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Alleviation of Voltage Excursions in Large Power Systems

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ABSTRACT: The purpose of reactive power scheduling is to improve the voltage profile of the system. This objective is achieved by installing reactive power sources at appropriate locations in a large power network. Proper adjustment of these sources is of paramount importance in obtaining the desired goal. This paper presents a methodology for alleviation of over voltage and under voltage conditions in the day to day operation of power systems by minimizing the sum of the squares of the voltage deviations from preselected desired values. The above objective function is selected to meet the recent requirements of utilities that are paying increasing attention to the problem associated with the voltage profile in power system. To achieve the desired objective, the control variable selected are tap position of transformers, reactive power injection of VAR sources and generator excitations. The proposed algorithm is applied to IEEE 30-bus systems and the results are obtained satisfactory with the proposed approach.

I. INTRODUCTION

The catastrophic disruptions of large power systems often occur due to cascading failures due to the interconnected power systems are usually operated near critical loading, which tend to yield cascading failure. On the other hand, many factors, including system engineering, economic concerns and operational policies, organize the system towards criticality which means the system is operating at its stable boundary. Thus, the study of criticality of interconnected power systems has been paid more and more attention.

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance causes a progressive and uncontrollable decline in voltage. Fundamentally, voltage instability is caused by the system's inability to meet reactive demands. Instability can occur following simple reactive load growth, or following contingencies which may bring on additional reactive demands due to such effects as increased losses in transmission lines, higher reactive requirements from devices such as induction motors, or diminished reactive supply from static capacitors.

A method for the online testing a power system is proposed which is aimed at the detection of voltage instabilities. Thereby an indicator L is defined which varies in the range between 0 (no load of system) and 1 (voltage collapse). A load flow result is obtained for a given system operating condition, which is otherwise available from the output of an on-line state estimator. Using the load flow results, the L-index[10] is computed as (the detailed description is given in appendix B).

Peschon et al. [1] developed the power flow sensitivity and cost sensitivity relationships to optimize the real and reactive power generations in the system. They also presented a linear programming approximation to this optimization problem of minimizing the production cost.

Dopazo et al. [2] presented a method of minimizing the production cost by coordinating real and reactive power allocations in the system. The procedure at first determines the real power dispatch based on the Lagrangian multipliers and then proceeds to optimize the reactive power allocation by a gradient approach. The objective function, which is system loss reduction, yields the required gradient vector.

Hano et al. [3] presented a method of controlling the system voltage and reactive power distributions in the system. They determined the required sensitivity relationships between controlled and controllable variables, and loss sensitivity indices, and then employed a direct search technique to minimize the system losses.

Peschon et al. [4] presented a method of minimizing the system losses by judicious selection of reactive power injections into the system and transformer tap settings. They also included a suitable adjustment algorithm to drive the solution towards a feasible optimal point.

Dommel and Tinney [5] developed and presented a nonlinear optimization technique to determine the optimal power flow solution. They minimized a nonlinear objective function of production costs or losses using Kuhn-Tucker conditions. J. Baskaran [6] presented an approach to optimal location of SVC by using GA based on the economic cost saving function, They minimized voltage deviation by placing optimal location of SVC.

II. PROBLEM DESCRIPTION

2.1 Problem Formulation

Redistribution of reactive power generation in a power system is necessary to improve the system voltage profiles and to minimize the real power losses. Reactive power distributions in the systems can be controlled by the system engineer by adjusting the transformer taps, generator voltages and switch able VAR sources.

If we consider a system with:
n = number of buses in the system,
g = number of generator buses,
1 = n – g number of load buses,
T = number of transformers,
S = number of switch able VAR sources amongst the load buses.
The control applied at:

(1) Transformer taps T_T .

(2) Generator voltages V_G .

(3) Switch able VAR sources (SVC) Q_S.

These variables are called control variables and are expressed as

$$X = (T_T V_G Q_S)^T \qquad \text{--------(1)}$$

Network performance variables comprise the vector of:

(1) Reactive powers of generators QG_G .

(2) Voltage magnitudes of buses other than generator buses V_L .

These variables are called dependent variables are expressed as

$$Y = (QG_G V_L)^T \qquad \text{-------(2)}$$

Minimizing of the sum of squares of voltage deviations from pre selected desired voltages is taken as the objective function and can be expressed as $S(X) = \sum_{i=g+1}^{n} [V_i^{des} - V_i^{cal}(X)]^2$ ------(3)

where V are the preselected desired voltages lying within the acceptable band (say 0.95 to l.10 p.u.).

In the aforementioned system 1 to g are the generator buses, (g + 1) to (g + s) are the SVC buses and (g + s+ 1) to n are the remaining buses.

Equation (1) can be written as: $\mathrm{X} = [T_1, ...T_t; V_1, ...V_g; Q_{g+1}, ...Q_{g+s}]^T$ --(4)

Equation (2) can be written as: $Y = [QG_1, ...QG_g; V_{g+1}, ...V_n]^T$ ---(5)

The condition for minimization of the objective function S(X) is given as:

$$\nabla_X S(X) = 0 \quad \text{---(6)}$$

Substituting the value of S(X) from equation (3) into equation (6) we have:

$$\nabla_X S(X) = 2\sum_{i=g+1}^{n} [V_i^{des} - V_i^{cal}] * (-1) \begin{bmatrix} \frac{\partial V_{g+1}}{\partial V_1} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial V_1} \\ \vdots & & & & \\ \frac{\partial V_{g+1}}{\partial V_g} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial V_g} \\ \frac{\partial V_{g+1}}{\partial Q_{g+1}} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial Q_{g+1}} \\ \vdots & & & & \\ \frac{\partial V_{g+1}}{\partial Q_{g+s}} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial Q_{g+s}} \\ \frac{\partial V_{g+1}}{\partial T_1} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial T_1} \\ \vdots & & & & \\ \frac{\partial V_{g+1}}{\partial T_t} & \cdot & \cdot & \cdot & \frac{\partial V_n}{\partial T_t} \end{bmatrix} \nabla_X S(X) = -2\sum_{i=g+1}^{n} [V_i^{des} - V_i^{cal}][J]^T$$

where J is the sensitivity matrix relating the dependent and control variables. The detailed equations required for obtain the elements of the sensitivity matrix will be given the next chapter.

$$J=\begin{bmatrix} \frac{\partial V_{g+1}}{\partial V_1} & . & . & . & \frac{\partial V_{g+1}}{\partial V_g} \\ \frac{\partial V_{g+1}}{\partial Q_{g+1}} & . & . & . & \frac{\partial V_{g+1}}{\partial Q_{g+s}} \\ \frac{\partial V_{g+1}}{\partial T_1} & . & . & . & \frac{\partial V_{g+1}}{\partial T_t} \\ & & . & & \\ & & . & & \\ & & . & & \\ \frac{\partial V_n}{\partial V_1} & . & . & . & \frac{\partial V_n}{\partial V_g} \\ \frac{\partial V_n}{\partial Q_{g+1}} & . & . & . & \frac{\partial V_n}{\partial Q_{g+s}} \\ \frac{\partial V_n}{\partial T_1} & . & . & . & \frac{\partial V_n}{\partial T_t} \end{bmatrix}$$

Thus

$$\nabla_X S(X) = -2[J]^T \begin{bmatrix} V_{g+1}^{des} & - & V_{g+1}^{cal} \\ . & . & . \\ . & . & . \\ V_n^{des} & - & V_n^{cal} \end{bmatrix} \quad \text{--(7)}$$

Expanding $\nabla_X S(X)$ in Taylor series and neglecting the second and higher order terms we have:

$$\nabla_X S(X) + (X - X^0)(\frac{\partial}{\partial X})\nabla_X S(X) = 0 \text{ or}$$

$$\nabla_X S(X) + (\Delta X)(\frac{\partial}{\partial X})\nabla_X S(X) = 0$$

$$\Delta X = -[(\frac{\partial}{\partial X})\nabla_X S(X)]^{-1}[\nabla_X S(X)] \quad \text{--(8)}$$

$$(\frac{\partial}{\partial X})\nabla_X S(X) = (\frac{\partial}{\partial X})\left(\left(-2[J]^T\right)\begin{bmatrix} V_{g+1}^{des} & - & V_{g+1}^{cal} \\ . & . & . \\ . & . & . \\ V_n^{des} & - & V_n^{cal} \end{bmatrix}\right) \quad \text{--(9)}$$

The Jacobian of $\nabla_X S(X)$ is calculated treating S as constant matrix .thus

$$(\frac{\partial}{\partial X})\nabla_X S(X) = 2[J]^T[J] \quad \text{--(10)}$$

Substituting the value of $(\frac{\partial}{\partial X})\nabla_X S(X)$ from equation (10) into equation (9):

$$\Delta X = -[2(J)^T(J)]^{-1}[-2(J)^T]\begin{bmatrix} V_{g+1}^{des} & - & V_{g+1}^{cal} \\ . & . & . \\ . & . & . \\ V_n^{des} & - & V_n^{cal} \end{bmatrix} \text{or}$$

$$\Delta X = [(J)^T(J)]^{-1}[J]^T[V_L^{err}] \text{ -(11)} \qquad \text{where } [V_L^{err}] = [V_L^{des}] - [V_L^{cal}]$$

The above equation gives the required adjustments (ΔX) for control variables in terms of error voltages at load buses $[V_L^{err}]$ and matrix J.

2.2 Network performance constraints

These are the constraints on dependent variables i.e., the reactive power generations of generators and voltages of load buses.

These limits are given as $Y^{\min} \le Y \le Y^{\max}$

Where Y is defined by equation (2) and thus $QG_G^{\min} \le QG_G \le QG_G^{\max}$

for G=1……g (12)

$V_L^{\min} \le V_L \le V_L^{\max}$ for L=g+1,….n (13)

The difference-values of Y with respect to the base case Y^0, are used instead of the actual values,

Thus $\Delta Y^{\min} \le \Delta Y \le \Delta Y^{\max}$

$$\Delta QG_G^{\min} \le \Delta QG_G \le \Delta QG_G^{\max}$$

$$\Delta V_L^{\min} \le \Delta V_L \le \Delta V_L^{\max}$$

where

$$\Delta Y^{\max} = Y^{\max} - Y^0 \quad \Delta Y^{\min} = Y^{\min} - Y^0$$

$$\Delta QG_G^{\max} = \Delta QG_G^{\max} - QG_G^0$$

$$\Delta QG_G^{\min} = \Delta QG_G^{\min} - QG_G^0$$

$$\Delta V_L^{\max} = \Delta V_L^{\max} - V_L^0$$

$$\Delta V_L^{\max} = \Delta V_L^{\max} - \Delta V_L^0$$

2.3 Constraints on independent variables
These are the limits on control variables and are given as

$$X^{\min} \le X \le X^{\max}$$

where X is defined by equation (1)
Again the difference values with respect to base case X^0 are used

$$\Delta X^{\min} \le \Delta X \le \Delta X^{\max}$$

or in terms of actual variables $\Delta V_G^{\min} \le \Delta V_G \le \Delta V_G^{\max}$

$$\Delta QG_S^{\min} \le \Delta QG_S \le \Delta QG_S^{\max} \qquad \Delta T_T^{\min} \le \Delta T_T \le \Delta T_T^{\max}$$

where $\Delta X^{\max} = X^{\max} - X^0$

$$\Delta X^{\min} = X^{\min} - X^0$$

2.4.5 Solution Algorithm:
Step 1: Perform the load-flow calculation to determine the state of the system with an optimal real power generation schedule.
Step 2: Compute the voltage value of all load buses for the desired operating conditions.
Step 3: Compute the voltage error vector:

$$[V_L^{err}] = [V_L^{des}] - [V_L^{cal}]$$

Step 4: If $[V_L^{err}]$ is within the specified tolerance, print the result.
Step 5: Compute the Sensitivity matrix J using the equations
Step 6: Compute the corrections required for the control vectors ΔX using formula:

$$\Delta X = [J^T J]^{-1} [J^T][V_L^{err}]$$

Step 7: The computed X are adjusted from suitable step- lengths by selecting proper values of ΔQ_{Step}, ΔT_{Step} and ΔV_{Step}

$$X^{new} = X^{old} + \Delta X^{new}$$

Step 8: Check for the limits of the control variables, limit the suitable one and go to **step1**

III. GENETIC ALGORITHM

3.1 Introduction
Genetic algorithms are a part of evolutionary computing, which is a rapidly growing area of artificial intelligence. Genetic algorithms are inspired by Darwin's theory of evolution. Simply said, problems are solved by an evolutionary process resulting in a best (fittest) solution (survivor) in other words, the solution is evolved.

3.1 Mathematical Model of SVC:
The primary purpose of SVC is usually control of voltages at weak points in a network. This may be installed at midpoint of the transmission line. The reactive power output of an SVC can be expressed as follows:
Q_{svc} =Vi (Vi−Vr) / Xsl.
Where, Xsl is the equivalent slope reactance in p.u.equal to the slope of voltage control characteristic, and Vr are reference voltage magnitude. The exact loss formula of a system having N number of buses is .

$$P_{lt}^{c} = \sum_{J=1}^{N}\sum_{k=1}^{N}[\alpha jk(PjPk+QjQk)+\beta jk(QjPk-PjQk)].$$

Where Pj, Pk and Qj, Qk respectively, are real and reactive power injected at bus-j and αjk, βjk are the loss coefficients defined by
Where

$$\alpha jk = \frac{Rjk}{ViVk}\cos(\delta j-\delta k)$$

$$\beta jk = \frac{Rjk}{ViVk}\sin(\delta j-\delta k).$$

Where Rjk is the real part of the j-kth element of [Zbus] matrix.

Objective Function:

The aim is that to utilize the SVC for optimal amount of power in a system is to supply without overloaded line and with an acceptable voltage level. The optimal location of SVC problem is to increases as much as possible capacity of the network .i.e loadability. In this work, the SVC has been considered to Economic saving function, which obtained by energy loss, it requires calculation of total real power losses at the day. Objective function is Minimize F is

$$PL\ (V, d, S)= \sum_{i=1} PLt*E_{loss}*\Delta T\ -Cin$$

F (b, v) =0, F1(s)<M1, F2(v)<M2.
Where,
M1=SVC Rating(-100MVAR to +100MVAR)
M2=Voltage Limit(0.94 to 1.1)
ΔT =Time duration
PLt = Total Real Power Loss
Ke= Energy loss cost factor
Cin =Investment cost of SVC

The cost function for SVC is:

Cin= T-limit + installation cost
where T-limit isthermal limit of the line.
$C_{insvc}=0.0003S^2–0.3051S+127.38$(US$/Kvar)
Where S is the operating rating of the SVC in Mvar, and C_{insvc}, is in US$/Kvar.
and energy loss cost 0.6[$/KWh]

The SVC can be used to change the power system parameters. These parameters derive different results on the objective function (3.1). The above-mentioned parameters are very difficult to optimize simultaneously by conventional optimization methods. To solve this type of combinatorial problem, the genetic algorithm is employed.

IV. CASE STUDIES AND RESULTS

The proposed algorithms have been tested on an IEEE 14 bus system and an IEEE 30 bus system and the results obtained are compared with the results given in reference [7]. Initially the results are obtained for optimization of the objective minimization of sum squared voltage deviations of the load buses with and without location of svc. For this objective the location of svc selected randomly. Later the economic saving function objective is considered for identifying the optimal location of svc. Finally for the second objective the results obtained are compared with svc for both random location and optimal location.

4.1 IEEE 30 bus system:

4.1.1. Results for the objective of minimization of sum squared voltage deviations of load buses without svc:

The proposed algorithm has been implemented on an IEEE 30 bus system. The single line diagram is shown in Fig 4.1.The system has six generators, four transformers, twenty four load buses and forty one transmission lines and the total load with real power of 283.4 MW and reactive power of 126.2 MVAR. For this loading condition the initial power flow shows that the voltage profile is about satisfactory (within ±5% of the nominal value).

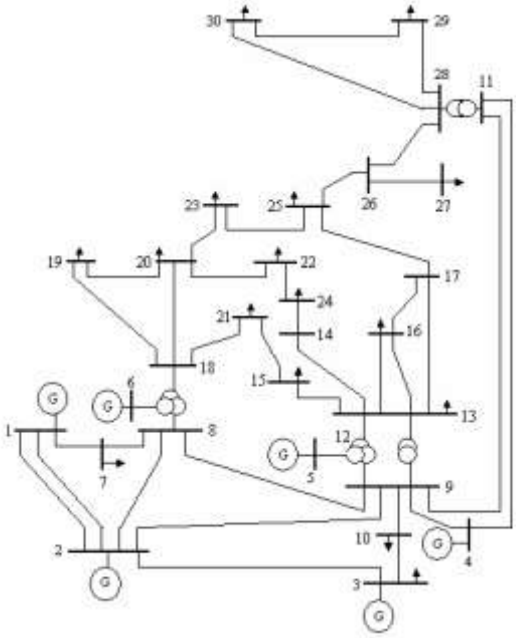

Fig.4.1 IEEE 30 Bus System

4.1.2. Results for the objective of minimization of sum squared voltage deviations of load buses with svc:

For testing the effectiveness of the proposed algorithm the load is deliberately increased by 2.5 times the normal value inorder to see the performance of the proposed method. The voltage profile is unsatisfactory, falling as low as 0.79p.u. Buses 12,19,24 and 30 have been selected as svc buses. Details of control variables are given in table 4.1.1. The corresponding bus voltages are indicted in table 4.1.2 and the corresponding plot is shown in fig 4.2.

Table 4.1.1: Settings of control variables

VAR controller	VAR control variable	Max.	Min.	Step	Initial	Optimum
Generation excitation	V_1	1.10	0.95	0.01	1.05000	1.09000
	V_2	1.10	0.95	0.01	1.03000	1.00000
	V_3	1.10	0.95	0.01	1.00000	1.06000
	V_4	1.10	0.95	0.01	1.06000	1.02000
	V_5	1.10	0.95	0.01	1.08000	1.10000
	V_6	1.10	0.95	0.01	0.97000	1.01000
Transformer taps(p.u)	T_1	1.10	0.90	0.025	1.0155	0.90
	T_2	1.10	0.90	0.025	0.9629	1.10
	T_3	1.10	0.90	0.025	1.0129	1.07
	T_4	1.10	0.90	0.025	0.9581	0.9581
SVC reactive power in p.u	Q_{12}	0.50	0.0	0.005	0.0	0.205
	Q_{19}	0.50	0.0	0.005	0.0	0.500
	Q_{24}	0.50	0.0	0.005	0.0	0.250
	Q_{30}	0.50	0.0	0.005	0.0	0.150

Table 4.1.2: voltages before and after placement of SVC

Bus No	Votages before placing svc	Votages after placing svc
1	1.0500	1.0900
2	1.0338	1.0000
3	0.9672	1.0600
4	0.9601	1.0200
5	1.0058	1.1000
6	0.9762	1.0100

7	0.9649	1.0000
8	1.0230	1.0200
9	0.9922	1.0400
10	0.9445	1.0500
11	1.0913	1.0000
12	0.9986	1.0300
13	1.0883	1.0000
14	0.9532	0.9800
15	0.9363	0.9600
16	0.9557	0.9800
17	0.9330	0.9700
18	0.9039	0.9560
19	0.8938	0.9500
20	0.9040	0.9600
21	0.9080	0.9600
22	0.9092	0.9500
23	0.8984	0.9500
24	0.8720	0.9800
25	0.8719	1.0100
26	0.8176	1.0500
27	0.8986	1.0400
28	0.9674	1.0200
29	0.8337	1.0100
30	0.7963	1.0100

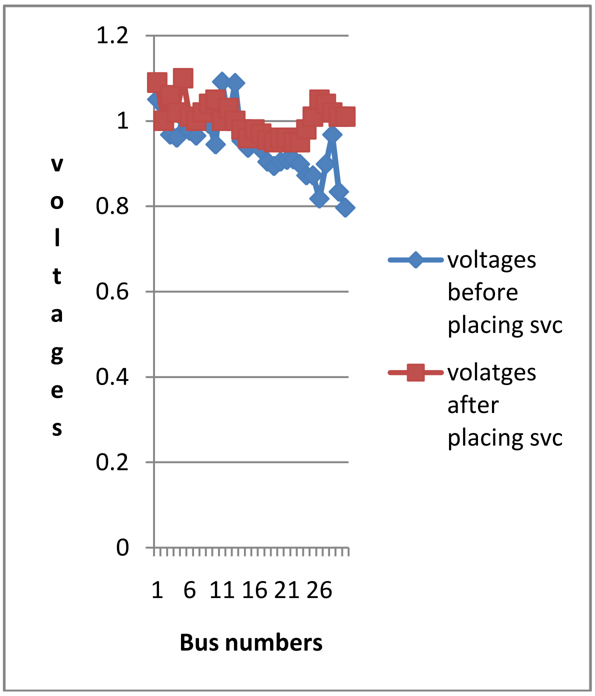

Fig4.2 Bus voltages before and after least square optimization

4.1.3. Results for the objective of minimization of economic saving function for optimal location of svc:
The objective of minimization of economic saving function is solved by using the genetic algorithm for identifying the optimal location of SVC's for the test system of IEEE 30 bus. The buses 10 , 19, 24 and 30 are found to be optimal location.

4.1.4. Results of comparison of different parameters of the system:

In the above case study SVC's are placed randomly at 12, 19, 24 and 30. Now the SVC's are placed optimally at buses 10, 19, 24 and 30 based on objective function. The results obtained with this objective with random location of svc and with optimal location of svc are indicated in table 4.1.3 and the corresponding voltage profile graph is shown in fig 4.3. From these results it is observed that the improved voltages are closure in both the cases. The other system parameters like power loss, voltage stability L index for critical buses and the sum square of voltage deviations are also obtained and indicated in tables 4.1.4 ,4.1.5 and 4.1.6 respectively. From these tables the loss reduction is slightly better with optimal placement of svc than random placement. The other parameter voltage stability L index of critical buses (as indicated in table 4.1.5) and sum square voltage deviations (as indicated in table 4.1.6) are close to each other in both cases.

Table: 4.1.3 Comparison of Voltages

Bus No	Base Voltage	Voltages after Optimal location of svc	Voltages after random location of svc
1	1.0500	1.0500	1.0500
2	1.0338	1.0338	1.0338
3	0.9672	0.9703	0.9703
4	0.9601	0.9638	0.9637
5	1.0058	1.0058	1.0058
6	0.9762	0.9798	0.9795
7	0.9649	0.9671	0.9669
8	1.0230	1.0230	1.0230
9	0.9922	1.0033	1.0011
10	0.9445	0.9651	0.9607
11	1.0913	1.0913	1.0913
12	0.9986	1.0084	1.0104
13	1.0883	1.0883	1.0883
14	0.9532	0.9669	0.9682
15	0.9363	0.9534	0.9539
16	0.9557	0.9704	0.9696
17	0.9330	0.9521	0.9487
18	0.9039	0.9284	0.9271
19	0.8938	0.9225	0.9202
20	0.9040	0.9308	0.9279
21	0.9080	0.9314	0.9271
22	0.9092	0.9331	0.9290
23	0.8984	0.9221	0.9212
24	0.8720	0.9039	0.9013
25	0.8719	0.9063	0.9044
26	0.8176	0.8545	0.8524
27	0.8986	0.9334	0.9320
28	0.9674	0.9737	0.9733
29	0.8337	0.8823	0.8808
30	0.7963	0.8585	0.8569

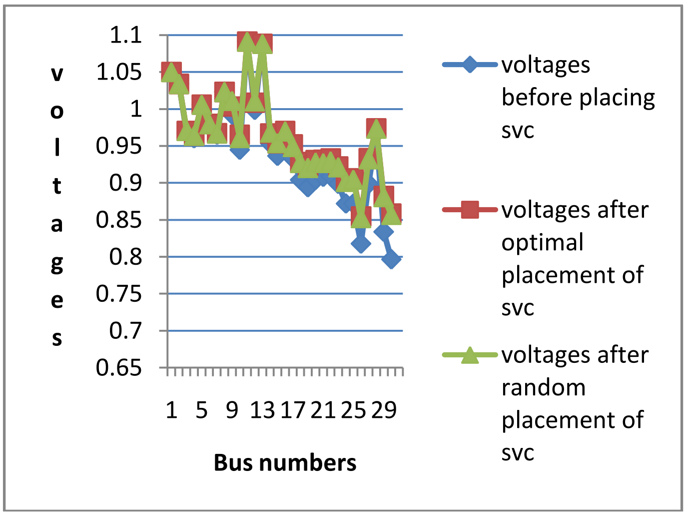

Fig 4.3. Voltage profile Curve

Table 4.1.4: comparison of losses

Before placing SVC	After placing SVC optimally	After placing SVC ramdom
114.3340MW	111.7446MW	111.8960MW

Table: 4.1.5 Comparison of L_ index

Bus No	L_index	L_index after optimal location of SVC	L_index after random location of SVC
3	0.0317	0.0314	0.0314
4	0.0880	0.0753	0.0754
6	0.2107	0.1853	0.1853
7	0.3977	0.3290	0.3294
9	0.2116	0.1912	0.1912
10	0.3308	0.2869	0.2871
12	0.3129	0.2836	0.2839
14	0.4302	0.3483	0.3485
15	0.4569	0.3577	0.3579
16	0.4607	0.3724	0.3726
17	0.4476	0.3667	0.3671
18	0.5464	0.4255	0.4259
19	0.5638	0.4421	0.4425
20	0.5267	0.4185	0.4190
21	0.5018	0.4057	0.4063
22	0.5077	0.4089	0.4094
23	0.5392	0.4108	0.4111
24	0.5910	0.4583	0.4589
25	0.5397	0.4264	0.4268
26	0.6899	0.5312	0.5318
27	0.4452	0.3598	0.3601
28	0.0387	0.0361	0.0361
29	0.6612	0.5216	0.5221
30	0.8329	0.6454	0.6460

Table : 4.1.6 Comparison of sum of squares of voltage deviations

Before placing SVC	After placing SVC optimally	After placing SVC random
1.2745	0.6385	0.6408

V. CONCLUSION

The developed algorithm has been tested on an IEEE 30 bus system. The proposed algorithm is giving encouraging results for improving the operational conditions of the system under normal and heavily loaded conditions. Then the objective has been solved with inclusion of static var compensator at the desired buses. The objective of minimization of economic saving function is also considered for identifying the optimal location of svc by using genetic algorithm. Then with this objective the results obtained with svc at random location compared with the results obtained with optimal location of svc. Both the objectives the results obtained are satisfactory.

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