The Optimal Power Flow Solution by Optimal Location of STATCOM Device using AHP Method

Yeshitela Shiferaw Maru, K. Padma

Abstract: Optimum power flow is a useful tool for planning and operating the electrical system and maintains the economy and safety of the modern electrical system. Teaching, Learning-based Algorithm is one of the new Metaheuristic algorithms which can influence both teachers and students by expediting the interaction among them in sharing the necessary knowledge. The proposed TLBO is designed here to solve the problem of an optimum power flow with STATCOM FACTS device. The optimal location of STATCOM FACTS device on the weak bus is obtained by Analytical Hierarchy Process (AHP) method. The main objective of this study is to reduce fuel cost of generation, reduce active and reactive power loss, improve voltage deviation and enhance voltage stability index within the given control variable constraints. The proposed TLBO algorithm with STATCOM device is evaluated on the standard IEEE-57 bus system. From the simulation result, it shows that the Teaching Learning-based algorithm gives the optimal solution as compared to the recent algorithm mentioned in the literature with some IEEE-57 bus test system.

Index Terms: - Constraints, Optimal power flow, STATCOM, TLBO, Voltage stability.

I. INTRODUCTION

The optimal power flow was at first developed by Carpenter in 1962 to minimize generator cost[1]. The power flow analyses forecast power flows and voltages in the network as a given category of generators and loads. Power flow modelling and analysis is effective requirement stability of the power system and optimization of control variables of the system. Optimal power flow is a part of a solution for an optimized selected objective function such as fuel cost, voltage stability indices, active and reactive power loss and optimal adjustment of power system control variables within the equality and inequality constraints.[2], [3]. Conventional methods are useful to solve optimal power flow as stated in the literature, such as Interior point methods [4]–[6], Newton’s methods [7], [8], linear programming method [9], [10], nonlinear programming and gradient method [11] are regularly facing problems of convergence and complications in obtaining the overall optimal solution.

Due to these problems, research focus has already shifted to Meta-heuristic algorithm. The varieties of Meta-heuristic algorithm that can solve optimal power flow complication like particle swarm optimizations (PSO) [12], animal migration optimization technique(AMO) [13], Slap Swarm Algorithm (SSA) [14], differential Evolution, [15], and hybrid fruit fly algorithm [16], Krill Herd Algorithm [1], Mouth Swarm Algorithm [17], NovelOppositional Krill Herd Algorithm [3], Multi-Verse Optimizer [18] and chemical reaction optimization [19] etc.

To maintain the transmission line transfer capability and power system stability, the flexible AC transmission system has been introduced. This new technology is vital to redistribute power flow and control the bus voltage as well as the power system stability and security within the operating limits to the smooth operation of the power system. [12], [15].This FACTS device is capable of controlling current, voltage, impedance and phase angle of the transmission system for increasing the system stability, power factor correction, loss minimization and most importantly management of active and reactive power flow and voltage profile [1]. Hence, the optimal power flow solution integrated with FACTS device controls the flow of active and reactive power. The proposed algorithm is applicable in some areas such as optimal power flow incorporated with HVDC system. In this case, the effectiveness of HVDC link converters on the active and reactive power flow is considered to minimize power loss and improve voltage magnitude. [20] Optimal location and size of the distributed generator, optimal setting TCSC FACTS device are being implemented using teaching-learning based optimization techniques.[21], [22]

In this paper, STATCOM FACTS device is considered at fixed locations of the selected bus. The effectiveness of TLBO algorithm with STATCOM tests on the standard IEEE-57 bus test system, considering four different objectives such as: (a) minimization of fuel cost, (b) minimization of transmission line active power, (c) improvement of the voltage profile in the load bus and (d) Enhancement of voltage stability index, while maintaining equality & inequality constraints and physical limits of STATCOM. The result obtained from the proposed algorithm is compared with those obtained from recent literature.

II. MODELLING OF STATCOM FACTS DEVICE

The STATCOM FACTS device is used to improve voltage magnitude for the system by adjusting reactive power. The STATCOM modelled as an adjustable voltage source in series with an impedance. The actual part of the impedance indicates the copper losses of the coupling transformer and the converter, whereas the imaginary part of the impedance indicates the leakage reactance of the coupling transformer. STATCOM absorbs the reactive power of the network to keep the bus voltage within the limits of the load on the power system. [19]

The placement of STATCOM FACTS device based on the PQ bus having low voltage magnitude[23], and the rate STATCOM MVAr rating is between -100 & +100MVAr. The bus at which the STATCOM is connected is represented as a PV bus which may change to a PQ bus in the event of limits changed.

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Yeshitela Shiferaw Maru , Dept. of EE, AUCE( A), Visakhatpatnam, (A.P), India. Email: yeshitela2010@gmail.com
K. Padma, Dept. of EE, AUCE (A), Visakhatpatnam, (A.P), India Email: padma315@gmail.com

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In such a case, the generated or absorbed reactive power would correspond to the violated limit [24]. A mathematical model for the controller to the inclusion of load flow algorithm is derived from Figure 2.

The active and reactive power equations for the STATCOM and bus k, is represented in the following equation (7), (8), (9), and (10):

\[ P_R = V_R^2 R + V_R I_V R (\cos(\delta_R - \theta_R) + B_R \sin(\delta_R - \theta_R)) \] (7)

\[ Q_R = -V_R^2 R + V_R I_V R (\cos(\delta_R - \theta_R) - B_R \sin(\delta_R - \theta_R)) \] (8)

\[ P_k = V_k^2 G_k + V_k I_V k (\cos(\delta_k - \delta_R) + B_k \sin(\delta_k - \delta_R)) \] (9)

\[ Q_k = -V_k^2 B_k + V_k I_V k (\cos(\delta_k - \delta_R) - B_k \sin(\delta_k - \delta_R)) \] (10)

By considering this power equation, the linearized STATCOM model is involved in the load flow solution and given in equation (11), where the voltage magnitude \( V_{IR} \) and phase angle \( \delta_{IR} \) are taken to be the state variables.

\[
\begin{bmatrix}
\Delta P_k \\
\Delta Q_k \\
\Delta P_R \\
\Delta Q_R \\
\Delta P_R \\
\Delta Q_R \\
\Delta P_k \\
\Delta Q_k
\end{bmatrix} = 
\begin{bmatrix}
\frac{\partial P_k}{\partial V_{IR}} & \frac{\partial Q_k}{\partial V_{IR}} & \frac{\partial P_k}{\partial \delta_{IR}} & \frac{\partial Q_k}{\partial \delta_{IR}} & \frac{\partial P_R}{\partial V_{IR}} & \frac{\partial Q_R}{\partial V_{IR}} & \frac{\partial P_R}{\partial \delta_{IR}} & \frac{\partial Q_R}{\partial \delta_{IR}} & \frac{\partial P_k}{\partial \delta_{IR}} & \frac{\partial Q_k}{\partial \delta_{IR}}
\end{bmatrix}
\begin{bmatrix}
\Delta V_{IR} \\
\Delta \delta_{IR}
\end{bmatrix}
\] (11)

### III. Teaching Learning Based Optimization

The Teaching-Learning Based Optimization (TLBO) algorithm is a process of teaching-learning in the class. The algorithm is developed by Rao et al and Savsani (2011). The algorithm has mainly two essential parts Teachers and Learner phase.

The optimization algorithm, consisting of a group of students considered to be a population and different topics presented to the students, is regarded as a variable of a different view of the optimization problem and the result obtained by the student is similar to the ability value of the optimization problem. The best solution in the entire population is considered a teacher. The design variables are the parameters involved in the objective function of the given optimization problem, and the best solution is the best value of the objective function.

a) Teachers phase

In TLBO the average of the decision vectors is calculated for each iteration and indicated by M, the student with the highest grade is designated as the teacher, after which the position of all students is updated with the following equation. [25]

\[ X_{\text{new}} = X_{\text{old}} + r (X_{\text{teacher}} - T_{F, M}) \] (12)

b) Learner phase

In a regular classroom, students learn from each other through formal discussions, presentations and communication.
In the student phase, for each student i, another student j is chosen at random, after which the student with a higher degree (fitness) is attracted to learn from the other student provided that student j is in better fitness than student i, then

\[ X_{i,\text{new}} = X_{i,\text{old}} + r(X_j - X_{i,\text{old}}) \] (13)

**IV. STATEMENT OF THE PROBLEM**

By improvement of all the given challenges of power system network, overall performance is improved and secured subjected to various constraints.

Mathematically the optimal power flow problem is formulated as:

Minimize, \( F(u, v) \) (14)

Subject to \( \{E(u,v)=0 \} \) (15)

Where \( F \) is the objective functions to be minimized, \( u \) and \( v \) are the vectors of dependent and control variable, respectively. Whereby \( F \ (u, v) \) is objective function; \( E(u,v) \) is set of equality constraints while \( I(u,v) \) represent set of inequality constraints.

In the case of optimal power flow problem formulations, the control variable considered in the system is active power generation in the generator bus without considering reference bus, generator bus voltage magnitude, transformer tap setting, and shunt VAR compensation. Therefore, \( u \) stated as

\[ u^T = [V_{G2} - V_{G1}, V_{G1} - V_{G2}, Q_{CL} - Q_{CL}, \theta - \theta_{NT}] \] (16)

Where \( NG, NT \) and \( NC \) are the numbers of generators, regulating transformers and the number of VAR compensators, respectively.

The sets of state variables are active power at the reference bus, voltage magnitude at load buses, reactive power at generator bus, line flows. Therefore, \( v \) stated as

\[ v^T = [P_{G1}, V_{L1}, Q_{CL2}, \theta_{CL2}] \] (17)

Where, \( NL, \) and \( nl \) are the number of load bus transmission line, \( NC \) number of reactive power at the generator bus. Hence, the following objective function given by the following equations

Cost Min., \( F = \sum_{i=1}^{NG} \left( a_{i} P_{i}^2 + b_{i} P_{i} + c_{i} \right) J + h + \text{penalty} \) (18)

Where \( a_{i}, b_{i}, \) and \( c_{i} \) are the fuel cost functions in the \( i^{th} \) generator.

Voltage deviation (VD) \( F = \sum_{i=1}^{NL} \left| V_{i} - 1.0 \right| + \text{penalty} \) (19)

The voltage stability index (L) at the load bus stated as:

\[ L_j = \sum_{i=1}^{NG} F_{ij} V_i \theta_{ij} + \delta_i - \delta_j + \text{penalty} \] (20)

Where \( \theta_{ij} \) is the power factor angle and \( \delta_i \) & \( \delta_j \) are voltage angle of the \( i^{th} \) and \( j^{th} \) bus respectively.

\[ \eta_{\text{loss}(i)} = \sum_{i=1}^{nl} g_{i,j} V_{i}^2 + V_{j}^2 - 2 V_{i} V_{j} \cos(\delta_i - \delta_j) + \text{penalty} \] (21)

Where \( nl \) is a number of the transmission line, \( g_{i,j} \) the conductance of transmission line, \( V_i \) & \( V_j \) is the voltage magnitude at the given bus.

**a. EQUALITY CONSTRAINTS**

The equality constraints in optimal power flow have to be compulsory for modelling of the power system. These equality constraints are stated as follows.
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i. Real power constraints
\[\Delta P_i = \Delta Q_i = \sum_{j=1}^{n} |V_j||I_j| \cos(\phi_j - \phi_i - \phi_j) = 0 \]  
(22)

ii. Reactive power constraints
\[\Delta Q_i = \sum_{j=1}^{n} |V_j||I_j| \sin(\phi_j - \phi_i - \phi_j) = 0 \]  
(23)

Where \( j \in [1, n] \) and, \( n=\)number of bus

b. INEQUALITY CONSTRAINTS

The inequality constraints are specified for control variables of the system in the following equation.

i. Generator constraints
\[P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} \]
(24)

\[V_{gi}^{\min} \leq V_{gi} \leq V_{gi}^{\max} \]

\[Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \]

ii. Transformer constraints
\[I_{li}^{\min} \leq I_{li} \leq I_{li}^{\max} \]
(25)

\[I_{li}^{\min} + I_{li}^{\max} = I_{li}^{\max} \]

iii. Shunt Var compensator constraints
\[Q_{gi}^{\min} \leq Q_{gi} \leq V_{gi}^{\max} \]
(26)

iv. Security constraints
\[V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max} \]
(27)

\[S_{bi}^{\min} \leq S_{bi} \leq S_{bi}^{\max} \]

v. STATCOM FACTS device constraints
\[V_{iR}^{\min} \leq V_{iR} \leq V_{iR}^{\max} \]
(28)

\[\delta_{iR}^{\min} \leq \delta_{iR} \leq \delta_{iR}^{\max} \]

The penalty function must take into account that the control variables are limited. The inequality limitations of the dependent variables having voltage magnitude at the load bus; generated real power on the slack or reference bus, and line load included in an objective function as a quadratic penalty form. In these terms, a factor multiplied by the square of the ignorance value of the dependent variable added to the objective function, and each obtained unrealizable solution decreased. The penalty function equation is found in (29).

\[or = r * \delta_{pen} = \delta_{pen}^{\max} \]
(29)

Where \( Kp, Kv, Kq, \) and \( Ks \) are the penalty factors, \( NL \) is the number of load buses, \( nl \) is a number of transmission lines.

V. ANALYTICAL HIERARCHY PROCESS METHODS

The analytic hierarchy process (AHP) is widely used in multi-criteria decision-making tool for tackling multi-attribute decision-making problems in real situations[26]. It represents a powerful technique for solving complicated and unstructured problems that may have interactions and correlations among different objectives and goals [27].

Implementation of AHP methods based on the following steps [27]:
Step 1: Selection and evaluation of attributes
Step 2: Selection of alternatives
Step 3: Formation of decision matrix
Step 4: Construction of pairwise comparison matrix Step 5: Find the relative normalized weight
Step 6: Calculate matrices
Step 7: Determine the maximum Eigen value
Step 8: Calculate the consistency index
Step 9: Obtain the random index
Step 10: Calculate the consistency ratio
Step 11: Find overall performance score of the alternatives.

VI. IMPLEMENTATION OF TLBO TECHNIQUE FOR OPTIMAL POWER FLOW INCLUDING STATCOM FACTS DEVICE

The following steps provide the stepwise procedure for the implementation of TLBO algorithms in solving the optimal power flow, including STATCOM FACTS device.

Step 1. Reading of the input parameter (transmission line data, including the tap setting of transformer, active and reactive load data, and generation unit data).
Step 2. Initializing dimension of the problem \( n \), size of population \( m \) and a maximum number of iterations.
Step 3. Initializing STATCOM FACTS device (voltage magnitude, voltage angle, MVAr rating).
Step 4. Run load flow using the Newton Raphson technique to select a weak bus for the location of STATCOM FACTS device.
Step 5. Calculating the mean of each design variables, and arrange the students based on the fitness value among the candidate solutions.
Step 6. Run optimal power flow without incorporating the STATCOM FACTS device, an objective function evaluated. The penalty factors are added to the real equation if the constraints are violated. Sort the students based on the objective function.
Step 7. Based on the fitness evaluation, modify candidate solution and check the violation from the limits for all control variables.
Step 8. Run optimal power flow problem (fuel cost of generation, real power loss, voltage deviation and voltage stability index) by incorporating the best fitness value.
Step 9. Compare the objective function values for the previous and updated solution. Accept the updated solution if it produces better results than the last value. Otherwise, keep the previous solution.
Step 10. Stop and report the optimal value if the maximum iteration is touched, then display the results otherwise return to step 5.

VII. RESULT AND DISCUSSION

The IEEE 57-bus test system has the following characteristics: seven generators at buses 1, 2, 3, 6, 8, 9, and 12, seventeen transformers with off-nominal tap ratio at branch 19, 20, 31, 35, 36, 37, 41, 46, 54, 58, 59, 65, 66, 71, 73, 76 and 80 and three shunt VAR compensation at buses 18, 25 and 53 [28].
The system base is 100MVA, 60Hz and the total load demand is 1280MW and 336.4MVAR. The cost coefficients and the line, the bus data, generator data and the minimum and maximum limits for the control variables of this test system are found from [28]. The proposed technique has been applied to solve the OPF problem without and with STATCOM FACTS device for optimizing four different objective functions.

### Table 1. OPF results and decision table for AHP method

| Alternatives | Attributes |
|--------------|------------|
| Load bus     | Fuel cost  | Power loss | VSI | LD |
| Bus 25       | 41159.2    | 0.716      | 0.24 | 14.0 |
| Bus 31       | 41159.3    | 0.797      | 0.256 | 14.103 |
| Bus 32       | 41160      | 0.78       | 0.28  | 13.8 |
| Bus 33       | 41159.14   | 0.786      | 0.257 | 14.1 |
| Bus 57       | 41158.8    | 0.606      | 0.28  | 14.1 |

In this case, AHP method is applied in order to differentiate the best alternative out of five considered alternatives. The OPF results with STATCOM device which is shown in Table 1 is used as decision matrix for the system and also given as an input to AHP method. This pairwise comparisons matrix given in Table 2 determines the preference of each attribute over another. Table 3 is weight matrix of the attributes. Since it is normalized, the sum of all attributes in priority vector is 1 and Priority vector shows relative weights among the things that we compare. This shows that considered preference matrix or pairwise comparisons is acceptable because the degree of consistency or Consistency ratio is 0.05984 which is smaller to 10% [26], where the consistency is acceptable. Random Consistency index (RCI) is 0.89 taken from [27]. From Table 4 shows that relative ranking of alternatives under four objective function by AHP method. Therefore the weakest bus is bus 31 for proposed test system. Meanwhile, after load flow the STATCOM shut voltage is 0.9668 pu, shunt angle 17.69 degree and Qsh is 0.3319 in pu.

### Table 2. Pair wise comparison matrix for attributes

| Attributes | Fuel cost | Power loss | VSI | LD |
|------------|----------|------------|-----|----|
| Fuel cost  | 1        | 3          | 2   | 2  |
| Power loss | 0.33     | 1          | 3   | 2  |
| VSI        | 0.25     | 0.33       | 1   | 4  |
| LD         | 0.25     | 0.5        | 0.25| 1  |

### Table 3. Weight matrix and value of attributes

| Attributes | Weight-Age | Subjective measurement of attributes | Assigned values |
|------------|------------|--------------------------------------|----------------|
| Fuel cost  | 0.44044    |                                      |                |
| Power loss | 0.28071    |                                      | 4.1598         |
| VSI        | 0.17936    |                                      | 0.05325        |
| LD         | 0.099495   |                                      | 0.05984        |

### Table 4. The weakest bus ranking by AHP methods

| Alternatives | AHP rankings |
|--------------|--------------|
| Bus 25       | 4            |
| Bus 31       | 1            |
| Bus 32       | 3            |
| Bus 33       | 2            |
| Bus 57       | 5            |

**a) Fuel cost minimization**

The generation fuel cost curve is expressed by a quadratic function; mathematically shown in equation (18). The proposed technique runs for this case and the result depicted in Table 5. It seems that the total fuel generation cost is much improved as compared to initial values. When Teaching Learning-based Algorithm is applied to fuel cost minimization, the objective minimum charge is as low as 41160$/hr without considering STATCOM FACTS device as it is displayed in Table 6 below. However, the proposed algorithm with STATCOM FACTS device and the minimum cost becomes reduced to 41159.5$/hr, as shown in Table 6. The convergence curve obtained in Fig. 4 shows that it reaches optimal global value before 150 iterations for both without and with STATCOM device.

### Table 5. Optimal setting of control variable IEEE-57 bus using TLBO without STATCOM FACTS device

| Control variable | Minimum value | Maximum value | Cost | VD | Ploss | Q loss | Lamax. |
|------------------|---------------|---------------|------|----|-------|--------|--------|
| P1               | 75            | 284.07        | 284.55| 284.07| 284.07| 280.01|
| P2               | 100           | 284.07        | 284.55| 284.07| 284.07| 280.01|
| P3               | 53.967        | 53.967        | 53.967| 53.967| 53.967| 52.858|
| P6               | 27.072        | 27.072        | 27.072| 27.072| 27.072| 28.822|
| P8               | 538.38        | 538.38        | 538.38| 538.38| 538.38| 542.7  |
| P9               | 199.76        | 199.76        | 199.76| 199.76| 199.76| 199.95|
| P12              | 47.464        | 47.464        | 47.464| 47.464| 47.464| 47.197|
| V1               | 1.0525        | 1.0525        | 1.0525| 1.0525| 1.0525| 1.0405|
| V2               | 1.0477        | 1.0452        | 1.0477| 1.0477| 1.0305|
| V3               | 1.03          | 1.03          | 1.03  | 1.03  | 1.03   | 1.0197|
| V6               | 1.0336        | 1.0307        | 1.0336| 1.0336| 1.0263|
| V8               | 1.0454        | 1.0454        | 1.0454| 1.0454| 1.0401|
| V9               | 1.0071        | 1.0071        | 1.0071| 1.0071| 1.0005|
| V12              | 0.98946       | 0.98946       | 0.98946| 0.98946| 1.0053|
| T19              | 0.90626       | 0.90626       | 0.90626| 0.90626| 0.90168|
| T20              | 0.94945       | 0.94945       | 0.94945| 0.94945| 1.1    |
| T31              | 1.011         | 1.011         | 1.011| 1.011| 1.0691|
| T35              | 0.90039       | 0.90039       | 0.90039| 0.90039| 0.90039|
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Fuel cost ($/hr.)

| Variable | Minimum value | Maximum value | cost ($/hr.) | VD | Ploss (MW) | Q loss (Mvar) | Lamax |
|----------|---------------|---------------|-------------|----|------------|---------------|-------|
| P1       | 0             | 575           | 288.07      | 290.55 | 289.07 | 288.09 | 291.01 |
| P2       | 0             | 100           | 100         | 100   | 98.956   | 98.956 | 98.956 |
| P3       | 0             | 140           | 56.967      | 57.414 | 53.8   | 53.967 | 56.858 |
| P6       | 0             | 100           | 29.072      | 28.738 | 27.92  | 27.92 | 30.822 |
| P9       | 0             | 550           | 540.38      | 540.81 | 541.38 | 542.21 | 543.7 |
| P12      | 0             | 200           | 199.78      | 199.82 | 199.76 | 199.8 | 199.98 |
| V1       | 0.95          | 1.1           | 1.0625      | 1.06  | 1.0525  | 1.052 | 1.055 |
| V2       | 0.95          | 1.1           | 1.0377      | 1.042 | 1.0477  | 1.048 | 1.025 |
| V3       | 0.95          | 1.1           | 1.03        | 1.028 | 1.03   | 1.03 | 1.017 |
| V6       | 0.95          | 1.1           | 1.06        | 1.087 | 1.033  | 1.035 | 1.035 |
| V8       | 0.95          | 1.1           | 1.054       | 1.052 | 1.044  | 1.0454 | 1.050 |
| V9       | 0.95          | 1.1           | 1.081       | 1.018 | 1.001  | 1.071 | 1.009 |
| V12      | 0.95          | 1.1           | 0.976       | 0.996 | 0.9894  | 0.989 | 1.063 |
| T19      | 0.9           | 1.1           | 0.916       | 0.959 | 0.906  | 0.906 | 0.908 |
| T20      | 0.9           | 1.1           | 0.945       | 1.034 | 0.949  | 0.949 | 1.1 |
| T31      | 0.9           | 1.1           | 1.031       | 0.929 | 1.011  | 1.016 | 1.069 |
| T35      | 0.9           | 1.1           | 0.909       | 0.91  | 0.900  | 0.903 | 1.026 |
| T36      | 0.9           | 1.1           | 0.985       | 0.94  | 0.965  | 0.962 | 0.904 |
| T37      | 0.9           | 1.1           | 1.005       | 1.076 | 1.05   | 1.006 | 1.044 |
| T41      | 0.9           | 1.1           | 0.949       | 0.992 | 0.923  | 0.928 | 0.916 |
| T46      | 0.9           | 1.1           | 0.983       | 0.957 | 0.962  | 0.937 | 0.909 |
| T54      | 0.9           | 1.1           | 0.900       | 0.905 | 0.909  | 0.908 | 0.907 |
| T58      | 0.9           | 1.1           | 0.954       | 0.950 | 0.918  | 0.917 | 0.909 |
| T59      | 0.9           | 1.1           | 0.920       | 0.955 | 0.907  | 0.904 | 0.9041 |
| T65      | 0.9           | 1.1           | 0.902       | 0.977 | 0.904  | 0.90 | 0.905 |
| T66      | 0.9           | 1.1           | 0.910       | 0.91  | 0.901  | 0.901 | 0.903 |
| T71      | 0.9           | 1.1           | 0.920       | 0.958 | 0.907  | 0.907 | 0.9 |
| T73      | 0.9           | 1.1           | 0.939       | 0.957 | 0.995  | 0.996 | 1.069 |
| T76      | 0.9           | 1.1           | 0.912       | 1.022 | 0.926  | 0.926 | 0.966 |
| T80      | 0.9           | 1.1           | 0.965       | 0.947 | 0.965  | 0.965 | 0.9144 |
| QC18     | 0             | 5             | 4.5         | 4.459 | 4.73   | 4.99 | 4.947 |
| QC25     | 0             | 5             | 4.84        | 4.687 | 4.8   | 5 | 4.952 |
| QC53     | 0             | 5             | 4.980       | 1.762 | 4.9   | 5 | 4.705 |

Fuel cost ($/hr.)

| Summation Voltage deviation (pu) | -     | -     | 2.1806 | 0.85621 | 2.1806 | 2.1806 | 2.2645 |
| Real power loss (MW)            | -     | -     | 14.91  | 15.134  | 14.8   | 14.821 | 15.543 |
| Reactive power loss (Mvar)      | -     | -     | 63.058 | 71.019  | 63.058 | 63.058 | 65.614 |
| Imax (pu)                       | -     | -     | 0.26321 | 0.28305 | 0.26321 | 0.26321 | 0.25784 |

Table 6. Optimal setting of control variable IEEE-57 bus using TLBO with STATCOM FACTS device
b) Voltage profile improvement

The variation of bus voltage occurred due to change of loads. To maintain the bus voltage within the given constraint, the development of voltage variation study is effective for stable operation of the power system. The minimization of fuel cost may provide an attractive or feasible result. Meanwhile, the minimization of fuel cost along with voltage profile improvement by minimizing the voltage variation of load bus is the optimal solution for power system operation. The inequality constrained when calculating voltage deviation is handled by using the penalty method. The penalty is adding using penalty equation (25) when it is violating from the given limits, but the measure of violation is zero if constraints are within limits, the objective function equation is expressed in (19). From Table 6 the total sum of voltage variation for 33 load bus is 0.797pu for the specific optimal solution of voltage deviation. The comparative TLBO and TLBO with STATCOM device based convergence profile of voltage deviation, shown in Fig.5 presents that TLBO with STATCOM device converges is faster than TLBO. The statistical value of voltage deviation obtained from the literature with different optimization techniques is displayed in Table 7, the results obtained by TLBO are better than other optimization techniques.

c) Real and reactive power loss Minimization

Power loss is mainly due to the more voltage drop on the transmission line, and reactive power has the most effect on the security of the power system since it affects voltage throughout the system. So voltage control in the system means to keep power loss within the tolerable value. The PV bus voltages, the reactive power source bus and the tap position of the transformer are control variables. Therefore, the penalty function is added to the objective function when the violation occurred on PQ buses and injected reactive power of PV buses. The total real power loss with and without STATCOM device compared in Tables 5 and 6. As a result, actual power loss is reduced from 14.8MW to 14.103 MW. It decreased by 0.697MW. As it is seen from Fig.4, the convergence characteristics for real power minimization, TLBO with STATCOM FACTS devices converged early. Although, from Table 7 it shows that the result obtained by the proposed TLBO algorithm compared with other optimization techniques mentioned in the literature is displayed. So, the real power loss is more reduced using the proposed TLBO algorithm. Yet, in most related research, there is no much comparison regarding reactive power loss. Hence, the proposed algorithm gives a better result.

d) Voltage stability enhancement

The measurement of voltage collapse point in the power system is determined by using voltage stability index. In some reasons transmission line operates close to security limits. Due to this voltage collapse may occur and the over system disturbed. The load flow algorithms incorporate load and generator control characteristics. The voltage stability indices value changed between no-load and voltage collapse situations. The voltage stability index is zero and one at no load and voltage collapse conditions respectively.
Table 5 shows that the optimal voltage stability index using TLBO algorithm is 0.25784 and when the TLBO is incorporated with STATCOM FACTS device in Table 7 the voltage stability is 0.256, it is reduced by 1.84e-3. As shown in Table 7, when the value with TLBO algorithm is compared with some recent literature, the proposed algorithm is superior to other algorithms. The variation of the voltage stability index over iteration shown in Fig.7 converges early when TLBO algorithm is incorporated with STATCOM FACTS device after 100 iterations.

The optimal power flow is mathematically formulated in the power system network with equality and inequality constraints.

Initialization of Teaching Learning-Based algorithm was done and incorporated with Newton Raphson load flow equations with STATCOM FACTS device.

The proposed algorithm result was compared without and with STATCOM FACTS device using TLBO algorithm and obtained results are in terms of the fuel cost generator, minimizing real power loss, improving voltage deviation and voltage stability indexes.

The simulation results verified that, the effectiveness of a TLBO based algorithm approach to solve the OPF problem, including STATCOM FACTS device. Hence, TLBO algorithm is a powerful method to solve optimal power flow on standard IEEE-57 bus test system, because it could not have more internal tuning parameter as compared to the other algorithm mentioned in the literature which confirms its effectiveness.

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VIII. CONCLUSION

This paper dealt with comparisons of optimal power flow solution using Teaching Learning Based Algorithm with and without STATCOM FACTS device for the standard IEEE-57 bus system. The total fuel cost saved by using STATCOM device is 1.5$/ hr. Similarly, the TLBO algorithm enhance the voltage stability index by 0.001. Table 2 and Table 3 reflects the robustness of TLBO with STATCOM device. In general, from Table 7, it is seen that the proposed TLBO algorithm gives a better optimal solution as compared to the recent literature of some algorithm.

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The simulation results verified that, the effectiveness of a TLBO based algorithm approach to solve the OPF problem, including STATCOM FACTS device. Hence, TLBO algorithm is a powerful method to solve optimal power flow on standard IEEE-57 bus test system, because it could not have more internal tuning parameter as compared to the other algorithm mentioned in the literature which confirms its effectiveness.
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**AUTHOR’S PROFILE**

Yeshitela Shiferaw Maru received his M.Tech degree in Power System and automation from Defense University, College of Engineering, Ethiopia in 2014. He is currently a Ph.D. candidate in Andhra University, Visakhapatnam, India. His area of research includes power system optimization, application of FACTS device in power system, and power system protection and coordination.

K.Padma received the B.Tech degree in electrical and electronics engineering from SV University, Tirupathi, India in 2005, M.E. and Ph.D degree from Andhra University, Visakhapatnam, India in 2010, and 2015. She is currently working as an Assistant Professor in the department of electrical engineering, AU College of engineering, Visakhapatnam, A.P, India. Her research interest includes power system operation, and control, power system analysis, power system optimization, soft computing applications and FACTS.