Distribution Generation and Capacitor Placement in Distribution Systems

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Abstract— Distribution systems form a critical part of the power system by linking the consumer to the transmission system. Distribution systems are extensive, complex and require adequate planning to ensure reliability and reduce installation and operation cost generated by both voltage instability and network power loss. High power losses and voltage instability are the main challenges facing power distribution companies. These challenges are mitigated by capacitor and distributed generation placement in the distribution network. The effectiveness of these measures is greatly dependent on optimally placing and sizing these components within the distribution network and also, how their operation is coordinated. Due to the complexity of the distribution networks, planning of placement becomes a complex task. It therefore requires network planners to develop methods that optimally place capacitors and distributed generations (DGs) in distribution networks. In this paper a novel way of DG and capacitor placement is proposed. The method uses Voltage Stability Index to find the optimal location of DGs and Capacitors. Evolutionary programming algorithm is employed to determine the sizes of the DGs and Capacitors to be placed at the identified locations. The aim is to enhance the voltage stability of the radial distribution network. This method is tested on the IEEE-33 bus radial distribution network. Simulation is carried out in MATLAB.

Keywords— Capacitor Placement, Distributed Generation, Evolutionary Programming, Voltage Stability

I. INTRODUCTION

Deconomic growth and increasing population especially in developing countries. As a result of this, distribution systems are being operated close to their maximum limits of voltage stability and power carrying capacity. In addition, distribution systems have changed from passive networks to active networks due to increased proliferation of distributed generation [1]. Increased proliferation of distributed generation has resulted in a number of adverse effects. These effects include voltage variations, degraded protection, altered transient stability, bi-directional power flows and increased fault level. Voltage variation has been addressed as the most dominant impact of distributed generation [2].

Voltage stability is a requirement for the secure operation of distribution systems. Proper planning of distributed generation and their control strategies determine the voltage stability situation of distribution system [3] [4]. The planning aspect involves proper location and sizing of the distributed generation

(DG) together with other reactive power sources in the distribution network. Control aspect involves the coordinated operation of these DGs together with conventional voltage and reactive power devices [5].

With the increased use of Distributed Generation, it has become critical to incorporate them in distribution system planning. The distributed generation problem has been a key area of research in the recent past. Different researchers have addressed distributed generation planning in different ways. The objective functions used by researchers in distributed generation planning include power loss minimization, reliability enhancement, minimization of operational and investment cost and voltage stability enhancement [6].

Researchers have used different methods in DG placement problems. These methods include analytical methods, numerical methods and heuristic methods. Heuristic methods have been found to work well for large and complex optimization problems such as DG and capacitor placement problem [7]. Heuristic methods that have been used in DG placement planning include particle swarm optimization [8] [9], bacteria foraging algorithm [10], differential evolution algorithm [11] and ant colony algorithm [12].

In this paper evolution programming algorithm is used to optimally place DGs and capacitors in order to enhance voltage stability.

II. PREVIOUS WORK

A. Voltage Stability

Voltage stability is the ability of power system to sustain acceptable voltage levels under normal operating conditions and after occurrence a disturbance [13]. Voltage stability is usually represented by P-V curves, Q-V curves and stability indices. Fig. 1 represents P-V curves for different load power factors.

The point of voltage collapse (PoVC) is the nose of the P-V curve. This is the point at which an increase of load leads to rapid voltage drop of the power system and consequently voltage collapse or network collapse. Voltage collapse usually occurs in heavily loaded systems that do not have sufficient local reactive power sources and consequently cannot provide secure voltage profile for the system [14]. The Q-V curves shown in fig. 2 show variation of receiving end voltage with

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variation in load reactive power for different real power loads. The region of the locus of knee point represents the stable region.



Fig. 1 P-V Curves for different load power factors



Fig. 2 Q-V Curves for different load real powers

When using the Q-V method, the sensitivity of voltage to changes in reactive power at a given bus is given by the slope of the Q-V curve. If the V-Q slope of the ith bus is positive, the system is voltage stable and if negative the system is voltage unstable. Other methods used for steady state voltage stability analysis are modal analysis and sensitivity analysis. These method use the Power Flow Jacobian that is obtained by solving a set of equations linearized about a given operating point.

The Jacobian is evaluated for singularity to determine the maximum loadability of the power system. The main disadvantages of these techniques is that they require considerable computation efforts and are time consuming especially for a large network.

Recently, researchers have developed indices for voltage stability analysis in power systems and more so for analysis in distribution systems. Distribution networks are large and complex and therefore require simple tools for stability analysis that do not require large computational effort. Many indices have been developed by researchers studying voltage stability of distribution system as a measure of how far or near a system is from voltage instability or voltage collapse. Some of the common indices include Voltage Stability Margin (VSM) [4], real Power Stability Index (PSI) [9], Voltage Stability Index (VSI) [15]] and L-index [16].

The Voltage Stability Index (VSI) presented by Charkravorty and Das [14] will be used in this work as the objective function. The index is simple and suitable for voltage stability determination in radial distribution networks. The VSI is formulated by equation (1).

$$VSI_{i} = V_{s}^{4} - 4V_{s}^{2} (R_{i}P_{Li} + X_{i}Q_{Li}) - 4(X_{i}P_{Li} - R_{i}Q_{Li})^{2}$$
(1)

where,

 VSI_i is Voltage Stability Index at Bus i

 V_s is distribution substation voltage which is 1 p.u

 R_i is the resistance between source bus and bus i

 X_i is reactance between source bus and bus i

 P_{Li} is active power flow through bus i

 Q_{Li} is reactive power flow through bus

B. Search Heuristics

For largest time of Power System Engineering, numerical optimization methods have been applied in power system planning and operation. Power system optimization is important since it has contributed to saving cost in terms of fuel cost, improved operational reliability and system security. Power systems have become large and complex and there has been a need to develop optimization techniques that will accommodate the large number of constraints in solving power system optimization problems. These methods are required to provide better solutions and have shorter computation times.

In recent times, researchers have widely used artificial intelligence methods for solving optimization problems because they can deal with complex problems that cannot be solved efficiently using conventional methods [17]. In addition, artificial intelligence methods have simple mathematical structure and simulate natural phenomena such as behavior of animals. Search heuristics are particularly applicable when objective functions are highly nonlinear and when the number of variables and constraints is large [18]. In addition, search heuristics reduce development time. This section gives a brief overview of Evolutionary Programming be used as the optimization method in this work.

Evolutionary Programming (EP) is a computational optimization method in the area of evolutionary computation which uses principles of natural evolution to find global optimal solution of a given problem [17]. As observed in [18], evolutionary programming is a useful method of optimization when other techniques such as gradient descent or direct analytical discovery methods are not possible and where the

search space may contain many local optimum solutions.

Evolution Programming is a general global optimization tool. EP seeks the optimal solutions over a number of generations or iterations. Evolution Programming uses mutation operator to generate a new population from an existing population. This technique is suitable in solving problems with real valued function optimization. The general procedure of Evolution Programming is as presented in fig. 3. EP has been applied by researchers to solve several power systems engineering problems. In [23], EP has been used to solve long term transmission network planning, estimating the transient and sub-transient parameters of a generator under normal operation, solving economic dispatch problem of units with non-smooth input-output characteristic functions and also solving the optimal power flow problem in FACTs.



Fig. 3 General Evolution Programming Algorithm

III. METHODOLOGY

The objective function that was used is the Voltage Stability Index and the optimization problem was formulated as shown in the following section. This index varies from 0 to 1, with zero representing voltage collapse point and 1 representing the most stable bus. The bus at which voltage collapse is most probable was identified.

In order to identify buses most prone to voltage collapse, voltage stability indices for all buses were calculated and ranked from the smallest to the largest. The maximum number of DGs locations was determined by dividing the maximum DG penetration by the maximum DG size allowable. This number determined the number of buses corresponding to the lowest ranked indices that were candidates for DG and Capacitor placement.

The DGs were taken to operate in PQ mode with a power factor of 1. They therefore produce only active power at the buses they are installed at. Reactive power is provided by the capacitors which are simultaneously placed at the candidate buses together with the DGs.

Once the location for placement is identified, the next task was to identify the optimal size of the DGs and Capacitors that will improve the Voltage Stability Indices of the candidate buses without violating the system constraints. To identify the optimal size, Evolution Programming Algorithm was used to search for optimal sizes that maximize the voltage stability index. The test networks that will be used are IEEE-33 which is shown in fig. 4. The network data is shown in Appendix A. All simulations were done using MATLAB



Fig. 4 Standard IEEE 33-bus system

A. Problem formulation

The optimization problem was formulated as follows: $max(VSI) = min(VSI_1, VSI_2, ...VSI_n)$ (2)

Where

$$VSI_{i} = V_{s}^{4} - 4V_{s}^{2} (R_{i}P_{Li} + X_{i}Q_{Li}) - 4 (X_{i}P_{Li} - R_{i}Q_{Li})$$
(3)

And i = 2, 3, 4..., n,

n = no.of buses

 Q_{Li} is the total reactive power fed through node *i*

 P_{Li} is the total active power fed through node *i*

 $i = 2, 3, 4..., n R_i$ is the resistance between source and bus *i*

 X_i is the reactance between source and bus *i*

For purposes of computation, equation (2) is modified as follows:

$$\max F(VSI) = \sum_{i=1}^{n} VSI_{n}$$
(4)

Equation (4) is maximized subject to the following constraints.

1) Equality constraints

The equality constraints include non-linear recursive power flow equations formulated as follows:

$$P_{i+1} = \left[P_{i,i+1} - \left(R_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2} \right) - P_{i+1}^L + \alpha_{P_{DG}} P_{i+1}^{DG} \right]$$
(5)

$$Q_{i+1} = \left[Q_{i,i+1} - \left(X_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2}\right) - Q_{i+1}^L + \alpha_{Q_c} Q_{i+1}^C\right]$$
(6)
and

$$\left|V_{i+1}\right|^{2} = \left|V_{i}\right|^{2} - 2\left(P_{i,i+1}R_{i,i+1} + Q_{i,i+1}X_{i,i+1}\right) + \left(P_{i,i+1}^{2} + Q_{i,i+1}^{2}\right)\frac{R_{i+1}^{2} + X_{i+1}^{2}}{\left|V_{i}\right|^{2}}$$
(7)

where,

i = 1, 2, 3, K, n

 P_{i+1} is active power flow through node i+1

 Q_{i+1} is reactive power flow through node i+1

 $|V_i|$ is the voltage magnitude at node *i*

 $P_{i,i+1}$ is the active power flow in the branch between node i and i+1

 $Q_{i,i+1}$ is the reactive power flow in the branch

between node i and i + 1

 P_{i+1}^L is the active power load at node i+1

 α_{DG} is the active power multiplier set to 1

where there is DG and 0 where there is none Q_{i+1}^{C} is the capacitive reactive power load at node i+1

 Q_{i+1}^L is the reactive power load at node i+1

 α_{oC} is the reactive power multiplier set to 1 whe re there is a capacitor and 0 where there is none

 $R_{i,i+1}$ is the resistace of branch between node *i*

and i + 1

 $X_{i,i+1}$ is the reactance of branch between node *i* and i + 1

2) Inequality constraints

a) Voltage operational tolerance

$$V_{i\min} \leq V_i \leq V_{i\max}$$

$$V_{i\min} \le V_i \le V_{i\max}$$
 (8)

b) Thermal capacity limits
$$\left| \boldsymbol{I}_{i,i+1} \right| \leq \left| \boldsymbol{I}_{i,i+1} \right|_{\max} \tag{9}$$

Total DG capacity constraint which should be within c) a given penetration level.

$$\frac{\sum_{i=1}^{n} P_{i+1}^{DG}}{P_{Load}} \le \eta$$
(10)

$$P_{DG\min} \le P_i^{DG} \le P_{DG\max} \tag{11}$$

$$Q_{C\min} \le P_i^{DG} \le Q_{C\max} \tag{12}$$

where,

n – total number of buses in the distribution system

B. Parameter setting

The optimization problem parameters were set as shown in Table 1.

TABLE 1				
OPTIMIZATION PROBLEM PARAMETERS				
Parameter	Value			
Maximum DG penetration, η	50%			
Maximum DG Size	500kW			
Maximum voltage at a bus $ V_i _{\text{max}}$	1.05p.u			
Minimum voltage at a bus $ V_i _{\min}$	0.95p.u			
Total network active power demand	3.715MW			
Maximum DG penetration in kW	1857.5kW			
No. of locations=Max. DG penetration/max. DG size	4			

C. Load flow

In order to calculate the initial network parameters, a load flow was done. The load flow technique used was the backward/forward sweep load flow method. In addition to the load flow, the voltage stability indices (VSI) for the network were calculated and a ranking done to determine the locations with lowest VSI that would be candidates for installation of DGs and capacitors. The load flow results and corresponding VSI are as shown in Table 2.

Bus Bus VSI VSI No. Vbus Rank No. Vbus Rank 1 1 1 33 18 0.9036 0.669 1 2 0.997 19 0.938 27 0.9993 32 0.9965 3 0.983 0.9846 30 20 0.9929 0.986 31 4 0.975 0.9314 0.9922 0.972 26 21 29 5 0.9033 0.968 23 22 0.9915 0.969 28 6 0.949 0.8739 21 23 0.9792 0.915 24 7 0.946 0.8119 19 24 0.9725 0.919 25 8 0.932 0.7987 25 0.894 17 0.9692 22 9 0.926 0.7545 0.9474 0.817 14 26 20 10 0.92 0.7343 13 27 0.9448 0.805 18 11 0.919 0.7161 10 28 0.9334 0.796 16 0.918 0.7134 9 29 0.9251 0.759 12 15 13 0.911 0.7085 0.9216 8 30 0.732 12 14 0.909 0.6898 5 31 0.9174 0.721 11 0.908 0.6829 0.9164 0.708 7 15 4 32 0.906 0.6787 3 33 0.9161 0.705 6 16 17 0.904 0.6746 2

 TABLE 2

 LOAD FLOW DATA AND VSI FOR IEEE-33 BUS NETWORK

From table 2, the buses that formed candidates for installation of DG and capacitor are 18, 17, 16 and 15 owing to their low VSIs.

D. Evolution programing Procedure

After identifying the location for installation of DGs and capacitors, Evolution Programming method was used to obtain the optimal sizes. The procedure was as shown in fig. 5.

IV. RESULTS AND DISCUSSION

After implementing the Evolutionary algorithm, the sizes of DGs and Capacitors at various buses were as shown in Table 3. In addition, the voltage magnitude and Voltage Stability indices after installation of DGs and capacitors were shown in Table 4. The voltage profile and voltage stability indices for all buses were plotted as shown in fig. 6 and 7 respectively.

TABLE 3				
OPTIMAL SIZES OF DGS AND CAPACITORS				

_		Size of	Size of Capacitor
	Bus No.	DG(kW)	(kVAr)
	15	80.3	77.6
	16	74.4	39.2
	17	126	117.3
_	18	214	217.5



Fig. 5 Evolutionary Programming Algorithm

TABLE 4
LOAD FLOW DATA AND VSI FOR IEEE-33 BUS NETWORK AFTER
DG AND CAPACITOR PLACEMENT

Bus No.	Vbus	VSI	Bus No.	Vbus	VSI
1	1	1	18	0.9189	0.7125
2	0.9971	0.9992	19	0.9966	0.9417
3	0.9837	0.9844	20	0.993	0.9864
4	0.9767	0.9341	21	0.9923	0.9723
5	0.9698	0.9079	22	0.9917	0.9696
6	0.9525	0.8783	23	0.9801	0.9203
7	0.9492	0.8199	24	0.9734	0.9224
8	0.9379	0.8051	25	0.97	0.8977
9	0.933	0.7703	26	0.9506	0.8289
10	0.9286	0.7543	27	0.9481	0.8164
11	0.928	0.7432	28	0.9366	0.8068
12	0.927	0.7411	29	0.9284	0.7692
13	0.9229	0.7333	30	0.9249	0.743
14	0.9213	0.7222	31	0.9207	0.7315
15	0.9206	0.718	32	0.9198	0.7185
16	0.9201	0.7165	33	0.9195	0.7156
17	0.9191	0.711			



Fig. 6 Bus Voltage profile for IEEE 33 bus network



Fig. 7 VSI profile for IEEE 33 Bus network



Fig. 8 Chart showing comparison of voltage magnitude at buses where DGs and Capacitors are installed



Fig. 9 Chart showing comparison of Voltage Stability Indices at buses where DGs and Capacitors are installed

Fig. 6 represents the voltage profile at all buses of the network before and after DG installation. The lowest value of voltage before installation of capacitors and DGs was 0.9036 p.u at bus 18 but after installation of DGs and capacitors the lowest value of voltage was 0.9189 p.u at bus 18 which represents 1.7% improvement. In addition, from fig. 7, it was noted that the lowest value of VSI before installing DGs and capacitors was 0.669 at bus 18. However, after installing DGs and capacitors, the lowest value of VSI became 0.7125. This represents an improvement of 6.6% of VSI on the weakest bus.

Fig. 8 and fig. 9 show a graphical representation of voltage and VSI values before and after installation of DGs and Capacitors. These are the buses where there is maximum impact on voltage profile and voltage stability index as a result of installing DGs and Capacitors. This can be attributed to the fact that voltage stability is a local phenomenon and not a global phenomenon. The maximum impact of voltage stability and voltage profile improvement will therefore be at the points where the DGs and capacitors will be installed. In other buses, the improvement will be minimal.

V. CONCLUSION

This work has demonstrated the application of search heuristics in optimizing the voltage stability of radial distribution network through installation of optimal sizes of distributed generation and capacitors. In addition, this work has introduced a novel method of determining the best location for placing distributed generation and capacitors in a given radial distribution network.

Through this technique, it has been demonstrated that distribution voltage profile and voltage stability can be greatly improved by optimal placement of distributed generation and capacitors.

TABLE 5:							
	IEEE 33 BUS NETWORK DATA						
	Load at Receiving						
ending	Receiving			1	Bus		
Bus	Bus	R(Ohms)	X(Ohms)	Р	Q		
1	2	0.0922	0.0477	100	60		
2	3	0.4930	0.2511	90	40		
3	4	0.3660	0.1864	120	80		
4	5	0.3811	0.1941	60	30		
5	6	0.8190	0.7070	60	20		
6	7	0.1872	0.6188	200	100		
7	8	1.7114	1.2351	200	100		
8	9	1.0300	0.7400	60	20		
9	10	1.0400	0.7400	60	20		
10	11	0.1966	0.6550	45	30		
11	12	0.3744	0.1238	60	35		
12	13	1.4680	1.1550	60	35		
13	14	0.5416	0.7129	120	80		
14	15	0.5910	0.5260	60	10		
15	16	0.7643	0.5450	60	20		
16	17	1.2890	1.7210	60	20		
17	18	0.7320	0.5740	90	40		
2	19	0.1640	0.1565	90	40		
19	20	1.5042	1.3554	90	40		

0.4095

0.7089

0.4512

0.8980

0.6960

0.2030

0.2842

1.0590

0.8042

0.5075

0.9744

0.3105

0.3410

APPENDIX

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33

System voltage is 12.66kV

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0.4784

0.9373

0.3083

0.7091

0.7011

0.1034

0.1447

0.9337

0.7006

0.2585

0.9630

0.3619

0.5302

90

90

90

90

520

320

60

60

120

200

250

210

60

40

40

40

40

200

200

25

20

70

600

70

100

40

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