MAXIMUM LOADABILITY ASSESSMENT OF IEEE-14 BUS SYSTEM USING FACTS DEVICES INCORPORATING STABILITY CONSTRAINTS

1VISHNU J, 2RISHI MENON, 3TIBIN JOSEPH, 4SASIDHARANSREEDHARAN, 5VIPINDAS P, 6SEBIN JOSEPH, 7CHITTEH V C

Email: Studentvishnu052@gmail.com, rishi.menon@saintgits.org, josephitibin@gmail.com, sasiai@gmail.com

Abstract: Considering constantly growing electricity demands and transactions, existing power networks required to be enhanced in order to increment its loadability such as to accomplish more power transfers with less network expansion cost. Existing power system loading margin can be upgraded by optimal allocation and setting of FACTS devices. This paper suggests a Particle Swarm Optimization (PSO) based algorithm to determine the optimal location and setting of FACTS devices to improve the loading margin as well as voltage stability and small signal stability. The objective function is formulated as maximizing the loadability of the power system with load generation balance as equality constraint as well as voltage stability, generation limit and line limit constraints as inequality constraint. IEEE 14 - Bus standard test system is taken into account to test the potency of the proposed approach using MATLAB/PSAT.

Keywords: Power system, Loading Margin, Optimal allocation, Stability, STATCOM, Particle Swarm Optimization, IEEE-14 bus.

I. INTRODUCTION

Recently power demand has increased extensively, although the expanse of power generation and transmission has been limited due to small-scale resources and environmental restraints. Subsequently some transmission lines are heavily loaded and system stability turns into a power transfer limiting factor. The gradual increase in demand for electric power has enforced utility companies to operate their systems closer to the limits of instability. This has aroused in stressed operating conditions, with related problems associated to system security. One of the primary issues that may relate with such a stressed system is voltage instability or voltage collapse. Voltage stability is the capability of the power system to sustain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Many events of system blackout have been announced worldwide owing to voltage collapse. Under stressed condition, one use to recover the system from voltage collapse is to provide reactive power support with FACTS controllers at appropriate locations. Locating FACTS devices is the most impressive way for utilities to advance the loading margin and voltage profile of the system. Anyway, to get better performance from these controllers, appropriate installation of these devices is vital.

Various methods have been used to find the optimal placement and control of FACTS devices to enhance loadability in transmission system. The techniques used for optimal placement of FACTS devices can be mainly divided into index based methods and optimization based methods. Earlier, a Fuzzy logic and Real Coded Genetic Algorithm based strategy is proposed for placement and sizing of shunt FACTS controller. Currently, Particle Swarm Optimization (PSO), Non-dominated Sorting Particle Swarm Optimization (NSPSO) and Genetic Algorithm based optimization techniques are also introduced to identify the optimal location together with setting of FACTS devices to improve voltage stability of the system. Multi-objective optimization methodologies are also used to find the optimal location of shunt-series FACTS controllers.

Improving the system’s reactive power handling capability by means of Flexible AC transmission System (FACTS) devices is a solution for avoidance of voltage instability issue. Enhancement of static voltage stability margin using STATCOM, TCSC and SSSC can be examined using continuation power flow process. Commonly, supplying sufficient reactive power support at the “weakest bus” or “sensitive node” increases system loading and static voltage stability limits. The bus which is ranked highest is tagged as the weakest bus as it is capable of withstanding a small amount of load before causing voltage collapse and is identified by a sensitivity based analysis called L-index method. Newton – Raphson power flow algorithm has been proposed for getting desired power transfer with Flexible AC Transmission Systems (FACTS) devices. FACTS devices can be incorporated in the Newton – Raphson power flow algorithm and, hence, whole system can be easily converted to power injection models without change of original admittance and the Jacobian matrices. Power flow algorithm has been modeled in such a way that it can easily be extended to multiple and multi-type FACTS devices by adding a new Jacobian corresponding to that new device.
Most of the researches on optimal FACTS placement are adapted to technical, economic or both concerns. In technical concerns, FACTS devices are practically installed at different locations to analyze the upsurge of loadability. While the genetic algorithm (GA) is used to select suitable locations for FACTS positioning to magnify system security as well as loadability. Differential Evolution (DE) is another important algorithm for the optimal location and control of FACTS devices to maximize the loadability. Maximization of power system loadability can be achieved by formulating a problem called mixed discrete-continuous nonlinear optimization problem (MDCP) for optimally fitting two types of FACTS devices, especially thyristor controlled series compensator (TCSC) and static var compensator (SVC) and for network reinforcement. The complexity of MDCP generates extensive simulations necessary with high computational requirements. So an ordinal optimization (OO) technique is proposed to solve the MDCP connecting above flexible ac transmission systems (FACTS) devices, for enhancing system loadability.

There are several techniques used for incorporation of differential algebraic equations (DAE) model of FACTS controllers as well as different type of loads such as a static, dynamic and composite load model in large-scale emerging power systems can be utilized for enhancement of loadability of power system network. Serious improvements in operating parameters of the power system networks such as small signal stability, transient stability, voltage profile, power transfer capability through the lines, power system oscillation damping, power system security, less active power loss, congestion management, efficiency of power system operations, quality of the power system, dynamic performances of power systems, and the increased loadability of the power system network can be attained via optimal allocation and coordination of multiple FACTS controllers in large-scale emerging power system networks.

In this paper, determination of weakest bus in IEEE 14 - bus system is performed first and then formulation of the problem for maximizing system loadability is validated through the steps of PSO. The problem formulation and subsequent steps of PSO applied to the problem are described in this paper. Enormous simulation results are supplied to highlight the approach.

II. STATCOM MODELLING

Static Synchronous Compensator (STATCOM) is a shunt connected Voltage-Source Inverter (VSI) that converts a DC input voltage into AC output voltage for compensating the active and reactive power required by the system. It is installed in parallel with a bus and regulates the voltage at the connected bus to the reference value by adjusting both voltage and angle of internal voltage source. Figures 1 and 2 show the schematic diagram and equivalent circuit of STATCOM, respectively. The STATCOM can be represented by a controllable voltage source \( V_{sh} \angle \theta_{sh} \) in the equivalent circuit. The \( V_{sh} \) can be regulated to control local bus voltage.

Power flow control equation of the STATCOM is given by Eq. (1) and the active power exchange through the DC link (operating constraint) is described by Eq. (2). Also, the mathematical description of the bus control equation is shown in Eq. (3) [18].

\[
P_{sh} + jQ_{sh} = V_{sh} \angle \theta_{sh} \left( \frac{V_i^* - V_{sh} \angle \theta_{sh}}{Z_{sh}} \right) \]

\[PE = \text{Re}(V_{sh} I_{sh}^*) = 0\]  

\[V_i - V_i^{\text{spec}} = 0\]

where,

\[V_i \angle \theta_i: i^{th} \text{ bus complex voltage}\]
The base case power is a global best and is less than or equal to the given initial position. The value of \( \lambda \) is a same ratio. The value of \( \lambda \) alters from base case (1 p.u.) to the maximum without violating the constraints. So, the objective function can be formulated as:

\[
\text{Max } \lambda(4)
\]

Where \( \lambda \) is the loadability factor in p.u.

Subjected to the following:

**B. Equality constraints**

The real and reactive power balance equations with loadability factor are:

\[
P_{gi} - \lambda P_i = P_i \quad \forall i \in N_b(5)
\]

\[
Q_{gi} - \lambda Q_i = Q_i \quad \forall i \in N_b(6)
\]

where, \( N_b \) - total number of buses

\( P_i \) - real power generation

\( P_i \) - real power demand

\( Q_{gi} \) - reactive power generation

\( Q_{gi} \) - reactive power demand

\( P_i \) - injected active power

\( Q_i \) - injected reactive power

**C. Inequality constraints**

Real power generation constraint

\[
P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad \forall i \in N_g(7)
\]

Reactive power generation constraint

\[
Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad \forall i \in N_g(8)
\]

Bus voltage constraint

\[
|V_i^{min}| \leq |V_i| \leq |V_i^{max}| \quad \forall i \in N_b \quad (9)
\]

Transmission line power flow constraint

\[
|S_i| \leq |S_i^{max}| \quad \forall i \in N_i(10)
\]

where, \( N_i \) - total number of transmission lines

\( P_{gi}^{min} \) and \( P_{gi}^{max} \) - minimum and maximum limits of real power generation

\( Q_{gi}^{min} \) and \( Q_{gi}^{max} \) - minimum and maximum limits of reactive power generation

\( |V_i^{min}| \) and \( |V_i^{max}| \) - minimum and maximum limits of bus voltage

\( |S_i| \) - magnitude of bus voltage

\( S_i^{max} \) - maximum limit of apparent power flow.

II. PSO Algorithm

**A. Overview**

PSO is a population based evolutionary computation technique developed by Eberhart and Kennedy in 1995, and was inspired by the social behavior of bird flocking and fish schooling. PSO has its essence in social psychology and artificial life as well as in computer science and engineering. In PSO, the population is termed as “swarm” and the individual in the swarm is termed as “particle”. Each particle is represented by its position and velocity and is referred to as a potential solution in n-dimensional search space of the problem. The particles fly through the problem hyperspace with some given initial velocities. In each iteration, the particles’ velocities are stochastically adjusted in consideration of the historical best position of the particles as well as their adjacent best position; where these positions are decided according to some pre-defined fitness function. Thus, the movement of each particle naturally results to an optimal or near-optimal solution.

The particle has memory, and every particle keeps track of its previous finest position and the comparable fitness value. The fitness value is also stored and this value is termed as \( P_{best} \). When a particle captures all the population as its topological neighbors, the best value is a global best and is termed as \( G_{best} \). After determining the two best values, both velocity and positions of the particle are updated according to the equations (11) and (12)

**B. Algorithm**

The algorithm for maximizing load ability with STATCOM is described below.

**Step 1:** Input bus data, line data, STATCOM data, voltage limits, line limits and PSO settings.

**Step 2:** Determine the best location for STATCOM placement by the calculation of total loadability of the system and connect STATCOM to that particular bus.

**Step 3:** Compute the base case power flow with STATCOM connected at the identified bus.

**Step 4:** Randomly produce an initial population (array) of particles with random positions as well as velocities on dimensions in the solution space. Set the iteration count \( i = 0 \).
Step 5: For each particle, compute and compare its objective function value with the individual best. If the objective value is greater than \( P_{\text{best}} \), fix this value as the current \( P_{\text{best}} \) and record the corresponding particle position.

Step 6: Choose the particle related with the minimum individual best \( P_{\text{best}} \) of all particles and set the value of \( P_{\text{best}} \) as the current overall \( G_{\text{best}} \).

Step 7: Update the velocity as well as position of particle by using the velocity and position update equations.

\[
\begin{align*}
V_{i}^{k+1} &= W 	imes V_{i}^{k} + C_{1} \times rand_{1} \times P_{\text{besti}} - S_{i}^{k} + C_{2} \times rand_{2} \times G_{\text{best}} - S_{i}^{k} \\
S_{i}^{k+1} &= S_{i}^{k} + V_{i}^{k+1}
\end{align*}
\]

Step 8: If the iteration number reaches the maximum limit, go to step 9. Else set iteration index \( i = i+1 \) and go back to step 5.

Step 9: Display the optimal solution to the target problem. The best position gives the site for STATCOM providing maximum loadability for the system.

The weight function is given by (13) [17],

\[ W = W_{\text{max}} - \frac{W_{\text{max}} - W_{\text{min}}}{\text{iter}_{\text{max}}} \times \text{iter} \]  

where,

- \( V_{i}^{k} \) = Velocity of agent \( i \) at \( k \)th iteration
- \( V_{i}^{k+1} \) = Velocity of agent \( i \) at \((k+1)\)th iteration
- \( W \) = The inertia weight
- \( W_{\text{max}} \) = Maximum weight = 0.9
- \( W_{\text{min}} \) = Minimum weight = 0.4
- \( C_{1} \) = \( C_{2} \) = Individual and social acceleration constants between 0 to 3
- \( rand_{1} = rand_{2} \) = Random numbers between 0 to 1
- \( S_{i}^{k} \) = Current position of agent \( i \) at \( k \)th iteration
- \( S_{i}^{k+1} \) = Current position of agent \( i \) at \((k+1)\)th iteration
- \( \text{iter}_{\text{max}} \) = Maximum iteration number
- \( \text{iter} \) = Current iteration number
- \( P_{\text{besti}} \) = Particle best of agent \( i \)
- \( G_{\text{best}} \) = Global best of the group

C. Optimal Parameter Value

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of particles</td>
<td>50</td>
</tr>
<tr>
<td>Number of iterations</td>
<td>50</td>
</tr>
<tr>
<td>Initial Inertial Weight</td>
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</tr>
<tr>
<td>Final Inertial Weight</td>
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<td>Individual acceleration constant</td>
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<tr>
<td>Social acceleration constant</td>
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<tr>
<td>( rand_{1} = rand_{2} )</td>
<td>0 to 1</td>
</tr>
<tr>
<td>Particle velocity</td>
<td>1</td>
</tr>
</tbody>
</table>

D. Flowchart

III. CASE STUDY AND SIMULATION RESULTS

E. Specification of Test System

The single line diagram of the IEEE 14-bus standard test system is shown in figure 4, which consists of five synchronous machines, including two generators, located at buses 1 and 2 as well as three synchronous compensators used only for reactive power support, located at buses 3, 6 and 8. The modified test system is realized by locating STATCOM at bus 14 in the original IEEE 14 - bus test system and making it as PV bus. The proposed technique was tested on IEEE 14-bus modified system. The modified test system consists of 2 generators, 3 synchronous compensators, 16 lines, 4 transformers, 11 loads and 14 buses, of which one is slack and five are PV buses. The methodology was executed in two steps. The first step is to identify the best location and setting of FACTS device and the second is the computation for maximum loadability. It is seen that, bus No. 14 is the weakest bus in IEEE.
14-bus test system. Conventionally, shunt FACTS controller is located at the weakest bus in the system and correspondingly, STATCOM is located at bus No. 14. Constant power loads (PQ loads) were used for load model and the problem was solved using Newton-Raphson power flow program. The program was coded in MATLAB.

Figure 6 shows the various bus voltage levels with STATCOM at maximum loadability case and without STATCOM at base case. The figure depicts that optimal placement of STATCOM slightly adjusted the voltages of PV buses for maximizing the loadability. The figure clearly reveals that all the bus voltages are within the set limits at maximum loadability with STATCOM at optimum location.

![Fig. 4: IEEE 14 - bus standard test system.](image)

**F. Results and Discussions**

The base case without STATCOM bus load levels is compared against the maximum loadability case with STATCOM together with PSO controller and is illustrated in figure 5. The thick dark blue bars represent the load levels at various buses at maximum loadability case with STATCOM and the white bars show the base case without STATCOM. The figure definitely indicates that loads at various buses in IEEE 14 – bus system are maximized, satisfies the objective function. Also, bus no.3 has the highest loading capability.

Figure 7 shows the bus generations with and without STATCOM. The thick dark brown bars present the active power generations at different buses at maximum loadability with STATCOM and the white bars, the base case without STATCOM.

![Fig. 7: Typical generation levels with and without STATCOM.](image)

The line flows in various lines are shown in figure 8. The thick red stacked area represents the line flows with STATCOM at maximum loadability case and the blue area gives the line flows without STATCOM, the base case.

![Fig. 8: Typical line flows with and without STATCOM.](image)
The active power flows in various lines are shown in figure 9. The yellow area represents the active power flows with STATCOM and the green stacked area represents the active power flows without STATCOM, the base case.

![Graph showing typical line real power flow with and without STATCOM.](image)

**Fig. 9:** Typical line real power flow with and without STATCOM.

Figure 10 shows the eigen values of the system with controller. From figure it is clear that all eigen values are present at the left hand side of the S-plane. So the system is stable.

![Graph showing eigen values of the stable system.](image)

**Fig. 10:** Eigen values of the stable system.

**CONCLUSION**

In this paper, implementation of PSO is executed, efficiently and successfully to identify optimal location of STATCOM to maximize the transmission system loadability as well as to improve the voltage profile and small signal stability margins. With this algorithm, it is able to find out the optimal solutions easily with nearly small number of particles and iterations, hence with less computational effort. Tests are performed on the IEEE-14 bus system. Results showed that the implementation of PSO has enhanced the transmission system loadability with increased voltage profile.

**REFERENCES**


Maximum Loadability Assessment of IEEE 14 Bus System by Using FACTS Devices Incorporating Stability Constraints
