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Application Of AHP Method For Optimal Placement Of SSSC Device Using TLBO

Sathupati kezia[1], Dr K Padma[2]

[1] Department of Electrical Engineering, Andhra University,
Visakhapatnam, Andhra Pradesh, India

[2] Department of Electrical Engineering, Andhra University,
Visakhapatnam, Andhra Pradesh, India

ABSTRACT

The concept of FACTS (Flexible Alternating Current Transmission System) refers to a family of power electronics-based devices able to enhance AC system controllability and stability and to increase power transfer capability. FACTS devices, thanks to their speed and flexibility, are able to provide the transmission system with several advantages such as: transmission capacity enhancement, power flow control, transient stability improved, and power oscillation damping and voltage stability. This paper investigates modeling and analysis of Static Series Synchronous Compensator (SSSC) and performance of SSSC in power system. The ability of these FACTS devices for power flow control of normal/steady state condition is examined. The ability of FACTS device with AHP method using Teacher Learning Based Optimization (TLBO) method is also examined. This paper shows the Optimal Location of Static Series Synchronous Compensator (SSSC) in Transmission line using TLBO based AHP method. The objective is to minimize the fuel cost of generation, voltage deviation, transmission losses and to determine the optimal value of control variables such as generator real power, generator voltage magnitudes, tap setting of the transformer and number of compensation devices and also maintain a reasonable system performance in terms of limits on generator real power and reactive power outputs, bus voltages and power flow of transmission lines. The proposed method is examined and implemented on IEEE 30-bus power system network.

Keywords: -*Analytical hierarchy process, static series synchronous compensator, Teacher learning based optimization.*

1. Introduction

Modern power system networks are being operated under highly stressed conditions due to continuous increase in power demand. This has imposed the threat of maintaining the required bus voltage and thus the systems have been facing voltage instability problem. Voltage stability refers to the potency of the system to sustain the sufficient voltage under normal operating condition, whereas the voltage instability refers to the lack of voltage stability, which results in a continuous voltage decrease or increase. Using Flexible Alternating Current Transmission System (FACTS) devices, the voltage stability and steady state and transient stabilities of a stressed power system can be enhanced effectively. The power system network can be modified to alleviate voltage instability or collapse by adding FACTS devices at the appropriate locations. FACTS devices can control the active and reactive power as well as become adaptive to voltage-magnitude control simultaneously, because of their flexibility and fast control characteristics. The devices are mainly used in power systems for increasing the power transmission capability, enhancing static and dynamic stability, increasing the availability and reducing the transmission loss. Also, the devices have the ability to control the parameter and variables of the transmission line, such as line impedance, terminal voltages and voltage angle in a rapid and effective manner.

2. Voltage stability index

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Voltage instability occurs in the form of a progressive fall or rise of voltages of some buses.

$$L_j = \left| 1 - \sum_{i=1}^{g} \overline{F}_{ji} \frac{\overline{V}_i}{\overline{V}_j} \right| \qquad (1)$$

Where the voltage stability index limit must lie between 0 to 1.

3. Modeling of Static Series Synchronous Compensator (SSSC)

A SSSC usually consists of a coupling transformer, an inverter and a capacitor. The SSSC is series connected with a transmission line through the coupling transformer.

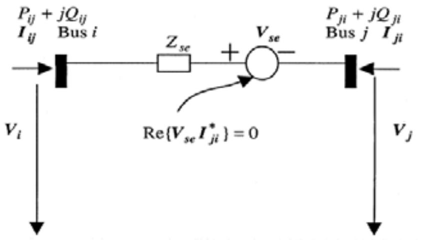

Figure 1: Equivalent Circuit of SSSC

The equivalent circuit of SSSC is as shown in the Figure 1. From the equivalent circuit the power flow constraints of the SSSC can be given as

$$P_{ij} = V_i^2 g_{ii} - V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) - V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) \\ + b_{ij} \sin(\theta_i - \theta_{se})) \qquad (2)$$

$$Q_{ij} = -V_i^2 b_{ii} - V_i V_j (g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}) - V_i V_{se} (g_{ij} \sin(\theta_i - \theta_{se}) \\ - b_{ij} \cos(\theta_i - \theta_{se})) \qquad (3)$$

$$P_{ji} = V_j^2 g_{ji} - V_i V_j (g_{ij} \cos\theta_{ji} + b_{ij} \sin\theta_{ji}) + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) \\ + b_{ij} \sin(\theta_j - \theta_{se})) \qquad (4)$$

$$Q_{ji} = -V_j^2 b_{jj} - V_i V_j (g_{ij} \sin\theta_{ji} - b_{ij} \cos\theta_{ji}) + V_j V_{se} (g_{ij} \sin(\theta_j - \theta_{se}) \\ - b_{ij} \cos(\theta_j - \theta_{se})) \qquad (5)$$

Where $g_{ij} + jb_{ij} = 1/Z_{se}$, $g_{ii} = g_{ij}$, $b_{ii} = b_{ij}$, $g_{jj} = g_{ij}$, $b_{jj} = b_{ij}$ Operating constraint of the SSSC (active power exchange via the DC link) is as

$$PE = \mathrm{Re}(V_{se} I_{ji}^*) = 0 \qquad or \\ -V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) - b_{ij} \sin(\theta_i - \theta_{se})) \\ + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) - b_{ij} \sin(\theta_j - \theta_{se})) = 0 \qquad (6)$$

The active power flow constraint is

$$P_{ji} - P_{ji}^{specified} = 0 \tag{7}$$

$$Q_{ji} - Q_{ji}^{specified} = 0 \tag{8}$$

Where z is specified active power flow

The equivalent voltage injection $V_{se}\angle\theta_{se}$ bound constraints are as

$$V_{se}^{\min} \le V_{se} \le V_{se}^{\max} \tag{9}$$

$$\theta_{se}^{\min} \le \theta_{se} \le \theta_{se}^{\max} \tag{10}$$

4. Teaching Learning Based Optimization Algorithm (TLBO)

Teaching Learning Based Optimization Algorithm is a new kind of population based global Rao et al in 2011.As in other population population-based algorithms, in TLBO, The basic idea of TLBO is that the teacher is considered as the most knowledgeable person in a class who shares his/her knowledge with the students to improve the output (i.e., grades or marks) of the class. The quality of the learners is evaluated by the mean value of the student's grade in class. Furthermore, learners also learn from interaction between themselves, which also helps in their results. The demonstration or working of TLBO Algorithm is divided into two parts:

1. "Teacher phase".
2. "Learner phase".

The first part consists of the "Teacher Phase" and the second part consists of the "Learner Phase". The "Teacher Phase" means learning from the teacher and the "Learner Phase" means learning through the interaction between learners. TLBO searches for the global optimum mainly through two steps: teacher phase and learner phase.

4.1 Teacher Phase

It is the first part of the algorithm where learners learn through the teacher. During this phase, a teacher tries to increase the mean result of the class in the subject taught by him or her depending on his or her capability. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by,

$$\text{Difference\_Mean}_{j,k,i} = r_i\left(X_{j,kbest,i} - T_F M_{j,i}\right) \tag{11}$$

Where,$X_{j,kbest,i}$ i is the result of the best learner in subject j. TF is the teaching factor which decides the value of mean to be changed, and r_i is the random number in the range [0, 1]. Value ofT_F can be either 1 or 2. The value of T_F is decided randomly with equal probability as,

$$T_F = \text{round}\,[1+\text{rand}\,(0,1)\,\{2-1\}] \tag{12}$$

$T_F$is not a parameter of the TLBO algorithm the existing solution is updated in the teacher phase according to the following expression.

$$X'_{j,k,i} = X_{j,k,i} + \text{Difference\_Mean}_{j,k,i} \tag{13}$$

Where;$X'_{j,k,i}$ is the updated value of $X_{j,k,i}$. $X'_{j,k,i}$ is accepted if it gives better function value. The learner phase depends upon the teacher phase.

4.2 Learner Phase

A learner interacts randomly with other learners for enhancing his or her knowledge. The random inter- action among learners improves his or her knowledge. In this stage a teacher choose a student randomly and tries to enhance his information and knowledge by means of interaction.

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,P,i} -\right), \text{If } X'_{total-P,i} < X'_{total-Q,i} \tag{14}$$

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,Q,i} X'_{j,P,i}\right), \text{If } X'_{total-Q,I} < X'_{total-P,i} \tag{15}$$

The equations (14) and (15) are for minimization problems. In the case of maximization problems, the eqs. (16) And (17) are used.

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,P,i} - X'_{j,Q,i}\right), \text{If} X'_{total-Q,i} < X'_{total-P,i} \tag{16}$$

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,Q,i} - X'_{j,P,i}\right), \text{If} X'_{total-P,I} < X'_{total-Q,i} \tag{17}$$

4.3 Pseudo Code for Teaching Learning Base Optimization Algorithm (TLBO)

```
STEP 1: Initialization
    Step 1.1. : Generate a well-distributed set of N weighting vectors $w^j = (w_1^j, \ldots\ldots, w_m^j)$, j=1,…, N and find the neighborhood of each sub-problems: B (j) = { $w^j$,……,$w^j$ }.
    Step 1.2.: Generate the initial population and evaluate its fitness.
    Step 1.3. : Initialize the reference point$z^*$.
STEP 2: For j= 1 to N do
    Step 2.1. : Determine the class according to: C=$\begin{cases} B(j) & if\ rand < \delta \\ \{1, \ldots., N\} & otherwise \end{cases}$
    Where rand is a random number within [0,1] and $\delta$ the probability to select the neighborhood as the class.
    Step 2.2. : Teacher phase
    Step 2.3. : Update the reference point$z^*$.
    Step 2.4. : Update $(S_r)$ solutions. Where $(S_r)$ is the maximal number of solutions replaced by each new solution obtained.
STEP 3: For j= 1 to N do
    Step 3.1. : Determine the class according to: C=$\begin{cases} B(j) & if\ rand < \delta \\ \{1, \ldots., N\} & otherwise \end{cases}$
    Step 3.2. : Learner Phase
    Step 3.3. : Update the reference point$z^*$.
    Step 3.4. : Update $(S_r)$ solutions.
STEP 4: Stop: If the stop condition is satisfied, then stop MOTLA/D. otherwise go to Step 2.
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5. Mathematical Model of OPF Problem

Four types of objective functions of OPF problem are identified as below:

Objective Function I: Min

$$f_1 = F(pg) = \sum_{i=1}^{ng}(a_i P_{gi}^2 + b_i P_{gi} + c_i) \text{ Is total generation cost function}$$

Objective Function II: Min

$$f_2 = P_L = \sum_{i=1}^{N_1} g_k[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_J)] \text{ Is total real power loss.}$$

Objective Function III: Min $f_3 = Lj2s = \sum_{j=g+1}^{nb} L_j^2$ is the sum of squared voltage stability index.

Objective Function IV: Min

$$f_4 = VD = \sum_{i=1}^{nb}(|V_i - 1|)^2 \text{ is the total voltage deviation.}$$

5.1 Constraints

The OPF problem has two categories of constraints.

5.1.1 Equality Constraints

These are the sets of nonlinear power flow equations that govern the power system, i.e.,

- load flow constraints:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{18}$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{19}$$

where P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at bus i respectively, the load demand at the same bus is represented by P_{Di} and Q_{Di}, and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij}.

5.1.2 Inequality Constraints

These are the set of constraints that represent the system operational and security limits like the bounds on the following:

- Generators real and reactive power output

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, i = 1, \ldots, ng \tag{20}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, i = 1, \ldots, ng \tag{21}$$

- Voltage magnitudes at each bus in the network

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1, \ldots, NL \tag{22}$$

Where NL is the number of load buses

- Transformer taps settings:

$$T_i^{\min} \le T_i \le T_i^{\max}, i = 1, \ldots, nt \tag{23}$$

Where nt is the number of tap changing transformers

- Reactive power injections due to capacitor banks:

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i = 1, \ldots, cs \tag{24}$$

Where cs is the number of shunt capacitor

- Transmission lines loading:

$$S_i \le S_i^{\max}, i = 1, \ldots, nl \tag{25}$$

- Voltage stability index:

$$L_j \le L_j^{\max}, \qquad j = 1, \ldots, NL \tag{26}$$

- FACTS device constraint:

$$V_{cR}{}^{\min} \le V_{cR} \le V_{cR}{}^{\max} \quad \text{SSSC voltage magnitude} \tag{27}$$

$$\theta_{cR}^{\min} \le \theta_{cR} \le \theta_{cR}^{\max} \quad \text{SSSC voltage angle} \tag{28}$$

5.2 Overall Computational Procedure for Solving the Problem

The implementation steps of the proposed TLBO based algorithm can be written as follows:

Step 1: Input the system data for load flow analysis using economical dispatch approach.

Step 2: Select a FACTS device and its location in the system.

Step 3: Initial population (the number of learners) is generated using the design variables which are the amount of rescheduling required by generators to manage congestion, (randomly within the limits).

Step 4: Using the generated (new) learners, the fitness function is evaluated (teacher phase).

Step 5: Mean of each design variable is computed and the best solution is identified as teacher among the learners based on their fitness value.

Step 6: All other learners are modified with reference to the mean and the fitness function is evaluated using the modified learners. Any two learners are randomly selected and their fitness values are compared. The student with better fitness value is accepted while the other is rejected (learner phase).

Step 7: Run the newton Raphson load flow for updated values from teacher phase for the improvement of the performance analysis.

Step 8: Repeat Step4, until all the learners participating in the test, confirms that any two learners do not repeat the test.

Step 9: If maximum number of iteration is reached then the program is stopped otherwise it goes back to Step 3.

Step 10: Print the results

6. Analytical Hierarchy process (AHP)

AHP is a decision-making tool, which helps in finding alternatives among alternative. It is a systematic method for comparing a list of objectives and the alternative

Solutions satisfying respective objectives. Some mathematical steps involved in AHP method are as follows.

Step 1: selection and evaluation of attributes

Step 2: selection of alternatives

Step 3: Formation of decision matrix

Step 4: construction of pair wise comparison matrix

Step 5: Find the relative normalized weight.

Step6: Calculate matrices $A3$ and $A4$ such that $A3 = A1 * A2$ and $A4 = A3 / A2$, where $A1$ is pair wise comparison matrix, $A2 = \left(W_1, W_2, W_3 ....W_j\right)^T$.

Step7: Determine the maximum Eigen value $\lambda_{\max}$ that is the average of matrix A_4.

Step8: Calculate the consistency index $CI = {}^{(\lambda_{\max} - M)}\!\Big/_{M-1}$. The smaller the value of CI, the smaller is the deviation from the consistency

Step10: Calculate the consistency ratio $CR = CI / RI$. Usually CR of 0.1 or less is considered as acceptable and it reflects an informed judgment attributable to the knowledge of the analyst regarding the problem under study.

Step11: The overall performance score of the alternatives is obtained by multiplying the relative normalized weight (W_j) of each attribute with its corresponding normalized weight value for each alternative and summing over the attributes for each alternative.

7. RESULTS AND DISCUSSION

The proposed TLBO algorithm is applied for solving optimal power flow problem on standard IEEE-30bus system without and with SSSC device installation.

7.1 IEEE 30-bus system results

This section presents the details of the study carried out on IEEE 30-bus system for power system performance enhancement. The network and load data and the cost coefficients along with real and reactive power generations upper and lower limits are given in Appendix. The maximum and minimum values for the generator voltage and tap changing transformer control variables are 1.1 and 0.9 in per unit respectively. The maximum and minimum voltages for the load buses are considered to be 1.05 and 0.95 in per unit. The proposed algorithm was implemented in MATLAB 10 running on Intel Core 2 Duo,2.5GHz and 4.0 B RAM PC. The case studies for simulation study are as follows:

Case I: Single-objective optimization with SSSC device at the selected locations.

Case II: Application of MADM methods for determination of optimal location of SSSC

7.1.1 Case I: Single-objective optimization with SSSC device at the selected locations

In the present power system operation, the utilities need to operate their power transmission system much more effectively, increasing their utilization degree. Reducing the effective reactance of lines by series compensation is a direct approach to increase transmission capability. However, power transfer capability of long transmission lines is limited by stability considerations. Because of the power electronic switching capabilities in terms of control and high speed, more advantages have been done in areas of FACTS devices and presence of these devices improve the performance of the power system.

The proposed TLBO algorithm is applied for solving the optimal power flow problems subjected to different equality and inequality constraints with SSSC device in the selected locations. The selected locations of SSSC are the lines connected between buses13-7, 11-13, 9-10, 12-14 and 12-16. These locations are taken based on maximum difference between MVA line rating and base case MVA line loading. The TLBO algorithm is applied for solving the OPF problem with four different objective functions. In each case study, four sets of 10 test runs were performed for solving the OPF problems under three operating conditions. All the solution satisfies the constraints on reactive power generation limits and line flow limits.

Figures 2(a)-2(d) shows the convergence characteristics of fuel cost of generation, total real power loss, sum of squared voltage stability index and voltage deviation with SSSC located at different locations of optimal value under three operating conditions. From these figures it can be observed that the TLBO algorithm reaches the best solution within 150 iterations under all the operating conditions. Table 5.1shows the OPF results with SSSC device located in the selected lines with respect to different objective functions. Table 5.1 shows four different attributes (objectives) such as total fuel cost of generation, total real power loss, sum of squared voltage stability index and voltage deviation with five different alternatives (different lines)such as 13-7, 11-13, 9-10, 12-14 and 12-16 lines has being taken for SSSC device installation.

This table also gives that SSSC candidate line 11-13 gives best minimum fuel cost of generation 797.6200$/hr, SSSC candidate line 9-10 gives best minimum power loss 0.0260p.u, SSSC candidate line 9-10 gives best minimum sum of squared voltage stability index 0.1020 and best minimum voltage deviation 0.0007in line 11-13 and 9-10 when compared to optimization without device and with SSSC in other alternatives under normal operation. From the Table 5.1.It can be observed that each candidate bus has given minimum attributes (objective function value) as best value when compared to optimization without SSSC device.

7.1.2 Case II: Application of MADM methods for determination of optimal location of SSSC

In this section, in order to differentiate the best alternative out of five considered alternatives 13-7, 11-13, 9-10, 12-14 and 12-16 MADM methods are applied. The decision making method considered for determination of best location of SSSC is AHP. This matrix is based on the preferences given to the four attributes i.e. the pair wise comparisons determines the preference of each attribute over another. Table 2 also used as priority vector of the attributes. Priority vector shows relative weights among the attributes that are used for comparison.

Table 1 gives the OPF results with SSSC device is located in the lines with respect to the different objective functions and is used in decision table for MADM methods. The considered decision matrix of MADM methods for the system consists of 5 alternatives (different lines)such as 13-7, 11-13, 9-10, 12-14 and 12-16 and 4 attributes(objectives) such as total fuel cost of generation, total real power loss, sum of squared voltage stability index and voltage deviation. This decision matrix is given as an input to all the methods. The element in this matrix indicates the performance of alternative when it is evaluated in terms of decision criterion.

Table 1 Decision Table For MADM Methods

Attributes	***Without Device***	***With SSSC (Alternatives)***				
		13-7	11-13	9-10	12-14	12-16
Cost	798.8986	798.2771	797.6200	797.6948	798.8999	798.2781
Power Loss	0.0316	0.0300	0.0261	0.0260	0.0287	0.0300
Voltage stability index	0.1057	0.1045	0.1024	0.1020	0.1029	0.1044
Voltage deviation	0.0008	0.0008	0.0007	0.0007	0.0008	0.0008

Table 2: Relative Ranking Of Alternatives Using AHP Method

Alternatives	***AHP***
13-7	5
11-13	2
9-10	1
12-14	3
12-16	4

As a best choice for the location of SSSC device among the lines considered for the system and this gives highest benefits to the power system operation in terms of performance parameters. Figure 3(a)-3(d) shows the convergence characteristics of fuel cost of generation, total real power loss, sum of squared voltage stability index and voltage deviation with SSSC located in optimal line 9-10.From Figures 5.2(a)-5.3(d), it is observed that the convergence characteristics of the four objectives obtained are better when compared to without SSSC device and at optimal location 9-10 SSSC gives better performance compared to other location.

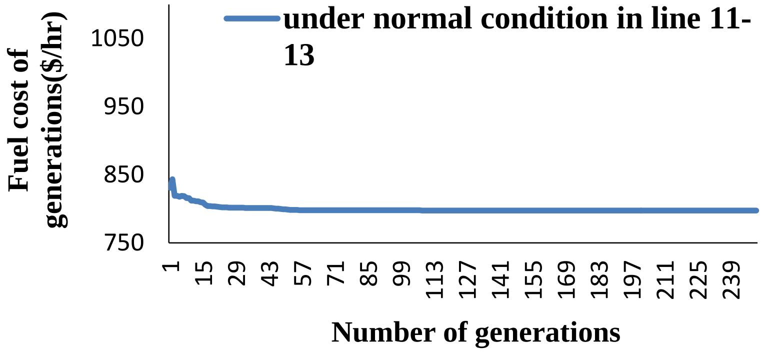

Figure 2(A): Convergence Of Fuel Cost Of Generation

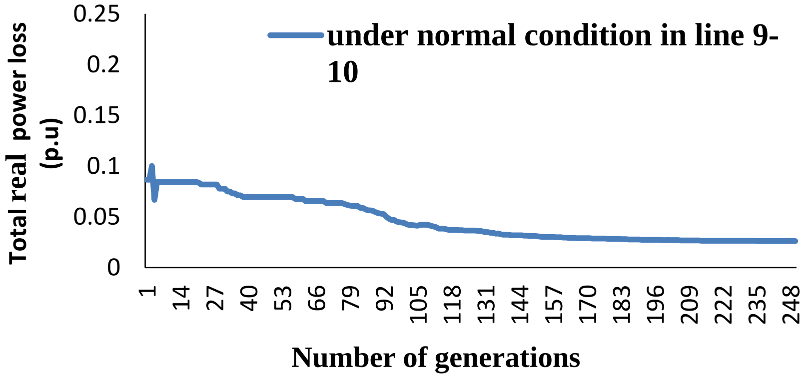

Figure 2 (B): Convergence Of Total Power Loss

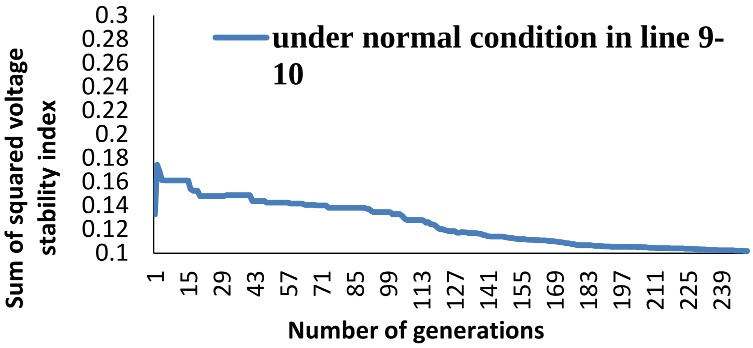

Figure 2 (C): Convergence Of Voltage Stability Index

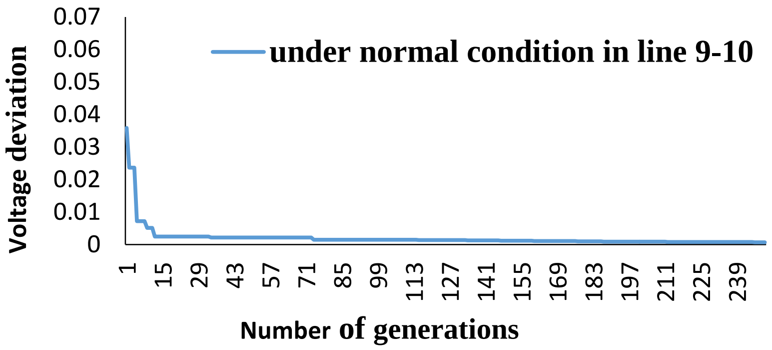

Figure 2 (d): Convergence of voltage deviation

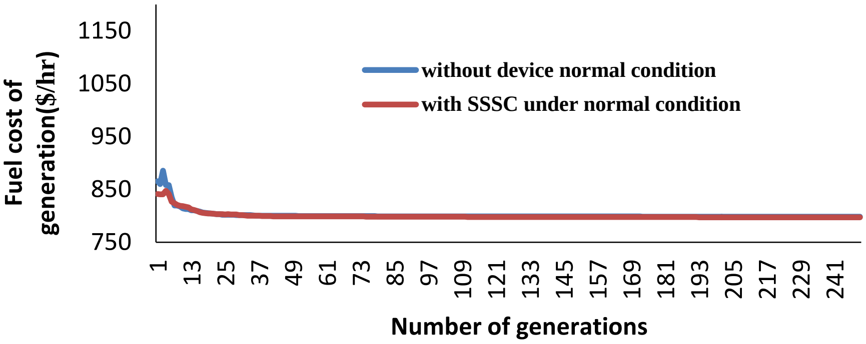

Figure 3(a): Convergence of fuel cost of generation of IEEE30 bus system with optimal location of SSSC

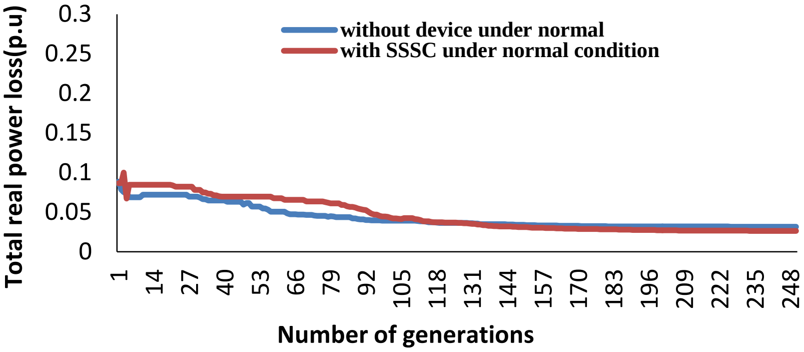

Figure 3(b): Convergence of power loss of IEEE 30-bus system with optimal location of SSSC

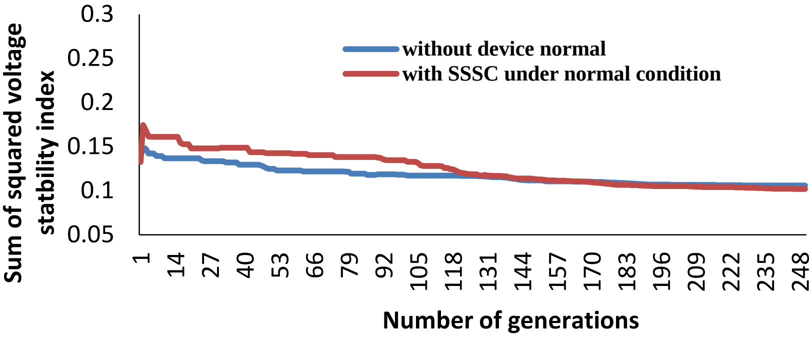

Figure 3(c): Convergence of voltage stability index of IEEE 30-bus system with optimal location of SSS

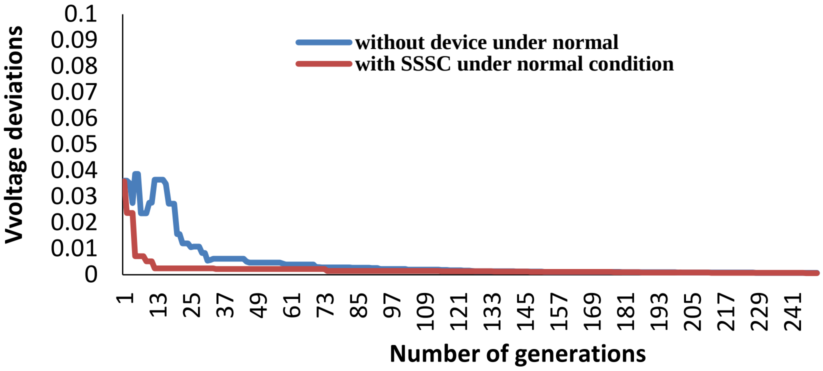

Figure 3(d): convergence of voltage deviations of IEEE 30-bus system with optimal location of SSS

8. Conclusions

In this paper, the TLBO has performed better to solve optimal placement of SSSC for reducing the active power loss, enhancing voltage stability index, improvement in voltage deviations and reducing the cost. It has been observed here, that TLBO has the efficiency to reduce the active power loss reasonably without violating any constraints. Moreover, TLBO owns excellent convergence characteristics. Therefore .from the simulation results it may be concluded that TLBO is superior to the other algorithms. Simulation results for IEEE 30 bus system are analyzed and graphs are generated for the optimal placement of SSSC in the transmission line using TLBO optimization technique based on the AHP method. Graphs are generated for convergence for cost of generator, power loss, and voltage stability index (VSI) and voltage deviation without and with SSSC FACTS device.

Appendix

OPF-Optimal power flow
SSSC-Static Series Synchronous Compensator
MADM-Multi attribute decision making
AHP-Analytical hierarchy process
TLBO-Teaching learning based optimization

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