Journal of Electrical and Electronic Engineering
2015; 3(3): 36-41
Published online May 13, 2015 (http://www.sciencepublishinggroup.com/j/jeee)
doi: 10.11648/j.jeee.20150303.13
ISSN: 2329-1613 (Print); ISSN: 2329-1605 (Online)

Effects of Distributed Generation on System Power Losses and Voltage Profiles (Belin Distribution System)

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To cite this article:
Chaw Su Hlaing, Pyone Lai Swe. Effects of Distributed Generation on System Power Losses and Voltage Profiles (Belin Distribution System). *Journal of Electrical and Electronic Engineering*. Vol. 3, No. 3, 2015, pp. 36-41. doi: 10.11648/j.jeee.20150303.13

Abstract: In present times, the use of DG systems in large amounts in different power distribution systems has become very popular and is growing on with fast speed. Although it is considered that DG reduces losses and improves system voltage profile, this paper shows that this is usually true. The paper presents voltage stability index based approach which utilizes combine sensitivity factor analogy to optimally locate and size a multi-type DG in 48-bus Belin distribution test system with the aim of reducing power losses and improving the voltage profile. The multi-type DG can operate as; type 1 DG (DG generating real power only), and type 2 DG (DG generating both real and reactive power). It further shows that the system losses are reduced and the voltage profile improved with the location of type 2 DG than with the location of type 1 DG. It reaches a point where any further increase in number of DGs in the network results for minimizing power losses and voltage profiles improvement.

Keywords: Distributed generation (DG), Voltage stability index (SI), System Loss Reduction, Voltage Profiles Improvement, Optimal Locating and Sizing

1. Introduction

Distributed generation (DG) is small-scale power generation that is usually connected to distribution system. The Electric Power Research Institute (EPRI) defines DG as generation from a few kilowatts up to 50MW [1]. Ackermann et al. have given the most recent definition of DG as: “DG is an electric power generation source connected directly to the distribution network or on the customer side of the meter.” [2].

In most power systems, a large portion of electricity demand is supplied by large-scale generators. This is because of economic advantages of these units over small ones. The distributed real power sources can be classified into two categories and referred in the following sections of this paper as type 1 DG and type 2 DG:

Type 1 DG: Distributed generations that supply real power, depending on the availability or demand, to the network without demanding any reactive power. Few examples of type 1 DG are photovoltaic cell, fuel cell, battery storage.

Type 2 DG: Distributed generations that supply both active and reactive power to the network. Type 2 is used for DG sources such as wind generation, combustion engines, and like synchronous generators [3].

Normally, the real power loss reduction draws more attention for the utilities, as it reduces the efficiency of transmitting energy to customers. Nevertheless, reactive power loss is obviously not less important. This is due to the fact that reactive power flow in the system needs to be maintained at a certain amount for sufficient voltage level. Consequently, reactive power makes it possible to transfer real power through transmission and distribution lines to customers [4]. System loss reduction by strategically placed DG along the network feeder can be very useful if the decision maker is committed to reduce losses and to improve network performance maintaining investments to a reasonable low level [5].

Studies indicate that poor selection of location and size of a DG in a distribution system would lead to higher losses than the losses without DG. In a power system, the system operator is obligated to maintain voltage level of each customer bus within the required limit [6]. Actually in practice, many electricity companies try to control voltage variations within the range of ±5% [7]. The DG units improve voltage profiles by changing power flow patterns. The locations and size of DGs would have a significant impact on the effect of voltage profile enhancement.

2. Voltage Stability Index

A system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude following a disturbance, increase in load demand or change in operating condition. It is usually identified by an index called steady state voltage stability index, evaluated using sensitivity analysis. Sensitivity analysis is the computation of voltage stability index of all the nodes in RDS. Voltage stability index, SI can be computed as follows:

SI Index, proposed by [8], is utilized to find the weakest voltage bus in power system. This index will find the most optimum weakest link in the system which could lead to voltage stability in future, when the load will increase. The value of index is given by Eq. (1) and termed as Stability index (SI).

$$SI = \left|V_s\right|^4 - 4\times\left[P_r x_{ij} - Q_r r_{ij}\right]^2 - 4\times\left[P_r r_{ij} + Q_r x_{ij}\right]\times\left|V_s\right|^2 \quad (1)$$

where, SI is the stability index, V_s is the sending bus voltage, P_r is active load at receiving end, Q_r is the reactive load at receiving end, r_{ij} is the resistance of the line i-j and x_{ij} is reactance of the line i-j.

Under stable operation, the value of SI should be greater than zero for all buses. When the value of SI becomes closer to one, all buses become more stable. In the proposed algorithm, SI value is calculated for each bus in the network and sort from highest to lowest value. For the bus having the lowest value of SI, will be considered in fitness function.

3. Objective Function

As the main objective of this work is to determine the optimal location and sizing of the distributed generation in the distribution network to minimize the losses (active power loss), the following objective function is selected as [9]:

$$F_l = \min P_{loss} = \sum_{k=1}^{ntl}\left|I_j\right|^2 \cdot r_j \quad (2)$$

where, F_l is the objective function to minimize power losses. P_{loss} is the active power loss. *ntl* is the number of lines in the distribution system.

Subjected to constraints:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (3)$$

$$I_i \le I_i^{\max} \quad (4)$$

$$V_{DG}^{\min} \le V_{DG} \le V_{DG}^{\max} \quad (5)$$

$$P_{DG}^{\min} \le P_{DG} \le P_{DG}^{\max} \quad (6)$$

where,

P_{DG} =real power generations of DG

V_i =voltage magnitudes at bus i

V_{DG} =voltage magnitudes at bus i

I_i =ith feeder current loading

4. Problem Formulation

The problem formulation for the optimal location and sizing of the distributed generation in the distribution network to minimize the active power loss includes the power flow with and without distributed generation in the distribution system. The distributed generation is considered as active power sources at a particular voltage, which is at unity power factor. The well-known basis load flow equations are [10]:

$$S_i = P_i + jQ_i = V_i I_i^* \quad (7)$$

$$S_i = V_i \sum_{j=1}^{n} Y_{ij}^* V_j^* = \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\angle\left(\delta_i - \delta_k + \theta_{ij}\right) \quad (8)$$

Resolving into the real and imaginary parts, then the power flow equations without DG are given as:

$$P_i = \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\cos\left(\delta_i - \delta_k + \theta_{ij}\right) = P_{Gi} - P_{Di} \quad (9)$$

$$Q_i = \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\sin\left(\delta_i - \delta_k + \theta_{ij}\right) = Q_{Gi} - Q_{Di} \quad (10)$$

The basic power balance equations:

$$P_{Gi} = P_{Di} + P_L \quad (11)$$

$$Q_{Gi} = Q_{Di} + Q_L \quad (12)$$

The power flow equations considering losses with DG for the practical distribution system and the DG is an active power source at unity power factor (PV generator) then flow are given as:

$$P_i + P_{DGi} = P_{Di} + P_L \quad (13)$$

$$Q_i + Q_{DGi} = Q_{Di} + Q_L \quad (14)$$

The DG is active power source only at unity power factor, so $Q_{DG} = 0$.

$$P_i + P_{DGi} = P_{Di} + P_L \quad (15)$$

$$Q_i = Q_{Di} + Q_L \quad (16)$$

The final power flow equations for distribution system are:

$$\sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\cos\left(\delta_i - \delta_k + \theta_{ij}\right) + P_{DGi} = P_{Di} + P_L \quad (17)$$

$$\sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\sin\left(\delta_i - \delta_k + \theta_{ij}\right) = Q_{Di} + Q_L \quad (18)$$

$$\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_k + \theta_{ij}) + P_{DGi} - P_{Di} - P_L = 0 \quad (19)$$

$$\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_k + \theta_{ij}) - Q_{Di} - Q_L = 0 \quad (20)$$

$$P_i^{\min} \le P_i \le P_i^{\max} \quad (21)$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \quad (22)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (23)$$

$$P_{DG}^{\min} \le P_{DG} \le P_{DG}^{\max} \quad (24)$$

where,

P_i, Q_i =real and reactive power flow at bus i

P_{Di}, Q_{Di} = real and reactive loads at bus i

V_i , V_k = voltage magnitudes at bus i and k

P_{DGi} =real power of DG at bus i

N=total number of buses

δ_i, δ_k=voltage angles of bus i and k

Y_{ik}= magnitude of the ik^{th} element in bus admittance matrix

θ_{ik} =angle of the ik^{th} element in bus admittance matrix

5. Solution Methodology

Following steps are involved in optimal siting and sizing of distributed generations:

Step: 1Determination of proposed locations for placing distributed generations

a) Perform load flow analysis to calculate the bus voltage magnitudes and total network power loss in the RDS.
b) Compute the voltage stability index (SI) using Eq. (1).
c) Arrange the buses in ascending order of the voltage stability index and select one or two buses with low value of voltage stability index from different laterals as the proposed locations for placing distributed sources.

Step: 2 Run the Base Case without DG using NR load flow using MATLAB software and calculate the bus voltage magnitude, angle, and real and reactive power loss respectively.

a) After Load flow identify the optimum sizing for each bus is calculated.
b) Find out the approximate losses for each bus by placing DG at the corresponding location with the optimum sizing obtains from the above step.
c) Check for constraint violation after DG placement.
d) Locate the bus at which the loss is minimum after DG placement and this is the optimum location for DG.

Repeat the above procedure till the termination condition is satisfied.

6. Results and Discussions

The solution methodology presented in this paper for optimal siting and sizing of distributed power sources are analyzed using 132 kV, 33 kV and 11 kV, 48-bus Belin distribution system. The data for 48-bus Belin distribution system is given in Table 4 in the appendix.

This system is supplied from Yeywa Generation Station of 487 MW and 400 MVAR, 230 kV with a total peak load of 79.53 MW and 41.87 MVAR. The total system power loss at the peak demand without DG connection (base case scenario) is 1.351MW and 17.56 MVAR. The single line diagram of 48-bus Belin distribution system is given in Fig.1.

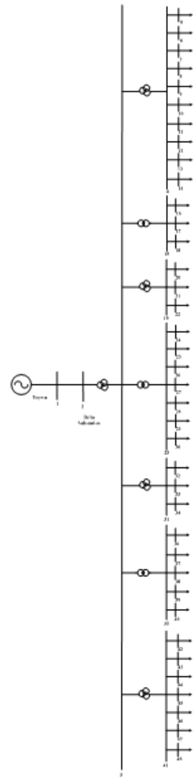

Figure 1. *The 48-bus Belin distribution system.*

6.1. Optimum Size Allocation

The number of DGs to be included in a power network can be limited by several factors. The two main factors are the undesirable effects on power system parameters and the economic factors. This research was mainly concerned with the system power losses and the voltage profile of the network and thus the effects of DG on these system parameters have been investigated. The DG limits were taken to be as follows; 0 MW – 53 MW for real power limit (Type 1, and 2 DGs), 0 MVAR – 31 MVAR for reactive power limit (Type 2 DG).

After calculating the combined sensitivity factors, the buses were arranged in order of sensitivity and those with a factor of less than 0.8 were selected as the proposed buses. Table 1 shows the results of the optimal DG sizes for each respective proposed location and the associated best fitness achieved for all the two types of DGs. Both real and reactive power losses are considered in while investigating the effect of DG on system power losses. The number of DGs was assumed to increase from one, two, three and then four. This was done sequentially ensuring that the proposed bus with the most optimal size was chosen first followed with the others in the same order. Thus the most optimal DG location and size was included in the four cases.

Table 1. *Results for SI and optimal DG sizes for multi-type DGs located on chosen proposed buses.*

Proposed Bus	SI index	Type 1 DG Optimal DG Size (MW)	Type 2 DG Optimal DG size (MW+jMVAR)
10	0.7827	6.4635	10.5250+j5.5639
24	0.6577	6.0899	12.9831+j5.9928
25	0.7082	6.1199	10.0045+j5.9844
26	0.7750	9.7073	52.3274+j30.8305
27	0.7349	6.7413	10.3567+j5.4865
28	0.7688	3.4966	7.4777+j3.9912
29	0.7663	6.5099	9.0574+j4.8620
30	0.7607	5.2389	3.4092+j1.8000
36	0.7781	4.6756	17.6717+j9.3471
37	0.7813	1.8338	6.4406+j3.4067
38	0.7118	4.8256	4.9556+j2.6225
39	0.7613	2.5351	1.9437+j1.0251
40	0.7884	2.5446	1.0499+j0.5530
43	0.7953	2.8892	6.2551+j3.3038
46	0.7794	3.4975	2.3135+j1.2223

Table 2. *Effects of type 1 DG on system power losses.*

Number of DGs	Bus No.	DG Size	Power Losses	% Power Loss Reduction
		MW	MW+jMVAR	%(MW+jMVAR)
One	24	6.0899	1.125+j15.16	16.73+j13.67
Two	24	6.0899	0.971+j13.19	28.13+j24.89
	25	6.1199		
Three	24	6.0899	0.887+j11.91	34.34+j32.18
	25	6.1199		
	38	4.8256		
Four	24	6.0899	0.774+j10.18	42.71+j42.03
	25	6.1199		
	38	4.8256		
	27	6.7413		

As it can be seen from Table 2, the introduction of only one type 1 DG on bus 24 reduced the real power losses from the base case scenario of 1.351 MW to 1.125 MW and the reactive losses from 17.56 MVAR to 15.16 MVAR. The inclusion of the second DG in the system further reduced both real and reactive power losses to 0.971 MW and 13.19 MVAR. The introduction of the third DG reduces both real and reactive power losses to 0.887 MW and 11.91 MVAR. The inclusion of the fourth DG in the system results to 0.774 MW and 10.18 MVAR less than the case without DG in both real and reactive power losses.

From the results in Table 3, the introduction of the first optimally placed and sized type 2 DG in the network reduced the real power losses from the base case value of 1.351 MW to 1.135 MW and the reactive power losses from 17.56 MVAR to 12.45 MVAR. The inclusion of the second and third DG in the network further reduces the real power losses to 1.019 MW and 0.915 MW and the reactive power losses to 9.13 MVAR and 7.71 MVAR respectively. It is evident that the introduction of the fourth DG in the network decreases both real and reactive power losses in the system from the previous case.

Table 3. *Effects of type 2 DG on system power losses.*

Number of DGs	Bus No.	DG Size	Power Losses	% Power Loss Reduction
		MW+jMVAR	MW+jMVAR	%(MW+jMVAR)
One	24	12.9831+ j5.9928	1.135+j12.45	15.99+j29.10
Two	24	12.9831+ j5.9928	1.019+j9.13	24.57+j48.01
	25	10.0045+ j5.9844		
Three	24	12.9831+ j5.9928	0.915+j7.71	32.27+j56.09
	25	10.0045+ j5.9844		
	38	4.9556+ j2.6225		
Four	24	12.9831+ j5.9928	0.862+j5.49	36.20+j68.74
	25	10.0045+ j5.9844		
	38	4.9556+ j2.6225		
	27	10.3567+ j5.4865		

6.2. Effect of DG on Bus Voltage Profile

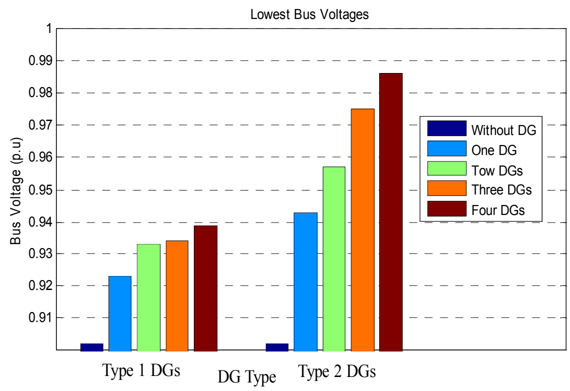

Figure 2. *A graph of the lowest bus voltages for different DG types and DG numbers.*

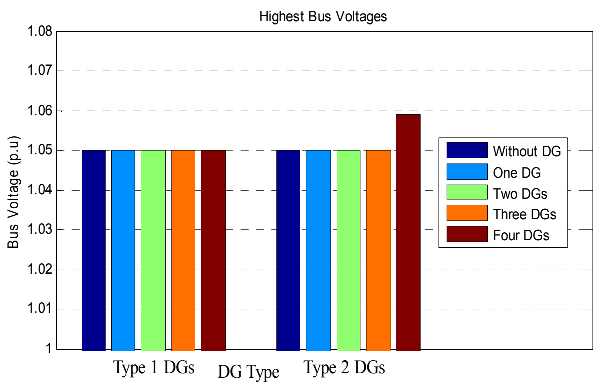

Figure 3. *A graph of the highest bus voltages for different DG types and DG numbers.*

From fig. 2 above it can be seen that all the two cases resulted to an increase in the lowest bus voltage level. It also important to note that there was an increase for each additional DG added in the network up to the fourth DG. Note that the minimum voltage level for the base case is about 0.902 p.u recorded at bus 24. Fig. 3 shows the highest bus voltages for different DG types and DG numbers.

After installation of type 1 DG, there are still buses which are lower than the pre-specified voltage limit of 0.95 p.u. After installation of type 2 DG, the voltage levels of these buses are improved with minimum 0.943 p.u of bus number 25 with one DG. Since the most ideal case was to have this voltage as close to 1 p.u as possible it can be concluded that type 2 DG performed better in this case compared to type 1 DG. This is because its bus voltage levels with three DGs in the system are within the range of ±5%.

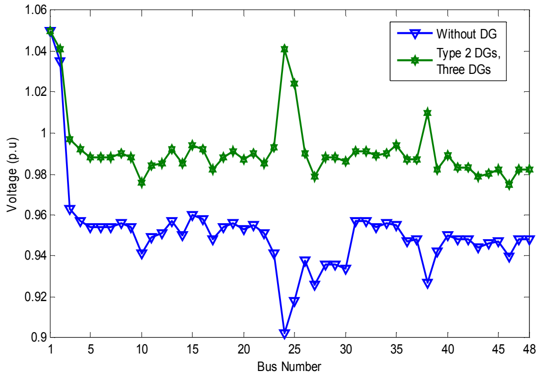

Figure 4. *Voltage profile before and after DG injection having optimum value.*

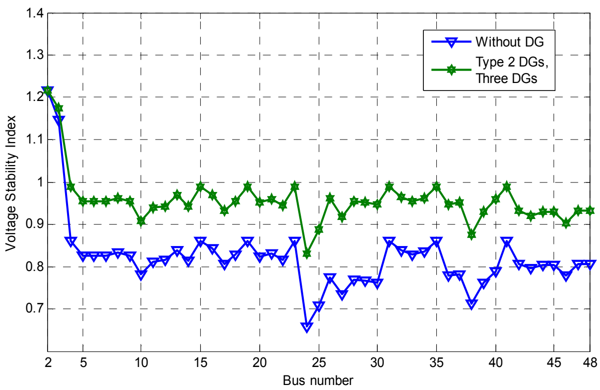

Figure 5. *Voltage Stability Index (SI) before and after DG installation at each bus of system.*

Fig.4. shows voltage profiles improvement at various nodes for 48-bus Belin distribution system before and after connecting DG. Improvement in voltage stability was observed from Fig.5. In this figure the voltage stability index at each buses of system is shown

7. Conclusion

The solution methodology for optimal siting and sizing of distributed generation in Belin distribution system, considering precise models for distributed generations is presented in this paper. The benefits and consequences of distributed sources for improvement in voltage profile, voltage stability index and reduction on total network power loss have been analyzed in detail. According to the objective function, the best location in 48-bus Belin distribution system is in the order 24, 25 and 38 corresponding type 2 optimal DG sizes of MW and MVAR are 12.9831 + j5.9928, 10.0045 + j5.9844 and 4.9556 + j2.6225. The results of the proposed system depict that the optimal size of type 2 DG with three DGs is the maximum possible penetration levels of distributed generation in Belin distribution system in terms of improved voltage profile and reduced total real and reactive power loss of 0.915 MW and 7.71 MVAR.

Acknowledgements

The author would like to express grateful thanks to her supervisor Dr. Pyone Lai Swe, Associate Professor, Department of Electrical Power Engineering at Mandalay Technological University for her valuable suggestions and supervision through this research work. She also wants to thank all her teachers from Department of Electrical Power Engineering at Mandalay Technological University. The author offers her appreciation to her parents and brothers for their supports, encouragement and valuable guidance.

Appendix

Table 4. *Data for 48-Bus Belin Distribution System.*

Sending Bus	Receiving Bus	R (p.u)	X (p.u)	Load at Receiving Bus	
				P (MW)	Q (MVAR)
1	2	0.00268	0.02232	0	0
2	3	0.00000	0.1418	0	0
3	4	0.01470	0.0356	0	0
3	15	0.02900	0.0818	0	0
3	19	0.02900	0.0818	0	0
3	23	0.02900	0.0818	0	0
3	31	0.03790	0.0920	0	0
3	35	0.03790	0.0920	0	0
3	41	0.08820	0.2486	0	0
4	5	0.36130	0.6974	0.45	0.24
4	6	0.30110	0.5812	0.61	0.32
4	7	0.37310	0.7199	0.44	0.23
4	8	0.07530	0.1453	1.14	0.60
4	9	0.15060	0.2906	1.1	0.58
4	10	0.16730	0.3228	4.5	2.37
4	11	0.18790	0.3626	2	1.05
4	12	0.17700	0.3416	1.8	0.948
4	13	0.00840	0.0161	0.15	0.079
4	14	0.08360	0.1614	3.94	2.075
15	16	0.09980	0.1294	0.925	0.487
15	17	0.30660	0.3975	2.204	1.158
15	18	0.23530	0.3051	1.429	0.753
19	20	0.03320	0.0719	4.52	2.38
19	21	0.13140	0.2844	0.375	0.197
19	22	0.06570	0.1153	4.146	2.185
23	24	0.30820	0.7736	4.846	2.554
23	25	0.25780	0.4522	4.279	2.254
23	26	0.02900	0.0559	4.4	2.317
23	27	0.13250	0.2868	4.85	2.554

Sending Bus	Receiving Bus	R (p.u)	X (p.u)	Load at Receiving Bus	
				P (MW)	Q (MVAR)
23	28	0.09840	0.2130	2.042	1.074
23	29	0.05910	0.1278	3.946	2.08
23	30	0.08860	0.1917	3.42	1.8
31	32	0.00840	0.0161	0.015	0.0079
31	33	0.04180	0.0807	3.129	1.648
31	34	0.01250	0.0242	3.713	1.954
35	36	0.18720	0.2426	2.308	1.216
35	37	0.43680	0.5662	0.868	0.457
35	38	0.49930	0.6472	3.049	1.606
35	39	0.49930	0.6472	1.422	0.748
35	40	0.24970	0.3236	1.051	0.553
41	42	0.13380	0.2583	0.065	0.034
41	43	0.11710	0.2260	1.46	0.769
41	44	0.05850	0.1130	1.925	1.016
41	45	0.07190	0.1388	0.58	0.305
41	46	0.17560	0.3390	2.21	1.164
41	47	0.10040	0.1937	0.102	0.054
41	48	0.07780	0.1501	0.12	0.063

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