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Optimal Placement of Static Series Voltage Regulator (SSVR) in Distribution System for Voltage improvement Using Particle Swarm Optimization

M. Laxmidevi Ramanaiah *, Dr. M. Damodar Reddy**, T. Chandra Sekhar***
**(Research Scholar, Department of E.E.E., S.V.University, Tirupati, Andhra Pradesh, India.*
*** (Professor, Department of E.E.E., S.V.University, Tirupati, Andhra Pradesh, India.*
**** (M.Tech student, Department of E.E.E., S.V.University, Tirupati, Andhra Pradesh, India.*

ABSTRACT
This paper presents optimal placement of Static Series Voltage Regulator (SSVR), for voltage profile improvement and power loss reduction in radial distribution systems under steady state condition. SSVR consists of a series compensator. The series compensator injects the series voltage in quadrature with the branch current in such a way that the receiving end voltage is maintained at desired value (up to 1 p.u). The criteria for selection of optimum location of SSVR are under voltage problem mitigation and loss reduction in the network under steady sate condition. Particle Swam Optimization (PSO) technique is used to find the rating of the device. The proposed model is tested using standard distribution system consisting of 33 nodes.

***Keywords*:** Static Series Voltage Regulator (SSVR), Voltage Source Converter (VSC), Series Voltage (Vse), Particle Swarm Optimization (PSO).

I. INTRODUCTION

The radial distribution system usually suffers from high power loss, poor voltage profile at the end buses, poor voltage stability and line loadability. Optimal reactive power compensation can improve all these problems. Therefore, there are several reactive power compensation devices reported in the literature. For instance, capacitor placement [1-2], combined operation of on load tap changer and capacitor banks [3], integration of distributed generation (DG) [4].

Flexible AC Transmission System (FACTS) devices were originally developed for transmission system to alleviate the system from the problem of congestion, FACTS used in distribution systems are called as Distribution FACTS (DFACTS) or Custom Power Devices (CPD). These devices are used mainly for compensation of power quality problems like voltage unbalance voltage sag and flicker. Some of the DFACTS devices are distribution static compensator (DSTATCOM) [5], Dynamic Voltage Restorer (DVR) [6]. Comparison of DVR and DSTATCOM are presented in [7] and Static Series Voltage Regulator in [8].

Most of the DFACTS devices are modeled and utilized for power quality problems in a small two bus distribution system with a sensitive load and source. But, the research on the effect of DFACTS on reactive power compensation in a large distribution system is very less in steady state conditions.

In the proposed work, a SSVR [8] model is used and its impact on voltage compensation is studied in a large radial distribution system. In the SSVR model, the voltage source converter injects controllable series voltage (V_{se}) in quadrature with the branch current. Thus, the load voltage magnitude changes to desired value (up to 1 p.u.) during healthy operating condition. Particle Swarm optimization (PSO) method is used to find the rating of SSVR.

II. RADIAL DISTRIBUTION SYSTEM LOAD FLOW IN STEADY STATE CONDITION

For any power system, load flow is the basic and essential method for analysis, planning and operation studies under steady-state condition. Most of the distribution systems are fed at one point and system has a radial structure as shown in Fig 1. Several load flow methods have been developed for radial distribution systems [9-10]. The load flow method [10] based on BIBC and BCBV matrices formulation is used in this paper. The proposed load flow algorithm requires formation of Bus Injection to Branch Current (BIBC) matrix with 1's & 0's as elements and Branch Current to Bus Voltage (BCBV) matrix with primitive impedances as elements and Distribution Load Flow (DLF) matrix. DLF matrix is the product of BCBV & BIBC matrices.

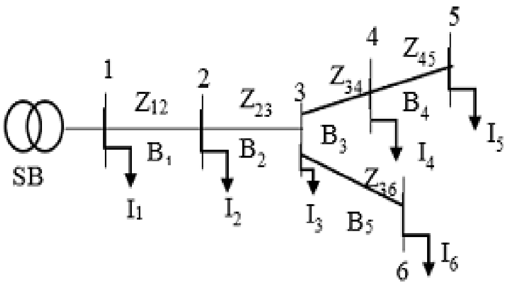


Fig 1: Simple 6 bus radial distribution system

At bus i the complex load S_{Li} is given by

$$S_{Li} = (P_{Li} + j\,Q_{Li}) \tag{1}$$

Where, i = 2 ….. N
S_{Li} is the complex power at i^{th} bus;
P_{Li} is the real power at i^{th} bus;
Q_{Li} is the reactive power at i^{th} bus
N=number of buses.
The load current at node i is given by

$$I_L = \left(\frac{P_{Li} + jQ_{Li}}{V_i^k}\right)^* \tag{2}$$

Where V_i^k is the bus voltage at k^{th} iteration for ith bus; I_L is load current at the k^{th} iteration for i^{th} bus.
The branch currents can be written as

$$[I_B] = [BIBC]\quad[I_L] \tag{3}$$

The relation between branch current and bus voltages is given by

$$[\Delta V] = [BCBV]\quad[I_B] \tag{4}$$

The formation of BIBC and BCBV matrices is presented in [11]. Substituting the $[I_B]$ matrix, the resultant equation expressed as

$$[\Delta V] = [BCBV]\,[BIBC]\,[I_L]$$

$$[\Delta V] = [DLF]\,[I_L]$$

Node voltage is obtained as

$$[V^{k+1}] = V^k - \Delta V^{k+1} \tag{5}$$

Thus, we obtain the voltage magnitude and phase angle, which completes the load flow.

2.1 Power loss calculations

The power losses in a distribution system can be written as

$$P_{Loss} = \sum_{m=1}^{b} I_{Bm}^2 R_m \tag{6}$$

$$Q_{Loss} = \sum_{m=1}^{b} I_{Bm}^2 X_m \tag{7}$$

Where m is number of branches, R_m is the resistance and I_{Bm} is the magnitude of m^{th} branch current.

III. STATIC SERIES VOLTAGE REGULATOR (SSVR) IN DISTRIBUTION SYSTEM

SSVR consists of a series compensator as shown in Fig.2.

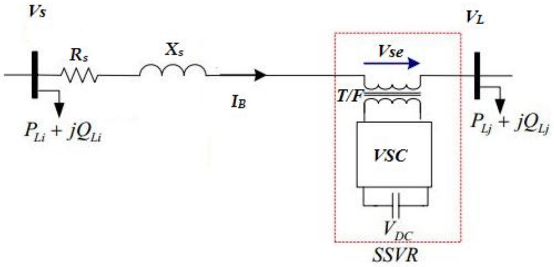


Fig 2: Single line diagram of two buses of a distribution system with SSVR

Here V_s is the sending end voltage; V_{se} is the voltage injected by series compensator; V_L is the load bus voltage; I_B is the branch current. From fig 1, if SSVR is placed in the branch B2, then the receiving end bus 3 is maintained at 1p.u. From Fig.3, the series compensator injects the series voltage (Vse) in quadrature with the branch current in such a way that the receiving end voltage (V_L) is maintained at desired value (up to 1 p.u).Since, SSVR injects the series voltage in quadrature to branch current it can provide only reactive power to the system. The phasor diagram in Fig 4 shows the effect of series injected voltage on the desired load bus voltage.

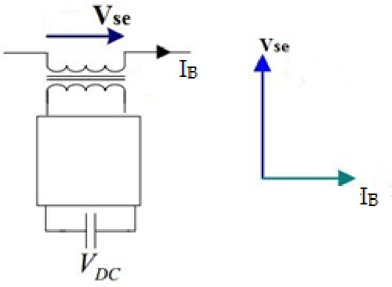


Fig 3: Model of SSVR and phasor diagram of reactive power exchange operation

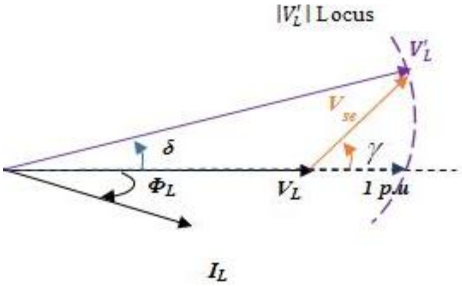


Fig 4: Phasor diagram for voltage and currents with series compensator

From the phasor diagram given in Fig.4, the new load bus voltage is given as,

$$V_L^{'}\angle\delta = V_L + V_{se}\angle\gamma \qquad (8)$$

Where

$V_L^{'}$ is magnitude of load bus voltage after injecting series voltage.

δ is displacement angle between V_L and $V_L^{'}$

V_{se} is series injected voltage

γ is the angle of series injected voltage with respect to the angle of load voltage V_L.

The series power is obtained as follows:

$$S_{SSVR} = V_{se}.(I_B)^{*} \qquad (9)$$

Where S_{SSVR} is the complex power rating of SSVR; V_{se} is series voltage injected by SSVR; I_B is branch current in which SSVR injects the series voltage

IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization is swarm intelligence based technique [2] that mimics the social behavior of a flock of birds. It has stable convergence characteristics. The behavior of birds to search for food is modeled in this optimization. PSO is found to be superior to evolutionary optimization methods. The terms associated with PSO are particle best and global best. The searching mechanism of PSO involves velocity update and position update.

The new velocities are calculated using equation (10)

$$V_{(m,n)}^{t+1} = k*(w*V_{(m,n)}^{t} + c_1 rand_1(\text{pbest}_{(m,n)}^{t} - \text{X}_{(m,n)}^{t}) + c_2 rand_2 (\text{gbest}_{(1,n)}^{t} - \text{X}_{(m,n)}^{t})) \qquad (10)$$

Where k is a constriction factor.

c_1, c_2 are the learning constants.

$rand_1$, $rand_2$ are the random numbers in the range of 0 and 1

$V_{(m,n)}^{t}$ = velocity of m^th particle in n^th dimension $\text{X}_{(m,n)}^{t}$ = position of m^th particle in n^th dimension $\text{pbest}_{(m,n)}^{t}$ = personal best of m^th particle in n^th dimension

$\text{gbest}_{(1,n)}^{t}$ =global best of the particle in n^th dimension.

W is the inertia weight given by

$$w = w_{\max} - ((\text{w}_{\max} - \text{w}_{\min}) * \text{t}/\text{T}) \qquad (11)$$

w is an adjustable parameter between w_{max} and w_{min}

t = current iteration number

T = maximum number of iterations

The positions of the particles are updated using equation (12)

$$\text{X}_{(m,n)}^{t+1} = \text{X}_{(m,n)}^{t} + V_{(m,n)}^{t+1} \qquad (12)$$

4.1. Algorithm to find optimum value of series injected voltage using PSO technique

Step 1: Initialize the particles, maximum iterations, and dimension, minimum and maximum reactive power limits of SSVR, inertia weights and velocity of the particles. Here w_{max} and w_{min} are taken as 0.9 and 0.4 respectively.c_1=c_2=2.05.

Step 2: Generate the particles and velocities randomly within the limits. Here the particles are reactive power rating of SSVR. Series voltage is calculated from reactive power rating of SSVR and branch current.

Step 3: Run the load flow by adding the series voltage in the branch as given in the equation (8). The voltage constraint imposed is the voltage at the optimal location should not exceed the desired value (1 p.u.). Discard the particles which violate the voltage constraint. Find the fitness. Here the fitness is minimization of real power losses.

Step 4: Obtain the pbest values for all the particles from the fitness values and the best value among all the pbest values (gbest) is identified.

Step 5: Iteration count is set to one.

Step 6: Calculate the velocity using equation (10) for all the particles.

Step 7: Update the position of each particle as given in equation (12).

Step 8: Calculate new fitness functions for the new positions of all the particles. Update the pbest as follows:

$$P_{(best,n)}^{t+1} = \begin{cases} P_{(best,n)}^{t} & if\ f\left(X_{(m,n)}^{t+1}\right) > f(P_{(best,n)}^{t}) \\ X_{(m,n)}^{t+1} & if\ f\left(X_{(m,n)}^{t+1}\right) \leq f(P_{(best,n)}^{t}) \end{cases} \qquad (13)$$

Update the gbest from the latest pbest.

Step 9: Increment the iteration count. If iteration count does not reach its maximum, then go to step 6.

Step 10: Identify the gbest particle which gives the SSVR rating and series voltage.

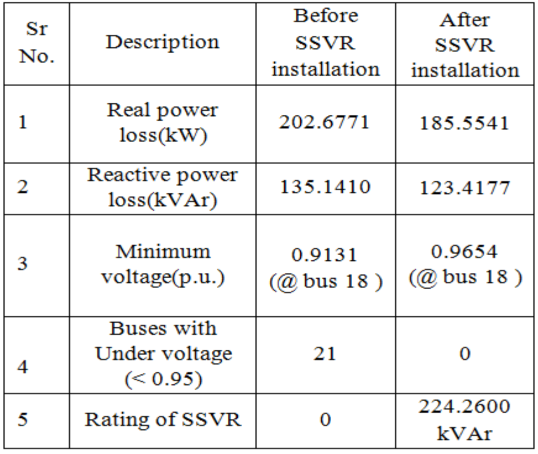
V. RESULTS OF 33-BUS TEST SYSTEM

The single line diagram of the 12.66 kV, 33-bus, 4-lateral radial distribution system and the data of the system are obtained from [11]. The total load of the system is considered as 3715 kW and 2300 kVAr. In 33 bus system 21 nodes out of 33 nodes of distribution system (63.63%) have under voltage problem.

Table 1 illustrates results of 33 bus system before and after installation of SSVR in branch 5 (6^th node). Table 2 gives voltage profiles. Table 3 shows results for SSVR Location, Series injected voltage, Reactive power rating, real and reactive power loss, loss reduction and number of nodes with under voltage problem for 33 bus distribution system.

SSVR placement in distribution system changes all the downstream node voltages, whereas upstream node voltages are slightly improved. When SSVR is placed in branch 5 (6th node), the number of nodes with under voltage problem are zero. The reduction in real and reactive power losses with SSVR placed in branch 5 is 17.1230 kW and 11.7233 kVAr respectively. Thus, from the viewpoint of loss reduction and under voltage problem mitigation, branch 5 is the optimal location. The rating of SSVR obtained for best location is 224.2600 kVAr. SSVR placement in the branches from 18 to 24 has no significant improvement in voltage and loss reduction.

Table 1: Results of 33 bus system



Sr No.	Description	Before SSVR installation	After SSVR installation
1	Real power loss(kW)	202.6771	185.5541
2	Reactive power loss(kVAr)	135.1410	123.4177
3	Minimum voltage(p.u.)	0.9131 (@ bus 18)	0.9654 (@ bus 18)
4	Buses with Under voltage (< 0.95)	21	0
5	Rating of SSVR	0	224.2600 kVAr

Table 2: Voltage profiles of 33 bus system without and with SSVR

Bus no	Voltage in p.u		Bus no	Voltage in p.u	
	Without SSVR	With SSVR		Without SSVR	With SSVR
1	1.0000	1	18	0.9131	0.9654
2	0.9970	0.9971	19	0.9965	0.9966
3	0.9829	0.9834	20	0.9929	0.9930
4	0.9755	0.9763	21	0.9922	0.9923
5	0.9681	0.9692	22	0.9916	0.9917
6	0.9497	1	23	0.9794	0.9799
7	0.9462	0.9967	24	0.9727	0.9732
8	0.9413	0.9921	25	0.9694	0.9699
9	0.9351	0.9862	26	0.9477	0.9982
10	0.9292	0.9807	27	0.9452	0.9957
11	0.9284	0.9799	28	0.9337	0.9849
12	0.9269	0.9784	29	0.9255	0.9771
13	0.9208	0.9727	30	0.9220	0.9738
14	0.9185	0.9705	31	0.9178	0.9698
15	0.9171	0.9692	32	0.9169	0.9690
16	0.9157	0.9679	33	0.9166	0.9687
17	0.9137	0.9660			

Table 3: SSVR Location, Series injected voltage, real and reactive power injected, real and reactive power loss, loss reduction and number of nodes with under voltage problem for 33 bus distribution system

SSVR Location (branch)	Series injected voltage (p.u)	Real power injected (kW)	Reactive power injected (kVAr)	Power loss		Loss Reduction		No. of Nodes with under voltage problem
				Real (kW)	Reactive (kVAr)	Real (kW)	Reactive (kVAr)	
1	0.0029 + 0.0048i	0	25.8606	201.2971	134.2188	1.3800	0.9222	19
2	0.0164 + 0.0272i	0	127.7100	195.1452	130.1111	7.5319	5.0299	14
3	0.0234 + 0.0355i	0	122.1400	193.5001	128.8989	9.1770	6.2421	10
4	0.0300 + 0.0464i	0	149.4800	191.1581	127.2746	11.5190	7.8664	3
5	0.0454 + 0.0737i	0	224.2600	185.5541	123.4177	17.1230	11.7233	0
6	0.0433 + 0.1321i	0	168.0000	191.5033	127.5493	11.1738	7.5917	8
7	0.0455 + 0.1501i	0	153.8000	192.0447	127.9254	10.6324	7.2156	9
8	0.0473 + 0.1769i	0	137.8100	192.7451	128.3799	9.9320	6.7611	10
9	0.0504 + 0.1904i	0	135.1200	192.7968	128.4073	9.8803	6.7337	11
10	0.0524 + 0.1853i	0	119.9300	193.7173	129.0231	8.9598	6.1179	12
11	0.0508 + 0.2016i	0	118.1900	193.8112	129.0839	8.8659	6.0571	13
12	0.0478 + 0.2411i	0	122.0100	193.5202	128.8801	9.1569	6.2609	14
13	0.0390 + 0.2833i	0	121.9500	193.5172	128.8754	9.1599	6.2656	15
14	0.0000 + 0.3194i	0	93.8061	195.4742	130.2074	7.2029	4.9336	16
15	0.0000 + 0.3627i	0	82.9298	196.2188	130.7063	6.4583	4.4347	17
16	0.0000 + 0.3790i	0	61.9845	197.7337	131.7331	4.9434	3.4079	18

17	0.0244 + 0.3526i	0	34.8108	199.8109	133.1544	2.8662	1.9866	19
18	0.0035 + 0.0079i	0	3.4196	202.6590	135.1281	0.0181	0.0129	21
19	0.0069 + 0.0162i	0	5.2032	202.6462	135.1183	0.0309	0.0227	21
20	0.0076 + 0.0179i	0	3.8252	202.6536	135.1233	0.0235	0.0177	21
21	0.0082 + 0.0194i	0	2.0767	202.6639	135.1309	0.0132	0.0101	21
22	0.0194 + 0.0451i	0	51.0598	201.3734	134.3725	1.3037	0.7685	21
23	0.0250 + 0.0617i	0	62.0383	201.0736	134.1913	1.6035	0.9497	21
24	0.0278 + 0.0705i	0	35.2720	201.7125	134.5614	0.9646	0.5796	21
25	0.0496 + 0.0540i	0	99.3743	193.7699	129.0734	8.9072	6.0676	12
26	0.0520 + 0.0545i	0	97.3326	193.7359	129.0308	8.9412	6.1102	13
27	0.0621 + 0.0632i	0	108.0000	192.5758	128.2116	10.1013	6.9294	14
28	0.0693 + 0.0674i	0	111.7200	192.1019	127.8751	10.5752	7.2659	15
29	0.0731 + 0.0645i	0	99.6253	193.0583	128.5330	9.6188	6.6080	16
30	0.0537 + 0.2198i	0	106.3300	192.4493	128.1172	10.2278	7.0238	17
31	0.0567 + 0.2144i	0	67.4496	196.0367	130.5669	6.6404	4.5741	18
32	0.0702 + 0.1538i	0	12.1930	201.4373	134.2829	1.2398	0.8581	20

VI. CONCLUSIONS

The effect of SSVR is considered by injecting series voltage in quadrature with branch current in such a way that the load bus voltage magnitude is maintained at desired value. The optimum location is the branch which has mitigated the problem of under voltage in all the load buses and which has minimum power loss. PSO has been used to find the optimum rating of SSVR. The results show the substantial improvement in voltage profile and considerable reduction in power loss after insertion of SSVR model in large radial distribution networks.

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Author Profile's:

M. Laxmidevi Ramanaiah is a Research Scholar in the Department of EEE, S.V.University, Tirupati, India. She received her M.Tech and B.Tech Degree from JNTU Anantapur, India in 2012 and 2009 respectively. Her research interests include Power System Optimization and FACTS.

Prof. M. Damodar Reddy is working as a Professor at S.V.University College of Engineering, Tirupati, India. His areas of interests include Power System Optimization and reactive power compensation.

T. Chandra Sekhar is a M. Tech student in S. V. University College of Engineering, S.V.University, and Tirupati, India. He received his B.Tech Degree from RVR & JC College of Engineering, Guntur, India in the year 2013