Research Article

Impact Assessment of Reactive Power Capabilities of Distributed Generating Units in Radial Distribution Network

Pankita Mehta[1], Praghnesh Bhatt[1*], Vivek Pandya[2]

[1]C S Patel Institute of Technology, CHARUSAT, Changa, India
[3] School of Technology, Pandit Din Dayal Petroleum University, Gandhinagar, India

Received: 12/01/2017
Revised: 00-00-0000
Accepted: 14/05/2017

Correspondence to:
*Praghnesh Bhatt:
pragneshbhatt.ee@charusat.ac.in

Abstract:

Power generation by renewable energy source has been promoted worldwide due to several reasons such as constrained resources for fossil fuel and greater environment concern. Hence, increasing amounts of Distributed Generation (DG) are being connected to radial distribution networks (RDN). The solar photovoltaic (PV), wind turbine generators, fuel cells and small micro turbine have been used for distributed generation system which have different active and reactive power generation capabilities. Hence, they have different impacts on system performance such as voltage profile, losses and voltage stability. The optimal location of DGs, their sizing and reactive power generation capabilities plays a vital role to enhance the performance of RDN. In this paper, optimal location and sizing of DGs has been ascertained with the use of Golden Section Search (GSS) method considering the objectives of minimizing the active power losses in RDN. Moreover, the impact of varying degree of DG penetration with different reactive power generation capabilities have been analyzed to exactly assess their impact on voltage profile, losses and voltage stability. The obtained results have provided the insight for selection of the optimal location of DG and utilization of reactive power generation capabilities of DG units to allow their more penetration in RDN.

Keywords: Distributed Generation, Reactive Power, Voltage Profile, Power Loss

I. INTRODUCTION

The policies for the power generation by renewable energy sources have been encouraged worldwide as they turned to be a crucial to provide clean, sustainable and eco-friendly environment (Ackerman, 2001). The Distributed Generation (DG) requires the generation capacity in the range of 5 kW to 5 MW and generally employs PV cell, wind turbine generator, small hydro plants or fuel cells. DGs are one of the most cost-effective and an economical solution to solve the problems of radial distribution network (RDN) such as voltage profile, loss minimization and stability (Walling, 2008). Several system problems such as voltage, relay coordination and protection, OLTC operations and islanding are discussed in (Walling, 2008) with the penetration of DGs in RDN.

(Georgilakis, 2013) presented a state of the art on several models and methods for optimal placement and sizing of DG, analysis methods and sketched the guidelines for future research trends in this field.The comprehensive literature review on the challenges and possible solutions with the DGs and capacitor placement in RDN has been addressed in (Mehta, 2015) with the focus on problems such as optimal placement and sizing of DGs, voltage stability enhancement and loss minimization. The strategy for optimal placement of DGs in RDN for voltage stability enhancement is proposed in (Mehta, (2015) with modal analysis and continuation power flow. The best location of DG and sizing of DG for voltage stability enhancement is proposed in (Al Abri, 2013) by mixed-integer nonlinear programming where bus voltages, line capacity and DG penetration level are set as constraints.

Keane (2011) addressed the voltage rise issues with penetration levels of DG and enhanced utilization of voltage control resources has been explored. (Ochoa, 2011) presented the benefits of reactive power capabilities of DG units by examining the possibilities for minimizing the reactive support by adopting enhanced pre-defined fixed power factors. Optimal sizing and optimal placement of generators for modified IEEE 6 bus, IEEE 14 bus and IEEE 30 bus systems has been solved in (Ghosh, 2010) with Newton-Raphson iterative method with the objective to minimize both cost and loss factors. Considering load growth in future and voltage regulation as a constraint, (Mistry, 2014) has addressed mulitple DG placement with the use of PSO with constriction factor approach.

Different types of DGs placement has been proposed by (Kansal, 2013) for minimizing the power distribution loss by maintaining optimal power factor for DG supplying, both real and reactive power using 33-nodes and 69-nodes RDN. More recently a backtracking search optimization algorithm (BSOA) is addressed by El-Fergany (2015) with the objective to reduce the network real loss and enhance the voltage profile where fuzzy rules are used with loss sensitivity factors and bus voltages to determine initial DG's locations.

In literature, many efforts have been reported in area of optimal location and sizing of DG to improve the performance of RDN. But there are limited papers on DG placement which has addressed the impact of reactive power generation capability of DGs while determining its placement. Hence, in this paper, the objectives of the work are set as below:

- To determine the optimal location of DG and its size by considering minimization of active power losses
- To propose different indices to assess the performance of RDN
- To increase the penetration of DG by its utilizing its reactive power capability
- To compare the voltage profile, active and reactive power losses and voltage stability indices for base case and with varying reactive power support from DG

ACTIVE AND REACTIVE POWER CAPABILITIES OF DGs

DG technologies are classified based on their capability of injecting real and/or reactive power in the system. Accordingly, DG technologies are grouped in the following manner (Mehta, 2015).

Type 1: DG capable of controlling active power (P) and reactive power (Q)

DG units that are based on synchronous machine for small hydro, geothermal, and combined cycles fall in Type 1 category. Recently developed variable speed wind turbine generators such as Double Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) also possess the similar characteristic. They generate active power as well as they are capable to generate or absorb the reactive power. They can be operated in either voltage control mode or power factor control mode. In voltage control mode, they are supposed to keep its terminal voltage constant at its specified voltage value. But it can do so only if it has sufficient reactive power generation capability. Once its maximum reactive power limit is reached, it will be unable to keep its voltage at specified value. In power factor mode, the DG will deliver the fixed amount of reactive power based on its set target of power factor. In this mode, terminal voltage is not guaranteed to be at specified level. DG in Type 1 category can reduces the import of power from the source, as a result associated active and reactive power losses gets reduced in lines and thus improves the voltage profile. It is evident that any loss reduction is beneficial to distribution utilities, which is generally the entity with an interest to minimize the loss.

Type 2: DG capable of injecting active power (P) only

Photovoltaic (PV), micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters are the examples of Type 2 category. These types of DG units may require reactive power for their operations if they are integrated to main grid with the help of line commutated converters. On the other hand, with the advancement in power electronics, they are capable to supply reactive power to the system when interfaced through the self-commutated converters. In this work, it is assumed that DG units in this category neither absorbs nor delivers reactive power to system and operates with unity power factor only.

Type 3: DG capable of injecting reactive power (Q) only

The DG units equipped with synchronous compensator are considered as Type 3 category. It will not generate any active power (P) but only supplies reactive power (Q) in a system when operating with over excitation.

Type 4: DG capable of injecting active power (P), but consuming reactive power (Q)

Fixed speed squirrel cage induction generator (SQIG) used for wind turbine generating (WTG) system falls under this category. SQIG in super-synchronous mode is capable of injecting real power in the system whereas it demands reactive power from the system. Generally, the reactive power demand of induction generator is compensated by capacitor banks or static var system (SVC) at its terminal. The operation of induction generator at higher wind speed raises the active power generation with simultaneous increase in reactive power consumption. As a result the induction generator will further depress the system voltage if the capacitors banks or SVC at its terminal are unable to compensate this increased reactive power demand. Hence, the problem of voltage stability is further aggravated.

Thus, it is worthwhile to note that the type of DG technology adopted will have a significant bearing on the performance of distribution network. The installation of synchronous machine-based DG units that are close to the loads can lead to beneficial impact on system voltage stability margin; on other end, the case with an induction generator may have detrimental impact on the system stability margin. Therefore, it is an utmost requirement to analyse the effect of different types of DG technologies on the voltage stability to enjoy the system wide benefits.

DETERMINATION OF OPTIMAL LOCATION AND SIZING OF DG

In this work, the one of the objectives are to determine optimal location and size of DG to achieve minimum voltage deviation as well as active power losses. The DG is placed on each bus individually and its size is varied from 0% to 100% in step size of 1% of load power. For finding out the optimal size and location of DG, Golden Section Search (GSS) method is used (Gozel, 2008). The complete flow chart of the GSS method is shown in Fig. 1.

To minimize $f\left(P_{dg}\right) = P_{loss}$ (1)

$|V_i| \le 1+0.05pu$ $i=1,2,\ldots,n$

Subject to $0 \le P_{dg} \le \sum P_{load}$ (2)

In Fig. 1, i bus number; n total number of buses; optsize(i) optimum size of DG at bus i,; optploss(i) total power losses with optimum size of DG at bus i,; DG_U upper bound of the search interval of DG; DG_L lower bound of the interval; Δ interval at each iteration step; S_1 and S_2 points within the interval where $S_1 < S_2$

The different performance measurement indices are defined and listed in Table 1 to assess the impact of DG on losses and voltage profile.

Table 1. Indices for the performance measurement of test system

Active Power Loss Indices	$APLI = \frac{P_{Loss} - P^{DG}_{Loss}}{P_{Loss}} \times 100\%$
Reactive Power Loss Indices	$QPLI = \frac{Q_{Loss} - Q^{DG}_{Loss}}{Q_{Loss}} \times 100\%$
Aggregate Voltage Deviation Index	$AVDI = \sum_{i=1}^{n} \left(V_i^{DG} - V_i^{basecase}\right)^2$

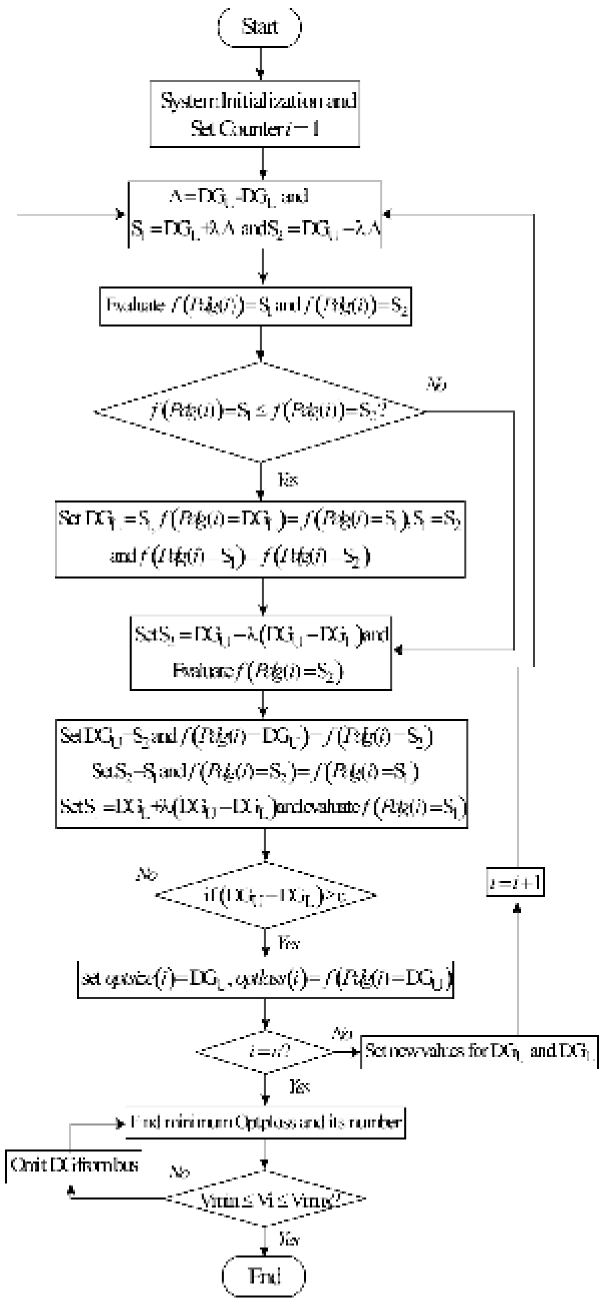

Fig. 1 Algorithm of Golden Section Search for determination of optimal DG location

RESULTS AND DISCUSSION

The test system of 33-nodes RDN is used for the analysis. The schematic of the test system and required data are given in (Mehta, 2015). The system has 3,715 kW active power and 2,300 kvar reactive power.

Determination of Optimal Location of DGs

The optimal location and size of DG has been determined by the method outlined in Fig. 1. In Fig. 2 (a), the optimal size of DG on each individual bus is presented whereas Fig. 2 (b) gives active power losses in a system after its placement on that bus. It can be noticed from Fig. 2 (b) that DG placed at node 6 results in minimum losses whereas DG placed at nodes 26-30 are the other buses which give comparatively higher losses. But sizing requirement of DG at node 6 is greater as compared to DG at node 29. Hence, grater reduction in DG sizing has been given more priority and it is decided to place DG at node 29 for the subsequent analysis.

Voltage Profile Improvement with Different Modes of Reactive Power Generation by DGs

Fig. 3 shows the voltage profile comparison for base case and with the placement of DG at node 29. In this comparison, DG penetration level of 30% has been considered. It means that DG generates power equal to 30% of total load demand of the system. Fig. 3 also represents the voltage profile obtained after considering the DG with different reactive power capability mode. With 30% penetration, DG is assumed to generate 1,200 kW power. The corresponding generations of reactive power by DG in different modes are listed in Table 2.

In Fig. 3, it can be clearly noticed that the test system without any DG source results in the highest voltage deviation. All node voltages get improved with the placement of DG at node 29 irrespective of the mode of its reactive power generation. Fig. 3 gives deep insight related to impact assessment of reactive power capability. It can be observed that with DG operating with 0.9 leading and 0.9 lagging are on two extreme boundaries. With 0.9 lagging PF, DG is supposed to deliver 0.5811 Mvar to the system which can supplement the reactive power demand of the RDN, thus have maximum impact on voltage profile improvement. On the other hand, DG with 0.9 leading PF is supposed to absorb 0.5811 Mvar from the RDN which ultimately distress the system, hence the voltage profile has become worsen even in comparison to DG with Unity PF operation. But this profile is better when it is compared to base case. Active power support in unity PF mode from DG results in lower power drawl from sub-station as compared to base case. Thus it results in lesser current and lesser reactive power losses and it results in voltage profile improvement.

Table 2 DG Penetration level and corresponding active and reactive power generation

	Level	PF Control	P_{DG} (MW)	Q_{DG} (MVAR)
Base Case	Zero	--	0	0
DG at Node 29	30 %	Unity	1.2	0
	60 %		2.4	0
	90 %		3.6	0
	30 %	0.95 Lag	1.2	0.3944
	60 %		2.4	0.5811
	90 %		3.6	1.18
	30 %	0.90 Lag	1.2	0.5811
	60 %		2.4	1.1623
	90 %		3.6	1.7435
	30 %	0.95 Lead	1.2	- 0.3944
	60 %		2.4	- 0.5811
	90 %		3.6	- 1.18
	30 %	0.90 Lead	1.2	- 0.5811
	60 %		2.4	- 1.1623
	90 %		3.6	- 1.74356

Impact of Penetration Level of DGs

The Penetration levels of DGs in RDN have significant impacts on its performance. The optimal level of penetration can definitely improve the voltage profile of all nodes in RDN and can also reduce active and reactive power losses. But it has been observed that penetration level of DG beyond certain level may deteriorate the performance of DG. Fig. 4 clearly depicts the impact of varying DG penetration level by considering base case, 30%, 60% and 90% comparison. It can be observed that as the DG penetration level increases, bus voltage values are continuously increases. DG penetration level up to 60 % gives promising improvement and tries to maintain the bus voltages within the strict band across their nominal values. The careful observation of Fig. 4 (a)-(e) reveal that DG reactive power generation capability play a vital role to maintain the bus voltages with varying DG penetration level.

The DG operating with 0.9 lagging PF affects severely with DG penetration level and many of the bus voltages magnitudes have crossed their maximum values. The bus voltages higher than their maximum

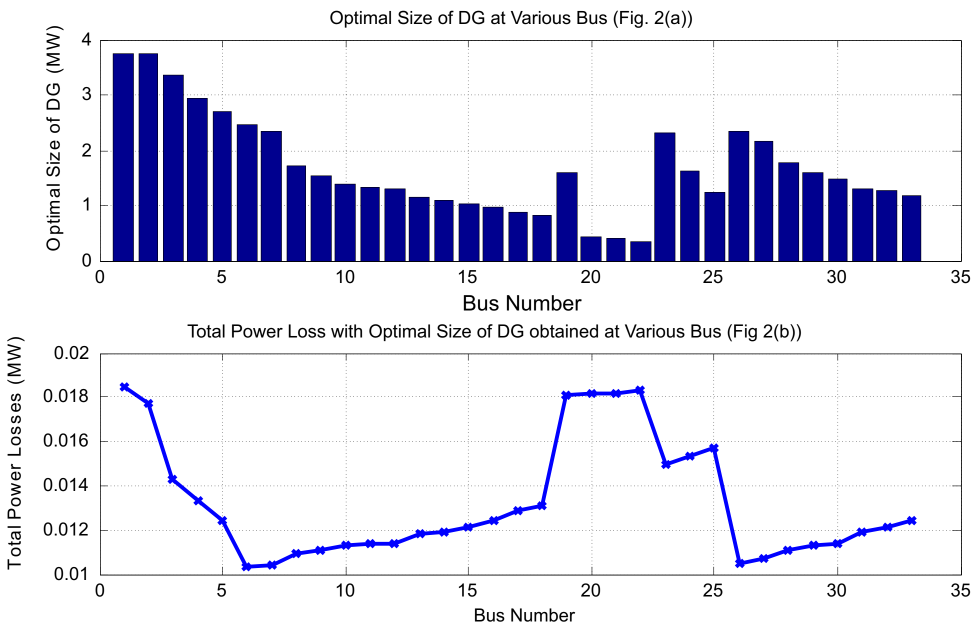

Fig.2. Optimal Size of DG at each bus and its corresponding active power losses

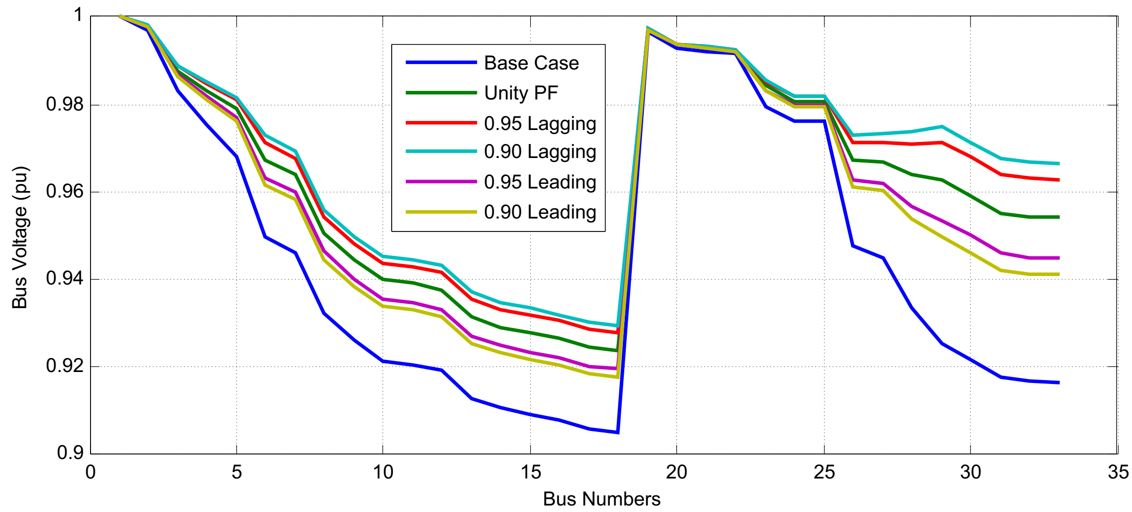

Fig. 3 Bus Voltage profile of 33-nodes RDN without and with DG in different reactive power generation mode

allowable values may damage the equipment connected at distribution level, hence larger DG penetration with lagging PF cannot be allowed in RDN. On the other hand, bus voltage values remain in a strict band of voltage regulation limit of ± 0.05 pu even with 90% DG penetration level. This is the most important and useful observable while planning for DG penetration in RDN. The system operator may go for the higher and higher power generation from DG sources if they have DGs capable of reactive power control. DGs with Type 1, Type 2 and Type 3 discussed in earlier section are the most suitable DG resources to explore the maximum benefits as the system operator can operate them as per the requirement.

Active and Reactive Power Losses with DG Placement and AVDI

Fig. 5 shows the variation in active and reactive power losses with the placement of DG at bus 29. In this case study, only 30 % DG penetration has been presented but similar results are observed with higher penetration level. From Fig. 5 (a), it can be noticed that placement of DG reduces the active power losses for all the cases, but the operation of DG in lagging PF mode is the most effective in active power loss reduction. On the other hand, DG in unity PF mode is the best options for minimizing reactive power loss as it does not allow further exchange of reactive power across the feeder

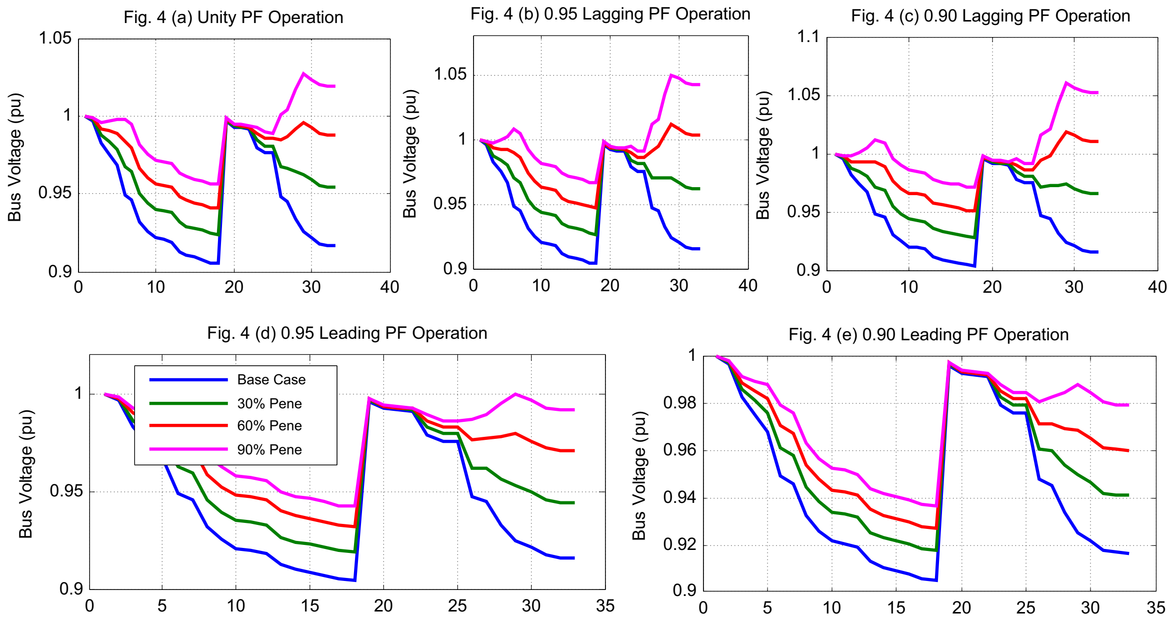

Fig. 4 Comparative voltage profile with different penetration level and PF operation mode

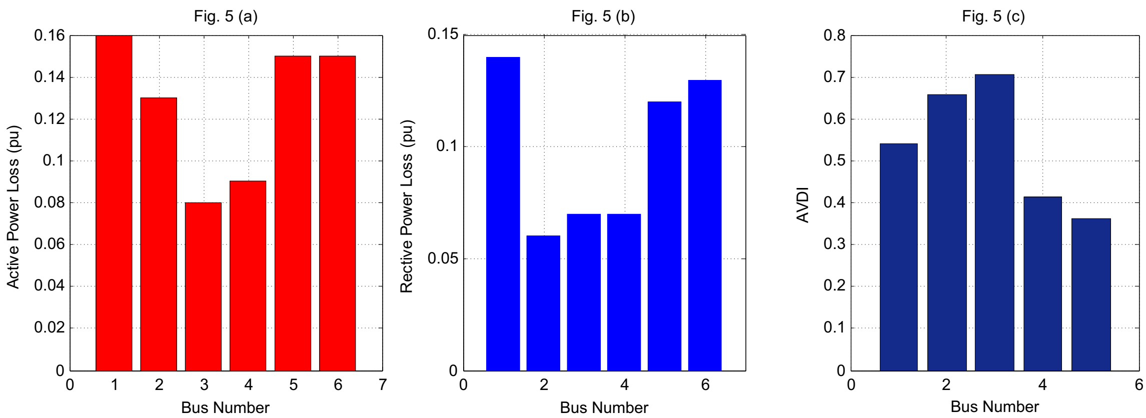

Fig. 5 Performance Indices for 33-Nodes RDN with different PF operation mode at 30% penetration level

sections. DG with leading PF results in highest reactive power loss as it force the DG to absorb the reactive power, thus creates highest losses as shown in Fig. 5 (b). But doing so it can greatly restricts the bus voltages to go beyond its nominal value of 1 pu which can be observed from Fig. 4 (d)-(e). Fig. 5 (c) represents the AVDI which is the highest for DG in 0.9 lagging PF operation as expected.

CONCLUSIONS

The proper selection of DG and its sizing results in better voltage profile across all the buses, reduction in active and reactive power losses and enhanced stability. The proper utilization of DG reactive power generation capacity allows more penetration of DG. The higher penetration of DG creates the voltage rise issue and thus limits its further penetration. The operation of DG in leading PF mode helps to absorb excess reactive power from the network, thus restores all the bus voltage magnitude within the limits. On the other hand, the losses in the system slightly increase in leading PF mode which can be taken care by proposing the multi objective optimization method in order to achieve multiple benefits of DG in RDN.

REFERENCES

1. Ackermann, T., Andersson, G., and Soder, L., (2001),' Distributed generation: a definition1', *Electric Power Systems Research*, vol. 57, issue 3, , April, pp. 195-204.
2. Mehta, P., Bhatt, P., and Pandya, V., (2016), 'Challenges and Solutions for Improvement in Radial Distribution Network: A Review', *International Conference on Women in Science and Technology: Creating Sustainable Career ICWSTCSC- 2016, Indian Journal of Technical Education* with ISSN 0971 – 3034, 28-30th January, pp. 170.
3. Georgilakis, P. S. and Hatziargyriou, N. D., (2013), 'Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research,' in *IEEE Transactions on Power Systems*, vol. 28, no. 3, August, pp. 3420-3428.
4. Mehta, P., Bhatt, P., and Pandya, V., (2015), 'Optimal Selection of Distributed Generating Units and its

Placement for Voltage Stability Enhancement and Energy Loss Minimization', *International Journal of Ain Shams Engineering*, *Elsevier online publication*, December.

5. Walling, R. A., Saint, R., Dugan, R. C., Burke, J. and Kojovic, L. A., (2008), 'Summary of Distributed Resources Impact on Power Delivery Systems,' in *IEEE Transactions on Power Delivery*, vol. 23, no. 3, July, pp. 1636-1644.
6. Al Abri, R. S., El-Saadany, E. F. and Atwa, Y. M., (2013), 'Optimal Placement and Sizing Method to Improve the Voltage Stability Margin in a Distribution System Using Distributed Generation', in *IEEE Transactions on Power Systems*, vol. 28, no. 1, February, pp. 326-334.
7. Keane, A., Ochoa, L. F., Vittal, E., Dent, C. J. and Harrison, G. P., (2011), 'Enhanced Utilization of Voltage Control Resources With Distributed Generation," in *IEEE Transactions on Power Systems*, vol. 26, no. 1, February, pp. 252-260.
8. Ochoa, L. F., Keane, A., and Harrison, G. P., (2011), 'Minimizing the Reactive Support for Distributed Generation: Enhanced Passive Operation and Smart Distribution Networks', in *IEEE Transactions on Power Systems*, vol. 26, no. 4, November, pp. 2134-2142.
9. Ghosh, Sudipta., Ghoshal, S.P. and Ghosh, Saradindu., (2010), 'Optimal sizing and placement of distributed generation in a network system', *International Journal of Electrical Power & Energy Systems*, ISSN 0142-0615, vol. 32, Issue 8, October, pp. 849-856.
10. Mistry, Khyati., Roy, Ranjit. (2014), 'Enhancement of loading capacity of distribution system through distributed generator placement considering techno-economic benefits with load growth', *International Journal of Electrical Power & Energy Systems*, vol. 54, January, pp. 505-515.
11. Kansal, Satish., Kumar, Vishal. and Tyagi, Barjeev., (2013), 'Optimal placement of different type of DG sources in distribution networks', *International Journal of Electrical Power & Energy Systems,* vol. 53, December, pp. 752-760.
12. El-Fergany, Attia. (2015), "Optimal allocation of multi-type distributed generators using backtracking search optimization algorithm", *International Journal of Electrical Power & Energy* Systems, vol. 64, January, pp. 1197-1205.
13. Gozel, T., Eminoglu, U., Hocaoglu, M., (2008), 'A tool for voltage stability and optimization (VS&OP) in radial distribution systems using MATLAB graphical user interface (GUI)', *Simulation Modelling Practice and Theory*, vol. 16, issue 5, May, pp. 505-518.