Optimal Placement of Synchronous Generator in distribution Networks

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Abstract–This paper presents the optimal placement of synchronous generator (SG) type DG for active and reactive power compensation of power distribution systems. The active and reactive power compensation can be obtained by the optimal placement of DG supplying both real and reactive powers. The evaluation of optimal power factor of the system has also been carried out in this work. To solve the optimal placement of SGproblem analytical approach has been used. The location of SG plays an important role in maintaining voltage profiles. To validate the proposed approach, results have been compared with existing fast improved analytical (IA) method results.The proposed technique is tested on 33-bus and 69-bus power distribution system.

Keywords—Synchronous Generator (SG);optimal size; optimal location;power factor;power loss.

I. INTRODUCTION

The global concerns about the environment, combined with the progress of technologies to connect renewable energy sources to the grid and deregulation of electric power market have diverted the attention of distribution system planners towards grid-connected distributed generation (DG). Employment of DG technologies makes it more likely that electricity supply system will depend on DG systems and will be operated in deregulated environment to achieve a variety of benefits. As DG systems generate power locally to fulfill customer demands, appropriate size and placement of DG can drastically reduce power losses in the system. DG inclusion also defers transmission and distribution upgrades, improves supply quality and reliability and reduces green house effects. Distributed generation is a topical area of research and interest in this area has been growing rapidly worldwide.

Including DG in distribution systems requires in-depth analysis and planning tools. This process usually includes technical, economical, regulatory, and possibly environmental challenges. Some of the factors that must be taken into account in the planning process of expanding distribution system with DG are: the number and capacity of DG units, best locations and technology, the network connection, capacity of existing system, protection schemes, among others.

Many optimization tools have been utilized to solve different DG problems, such as: A methodology for evaluating the impact of DG-units on power loss, reliability, and voltage profile of distribution networkswas presented in [1].The authors implied that on-line systems including DG-units can achieve better reliability during interruption situations to keep customers supplied.The impacts of capacitor placement on distribution system reliability was considered in [2] by defining two objective functions. The first one is the sum of reliability cost and investment cost, and the second one is the sum of reliability cost, cost of losses and investment cost.

The genetic algorithm to find the optimal placement of DG in the compensated network for restoration the system caused by CLPU condition and to conserve load diversity for reduction in losses, improvement in voltage regulation was discussed in [3]. In [4],[5], genetic algorithm (GA) based method is also used to determine size and location. GA is suitablefor multi objective problems like DG allocation and can give near optimal results, but they are being computationally demanding and slow in convergence. The improved Tabu Search algorithm with the introduction of mutation operator to improve the local search ability and to reduce computation time to minimize the loss in large scale distribution systems was introduced in [6]. The authors in [7] reconfigure the distribution network using ant colony search algorithm by minimize the system losses. In [8], the authorsanalyzed the DG optimal location analytically for two continuous load distributions, uniformly distributed and uniformly increasing loads. The goal of their studies was to minimize line losses and observed that the optimal location of DG which is highly dependent on the load distribution along the feeder; significant losses reduction would take place when DG is located toward the end of a uniformly increasing load and in the middle of uniformly distributed load feeder. The analytical approach has been demonstrated in [9, 10] to find the optimal size and location of DG to minimize the real power losses and enhancement in voltage profile. In [11], an analytical method to determine the optimum location–size pair of a DG unit was proposed in order to minimize only the line losses

of the power system. A fast analytical approach to find the optimal size of DG at optimal power factor to minimize the power loss however only type III has been exploited [12]. The authors find the optimal location in [13], based on the sensitivity test independently to overcome the limitation of right-of-way or real estate cost and heuristic curve-fitted technique is applied to find the optimal size of DG at predetermined power factor to minimize the power system loss.

Optimal placement of capacitor for loss reduction, a well known 2/3 rule is presented in [14] for uniformly distributed loads. Many researchers have applied other techniques such as GA [15] to improve the power quality in the presence of voltage and current harmonics. The objective function was to minimize the cost of power loss and capacitor banks taking the voltage limits, number and size of capacitor bank as constraints. In [16] the authors proposed a fuzzy expert system based on voltage and power loss reduction indices to minimize peak power loss reduction by means capacitor placement. The hybrid approach Tabu search combination with heuristic techniques was employed in [17] for capacitor placement to minimize the objective function in terms of cost and loss.

Most of the approaches presented so for model the optimal placement of DG supplying real power or supplying reactive power only. However optimal placement of synchronous type DG being integrated into distribution systems. The present work develops the comprehensive formula by extending the analytical expression presented in [10] to find the optimal size, optimal locationof synchronous generator type DGs to achieve the objective by compensating the active and reactive powers. The paper is organized as follows: Section II presents brief summary of location and sizing issue for reduction of line losses. Section III presents the problem formulation with assumptions and constraints. The proposed algorithm for optimal sizing of SG at optimal locations to achieve active and reactive power compensation is introduced in section IV. Section V presents the numerical results of the proposed analyticalapproach, interesting observations along with discussions. Finally, the major contribution and conclusions are summarized in section VII.

II. LOCATION AND SIZING ISSUES

Fig. 1 shows a 3D plot of typical power loss versus size of DG at each bus in a standard 33-bus distribution test system. From the figure, it is obvious that for a particular bus, as the size of DG is increased, the losses are reduced to a minimum value and increased beyond a size of DG (i.e. the optimal DG size) at that location. If the size of DG is further increased, the losses starts to increase and it is likely that it may overshoot the losses of the base case. Also notice that location of DG plays an important role in minimizing the losses. The important conclusion that can be drawn from Fig. 1 is that,

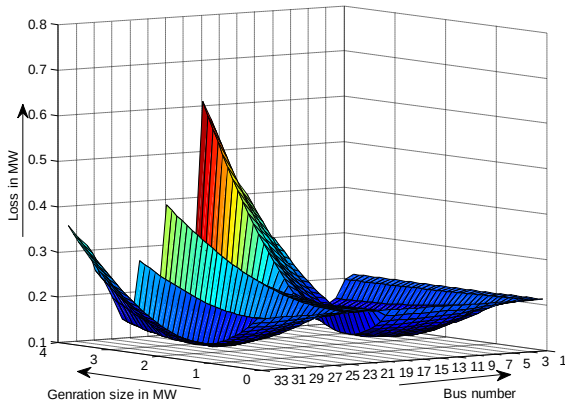

Fig.1 Effect of size and location of DG on system loss.

given the characteristics of the distribution system, it is not advisable to construct sufficiently high DG in the network. The size at most should be such that it is consumable within the distribution substation boundary. Any attempt to installhigh capacity DG with the purpose of exporting power beyond the substation (reverse flow of power though distribution substation), will lead to very high losses [10]. In distribution system load capacity (MW) will play important role inselecting the size of DG. The reason for higher losses and high capacity of DG can be explained by the fact that the distribution system was initially designed such that power flows from the sending end (source substation) to the load and conductor sizes are gradually decreased from the substation to consumer point. Thus without reinforcement of the system, the use of high capacity DG will lead to excessive power flow through small-sized conductors and hence results in higher losses.

III. PROBLEM FORMULATION

A. Objective Function

The main objective is to compensate the active power and reactive power as given in eq. (1) while meeting the following constraints.

$$MinP_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \dots (1)$$

B. Assumptions and Constraints

- For each bus, the following power flow equations must be satisfied.

$$P_{Gi} - P_{Di} = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\cos\left(\delta_i - \delta_j\right) + B_{ij}\sin\left(\delta_i - \delta_j\right)\right]$$

$$\forall i = 1,2,3,\dots..N \dots (2)$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\sin\left(\delta_i - \delta_j\right) - B_{ij}\cos\left(\delta_i - \delta_j\right)\right]$$

$$\forall i = 1,2,3,\dots..N \dots (3)$$

- The SG under study are supplying both real power & reactive powers.
- The sizing and locations are considered at peak load only.
- The voltage at every bus in the network should be within the acceptable range (Utility's standard ANSI Std. C84.1-1989) i.e., within permissible limit (±5%) [19],

$V_{min} \leq V_i \leq V_{max} \forall_i \in \{buses\ of\ the\ network\}$… (4)

- Current in a feeder or conductor, must be well within the maximum thermal capacity of the conductor

$I_i \leq I_i^{Rated} \forall_i \in \{branches of the network\},$

Here, I_i^{Rated} is current permissible for branch i withinsafe limit of temperature. …(5)

IV. PROPOSEDALGORITHM

A. Optimal Sizing of Synchronous Generator

The total power loss in power systems is represented by "Exact Loss" formula (1) [18].

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \ldots (1)$$

Where,

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)\ \beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$$

and

$Z_{ij} = r_{ij} + jx_{ij}$are the ijth element of [Zbus] matrix

$P_i = P_{Gi} - P_{Di}$ and $Q_i = Q_{Gi} - Q_{Di}$

P_{Gi}&Q_{Gi} are generated power of generators at ith bus.

P_i & Q_i are active and reactive power injections at ith bus.

P_{Di}&$Q_{Di}$are the loads at ith bus .

The total power loss against real power injection is a parabolic function and at minimum losses, the rate of change of losses with respect to injected power becomes zero.

$$\frac{\partial P_L}{\partial P_i} = 2\alpha_{ii}P_i + 2\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j) = 0 \quad \ldots (6)$$

It follows that

$$P_i = -\frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)\right] \ldots (7)$$

Where P_i is the real power injection at node i, which is the difference between real power generation and the real power demand at that node:

$P_i = (P_{DGi} - P_{Di})$

Where $P_{DGi}$is the real power injection from SG placed at node i, (P_{Di} is the load demand at node i), By combining the above

$$P_{DGi} = P_{Di} - \frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)\right] \ldots (8)$$

Similarly for reactive power injection

$$\frac{\partial P_L}{\partial Q_i} = 2\alpha_{ii}Q_i + 2\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) = 0 \quad \ldots (9)$$

$$Q_{DGi} = Q_{Di} - \frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j)\right] \ldots (10)$$

The equation (8) gives the active power injection and (10) gives the reactive power injectionat each bus i, for the loss to be minimum. The equations (8) and (10) can be combined to determine the size and power factor of synchronous generator type DG to be placed at bus i.Any size of SG other than this placed at bus i, will lead to higher loss. The optimal size of SG can be determined by satisfying the system constraints.

B. Optimal Power Factor

SG can be placed at bus i with real power and reactive power values calculated by (8) and (10) respectively. Power factor of the SG for this case may also be represented by (11). In this work, SG is considered which are used to generate real and reactive power. In case of leading power factor of load, the SG with more reactive power absorption capability will be required.Then the optimal power factor of the system can be obtained as

$$OPF = \frac{P_{DG_i}}{\sqrt{{P_{DG_i}}^2 + {Q_{DG_i}}^2}} \quad \ldots (11)$$

C. Optimal Location of DG

The bus having least power loss may consider as the optimal location for the placement of the SG subject to the satisfaction of system constraints. The equations (8) and (10) can be combined to determine the power factor to be placed at bus i [12]. The computational procedure

to find the optimal size, location and power factor of the SG is described below.

Step 1: Run load flow for base case (without SG).

Step 2: Find the base case loss using (1).

Step 3: Find the sizes of SG at each bus except the reference bus using (8) and (10) for minimum distribution loss.

Step 4: Check constraint violation after the placement of SG determined in step 3 at each bus.

Step 5: Select the bus for minimum loss while satisfying all the constraints for optimal placement.

Step 6: Calculate optimal power factor using (11) forSG.

Step 7: Run the load flow with the optimal size of SG placed at the optimal bus.

Step 8: Calculate the reduction in real power loss after placement of the SG.

V. NUMERICAL RESULTS

A. Test systems

The proposed methodology is tested on two different test systems. The first system used in this paper is 33-bus radial distribution systems with total load of 3.72 MW and 2.3 MVAr [21] as shown in Fig.2 and the second one is 69-bus radial distribution system with a total load of 3.80 MW and 2.69 MVAr [22] with Beaver conductors.

Based on the proposed methodology, a computer software program has been developed in MATLAB environment to run load flow, calculate distribution loss and identify the optimal size and location by analytical approach.

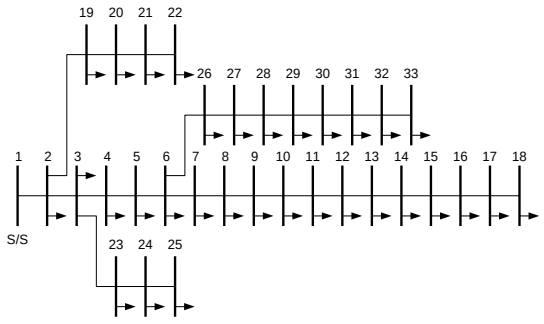

Fig.2 Single line diagram of 33 bus distribution test system.

B. 33-Bus Test System:

Table I presents the simulation results of placing SGby analytical approach. The results of the base case and reduction in line loss with the placement of SG are given in the table. The results include the optimal size and location of SG w.r. t. losses by proposed analytical approach. The base case loss of the test system is 211kW. For SG placement the loss reduction is 67.8%, by the proposed analytical approach and with fast analytical approach is 67.6%.

TABLE I

Optimal placement of SG with optimal power factor with different approaches of 33-bus system

Cases	Bus No.	Capacity of Synchronous Generator		Loss in (kW)	Loss Reduction (%)
		(MVA)	(p.f)		
Base case				211.0	0.00
Synchronous Generator	6	3.022	0.82	67.95	67.8
Fast Analytical Method [12]	6	3.025	0.85	68.28	67.6

The reduction in line losses with proposed analytical approach is significantly more as compared to the existing fast analytical approach results.

C. 69-Bus Test System:

Table II presents the results obtained by the placement of SG by analytical approach of 69-bus test system. The results of the base case and reduction in line loss with the placement of SG by the proposed approach and fast analytical method are given in the table. The base case loss of the test system is 225kW. For SG placement the loss reduction is 89.7%, by the proposed analytical approach and with fast analytical method is 89.7%. The results of the proposed approach are same as those by fast analytical method in terms of loss reduction, optimal locations and optimal power factors with negligible change in SG size.

TABLE II

Optimal placement of SG with optimal power factor with different approaches of 69-bus system

Cases	Bus No.	Capacity of Synchronous Generator		Loss in (kW)	Loss Reduction (%)
		(MVA)	(p.f)		
Base case				225.0	0.00
Synchronous Generator	61	2.24	0.81	23.19	89.7
Fast Analytical Method [12]	61	2.22	0.81	23.20	89.7

D. Voltage Profile

Fig 3 and Fig 4 shows the improvement in voltage profile of 33-bus and 69-bus test systems respectively by the placement of synchronous generator in the distribution system.

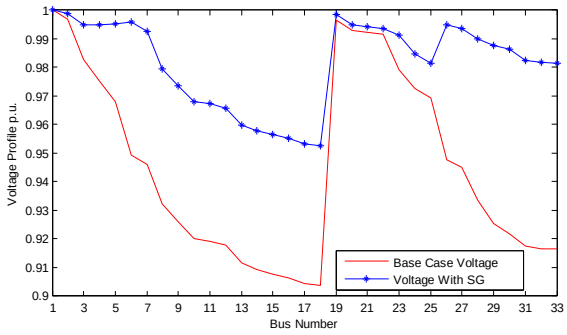

Fig. 3 Voltage profile of the 33-bus system

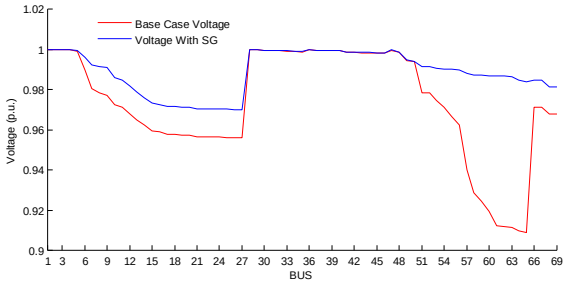

Fig. 3 Voltage profile of the 33-bus system

It is seen that in both the cases the voltage profile improves, when the synchronous generator is installed in the system, while satisfy all the constraints.

VII. CONCLUSION

This paper has proposed the analytical approach for the optimal placement of synchronous generator type DG at optimal locations for active and reactive power compensation to minimizing the losses in the primary distribution systems. The placement of SG not only reduces the losses to the great extent, but also improves the voltage profile of the system. The placement provides more economy solution for loss reduction. In the age of integrated grid, the placement and analysis of SG give guidance for optimal operation of power system.

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