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Optimal Allocation of Combined DG and Capacitor Units for Voltage Stability Enhancement

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Abstract

Due to high penetration of distributed generation (DG) in distribution networks, transmission networks are no longer responsible solely for security issues in low-voltage distribution networks. DG units may also participate in security as well as power generation depending on their locations. In this paper, stability of Distribution system is studied based on voltage stability analysis as a security measure. Basic load flow is carried out on the well known 33- bus radial distribution network using forward backward sweep algorithm in MATLAB and voltage stability indices have been calculated. A priority list of DG and capacitor unit allocation for minimization of losses and improvement in voltage magnitude will be evaluated by evolutionary search algorithm i.e. Genetic Algorithm.

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Keywords: Distributed Generation(DG);Voltage Stability Index(SI);Radial Distribution Network; Genetic Algorithm.

1. Introduction

The three basic requirements of distribution system is proper voltage, availability of power on demand and reliability. Due to the load fluctuations in distribution system, the distribution system suffers low voltage and voltage variations. And in a radial distribution system the voltage level at the farther end is lower and low voltage levels hinders the performance of the equipments and loads connected to the system. So maintaining voltage levels within the acceptable limit is necessary. Also supplying power on demand becomes an important aspect with which comes the reliability of the system. As an effective solution to improve the performance of the distribution system

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interconnection of "Distributed generation (DG)" have emerged. Distribution generation reduces losses in the distribution system, supply power and improves the voltage profile of the system. DG's are the small scale electric power generators that produce electricity at the distribution side of the power system [1]. Capacitors are used at the distribution side to locally provide reactive power and hence improve the voltage levels. Installing capacitor banks in distribution system can effectively reduce power loss and provide additional benefits for system operation [2].In order to voltage stability in the distribution system a stability index (SI) is used. The active power and the reactive power transferred are used for developing the stability index (SI). In this paper the optimal placement of DG and capacitors in the radial distribution network i.e. IEEE 33 test system is carried out as a multi objective optimization function. Genetic algorithm (GA) is used as the optimization tool. GA operates on a population of potential solutions applying the principle of survival of the fittest to produce (hopefully) better and better approximations to a solution. The impact of DG and capacitors on the network voltage profile and also reduction in the losses of the system is studied.

2. Distribution generation (DG)

Distributed generation (DG), unlike traditional generation, aims to generate part of required electrical energy on small scale closer to the places of consumption and interchanges the electrical power with the network. Distributed generation, also termed as embedded generation or dispersed generation or decentralized generation, is defined as small electric power source that can be connected to a distribution network.

2.1 *Types of Distributed Generation (DG).*

The DG's are grouped into four major types based the real and reactive power delivering capability [3].

Type1: This type DG is capable of delivering only active power such as photovoltaic, micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters.

Type2: DG capable of delivering only reactive power. Synchronous compensators such as gas turbines and capacitor banks are the example of this type and operate at zero power factors.

Type3: DG capable of delivering active power but consuming reactive power. Mainly induction generators, which are used in wind farms, come under this category. However, doubly fed induction generator (DFIG) systems may consume or produce reactive power i.e. operates similar to synchronous generator.

Type4: DG capable of delivering both active and reactive power. DG units based on synchronous machines (cogeneration, gas turbine, etc.) come under this type.

2.2 *Modeling of DG units.*

In order to model the DG in the optimization problem considering the type of DG, the injected active and reactive power at ith bus are modeled as follows [4].

$$P_i = P_{DG_i} - P_{D_i} \tag{1}$$

$$Q_i = Q_{DG_i} - Q_{D_i} = \propto_i \times P_{DG_i} - Q_{D_i} \tag{2}$$

$$\alpha_i = (sign) \times \tan(cos^{-1}(PF_{DG_i})) \tag{3}$$

$P_{DG_i}$is active power generated from DG at ith bus, $Q_{DG_i}$is reactive power generated from DG at ith bus, $P_{D_i}$is active power demand at ith bus, Q_{D_i} is reactive power demand at ith bus and PF_{DG_i} is the DG power factor.

The power factor depends on the type of DG and the operating condition of the DG unit.

- Type 1 - PF_{DG_i}=1
- Type 2 - PF_{DG_i}= 0
- Type 3 – 0 < PF_{DG_i} < 1 and sign = -1
- Type 4 – 0 < PF_{DG_i} < 1 and sign = +1

In this paper the power factor for type 3 is taken as 0.9 lag and for type 4 DG the maximum and minimum reactive power produced is taken as ±0.8 time the active power produced. Power factor for type 4 is taken as 0.6 lead.

3. Voltage Stability Index

Voltage stability analysis could be performed in a power system by evaluating the derived voltage stability index. The values of the voltage stability index would indicate the distance to voltage collapse for a given loading condition. These indices are taken as an instrument that will measure the stability condition and used to rank the contingencies in a power system.

The voltage stability index (SI) used in this paper is developed for distribution line model from the quadratic equation which is mostly used for the calculation of the line sending end voltages [5].

The voltage stability index (SI) is given by,

$$SI(i) = \boldsymbol{V_s^4} - 4\,\boldsymbol{V_s^2}(R_i P_{Li} + X_i Q_{Li}) - 4\,(X_i P_{Li} + R_i Q_{Li})^2 \quad ; \ i = 1, 2 \ldots N \tag{4}$$

Where,
SI- Voltage stability index
V_s- Sending end voltage
R_i- Resistance of the line
X_i- Reactance of the line
P_{Li}- Active power load at i^{th} bus
Q_{Li}- Reactive power load at i^{th} bus
N- Number of buses
The node at which the value of the stability index is minimum, is more sensitive to the voltage collapse.

4. Forward –Backward Sweep Algorithm

4.1 Introduction

The load flow of a single source network can be solved iteratively from two sets of recursive equations. The first set of equations for calculation of the power flow through the branches starting from the last branch and proceeding in the backward direction towards the root node. The other set of equations are for calculating the voltage magnitude and angle of each node starting from the root node and proceeding in the forward direction towards the last node [6].

4.2 Backward sweep

Starting from the end node/bus moving backwards to the slack bus the power flow in each branch can be calculated using,

$$\boldsymbol{S_n = S_i + \sum_{m \epsilon M} S_m + Loss_n} \tag{5}$$

Where,

$\boldsymbol{S_n}$ is power flow in the n^{th} branch ,'i' is the end node of branch 'n', $'\boldsymbol{S_i}'$ is power of load connected to the i^{th} bus/node, 'M' is number of branches connected to the n^{th} branch in i^{th} node, $'\boldsymbol{S_m}'$ is power of m^{th} branch, $'\boldsymbol{Loss_n}'$ is the m^{th} branch loss (which is considered as 0 in first iteration).

4.3 Forward sweep

Starting from the branches connected to the slack bus and moving forward towards the end branches, the current in sending bus 'j' of n^{th} branch and voltages in the receiving bus 'i' are calculated using the equations (6) and (7).

$$\boldsymbol{I_n} = \left(\frac{S_n}{Vj}\right)^* \tag{6}$$

$$\boldsymbol{V_i = V_j - Z_n \times I_n} \tag{7}$$

The branch power losses can be calculated using,

$$\boldsymbol{Loss_n} = (\boldsymbol{V^j} - \boldsymbol{V^i}) \times \boldsymbol{I_n^*} \quad (8)$$

4.4 Convergence criterion

The voltages calculated in the previous and present iterations are compared. In the successive iterations if the maximum mismatch between the voltages is less than the specified tolerance i.e., 0.0001, the solution is said to be converged.

The voltage deviation can be calculated using equation (9),

$$\Delta \boldsymbol{V}^{\boldsymbol{i}^{(\boldsymbol{k})}} = \left|\boldsymbol{V}^{\boldsymbol{i}^{(\boldsymbol{k})}}\right| - \left|\boldsymbol{V}^{\boldsymbol{i}^{(\boldsymbol{k-1})}}\right| \quad (9)$$

Where ‘k’ is iteration number.

4.5 Considering Dg Units in Power Flow Algorithm

- DG units as PQ bus

DG units considered as PQ buses can be modeled as the passive load i.e. like negative loads. The overall load gets reduced by the amount of DG produced.

- DG units as PV bus

Modeling of DG units that are controlled like PV buses is more complicated compared to that of PQ buses. In order to control the voltage of PV nodes, the compensation technique from [7] is used.

5. Optimization Problem Formulation

The objective function used in the paper is given by,

$$\min F = \left(k_1 \times \frac{P_{loss}}{P_{loss\,0}} + k_2 \frac{\sum Cost_{\ cap}}{Cost_{\ cap\ max}} + k_3 \frac{\sum Cost_{\ DG}}{Cost_{\ DG\ max}} - k_4 \frac{VSI}{VSI_0}\right) \quad (10)$$

Where,

$P_{Loss\,0}$ is the total losses of the network before the installation of the DG units and the capacitors
P_{Loss} is the total losses of the network after the installation of the DG units and the capacitors
$\sum Cost_{cap}$ is the sum of the cost of the installed capacitors
$Cost_{cap^{max}}$ is the cost of the biggest summation of capacitors that can be installed
$\sum Cost_{\ DG}$ is the sum of cost of installed DG units
$Cost_{\ DG^{max}}$ is the cost of largest DG unit that is installed
VSI is stability index before installation of DG and capacitor unit
VSI_0 is the stability index after the installation the DG and capacitor units
k_1, k_2, k_3 and $k_4$are the weighting coefficients,

Also, $\sum_i^4 K_i$=1
Therefore $k_1 = 0.6, k_2 = 0.1, k_3 = 0.1\ and\ k_4 = 0.2$

Optimization problem is a minimization problem which includes power loss, cost of capacitors and DGs installed and also voltage stability index. In this paper, 8 generators exist such that capacity of DG varies in steps of 250kW from 0 to 2000kW. The capacity of DG ranges between (0 - $P_{DG^{max}}$). Also capacity of capacitor varies from (0 - $Q_{C^{max}}$). The capacity of capacitors varies in steps of 150kvar from 0 to 1500kvar.

For the cost evaluation of the capacitor units following data is considered [2].

$$Cost_{\ cap} = K_c \times Q_c \quad (11)$$

Where, K_c is the constant co-efficient (US$/kvar) and $'Q_c'$ is the capacity of capacitor (kvar)

The capital cost of the DG units is different because of their types [9], but in general it can be defined as in Eqn. (12):

$$Cost_{DGi} = K_i \times P_{DGi} \qquad (12)$$

Where, K_i is the constant coefficient (US$/kW)

Consider the number of buses in a system to be 'N', then the number of candidate buses for interconnection of DG and capacitor units is 'N-1' i.e. excluding slack bus. The length of chromosome is taken as '2N-2'. The arrangement of chromosome is shown in Fig. 1. If '0' is placed in any of the bits, it shows that no DG unit or capacitor is placed in that bus. Genetic algorithms are a family of computational models inspired by evolution [8]. For optimization the GA parameters chosen are given below in the Table 1.

X_1	X_2	…	X_{N-1}	X_N	X_{N+1}	X_{N+2}	…	X_{2N-1}	X_{2N-2}

← DG capacity in each node → ← capacitor capacity in each node →

Fig 1. Structure of chromosome

6. Results and discussion

The proposed method is applied on the IEEE 33 test bus system [10] using the MATLAB. The obtained active power loss and reactive power loss for the base is 196.2681kW and 130.6335kvar respectively. The SI is calculated from the equation (10). From the results and graph shown in Fig. 2, it is evident that 18^{th} bus is the weakest bus with voltage Stability Index SI 0.7061.

The study carried out for two cases,

- Installation of DG only
- Simultaneous installation of capacitor units and DG

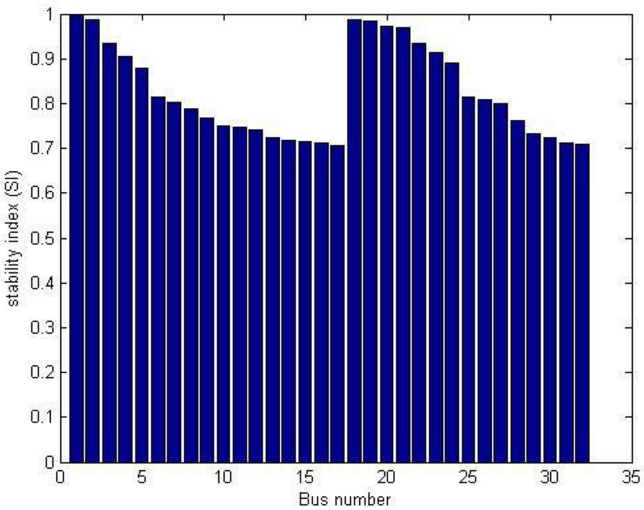

Fig. 2 SI of the IEEE 33- bus system without DG and capacitors.

Table 1. GA parameters

Population function	Section function	Number of variables	Crossover	Crossover rate	Mutation rate
120	Roulette	64	Single point	0.9	0.035

Table 2. Results for case 1

Type Of DG	DG Capacity (KW/KVAR)	DG location	Function value	Power loss (KW)	SI of the system	$\Delta P_{loss}/P_{loss0}$ Reduction in losses(%)
With only one DG for each type						
1	2000	7	0.5	115.07	0.77	41.37
2	1200	30	0.75	151.34	0.75	22.88
3	1500	6	0.8	173.43	0.80	11.63
4	2000	30	0.33	78.62	0.77	59.94
With two DG for each type						
1	750 1250	14 29	0.49	87.64	0.87	55.34
2	450 1050	13 30	0.79	141.89	0.76	27.71
3	500 1000	14 26	0.9	162.96	0.75	16.97
4	1500 1000	30 11	0.25	44.49	0.92	77.33

Case 1: Installation of DG only

The proposed method is used to find the optimal location of all the four type of DGs separately in the IEEE 33 bus system. For type 1, 3 and 4 the term related to capacitor cost is eliminated and for type 2 the term related DG unit cost is eliminated in the objective function as stated in equation (10). The number of DG units installed in the system is also changed and their impact is also studied. The results obtained for are tabulated in the Table 2 which includes power loss, DG size and respective location and function value. Fig. 3 and Fig. 4 give the voltage profile and stability index (SI) for the case 1.

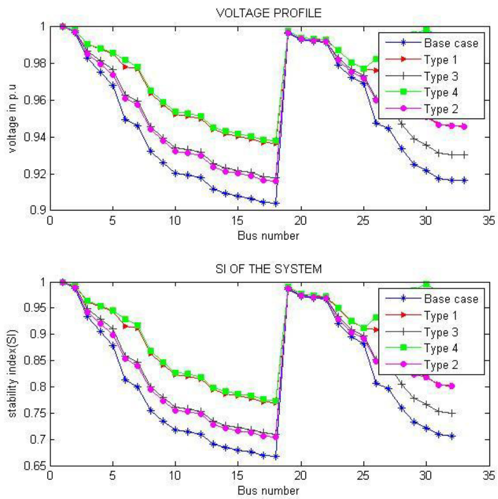

Fig 3. Voltage profile and stability index (SI) for case 1 with only DG for each type

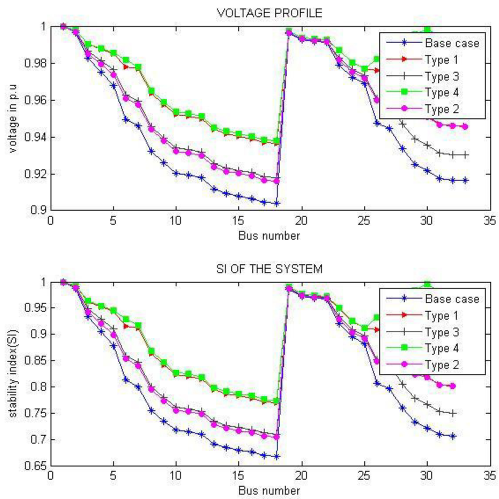

Fig 4. Voltage profile and stability index (SI) for case 1 with two DG for each type

Case 2: Simultaneous installation of capacitor units and DG

In this case all the type of DG along with capacitor (type 2 DG) are optimally placed using the proposed method and the results are tabulated in Table 3. The number of DG units and also capacitor units can be varied in this case also. The voltage profile of the system and SI at all the buses is presented in Fig. 5. From the above simulation results, it is evident that the there is improvement in voltage profile from all type of DG. Also performance of DGs with capacitors is better compared to their operation individually. It is to be noted that type 3 DG performance has improved drastically with its combination along capacitor. The type 1 and type 4 DG are better compared to other two types. Numbers of DGs also affect the system voltage where improvement is observed.

Table 3. Results for case 2

Type of DG	DG capacity (KW/KVAR)	DG location	Function value	Power loss (KW)	SI of the system	$\Delta P_{loss}/P_{loss0}$ Reduction in losses(%)
1	2000KW 600KVAR	4 30	0.39	82.51	0.78	57.96
3	1750KW 1350KVAR 900KVAR	30 9 31	0.52	91.00	0.87	53.63
4	1000KW 1250KW	29 15	0.29	49.12	0.91	74.97

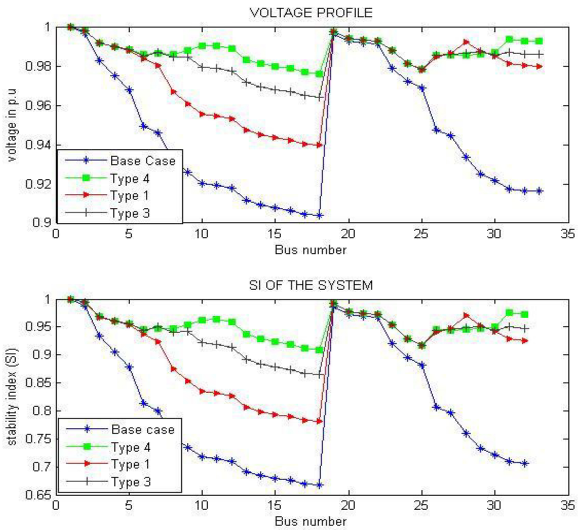

Fig 5. Voltage profile and stability index (SI) for case 1 with only DG for each type

7. Conclusion

In this paper work has been carried out to find out the optimal siting and sizing of distributed generation in the radial distribution system, considering precise model for DG's and in this work has presented a new approach for optimum simultaneous distributed generation (DG) Units and capacitors placement and sizing on the basis of voltage stability index for improvement in voltage profile. The optimal locations of distributed power sources has been identified by means of voltage stability index of the bus and optimal rating of the DG source are determined by using Genetic Algorithm (GA). A coding scheme in MATLAB is developed to carry out the allocation problem. The study has been carried out on 33-bus radial distribution system with DG allocations. From the study the following conclusions are drawn

- The amount of voltage deviation reduced is more in the case where DG units are allocated when compared to that of case no DG units are allocated.
- The allocation of DG units increases the minimum voltage among all the buses and reduction of power loss in the network.
- Power losses can be reduced up to 40-75%.

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