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Multi-Objective Teaching Learning Based Optimization Technique for Loss Reduction and Fast Voltage Stability Index Minimization

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Abstract - *This paper presents the application of Multi-Objective Teaching Learning Based Optimization (MOTLBO) Technique to Voltage Stability Analysis of transmission systems. Simultaneous minimization of Real Power Loss and improvement of Voltage Stability margin in an overloaded transmission network ensures that the system is stable and efficient even under stressed conditions. Fast voltage Stability Index (FVSI) is used here to assess the health of the lines and the weak buses are identified for reactive power compensation. Flexible AC Transmission System (FACTS) devices are applied to the stressed lines to prevent occurrence of voltage collapse. The paper demonstrates the superiority of Multi-objective TLBO over other Optimization methods like Genetic Algorithm (GA), in determining the optimum ratings of FACTS devices for simultaneous minimization of Total Real power loss and FVSI in the weak lines. Bus voltage enhancement, improved line flows and loss reduction with application of series FACTS compensation have also been discussed. The tests have been carried out on an IEEE 30 bus system.*

Key Words: **Multi-Objective optimization, voltage stability, Reactive power compensation, FVSI, FACTS**

1. INTRODUCTION

With the ever increasing demands on the power system networks all over the world, transmission systems tend to operate under extremely stressed conditions. With increased demand of the power system utilities all over the world, the lines become heavily stressed and this leads to a low voltage condition or voltage collapse. Many power system blackouts are caused by such a condition and hence voltage stability analysis is of utmost importance in ensuring the smooth function of large transmission networks. As the name indicates, voltage stability can be defined as the capability of a power system to retain voltages at all buses within acceptable limits under normal conditions and when subjected to a disturbance [1]. Voltage instability results in voltage collapse, which means the voltage falls to a low unacceptable value [2]. Voltage collapse is a common phenomenon in power systems which are usually heavily loaded, faulted and/or has reactive power shortages [3].
Improvement of the voltage profile and prevention of voltage collapse can be achieved with application of sources of reactive power like shunt capacitors and/or Flexible AC Transmission System (FACTS) controllers at strategic and appropriated locations [4]. The power transfer capability is also enhanced and line losses minimized by introduction of FACTS devices. Shunt FACTS controllers are applied to the weakest bus whereas series FACTS devices are applied to the line which is most heavily stressed [5]. TCSC (Thyristor Controlled Series Capacitor) is a series connected FACTS device, used to increase power flow capacity in stressed lines and decrease system losses significantly.
In this paper, TCSC of optimum ratings are applied to the stressed lines to enhance the line flows and minimize the real power losses. FVSI (Fast voltage Stability Index) is used to identify the location of the TCSCs and for parameter settings Multi-objective TLBO algorithm is used. TLBO is a new evolutionary population-based method and uses a population of solutions to proceed to the global solution. It is based on the effect of the influence of a teacher on the output of the learners in a class [6]. It is easily implemented and requires less computational memory [6, 7].

Nomenclature

i	Sending end bus or node
j	Receiving end bus or node
Z_{ij}	Impedance of line connecting bus i and bus j
X_{ij}	Impedance of line connecting bus i and bus j
Q_j	Reactive power flow at the receiving end bus j
V_i	Voltage magnitude at bus i
V_j	Voltage magnitude at bus i
X_{TCSC}	TCSC Reactance
γ_{TCSC}	Compensation factor of TCSC

2. FAST VOLTAGE STABILITY INDEX (FVSI) FORMULATION

The power system network is observed to have higher number of lines than the number of buses, in order to ensure power delivery to the utilities and to improve system stability. Hence, it is essential that the weak lines of the network be identified and corrective measures taken to avoid outages and system collapse. There are several line voltage stability indices used for stressed line identification. Some of them are Lmn index, FVSI index, LQP index, VCPI (Power) Index, VCPI (Losses) index etc. [8, 9, 10, 11]. The Line Stability Index FVSI (Fast Voltage Stability Index) was proposed by I. Musirin et al [9]. It is based on the concept of power flow through a single line. It results from the voltage quadratic equation at the receiving bus of a two-bus system [9, 11, 12, 13, 14].

In an interconnected transmission line, the stability index is calculated by (1):

$$FVSI_{ij} = \frac{4Z_{ij}^{2}Q_j}{V_i^2 X_{ij}} \tag{1}$$

The line having FVSI value close to 1 is approaching its instability point. Any further increase in load may lead to either of the buses connecting the line to experience voltage collapse. FVSI > 1 implies that the line is experiencing voltage instability. FVSI helps to identify the weakest buses and the most heavily loaded lines. Therefore, the knowledge of the FVSI also helps in proper placement of reactive power compensation in the power system network.

3. TCSC MODELLING

Among all important FACTS controllers, SVC (Static VAR Compensator) and TCSC are most suitable for voltage control [15]. TCSC is one of the most popular series FACTS controllers, which allows rapid and continuous modulation of the transmission line impedance. It consists of a capacitor (C) inserted directly into the transmission line and the TCR are mounted in parallel with the capacitor [16]. The structure of TCSC is shown in Fig.1.

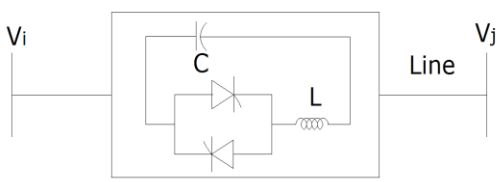

Fig-1: Structure of TCSC

The TCSC is connected in series with the line to compensate the inductive reactance of the transmission line. The reactance of the TCSC depends on its compensation ratio and the reactance of the transmission line where it is located [17]. The model of TCSC is shown in Fig. 2

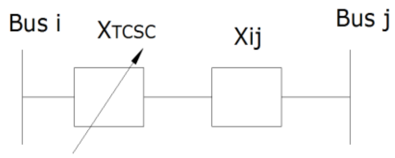

Fig.2: TCSC Model

The TCSC modeled by the reactance, X_{TCSC} is given as follows: [6, 17, 18]:

$$X_{ij} = X_{line} + X_{TCSC} \tag{2}$$

$$X_{TCSC} = \gamma_{TCSC} \cdot X_{line} \tag{3}$$

The level of applied compensation of the TCSC varies between 20% inductive reactance and 80% capacitive reactance.

4. TLBO METHOD

The Teaching Learning Based Optimization (TLBO) algorithm is a global optimization method originally developed by R.V Rao et al., inspired by the nature of influence of a teacher on learners. Compared to other algorithms, TLBO is a simple and robust technique involving fewer computations [6]. It is also a population based method and uses a population of solutions to achieve a global solution. The population is considered to be a group of learners or a class of students. The different variables are analogous to the different subjects offered to learners and the student score is analogous to the fitness [19]. As the teacher is considered the most learned person in the society, the best solution is analogous to Teacher in TLBO.
The process of TLBO is divided into two parts. The first part is the 'Teacher Phase' and the second part is the 'Learner Phase'.

4.1 Initialization:

For any iteration i, we assume that there are 'm' number of subjects (i.e. design variables), 'n' number of learners (i.e., population size, k=1, 2, ..., n) and $M_{j,i}$ be the mean result of the learners in a particular subject (j=1, 2, ..., m).

4.2 Teacher Phase:

It is the first part of the algorithm where learners learn through the teacher and improve their knowledge, which in turn, improves the mean result of the class.
The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by:

$$Diff\_mean_{j,k,i} = r_i .(X_{j,kbest,i} - T_f M_{j,i}) \quad (4)$$

$$X'_{j,k,i} = X_{j,k,i} + Diff\_mean_{j,k,i} \quad (5)$$

Where,
$X_{j,kbest,i}$: result of the best learner in subject j
T_f : Teaching factor, value of T_f can be either 1 or 2
r_i : random number in the range [0, 1]
$X'_{j,k,i}$: updated value of $X_{j,k,i}$, accepted if it gives better function value.

All accepted function values at the end of the Teacher phase become the input to the learner phase.

4.3 Learner Phase:

In this phase the interaction of learners with one another takes place. The random interactions among learners improve their knowledge. Two learners P and Q are randomly selected such that $X'_{total\text{-}P,i} \neq X'_{total\text{-}Q,i}$ (where $X'_{total\text{-}P,i}$ and $X'_{total\text{-}Q,i}$ are the updated function values of $X_{total\text{-}P,i}$ and $X_{total\text{-}Q,i}$ of P and Q at the end of the Teacher phase).

For minimization problems,

$$X"_{j,P,i} = X'_{j,P,i} + r_i(X'_{j,P,i} - X'_{j,Q,i}) \quad (6)$$
$$\text{if } X'_{total\text{-}P,i} < X'_{total\text{-}Q,i}$$

$$X"_{j,P,i} = X'_{j,P,i} + r_i(X'_{j,Q,i} - X'_{j,P,i}) \quad (7)$$
$$\text{if } X'_{total\text{-}Q,i} < X'_{total\text{-}P,i}$$

Where
r_i : randomly generated number in the range [0, 1]

TLBO requires only the common control parameters such as population size and the number of generations and does not require any algorithm-specific control parameters.

5. PROBLEM FORMULATION:

5.1 Problem: The main objective of this work is to optimize the TCSC design parameter (γ_{TCSC}) for simultaneous minimization of the system Real power loss and FVSI of the compensated lines, thereby improving the line voltage stability of the system and enhancing line flows. Multi-objective TLBO for Real power loss reduction and FVSI minimization is performed on a standard IEEE 30 bus test system.

5.2 Multi-objective TLBO problem formulation:

The objective function is:

$$Min\ F = w.\sum_{k=1}^{nL} P_{Lk} + (1-w).\sum_{l=1}^{SL} FVSI_l \quad (8)$$

Where,
F : objective function
P_{Lk} : Real power loss of line k
nL : no. of lines
SL : stressed lines where TCSCs are connected
$FVSI_l$: FVSI value of line l
w, (1-w) : weight adjustments for P_{Lk} and $FVSI_l$

Constraints:

The minimization problem is subject to the following equality and inequality constraints:

Equality constraints:

The equality constraints represent the load flow equations, as given below for the ith bus:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{nB} V_i V_j Y_{ij} Cos(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (9)$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{nB} V_i V_j Y_{ij}\ \mathrm{Sin}(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (10)$$

Where,
P_{Gi}, Q_{Gi} : active and reactive powers of the i^{th} generator
P_{Di}, Q_{Di} : active and reactive powers of the i^{th} load bus
θ_{ij} : Power angle
nB : no. of buses
nG : no. of generators

Inequality constraints:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, \quad i \in nG$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, \quad i \in nG$$

$$V_i^{min} \leq V_i \leq V_i^{max}, \quad i \in nB$$

$$\theta_{ij}^{min} \leq \theta_{ij} \leq \theta_{ij}^{max}, \quad i \in nB$$

$$\gamma_{TCSC}^{\ min} \leq \gamma_{TCSC} \leq \gamma_{TCSC}^{\ max}$$

6. RESULTS AND DISCUSSION

6.1 Placement of FACTS devices:

NR load flow and Continuation Power Flow Analysis [20] have been carried out on the standard IEEE 30 bus, 41 line test system.

The FVSI of each line is calculated after increasing the loading to 150% and the highest values of FVSI are associated with lines 12, 15 and 36, indicating that these are the most stressed lines approaching or experiencing voltage collapse. The voltage magnitudes of the corresponding buses are noted. FVSI, Power flows and Lines losses of these lines are calculated. These lines are selected for series FACTS compensation (TCSC).

6.2 Implementation of MOTLBO for determining the capacity of TCSCs:

TCSCs with random capacity are installed in the selected weak lines. Multi-objective TLBO (MOTLBO) is then carried out with Minimization of Total Real Power Loss and FVSI of the stressed lines as the objective function. The tests are carried out for different weights and it is found that the optimum value for γ_{TCSC} is -0.76892845 under overload (150% load) conditions. Using the optimized ratings, NR load flow is performed. System losses and FVSI of the compensated lines are then calculated. Results of the multi-objective TLBO are shown in Table-1 and Figs 3 and 4. Total losses of the system and Sum of FVSI of the stressed lines reduce [Table-1], even under overload conditions, indicating enhanced line voltage stability.
Voltage magnitudes at the two end nodes of the stressed lines are computed and tabled [Table-2]. An improvement in Voltage magnitudes is observed [Table-2 & Fig-5] with the application of the optimum rated TCSCs.

Table-1: Results of Multi-objective TLBO (IEEE 30 bus system)

Result (*Multi-objective TLBO)* (p.u.)	Without TCSC	With TCSC in weak lines (γ_{TCSC} = -0.76893)
Total Real power loss	0.46203	0.45468
Sum FVSI	1.7251	0.7018

Fig-3 and Fig-4 are representation of the objectives of this paper, achieved through Multi-objective TLBO.

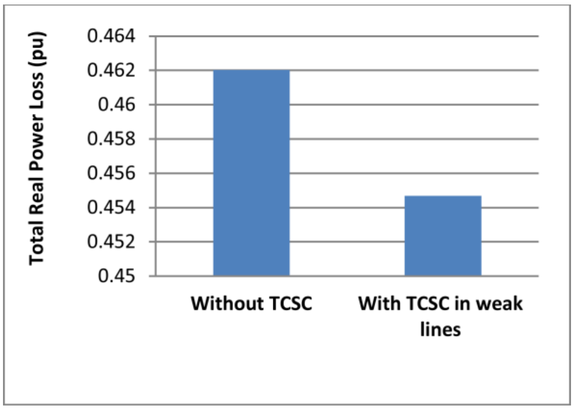

Fig -3: Total Real Power Loss profile (IEEE 30 bus system)

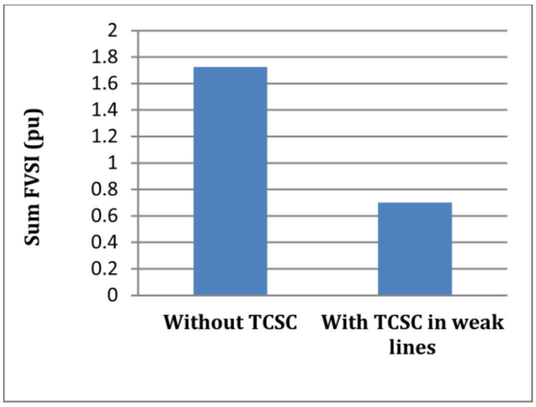

Fig -4: Sum FVSI profile of compensated lines (IEEE 30 bus system)

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Table-2: Voltage magnitudes of the connected buses (IEEE 30 bus system)

Line No.	Bus No.	Voltage (p.u)	
		Without TCSC	With TCSC in weak lines (γ_{TCSC} = -0.76892845)
12	6	0.967	0.9834
	10	0.9753	1.0087
15	4	0.9692	0.9802
	12	1.0003	1.0439
36	28	0.9636	0.9807
	27	0.9548	1.0039

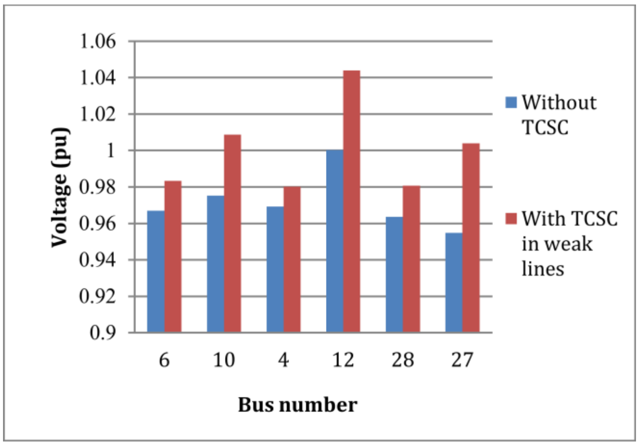

Fig-5: Voltage profile of the connected buses (IEEE 30 bus system)

It is observed that the reactive power losses of the compensated lines and the total reactive power loss of the system are also minimized in the process (Table-3 and Fig-6).

Table-3: Reactive Power Losses (IEEE 30 bus system)

Line No.	Reactive Power Loss (MVAR)	
	Without TCSC	With TCSC in weak lines
12	3.247	2.141
15	11.596	10.961
36	3.189	1.311
System	176.893	165.270

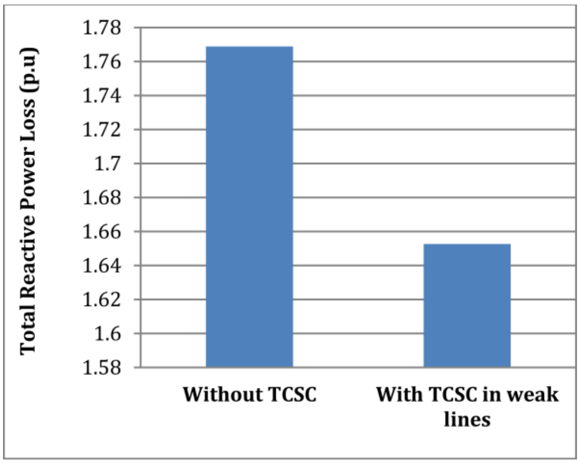

Fig -6: Total Reactive Power Loss profile (IEEE 30 bus system)

The convergence characteristics of Multi-objective TLBO method applied to the IEEE 30 bus system are shown in Fig- 7. When the same optimization problem is executed using GA, the number of iterations required are 28, compared to Multi-objective TLBO (which requires 18 iterations), indicating the superiority of TLBO technique over GA.

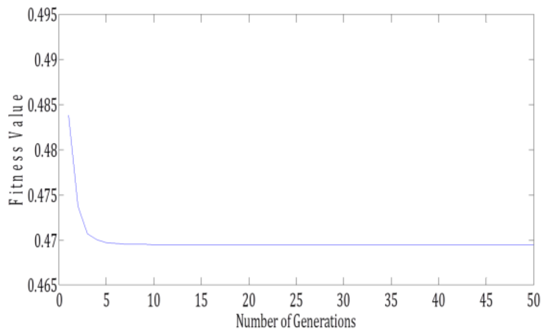

Fig-7: Convergence characteristic of Multi-Objective TLBO for IEEE 30 bus system

7. CONCLUSION

Voltage Stability improvement of transmission lines under stress include enhancement of voltage stability margin together with minimization of transmission loss. The optimal location and rating of TCSCs play a vital role in achieving these objectives. This paper aims to establish the importance and superiority of Multi-objective TLBO technique in proper optimization of TCSC ratings for Real Power Loss and FVSI minimization, and improved voltage profile of the stressed lines of a standard IEEE 30 bus system. In any evolutionary algorithm, the convergence rate is given utmost importance without compromising on the quality of objectives. Multi-objective TLBO performed in this paper is able to achieve its objectives at minimum convergence time when compared to Genetic Algorithm (GA). This work also highlights the simplicity of Multi-objective TLBO method and its effectiveness while applying it to Voltage Stability studies.

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