An Analytical Approach to Find Optimal Location and Sizing of DGs for Power Loss Reduction and Voltage Stability Improvement

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***Abstract*—Distribution Generation (DG) is emerging as potential alternative against the rapidly depleting conventional energy resources. Integration of DG in distribution system has significant impact on total energy losses, voltage profile and voltage stability. In this paper new technique is proposed to determine optimal location and size of DGs for power loss reduction and improvement in voltage profile. Distribution System Voltage Stability Index (DSVSI) based approach is carried out to identify critical buses and allocation of different types of DGs supplying real and reactive power. The proposed method is tested on 33-bus radial distribution system and results show the effectiveness of proposed method.**

***Index Terms*—DG, optimal location, radial distribution system, voltage stability**

I. Introduction

Due to incessantly increasing energy demand of conventional energy resources, the Indian power sector is witnessing revolution about the harnessing electricity from various renewable energy resources [1]. In order to accrue benefits of non-conventional energy resources, global penetration of renewable energy is rapidly increasing in power sector. Distribution Generation (DG) uses generation from few kW to MW at different locations near load centers against conventional power plants which are located far away from load as per the availability of natural resources [2]. Distribution generators are available in different form such as micro turbine, diesel engine, reciprocating engines, combustion gas turbines, fuel cells, wind, photovoltaic etc.

According to nature of power supplied, DG can be categorized in three types [3]:

Type I: DGs which can supply real power only. Photovoltaic cells and fuel cells are good examples of type- I DG.

Type-II: DGs which can supply reactive power only comes under type-II category. KVAr compensator, synchronous compensator, capacitor are examples of type-II DG.

Type-III: DGs capable of supplying real power but consumes reactive power falls under the category of type-III DG; e.g. induction generators used in wind farms.

DG is increasingly being incorporated in transmission and distribution system as it offers myriad of benefits in terms of reduced cost, loss reduction, and improved voltage profile. Integration of DG can have impact on different performance parameters such as voltage profile, power quality, reliability, stability and protection [4]. DG location and sizing play an integral role in reducing losses and voltage profile improvement. DGs allocated at non optimal places can result in increase losses and bad voltage profile. Therefore DG sizing and sitting have generated considerable recent interest.

Much research in recent years focused on optimal placement and sizing of distributed generation. An analytical framework to determine optimal location and size of DG with objective of minimizing losses in distribution networks is proposed in [5]. However methodology adopted is computationally exhaustive. Kalman filter algorithm is proposed for multiple DG placements in transmission network while considering only fixed dispatch of active power [6]. Sensitivity analysis is used to determine optimal location for placement of DG [7]. However in this approach prior data analysis of network is required. Most sensitive buses to voltage collapse are identified using continuation power flow (CPF) and modal analysis. Consequently these buses are considered for DG placement [8]. An objective to minimize number of DG and power losses simultaneously maximizing Voltage Stability Margin (VSM) is presented in [9]. Particle Swarm Optimization (PSO) based approach is proposed to find optimal location of wind and solar based DG with objective of minimizing power loss and voltage profile improvement in radial distribution network [10]. Both sensitivity index and Genetic Algorithm (GA) is incorporated to determine optimal location and size respectively for voltage stability enhancement and minimization of DG investment cost [11]. Novel voltage stability index is proposed to locate the optimal location for DG in order to reduce losses. In this work voltage stability index is proposed to maximize voltage stability margin. Multi-objective problem is solved by using Imperialistic Colony Algorithm (ICA) to determine optimal location for allocation of DG [12].

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Hybrid Particle Swarm Optimization Gravitational Search Algorithm (PSOGSA) based approach is proposed to maximize the number of DGs and reduction of greenhouse gases [13]. Sensitivity index based heuristic algorithm is used to determine optimal location [14]. PSO based methodology is used to allocate different type of DG on buses near to voltage collapse [15]. Combined power loss sensitivity based method is suggested to find optimal location of different types of DG [16]. Power sensitivity index and search algorithm is carried out to find optimum bus and optimum size of DG to improve voltage profile [17].

The paper presents Distribution System Voltage Stability Index (DSVSI) to identify critical buses for placement for of DGs. In this work placement of Type-I and Type-III DGs is considered to minimize power losses and improvement in VSM in distribution network. Different types of DGs of optimal size are placed on sensitive buses such that voltage constraints are not violated. Type-I DG injecting real power at unity power and Type-III DG injecting real power at 0.9 lagging power factor (pf) are considered for minimization of losses and voltage profile improvement. The investment cost of DG is also estimated by evaluating cost of energy loss, cost of power from supplied from DG and consequently savings are calculated. The proposed technique is tested on 33-radial test bus system.

This paper is organized as follows: Section II discuss index formulation, Section III presents cost benefit analysis of DG. In Section IV proposed methodology is tested on 33-bus radial distribution system and results are shown and discussed in detail.

II. Index Formulation

Voltage stability analysis [18] of Radial Distribution System (RDS) can be illustrated by considering two bus equivalent circuit as shown in Fig. 1. The two bus equivalent model can be analyzed using two port equivalent circuit in terms of ABCD-matrix. From the Fig. 1:

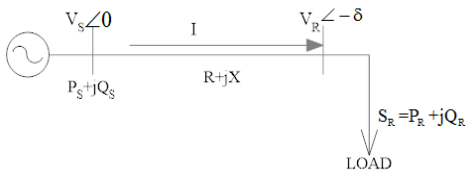

Figure 1. Two bus equivalent of RDS

V_R, V_S = Receiving and Sending end voltages.
P_R, Q_R, P_S, Q_S, S_R = Receiving and Sending end active and reactive powers, receiving end complex power.
$\delta = \delta_1 - \delta_2$ Angle difference between sending and receiving end buses.

The relationship among parameters can be expressed as:

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{1}$$

where A, B, C and D are transmission parameters of two port equivalent circuit. Following value are assigned to A, B, C, and D parameters in distribution network:

$$A=1,\ B=Z,\ C=0,\ D=A \tag{2}$$

By taking sending bus as reference i.e. $\delta_1=0$, $\delta_2=\delta$ branch current in system can be expressed as:

$$I = \left[\frac{P_R - jQ_R}{V_R}\right] \tag{3}$$

We can express receiving end current in following form:

$$\begin{bmatrix} V_R \\ I_R \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} V_S \\ I_S \end{bmatrix} \tag{4}$$

So receiving end bus voltage can be written as:

$$V_R\angle\delta = DV_s\angle 0 - BI_S \tag{5}$$

Substituting value of I from (3) in (5):

$$V_R\angle\delta = AV_S\angle 0 - B\left[\frac{P_R - jQ_R}{V_R\angle -\delta}\right] \tag{6}$$

$$V_R^2 = AV_SV_R\angle -\delta - B\left[P_R - jQ_R\right] \tag{7}$$

$$V_R^2 = AV_SV_R\left(\cos\delta - j\sin\delta\right) - (B\cos\beta + j\sin\beta)\left[P_R - jQ_R\right] \tag{8}$$

where β is phase angle of parameter B.

Separating real and imaginary parts of (8) and assuming $\delta \cong 0$.

$$V_R^2 + B\cos\beta\, P_R + B\sin\beta\, Q_R = AV_sV_R \tag{9}$$

$$B\sin\beta\, P_R - B\cos\beta\, Q_R = 0 \tag{10}$$

$$B\cos\beta = \frac{B\sin\beta P_R}{Q_R} \tag{11}$$

Substituting (11) in (9):

$$V_R^2 + B\sin\beta\left(\frac{S_R^2}{Q_R}\right) = AV_RV_S \tag{12}$$

$$V_R^2 - AV_SV_R + B\sin\beta\left(\frac{S_R^2}{Q_R}\right)X = 0 \tag{13}$$

This is quadratic equation in terms of sending and receiving end voltages. For system to be stable $b^2-4ac \geq 0$.

$$AV_S^2 - 4\left(\frac{S_R^2}{Q_R}\right)B\sin\beta \geq 0 \tag{14}$$

Therefore a new distribution system voltage stability index (DSVSI) is proposed as:

$$DSVSI = \frac{4}{AV_S^2}\left(\frac{S_R^2}{Q_R}\right)B\sin\beta$$

For system to be stable proposed stability index must be less then unity i.e. DVSI < 1.

Thus *DSVSI* is formulated from above analysis, to quantify voltage stability of buses of radial distribution network. *DSVSI* closer to zero represent secure and stable operating conditions. Therefore *DSVSI* should be maintained less than 1 for stable system, when *DSVSI* exceeds 1 system loses its stability and voltage may collapse.

DSVSI delineate weakest buses of the system which can lead to onset of voltage instability condition of whole system. Thus most sensitive buses can be pre determined

at planning stage and appropriate action can be suggested to avoid voltage collapse of the system. In this work DG is installed at most critical buses indicated by index *DSVSI*.

III. Cost Benefit Analysis of DG

The loss minimization can be evaluated in term total savings from losses and investment cost for power supplied from DG. This analysis evaluates total benefit obtained from installation of DG in system.

(i) Total annual cost of energy loss (CL) can be formulated as [16]:

$$\text{CL}=\alpha * \left(K_p + K_e * L_{sf} * 8760\right) \tag{15}$$

where,

α = Total Real Power Loss

K_p= Cost of power ($/kW)

K_e= Cost of energy loss ($/kWh)

L_{sf}= Loss factor

Loss factor can be expressed in terms of load factor as shown below:

$$L_{sf} = k * L_f + (1-k) * L_f^2 \tag{16}$$

In this paper following values are taken for evaluation of loss factor:

k=0.2, L_f = 0.47, K_p = 57.6923$/kW, K_e=0.00961538$/kWh.

(ii) Cost component of DG for real and reactive power

Cost of real power supplied by DG can be estimated as [19]:

$$P_{dg} = a * P_{dg}^2 + b * P_{dg} + c \ \ \$/h \tag{17}$$

Cost coefficients are taken as: a=0, b=20, c=25

Cost of reactive power supplied by DG can be estimated as [20]:

$$C\left(Q_{dg}\right)=\left[Cost\left(S_g^{max}\right)-Cost\left(\sqrt{S_g^{max}-Q_g^2}\right)\right]*k \ \$/h \tag{18}$$

$$S_g^{max} = \frac{P_g^{max}}{\cos\theta}$$

$$P_g^{max} = 1.1*P_g$$

$$k = 0.05 \text{ to } 0.1$$

In this work value of factor k is taken as 0.1.

IV. Simulation Results and Discussion

To illustrate the effectiveness of proposed method, 33-bus [21] radial test system is considered. Multiple DGs of optimal size are incorporated at the locations as identified by proposed *DSVSI*. Bus voltage and losses are observed after placement of each DG. DG sizes are varied in steps to find the optimal size which will result in minimum losses in the system. The proposed method is developed and simulated in MATLAB environment. The results are obtained for voltage profile, real and reactive power losses, and real and reactive power flow in system, cost of DG placement in terms of supplied real and reactive powers annual cost of savings with and without installation of the DG. Also impact of single and multiple DG is also compared in terms of above mentioned parameters.

The results are obtained for 33-bus system with base kV of 12.66kV and base MVA of 100 MVA. For system without DG installation real power loss is 208kW and reactive power loss is 143KVAr. Real and reactive power demand at substation is 3832 kW and 2442kVAr respectively.

From Fig. 2 it can be observed that bus 7, bus 8, bus 17, bus 24, bus 25 are critical buses. So these locations are selected as potential node for allocation of DG. DGs are placed at selected locations and losses are observed by observing load flow analysis with each placement. Bus 8, bus 24 and bus 25 are found to be most appropriate locations for placement of DGs as with this sequence of DG, optimum results are obtained for voltage profile and losses. DG placement at bus 7 and 17 results in increased losses and bad voltage profile and therefore no power is supplied from DG at these locations. Hence selection of optimum location for DG placement has significant impact on system.

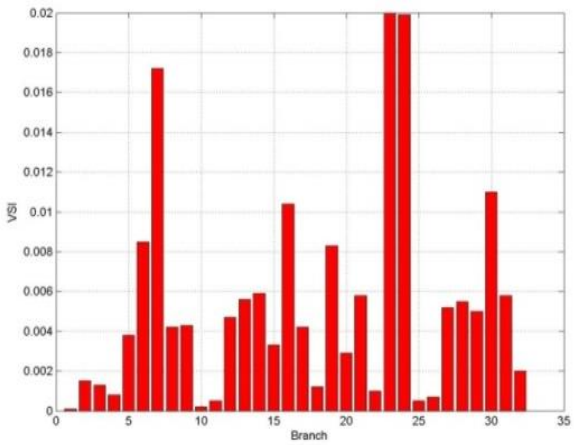

Figure 2. VSI for 33-bus system

A. Improvement of Voltage Profile

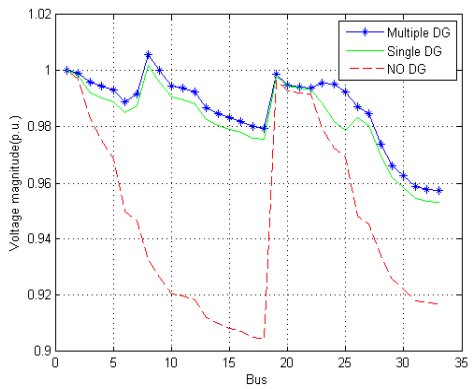

Figure 3. Voltage profile with single, multiple and no DG

Voltage profile obtained after DG placement is shown in Fig. 3. It can be observed that overall voltage profile is improved in presence of DG as compared absence of DG. It is observed that by installing Type-III DG at bus 8 reactive power required by load can be supplied locally.

Thus reactive power demand from supply can be reduced consequently voltage profile is improved. It is observed that with installation of DGs voltage at bus 8 increased from 0.932 p.u. to 1 p.u. and also reached to 0.995 p.u. and 0.992 from 0.973p.u. and 0.969 p.u. at bus 24 and bus 25 respectively. Thus multiple DG installation is significant in terms of improved voltage profile.

B. Reduction in Real and Reactive Power Losses

Without installation of DG real and reactive power losses are 209 kW and 143KVAr. Real and reactive power loss are observed after inserting of DGs of capacity 2100 kVA at 0.9 lagging p.f. at bus 8,1000 kW at bus 24 and 80 kW at bus 25 in distribution network. With this combination of DG installation real and reactive power losses are reduced to 69 kW from 209kW and 53KVAr from 143kVAr. Real power supplied from substation reduced from 3923kW to 814 kW and reactive power reduced to 1438 KVAr from 2442KVAr.

C. Cost Comparision

The cost of enrgy loss in distribution system can be compared in presence of multiple DGs. While with single DG cost of energy loss is 6799$, it is reduced to 5554$ in presence of multiple DGs. This results in annual savings of 9943$ with single DG placement and 11188$ with multiple DG placement. Therefore it can be concluded that multiple DG placement is more beneficial in terms of profit obtained from single DG placement.

The results obtained with placement of multiple DGs can be compared with single DG placement based on combined power loss sensitivity method [16]. Results can be compared on the basis of real and reactive power losses, cost of power supplied by DG, total annual savings from reduced losses. The results are summarized in Table I. This is presented to illustrate advantages of placing multiple DG over single DG placement.

TABLE I. COMPARISON OF RESULTS FOR DIFFERENT TEST SYSTEMS

	Without DG	With Single DG	With Multiple DG
DG location bus	-	8	8, 24, 25
DG size(kVA)	-	2100 0.9 p.f.	2100,0.9p.f. @ bus8 1000 unityp.f.@ bus24
Total P Loss (kW)	209	84	69
Total Q Loss (KVAr)	143	62	53
Minimum bus voltage (p.u.)	0.917 @bus33	0.953 @bus33	0.957@ bus33
Cost of energy losses($)	16742.544	6799.40	5554.017
Cost of PDG ($/MWh)	-	38.05	54.75
Cost of QDG ($/MVAR h)	-	3.77	3.24
Annual Savings in Cost of Energy Loss ($)	-	9943.144	11188.527

V. CONCLUSION

In this work a framework is outlined for optimal allocation of DG for loss minimization and improvement of voltage profile. The proposed technique discusses DSVSI based approach to find optimal locations of DG required and corresponding size. The study is carried out on 33 bus radial system in preset of single and multiple DG. It is observed that placement of multiple DG of appropriate type can result in remarkable reduction in losses and improved voltage profile. The comparative results elucidate that placement of multiple DGs of small capacity is more beneficial than single DG of huge capacity. Therefore determination of optimal number, location and size of DG is of utmost importance for gain optimal benefit.

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