Voltage Stability Analysis of Radial Distribution Networks with Distributed Generation

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Abstract: This paper presents voltage stability analysis of radial distribution networks in the presence of distributed generation. The analysis is accomplished using a voltage stability index which can be evaluated at each node of the distribution system. The location of DG has the main effect voltage stability on the system. Artificial bee colony algorithm (ABC) is proposed to determine the optimal DG-unit size and location by loss sensitivity index (LSI) in order to improve the voltage stability in radial distribution system. Constant power, constant current, constant impedance and composite load modelling are considered for the purpose of voltage stability analysis.

Keywords: distributed generation, artificial bee colony algorithm, voltage stability index, radial distribution network.

1. Introduction

Distribution systems are usually radial in nature for operational simplicity. The Radial Distribution Systems (RDS) are fed at only one point, which is the substation. The substation receives power from the centralized generating stations through interconnected transmission network. The end users of electricity receive electrical power from the substation through RDS, which is a passive network. Hence, the power flow in the RDS is unidirectional. The high R/X ratio of the distribution lines results in large voltage drops, low voltage stability and power losses. Under critical loading conditions in certain industrial areas, RDS experiences sudden voltage collapse due to low value of voltage stability index at most of its nodes .

Voltage stability concerns stable load operation, and acceptable voltage levels all over the system buses. Its instability has been classified into steady state and transient voltage instability, according to the time spectrum of the occurrence of the phenomena. A power system is said to have entered a state of voltage instability when a disturbance causes a progressive and uncontrollable decline in voltage [1, 2]. Voltage stability analysis often requires examination of lots of system states and many contingency scenarios. For this reason the approach based on steady state analysis is more feasible, and it can also provide global insight of the voltage reactive power problems [2]. The voltage stability phenomenon has been well recognized in distribution systems. Radial distribution systems having a high resistance to reactance ratio causes a high power loss so that the radial distribution system is one of the power systems, which may suffer from voltage instability [1, 3].

In certain industrial areas, it has been observed that under certain critical loading conditions, the distribution system experience voltage collapse. Voltage collapse is a local phenomenon. It occurs at a node within the area with high loads and low voltage profile. Due to the rapid growth in power demand of certain industrial loads, incident of unexpected voltage collapse has been experienced. When such incident occurs, some industrial loads will be disconnected through automatic cutoff switches resulting in service interruptions. Hence, a major concern in power distribution systems, which have surfaced fairly, recently is the problem of voltage stability.

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DG renders a group of advantages, such as, economical, environmental and technical. The economical advantages are reduction of transmission and distribution cost, electricity price and saving of fuel. Environmental advantages entail reductions of sound pollution and emission of green house gases. Technical advantages cover wide varieties of benefit, like, line loss reduction, peak shaving, increased system voltage profile and hence increased power quality and relieved transmission and distribution congestion as well as grid reinforcement. It can also provide the stand-alone remote applications with the required power. So, optimal placement of DGs and optimal sizing attract active research interests.

Due to considerable costs, the DGs must be allocated suitably with optimal size to improve the system performance such as to reduce the system loss, improve the voltage profile while maintaining the system stability. The problem of DG planning has recently received much attention by power system researchers. Selecting the best places for installing DG units and their preferable sizes in large distribution systems is a complex combinatorial optimization problem.

Literature survey shows that a lot of work has been done on the voltage stability analysis of transmission systems [4] but very little work has been reported on the voltage stability analysis of radial distribution systems. Jasmon and Lee [5] and Guleina and Strmchnic [6] have studied the voltage stability analysis of radial distribution systems. They have represented the whole system by a single line equivalent. The single line equivalent derived by these authors [5, 6] is valid only at the operating point at which it is derived. It can be used for small load changes around this point.

The effect of DG capacity and location on voltage stability analysis of radial distribution system is investigated in this paper. The analysis process is performed using a steady state voltage stability index. This index can be evaluated at each node of radial distribution system.

2. Voltage Stability Index

A new steady state voltage stability index is proposed by M. Charkravorty et.al in [7] for identifying the node, which is most sensitive to voltage collapse. Figure 1 shows the electrical equivalent of radial distribution system.

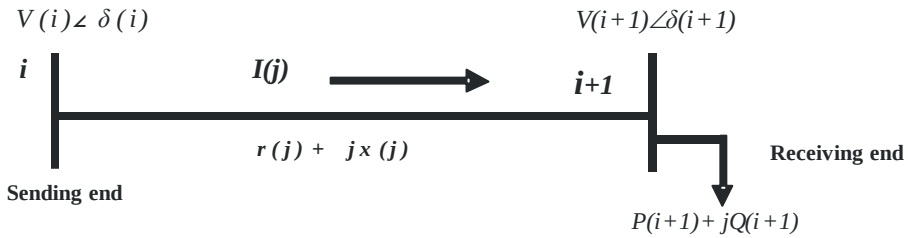

Figure 1. Electrical equivalent of two node system

From Figure 1, the following equation can be written:

$$I(j) = \frac{V(i) - V(i+1)}{r(j) + jx(j)} \quad (1)$$

Where

j = branch number,
i = sending end node,
$i+1$ = receiving end node,
$I(j)$ = current of branch j,
$V(i)$ = voltage of node i,
$V(i+1)$ = voltage of node $i+1$,
$P(i+1)$ = total real power load fed through node $i+1$,
$Q(i+1)$ = total reactive power load fed through node $i+1$.

From Eq. (1)

$$|V(i+1)|^4 - b(j)|V(i+1)|^2 + c(j) = 0 \quad (2)$$

Let,

$$b(j) = \left\{|V(i)|^2 - 2P(i+1)r(j) - 2Q(i+1)x(j)\right\} \quad (3)$$

$$c(j) = \left\{\left|P^2(i+1)\right| + Q^2(i+1)\right\}\left\{r^2(j) + x^2(j)\right\} \quad (4)$$

The solution of Eq. (2) is unique. That is

$$|V(i+1)| = 0.707\left[b(j) + \left\{b^2(j) - 4\,c(j)\right\}^{\frac{1}{2}}\right]^{\frac{1}{2}} \quad (5)$$

$$b^2(j) - 4\,c(j) \geq 0 \quad (6)$$

From Eqs. (3), (4) and (6) we get

$$\left\{|V(i)|^2 - 2P(i+1)r(j) - 2Q(i+1)x(j)\right\}^2 - 4\left\{P^2(i+1) + Q^2(i+1)\right\}\left\{r^2(j) + x^2(j)\right\} \geq 0$$

After simplification we get

$$\left\{|V(i)|^4\right\} - 4\left\{P(i+1)x(j) - Q(i+1)r(j)\right\}^2 - 4\left\{P(i+1)r(j) + Q(i+1)x(j)\right\}|V(i)|^2 \geq 0 \quad (7)$$

Let

$$SI(i+1) = \left\{|V(i)|^4\right\} - 4.0\left\{P(i+1)x(j) - Q(i+1)r(j)\right\}^2 - 4.0\left\{P(i+1)r(j) + Q(i+1)x(j)\right\}|V(i)|^2 \quad (8)$$

Where

SI (i+1) = voltage stability index of node *i+1*.

For stable operation of the radial distribution networks, $SI\,(i+1) \geq 0$.

The node at which the value of the stability index is minimum, is more sensitive to the voltage collapse.

3. Load Modelling

In distribution systems, voltages vary widely along system feeders as there are fewer voltage control devices. Therefore, the V–I characteristics of load are more important in distribution system load flow studies. The real and reactive power loads of node ' *i*' is given as:

$$PL(i) = PL_o(i)\left[c1 + c2|V(i)| + c3|V(i)|^2\right] \quad (9)$$

$$QL(i) = QL_o(i)\left[d1 + d2|V(i)| + d3|V(i)|^2\right] \quad (10)$$

Static load models are typically categorized as follows

Constant power load model (constant P): A static load model where the power does not vary with changes in voltage magnitude. It is also known as constant MVA load model. For constant power load, *c1=d1=1, c2=c3=d2=d3=0.*

Constant current load model (constant I): A static load model where the power varies directly with voltage magnitude. For constant current load, *c2=d2=1, c1=c3=d1=d3=0.*

Constant impedance load model (constant Z): A static load model where the power varies with the square of the voltage magnitude. It is also referred to as constant admittance load model. For constant impedance load, *c3=d3=1, c1=c2=d1=d2=0.*

Composite load model: A composition of 40% constant power, 30% of constant current and 30% of constant impedance loads are considered.

4. Artificial Bee Colony Algorithm (ABC)

An Artificial bee colony algorithm is an optimization tool provides a population based search procedure. It was defined by Dervis Karaboga in 2005 and motivated by the intelligent behavior of honeybees. The colony of artificial bees consists of three groups of bees: employed bees, onlookers and scouts [8-9]. First half of the colony consists of the employed artificial bees and the second half includes the onlooker's bees. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source has been abandoned becomes a scout [10].

Thus, ABC system combines local search carried out by employed and onlooker bees, and global search managed by onlookers and scouts, attempting to balance exploration and exploitation process [11].

The ABC algorithm has the following control parameters: 1) the colony size *CS*, that consists of employed bees E_b plus onlooker bees E_b ; 2) the limit value, which is the number of trials for a food-source position (solution) to be abandoned; and 3) the maximum cycle number *MCN* .

The proposed ABC algorithm is as follows:

Step-1: Read the system data and Initialize the random power generation between the minimum and maximum limits as food-source positions x_f (solutions population), where $f = 1,2,.....,E_b$.

Step-2: Calculate the fitness value of the population using

$$fitness = \frac{1}{1 + powerloss} \tag{11}$$

$$Power\ loss = min \sum_{k=1}^{n-1} R_k \left| I_k \right|^2$$

Where *n* is number of nodes in the distribution network, R_k is resistance of k^{th} line, $|I_k|$ is absolute of k^{th} line current.

Step-3: Generate new solutions x_{fg} using Equation

$$x_{fg}^{new} = x_{fg}^{old} + u\left(x_{fg}^{old} - x_{mg} \right) \tag{12}$$

and evaluate them as indicated by Step 2.

Where $m \neq 1$ and both are $\in \left\{1,2,...,E_b\right\}$. The multiplier *u* is a random number between [-1, 1]

x_{fg} is the g^{th} parameter of a solution x_f that was selected to be modified.

Step-4: Apply the greedy selection process.

Step-5: If all onlooker bees are distributed, go to Step 9. Otherwise, go to the next step.

Step-6: Calculate the probability values P_f for the solutions x_f using Equation

$$P_f = \frac{fitness}{\sum_{f=1}^{E_b} fitness_f} \quad (13)$$

Step-7: Produce the new solutions for the selected onlooker bee, depending on the value, using Eqs. (12) and evaluate them as Step 2 indicates.

Step-8: Follow Step 4.

Step-9: Determine the abandoned solution for the scout bees, if it exists, and replace it with a completely new solution using Equation

$$x_{fg}^{(new)} = min\left(x_{fg}\right) + u\left[max\left(x_{fg}\right) - min\left(x_{fg}\right)\right] \quad (14)$$

and evaluate them as indicated in Step 2.

Step-10: Memorize the best solution attained so far.

Step-11: If cycle = MCN, stop and print result. Otherwise follow Step 3.

5. Results and Analysis

Table 1. Critical loading condition for different types of load without DG [7].

Load type	Substation voltage (p.u)	Critical loading condition			
		TPL (MW)	TQL (MVAr)	SI_{min}	V_{min}(p.u)
Constant Power (CP)	1.000	12.212	8.654	0.0491	0.4708
	1.025	12.767	9.047	0.0728	0.5194
	1.050	13.422	9.537	0.0756	0.5244
Constant current (CI)	1.000	15.051	10.656	0.1044	0.5028
	1.025	15.812	11.199	0.1152	0.5826
	1.050	16.594	11.752	0.1269	0.5969
Constant impedance (CZ)	1.000	14.055	9.954	0.2195	0.6845
	1.025	14.764	10.458	0.2423	0.7016
	1.050	15.492	10.974	0.2669	0.7188
Composite load	1.000	14.651	10.377	0.0745	0.5224
	1.025	15.468	10.956	0.0818	0.5349
	1.050	16.244	11.506	0.0929	0.5521

To check the effectiveness of the proposed method, 69-bus radial distribution network [7] is considered. First, load flow [12] is conducted for 69-bus bus test system for base case. The loss sensitivity factors [13] at different buses have been evaluated to select appropriate buses for DG planning. These sensitivity factors reflect how the feeder power losses change if more real

power is injected at a particular bus and it also allows obtaining the candidate buses to locate DG. Loss sensitivity factors are evaluated for the base case first to decide the first appropriate location. Artificial bee colony algorithm (ABC) is proposed to determine the optimal DG-unit size in order to improve the voltage stability in radial distribution system. Critical loading condition for different types of load and different values of substation voltage results before and after DG placement is shown in Table 1 and 2. The Control parameters of ABC method are colony size (*Cs)* is 30 and *MCN* is 40. Penetration of DG is considered in a range of 10% – 80% of total load.

A DG is connected at node 61, it increase and support the voltage and stability in the system. The optimal size of DG is shown in Table 2 for different load models and different values of substation voltage. The connection point of DG influences the voltage stability in the system. DG strongly supports the voltage at nearby nodes and has less impact on distant nodes.

From Table 2, it is seen that the critical loading for constant current load is the maximum and that for constant power load is minimum before and after DG placement. The critical loading for constant impedance lies between these two and that for the composite load solely depends on the percentage composition of the three loads. The stability index and consequently the voltage are minimum for constant power load and maximum for constant impedance load and that for constant current load is in between these two. Similarly, the composition of loads governs the position of the stability index for the composite load.

Table 2. Critical loading condition for different types of load with DG

Load type	**Substation voltage (p.u)**	**Critical loading condition**				**DG Size (MW)**
		TPL (MW)	**TQL (MVAr)**	**SI_{min}**	**V_{min}(p.u)**	
Constant Power (CP)	1.000	38.84	28.70	0.0459	0.4617	1.8775
	1.025	40.69	30.08	0.0542	0.4801	1.8740
	1.050	42.60	31.50	0.0598	0.4909	1.8707
Constant current (CI)	1.000	75.80	54.07	0.0527	0.4781	1.7298
	1.025	77.61	55.36	0.0582	0.4901	1.7760
	1.050	79.46	56.67	0.0640	0.5019	1.8213
Constant impedance (CZ)	1.000	49.29	34.88	0.0625	0.4961	1.6139
	1.025	49.75	35.21	0.0690	0.5085	1.6957
	1.050	49.79	35.23	0.0744	0.5202	1.7796
Composite load	1.000	22.29	15.77	0.0600	0.4908	1.7466
	1.025	23.05	16.31	0.0655	0.5018	1.7866
	1.050	23.81	16.85	0.0715	0.5131	1.8265

The total real power load, total reactive power load, minimum voltage stability index and minimum voltage without DG for constant power load at 1.0 p.u substation voltage are 12.212 MW, 8.654 MVAr, 0.0491 and 0.4708 p.u , they are improved to 38.84 MW, 28.70 MVAr, 0.0459 and 0.4617 p.u after DG placement. For constant current load, The total real power load, total reactive power load, minimum voltage stability index and minimum voltage without DG for 1.0 p.u substation voltage are 15.051 MW, 10.656 MVAr, 0.1044 and 0.5028 p.u , after DG placement they are improved to 75.8 MW, 54.07 MVAr, 0.0527 and 0.4781 p.u . For

constant impedance load, The total real power load, total reactive power load, minimum voltage stability index and minimum voltage without DG for 1.0 p.u substation voltage are 14.055 MW, 9.954 MVAr, 0.2195 and 0.6845 p.u , after DG placement they are improved to 49.29 MW, 34.88 MVAr, 0.0625 and 0.4961 p.u . The total real power load, total reactive power load, minimum voltage stability index and minimum voltage without DG for composite load at 1.0 p.u substation voltage are 14.651 MW, 10.377 MVAr, 0.0745 and 0.5224 p.u , they are improved to 22.29 MW, 15.77 MVAr, 0.0600 and 0.4908 p.u after DG placement.

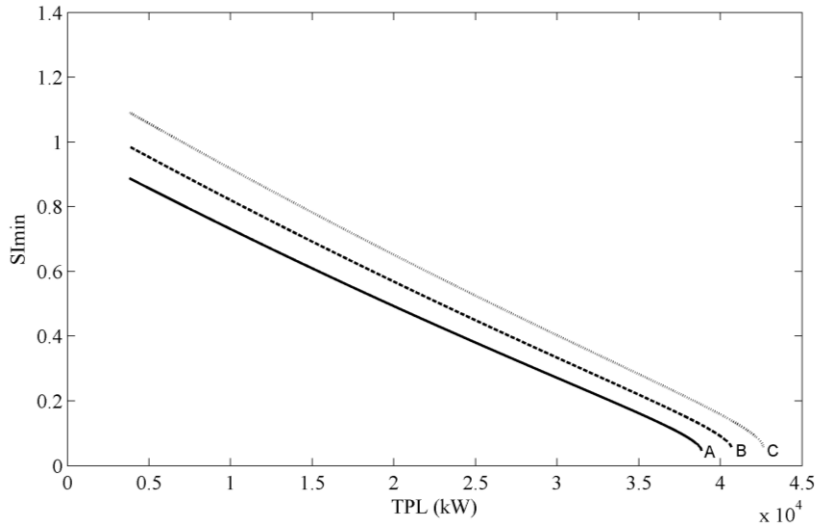

Figure 2. Plot of *TPL* vs *SImin* with DG

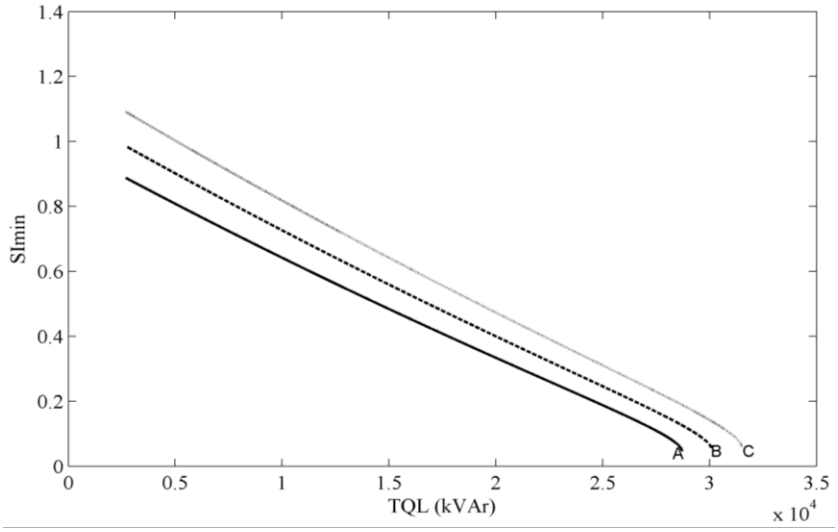

Figure 3. Plot of *TQL* vs *SImin* with DG

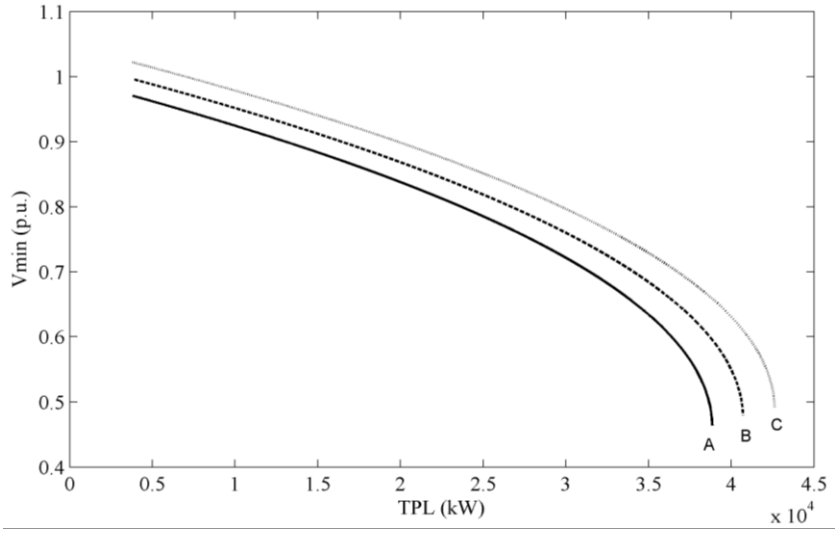

Figure 4. Plot of *TPL* vs *Vmin* with DG

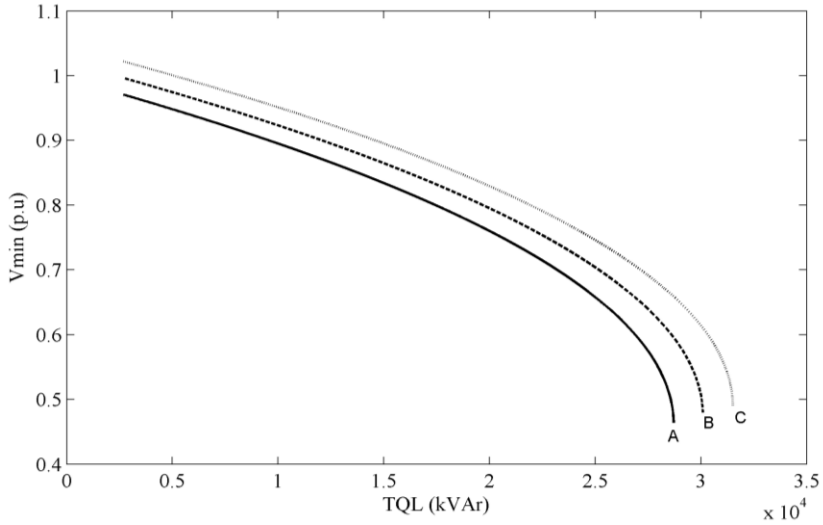

Figure 5. Plot of *TQL* vs *Vmin* with DG

The plots of total real power load versus voltage stability index with DG is shown in Figure 2 and the total reactive power load versus voltage stability index with DG for constant power load at different substation voltage is shown Figure 3. Figs 4 and 5 show the plots of total real power load versus minimum voltage and total reactive power load versus minimum voltage with DG for constant power load at different substation voltage. A, B and C indicate the critical loading point with DG beyond which a small increment of loading causes the voltage collapse.

6. Conclusions

This paper presents an artificial bee colony algorithm to place the DG optimally in radial distribution system to improve the voltage stability. Using voltage stability index, it is possible to compute the voltage stability index at every node and identify the node at which the value of the voltage stability index is minimum and is most sensitive to voltage collapse. Effectiveness of the proposed method has been demonstrated through a 69-bus radial distribution network. Different load models, i.e., constant power, constant current, constant impedance and

composite load modelling are considered for the purpose of voltage stability analysis. It was observed that before and after DG placement the critical loading for constant current load is maximum and constant power load is minimum. But a great improvement in voltage stability and critical loading conditions for all load models after DG placement.

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