Firefly Algorithm based Optimal Power Flow for Sizing of Thyristor Controlled Series Capacitor to enhance line based voltage stability

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Abstract. Reactive power compensation in transmission systems improves the stability of the system and also reduces the transmission line losses. Installing Flexible AC Transmission System (FACTS) devices are the effective means to control reactive power compensation. However, due to the high cost of FACTS devices, it is important to optimally place these controllers in the system. Out of the different FACTS devices, TCSC is the most effective device for series compensation. This paper presents a Sensitivity analysis based Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at an appropriate location. Once the location to install TCSC is identified, the optimal sizing of TCSC is determined through Firefly Algorithm based multi-criterion objective function comprising of four objectives minimize total real power loss, minimize total voltage magnitude deviations, minimize the fuel cost of total real power generation and minimize the branch loading to obtain the optimal power flow. Simulations have been carried out in MATLAB environment for the IEEE 14-bus system, the IEEE 30-bus system and IEEE57 bus system. The results have been taken for Firefly Algorithm based Optimal Power Flow without and with TCSC. The results obtained with Firefly Algorithm were compared with Genetic Algorithm (GA). The results indicate that FA is an easy to use and better optimization technique compared with GA.

Keywords

Firefly Algorithm, Optimal placement, Sensitivity index, TCSC.

1. Introduction

Power systems are becoming increasingly more complex due to the interconnection of regional system and deregulation of the overall electricity market [1, 2]. It has become essential to better utilize the existing power networks to increase capacities by installing Flexible AC Transmission System (FACTS) controllers. The variables and parameter of the transmission line, which include line reactance, voltage magnitude, and phase angle are able to be controlled using FACTS controllers in a fast and effective way. The benefits derived from FACTS controllers include improvement of the stability of power system networks, such as voltage stability, line stability, small signal stability, transient stability, enhance power transfer capability and thus enhance system reliability. However, controlling power flows is the main function of FACTS [3-6].

Out of the several preventive and corrective measures suggested in literature to protect power system networks against voltage collapse, the placement of FACTS controllers has been established as an effective means. However, due to high cost of the FACTS devices, it is important to optimally place these controllers in the system. The Thyristor Controlled Series Capacitor (TCSC) is one of the most effective Flexible AC Transmission System devices [7-10]. It offers fast-acting reactive power compensation on high-voltage electricity transmission networks with much faster response compared to the traditional control devices [11].

This paper presents Sensitivity analysis based Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at appropriate location. A new Meta heuristic optimization technique called Firefly Algorithm is introduced to find the optimal size of TCSC device to improve line stability. Its performance is compared with Genetic Algorithm (GA) [12-17] technique. The real and reactive power generation values and voltage limits for generator buses are taken as constraints, along with reactance limits of the TCSC, during the optimization. Computer simulations using MATLAB were done for the IEEE14 bus system, the IEEE 30 bus system and the IEEE57 bus system. In this paper, a new line-based voltage stability index is implemented to evaluate the line stability condition in a power system.

2. Problem Formulation

In this paper, the multi objective function is formulated to find optimal sizing of TCSC device by minimizing certain objective functions subject to satisfying some network constraints. The multi-objective problem can be written mathematically as follows.
2.1. Objective function

For a given system load, the best configuration of TCSC device is obtained by minimizing the objective function:

\[
\text{Min}(F) = \text{Min}(W_1 \cdot F_{\text{g}} + W_2 \cdot F_{\text{pl}} + W_3 \cdot F_{\text{v}} + W_4 \cdot F_{\text{c}})
\]

Where \( W_1, W_2, W_3, W_4 \) are the weighting factors
\( W_1 + W_2 + W_3 + W_4 = 1 \)
\( W_1 = W_2 = W_3 = W_4 = 0.25 \)

Reactance of TCSC has been added as a control variable along with real power generation of the generator buses for optimization problem. TCSC limits are given as:

\[
X_{\text{TCSC}}^{\text{min}} \leq X_{\text{TCSC}} \leq X_{\text{TCSC}}^{\text{max}}
\]

1) Fuel cost:

The objective function considering the minimization of total generation cost can be represented by following quadratic equation

\[
F_{\text{c}} = \text{Min} \left( \sum_{i=1}^{\text{ng}} \left( a_i P_{Gi}^2 + b_i P_{Gi} + c_i \right) \right)
\]

Where \( \text{ng} \) = no. of generator buses
\( a, b, c \) are the fuel cost coefficients of a generator unit

2) Active Power Loss:

The objective of this function is to minimize real power losses in the transmission lines. It can be expressed as

\[
F_{\text{pl}} = \text{Min} \left( \sum_{k=1}^{\text{ntl}} \left( S_{ij}^2 + S_{ji}^2 \right) \right)
\]

Where \( \text{ntl} \) = no. Of transmission lines
\( S_{ij} \) is the total complex power flow of line \( i - j \)

3) Voltage Deviation:

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. The Voltage Deviation (VD) can be expressed as:

\[
F_{\text{v}} = \text{Min} \left( \sum_{k=1}^{\text{nb}} \left( V_k - V_k^{\text{ref}} \right)^2 \right)
\]

\( V_k \) is the voltage magnitude at bus \( k \)
\( V_k^{\text{ref}} \) is the reference voltage magnitude at bus \( k \)

4) Branch loading:

The objective of minimizing the branch loading in the transmission lines is to enhance the security level of the system. It can be expressed as

\[
F_s = \text{Min}(S) = \text{Min} \left( \sum_{k=1}^{\text{ntl}} \left( S_k \right)^2 \right)
\]

\( S_k \) is the apparent power in line \( k \) and \( S_k^{\text{max}} \) is the maximum apparent power in line \( k \).

5) Equality constraints:

\[
\sum_{i=1}^{\text{N}} P_{Gi} = \sum_{i=1}^{\text{N}} P_{Di} + P_L
\]

Where \( i = 1, 2, 3, \ldots, N \) and \( N \) = no. of. Buses
\( P_L \) is total active power losses
\( Q_L \) is total reactive power losses

6) Inequality constraints:

Generator bus Voltage limits:

\[
V_{\text{Gi}}^{\text{min}} \leq V_{\text{Gi}} \leq V_{\text{Gi}}^{\text{max}}
\]

Where \( i = 1, 2, 3, \ldots, N \) and \( N \) = no. of. buses

Real power generation limit:

\[
P_{\text{Gi}}^{\text{min}} \leq P_{\text{Gi}} \leq P_{\text{Gi}}^{\text{max}}
\]

Where \( i = 1, 2, 3, \ldots, \text{ng} \) and \( \text{ng} \) = no.of generator buses

Reactive Power generation limits:

\[
Q_{\text{Gi}}^{\text{min}} \leq Q_{\text{Gi}} \leq Q_{\text{Gi}}^{\text{max}}
\]

2.2. Fast Voltage Stability Index (FVSI)

Several techniques were proposed to analyse the static voltage stability condition in a system. Some of them were utilized the voltage stability indices referred either to a bus or to a line as an indicator to voltage collapse. In this paper, a new line-based voltage stability index is proposed to evaluate the line stability condition in a power system. This index is called as Fast Voltage Stability Index (FVSI). The system becomes unstable if FVSI is equal to or greater than unity.

FVSI can be expressed as

\[
\text{FVSI}_{ij} = \frac{4 Z^2 Q_j}{V_i^2 X}
\]

Where \( Z \) is the line impedance
\( X \) is the line reactance
\( Q_j \) is the reactive power at bus \( j \) (receiving end bus)
\( V_i \) is the voltage magnitude at bus \( i \) (sending end bus)

Any line in the system that exhibits FVSI close to unity indicate that the line is may lead to system violation. Therefore, FVSI has to be maintained less than unity in order to maintain a stable system.
3. Thyristor controlled series capacitor (TCSC)

The basic Thyristor-controlled series capacitor scheme proposed in 1986 by Vithaythil with others is a method of "rapid adjustment of network impedance". Apart from controlling the line power transfer capability, TCSC also enhances system stability [18-21]. The basic module of the TCSC is shown in Fig. 1. It consists of a series compensating capacitor shunted by thyristor controlled reactor [22-24]. Thyristor inclusion in the TCSC module enables it to have a smoother control of reactance against system parameter variations. In view of a huge power system, TCSC implementation requires several such basic compensators to be connected in series to obtain the desired voltage rating and operating characteristics. It is modeled as a controllable reactance, inserted in series with the transmission line to adjust the line impedance and thereby control the power flow.

\[
\begin{bmatrix}
I_i \\
I_j
\end{bmatrix} = \begin{bmatrix}
jB_{ii} & jB_{ij} \\
jB_{ji} & jB_{jj}
\end{bmatrix} \begin{bmatrix}
V_i \\
V_j
\end{bmatrix}
\] (16)

For capacitive operation, we have
\[
B_{ii} = B_{jj} = -\frac{1}{X_{TCSC}}
\] (17)
\[
B_{ij} = B_{ji} = -\frac{1}{X_{TCSC}}
\] (18)

For inductive operation the signs are reversed

The active and reactive power equations at bus k are:
\[
P_i = V_i V_j^* \sin(\theta_i - \theta_j)
\] (19)
\[
Q_i = V_i^2 B_{ij} - V_i V_j^* \cos(\theta_i - \theta_j)
\] (20)

The series reactance regulates the amount of active power flowing from bus i to bus j the change in reactance in reactive operation of TCSC is
\[
\Delta X_{TCSC} = X_{TCSC} - X_{TCSC}^{(i-1)}
\] (21)

The state variable \(X_{TCSC}\) of the series controller is updated based on optimization rules.

4. Complex Power Flow Sensitivity Index for Optimal Placement of TCSC

A method based on the sensitivity of the sum of variations of complex power flow in all lines with respect to the change of reactance of a line is proposed. The TCSC has been modelled as a variable series capacitive reactance \(X_{TCSC}\), resulting in a decrease of the total line reactance. The index is computed using Newton Raphson power flow. CPSI, at a line j is given as:

\[
\text{CPSI}_j = \sum_{n=1}^{ntl} \left( \frac{\Delta S}{\Delta X_j} \right)
\] (22)

Where \(n=1, 2, 3, \ldots, \) ntl and ntl = no.of transmission lines.
\(\Delta S_j\) is change in complex power flow in line n
\(\Delta X_j\) is the reactance of the line j

This index is calculated for all the lines. The minimum and maximum values of CPSI are obtained. Normalized complex power flow sensitivity index is defined as:

\[
\text{CPSI}_{ij} = \frac{\text{CPSI} - \text{CPSI}_{\text{min}}}{\text{CPSI}_{\text{max}} - \text{CPSI}_{\text{min}}}
\] (23)

Where \(\text{CPSI}_{ij}\) is the normalized complex power flow sensitivity index at line j.

Highest positive normalized complex power flow sensitivity index is the best location for placement of TCSC.
5. Optimal sizing of TCSC using the Firefly Algorithm

The Firefly algorithm has been used to find the optimum sizing of TCSC. It was developed by Dr Xin-She Yang at Cambridge University in 2007. FA is based on natural behaviour of the firefly, developed for solving the multimodal optimization problem [27, 28]. Fireflies called as lighting bugs, are one of the most special and fascinating creatures in nature. For simplicity, the following three ideal rules are introduced in FA development those are 1) All the fireflies are gender-free that is every firefly will attract the other firefly substantive of their sex, 2) Attractiveness depend on their brightness. The less bright one will move towards the brighter one, 3) the landscape of the objective function affects the firefly brightness. Let us consider the continuous constrained optimization problem where the task is to minimize multi objective function f(x). Firefly algorithm is a dynamic converging algorithm. The solution for the algorithm depends on the selection of swarm size, maximum attractiveness value, the absorption coefficient value and the iteration limit. The basic steps of the FA can be summarized by the pseudo code [29, 30]. Firefly Algorithm

…………………………………………………………………………………………………………………………

Objective function f(x), x = (x1, ..., xd)T
Generate initial population of fireflies x_i (i = 1, 2, ..., n)
Light intensity l_i at x_i is determined by f(x_i)
Define light absorption coefficient γ
while (t < MaxGeneration)
    for ii = 1: n all n fireflies
        for jj = 1: ii all n fireflies
            if (l_jj > l_i), More firefly ii towards jj in d-dimension; end
            if
                Attractiveness varies with distance r
                Evaluate new solutions and modify the light intensity
                end for ii
            end for j
        Rank all the fireflies and find the current best firefly
    end while
Post process results and visualization
………………………………………………………………………………………………………………

Pseudo code of the FA.

6. Results and Discussion

In order to find the effectiveness of the proposed Firefly Algorithm for Optimal Power Flow with TCSC, the IEEE14, IEEE30 and IEEE 57 bus systems are taken. An OPF program using Firefly algorithm is implemented in MATLAB software without and with TCSC. The results are presented and analysed. The input parameters of Firefly Algorithm for the test system are given in the Tab. 3.

<p>| Tab.1: Complex power flow sensitivity indexes for all lines in the IEEE14 bus system. |
|-----------------------------------|------|--------|--------|--------|</p>
<table>
<thead>
<tr>
<th>Line No</th>
<th>Line</th>
<th>CPSIn(j)</th>
<th>S. No</th>
<th>Line</th>
<th>CPSIn(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>0.8331</td>
<td>11</td>
<td>4-9</td>
<td>0.4319</td>
</tr>
<tr>
<td>2</td>
<td>2-3</td>
<td>0</td>
<td>12</td>
<td>7-9</td>
<td>0.5345</td>
</tr>
<tr>
<td>3</td>
<td>2-4</td>
<td>0.4189</td>
<td>13</td>
<td>9-10</td>
<td>0.482</td>
</tr>
<tr>
<td>4</td>
<td>1-5</td>
<td>0.2641</td>
<td>14</td>
<td>6-11</td>
<td>0.4657</td>
</tr>
<tr>
<td>5</td>
<td>2-5</td>
<td>0.8747</td>
<td>15</td>
<td>6-12</td>
<td>0.4977</td>
</tr>
<tr>
<td>6</td>
<td>3-4</td>
<td>0.6675</td>
<td>16</td>
<td>6-13</td>
<td>0.4155</td>
</tr>
<tr>
<td>7</td>
<td>4-5</td>
<td>1</td>
<td>17</td>
<td>9-14</td>
<td>0.4727</td>
</tr>
<tr>
<td>8</td>
<td>5-6</td>
<td>0.3855</td>
<td>18</td>
<td>10-11</td>
<td>0.4722</td>
</tr>
<tr>
<td>9</td>
<td>4-7</td>
<td>0.5619</td>
<td>19</td>
<td>12-13</td>
<td>0.4832</td>
</tr>
<tr>
<td>10</td>
<td>7-8</td>
<td>0.4829</td>
<td>20</td>
<td>13-14</td>
<td>0.4759</td>
</tr>
</tbody>
</table>

<p>| Tab.2: Complex power flow sensitivity indexes for all lines in the IEEE30 bus system. |
|-----------------------------------|------|--------|--------|--------|</p>
<table>
<thead>
<tr>
<th>Line No</th>
<th>Line</th>
<th>CPSIn(j)</th>
<th>S. No</th>
<th>Line</th>
<th>CPSIn(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>0.4232</td>
<td>21</td>
<td>16-17</td>
<td>0.7326</td>
</tr>
<tr>
<td>2</td>
<td>1-3</td>
<td>0.7943</td>
<td>22</td>
<td>15-18</td>
<td>0.7082</td>
</tr>
<tr>
<td>3</td>
<td>2-4</td>
<td>0.7952</td>
<td>23</td>
<td>18-19</td>
<td>0.7266</td>
</tr>
<tr>
<td>4</td>
<td>3-4</td>
<td>0.8800</td>
<td>24</td>
<td>19-20</td>
<td>0.7576</td>
</tr>
<tr>
<td>5</td>
<td>2-5</td>
<td>0</td>
<td>25</td>
<td>10-20</td>
<td>0.6973</td>
</tr>
<tr>
<td>6</td>
<td>2-6</td>
<td>0.6988</td>
<td>26</td>
<td>10-17</td>
<td>0.7584</td>
</tr>
<tr>
<td>7</td>
<td>4-6</td>
<td>0.8331</td>
<td>27</td>
<td>10-21</td>
<td>0.7547</td>
</tr>
<tr>
<td>8</td>
<td>5-7</td>
<td>0.8282</td>
<td>28</td>
<td>10-22</td>
<td>0.5547</td>
</tr>
<tr>
<td>9</td>
<td>6-7</td>
<td>1.0000</td>
<td>29</td>
<td>21-22</td>
<td>0.9930</td>
</tr>
<tr>
<td>10</td>
<td>6-8</td>
<td>0.8254</td>
<td>30</td>
<td>15-23</td>
<td>0.5485</td>
</tr>
<tr>
<td>11</td>
<td>6-9</td>
<td>0.6773</td>
<td>31</td>
<td>22-24</td>
<td>0.4224</td>
</tr>
<tr>
<td>12</td>
<td>6-10</td>
<td>0.5921</td>
<td>32</td>
<td>23-24</td>
<td>0.5465</td>
</tr>
<tr>
<td>13</td>
<td>9-11</td>
<td>0.6805</td>
<td>33</td>
<td>24-25</td>
<td>0.6404</td>
</tr>
<tr>
<td>14</td>
<td>9-10</td>
<td>0.4868</td>
<td>34</td>
<td>25-26</td>
<td>0.6914</td>
</tr>
<tr>
<td>15</td>
<td>4-12</td>
<td>0.6793</td>
<td>35</td>
<td>25-27</td>
<td>0.6360</td>
</tr>
<tr>
<td>16</td>
<td>12-13</td>
<td>0.7023</td>
<td>36</td>
<td>28-27</td>
<td>0.5584</td>
</tr>
<tr>
<td>17</td>
<td>12-14</td>
<td>0.7236</td>
<td>37</td>
<td>27-29</td>
<td>0.6963</td>
</tr>
<tr>
<td>18</td>
<td>12-15</td>
<td>0.4829</td>
<td>38</td>
<td>27-30</td>
<td>0.6745</td>
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<tr>
<td>19</td>
<td>12-16</td>
<td>0.7365</td>
<td>39</td>
<td>29-30</td>
<td>0.6954</td>
</tr>
<tr>
<td>20</td>
<td>14-15</td>
<td>0.7215</td>
<td>40</td>
<td>8-28</td>
<td>0.7008</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
6.1. For 14 bus system

In the IEEE 14 bus system bus no 1 is considered as a slack bus and bus numbers 2,3,6,8 are considered as a PV buses all other buses are considered as load buses. This system has 20 interconnected lines. A MATLAB program is written for the test system and the results have been presented and analysed. Table 4 indicates the generators coefficients, minimum and maximum limit of real power generation for generator buses.

Table 5 indicates the voltage magnitudes in FA-OPF without TCSC and FA-OPF with TCSC (By placing TCSC at line No 7). The results indicate that there is a good improvement in voltage profile with TCSC in Firefly Algorithm based OPF.

The active power generation and power loss for the IEEE 14 bus test system without and with TCSC is shown in Table 6. It is observed that active power losses are reduced to 5.0631 MW from 5.4104 MW by placing TCSC in Firefly Algorithm based Optimal Power Flow. TCSC value was tuned to 0.0220 ohms using Firefly Algorithm. In case of Genetic Algorithm based Optimal Power Flow the TCSC value has been tuned to 0.031 ohms. Table 7 represents the voltage deviation, TCSC reactance value, total active power generation cost, branch loading, FVSI for all lines, Objective function value and active power losses for the IEEE 14 bus system without TCSC and with TCSC using GA-OPF and FA-OPF. The results clearly indicate the effectiveness of Firefly Algorithm over Genetic Algorithm.

Table 8 & 9 indicates the FVSI values for Firefly Algorithm based Optimal Power Flow without and with TCSC with different reactive load conditions at bus number 14. From these tables it can be inferred that increase in reactive load would result in FVSI value to unity leading to less line stability. By installing the TCSC in Firefly Algorithm based Optimal Power Flow can improve the FVSI that means line stability has been improved.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameters</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of fireflies</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Max Generation</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>Alpha (random movement factor)</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Beta (attractiveness parameter)</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>Gama (absorption parameter)</td>
<td>1</td>
</tr>
</tbody>
</table>

Tab.3: Input parameters of FA Algorithm

<table>
<thead>
<tr>
<th>Generator BUS NO</th>
<th>a ($/MW^2/\text{hr}$)</th>
<th>b ($/\text{MW}/\text{hr}$)</th>
<th>c ($/\text{hr}$)</th>
<th>$p_{\text{min}}$ (MW)</th>
<th>$p_{\text{max}}$ (MW)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>2.45</td>
<td>105</td>
<td>10</td>
<td>400</td>
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<td>2</td>
<td>0.005</td>
<td>3.51</td>
<td>44.1</td>
<td>20</td>
<td>80</td>
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<td>3.89</td>
<td>40.6</td>
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<td>50</td>
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<td>0.005</td>
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<td>10</td>
<td>35</td>
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<td>5</td>
<td>0.005</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>30</td>
</tr>
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</table>

Tab.4: GENERATOR CHARACTERISTICS OF IEEE 14 BUS SYSTEM

Tab.5: Comparison of bus voltages for 14 bus system using GA-OPF and FA-OPF without and with TCSC

Tab.6: Comparison of Real power loss for 14 bus system without and with TCSC (TCSC placed at line number 7)
### Tab. 7: Comparison of objective function parameters before and after installation of TCSC

<table>
<thead>
<tr>
<th>Line NO</th>
<th>Total Real Power Losses</th>
<th>Total Voltage Deviation(p.u)</th>
<th>Branch loading</th>
<th>Fuel cost</th>
<th>Objective value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GA-OFF with out TCSC</td>
<td>GA-OFF with TCSC</td>
<td>FA-OFF with out TCSC</td>
<td>FA-OFF with TCSC</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.9251</td>
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<td>5.4104</td>
<td>5.0631</td>
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<td>1206.3879</td>
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<td>1.9871</td>
<td>1.6300</td>
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</tr>
<tr>
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<td>336.207</td>
<td>364.2483</td>
<td>333.6814</td>
<td></td>
</tr>
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</table>

### Tab. 8: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

<table>
<thead>
<tr>
<th>Line NO</th>
<th>FVSI (Q14=30 MVAR)</th>
<th>FVSI (Q14=40 MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FA-OFF with out TCSC</td>
<td>FA-OFF with TCSC</td>
</tr>
<tr>
<td>1</td>
<td>0.0257</td>
<td>0.0254</td>
</tr>
<tr>
<td>2</td>
<td>0.1277</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>0.0918</td>
<td>0.013</td>
</tr>
<tr>
<td>4</td>
<td>0.1176</td>
<td>0.0202</td>
</tr>
<tr>
<td>5</td>
<td>0.0772</td>
<td>0.0247</td>
</tr>
<tr>
<td>6</td>
<td>0.0071</td>
<td>0.0429</td>
</tr>
<tr>
<td>7</td>
<td>0.0204</td>
<td>0.0171</td>
</tr>
<tr>
<td>8</td>
<td>0.1116</td>
<td>0.1309</td>
</tr>
<tr>
<td>9</td>
<td>0.0751</td>
<td>0.038</td>
</tr>
<tr>
<td>10</td>
<td>0.175</td>
<td>0.2213</td>
</tr>
<tr>
<td>11</td>
<td>0.1965</td>
<td>0.0651</td>
</tr>
<tr>
<td>12</td>
<td>0.1307</td>
<td>0.1011</td>
</tr>
<tr>
<td>13</td>
<td>0.0083</td>
<td>0.0144</td>
</tr>
<tr>
<td>14</td>
<td>0.0586</td>
<td>0.0998</td>
</tr>
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<td>15</td>
<td>0.0604</td>
<td>0.0589</td>
</tr>
<tr>
<td>16</td>
<td>0.1086</td>
<td>0.1091</td>
</tr>
<tr>
<td>17</td>
<td>0.2602</td>
<td>0.1847</td>
</tr>
<tr>
<td>18</td>
<td>0.0404</td>
<td>0.0879</td>
</tr>
<tr>
<td>19</td>
<td>0.0578</td>
<td>0.0603</td>
</tr>
<tr>
<td>20</td>
<td>0.2363</td>
<td>0.2551</td>
</tr>
<tr>
<td>Total</td>
<td>1.98</td>
<td>1.6299</td>
</tr>
</tbody>
</table>

### Tab. 9: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

<table>
<thead>
<tr>
<th>Line NO</th>
<th>FVSI (Q14=60 MVAR)</th>
<th>FVSI (Q14=70 MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FA-OFF with out TCSC</td>
<td>FA-OFF with TCSC</td>
</tr>
<tr>
<td>1</td>
<td>0.1017</td>
<td>0.0228</td>
</tr>
<tr>
<td>2</td>
<td>0.1899</td>
<td>0.0673</td>
</tr>
<tr>
<td>3</td>
<td>0.207</td>
<td>0.0073</td>
</tr>
<tr>
<td>4</td>
<td>0.2769</td>
<td>0.028</td>
</tr>
<tr>
<td>5</td>
<td>0.1777</td>
<td>0.0146</td>
</tr>
<tr>
<td>6</td>
<td>0.0532</td>
<td>0.0309</td>
</tr>
<tr>
<td>7</td>
<td>0.0413</td>
<td>0.0235</td>
</tr>
<tr>
<td>8</td>
<td>0.3341</td>
<td>0.1467</td>
</tr>
<tr>
<td>9</td>
<td>0.2482</td>
<td>0.0046</td>
</tr>
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<td>0.2145</td>
<td>0.2797</td>
</tr>
<tr>
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<td>0.4383</td>
<td>0.141</td>
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<tr>
<td>12</td>
<td>0.2409</td>
<td>0.1461</td>
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<tr>
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<td>0.0019</td>
<td>0.0537</td>
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<tr>
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<td>0.0951</td>
<td>0.1459</td>
</tr>
<tr>
<td>15</td>
<td>0.13</td>
<td>0.097</td>
</tr>
<tr>
<td>16</td>
<td>0.2462</td>
<td>0.1866</td>
</tr>
<tr>
<td>17</td>
<td>0.6884</td>
<td>0.4137</td>
</tr>
<tr>
<td>18</td>
<td>0.0747</td>
<td>0.1414</td>
</tr>
<tr>
<td>19</td>
<td>0.1561</td>
<td>0.1173</td>
</tr>
<tr>
<td>20</td>
<td>0.6324</td>
<td>0.4974</td>
</tr>
<tr>
<td>Total</td>
<td>4.5485</td>
<td>2.5475</td>
</tr>
</tbody>
</table>

From fig 3 it can be observed that by increasing the reactive load at bus number 14, total FVSI value also increases. Incorporating the TCSC in Firefly Algorithm based Optimal Power Flow total FVSI value has been reduced that indicates that line stability has been improved.
6.2. For 30 Bus System

In IEEE 30 bus system bus no 1 is considered as a slack bus and bus no’s 2,5,8,11,13 are considered as a PV buses all other buses are considered as load buses. This system has 41 interconnected lines. A MATLAB program is coded for the test system and the results have been tabulated. Table 10 represents the generators a coefficient, minimum and maximum limits of real power generation for generator buses.

Table 2 indicates that the optimal location for TCSC is line no 9. By placing the TCSC at line no 9 in both Genetic Algorithm and Firefly Algorithm based Optimal Power Flows and the results have been presented. Table 11 indicates the voltage magnitudes in FA-OPF without TCSC and FA-OPF with TCSC (By placing TCSC at line No 9). The results indicate that there is a good improvement in voltage profile with TCSC in Firefly Algorithm based OPF. The active power generation and power loss for IEEE 30 bus test system without and with TCSC is shown in Tab. 12 and it is observed that active power losses are reduced to 11.5926 MW from 12.5466 MW by placing TCSC in Firefly Algorithm based Optimal Power Flow. TCSC value was tuned to 0.0400 using Firefly Algorithm and for the same the TCSC value has been tuned to 0.0468 using Genetic Algorithm based Optimal Power Flow.

**Fig. 3:** FVSI values for different reactive load conditions

**Table 10:** GENERATOR CHARACTERISTICS OF IEEE 30 BUS SYSTEM

<table>
<thead>
<tr>
<th>Generator BUS NO</th>
<th>$a$ ($/MW^2/ \text{hr}$)</th>
<th>$b$ ($/MW/ \text{hr}$)</th>
<th>$c$ ($/\text{hr}$)</th>
<th>$p_{\text{min}}$ (M$\text{W}$)</th>
<th>$p_{\text{max}}$ (M$\text{W}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00375</td>
<td>2</td>
<td>0</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>0.0175</td>
<td>1.75</td>
<td>0</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>0.0825</td>
<td>1</td>
<td>0</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>8</td>
<td>0.00834</td>
<td>3.25</td>
<td>0</td>
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<td>35</td>
</tr>
<tr>
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<td>0.025</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>0.025</td>
<td>3</td>
<td>0</td>
<td>12</td>
<td>40</td>
</tr>
</tbody>
</table>

**Table 11:** Comparison of bus voltages for 30 bus system using GA-OPF and FA-OPF without and with TCSC

<table>
<thead>
<tr>
<th>BUS No</th>
<th>GA-OPF without TCSC</th>
<th>GA-OPF with TCSC connected at Line No 9</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC connected at Line No 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (p.u)</td>
<td>Voltage (p.u)</td>
<td>Voltage (p.u)</td>
<td>Voltage (p.u)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>2</td>
<td>1.045</td>
<td>1.045</td>
<td>1.045</td>
<td>1.045</td>
</tr>
<tr>
<td>3</td>
<td>1.0145</td>
<td>1.0196</td>
<td>1.0196</td>
<td>1.0219</td>
</tr>
<tr>
<td>4</td>
<td>1.0044</td>
<td>1.0106</td>
<td>1.0107</td>
<td>1.0135</td>
</tr>
<tr>
<td>5</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>6</td>
<td>0.9981</td>
<td>1.0043</td>
<td>0.999</td>
<td>1.0056</td>
</tr>
<tr>
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<td>0.9946</td>
<td>0.9888</td>
<td>0.995</td>
<td>0.9888</td>
</tr>
<tr>
<td>8</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>9</td>
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<td>0.991</td>
<td>0.9663</td>
<td>0.9912</td>
</tr>
<tr>
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<td>0.908</td>
<td>0.9379</td>
<td>0.9093</td>
<td>0.9371</td>
</tr>
<tr>
<td>11</td>
<td>1.0427</td>
<td>1.082</td>
<td>1.0446</td>
<td>1.082</td>
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<td>12</td>
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<td>0.9853</td>
<td>0.9532</td>
<td>0.9884</td>
</tr>
<tr>
<td>13</td>
<td>1.0085</td>
<td>1.071</td>
<td>1.0142</td>
<td>1.071</td>
</tr>
<tr>
<td>14</td>
<td>0.8874</td>
<td>0.9273</td>
<td>0.8944</td>
<td>0.9303</td>
</tr>
<tr>
<td>15</td>
<td>0.8917</td>
<td>0.9302</td>
<td>0.8974</td>
<td>0.9322</td>
</tr>
<tr>
<td>16</td>
<td>0.9218</td>
<td>0.9576</td>
<td>0.9262</td>
<td>0.9587</td>
</tr>
<tr>
<td>17</td>
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<td>0.938</td>
<td>0.9082</td>
<td>0.9377</td>
</tr>
<tr>
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<td>0.9193</td>
<td>0.8873</td>
<td>0.9202</td>
</tr>
<tr>
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<td>0.8819</td>
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<td>0.8851</td>
<td>0.9167</td>
</tr>
<tr>
<td>20</td>
<td>0.8875</td>
<td>0.9209</td>
<td>0.8902</td>
<td>0.9209</td>
</tr>
<tr>
<td>21</td>
<td>0.8735</td>
<td>0.9047</td>
<td>0.8751</td>
<td>0.904</td>
</tr>
<tr>
<td>22</td>
<td>0.8679</td>
<td>0.8993</td>
<td>0.8696</td>
<td>0.8986</td>
</tr>
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<td>0.8754</td>
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<tr>
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<td>0.8095</td>
<td>0.7777</td>
<td>0.8097</td>
</tr>
<tr>
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<td>0.8624</td>
<td>0.8388</td>
<td>0.8621</td>
</tr>
<tr>
<td>26</td>
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<td>0.8414</td>
<td>0.8172</td>
<td>0.841</td>
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<tr>
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<tr>
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<td>0.9928</td>
<td>0.9873</td>
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<td>0.8657</td>
<td>0.8834</td>
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<tr>
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<td>0.8516</td>
<td>0.8708</td>
<td>0.8523</td>
<td>0.8703</td>
</tr>
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</table>

Tab.12: Comparison of Real power loss for 30 bus test system without and with TCSC (TCSC placed at line number 9)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GA-OPF with TCSC</th>
<th>GA-OPF without TCSC</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power Generation in MW</td>
<td>300.1323</td>
<td>298.9865</td>
<td>295.9466</td>
<td>294.9926</td>
</tr>
<tr>
<td>Reactive Power Generation in MVAR</td>
<td>256.8372</td>
<td>253.2349</td>
<td>239.7242</td>
<td>237.0999</td>
</tr>
<tr>
<td>Active Losses in MW</td>
<td>16.7323</td>
<td>15.5865</td>
<td>12.5466</td>
<td>11.5926</td>
</tr>
<tr>
<td>Reactive Losses in MVAR</td>
<td>51.9372</td>
<td>47.8382</td>
<td>34.8242</td>
<td>31.9679</td>
</tr>
<tr>
<td>TCSC size</td>
<td>-------</td>
<td>0.0468</td>
<td>-------</td>
<td>0.0400</td>
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</table>
### Tab.13: Comparison of objective function parameters before and after installation of TCSC

<table>
<thead>
<tr>
<th>Objective function parameters</th>
<th>GA-OPF without TCSC</th>
<th>GA-OPF with TCSC</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Real Power Losses</td>
<td>16.7323</td>
<td>15.5865</td>
<td>12.5466</td>
<td>11.5926</td>
</tr>
<tr>
<td>Total Voltage Deviation(p.a)</td>
<td>2.4521</td>
<td>1.7663</td>
<td>2.3984</td>
<td>1.7642</td>
</tr>
<tr>
<td>Branch loading</td>
<td>5.4414</td>
<td>5.4378</td>
<td>4.6713</td>
<td>4.6066</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>1122.228</td>
<td>1118.183</td>
<td>1023.9813</td>
<td>1021.4473</td>
</tr>
<tr>
<td>FVSI for all lines</td>
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<td>5.243</td>
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</tr>
<tr>
<td>Objective function value</td>
<td>324.097</td>
<td>322.32</td>
<td>312.9326</td>
<td>311.6005</td>
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</table>

### Tab.14: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC in IEEE 30 bus system

<table>
<thead>
<tr>
<th>Line NO</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0196</td>
<td>0.0234</td>
<td>0.0164</td>
<td>0.0208</td>
</tr>
<tr>
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<td>0.1094</td>
<td>0.0934</td>
<td>0.1258</td>
<td>0.0949</td>
</tr>
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<td>3</td>
<td>0.1038</td>
<td>0.0783</td>
<td>0.126</td>
<td>0.0813</td>
</tr>
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<td>0.0238</td>
<td>0.0199</td>
<td>0.0278</td>
<td>0.0202</td>
</tr>
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<td>0.0492</td>
<td>0.037</td>
<td>0.042</td>
</tr>
<tr>
<td>6</td>
<td>0.0958</td>
<td>0.0929</td>
<td>0.0977</td>
<td>0.0914</td>
</tr>
<tr>
<td>7</td>
<td>0.039</td>
<td>0.0198</td>
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<td>0.0157</td>
</tr>
<tr>
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<td>0.0719</td>
<td>0.058</td>
<td>0.0792</td>
<td>0.0617</td>
</tr>
<tr>
<td>9</td>
<td>0.0101</td>
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<td>0.0152</td>
<td>0.002</td>
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<td>0.0192</td>
<td>0.0609</td>
<td>0.0252</td>
</tr>
<tr>
<td>11</td>
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<td>0.0563</td>
<td>0.1543</td>
<td>0.0614</td>
</tr>
<tr>
<td>12</td>
<td>0.3215</td>
<td>0.2484</td>
<td>0.3596</td>
<td>0.2599</td>
</tr>
<tr>
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<td>0.3564</td>
<td>0.4066</td>
<td>0.3642</td>
<td>0.4024</td>
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<tr>
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<td>0.3244</td>
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<tr>
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<td>0.1962</td>
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</tr>
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<td>0.0599</td>
<td>0.0907</td>
</tr>
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<td>0.0741</td>
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<td>0.1965</td>
<td>0.1543</td>
</tr>
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<td>0.0738</td>
<td>0.0372</td>
<td>0.0699</td>
</tr>
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<td>0.0166</td>
<td>0.0219</td>
<td>0.0053</td>
</tr>
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<td>0.0213</td>
<td>0.004</td>
</tr>
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</tr>
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</table>

### Tab.15: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

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So it is the best location. Optimal Power Flow (OPF) can improve the FVSI that means line stability. By increasing the reactive load FVSI values are observed that by incorporating the TCSC in Firefly Algorithm based Optimal Power Flow real power losses were minimized. Table 13 represents the voltage deviation, TCSC reactance value, total active power generation cost and active power losses for IEEE 30 bus system without TCSC and with TCSC using GA-OPF and FA-OPF. Table 14 & 15 indicates the FVSI values for Firefly Algorithm based Optimal Power Flow without and with TCSC at different reactive load conditions at bus number 14. From this table it can be observed that by increasing the reactive load FVSI values reach towards one that indicates less line stability. By installing the TCSC in Firefly Algorithm based Optimal Power Flow can improve the FVSI that means line stability has been improved.

### 6.3. For 57 Bus System

In IEEE 57 bus system, bus 1 is considered as slack bus and buses 2, 3, 6, 8, 9, 12 are considered as generator buses. It consists of 50 load buses and 80 transmission lines. From the Tab. 16 it is observed that highest positive value for CPSIn(j) is 1 for line no 76. So it is the best location for placement of TCSC in the IEEE 57 bus system. After placing the TCSC consider all the parameters of the system, generation reallocation is carried out with a multi-objective function which is formed by considering the cost of the real power generation, active power losses, voltage deviation and branch loading. Results are presented in Tab. 17 to 19.

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<th>S. No</th>
<th>Line No</th>
<th>CPSIn(j)</th>
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</table>

Fig. 4: Fig: 4 comparisons of Real Power Losses
The results from Tab. 17 show that, for minimization of the multi objective function, Firefly algorithm with TCSC, the generation cost of the best solution is 46412.3565$/hr with 44.8432 MW line loss, 4.5350 voltage deviation and 12.7971 branch loading. The results in Tab.17 indicate the values of the different parameters of the multi objective function using Firefly algorithm and Genetic algorithm considering without & with TCSC. From this table it is observed that Firefly algorithm gives better results compared to genetic algorithm. Tab.18 shows that after placing the TCSC in the system voltage profile has been improved. Tab. 19 shows the comparison of FVSI before and after installation of TCSC in IEEE 57 bus system. From this table it is observed that by incorporating the TCSC in the system improves the line based stability.

Tab.17: Comparison of objective function parameters using GA and FA-OPF considering without and with TCSC in IEEE 57 bus system

<table>
<thead>
<tr>
<th>Variables</th>
<th>GA-OPF without TCSC</th>
<th>FA-OPF without TCSC</th>
<th>GA-OPF with TCSC at line no 76</th>
<th>FA-OPF with TCSC at line no 76</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total real power generation (MW)</td>
<td>1245.255</td>
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<td>1244.255</td>
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<td>Total real power generation cost ($/hr)</td>
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<td>Active power Loss (MW)</td>
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</tr>
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<td>Voltage deviation (p.u)</td>
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</tr>
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<td>Branch loading (p.u)</td>
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Tab.18: Comparison of bus voltages for 57 bus system using FA-OPF without and with TCSC

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<th>BUS No</th>
<th>FA-OPF without TCSC</th>
<th>FA-OPF with TCSC at Line No 76</th>
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<td>Voltage (p.u)</td>
<td>Voltage (p.u)</td>
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Tab.19: Comparison of FVSI before and after installation of TCSC in IEEE 57 bus system

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<th>Line No</th>
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7. Conclusion

In this paper, Sensitivity Analysis based Complex Power Flow Sensitivity Index (CPSI) has been implemented for optimal location of TCSC. After placing the TCSC in best location, a new swarm based Firefly Algorithm has been presented to solve the optimal sizing of TCSC. The effectiveness of Firefly Algorithm was presented. The results show that incorporating the TCSC in the IEEE 14, IEEE 30 and IEEE57 bus systems can reduce the total active power losses, improve the voltage profile of the system and enhance the line stability. For finding the best size of a TCSC, Firefly Algorithm based optimization technique, with the objective of reducing total generation cost, voltage deviation, active power losses and branch loading were implemented. The comparative study of the Firefly Algorithm based Optimal Power Flow with GA based Optimal Power Flow in solving the optimal tuning problem also reflected the effectiveness of the proposed approach. The obtained results show that TCSC is the most effective series compensation device that can significantly increase the line stability of the power system.

References


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