

# Voltage Profile Improvement By Optimal Placement Of Svc Using Pso

Dr.P.Selvan<sup>1</sup>, Dr.R.Anita<sup>2</sup>

<sup>1</sup> Associate Professor, Department of Electrical and Electronics Engineering, M.P.Nachimuthu M.Jaganathan Engineering College  
Chennimalai, Erode - 638 112.

<sup>2</sup> Professor and Head, Department of Electrical and Electronics Engineering, Institute of Road and Transport Technology,  
Erode – 638 316.

**Abstract** - Modern power systems are at risks of voltage instability problems. Hence, it is very important to analyze the power system with respect to voltage stability. The voltage level of the system changes when there is change in load and the drop in the load voltage leads to an increased demand for the reactive power that, if not met by the power system leads to a further decline in the bus voltage. In this paper, Static VAR Compensators (SVC) is used to maintain the voltage within the limits. A SVC is one of the controllers which could be used to increase the capacity and the flexibility of a transmission network. The Particle Swarm Optimization (PSO) method is used to compute the power flow in optimum value. PSO is efficient in exploitation of solutions of the search space of the problem and easy to implement. The performance of this technique is tested using IEEE-30 bus system through the MatLab/Simulink simulation software package. The simulation results of test power system show that the location of the SVC has been able to enhance the voltage level of the test power system and also minimize the transmission line losses.

**Keywords** - Flexible AC Transmission Systems (FACTS), Particle Swarm Optimization (PSO), Real and Reactive Power, Static Var Compensator(SVC), Voltage Stability.

## 1.INTRODUCTION:

Modern power systems are prone to widespread failures. With the increase in power demand, operation and planning of large interconnected power system are becoming more and more complex, so power system will become less secure. In some cases, changes in operating conditions could cause a progressively and uncontrolled fall of voltages leading to voltage collapse. The system operating conditions can be improved by controlling system devices such as generators, voltage depression or even a voltage collapse. A rapidly operating SVC can continuously provide the reactive power required to control dynamic voltage swings under various system conditions and thereby improve the power system transmission and distribution performance. Installing an SVC at one or more suitable points in the network can increase

transformers and switching VAR sources etc. Application of FACTS technology is currently being pursued very intensively to achieve better control over the transmission lines. One of the most important operational functions is the optimal reactive power control, since inadequate reactive power supply can bring up some problems such as bad voltage profiles, additional losses and equipment overloads. Much research work mainly based on non-linear and linear programming, have been carried out to solve this problem. This paper presents a detailed study on the use of SVC to increase the capacity and flexibility of a transmission network. SVC is one of the best device, can contribute to improve the voltage profile in the transient state and therefore, in improving the quality performance of the electric service. Optimization methods and techniques have also been used in solving voltage stability problems. Optimal power flow is one of non-linear constrained and occasionally combinational optimization problems of power systems. The various algorithms for solving such problems can be found in the literature. Many different mathematical approaches includes i) Lambda iteration method, ii) Gradient method, iii) Newtons method, iv) linear programming and v) Interior point method. Apart from analytical approaches, there also exist intelligent search methods. Intelligent search methods includes genetic algorithm, evolutionary programming, particle swarm optimization etc. This paper proposes an application of swarm intelligences to solve optimal power flow problems. The objective used herein is to minimize the overall power transmission losses by optimizing the control variables within their limits. The proposed technique was tested on the IEEE 30 bus system and SVC can be installed at any of the weakest voltage at load buses.

## 2. BASIC CIRCUIT OF SVC

Electrical loads, both generate and absorb reactive power. Since, the transmitted load varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations, a

transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. In addition, an SVC can mitigate active power oscillations through voltage amplitude modulation. Fig.1 shows the single line diagram of SVC.

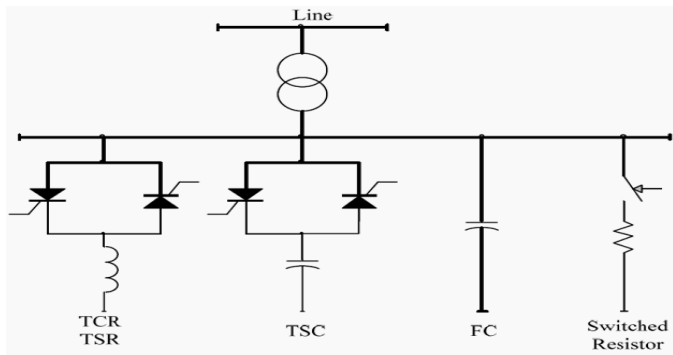


Fig.1 Single line diagram of SVC.

The SVC consists of a Thyristor Controlled Reactor (TCR) and a Fixed Capacitors(FC) banks. The TCR is a thyristor controlled inductor whose effective reactance varied in a continuous manner by partial conduction control of thyristor valve. [1], [2]. The basic elements of a TCR are a reactor in series with a bidirectional thyristor switch as show in figure 2.

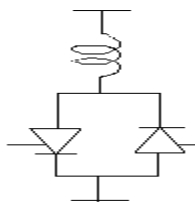


Fig. 2. Basic elements of TCR

The thyristors conduct alternate half-cycles of supply frequency depending of the firing angle  $\alpha$ , which is measured from a zero crossing of voltage. Full conduction is obtained with a firing angle of  $90^\circ$ . The current is essentially reactive and sinusoidal. Partial conduction is obtained with firing angles between  $90^\circ$  and  $180^\circ$ . Firing angle between  $0^\circ$  and  $90^\circ$  are not allowed as they produced asymmetrical current with a dc component. The effect of increasing the firing angle is to reduce the fundamental harmonic component of the current. This is equivalent to an increase in the inductance of the reactor, reducing its reactive power as well as its current. So far, as the fundamental component of current is concerned, the TCR is a controllable susceptance, and can therefore be applied as a static compensator[1].The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off or phase-controlled.

### 3. MODEL OF SVC

The SVC is a shunt connected FACTS controller and is modeled as a variable reactive power connected to a bus in a power system. The effect of SVC is incorporated in power flow problem as reactive power generation/absorption. The range o reactive power generation is limited between maximum and minimum values of -30 MVAR to +30 MVAR to keep the size minimum for reducing the cost of SVC.

The reactive power generated by SVC is given by

$$Q_{sVC}^{\min} \leq Q_{sVC}^{\max} \leq Q_{sVC} \quad (1)$$

### 4. PARTICLE SWARM OPTIMIZATION TECHNIQUE

PSO is originally attributed to Kennedy, Eberhart and Shi and was first intended for simulating social behavior, as a stylized representation of the movement of organisms in a bird flock or fish school. PSO is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. PSO optimizes a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position and is also guided toward the best known positions in the search-space, which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

PSO is a meta heuristic as it makes few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions. However, meta heuristics such as PSO do not guarantee an optimal solution is ever found. More specifically, PSO does not use the gradient of the problem being optimized, which means PSO does not require that the optimization problem be differentiable as is required by classic optimization methods such as gradient descent and quasi-newton methods. PSO can therefore also be used on optimization problems that are partially irregular, noisy, change over time, etc.

The PSO approach utilizes a cooperative swarm of particles, where each particle represents a candidate solution, to explore the space of possible solutions to an optimization problem. Each particle is randomly or heuristically initialized and then allowed to 'fly'. At each step of the optimization, each particle is allowed to evaluate its own fitness and the fitness of its neighboring particles. Each particle can keep track of its own solution, which resulted in the best fitness, as well as see the candidate solution for the best performing particle in its neighborhood. At each optimization step, indexed by  $t$ , each particle, indexed by  $i$ , adjusts its candidate solution (flies)

#### 4.1.PSO ALGORITHM

Basic algorithm as proposed by Kennedy and Eberhart (1995)

- $x_k^i$  - Particle position
- $v_k^i$  - Particle velocity
- $p_k^i$  - Best "remembered" individual particle position
- $p_k^g$  - Best "remembered" swarm position
- c1,c2- Cognitive and social parameters
- r1,r2- Random numbers between 0 and 1

Position of individual particles updated as follows:

$$x_k^{i+1} = x_k^i + v_{k+1}^i \quad (2)$$

with the velocity calculated as follows:

$$v_{k+1}^i = v_k^i + c1r1(p_k^i - x_k^i) + c2r2(p_k^g - x_k^i) \quad (3)$$

#### 4.2.PSO ALGORITHM DESCRIPTION AND FLOWCHART

##### 1. Initialize

- (a) Set constants  $k_{max}$ , c1,c
- (b) Randomly initialize particle positions  $x_0^i \in D \subset R^n$  for  $i=1,2,\dots,p$
- (c) Randomly initialize particle velocities  $0 \leq v_0^i \leq v_0^{max}$  for  $i=1,2,\dots,p$
- (d) Set  $K=1$

##### 2. Optimize

- (a) Evaluate function value  $f_k^i$  using design space coordinates  $x_k^i$
- (b) If  $f_k^i \leq f_{best}^i$  then  $f_{best}^i = f_k^i$ ,  $p_k^i = x_k^i$
- (c) If  $f_k^i \leq f_{best}^g$  then  $f_{best}^g = f_k^i$ ,  $p_k^g = x_k^i$
- (d) If stopping condition is reached go to step 3
- (e) Update all particle velocities  $v_0^i$  for  $i=1,2,\dots,p$  with the equation (2)
- (f) Update all particle positions  $x_k^i$  for  $i=1,2,\dots,p$  with the equation (1)
- (g) Increment k
- (h) Go to 2(a)

##### 3. Terminate.

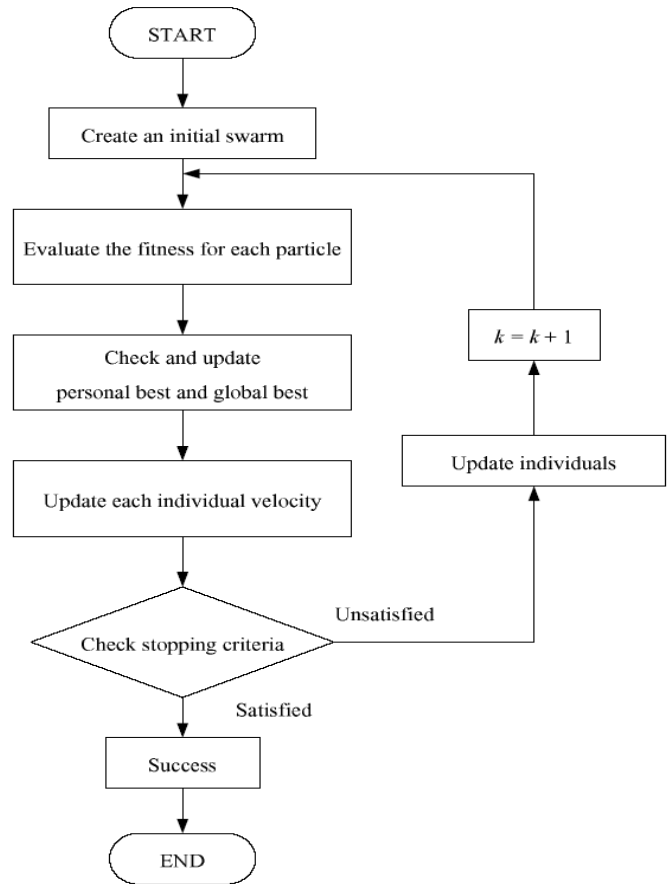


Fig 3 Flowchart of PSO algorithm

#### 4.3 PSO PARAMETER CONTROL

The following parameters are subjected to vary and their values are given in Table I.

TABLE 1 VARIOUS PARAMETERS AND THEIR VALUES

Sl.No	Parameter	Value
1.	Number of particles	50
2.	Dimension of particles	30
3.	Number of iterations	200
4.	Range of particles	0-1
5.	Velocity bounds	{-5,5}
6.	Learning factors C1 & C2	1.4
7.	Inertia weight Wmin & Wmax	0.4,0.9

**4.4. FITNESS FUNCTION**

The goal of optimal reactive power planning is to minimize the real power loss, reactive power generation and reactive power loss by optimal positioning of SVC and their corresponding parameters. Hence, the objective function can be expressed as

$$F(i) = (P_{gt} - P_{dt}) / \text{base mva};$$

**5. RESULTS AND DISCUSSION**

The optimal reactive power planning is formulated with the primary objective of minimization of reactive power generation and secondary objective of minimization of real power loss subject to voltage limit and reactive power limit constraints. The effectiveness of proposed approach has been illustrated using the medium size IEEE 30 bus test system shown in fig 4. The system has 6 generator buses, 24 load buses and 41 transmission lines. The possible location for installation of SVC device is only the 24 load buses.

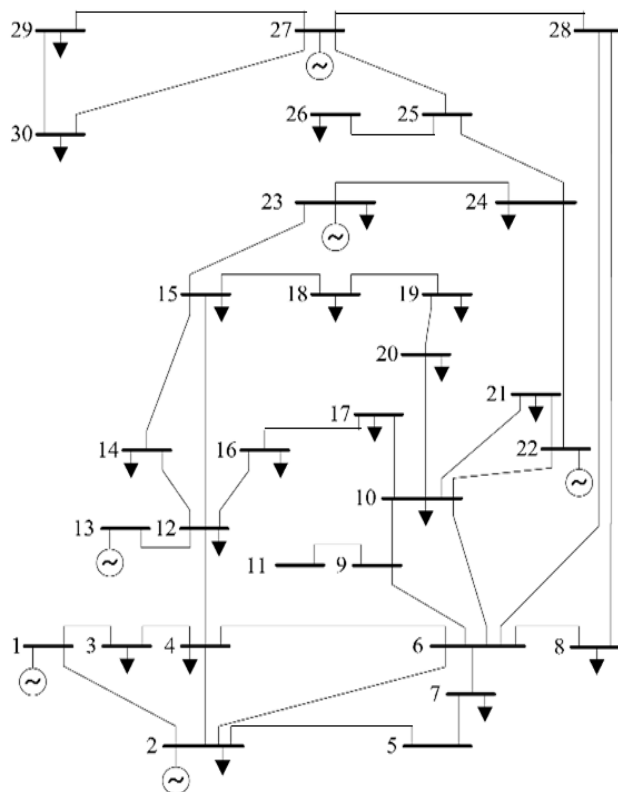


Fig 4. Single line diagram of IEEE 30 bus system

SVC has been included in the buses 2,6,8,9,11,12,15,16,21 and 28 in IEEE 30 bus system for random increase in load in buses. Table 2 shows the voltage profile without and with

SVC. Table 3 and 4 show power flow results of IEEE 30 bus system without and with SVC respectively. Table 5 shows the comparative results of proposed system. From the tables, it is concluded that the system voltages have been improved and the losses are reduced, when SVC is installed.

Table 2 VOLTAGE PROFILE OF IEEE 30 BUSES

BUS NO.	VOLTAGE PROFILE		
	WITH BASE LOAD	WITH INCREASE IN LOAD	AFTER COMPENSATION BY SVC
1	1.0500	1.0500	1.0500
2	1.0438	1.0038	1.0038
3	1.0058	0.9558	0.9558
4	1.0230	0.9730	0.9730
5	1.0913	1.0913	1.0913
6	1.0883	1.0883	1.0883
7	1.0410	0.9933	0.9933
8	1.0380	0.9838	0.9838
9	1.0311	0.9744	0.9744
10	1.0131	0.9469	0.9469
11	1.0663	1.0148	1.0148
12	1.0770	1.0028	1.0028
13	1.0763	1.0383	1.0383
14	1.0748	1.0278	1.0278
15	1.0732	1.0161	1.0161
16	1.0748	1.0145	1.0145
17	1.0703	1.0014	1.0014
18	1.0689	1.0044	1.0044
19	1.0719	0.9995	0.9995
20	1.0709	1.0011	1.0011

21	1.0728	0.9805	0.9805
22	1.0731	0.9833	0.9833
23	1.0703	0.9910	0.9910
24	1.0702	0.9703	0.9703
25	1.0836	0.9491	0.9491
26	1.0792	0.9333	0.9333
27	1.0879	0.9401	0.9401
28	1.0307	0.9732	0.9732
29	1.0878	0.9265	0.9265
30	1.0777	0.9129	0.9129

Table 4. BUS DATA OF INCREASE IN LOAD

From Bus	To bus	Voltage mag	Angle	Load		Gen		Q min	Q Max	Injected MVAR
				MW	MVAR	MW	MVAR			
1.0000	1.0000	1.0500	0	0	0	0	0	0	0	0
2.0000	2.0000	1.0038	-9.5926	32.5500	19.0500	57.5600	0	0	60.0000	0
3.0000	2.0000	0.9558	-29.4322	235.5000	47.5000	24.5600	0	0	62.0000	0
4.0000	2.0000	0.9730	-19.4532	60.0000	60.0000	35.0000	0	0	50.0000	0
5.0000	2.0000	1.0913	-21.4444	0	0	17.9300	0	0	40.0000	0
6.0000	2.0000	1.0883	-23.1130	0	0	16.9100	0	0	45.0000	0
7.0000	0	0.9933	-13.1698	3.6000	1.8000	0	0	0	0	0
8.0000	0	0.9838	-15.9715	7.6000	1.6000	0	0	0	0	0
9.0000	0	0.9744	-18.8381	0	0	0	0	0	0	0
10.0000	0	0.9469	-24.2936	45.6000	21.8000	0	0	0	0	0
11.0000	0	1.0148	-23.3742	0	0	0	0	0	0	0
12.0000	0	1.0028	-26.7796	11.6000	4.0000	0	0	0	0	0
13.0000	0	1.0383	-24.3134	11.2000	7.5000	0	0	0	0	0
14.0000	0	1.0278	-26.0295	6.2000	1.6000	0	0	0	0	0
15.0000	0	1.0161	-26.6379	8.2000	2.5000	0	0	0	0	0
16.0000	0	1.0145	-25.9768	7.7000	3.9600	0	0	0	0	0
17.0000	0	1.0014	-26.8753	11.7000	7.5400	0	0	0	0	0
18.0000	0	1.0044	-27.6919	4.4800	1.2600	0	0	0	0	0
19.0000	0	0.9995	-27.9672	9.5000	3.4000	0	0	0	0	0
20.0000	0	1.0011	-27.7696	2.2000	0.7000	0	0	0	0	0
21.0000	0	0.9805	-28.2521	38.5000	24.6400	0	0	0	0	0
22.0000	0	0.9833	-28.3378	0	0	0	0	0	0	0
23.0000	0	0.9910	-28.9025	8.0000	4.0000	0	0	0	0	0
24.0000	0	0.9703	-30.7920	8.7000	6.7000	0	0	0	0	0
25.0000	0	0.9491	-36.1187	0	0	0	0	0	0	0
26.0000	0	0.9333	-37.8018	4.2000	2.7600	0	0	0	0	0
27.0000	0	0.9401	-38.3876	0	0	0	0	0	0	0
28.0000	0	0.9732	-19.2199	0	0	0	0	0	0	0
29.0000	0	0.9265	-40.7904	3.8400	1.4400	0	0	0	0	0
30.0000	0	0.9129	-41.9872	12.7200	2.2800	0	0	0	0	0

From Bus	To bus	Voltage mag	Angle	Load		Gen		Q Min	Q max	Injected MVAR
				MW	MVAR	MW	MVAR			
1.0000	1.0000	1.05	0	0	0	0	0	0	0	0
2.0000	2.0000	1.0438	-2.9166	21.7	12.7000	57.5600	0	0	60.0000	0
3.0000	2.0000	1.0058	-8.9305	94.2000	19.0000	24.5600	0	0	60.0000	0
4.0000	2.0000	1.0230	-6.3379	30.0000	30.0000	35.0000	0	0	62.5000	0
5.0000	2.0000	1.0913	-7.2562	0	0	17.9300	0	0	50.0000	0
6.0000	2.0000	1.0883	-9.0927	0	0	16.9100	0	0	40.0000	0
7.0000	0	1.0410	-4.8937	2.4000	1.2000	0	0	0	45.0000	0
8.0000	0	1.0380	-5.8656	7.6000	1.6000	0	0	0	0	0
9.0000	0	1.0311	-6.5871	0	0	0	0	0	0	0
10.0000	0	1.0131	-8.0747	22.8000	10.9000	0	0	0	0	0
11.0000	0	1.0663	-9.0927	0	0	0	0	0	0	0
12.0000	0	1.0770	-11.3261	5.8000	2.0000	0	0	0	0	0
13.0000	0	1.0763	-10.2508	11.2000	7.5000	0	0	0	0	0
14.0000	0	1.0748	-11.5603	6.2000	1.6000	0	0	0	0	0
15.0000	0	1.0732	-11.9897	8.2000	2.5000	0	0	0	0	0
16.0000	0	1.0748	-11.0979	3.5000	1.8000	0	0	0	0	0
17.0000	0	1.0737	-11.5071	9.0000	5.8000	0	0	0	0	0
18.0000	0	1.0703	-12.5898	3.2000	0.9000	0	0	0	0	0
19.0000	0	1.0689	-12.6949	9.5000	3.4000	0	0	0	0	0
20.0000	0	1.0719	-12.4459	2.2000	0.7000	0	0	0	0	0
21.0000	0	1.0709	-12.2542	17.5000	11.2000	0	0	0	0	0
22.0000	0	1.0728	-12.3942	0	0	0	0	0	0	0
23.0000	0	1.0731	-13.4090	3.2000	1.6000	0	0	0	0	0
24.0000	0	1.0703	-14.6775	8.7000	6.7000	0	0	0	0	0
25.0000	0	1.0836	-18.8533	0	0	0	0	0	0	0
26.0000	0	1.0792	-20.1289	3.5000	2.3000	0	0	0	0	0
27.0000	0	1.0879	-20.4699	0	0	0	0	0	0	0
28.0000	0	1.0307	-6.4885	0	0	0	0	0	0	0
29.0000	0	1.0878	-22.0561	2.4000	0.9000	0	0	0	0	0
30.0000	0	1.0777	-22.8223	10.6000	1.9000	0	0	0	0	0

Table 3. BUS DATA OF BASE CASE

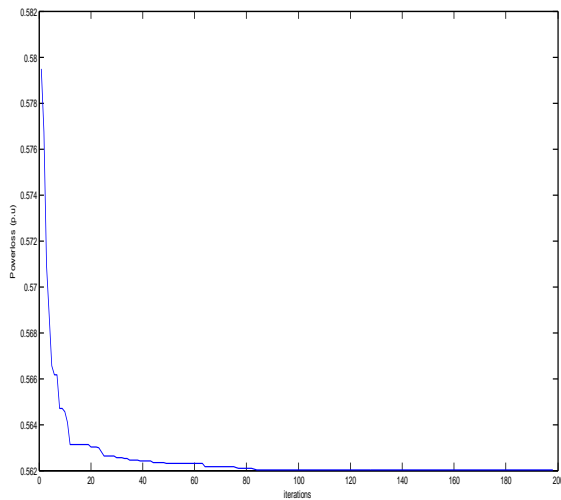


Fig 5 Plot of power loss for random increase in load

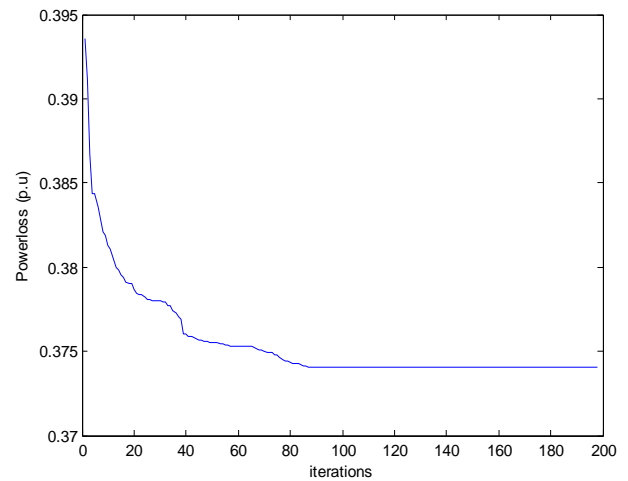


Fig 6 Plot of power loss for 67% increase in load

TABLE 5. BUS DATA AFTER SVC COMPENSATION

From Bus	To bus	Voltage mag	Angle	Load		Gen		Q min	Q max	Injected MVAR
				MW	MVAR	MW	MVAR			
1.0000	1.0000	1.0500	0	0	0	0	0	0	0	0
2.0000	2.0000	1.0238	-9.6817	32.5500	19.0500	57.5600	0	0	60.0000	16.0000
3.0000	2.0000	0.9558	-28.4419	235.5000	47.5000	24.5600	0	0	62.5000	0
4.0000	2.0000	1.0030	-19.2642	60.0000	60.0000	35.0000	0	0	50.0000	0
5.0000	2.0000	1.0913	-21.1568	0	0	17.9300	0	0	40.0000	0
6.0000	2.0000	1.1083	-22.3399	0	0	16.9100	0	0	45.0000	6.0000
7.0000	0	1.0218	-13.2540	3.6000	1.8000	0	0	0	0	0
8.0000	0	1.0183	-16.0126	7.6000	1.6000	0	0	0	0	12.0000
9.0000	0	1.0103	-18.7683	0	0	0	0	0	0	25.0000
10.0000	0	0.9690	-23.7489	45.6000	21.8000	0	0	0	0	0
11.0000	0	1.0665	-22.9931	0	0	0	0	0	0	12.0000
12.0000	0	1.0775	-26.0390	11.6000	4.0000	0	0	0	0	2.0000
13.0000	0	1.0891	-23.4638	11.2000	7.5000	0	0	0	0	0
14.0000	0	1.0875	-25.1213	6.2000	1.6000	0	0	0	0	0
15.0000	0	1.0830	-25.9035	8.2000	2.5000	0	0	0	0	8.0000
16.0000	0	1.0924	-25.5183	7.7000	3.9600	0	0	0	0	15.0000
17.0000	0	1.0777	-26.1796	11.7000	7.5400	0	0	0	0	0
18.0000	0	1.0755	-26.8535	4.4800	1.2600	0	0	0	0	0
19.0000	0	1.0726	-27.0999	9.5000	3.4000	0	0	0	0	0
20.0000	0	1.0747	-26.9271	2.2000	0.7000	0	0	0	0	0
21.0000	0	1.0679	-27.5804	38.5000	24.6400	0	0	0	0	20.0000
22.0000	0	1.0694	-27.6291	0	0	0	0	0	0	0
23.0000	0	1.0688	-28.0395	8.0000	4.0000	0	0	0	0	0
24.0000	0	1.0602	-29.8230	8.7000	6.7000	0	0	0	0	0
25.0000	0	1.0548	-34.5979	0	0	0	0	0	0	0
26.0000	0	1.0441	-36.0755	4.2000	2.7600	0	0	0	0	0
27.0000	0	1.0519	-36.5477	0	0	0	0	0	0	0
28.0000	0	1.0114	-19.2776	0	0	0	0	0	0	6.0000
29.0000	0	1.0438	-38.5628	3.8400	1.4400	0	0	0	0	0
30.0000	0	1.0320	-39.5061	12.7200	2.2800	0	0	0	0	0

TABLE 6. POWER LOSS FOR VARIOUS CASES

Power Loss for various case of load variation(in p.u)		
INCREASE IN LOAD	BEFORE COMPENSATION	AFTER COMPENSATION
Random load change	0.581417	0.562025
50%	0.295557	0.282844
65%	0.426161	0.36991
67%	0.469627	0.374027

## 6. CONCLUSION

This paper presents the application of PSO technique in power system state estimation with and without SVC. PSO technique is used to compute the power flow. The effectiveness of the proposed method was demonstrated through computer simulation using an IEEE 30 bus system. Results show that the real power loss and voltage violation have been greatly reduced after optimization using the proposed method. From the results it is concluded that the system performs better when the SVC is connected.

## 7. REFERENCES

[1] A.S. Kannan and R. Kayalvizhi, "Utility of PSO for loss minimization and Enhancement of voltage profile using

UPFC", International Journal of Scientific & Engineering Research, Volume 2, Issue 2, February-2011.

[2] M.R AlRashidi and M.E El-Hawary, "Hybrid Particle Swarm Optimization Approach for Solving the Discrete OPF Problem Considering the Valve Loading Effects," *IEEE Transactions on Power Systems*, Issue 4, Vol. 22, pp.2030-2038, 2007.

[3] B. Zhao, C.X. Guo and Y.J. Cao, "Improved particle swarm optimization algorithm for OPF problems," *IEEE-PES Power Systems Conference and Exposition*, Vol. 1, pp.233 - 238, 10-13 October 2004.

[4] C. A. Canizares, "Voltage stability assessment, procedures and guides", Technical Report, IEEE/PES Power System Stability Subcommittee, available at: <http://www.power.uwaterloo.ca>

[5] S. Jshak, A. F. Abidiii and T. K. A. Rahinan Static Var Compensator Planning Using Artificial Immune System For loss minimization And Voltage Improvement. *National Power & Energy Conference (PECon) 2004ES*

[6] T. Van Cutsem, "Voltage instability: phenomena, countermeasures, and analysis methods", *Proceedings of the IEEE*, Vol.88, No.2, Feb.2000, pp.208-227.

[7] C. A. Canizares, "Applications of Optimization to Voltage Collapse Analysis," *IEEE/PES Summer Meeting*, San Diego, July 14, 1998.

[8] R. Eberhart, and J. Kennedy, "Particle Swarm Optimization," *Proc. Of IEEE International Conf. on Neural Networks*, Vol. 4, pp. 1942-1948, 1995.

[9] IEEE Special Stability Controls Working Group, "Static Var compensator Models for Power Flow and Dynamic Performance Simulation", *IEEE Trans.on Power Systems*, Vol.9, pp229-240, Feb 1994

[10] IEEE Special Stability Controls Working Group, "Static Var compensator Models for Power Flow and Dynamic Performance Simulation", *IEEE Trans.on Power Systems*, Vol.9, pp229-240, Feb 1994

[11] S.M. Shahidehpour and N.I. Deeb, "An Overview of the reactive power allocation in Electric Power Systems," *Electric Machines and Power Systems*, pp. 495-518, 1990.