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