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Optimal DG allocation and sizing in a Radial Distribution System using Analytical Approach

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Abstract— **This paper proposes a comprehensive approach for DG placement and sizing in a Radial Distribution system using conventional Forward and Backward Sweep Approach and loss minimization techniques. The paper throws light on an innovative method where Forward/Backward Sweep approach has been utilized for finding an optimized distribution system with DG placement. For DG placement, a modified 'exact loss formula' has been considered. The proposed paper also suggests optimal locations for DG placement through which system's total real power loss could be minimized. All these have been blended with an efficient load flow tool called Forward and Backward Sweep approach. The extensive procedure has been carried out on an IEEE 33-bus Radial Distribution System. Through this system, encouraging results were obtained with regard to losses.**

Index Terms— **Analytical Expression, Exact loss formulae, Forward and backward sweep approach ,Optimal DG sizing,DG Location.**

I. INTRODUCTION

DG allocation in primary distribution networks is the emerging area in power systems arena. While a lot of research has been done in the recent years, the interest in this area of research is still surging. The probable reason could be the amount of real power losses which accounts for 70% of the total power losses according to statistics in the year 2005. The fact behind the enormous losses in the distribution feeders is the high R/X ratio. Loss minimization has posed a major challenge to the researchers in this field. With the ever increasing demand of electric power, the need has arisen to introduce DGs at various locations in the primary distribution system. Moreover, DG allocation in power distribution system can mitigate losses, enhance the voltage profile and thereby improves the reliability of the overall system. Hence, it can be understood that DG can play a pivotal role if properly placed and sized in the system. Various innovative and rational techniques have been introduced in the recent years which concentrate on DG sizing and placement. Few of them are based on Genetic Algorithm [1], Fuzzy logic[2], analytical approaches[3] etc. The real challenge is to optimize the losses after DG sizing and allocation. The immediate next step is to perform load flow. The traditional approaches like Newton-Raphson method and other load flow techniques have taken a back seat since they are assumed to be exhaustive in nature.

In the past, many researchers have tried to obtain a solution for this load flow problem. The conventional Newton's method was put forward by Tinny et al [3] and the fast decoupled method by Stott and Alsac [4]. Others have proposed a modification to the fast decoupled method to suit the nature of radial distribution systems for distribution networks which are loosely meshed. Baran and Wu [5] have presented an iterative methodology of solving three simplified equations for real power magnitude, reactive power magnitude and voltage magnitude. The technique of determining nodes belonging to branches has been shown to be efficient in determining voltage magnitudes and phase angles by Hamouda and Zehar [6] Renato et al [7]. This technique was named as Forward sweep approach.

Through this paper a conventional load flow technique called Forward/Backward sweep algorithm [8] has been implemented to observe its impact on the Radial Distribution system with DG penetration. This approach helps in achieving the accurate load flow result as the number of iterations involved are carried out until convergence is reached. Even though the load flow analysis for power loss estimation has been deduced from FBS algorithm, the DG size has been presented using the most renowned analytical expression which is present in the literature called 'Exact loss Formula'[9]. This formula has been defined in terms of real and reactive power injections at all the buses along with the bus voltages. The proposed method is a perfect blend of load flow and analytical loss estimation methods. The results obtained have been quiet encouraging. This paper is segmented into two phases, one is for explaining the lucid load flow analysis using forward/backward sweep. The other segment is for explaining the overall algorithm of DG sizing and placement using analytical expressions [10].The paper has been organized into following sections: 1. A brief summary on load flow analysis based on Forward and Backward sweep approach. 2. A brief analysis of load flow and DG sizing using mathematical formulation. 3. Implementation of loss reduction techniques for optimization of real power losses in the radial distribution network.4.presentation of results. In results and discussions section, plots presented depict overall system power losses at

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two different power factors.

II. FORWARD/BACKWARD SWEEP ALGORITHM FOR LOAD FLOW IN RADIAL DISTRIBUTION SYSTEM

Load varies continuously for the known reasons and therefore distribution networks are designed as ever-changing structures so as to meet the incessantly changing loads. Analyzing such a varying system would is a tedious task for engineers. A steady state solution of the system is needed to improve the reliability of such systems, which can be attained by performing the load flow calculations for the distribution system. The traditional approaches that are being suggested in literature [11] failed to convergence even after considerable number of iterations in case of distribution systems. The present load flow technique [8] has proved to be appropriate and efficient over traditional approaches. Moreover the FBS approach is quiet robust and can be simply analyzed. The Forward sweep approach is for estimating bus voltages after taking branch voltage drops into consideration. It starts from starting node of a lateral to farther end of the lateral. The updated voltage at every bus is then utilized for the Backward sweep approach which mainly focuses on current estimation from the farther end to the nearer end or sending end. Basic Kirchhoff's laws are involved in determining the branch parameters of the radial distribution systems. The unique numbering scheme for different laterals of the network being proposed in [12] has been put to use in developing the logic for MATLAB coding.

III. MATHEMATICAL FORMULATION OF FBS LOAD FLOW ALGORITHM

Before going ahead with the formulation, one needs to know about the initial assumptions that were considered regarding the distribution system. First and foremost condition was that the loads of the network were assumed to be constituted by three phase balanced loads. Second assumption was to ignore the line shunt capacitance for simpler analysis. The system being chosen for study is an IEEE 33-bus test system. The numbering scheme will be clear only after looking at the bus diagram

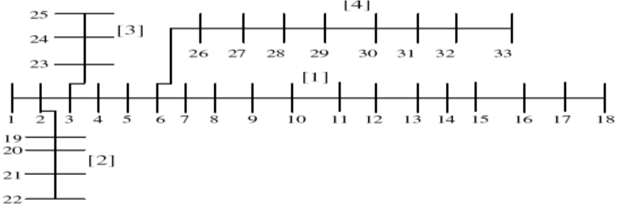


Fig 1.IEEE 33-bus Radial Distribution Network

For detailed analysis of the expressions used in load flow, the electrical equivalent of the distribution branch is considered.

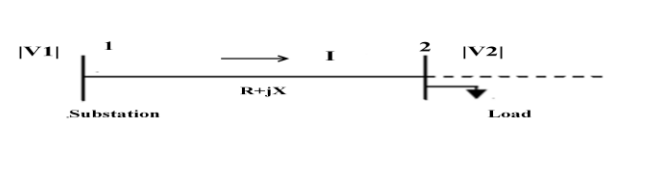


Fig.2 Electrical Equivalent of a Distribution Network

The following expressions can be deduced from the above branch diagram:

$$I = \frac{|V1|\angle\delta(1) - |V2|\angle\delta(2)}{R(1)+jX(1)} \quad (1)$$

$$P(2) - jQ(2) = V(2) * I \quad (2)$$

$$P(2) = \sum_{i=2}^{NB} PL(i) + \sum_{i=2}^{NB-1} LP(i) \quad (3)$$

$$Q(2) = \sum_{i=2}^{NB} QL(i) + \sum_{i=2}^{NB-1} LQ(i) \quad (4)$$

Also

$$LP(i) = \frac{R(i)*(P^2(i+1)+Q^2(i+1))}{|V(2)|^2} \quad (5)$$

$$LQ(i) = \frac{X(i)*(P^2(i+1)+Q^2(i+1))}{|V(2)|^2} \quad (6)$$

The above loss equations can be generalized as

$$P(i+1) = \sum_{j=i+1}^{NB} PL(j) + \sum_{j=i+1}^{NB-1} LP(j) \quad (7)$$

$$Q(i+1) = \sum_{j=i+1}^{NB} QL(j) + \sum_{j=i+1}^{NB-1} LQ(j) \quad (8)$$

$$LP(i) = \frac{R(i)*(P^2(i+1)+Q^2(i+1))}{|V(i+1)|^2} \quad (9)$$

$$LQ(i) = \frac{X(i)*(P^2(i+1)+Q^2(i+1))}{|V(i+1)|^2} \quad (10)$$

Prior to running load flow, loss powers are assumed to be zero. The expressions from (7-10) are analyzed with regard to base case load flow, i.e., for running load flow of the distribution network without any DG injection. A unique numbering scheme is followed for numbering the buses according to their position in the radial system. The numbering scheme being adopted helps in analyzing Forward and Backward sweep approach in a convenient manner. Loss powers determined in equations (9&10) are based on the numbering scheme of the radial distribution network.

The load flow procedure for FBS approach is followed using these steps:

1. Basing on KCL and KVL, branch currents and bus voltages are computed in forward direction metaphorically called Forward Sweep.

2. The voltage of upstream bus obtained by KVL is established as calculated voltage for each bus voltage.

3. The updated voltages thus obtained in first step are then utilized in the backward sweep phase of expressions.

4. The above mentioned approach's significance lies in the fact that it is based on decomposition of real and imaginary components of voltages at respective buses, currents in the branches and line impedances.

5. The new forward sweep is started again after each new bus voltage is attained in the backward sweep procedure.

6. The above steps are continued until the mismatch in the updated voltage values is suppressed below a certain tolerance value.

1) A. LOAD FLOW USING FBS APPROACH WITH OPTIMAL DG INJECTIONS

Many studies suggested that load flow analysis for loss estimation could be done using myriad of algorithms. Few of them are Genetic Algorithm, ant colony search , 2/3 rule, approximated power flow technique[13]. DG injections into the buses of radial distribution systems play a pivotal role. They not only help in meeting power demands but also improve the voltage profile at that specific bus. The current flowing in the feeder is reduced due to DG injections which in turn lead to lesser power losses in the system. Conventional approaches like Genetic algorithm, Capacitor placement lay least stress on optimal DG sizing. The optimal DG sizing helps in finding a reliable solution for load flow. The discussion presented here stresses on optimal sizing of DG along with loss minimization using a unique approach. This approach mainly focuses on establishing DG size with the help of analytical expressions [10].The root expression for analytical approach is the *Exact Loss Formula.* In the following approach, load flow for base case and for the case indulging DG injections is done through FBS algorithm. Moreover the loss calculations involved in load flow are not conventional expressions based on voltages and currents. Power losses are based on modified exact loss formula.

2) PROPOSED TECHNIQUE

The uniqueness of the strategy proposed is that it implements the conventional FBS approach for DG calculations and optimal loss estimations of the primitive distribution network. However, for loss calculations the system relies on *Modified Exact Loss Formula.* The integration of both the methodologies mentioned above has given immensely satisfying results in terms of voltage profiles and real power losses. The number of DGs placed could be more than one. On increasing the number of DGs, the overall system configuration does change in terms of bus voltages and overall system losses. Moreover, improper sizing of DGs may lead to increased power losses, less reliability and power quality degradation. The total losses of the system vary for different load power factors given by equation (15).

3) OPTIMAL DG SIZING

For establishing a relation for optimal DG size, the Exact Loss Formula has been deduced further as suggested in [19]. The formula is given as:

$$P_{L=} \sum_{i=1}^{N} \sum_{j=1}^{N} [\alpha_{ij} (P_i P_j + Q_i Q_j) + \beta_{ij} (Q_j P_j - P_i Q_j)] \quad (11)$$

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \quad (12)$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \quad (13)$$

P_i and P_j are real power injections at bus i and j respectively.

$V_i \angle \delta$ = Voltage at bus i

$r_{ij} + x_{ij} = z_{ij,}$ any element of [Zbus] matrix

4) TYPE OF DG CHOSEN FOR PROPOSED METHODOLOGY

DGs are generally power injecting sources that could be allocated at different levels of power systems. Since the major focus of the proposed methodology is on Radial Distribution Systems, it has to be decided about which category of DG would suit the requirements of the system. Even though different terminal characteristics are defined in literature [20], it would be convenient to go for DG injecting active power and consuming reactive power. Sizing of DG could be performed through the following expressions that are being deduced from the exact loss formula in (11). The expressions (12-16) when implemented in the system can provide with appropriate DG sizing criteria. The modified loss formula in (15) gives the approximate system power loss for DG allocation at various buses for IEEE 33-bus radial system. At a time only one DG is considered for loss estimations. The generalized DG sizing expression is presented in (16) for any DG category as in [10].

The reactive power consumed by DG is given as:

$$Q_{dgi} = a * P_{dgi} \quad (14)$$

Where

$$a = (\text{sign}) \tan(\cos^{-1}(pf_{dg}))$$

Sign= +1; for DG injecting reactive power

Sign= -1; for DG consuming reactive power

The active and reactive power injections at bus 'i' are given as:

$$P_i = P_{dgi} - PL_i \quad (15)$$

$$Q_i = aP_{dgi} - QL_i \quad (16)$$

Here

PL_i = Real power demand at bus i.

QL_i = Reactive power demand at bus i

Using relations from (12-14), the total real power loss of the system can be established, which is a modified form of exact loss formula presented in equation (11).

$$P_{dgi} = \frac{\alpha_{ii}(PL_i - aQL_i) + \beta_{ij}(aPL_i - QL_i) - X_i - aY_i}{a^2 \alpha_{ii} + \alpha_{ii}} \quad (17)$$

Where $X_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} [\alpha_{ij}(P_j) - \beta_{ij}(Q_j)]$

$$Y_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} [\alpha_{ij}(Q_j) + \beta_{ij}(P_j)]$$

The electrical equivalent of a distribution system with DG injection is shown in fig (3).

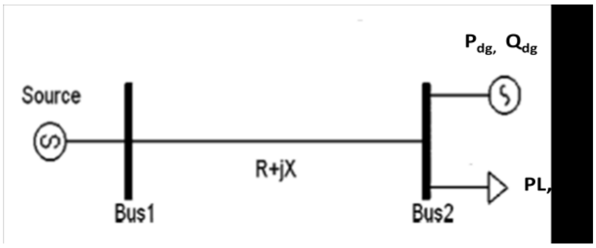


Fig.3 The electrical equivalent of a distribution system with DG

5) LOCATION OPTIMIZATION FOR DG ALLOCATION

DG placement in the radial distribution for the methodology presented in this paper is based on loss reduction or loss optimization technique which is proposed in [14]. The strategy adopted in this paper is unique in terms of location optimization. System power loss acts as basis for loss optimization as well as location optimization. Using trial and error basis, the bus location could be identified as the voltage profiles in the base case helps in suggesting preferred locations for DG placement. However, the optimal values being suggested through equation (16) have to be chosen for further analysis. This is due to the fact that values that deviated from the values obtained in (16) may result in undesirable outcome which is in this case increased loss power in the system.

IV. RESULTS AND DISCUSSIONS

The system has been studied with the help of MATLAB R2010a. The test system being taken for analysis has total real power load of 3.7 MW and reactive power load of 2.3 MVAr as presented in literature [15]. It is assumed for convenience that the system is experiencing peak load conditions. The results presented here in this section are for the cases where load power factors are 0.85 lag, 0.85 lead and unity power factor. Using MATLAB programming the below results are acquired. The following results include optimal DG size in MVA as shown in Figure 4, also the total power losses versus bus number for 2 different power factors as in Figure 5(a), 5(b) and Figure 6. The voltage profiles for base case and for case with DG injection has significant difference. While with DG injected, the system shows peculiar improvement in terms of improved voltage profile as in Figure 8.

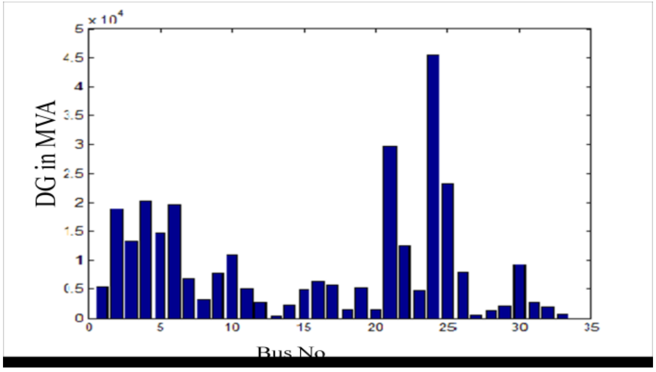


Fig 4. Bus no Vs optimal DG size

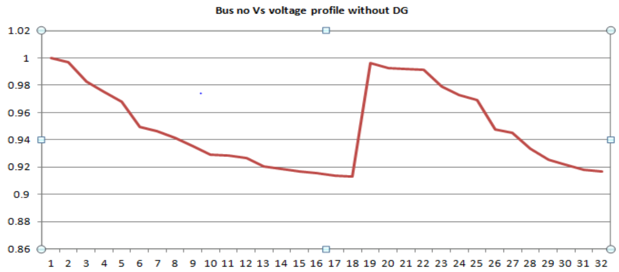


Fig 5. Voltage profile versus bus no

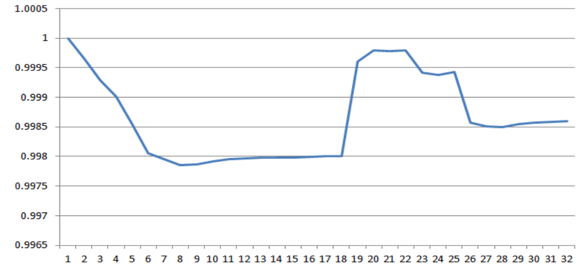
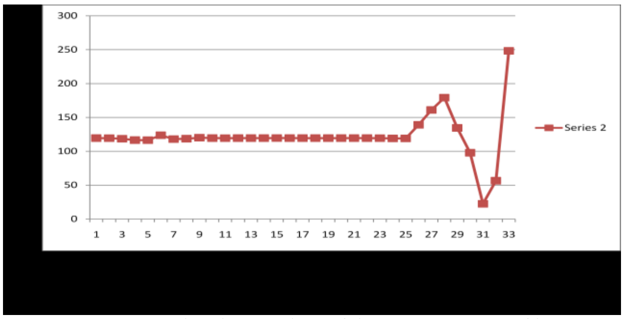


Fig 6. Bus voltage versus bus no with DG allocation



5(a): Bus no Vs Total real power loss of the system at 0.85 pf lag

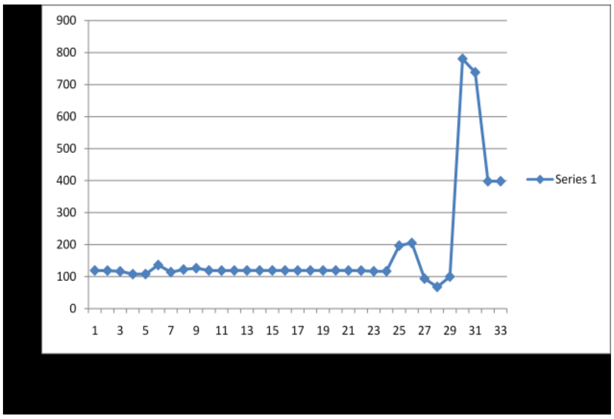


Fig 5(b): Bus no Vs Total real power loss of the system at 0.85 pf lead

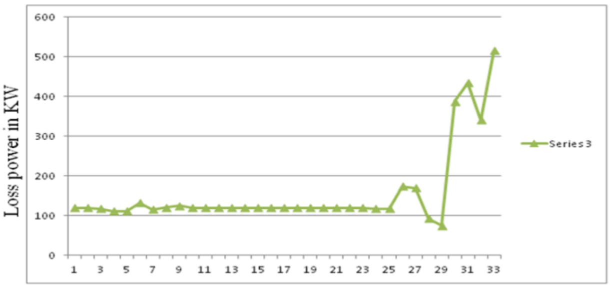


Fig 6. Loss Vs bus no at unity pf

Consolidated results:

Power Factor	Minimum power loss (KW)	DG size (MVA)	Optimal Bus location
Unity	75.1035	2.708	29
0.85 lag	22.4798	5.02	31
0.85 lead	94.1118	1.26	28

Bus no	Voltage without DG	Voltage with DG
1	1.00000	1
2	0.99702	0.99966
3	0.98293	0.99929
4	0.97545	0.99901
5	0.96805	0.99855
6	0.94965	0.99806
7	0.94616	0.99795
8	0.94132	0.99786
9	0.93505	0.99787
10	0.92923	0.99792
11	0.92837	0.99796
12	0.92687	0.99797
13	0.92072	0.99798
14	0.91846	0.99798
15	0.91704	0.99798
16	0.91568	0.99799
17	0.91365	0.998
18	0.91304	0.998
19	0.99649	0.99961
20	0.99292	0.99979
21	0.99221	0.99978
22	0.99157	0.99979
23	0.97934	0.99941
24	0.97267	0.99938
25	0.96935	0.99943
26	0.94772	0.99857
27	0.94515	0.99851
28	0.93371	0.9985
29	0.92550	0.99855
30	0.92194	0.99857
31	0.91778	0.99859
32	0.91686	0.9986

V. CONCLUSION

The proposed work on DG allocation based on analytical expressions and Forward/Backward sweep load flow technique has yielded satisfying results as far as bus locations for DG allocation are concerned. The sizing and allocation was purely based on minimal or optimal real power losses for various bus locations. Power losses were estimated at various power factors using 'Exact Loss Formula'. The results obtained were quiet encouraging as the Voltage profile was phenomenally improved and also losses were considerately minimized.

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