Analytical Approach for Optimal Distributed Generation Allocation in Primary Distribution Networks

Conference Paper · March 2019

Oluwafunso Osaloni
University of KwaZulu-Natal
12 PUBLICATIONS 44 CITATIONS
SEE PROFILE

Kehinde Awodele
University of Cape Town
93 PUBLICATIONS 420 CITATIONS
SEE PROFILE

Analytical Approach for Optimal Distributed Generation Allocation in Primary Distribution Networks

O O Osaloni* and K O Awodele
University of Cape Town, Department of Electrical Engineering, Rondebosch, 7701, Cape Town, South Africa
*Email: wole_osaloni@yahoo.com

Abstract: This paper proposes an analytical expression to calculate the optimal size and an effective methodology to identify the corresponding optimum location for DG placement for minimizing the total power losses in primary distribution systems. The analytical expression and the methodology are based on the exact loss formula. The effect of size and location of DG with respect to loss in the network is also examined in detail. The proposed methodology was tested and validated on a 33-bus radial distribution test system. Results obtained from the proposed methodology are compared with that of the exhaustive load flow and loss sensitivity method. Results show that the proposed approach achieves better placement for loss reduction than the loss sensitivity factor based approach.

Key words: Distributed generation, Exact loss formula, Optimum size, Optimum location, Sensitivity factors.

1 INTRODUCTION

With the increasing demand for clean and renewable energy, the issue of distributed generation (DG) is drawing more attention worldwide. DG stands as one better way of fulfilling the higher demand for electricity. Moreover, it provides voltage support to large scale distribution power systems, which results in reliability improvement and loss reduction in the power system. DG technology is one of the current areas of intense research given the increasing global concerns about environmental protection, energy conservation, and increasing sophistication of wind power, photovoltaic power generation and other renewables energy technologies [1]. The planning of the electric power systems with the presence of DG requires several factors to be taken into considerations, such as; the best technology to use, the number and the capacity of the units, the best location, and the type of network connection etc. [2].

However, there are some integration issues which should be analysed to maximize these technical benefits. From previous studies, it has been seen that different penetration levels and various placement of DG will impact the distribution system differently [3].

Studies have indicated that inappropriate selection of location and size of DG, may lead to greater system losses than the losses without DG [4]. Utilities already facing the problem of high power loss and poor voltage profile, especially in the developing countries cannot tolerate any increase in losses. By optimum allocation, utilities take advantage of reduction in system losses, improved voltage regulation and improvement in reliability of supply [5]. It will also relieve capacity from transmission and distribution system and hence, defer new investments, which have a long lead-time.

Therefore, a detailed and exact analysis method is required to determine the proper location and size of DG more accurately and precisely [6]. In distribution systems, DG should be allocated in an optimal way such that it will reduce system losses and hence improve the voltage profile. In this paper, an analytical expression to calculate optimum size and an effective methodology to identify the optimum location for DG placement are proposed, its accuracy and superiority over loss sensitivity factor method is investigated.

2 DEFINITION OF DISTRIBUTED GENERATION AND RATING (SIZE) OF DG

Generally, Distributed generation means the electric power generation within a distribution network to fulfil the rapid energy demand of consumers. However, distributed generation can be defined in a variety of ways.

i. The Electric Power Research Institute (EPRI) defines distributed generation as generation from ‘a few kilo-watts up to 50 MW [7].

ii. International Conference on large High Voltage Electric Systems (CIGRE) defines DG as ‘smaller than 50-100 MW [7].

iii. International Energy Agency (IEA) defines distributed generation as generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution level voltages [8].

3 LOCATION AND SIZING ISSUES

Typical graphs of power loss versus size of DG at each bus in a distribution system are shown in Fig. 1 below. 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 start to increase and it is likely that it may overshoot the losses of the base case. Also notice that the location of DG plays an important role in minimizing the losses.

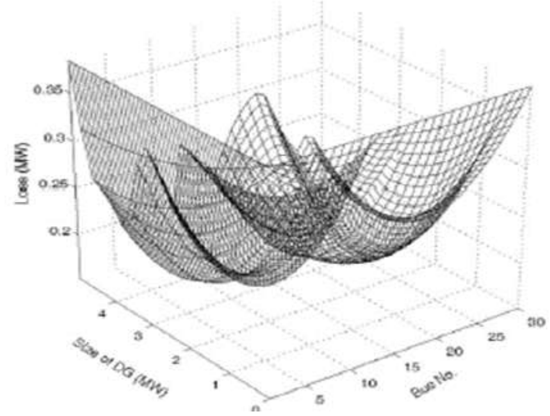


Fig.1: Effect of size and location of DG on system losses [6].

The important conclusion that can be drawn from Fig. 1 is that, given the characteristics of the distribution system, it is not advisable to integrate very high DG capacity in the network. The size at most should be such that it is consumable within the distribution substation boundary.

4 LOSS SENSITIVITY

The real power loss in a system is given by (1). This is popularly known to as the ‘‘exact loss’’ formula

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

Where,

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

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

$$r_{ij} + jx_{ij} = z_{ij}$$

are the $ijth$ element of [Zbus] matrix with [Zbus]= $[Ybus]^{-1}$

The sensitivity factor of real power loss with respect to real power injection from DG is given by

$$\alpha_i = \frac{\partial P_L}{\partial P_i} = 2\sum_{i=1}^{N}(\alpha_{ij}\,P_j - \beta_{ij}Q_j) \qquad (2)$$

Sensitivity factors are evaluated at each bus, firstly using the values obtained from the base case power flow. The buses are ranked in descending order of the values of their sensitivity factors to form a priority list. The top-ranked buses in the priority list are the first to be studied alternatives location. This is generally done to take into account the effect of nonlinearities in the system. The first order sensitivity factors are based on the linearization of the original nonlinear equation around the initial operating condition and is biased towards a function which has a higher slope at the initial condition that might not identify the global optimum solution. This condition is depicted in Fig. 2. Therefore, a priority list of candidate locations is a prerequisite to get the optimum solution [9]. The curve with a solid line has a higher sensitivity factor at the initial operating condition than the dotted curve, but does not give the lowest loss, as PL1 > PL2. It shows why the sensitivity factor may not give the optimum result if a number of alternative locations are not taken into account.

4.1 Priority list

The sensitivity factor will reduce the solution space to few buses, which constitute the top ranked buses in the priority list. The number of buses taken in priority will have an effect on the optimum solution obtained for a system. For each bus in the priority list, the DG is placed and the size is varied from minimum (0 MW) to a higher value until the minimum system losses is found with the DG size.

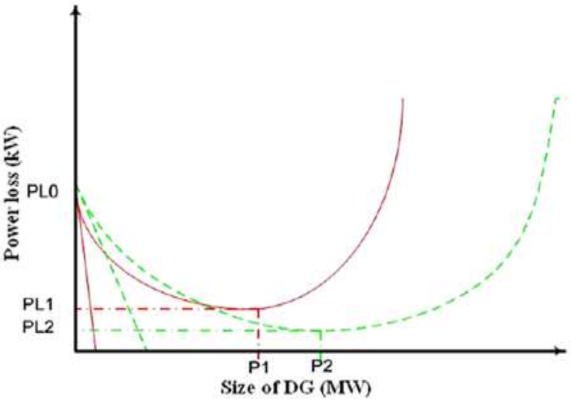


Fig. 2: Nonlinearity in loss curve [6].

In this study, 30% of the total number of buses is considered in preparing the priority list for each case. The process is computationally demanding as one needs a large number of load flow solutions.

4.2 Computational procedure

The computational procedure is given below:

Step 1: Run the base case load flow.

Step 2: Find the sensitivity factor using Eq. (2) and rank the sensitivity in descending order to form the priority list.

Step 3: Select the bus with the highest priority and place DG at that bus.

Step 4: Change the size of DG in ‘‘small’’ steps and calculate the loss for each by running load flow.
Step 5: Store the size of DG that gives the minimum loss.
Step 6: Compare the loss with the previous solution. If the loss is less than the previous solution, store this new solution and discard the previous solution.
Step 7: Repeat Step 4 to Step 6 for all buses in the priority list.

5 PROPOSED METHODOLOGY

In this section, an analytical approach is proposed to find the optimum size and location of DG in the distribution system. This methodology requires load flow to be carried out only two times, one for the base case and another at the end with DG included to obtain the final solution.

5.1 Sizing at various locations

As shown in Section 3, the total power loss against injected power is a parabolic function and at minimum losses the rate of change of losses with respect to injected power becomes zero.

$$\frac{\partial P_L}{\partial P_i}=2\sum_{i=1}^{N}(\alpha_{ij}P_j-\beta_{ij}Q_j) \qquad (3)$$

It follow that

$$\alpha_{ii}P_i-\beta_{ii}Q_i+\sum_{j=1 j\neq i}^{N}\left(\alpha_{ij}P_j-\beta_{ij}Q_j\right)=0 \qquad (4)$$

$$P_i=\frac{1}{\alpha_{ii}}[\beta_{ii}Q_i+\sum_{j=1 j\neq i}^{N}\left(\alpha_{ij}P_j-\beta_{ij}Q_j\right)] \qquad (4a)$$

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

$$P_i=P_{DGi}-P_{Di} \qquad (5)$$

Where, P_{DGi} is the real power injection from DG placed at node i and P_{Di} is the load demand at node i. By combining (4) and (5) equation (6) is obtained.

$$P_{DGi}=P_{Di}+\frac{1}{\alpha_{ii}}[\beta_{ii}Q_i+\sum_{j=1 j\neq i}^{N}\left(\alpha_{ij}P_j-\beta_{ij}Q_j\right)] \qquad (6)$$

The above equation gives the optimum size of DG for each bus i, for the loss to be minimum. Any size of DG other than P_{DGi} placed at bus i will lead to higher loss. This loss, however, is a function of loss coefficients α and β.

5.2 Location to minimize losses

The next step is to find the optimum DG location, which will give the lowest possible total losses. Calculation of loss with DG one at a time at each bus again requires several load flow solutions, as many as the number of buses in the system. Therefore a new methodology is proposed to quickly calculate approximate loss, which would be used for the purpose of identifying the best location. Numerical results show that the approximate loss follows the same pattern as that calculated by accurate load flow. It means that, if accurate loss calculation from load flow gives minimum for a particular bus then, loss calculated by approximate loss method will also be minimum at that bus.

5.3 Computational procedure

Step 1: Run the base case load flow.
Step 2: Find the optimum size of DG for each bus using Eq. (6).
Step 3: Compute approximate loss using Eq. (1) for each bus by placing DG of optimum size obtained in step 2 for that bus. Add the injection from DG for that bus and use base case values for state variables.
Step 4: Locate the bus at which the loss is minimum after DG placement. This is the optimum location for DG.
Step 5: Run load flow with DG to get the final result.

6 TEST SYSTEM AND ANALYTICAL TOOLS

The proposed methodology is tested on a 33-bus test system shown in Fig. 3. It is a radial system with a total load of 3.72 MW and 2.3 Mvar [10]. The line and bus data of this test system can be found in the appendix. Also a computer program has been written in MATLAB 7 to calculate the optimum sizes of DG at various buses and approximate total losses with DG at different locations to identify the best location. A Newton–Raphson algorithm based load flow program is used to solve the load flow problem.

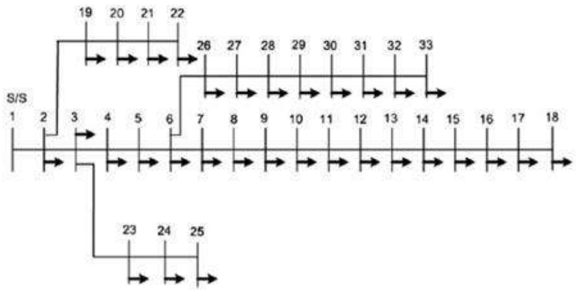


Fig. 3: Single line diagram of the 33-bus distribution test system.

7 SIMULATION RESULTS

7.1 Sizes allocation

Based on the proposed analytical expression, optimum sizes of DGs are calculated at various nodes of the test system. Fig. 4 shows optimum sizes of DG at various nodes for the 33-bus distribution test systems.

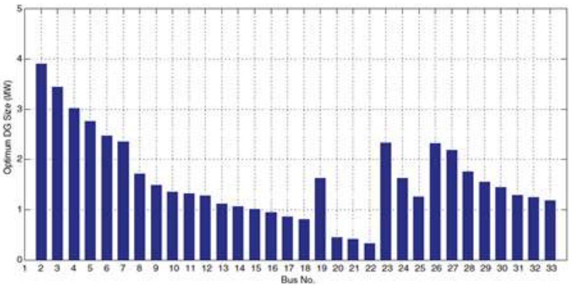


Fig. 4: Optimum size of DG at various locations for the 33-bus distribution system.

As far as one location is concerned, in a distribution test system, the range of DG sizes for the test system at various locations is between 0.1–4.0 MW. However, it is important to identify the location at which the total power loss is minimum. This can be identified with the help of the approximate method described in section 5.2.

7.2 Location selection

The approximate total power losses for the 33-bus distribution system is shown in Fig. 5 with optimum DG sizes obtained at various nodes of the system. The figure also shows the accurate loss. As can be seen from these figures the trend of the losses is captured with the help of approximate solution which is good enough to identify the location that would lead to the least total power losses. Notice that approximate losses pattern of the system with optimum sizes of DG at various nodes follows the accurate losses in all the cases. For the 33-bus distribution test system, the best location is bus 6 with a total power loss of 0.111 MW and the second best location is bus 7 with slightly higher total power losses as shown in Fig. 5 below.

8 SUMMARY

The summary of results, optimum location, corresponding optimum size of DG and total power loss with and without DG, of the test system is shown in Table 1. The reduction in real power loss is 47.3%. As can be seen from the results of various approaches the location and size of DG play an important role in loss reduction of primary distribution systems. From the results obtained for the test system one can conclude that by placing DG of optimum size at optimum location, significant reduction in loss can be achieved.

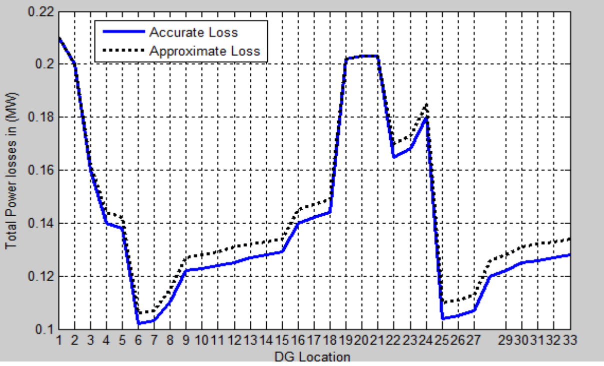


Fig. 5: Approximate and accurate losses of the 33-bus distribution test system.

Voltage profile improvement, reduction in thermal loading of the main feeder and better voltage regulation are some consequent results apart from power quality and reliability improvement.

Tab. 1: Summary of the simulation results

Test system	Optimum location	Optimum Size(MW)	Power loss (kw)	
			Without DG	With DG
33-bus	Bus 6	2.49	211.20	111.24
	Bus 7	2.12	211.20	101.25

8.1 Comparison of results

In this section, the traditional loss sensitivity approach for DG location selection is compared with the proposed approach and repeated load flow or ‘‘exhaustive’’ approach. Table 2 shows the best locations obtained. The loss sensitivity approach is not able to identify the best location, instead it picked up the ninth optimum location as its first choice in the 33-bus distribution test system. Also power losses in this case is higher compare to the analytical approach. This happens due to the linearization and approximation as explained in Section 4. Table 2 also shows the optimum sizes of DG. In calculating the optimum sizes of DG at various locations using Equation (6), it was assumed that the values of variables remain unchanged.

Tab. 2: Comparison of the results of different approaches

Approach	Test System	Optimum Location	Optimum size MW)	Real power loss (kw)
Loss sensitivity	33-bus	Bus 10	3.2	156.28
Proposed approach		Bus 6	2.49	111.24
Repeated Load Flow		Bus 6	2.6	111.1

This is the reason why there is a small difference between the optimum size obtained from the proposed approach and repeated load flow. However, in reality, one would go for the closest size available in the market and these differences are within margin of error.

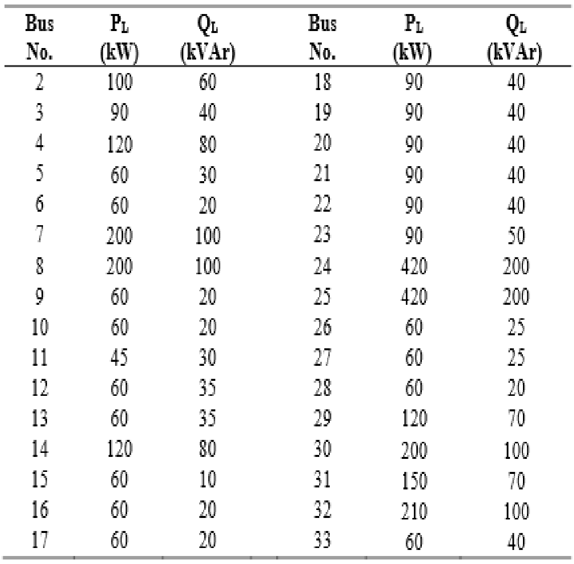
9 CONCLUSION

Size and location of DG are crucial factors in the application of DG for loss minimization. This paper presents an algorithm to calculate the optimum size of DG at various buses and proposes a fast methodology to identify the best location corresponding to the optimum size for reducing total power losses in primary distribution networks. The benefit of the proposed algorithm for size calculation is that a look up table can be created with only one power flow calculation and the table can be used to restrict the size of DG at different buses, with the view of minimizing total losses. However, if a DG is installed in the system, the look up table needs to be updated with new calculation. The proposed methodology for location selection correctly identifies the best location for single DG placement in order to minimize the total power losses.

In practice, the choice of the best site may not be always possible due to many constraints. However, the analysis here suggests that the losses arising from different placement varies greatly and hence this factor must be taken into consideration while determining appropriate location. The paper also shows that the loss sensitivity factor approach for location selection may not lead to the best choice.

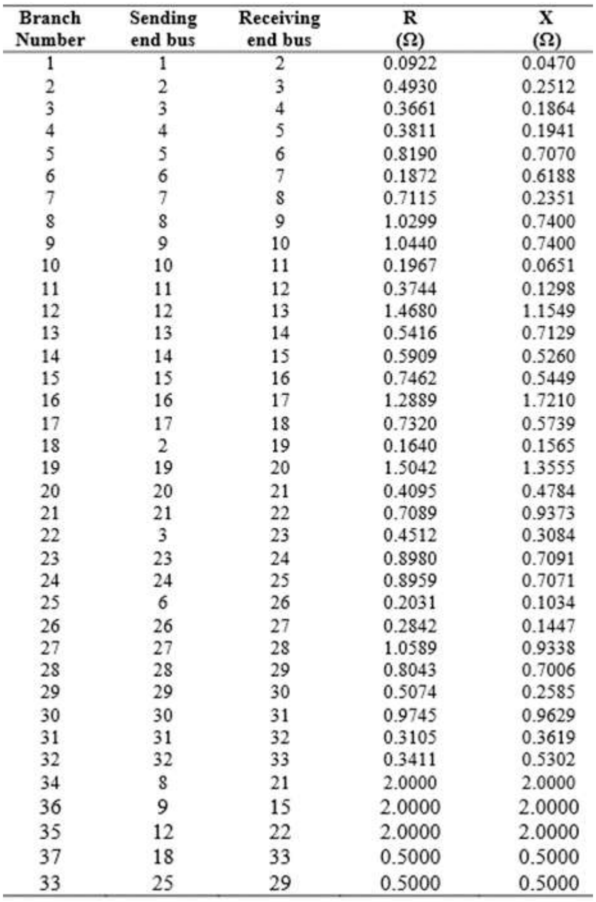
10 APPENDIX

Tab. AI Load data for 33-bus distribution system



Bus No.	P_L (kW)	Q_L (kVAr)	Bus No.	P_L (kW)	Q_L (kVAr)
2	100	60	18	90	40
3	90	40	19	90	40
4	120	80	20	90	40
5	60	30	21	90	40
6	60	20	22	90	40
7	200	100	23	90	50
8	200	100	24	420	200
9	60	20	25	420	200
10	60	20	26	60	25
11	45	30	27	60	25
12	60	35	28	60	20
13	60	35	29	120	70
14	120	80	30	200	100
15	60	10	31	150	70
16	60	20	32	210	100
17	60	20	33	60	40

Tab. AII. Branch data for 33-bus distribution system



Branch Number	Sending end bus	Receiving end bus	R (Ω)	X (Ω)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2512
3	3	4	0.3661	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7115	0.2351
8	8	9	1.0299	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1967	0.0651
11	11	12	0.3744	0.1298
12	12	13	1.4680	1.1549
13	13	14	0.5416	0.7129
14	14	15	0.5909	0.5260
15	15	16	0.7462	0.5449
16	16	17	1.2889	1.7210
17	17	18	0.7320	0.5739
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3555
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3084
23	23	24	0.8980	0.7091
24	24	25	0.8959	0.7071
25	6	26	0.2031	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0589	0.9338
28	28	29	0.8043	0.7006
29	29	30	0.5074	0.2585
30	30	31	0.9745	0.9629
31	31	32	0.3105	0.3619
32	32	33	0.3411	0.5302
34	8	21	2.0000	2.0000
36	9	15	2.0000	2.0000
35	12	22	2.0000	2.0000
37	18	33	0.5000	0.5000
33	25	29	0.5000	0.5000

11 ACKNOWLEDGEMENT

The authors gratefully acknowledge the provision of financial support and research infrastructure by Eskom Holdings through TESP and the University of Cape Town respectively in carrying out this research.

12 REFERENCES

[1] D. R. Gavane, C. Mallareddy, J. Patil and S. B. Bhosale, "Optimal placement of Distributed Generation for loss reduction in Distribution System," *International Journal of Innovations in Engineering Research and Technology*, vol. 2, no. 5, may 2015

[2] M. F. Kotb, K.M. Shebl, M. El Khazaendar and A. El Husseiny, "Genetic Algorithm for optimum Siting and Sizing of Distributed Generation," International Middle East Power System Conference, Cairo, 2010.

[3] A. Anwar, and H. R. Pota, "Loss reduction of Power Distribution Network using optimum size and location of Distributed Generation," Australia Universities Power Engineering Conference (AUPEC), 2011 21st Australalasian, Brisbane, QLD, 2011.

[4] T. Griffin, K. Tomosovic, D. Secrest, and A. Law, "Placement of Dispersed Generations Systems for reduced losses." *Proceedings of the 33rd Hawaii international conference on sciences,* Hawaii,, 2000.

[5] N. Mithulananthan, O.O. Than, and V. Phu Le., "Distributed Generator placement in Power Distribution System using Genetic Algorithm to reduce losses," *Thammasat International Journal of Science And Technology*, vol. 9, no. 3, pp. 55 - 62, 2004.

[6] N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," *Elsevier, Electrical Power and Energy Systems*, vol. 28, no. 22, pp. 669-678, 2006.

[7] T. Ackermann, G. Anderson, and L. Sder, "Distributed Generation: a definition," *Electric Power Systems Research*, vol. 57, no. 3, pp. 195-204, 2001.

[8] IEA, publication, “Distribution generation in liberalized electricity market” [Online]. Available: http//www.iea.org/textbase/nppdf/free/2000distributed 2002, 2002Page 19. [Accessed 31 03 2015].

[9] K. C. Julius, and N. A. Odero, "A combined sensitivity factor based GA-IPSO approach for system loss reduction and voltage profile enhancement." *International Journal of Research in Engineering & Science*, vol. 2, no. 3, 2013.

[10] M. A. Kashem, V. Ganapathy, G.B. Jasmon, and G. B. Buhari, "A novel method for loss minimization in Distribution Networks.," *in Proceedings of International Conference on Electric Utility Deregulation and Restructuring and Power Technologies* pp . 251–255., 2000.