COMPARATIVE ANALYSIS OF PERFORMANCE OF SHUNT FACTS DEVICES USING PSO BASED OPTIMAL POWER FLOW SOLUTIONS

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Abstract*: This paper incorporates two FACTS devices such as SVC and STATCOM in optimal power flow solutions to enhance the performance of the power systems. The particle swarm optimization (PSO) is used for solving the optimal power flow problem for steady-state studies by maintaining thermal and voltage constraints. The effectiveness of the proposed approach has been examined and tested on the standard IEEE 14-bus test system with shunt FACTS devices. Results show that the proposed algorithm gives better solutions to enhance the system performance with STATCOM compared to SVC.*

Keywords: *Optimal Power Flow, Particle Swarm Optimization (PSO) technique, shunt FACTS devices, Newton Raphson's method.*

1. Introduction

In today's highly complex and interconnected power systems, there is a great need to improve electric power utilization while still maintaining reliability and security. While power flows in some of the transmission lines are well below their normal limits, other lines are overloaded, which has an overall effect on deteriorating voltage profiles and decreasing system stability and security. Because of all that, it becomes more important to control the power flow along the transmission lines to meet the needs of power transfer. On the other hand, the fast development of solid-state technology has introduced a series of power electronic devices that made FACTS a promising pattern of future power systems. Power flow is a function of transmission line impedance, the magnitude of the sending end and receiving end voltages and the phase angle between voltages. By controlling one or a combination of the power flow arrangements, it is possible to control the active, as well as, the reactive power flow in the transmission line [1]. With FACTS technology [2], such as Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs),
Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controller (UPFC) etc., bus voltages, line impedances and phase angles in the power system can be regulated rapidly and flexibly. Thus, FACTS can facilitate the power flow control, enhance the power transfer capability, decrease the generation cost, and improve the security and stability of the power system.

In this paper, the shunt FACTS devices such as, SVC and STATCOM controllers are incorporated to solve an optimization problem with different objectives such as minimization of cost of generation, real power loss, voltage profile enhancement and improvement of voltage stability L-index as these are the basis for improved system performance. The particle swarm optimization(PSO) based algorithm is used effectively to solve the optimal power flow problem, it present great characteristics and capability of determining global optima, incorporating a set of constraints including voltage stability and FACTS devices. In order to calculate the power losses and check the system operating constraints such as voltage profile, a load flow model is used. An existing Newton-Raphson load flow algorithm is introduced [2]. In this paper, this model is further modified in order to include the SVC and STATCOM devices presented into the network, and PSO has applied to enhance the performance of the power systems. The effectiveness of the proposed method was tested on standard IEEE 14-bus system and comparison was made on the performance of the two FACTS devices.

Further investigations can be carried out by the installation of shunt reactive power sources involves the investment cost. The location of FACTS device and its size also involves the investment cost. These issues can be considered in the solution of optimal power flow problems with different objective functions.

2. Voltage Stability Index (L-index)

The voltage stability L-index is a good voltage stability indicator with its value change between zero (no load) and one (voltage collapse) [3-5] the voltage stability index is computed as (1)

$$L_j = \left| 1 - \sum_{i=1}^{g} \overline{F}_{ji} \frac{\overline{V}_i}{\overline{V}_j} \right| \quad (1)$$

The values of F_{ji} are obtained from the network *Y*-bus matrix. An L_j -index value away from 1 and close to 0 indicates an improved system security. The advantage of this L_j -index lies in the simplicity of the numerical calculation and expressiveness of the results.

3. Shunt FACTS controllers

The shunt FACTS controllers [6-8] such as static var compensator and statcom are the most recent developed power electronic controllers, makes possible to control nodal voltage or reactive power injected at the selected bus for optimal operation of power systems.

3.1 Static Var Compensator Models

A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control the bus voltage by adjusting reactance with either firing angle limits or reactance limits. The transfer admittance equation for the variable shunt compensator, in general, is given by (2),

$$I = jB.V_k \quad (2)$$

The reactive power equation is,

$$Q_k = -V_k^2 B \quad (3)$$

3.1.1 Total Susceptance Model (B = B_{SVC})

The linearized equation for the total susceptance model, with susceptance (B_{SVC}) as the state variable, is given by (4) and is derived from the figure1.

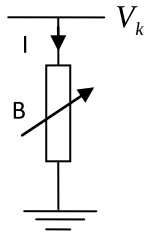

Figure 1. Variable shunt susceptance

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^i = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix}^i \begin{bmatrix} \Delta \theta_k \\ \Delta B_{SVC}/B_{SVC} \end{bmatrix} \quad (4)$$

At the end of i^{th} iteration, the variable shunt susceptance B_{SVC} is updated according to the equation (5),

$$B_{SVC}^{i+1} = B_{SVC}^{i} + \left(\frac{\Delta B_{SVC}}{B_{SVC}} \right)^i .B_{SVC}^{i} \quad (5)$$

This changing susceptance represents the total SVC susceptance necessary to maintain the nodal voltage magnitude to a specified value.

3.1.2 Firing Angle Model (B =B_{eq})

The linearized equation for the SVC f*iring angle model*, with f*iring angle* as the state variable, is given by (6) and is derived from the figure 2.

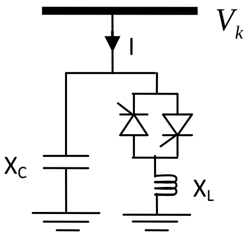

Figure 2. SVC structure

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^i = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{\partial Q_k}{\partial \alpha} \end{bmatrix}^i \begin{bmatrix} \Delta \theta_k \\ \alpha \end{bmatrix}^i \quad (6)$$

Where $\dfrac{\partial Q_k}{\partial \alpha} = \dfrac{2V_k^2}{X_L}\left(\cos(2\alpha)-1\right).$

At the end of i^{th} iteration, the variable firing angle α is updated according to (7),

$$\alpha^{i+1} = \alpha^i + \Delta\alpha^i \quad (7)$$

and the new SVC susceptance B_{eq} is calculated. Thus, the susceptance model and the firing angle model observe good numerical properties.

3.2 Static synchronous Compensator (STATCOM)

The STATCOM is solid-state synchronous converter which consists of VSC and its associated shunt-connected transformer. By incorporating STATCOM, the output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus. A schematic representation of the STATCOM circuit is shown in figure 3.

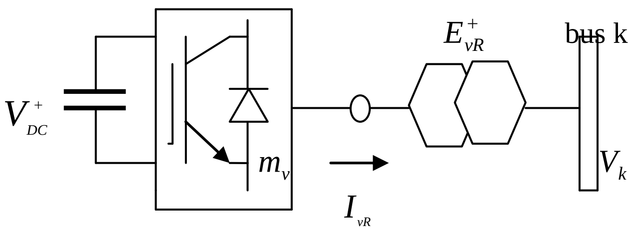

Figure 3. STATCOM circuit

The transfer admittance equation can be written as (8)

$$[I_k] = [Y_{vR} \quad Y_{vR}]\begin{bmatrix} V_k \\ E_{vR} \end{bmatrix} \quad (8)$$

The active and reactive power flow equations for the converter and bus k respectively,

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR}V_k[G_{vR}\cos(\delta_{vR}-\theta_k) + B_{vR}\sin(\delta_{vR}-\theta_k)], \quad (9)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR}V_k[G_{vR}\sin(\delta_{vR}-\theta_k) - B_{vR}\cos(\delta_{vR}-\theta_k)] \quad (10)$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR}[G_{vR}\cos(\theta_k-\delta_{vR}) + B_{vR}\sin(\theta_k-\delta_{vR})], \quad (11)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR}[G_{vR}\sin(\theta_k-\delta_{vR}) - B_{vR}\cos(\theta_k-\delta_{vR})] \quad (12)$$

The linearized equation for STATCOM model is given by,

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_k}{\partial \theta_k} & \dfrac{\partial P_k}{\partial V_k}V_k & \dfrac{\partial P_k}{\partial \delta_{vR}} & \dfrac{\partial P_k}{\partial V_{vR}}V_{vR} \\ \dfrac{\partial Q_k}{\partial \theta_k} & \dfrac{\partial Q_k}{\partial V_k}V_k & \dfrac{\partial Q_k}{\partial \delta_{vR}} & \dfrac{\partial Q_k}{\partial V_{vR}}V_{vR} \\ \dfrac{\partial P_{vR}}{\partial \theta_k} & \dfrac{\partial P_{vR}}{\partial V_k}V_k & \dfrac{\partial P_{vR}}{\partial \delta_{vR}} & \dfrac{\partial P_{vR}}{\partial V_{vR}}V_{vR} \\ \dfrac{\partial Q_{vR}}{\partial \theta_k} & \dfrac{\partial Q_{vR}}{\partial V_k}V_k & \dfrac{\partial Q_{vR}}{\partial \delta_{vR}} & \dfrac{\partial Q_{vR}}{\partial V_{vR}}V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \dfrac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \dfrac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \quad (13)$$

Where, the voltage magnitude V_{vR} and phase angle δ_{vR} are taken as state variables.

4. Mathematical formulation of OPF problem

The OPF problem can be mathematically stated as,

Minimize $F = \sum\left(a_i P_{gi}^2 + b_i P_{gi} + c_i\right)$ (14)

The minimization problem is subjected to the following equality and inequality constraints [9-11]

4.1 Equality Constraints

These are the sets of nonlinear power flow equations that govern the power

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (15)$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (16)$$

Where P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at bus i respectively, the load demand at the same bus is represented by P_{Di} and Q_{Di}, and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij}.

4.2 Inequality Constraints

These are the set of constraints that represent the system operational and security limits like the bounds on the following:

(i) Generators real and reactive power outputs

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, \forall i \in ng \quad (17)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, \forall i \in ng \quad (18)$$

(ii) Voltage magnitudes at each bus in the network

$$V_i^{\min} \le V_i \le V_i^{\max}, \forall i \in NL \quad (19)$$

Where NL is the number of load buses

(iii) Transformer tap settings

$$T_i^{\min} \le T_i \le T_i^{\max}, \forall i \in nt \quad (20)$$

(iv) Reactive power injections due to capacitor banks

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, \forall i \in cs \quad (21)$$

(v) Transmission lines loading

$$S_i \le S_i^{\max}, \forall i \in nl \quad (22)$$

(vi) Voltage stability index

$$L_j \le L_j^{\max}, \qquad \forall j \in NL \quad (23)$$

(vii) FACTS device constraint:

$$B_{svc}^{\min} \le B_{svc} \le B_{svc}^{\max} \text{ SVC susceptance} \quad (24)$$

$$V_{vR}^{\min} \le V_{vR} \le V_{vR}^{\max} \text{ STATCOM voltage magnitude} \quad (25)$$

$$\delta_{vR}^{\min} \le \delta_{vR} \le \delta_{vR}^{\max} \text{ STATCOM voltage angle} \quad (26)$$

The equality constraints are satisfied by running the power flow program. The generator bus real power generations (P_{gi}), generator terminal voltages (V_{gi}), transformer tap settings (T_i), the reactive power compensation (Q_{Ci}), SVC target node voltage (V_k) are the control variables and they are self-restricted by the representation itself. The active power generation at the slack bus (P_{gs}), load bus voltages (V_{Li}) and reactive power generation (Q_{gi}), line flows (S_i), and voltage stability (L_j)-index are state variables which are restricted through penalty function approach.

5. Overview of Particle Swarm Optimization

PSO is one of the optimization techniques and belongs to evolutionary computation techniques [12]. PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each individual (agent) is represented by XY axis position Modification of the agent position is realized by the position and velocity information.

An optimization technique based on the above concept can be described as follows: namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value so far in the group (gbest) among pbests. Each agent tries to modify its position. This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 * (pbest_i - s_i^k) \quad + c_2 rand_2 * (gbest - s_i^k) \qquad (27)$$

Where,

- v_i^k : velocity of agent i at iteration k,
- w : weighting function,
- c_1 & c_2 : weighting factors,
- rand : random number between 0 and 1
- s_i^k : Current position of agent i at iteration k,
- $pbest_i$: the pbest of agent i,
- gbest : gbest of group

Using the above equation, a certain velocity which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \qquad (28)$$

6. **Overall Computational Procedure for solving the problem**

The implementation steps of the proposed PSO based algorithm [13-15] can be written as follows:

Step 1: Input the system data for load flow analysis

Step 2: Select a FACTS device and its location in the system

Step 3: At the generation Gen =0; set the simulation parameters of PSO parameters and randomly initialize k individuals within respective limits and save them in the archive.

Step 4: For each individual in the archive, run power flow under the selected network contingency to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.

Step 5: Evaluate the penalty functions

Step 6: Evaluate the objective function values and the corresponding fitness values for each individual.

Step 7: Find the generation local best **xlocal** and global best **xglobal** and store them.

Step 8: Increase the generation counter Gen = Gen+1.

Step 9: Apply the PSO operators to generate new k individuals

Step 10: For each new individual in the archive, run power flow to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.

Step 11: Evaluate the penalty functions

Step 12: Evaluate the objective function values and the corresponding fitness values for each new individual.

Step 13: Apply the selection operator of PSO and update the individuals.

Step 14: Update the generation local best **xlocal** and global best **xglobal** and store them.

Step 15: If one of stopping criterion have not been met, repeat steps 4-14. Else go to stop 16.

Step 16: Print the results.

7. Simulation results

The proposed PSO algorithm to solve optimal power flow problems incorporating shunt FACTS devices for enhancement of system performance is tested on standard IEEE 14-bus test system.
The PSO parameters used for the simulation are summarized in Table 1

Table 1
Optimal parameter settings for PSO

Parameter	PSO
Population size	20
Number of iterations	150
Cognitive constant, c1	2
Social constant, c2	2
Inertia weight, W	0.3-0.95

The network and load data for this system is taken from [16]. To test the ability of the proposed PSO algorithm ,one objective function is considered for the minimization using the proposed PSO algorithm. In order to show the affect of power flow control capability of the shunt FACTS devices in proposed PSO algorithm, three sub case studies are carried out on standard IEEE 14-bus system.

Case (a): power system normal operation.

Case (b): one SVC is installed at 6^{th} bus for a target voltage value of 1 per unit and with B_{SVC} value of 0.1PU and $1 \leq B_{SVC} \leq -1$.

Case (c): one STACOM is installed at 6th bus for a target voltage value of 1 per unit with V_{vR} value of 1.0 and 1.1 ≤ V_{vR} ≤ 0.9. and with δ_{vR} value of 0 and pi ≤ δ_{vR} ≤ -pi.

The first case is the normal operation of network without using any FACTS device. In second and third cases, optimal location of one device has been considered.
From the Table 2 it can be seen that details of the control variables and the STATCOM location at bus 6 gives the best performance of the system compared to the location of SVC in terms of reduction in cost of generation, power loss reduction, maximum of voltage stability indices.

Table 2 Optimal settings of control variables for standard IEEE14-bus system

Control Variables	Limits(p.u)		Without FACTS	With FACTS	
	Min	Max		SVC	STATCOM
P_{G1}	0.0	3.324	1.9447	1.9418	1.9550
P_{G2}	0.0	1.400	0.3647	0.3685	0.3686
P_{G3}	0.0	1.000	0.2919	0.3028	0.3030
P_{G4}	0.0	1.000	0.0000	0.0004	0
P_{G5}	0.0	1.000	0.0830	0.0702	0.0578
V_{G1}	0.95	1.10	1.0557	1.0559	1.0592
V_{G2}	0.95	1.10	1.0292	1.0311	1.0355
V_{G3}	0.95	1.10	1.0046	1.0005	1.0025
V_{G4}	0.95	1.10	0.9961	1.0331	1.0430
V_{G5}	0.95	1.10	0.9974	1.0440	1.0489
Tap – 1	0.9	1.1	1.0152	0.9324	0.9710
Tap – 2	0.9	1.1	0.9488	1.0272	0.9572
Tap - 3	0.9	1.1	1.0539	1.0008	0.9854
Q_{C6}	0.0	0.10	0.0639	0.1000	0.0644
Q_{C8}	0.0	0.10	0.0357	0.0580	0.0334
Q_{C14}	0.0	0.10	0.0556	0.0832	0.0739
Cost ($/h)			8087.200	8085.00	8084.600
Ploss (p.u.)			0.0942	0.0936	0.08900
Ljmax			0.0872	0.0770	0.0765
CPU time (s)			120.0470	133.203	138.8120

The Figure 4. shows the convergence characteristic of the cost of generation without and with SVC/STATCOM (one at a time) at optimal location.

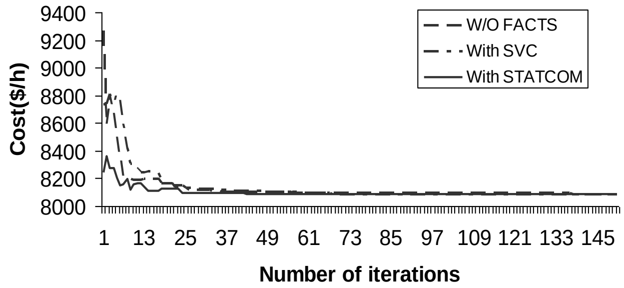

Figure 4 Convergence of cost of generation without and with FACTS device for IEEE 14-bus system

The Figures 5-6 shows the percentage MVA loading of the lines, voltage profiles, voltage angles, and voltage stability indices of buses without and with SVC/STATCOM optimal location.

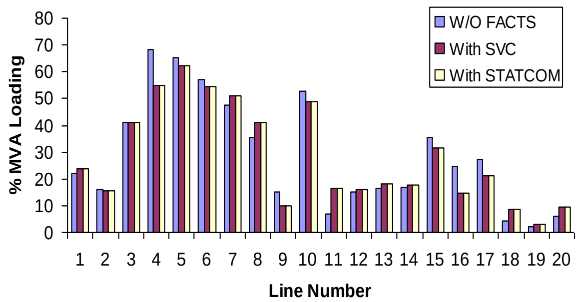

Figure 5 Percentage MVA line loadings of IEEE 14-bus system after optimization without and with SVC/STACOM

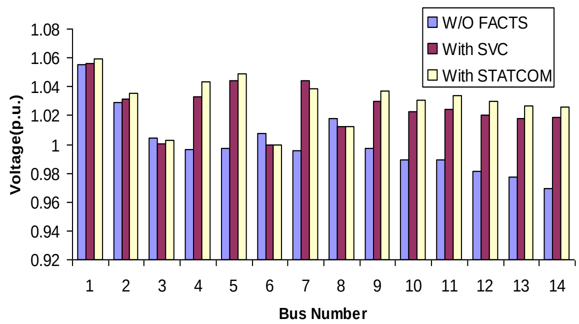

Figure 6 Voltage profiles of IEEE 14-bus system after optimization without and with SVC/STATCOM

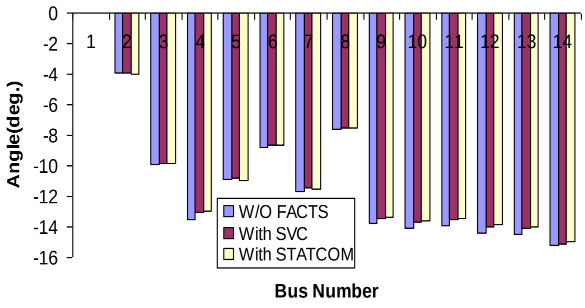

Figure 7 Voltage angles of IEEE 14-bus system after optimization without and with SVC/STATCOM

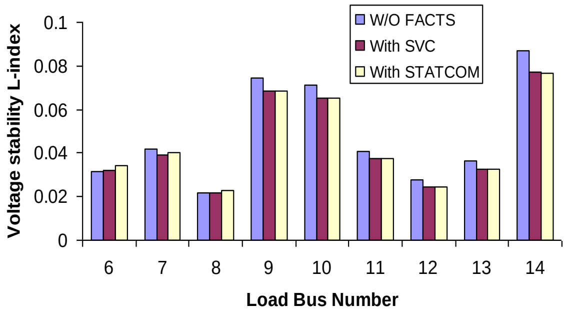

Figure 8 Voltage stability indices of IEEE 14-bus system after optimization without and with SVC/STATCOM

8. Conclusions

This paper has presented an OPF model incorporating shunt FACTS controllers such as SVC and STATCOM using the PSO algorithm for enhancement of system performance. This model is able to solve power networks of any size and converges with minimum number of iterations and independent of initial conditions. The standard IEEE 14-bus systems have been used to demonstrate the proposed methods over a wide range of power flow variations in the transmission system. The results shows that the proposed OPF with Static Synchronous Compensator (STATCOM) scheme is very effective compared to SVC device in improving the security of the power system.

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