Particle Swarm Optimization for Optimal Allocation of STATCOM on Transmission Network

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Abstract. Static Synchronous Compensator (STATCOM) is one of the members of flexible alternating current transmission systems (FACTS) devices that controls one or more network parameters to increase system power transfer capability. However, it needs be optimally allocated to fully maximize its usage. Allocation of STATCOM simply refers to optimal placement and size of a STATCOM to solve some of the transmission network problems. This paper therefore utilizes particle swarm optimization (PSO) to allocate STATCOM to enhance the system voltage magnitudes and minimize the active power loss. A Matlab programme was developed for the proposed method and applied to IEEE 14 bus network and the results presented. The results showed that the total active power loss was reduced by 6.90%. The voltage magnitudes at buses 7 and 13, which were above the upper voltage limit, were reduced and brought to within acceptable voltage limits and hence improvement in the system voltage profile. Therefore, the optimal allocation of STATCOM improves the efficiency and operation of the network.

1. Introduction
Power is transmitted to load centers from the generating station primarily via the transmission systems. The transmission network bears the overhead or underground lines that transport the generated power from generating station to the distribution substations [1]. The two main functions of transmission systems are to transport the generated electrical power from the power generation stations to primary sub-stations and link two or more generation stations [2].

Increase in population and industrialization has resulted in increase in power demand. Consequently, the power line losses and hence voltage profile deviation, occurs due to inadequate reactive power in the network. Inadequate reactive power could result in system voltage collapse hence disruption of power to industrial and domestic consumers [3].

The solution to these problems is either the expansion/construction of a new transmission line, which is expensive, or by means of reactive power compensation. Reactive power compensation is achieved by either capacitor bank or FACTS device placements. STATCOM is a power electronics-based static controller that can control some of the system parameters so as to increase power transfer capability. It has been effectively utilized to regulate voltage and minimize power loss in transmission systems [4].

To effectively utilize a STATCOM device in transmission network, it needs to be appropriately allocated. Several methodologies for solving optimal placement of STATCOM devices have been proposed which include genetic algorithm (GA), biogeography-based optimization (BBO), evolutionary programming (EP) [5], etc. This paper implemented PSO algorithm to optimally allocate STATCOM with the objective to minimize active power loss and voltage magnitude deviations to improve the system performance. Simulations were performed on IEEE 14-bus network.
2. Structure and mode of operation of STATCOM

STATCOM is a shunt connected controller and a switching converter type static VAR generator, which can either generate or absorb reactive power through several switching patterns within its converter, without the use of any capacitor or inductor banks [6]. It is optimally placed in the transmission network to compensate for reactive power to minimize losses and improve voltage profile. Figure 1 shows the simple configuration of STATCOM. The VSC is the essential electronic part, which is responsible for converting dc voltage to a set of output voltages with desired frequency, amplitude, and phase [7]-[8]. The exchange of reactive power between the network and converter is controlled by changing the converter 3-phase output voltage amplitude $V_{vsc}$. When the converter output voltage $V_{vsc}$ is greater than the ac bus voltage $V_{ac}$ (i.e. $V_{vsc} > V_{ac}$), reactive power is injected to the network by the STATCOM otherwise, it absorbs reactive power from the network. Also, if the magnitude of $V_{vsc}$ and $V_{ac}$ are equal (i.e. $V_{vsc} = V_{ac}$), the STATCOM will be in standby mode. The STATCOM power flow equations are expressed in equation (1) to equation (4) [9].

$$P_m = P_{sh} + \sum_{j=1}^{N} |V_m||V_j||y_{mj}| \cos (\theta_m - \delta_{mj}) \quad (1)$$

$$Q_m = Q_{sh} + \sum_{j=1}^{N} |V_m||V_j||y_{mj}| \sin (\theta_m - \delta_{mj}) \quad (2)$$

$$P_{sh} = G_{sh} |V_{m}|^2 - |V_{m}||V_{m}||y_{sh}| \cos (\theta_{sh} - \delta_{sh}) \quad (3)$$

$$Q_{sh} = B_{sh} |V_{m}|^2 - |V_{m}||V_{m}||y_{sh}| \sin (\theta_{sh} - \delta_{sh}) \quad (4)$$

where, $V_m \angle \theta_m$ = voltage and phase at bus $m$, $V_{sh} \angle \theta_{sh}$ = injected shunt voltage and its phase angle. $P_m$, $Q_m$ = real and reactive powers at bus $m$, $P_{sh}$, $Q_{sh}$ = real and reactive power STATCOM connected bus, $G_{sh}$, $Y_{sh}$, and $B_{sh}$ = conductance, susceptance, and admittance of the STATCOM, respectively, $y_{sh}$ = admittance of the line between node $m$ and $j$, $N$ = number of buses connected to bus $m$.

3. Problem formulation

3.1 Load flow analysis

It involves the solution of a set of nonlinear algebraic equations of power system under steady-state conditions. In this work Newton Raphson method of solving power flow problems was adopted. And the STATCOM power equations were incorporated into the existing power flow algorithm.
3.2 Objective function
The objective function is the mathematical expression that reduces power loss as given in equation (5):

\[ \text{Min } P_{\text{loss}} = \sum_{i=1}^{n} G_i (V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}) \]  \hspace{1cm} (5)

3.2.1 Equality constraints. These are the power balanced equations that are expressed as equation (6) and equation (7), below

\[ P_{Gi} - P_{Di} = P_i (V, \delta) \]  \hspace{1cm} (6)

\[ Q_{Gi} - Q_{Di} = Q_i (V, \delta) \]  \hspace{1cm} (7)

3.2.2 Inequality constraints. These are the limitation imposed on the system and the STATCOM limit; Eq. (8), below gives voltage constraints on the generator (PV) buses.

\[ V_{\text{min}}^i \leq V_i \leq V_{\text{max}}^i \]  \hspace{1cm} (8)

The load (PQ) bus reactive power generation limit is expressed as equation (9):

\[ Q_{\text{min}}^{\text{max}} \leq Q_{Gi} \leq Q_{\text{max}}^{\text{max}} \]  \hspace{1cm} (9)

3.3 Particle swarm optimization algorithm
The PSO is defined by [10] with equation (10) and equation (11) updating the personal and global best, respectively as:

\[ y(t+1) = \begin{cases} y_i(t) & \text{if } f(y_i(t)) \leq f(x_i(t+1)) \\ x_i(t+1) & \text{if } f(y_i(t)) > f(x_i(t+1)) \end{cases} \]  \hspace{1cm} (10)

\[ y(t) = \min \{ f(y), f(x(t)) \} \]  \hspace{1cm} (11)

Every of the particles is updated at every of the iterations according to equation (10) and equation (11).

The velocity \( v_i, (t+1) \), is updated according to equation (12)

\[ v_i, (t+1) = w v_i, (t) + c_1 r_1 (t) [y_i, (t) - x_i, (t)] + c_2 r_2 (t) [x_i, (t) - x_i, (t)] \]  \hspace{1cm} (12)

The next position is given by equation (13)

\[ x_i(t+1) = x_i(t) + v_i(t+1) \]  \hspace{1cm} (13)

Where, \( x_i, y_i \), and \( v_i \) are current position, current personal best position and velocity of the \( j \)th dimension of the \( i \)th particle.

The inertial weight, in equation (12) that controls PSO convergence behavior given as equation (14).

\[ w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \cdot \text{iter} \]  \hspace{1cm} (14)

Where, \( \text{iter}_{\text{max}} \) = maximum number of iteration, \( \text{iter} \) = current iteration number, \( w_{\text{max}} \) and \( w_{\text{min}} \) are the maximum and minimum number of weighting factors.

3.4 PSO algorithm applied to IEEE 14 bus system
The algorithm for the methodology of this work is given as follows

1. Definition of the control variables, population size and iteration number including PSO parameters and IEEE 14-bus system data.
2. Set \( \text{iter} = 0 \).
3. Randomly generate the particle populations and their velocities.
4. Run N-R load flow for each of the particles to obtain losses.
5. For each particle, compute the fitness function by equation (10).
6. Find Pbest and best of the particles from their fitness function.
7. Set \( \text{iter} = \text{iter} + 1 \) if the current fitness \( P \) of each of the particles is better than \( P_{\text{best}} \).
8. Compute each particle velocity by equation (12) and check possibility of any limit violations.
9. Compute new particle position by equation (13).
10. Run N-R load flow with STATCOM incorporated for each of the particles and obtain the losses.
11. Compute the fitness function of each by equation (10).
12. If the current fitness \( P \) of each of the particles is better than \( P_{\text{best}} \) then set \( P_{\text{best}} = P \)
13. Set \( g_{\text{best}} \) as \( P_{\text{best}} \).
14. Repeat steps 7 to 13 until convergence is achieved.

4. Results and discussion

The load flow solution results and the effectiveness of PSO for optimal STATCOM placement for reducing active power loss and improving voltage magnitudes on IEEE 14-bus network in [10], are discussed in this section. Table 1 shows the control variables for PSO parameters used in this research.

| S/N | Control Variable                        | Limit          |
|-----|----------------------------------------|----------------|
| 1   | Generator Voltage                      | (0.95 – 1.05) p.u. |
| 2   | Transformer Tap Settings                | (0.90 – 1.10) p.u. |
| 3   | MVAR by Static Compensator             | (0.00–100) MVAR |

4.1 Voltage profile improvement with PSO placed STATCOM
Table 2 presents the results of voltage magnitudes for load flow solution. The voltage magnitudes at buses 7 and 13 for base case are 1.068 and 1.067 p.u., respectively. These violated the upper voltage limit. However, with PSO algorithm, the optimal location and size of STATCOM were bus 11 and 8.96 MVAR, respectively. When the optimal size of STATCOM (8.96 MVAR) was placed at the optimal location (bus 11), the voltage magnitudes at buses 7 and 13 were reduced to 1.040 and 1.035 p.u., respectively. The incorporation of STATCOM with PSO ensures that bus voltage limit is not violated. The implementation of this, resulted in improvement in the overall network voltage profile. The graph showing the voltage profile comparison is depicted in figure 2. All the terminal voltages are within acceptable voltage limits resulting into a more stable network operation and performance.

| Bus No. | Bus Type | Steady State (Base Case) Voltage Magnitude (p.u.) | STATCOM (PSO placed) Voltage Magnitude (p.u.) |
|---------|----------|-------------------------------------------------|-----------------------------------------------|
| 1       | Swing    | 1.060                                           | 1.060                                         |
| 2       | PV       | 1.045                                           | 1.048                                         |
| 3       | PV       | 0.960                                           | 0.982                                         |
| 4       | PQ       | **0.969**                                       | **0.978**                                     |
| 5       | PQ       | 0.963                                           | 0.978                                         |
| 6       | PV       | 1.020                                           | 1.012                                         |
| 7       | PQ       | **1.068**                                       | **1.040**                                     |
| 8       | PV       | 0.990                                           | 0.972                                         |
| 9       | PQ       | 1.027                                           | 1.026                                         |
| 10      | PQ       | 1.033                                           | 1.031                                         |
| 11      | PQ       | 1.030                                           | 1.025                                         |
| 12      | PQ       | 1.033                                           | 1.026                                         |
| 13      | **PQ**   | **1.067**                                       | **1.035**                                     |
| 14      | PQ       | 1.047                                           | 1.044                                         |
Figure 2. Bus voltage profile

4.2 Active power loss reduction with PSO placed STATCOM

Table 3 gives the details of the active power loss for the base case and when PSO was optimally allocated. The total loss without any device stood at 6.251 MW which reduced by 0.432 MW, corresponding to 6.90%, when STATCOM was incorporated with PSO optimization algorithm. The losses on various lines are well detailed in Table 3. In figure 3, a comparison of the effect of STATCOM device on active power loss reduction, based on optimally placed method, is depicted for better understanding.

| Bus No. | Bus Type | Steady State Base Case (MW) | STATCOM (PSO placed) (MW) |
|---------|----------|----------------------------|---------------------------|
| 1       | 2        | 2.366                      | 2.336                     |
| 1       | 5        | 1.165                      | 1.130                     |
| 2       | 3        | 0.942                      | 0.792                     |
| 2       | 4        | 0.729                      | 0.689                     |
| 2       | 5        | 0.388                      | 0.358                     |
| 3       | 4        | 0.221                      | 0.142                     |
| 4       | 5        | 0.222                      | 0.024                     |
| 4       | 7        | 0.000                      | 0.024                     |
| 4       | 9        | 0.000                      | 0.028                     |
| 5       | 6        | 0.000                      | 0.020                     |
| 6       | 11       | 0.019                      | 0.019                     |
| 6       | 12       | 0.029                      | 0.002                     |
| 6       | 13       | 0.086                      | 0.046                     |
| 7       | 8        | 0.000                      | 0.020                     |
| 7       | 9        | 0.000                      | 0.020                     |
| 9       | 10       | 0.007                      | 0.017                     |
| 9       | 14       | 0.052                      | 0.012                     |
| 10      | 11       | 0.004                      | 0.014                     |
| 12      | 13       | 0.002                      | 0.002                     |
| 13      | 14       | 0.019                      | 0.003                     |
| **Total** |          | **6.251**                  | **5.819**                 |
Figure 3. Active loss reduction

5. Conclusion
In this research, the use of PSO for optimal allocation of STATCOM has been discussed. The following conclusions were made, optimal parameter setting and location of STATCOM were able to improve the network voltage profile so that the voltage magnitudes of all the buses were brought to within acceptable voltage limits. Also, the overall active power loss on the transmission line was reduced. Therefore, this study shows the effectiveness of PSO for STATCOM optimal allocation.

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