Performance of two modified optimization techniques for power system voltage stability problems

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Abstract The development of optimization techniques in power system is to determine the sizing of Flexible AC Transmission System (FACTS) devices such as Unified Power Flow Series Compensator (UPFC) controller in improving the voltage stability and bus voltage margin. An attempt is made to modify the Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) with Hybrid-Genetic Algorithm (H-GA) for determination of sizing of the device. Fast Voltage Stability Index (FVSI) is used to identify the location of the device to be connected. The proposed methods are implemented in IEEE 30 Bus system and its results are tabulated for each technique.

1. Introduction

The development in infrastructure leads to a non-linear increase in load demand, which in turn leads to maximum utilization of power system equipments. Economic and environment are the two main factors for construction of new transmission lines. As the systems are more heavily loaded, maintenance of stability in the power system becomes a major problem with system operating very close to its instability point. There are many methods for determining the system stability, but, still research is in progress for predetermining a solution for the stability problem that could prevail in the network [1,2]. Evaluation of system stability is based on the voltage profile of each bus. The stability of the system was analyzed initially by PV curve and QV curve [3] by P. Kunder et al. Then, many other methods emerged such as L-Index [4], Modal analysis [5], Line Stability Index (Lmn) [6], Line Stability Index (LQP) [7], Bus Power Index [8], Power Transfer Stability Index (PTSI) [9], New Voltage Stability Index (NVSI) [10], Fast Voltage Stability Index (FVSI) [11,12], Global Voltage Stability Index (GVSI) [13] and other methods. Each index has its own merits and demerits in identification of the stability index of the power system network. The stability problem has provoked the use of FACTS device to improve the power system stability by injection or absorption of real and reactive power in the power system network depending upon the power

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system loading conditions. Various advantages of FACTS devices in the power system network are improvement in steady state stability, dynamic behavior of the system and system reliability.

The recent developing methods to improve the stability of power system network are to implement Optimization Technique in determining the rating for FACTS devices to be connected based on system loading pattern. In this paper, two Swarm Intelligence (SI) [14] optimization techniques are implemented to identify the FACTS device rating to be connected in the power system network based on line stability index value. The device rating is taken as optimization problem and index value of the line to which the device is connected as the fitness value. Particle Swarm Optimization (PSO) algorithm and Artificial Bee Colony (ABC) Algorithm are coded on the bases of electrical parameters and modified as Voltage Stability Particle Swarm Optimization (VS-PSO) algorithm and Voltage Stability Artificial Bee Colony algorithm (VS-ABC) is used to identify the FACTS device rating. Enhanced Genetic Algorithm (EGA) is incorporated with optimization techniques to have a higher rate of convergence and accuracy in determination of the device rating. The change in system stability, loadability and critical line is analyzed and compared with optimization techniques for FVSI index.

2. Voltage stability indices

FVSI index is formed based on two bus system for simplicity purpose and implementation in the actual system. The line diagram of two bus system model is shown in Fig. 1.

The system stability will be within the stable operating state, when the indices are from ‘0.0000’ to ‘0.9999’, above which the system is said to be in unstable state.

2.1. Fast Voltage Stability Index (FVSI)

The FVSI index was first framed by Dr. Ismail Musirin et al. in 2002 [12]. It is based on the line voltage and the reactive power which the system is said to be in unstable state. The FVSI index is formed based on two bus system for simplicity purpose and implementation in the actual system. The line diagram of two bus system model is shown in Fig. 1.

FVSI index is formed based on two bus system for simplicity purpose and implementation in the actual system. The line diagram of two bus system model is shown in Fig. 1.

The apparent power at the receiving end bus j can be written as

\[ S_j = V_j V_j^* \]

Rearranging Eq. (2) we get

\[ I = \left( \frac{S_j}{V_j} \right)^* \]

Substituting Eq. (8) in (6) and rearrange it with respect to \( P_j \)

\[ P_j = \frac{RQ_j - V_j V_j^* \sin \delta}{X_j} \]

Substituting Eq. (8) in (6) and rearrange it with respect to \( V_j \), we get

\[ V_j^2 = \frac{R^2}{X_j^2} + \frac{Q_j^2}{X_j^2} \]

To get the real roots for \( V_j \) the discriminant must be greater than or equal to zero; Eq. (9) is in the form of \( Ax^2 + Bx + C = 0 \); hence, \( B^2 - 4AC \geq 0 \)

\[ \left( \frac{R}{X_j} \sin \delta + \cos \delta \right) V_j - 4 \left( \frac{X_j + R^2}{X_j} \right) Q_j \geq 0 \]

\[ \frac{4Z^2Q_j}{(V_j)^2(R \sin \delta + X_j \cos \delta)} \leq 1 \]

Since \( \delta \) is normally very small we can assume \( \delta \approx 0 \). Hence, \( R \sin \delta \approx 0 \), \( X \cos \delta \approx X \), then Eq. (11) can be rewritten as

\[ \text{FVSI}_{ij} = \frac{4Z^2Q_j}{(V_j)^2(X_j \cos \delta)} \]

3. FACTS devices sizing

UPFC controller is selected as it has the property of both shunt and series compensation. The rating of FACTS devices [15] for UPFC controller is given in Eq. (13), to improve the power system stability and voltage profile.

\[ R_{\text{UPFC}} = r_f * 180 \text{ (MVAR)} \]

where \( r_f \) is the rating factor of the devices in the range of 0.1–1.8 for UPFC.

4. Optimization techniques

In 1940, George Dantzig was the first person to introduce the use of Optimization techniques. It is a process of finding the maxima and the minimum value of the concerned function. Initially George Dantzig used this optimization method for military application only and for further development and it
Two modified optimization techniques for power system voltage stability problems

has found its application in many places. One of the most popular optimization techniques is the Swarm Intelligence (SI) optimization. Here are few lists of the algorithm classified under SI techniques and they are Particle Swarm Optimization (PSO) algorithm, Ant Colony Optimization (ACO), Artificial Bee Colony (ABC) algorithm, Differential Evolution (DE), Artificial Immune System, Grey Wolf Optimizer, Bat Algorithm, Gravitational Search Algorithm, Altruism Algorithm, Glow-worm Swarm Optimization, River Formation Dynamics, Self-Propelled Particles, Stochastic Diffusion Search and Multi-Swarm Optimization.

Of all the SI optimization techniques most widely used techniques in many applications are PSO, ABC, ACO and DE. ABC and PSO optimization techniques are modified based on power system electrical parameters in this paper and used as an analyzing tool to predetermine the stability conduction of the power system network.

4.1. Voltage Stability Particle Swarm Optimization [VS-PSO]

4.1.1. General PSO algorithm

Dr. Kennedy and Dr. Eberhart first introduced PSO algorithm, based on the social behavior of particles. The algorithm is grouped under SI optimization techniques in the book “A New Optimizer Using Particle Swarm Theory” [16]. This PSO algorithm has found its application in many fields, where the other methods fail to optimize due to incessant and inflexibility.

In general PSO, the input parameters given are the evaluated solution. That is, the results obtained from the load flow method are fed as an input to the PSO algorithm to determine the stability index by optimization techniques. Based on the parameters to be optimized [17–20], each parameter value is restricted to its maximum and minimum values, of its current positions. Each particle moves randomly to the possible best position of all. This value is determined on the basis of the moment velocity of the particle moves to the best position. The velocity of each particle generated in each generation is swapped.

Step 1: Initialize number of populations (nbr no. of branches), weight factor (real and reactive power), minimum and maximum value.

Step 2: Based on number of populations, nbr random population is generated for the pBest.

Step 3: For each individual line velocity and position are calculated. Velocity is modified each time and position is updated until the condition is satisfied.

Step 4: The pBest solution obtained is compared with the fitness value for better solution if the better values are swapped.

Step 5: Set pBest as the gbest solution for that line.

Step 6: Repeat step 3 and step 5 for different rating factors.

Step 7: Return gBest as the best solution.

Step 8: End.

4.1.2. VS-PSO algorithm

The modification of PSO algorithm is implemented in two phases. They are as follows:

1. The input of the data to the PSO algorithm.
2. Convergence of the velocity of each particle

As stated, the input data for the general PSO algorithm are the load flow result. But, in the modified PSO algorithm the line data and bus data are given as an input to VS-PSO algorithm directly and not the converged result of NR load flow method.

The velocity of each particle generated in each generation is modified, with the generation selection process of Hybrid Genetic algorithm. Hence, the generation of each particle is modified, which internally converges the velocity of the particles at a better rate than the general PSO algorithm.

4.2. Voltage Stability Artificial Bee Colony Algorithm [VS-ABC]

4.2.1. General ABC algorithm

Karaboga in 2005 proposed the Artificial Bee Colony Algorithm [21,22] based on the honeybee swarm behavior of sharing information on finding the best nectar food source to the other bees in the hive.

In a real bee hive colony, the bees can be categorized into three types such as the onlooker bees (40–45%), the scout bees (5–10%) and the employer bee (50%). Based on the food sources the numbers of employer bee are selected, that are based on the number of lines for which the index to be found. The onlooker bees look out for the patron of the movement of the employee bee to find the best food source or position, i.e., the best index value for each line found by the employee bee and identified by the onlooker bee based on the bee patron movement. The probability of selecting a food source is given by

\[ P_i = \frac{F(\theta_i)}{\sum_{k=1}^{S} F(\theta_k)} \]

where

\[ P_i: \text{The probability of selecting the } i\text{th employed bee.} \]

\[ S: \text{The number of employed bees.} \]

\[ \theta_i: \text{The position of the } i\text{th employed bee.} \]

\[ F(\theta_i): \text{The fitness value.} \]

When the employee bee completes its tasks, the scout bee moves to the next food source, its new position is calculated with Eq. (17) and the movement of the scout bee velocity is determined by Eq. (18):

\[ x_{ij}(t + 1) = x_{ij}(t) + \varphi(x_{ij}(t) - x_{ij}(t)) \]
\[ x_i = x_i^{\min} + r \cdot (x_i^{\max} - x_i^{\min}) \]

where

- \( x_i \): The position of the onlooker bee.
- \( r \): The iteration number.
- \( k \): The randomly chosen employed bee.
- \( f \): The dimension of the solution.
- \( \Omega(\cdot) \): A series of random variables in the range.
- \( r \): A random number.

The peso code [23,24] for the ABC algorithm is given in the following steps:

1. **Step 01:** Initialize number of populations (nbr no. of branches), weight factor (real and reactive power), minimum and maximum value.
2. **Step 02:** The number of food sources is initialized as the number of line.
3. **Step 03:** For each individual bee velocity and position are calculated. Velocity is modified each time and position is updated until the condition is satisfied.
4. **Step 04:** Calculate the fitness function for the corresponding value.
5. **Step 05:** Check for the best solution that is either fitness function value or the initialized value.
6. **Step 06:** Repeat step 3 and step 5 until the fitness function value becomes the best solution.
7. **Step 07:** Check for the maximum number of iterations reached else increase count by 1 and go to step 3.
8. **Step 08:** Return the final fitness function value.
9. **Step 09:** End.

### 4.2.2. VS-ABC algorithm

In ABC algorithm too the modification is implemented in two stages.

1. Input data to the algorithm.
2. Convergence of the velocity of each particle selection of the best source of the root from the onlooker group.

The convergence of the velocity of the onlooker bees is updated with the Hybrid Genetic algorithm. It is implemented for the selection process of the best onlooker bees and updated in each stage to have convergence rate at a better rate.

The fitness function taken for the optimization problem is the line stability index after placement of UPFC controller in the power system network.

**Fitness Function** = \( \min(FVSI_{i,j}) \)

### 5. Test result and discussion

The test system considered is IEEE 30 bus system, which consists of 6 generator busses (1, 2, 5, 8, 11, 13), 49 transmission lines, 4 tap-changing transformers and 24 load busses (3, 4, 6, 7, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30); of it 6 load busses are just interconnecting load busses, which do not possess any real load power or reactive load power, and they are 6, 9, 22, 25, 27 and 28 busses. Fig. 2 shows single line representation of IEEE 30 bus system. The minimum system loading is 283.2 MW and 126.2 MVAR.

The line data along with the bus data are coded with Newton–Raphson (NR) load flow program and with the optimization techniques in the MATLAB coding environment.

The test results are sub-divided into three sub-divisions. In first sub-division of the analysis, the weak line in the system is identified by Voltage Stability Analysis (VSA) by conventional Newton–Raphson load flow method, to which the UPFC controller has to be connected. In second sub-division optimization process is implemented to determine the rating of UPFC controller to be connected in the system. These analyses are performed with two different algorithms and its results are discussed. And in last sub-division, the system bus voltage profile and line stability index after placement of UPFC are discussed.

#### 5.1. Voltage Stability Analysis

All the load busses in the system are loaded linearly until the FVSI index by the conventional NR method reaches a critical index value (0.9999). It is analyzed that the system attends its critical index, when the real power loading value is 508.0056 MW and reactive power loading value is 231.65 MVAR. The results are tabulated in Table 1 for top 10 critical lines ranked based on FVSI index value.

![Figure 2](image-url)  
**Figure 2** Single line representation of IEEE 30 bus system.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Critical line</th>
<th>Critical voltage (P.U)</th>
<th>Bus no.</th>
<th>FVSI index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36 (28–27)</td>
<td>0.7884</td>
<td>27</td>
<td>0.9999</td>
</tr>
<tr>
<td>2</td>
<td>12 (6–10)</td>
<td>0.8519</td>
<td>10</td>
<td>0.6722</td>
</tr>
<tr>
<td>3</td>
<td>38 (27–30)</td>
<td>0.8530</td>
<td>30</td>
<td>0.5988</td>
</tr>
<tr>
<td>4</td>
<td>15 (4–12)</td>
<td>0.9133</td>
<td>12</td>
<td>0.5127</td>
</tr>
<tr>
<td>5</td>
<td>2 (1–3)</td>
<td>0.9255</td>
<td>3</td>
<td>0.4809</td>
</tr>
<tr>
<td>6</td>
<td>14 (9–10)</td>
<td>1.0320</td>
<td>11</td>
<td>0.4118</td>
</tr>
<tr>
<td>7</td>
<td>16 (12–13)</td>
<td>1.0210</td>
<td>13</td>
<td>0.3774</td>
</tr>
<tr>
<td>8</td>
<td>13 (9–11)</td>
<td>0.8519</td>
<td>10</td>
<td>0.3280</td>
</tr>
<tr>
<td>9</td>
<td>37 (27–29)</td>
<td>0.7025</td>
<td>29</td>
<td>0.3243</td>
</tr>
<tr>
<td>10</td>
<td>34 (25–26)</td>
<td>0.7927</td>
<td>26</td>
<td>0.3222</td>
</tr>
</tbody>
</table>

Bold values to highlight the critical line of the system considered.
Line 36(28–27) is identified as the critical line for IEEE 30 bus system. Hence, it is feasible to connect the device at line no. 36(28–27) with a shunt terminal at bus no. 28 and a series terminal connecting toward bus no. 27. Also, the voltage profile tabulated in Table 1, shows that the voltage profile at bus no. 27 has a lower voltage profile than the remaining bus voltage profile in IEEE 30 Bus system.

5.2. UPFC controller sizing

The weak line determined by VAS analysis is coded with both the optimization techniques to determine the sizing of UPFC controller to enhance the system stability. Input data for the optimization techniques are line data, bus data and UPFC controller minimum and maximum limits. A maximum of 200 iterations are set for the optimization techniques and analysis is carried out. The result of VS-ABC and VS-PSO is tabulated in Table 2 with its sizing and FVSI line index before and after placement of UPFC controller. It could be stated that UPFC rating required by VS-ABC algorithm is much lesser than VS-PSO algorithm, as well as after placement of UPFC controller with VS-ABC algorithm rating has a lower index value than VS-PSO algorithm rating.

The fitness function values are plotted in Figs. 3 and 4 for VS-ABS and VS-PSO algorithm. Both the plots show a variation in fitness function value for each iteration. As for VS-ABC algorithm the fitness function reaches its minimum value after about 150 iterations with a sizing of 0.1828 p.u and maintains the same. But, for VS-PSO algorithm a constant change in fitness value can be seen throughout the process and does not maintain the same sizing value in any range of iteration process.

5.3. Voltage stability enhancement analysis

On consideration of the cost and space complexity the lower rating of UPFC is considered for further analysis. The UPFC device rating 0.1828 p.u by VS-ABC algorithm is incorporated with IEEE 30 bus system and loaded to its critical loading value determined in VSA. The line stability index values along with the bus voltage profile are tabulated in Table 3, for the top ranked lines tabulated in Table 1.

From Table 3 it is analyzed the change in line stability index, bus voltage profile after the placement of UPFC at line no. 36 (28–27) and the system is far away from point of instability. Overall system loadability is further increased until the system reaches its critical loading point or critical index value.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Critical line</th>
<th>Bus no.</th>
<th>No devices</th>
<th>Critical voltage (P.U)</th>
<th>Index</th>
<th>Critical voltage (P.U)</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36 (28–27)</td>
<td>27</td>
<td></td>
<td>0.7884</td>
<td>0.9999</td>
<td>0.9583</td>
<td>0.1499</td>
</tr>
<tr>
<td>2</td>
<td>12 (6–10)</td>
<td>10</td>
<td></td>
<td>0.8519</td>
<td>0.6722</td>
<td>0.8836</td>
<td>0.5386</td>
</tr>
<tr>
<td>3</td>
<td>38 (27–30)</td>
<td>30</td>
<td></td>
<td>0.8530</td>
<td>0.5988</td>
<td>0.8581</td>
<td>0.2678</td>
</tr>
<tr>
<td>4</td>
<td>15 (4–12)</td>
<td>12</td>
<td></td>
<td>0.9133</td>
<td>0.5127</td>
<td>0.9303</td>
<td>0.4663</td>
</tr>
<tr>
<td>5</td>
<td>2 (1–3)</td>
<td>3</td>
<td></td>
<td>0.9255</td>
<td>0.4809</td>
<td>0.9397</td>
<td>0.3937</td>
</tr>
<tr>
<td>6</td>
<td>14 (9–10)</td>
<td>10</td>
<td></td>
<td>0.8519</td>
<td>0.4118</td>
<td>0.8836</td>
<td>0.2574</td>
</tr>
<tr>
<td>7</td>
<td>16 (12–13)</td>
<td>13</td>
<td></td>
<td>1.0210</td>
<td>0.3774</td>
<td>1.0210</td>
<td>0.3237</td>
</tr>
<tr>
<td>8</td>
<td>13 (9–11)</td>
<td>11</td>
<td></td>
<td>1.0320</td>
<td>0.3280</td>
<td>1.0320</td>
<td>0.3470</td>
</tr>
<tr>
<td>9</td>
<td>37 (27–29)</td>
<td>29</td>
<td></td>
<td>0.7025</td>
<td>0.3243</td>
<td>0.8947</td>
<td>0.1601</td>
</tr>
<tr>
<td>10</td>
<td>34 (25–26)</td>
<td>26</td>
<td></td>
<td>0.7927</td>
<td>0.3222</td>
<td>0.8386</td>
<td>0.2119</td>
</tr>
</tbody>
</table>

**Bold values to highlight the change in voltage profile and index for the critical line.**
The system reaches its critical stability index when real load power is 572.9812 MW and 261.27803 MVAR of reactive load power. The percentage increase in load power from the minimum load with UPFC and maximum load with UPFC is found to be 12.79% for both real and reactive load power and is tabulated in Table 4.

### Table 4 System loadability enhancement with UPFC.

<table>
<thead>
<tr>
<th>Load</th>
<th>System base load</th>
<th>Minimum load with UPFC</th>
<th>Maximum load with UPFC</th>
<th>% increase in load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real load power (MW)</td>
<td>283.2</td>
<td>508.0056</td>
<td>572.9812</td>
<td>12.79</td>
</tr>
<tr>
<td>Reactive load power (MVAR)</td>
<td>126.2</td>
<td>231.65</td>
<td>261.27803</td>
<td>12.79</td>
</tr>
</tbody>
</table>

6. Conclusion

In this research, FVSI index is implemented to identify the critical line and system loading value. The two modified optimization techniques have been efficiently implemented and its results are compared for IEEE 30 bus system for selection of UPFC controller sizing to be connected. The sizing of UPFC obtained by both the optimization techniques is effectively compared and analyzed and sizing is selected to be connected. By this analysis, after controller placement the improvement in system stability and bus voltage profile are discussed. Also, maximum system loadability after placement of UPFC in the power system network is also investigated, analyzed and discussed.

### References


