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Distributed Resource Planning for improved Voltage Stability of Radial Distribution System

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Abstract: In modern power systems, deregulation and restructuring have created increased interest in distributed resource planning, as they are expected to play an important role in improving the operational efficiency. The distribution systems are constantly being faced with an ever growing power demands and usually operates on the verge of its loadability limit. To operate the distribution system under such critical conditions the integration of distributed resource improves the reliability of supplying power by improving voltage stability and reducing the power losses. Therefore, in order to strengthening the power quality and reliability the power utilities need to ensure the optimum size and location of distributed resources. This paper considered the effect of distributed resource placement on voltage stability and the results are demonstrated on an IEEE 33-bus radial distribution system.

Keywords: Distribution system, distributed resource planning, loadability limit, power loss, voltage stability.

I. INTRODUCTION

Voltage instability due to voltage collapse is a dynamic phenomenon in distribution system operation [1]. The problem of the voltage stability has risen since the beginning due to large difference in generation and load demands, and to the limited expansion because of high investment cost of equipments, of distribution systems. In order to meet the load demand distribution company usually integrate the distributed resources to the existing system. Distributed resources are the power sources (active or reactive) that can be connected to a distribution system by a distribution company or by the customer at the customer side of the meter. The distributed resources, if strategically located and operated, defer or eliminate system upgrades by improving various energy efficiency defining parameters like voltage profile, power losses and loadability limit. However, for better energy performance the simultaneous improvement in these parameters is required [2]. Here, voltage stability is the major concern as it improves the reliability of supplying power to the consumers.

In the past, for evaluation and to improve voltage stability using soft computing and index based techniques, numerous works has been reported in [3]-[15]. Also, for mathematical modelling, authors in their works use the single line representation of distribution system. In [3] and [4], the system parameters of equivalent model are obtained using thevenin's theorem. In [5] a voltage sensitivity based technique is used to develop an index to identify the node which is closest to voltage collapse. Authors in [6] developed an algorithm for enhancement of voltage stability by network reconfiguration. On the other hand, in order to improve the worst loadability limit at a particular node and for better voltage profile network reconfiguration is performed using the fuzzy logics in [7]. Authors noticed that the configuration obtained for better node voltage profile differ to that for the improved loadability.

The improvement in system performance by network reconfiguration is limited to the load balancing, as the resultant power flow remains the same [8]. Therefore, in order to meet the growing load demand the power utilities integrate the distributed resources with the existing system. However, this is a big challenge to find the optimal size and location of these resources as the load varies with time, weather condition and the state of economy. There exists an extensive effort to find the optimal placement of distributed resources in [9]-[15].

The effect of load behavior using the different load models has been presented in [9] and [10] while finding the optimal size and location of the distributed resources using multi-objective approach. On the other hand, in [11] the size of the distributed resource for voltage support is obtained under particular loading conditions. The effect of capacitor placement while finding the optimal configuration for different loading patterns is presented in [12]. Authors in [13] and [14] achieve the same objective for distributed generator (DG) placement. Also, in [14] a voltage quality index is

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developed, in order to find the optimal location for DG in distribution system. Using the recursive load flow equations, paper [15] presents the expression for the calculation of the size of DG and optimizes the system operation for maximum loss reduction with single and multi placement of DG.

From the literature, it can be observed that the different approach uses voltage profile as main objective in order to improve the system performance. However, the improvement in voltage profile does not guarantee that the system can serve more loads at the respective node. Therefore, in order to improve the reliability of supplying power the distribution company need to enhance the voltage stability rather considering the node voltage profile, as the distribution system usually operate on the verge of its loadability limit. This paper contributes on this subject and finds the size and location of distributed resources, in order to improve the system voltage stability.

II. MATHEMATICAL FORMULATIONS

The radial distribution system for the calculations of evaluating parameters is represented by single line diagram, as shown in Fig.1. Here, for a system having *N* number of nodes *SN* represents the source node and '*i*' is the any intermediate node. Also, it can be noted that the power at candidate nodes is equal to the sum of the node powers, including candidate node, and line power loss beyond the candidate node. A radial distribution system can be consider a line segment between two nodes, represented as sending end (N_{i-1}) and receiving end node (N_i) respectively, in Fig. 1. Therefore, the voltage stability and loadability limit at candidate node can be calculated as,

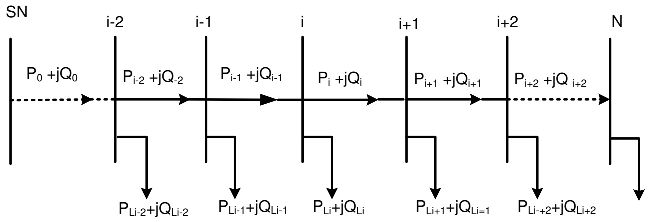

Fig. 1. Single Line Representation of Radial Distribution System.

In a radial distributed system, the power flows usually computed by using the set of generalised recursive equations as described in [16]. Therefore, the power flow equation for active power is as follows,

$$P_{i+1} = P_i - P_{Loss,i} - P_{Li+1} \quad (1)$$

$$= P_i - r_i * \frac{P_i^2+Q_i^2}{|V_i|^2} - P_{Li+1} \quad (2)$$

Similarly, the power flow equation for reactive power can be derived as,

$$Q_{i+1} = Q_i - Q_{Loss,i} - Q_{Li+1} \quad (3)$$

$$= Q_i - x_i * \frac{P_i^2+Q_i^2}{|V_i|^2} - Q_{Li+1} \quad (4)$$

In order to find the node voltage the above equations are rearranged and the equation for voltage at respective node is derived as follows,

$$|V_{i+1}|^2 = |V_i|^2 + \frac{r_i^2+x_i^2}{|V_i|^2}(P_i^2 + Q_i^2) - 2(r_iP_i^2 + x_iQ_i^2) \quad (5)$$

Here, P_i and Q_i are the real and reactive powers flow at node '*i*' and the P_{i+1} and Q_{i+1} are the real and reactive powers at node '*i*+1'. Also, in the above equations it is assumed that the shunt admittance is negligibly small at distribution level of voltage, and hence can be ignored. The resistance and reactance of line between node '*i*' and '*i*+1' are represented with r_i and x_i respectively. Further, the power loss in the line between two nodes is calculated as under,

$$P_{Loss}(i, i+1) = r_i * \frac{P_i^2+Q_i^2}{|V_i|^2} \quad (6)$$

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In order to evaluate the system voltage stability, power utilities need to know the possible load that can be connected at a respective node. This can be easily defined by knowing the loadability factor at the respective node, as described in [2]. Therefore, in order to find the maximum loadability at respective node the equation (5) is further rearranged and the loadability factor is obtained as under,

$$LF_{i+1} = \frac{V_i^2\left[-(r_iP_i+x_iQ_i)+\sqrt{(r_i^2+x_i^2)(P_i^2+Q_i^2)}\right]}{2(x_iP_i-r_iQ_i)^2} \qquad (7)$$

Here, LF_{i+1} is the loadability factor at node '$i+1$' which when multiply with the existing load demand (in kVA) at respective node defines its loadability, i.e. the load that can be connected before voltage collapses at respective node. Equation (7) also represents that the loadability factor depends upon the load demands therefore; it can vary significantly with the placement of distributed resources as they alter load demand at respective node. However, the placement of these resources at a particular node doesn't guarantee for simultaneous improvement in any other energy efficiency defining parameters. This paper finds the location and size of distributed resources for improvement of voltage stability, in order to serve as maximum as possible number of consumers at a node having worst level of loadability limit, in the system configuration.

III. SOLUTION TECHNIQUES FOR PLACEMENT OF DISTRIBUTED RESOURCES FOR IMPROVED VOLTAGE STABILITY

The computational steps involved in the solution technique for improvement in voltage stability of radial distribution system, based upon the mathematical formulation presented in sections II, are as follows:

Step1: Run the load flow program by assuming flat voltage profile, and calculate active and reactive load demand at each node.

Step2: Compute the node voltage, loadability factor and distributed resource size at each node for base case.

Step3: Place a distributed resource, one at a time, as DG of size equal to active and capacitor of size equal to reactive components of load demand respectively.

Step4: Run the load flow and re-calculate the node voltage and loadability limit at each node.

Step5: Print the size of the distributed resources for which the system can serve as maximum as possible number of consumers at a node having worst level of loadability limit. Also, print system power loss, minimum node voltage and worst level of loadability limit..

IV. TEST RESULTS AND DISCUSSION

The test system under study is a 12.66kV, IEEE 33-Bus radial distribution network as shown in Fig. 2. The line and load data of the system for base configuration are obtained from [7]. The substation voltage is maintained at 1.0p.u. and the loading is considered fixed.

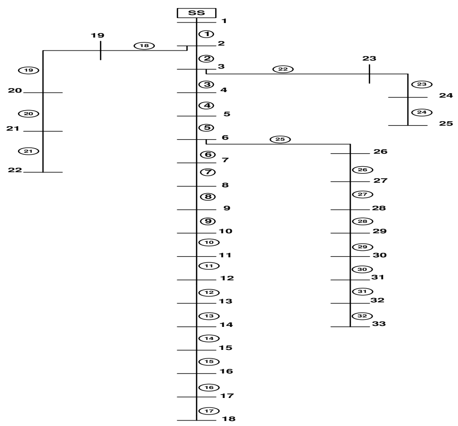

Fig. 2. IEEE 33-node radial distribution system

In this paper, the following assumptions are made for the placement of distributed resources:

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a. In case of DG it is considered that the source is operating at unity power factor. This is because the maximum benefits can be extracted when generator operates on unity power factor as the cost of real power is higher and it also leads to maximum capacity utilization.
b. The maximum size of distributed resources at candidate node is equal to the total load demand at that node. This is because the over compensation further leads to the extra power loss in the system and also the local power generation is costly than supply mains from distributed company.
c. In the planning, it is considered that the distributed resources are available to place at each node whereas; the final location is selected based upon the improvement in the objective function.

From the load flow results, for base network, the minimum voltage profile, power loss and the minimum loadability limit are found as 0.9131p.u at node 18, 202.67kW and 16.85MVA at node 17 respectively. In order to improve these parameters the network performance is analysed with optimal placement of distributed recourses and the results are discussed below.

Table I shows the results for system performance with DG placement. Column 2nd, in Table I, shows the results for improved voltage stability. In this case, the optimal size of DG is obtained as 2106kW at node 6. Here, with DG placement at node 6, the minimum voltage is obtained as 0.9444p.u at node 18. The power losses are reduced by 95.97kW (47.18%) and minimum loadability limit is obtained as 18.03MVA at node 17. Here, a significant improvement in the worst level of loadability limit, at node 17 in the test system, can be observed in comparison to base case.

The improvement in minimum loadability limit indicates that now the system can meet more demand, at the respective node, before the voltage collapse. The improvement in lowest loadability factor also indicates that the more load, as a multiplier of existing load, can be connected at the candidate node. Therefore, the simultaneous improvement in minimum loadability and loadability factor enhances the system voltage stability.

TABLE I
RESULT ANALYSIS FOR DG PLACEMENT

Items/Parameters	Selection Criterion	
	Voltage Stability	Loss Reduction
DG size in kW (at node)	2106.0 (6)	2106.0 (6)
Minimum voltage in p.u. (at node)	0.9444(18)	0.9444(18)
Loss reduction in kW (%age)	95.97(47.18%)	95.97(47.18%)
Minimum loadability in MVA (at node)	18.03(17)	18.03(17)
Lowest loadability factor (at node)	22.21(28)	22.21(28)

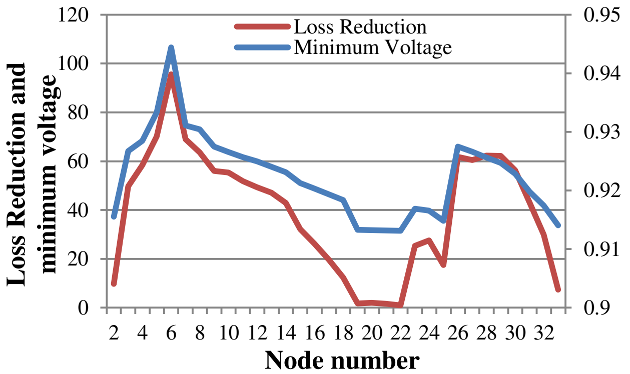

Fig. 3. Variation in loss reduction and minimum voltage profile with DG placement at each node.

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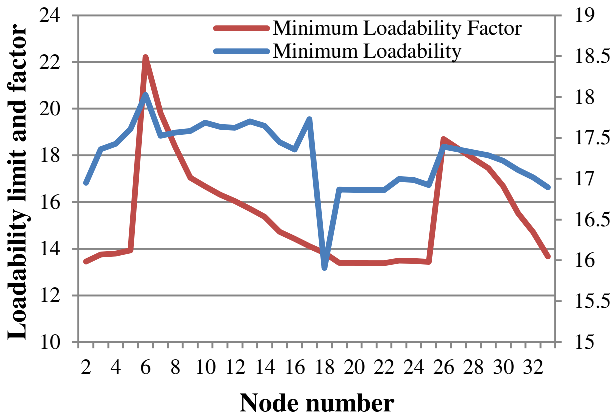

Fig. 4. Variation in minimum loadability factor and limit with DG placement at each node.

The results in column 3rd, in Table I, show the performance of distribution system with optimal placement of distributed resource for minimizing power losses. Fortunately, for this system configuration, the results are same as that of obtained for improved voltage stability for DG placement. Fig. 3 shows the variation in loss reduction and minimum voltage for individual placement of distributed resource at each node. However, Fig. 4 shows the variation in the loadability factor and loadability limit. Here, it is observed that the maximum improvement in these parameters occurs when a DG is placed at the same node (i.e. node 6 in this case).

Table II shows the test result for capacitor placement in the system configuration for improved voltage stability and reduction in power loss. Column 2nd , in Table-II, shows the system performance for improved voltage stability. Here, the optimal size of capacitor is obtained as 60kVAr at node 17. With the placement of capacitor at node 17 the minimum voltage 0.9167p.u at node 18 and minimum loadability at node 17 is obtained. The power losses are reduced by 4.78kW (2.35%) which are comparatively much less then reduced in case of DG placement. Here, a significant improvement in the worst level of loadability limit, at node 17 in the test system, can be observed in comparison to base case.

TABLE II
RESULT ANALYSIS FOR CAPACITOR PLACEMENT

Items/Parameters	Selection Criterion	
	Voltage Stability	**Loss Reduction**
Capacitor size in kVAr (at node)	60.0 (17)	811.8 (30)
Minimum voltage in p.u. (at node)	0.9167(18)	0.9214(18)
Loss reduction in kW (%age)	4.78(2.25%)	52.04(25.67%)
Minimum loadability in MVA (at node)	19.08(17)	17.17(17)
Lowest loadability factor (at node)	13.59(6)	16.51(6)

Third column, in Table II, shows the test results for loss reduction with capacitor placement. In this case, the size of capacitor is obtained as 811.8kVAr at node 30. In comparison with DG placement, the size and location of capacitor differ in order to improve voltage stability and to minimize the power loss. From the test result it can be observed that there is a significant improvement in minimum voltage and reduction in power loss. However, in this case, the size of resource is comparatively higher but the improvement in minimum loadability limit is less than the value obtained for improved voltage stability. On the other hand, the lowest loadability factor is significantly higher but it is limited to the improvement in loadability limit, as a multiplier of existing load, at respective node.

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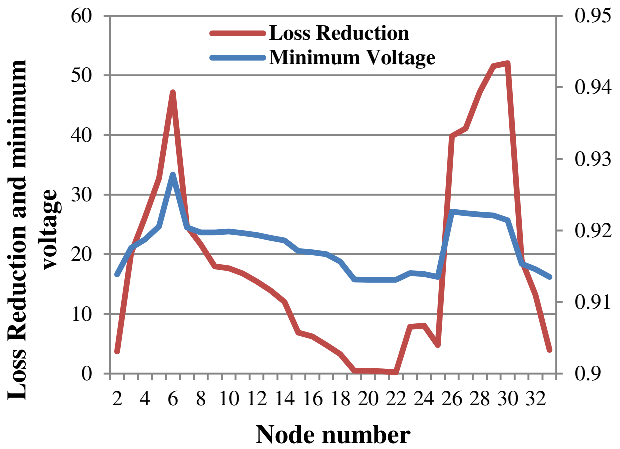

Fig. 5. Variation in loss reduction and minimum voltage profile with capacitor placement at each node.

Fig. 5 shows the variation in loss reduction and minimum voltage for individual placement of capacitor at each node. However, Fig. 6 shows the variation in the loadability factor and loadability limit. Fig. 5 shows that the maximum improvement in loss reduction takes place when a capacitor of size 811.8kVAr is placed at node 30. However, the improvement in minimum voltage profile occurs when capacitor is to be placed at node 6, in this case. Similarly, in Fig. 6, the maximum improvements in the corresponding parameters can be observed when a distributed resource is placed at node 6 and 17 respectively.

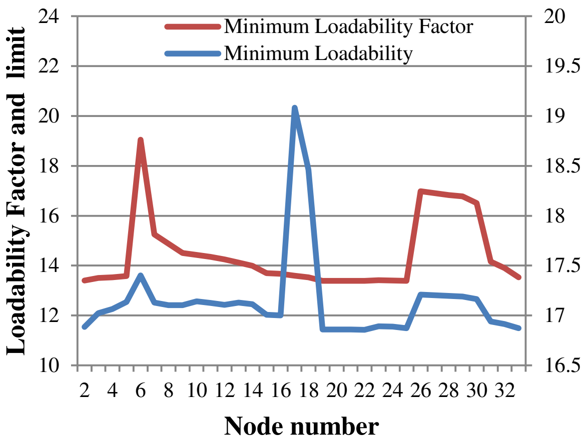

Fig. 6. Variation in minimum loadability factor and limit with capacitor placement at each node.

From the test results it can be observed that the system performance significantly varies with the placement of distributed resources. In case of DG placement the size and location of the optimal resource obtained is same for voltage stability and for loss reduction as well. However, this may not be true for any other load combination or in different system configuration, as it has been noticed in case of capacitor placement. Therefore, in distribution systems planning the size and location of distributed resources need to be re-calculated in order to operate the system for improved voltage stability when the load demand or the nature of load changes.

V. CONCLUSION

Performance of distribution system depends upon the behaviour of connected load and the integration of the distributed resource. From the test results, it can be observed that the optimal placement of distributed resources performed for reduction in power losses do not guarantee to improve the system voltage stability. Also, the size and location of distributed resource obtained for better voltage profiles, loadability limit, power loss and voltage stability differ from each other. Voltage stability, in order to meet the load demand, depends upon loadability factor at each node and loadability limit at a node which is operating at its worst level. Therefore, the simultaneous improvement in these parameters is required for stable operation. This will ensure the enhanced reliability of supplying the power to as maximum as number of customers however; it is not necessarily minimizing the power loss.

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