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Voltage Profile Improvement in Radial Distribution Networks with Analytical Method of Simultaneous Optimal DG Sizing

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***Abstract*—This paper investigates the usefulness of analytical expressions for finding optimal sizes of Distributed Generators (DGs). Results in this study revealed some interesting and useful features of analytical expression in regard to voltage profile improvement. Method was applied on IEEE 37 node radial test system and simulations were performed in DigSILENT PowerFactory coupled with Python. The validation of results was performed by comparing the voltage profiles of proposed method with two study cases; one without any DG while other with DGs of sizes equal to the cumulative load. DGs of different types, based on their output power, have been tested and results are presented. Moreover, results proved that the proposed method is better as compared to the methods in other study cases for static and time varying loads.**

Keywords*—*voltage profile, distributed generation, analytical expressions, simultaneous optimal sizing, static load, radial distribution system

I. INTRODUCTION

The use of Distributed Generation (DG) is increasing day by day due to many factors including their environmentally friendly nature, increased power demand and many others. DGs placement can be optimized and controlled to get very important benefits other than only green energy. Power loss minimization, voltage profile improvement, congestion management and deferring the grid reinforcement are some of them.

Research has proved that the technical benefits from DGs cannot be easily achieved when they are placed just to generate energy. In fact, there is a need of proper study and detailed procedure to locate DGs of optimal sizes at optimal locations in the network. Moreover, DGs can play an important role in providing ancillary services like, spinning reserve, reactive power support, frequency control and other fast response services [1]. It is a proven fact that non-optimal positioning and sizing of DGs may affect the systems to the worst, resulting in increased losses [2], power quality issues, reverse power flows, overheating of feeders [1], and earlier and costly grid reinforcement[3], [4].

Due to such important impacts, the optimal DG placement has been focussed a lot in recent years. In literature, various algorithms are used to solve the problem of optimal placement for acquiring one or more of the intended benefits. Authors in [5] and [6] tried to improve the voltage profile and reduce the THD with optimal DG placement by using Particle Swarm Optimization (PSO). Similarly [7] used evolution technique to place DGs optimally for achieving benefits like loss minimization and Voltage Profile Improvement (VPI). The problem of congestion management and ultimately improving the voltage profile has been addressed in [8], where authors used PSO and tested their method on meshed network i.e., IEEE 14 bus system. Evolutionary Programming (EP) is used in [9] to optimize the placement of renewable based DGs. Chance Constrained Programming [10] method is used for optimal DG placement with the uncertainties and stochastic nature of renewable based DGs.

The policy makers and investors have made it very clear that the share of small scale generation, in particular renewable based, will be increased drastically in coming years. This has made the research community to stand in front of a big challenge of developing methods for penetration of not only one but multiple DGs. Moreover, the developed methods should also have ability to find optimal placement for more than one objective. On these lines, the problem becomes a multiobjective optimization problem for placement of multiple DGs. Heuristic techniques are preferred in some researches while other preferred exact/anlaytical methods. An important point about the methods presented in the literature is their lack of openness for more objectives than those they are designed for. Therefore, there is a need to split the problem of optimal placement in sub-parts where the size and location optimization become independent of each other. Moreover, the methods should be open for incorporation of as many desired variable as one wants to make the method usable in real world scenario.

Analytical expression for optimal sizing provide one such possibility of diversity in options because such method provide option of choosing the location as per specific criteria of network. Examples of such methods include [11] and [2]. These methods, along with the one presented in [12], derived expression for optimal sizes of DGs for specific bus in the system which can ensure the least active power losses. These

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methods could not provide some detailed procedure for finding optimal location, instead these could find optimal size of any input bus number. In [12], authors used iterative method to find the optimal locations, which are only suitable for loss minimization and not for any other objective such as VPI. Another important point about these methods, being iterative, is that these do not consider the impact of oncoming DGs when finding the size of current DG.

The problem of optimal sizing and sitting is usually considered as a theoretical research problem. This is because of the unbundled regulations which do not allow the network operators to dictate the investors about sizing and sitting. As can be seen from the presented results that the optimal placement can help in improving the power quality, this, in turn, helps to defer the investment for addressing such problems by the network operators. Therefore, it is a highly needful that the network operators work toward planning and steering the direction of the DGs penetration, thereby saving the cost on grid reinforcement, managing the congestion and improving the power quality. To get some control, network operators can consider offering benefits for investors to make them comply with the suggestions resulted from such planning phase recommendations.

This work is continuation of the work presented in [13] in which the analytical expressions for finding the optimal sizes of multiple DGs simultaneously were developed. This helped to reduce the computation cost along with improving the sizes further, because this method inherently include the impact of interdependencies. This, in turn, reduced the error in calculating the sizes of multiple DGs. In the presented work, the usefulness of same method has been further explored by discussing the improvement in voltage profile caused by placing optimally sized DGs. Another important contribution is that the method, which proved better for meshed networks already, has performed well in radial networks too. For comparison purpose, the voltage profile without any DGs and voltage profile with DGs of size equal to the cumulative load in the area is considered, as proposed by authors in [14]. The results with different types of DGs i.e., with unity power factor, with 0.95 lagging power factor, with 0.95 leading power factor and DG with only reactive power output have also been presented.

The rest of the paper is structured as follows. Section II explains necessary analytical expression for calculating optimal DG sizes and description of the methodological steps taken in this simulation. Section III contains brief description of simulation setup and IEEE 37 node system used for this work. Results and discussion along with the experimentation use cases are given in Section IV, followed by conclusion in Section V.

II. Optimal DG Sizes

There have been different methods to optimize the sizing and sitting of DGs, some of them are referenced in the previous section. To incorporate the possibility of multiple DGs, a method has been presented in [13]. This is a useful method in regards to the current trend in energy sector where DGs are the primary interest for all the stack holders in energy sector. Simultaneous placement can also provide the Distribution Network Operators (DNOs) with a possibility of controlling the direction of DG placement. Although this approach seems to be opposing the current trend of unbundling regulations (particularly in Europe), yet it is getting increased focus in research. This is because, it provides options to delay the cost on grid reinforcement, improved power quality and many other technical and economic benefits.

A. Methodological Steps

This subsection provides the list of steps taken in this work for obtaining the final results. These steps can be applied as these are for the static load condition whereas, for time varying load condition, these steps need to be repeated at every time step.

1. Enter the base case network and find the bus voltages.
2. Enter the desired number of DGs to be placed.
3. Enter the bus numbers where DGs need to be placed.
4. Calculate the DG sizes simultaneously, using the analytical expressions given in section II-B
5. Place the DG with calculated size in network, and again find the bus voltages.
6. Compare the results with those taken in step 1.

A noteworthy point in these steps is that the presented method takes the locations as an input from user. This means that distributing the network in regions and further description of regions is not compulsory. In use case 3 presented in section IV-C, the DG sizes were not calculated using step 4. Instead, the DGs output were kept fixed based on the method given there in section IV-C.

B. Analytical Expression

The final outcome of the method for simultaneous optimal DG sizing for four DGs is given in simplified form as:

$$X = A^{-1}B \tag{1}$$

Where,

$$A = (1+a^2)\begin{bmatrix} \alpha_{x_1x_1} & \alpha_{x_1x_2} & \alpha_{x_1x_3} & \alpha_{x_1x_4} \\ \alpha_{x_2x_1} & \alpha_{x_2x_2} & \alpha_{x_2x_3} & \alpha_{x_2x_4} \\ \alpha_{x_3x_1} & \alpha_{x_3x_2} & \alpha_{x_3x_3} & \alpha_{x_3x_4} \\ \alpha_{x_4x_1} & \alpha_{x_4x_2} & \alpha_{x_4x_3} & \alpha_{x_4x_4} \end{bmatrix}$$

$$X = \begin{bmatrix} P_{DG_1} \\ P_{DG_2} \\ P_{DG_3} \\ P_{DG_4} \end{bmatrix} \quad B = \begin{bmatrix} B_{x_1} \\ B_{x_2} \\ B_{x_3} \\ B_{x_4} \end{bmatrix}$$

And,

$$\begin{aligned} B_{x_n} = & \sum_{m=1}^{NDG} [P_{D_{x_n}}(\alpha_{x_nx_m} + \beta_{x_nx_m}a) \\ & + Q_{D_{x_n}}(\alpha_{x_nx_m}a + \beta_{x_nx_m})] \\ & - \sum_{j=1, j\neq x_n}^{Nbus} [(\alpha_{x_nj}P_j - \beta_{x_nj}Q_j) \\ & + a \sum_{j=1, j\neq x_n}^{Nbus} [(\alpha_{x_nj}Q_j + \beta_{x_nj}P_j)] \end{aligned}$$

$$\alpha_{ij} = \frac{R_{ij}}{|V_i||V_j|}cos(\delta_i - \delta_j)$$
$$\beta_{ij} = \frac{R_{ij}}{|V_i||V_j|}sin(\delta_i - \delta_j)$$

P_i, P_j, Q_i and Q_j are the active and reactive power injection at i_th and j_th buses respectively; $P_{D_{x_n}}$ and $Q_{D_{x_n}}$ are the active and reactive power demands at x_nth bus while x_n is the set of bus where DG needs to be placed; $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are complex voltages at respective buses; R_{ij} is the ij_{th} element of bus impedance matrix; NDG is the total number of DGs to be placed; $Nbus$ is total number of buses in the system.

The optimal active power output of DGs can be found by solving Eq. 1. Then the optimal reactive power will be given as:

$$Q_{DGi} = aP_{DGi} \tag{2}$$

Where,

$$a = (sign)tan[cos^{-1}(pf_{DG})]$$

sign = +1 for DG injecting reactive power and -1 for DG consuming reactive power.

III. Tools and Test Bench

The necessary details of the simulation platform and test network are explained in this section. The tool selection is a crucial part that need to be thoroughly analysed and evaluated based on various factors as asserted in [15].

A. Software Tools

The simulation platform consisted of two separate tools namely Python and DigSILENT PowerFactory. PowerFactory was used as a simulator of Power System. It is dedicated tool capable of modelling, simulating and analysing the complex power system with options of various load types, generators and other important power system parameters. It has the possibility of various network models, data management, results and reporting, and scripting languages. Along with the usual functionalities any power system simulator should have, it provides the user with the option of importing and exporting model in various formats. Further details can be found in [16]

This approach of coupling different tools expands the opportunities to provide extended options. There have been different methods explained in the literature to couple DigSILENT PowerFactory with various other independent software tools like MATLAB as given in [17]. Some more possibilities are discussed in [18]. In this work, Python based PowerFactory API was used to simulate the proposed test case. PowerFactory API provides full control over the network developed in PowerFactory from Python script to run various simulations. Programming the optimal sizes in Python is computationally less demanding and easy.

B. Test Network

IEEE 37 node radial network is used for the purpose of validation of results. The network data given in [19] has been used with some minor modifications including addition of DGs at various buses for experimentation purpose.

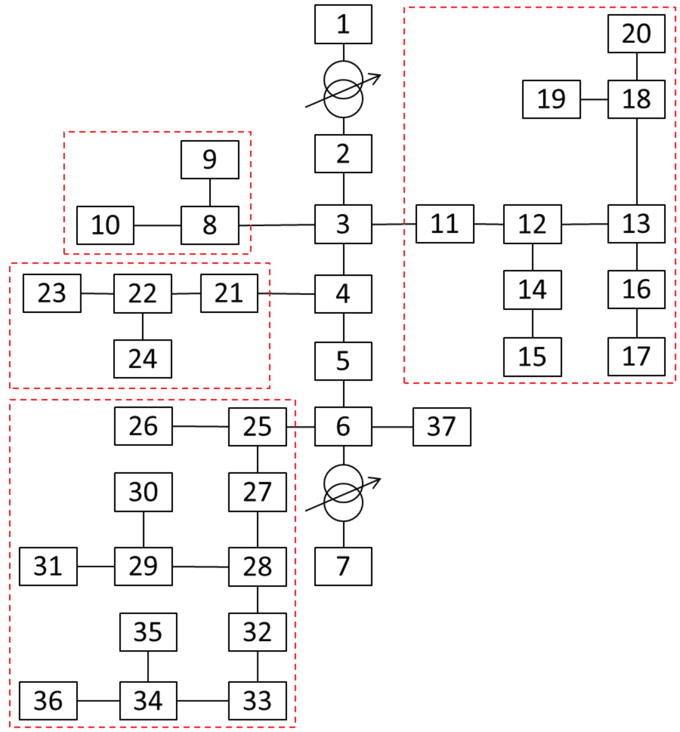

Fig. 1. Regions in IEEE 37 Node Radial System

For checking the proposed method with different options and highlighting the versatility of it, the system has been distributed in 4 different regions. Results for this test case are also presented here, in comparison to the case when whole system is taken as a single region. Distributing in more than one regions is not a compulsory but desired for bigger networks, because it can avoid the chance of congesting the DGs in single small portion of the network. The regions considered here are merely based on the feeder and its orientation from main branch originating from HV/MV transformer. Hence, only four regions are decided, details of which are given in Fig. 1.

The nodes on the main feeder originating from slack bus are not taken into account for placement of DGs. This is because of the fact that these buses already contain high line flows and hence chance of them to become overloaded increase by placing DG over them. Instead of this, by placing DGs on the buses other than this main feeder (buses 1 to 7), provide an additional benefit of reducing the line flows. Node 37 was considered in bottom left region shown in Fig. 1. Moreover, the optimal locations are desired as an input to the method. Therefore, when carrying out the simulations, buses were chosen randomly to place DGs and optimal sizes were found based on the method and equations mentioned in previous section. This approach has a potential benefit that the method can be applied in general to any network with any size and specifications. Ultimately, this increases the chances of method to be applied in real world scenario because it is not always possible to place DGs at locations found due to many reasons such as environmental, geographical, network constraints and others.

IV. Results and Discussion

To prove the ability of optimal sizing with the method explained in Section II for voltage profile improvement, three different use cases are considered.

A. Use Case 1

In first use case, whole network except the main feeder and nodes (buses 1 to 7) is considered as single region and optimal DG sizes are calculated at given locations. The given locations were bus numbers 12, 18, 22 and 32. The results are compared with base case which is the one without any DGs. To further explore the consistency in providing better results, the same method was tested with static and time varying load profiles. Moreover, DGs of different output types are considered. These types include:

- Power factor of unity (No reactive power output)
- Power factor of 0.95 Leading
- Power factor of 0.95 Lagging
- DGs with only reactive power output

B. Use Case 2

It is sometimes needed to distribute the network in regions. The sizes and locations of these regions are fully dependent on the specific requirements. A method of sizing and sitting should be able to produce best possible results for any specific requirements. For this purpose, the regions were defined in the system and one bus in each region was chosen for optimal sizing. In this case, given locations were bus numbers 8, 12, 22 and 32. All the tests are performed for the use case 1 were also done for this use case. Different types of DGs as mentioned above were also considered.

C. Use Case 3

For the purpose of comparison, another scenario is also studied where DG locations kept same as those in use case 2 but the DG sizes were not calculated. Instead, the DGs were set to the sizes equal to the active and reactive power demand in their respective region. The procedure is the same as adopted in [14] for the purpose of comparison and validation of their proposed method.

D. Test Results

1) Static Load: The optimal sizes found by the method are given in the Table I. When DGs with these sizes were placed at the given locations, the load profile improved significantly. Although any type of DG has produced better results in comparison with the base case (no DGs), the best improvement was observed when DGs with power factor of 0.95 (leading) or unity were placed. DGs with lagging power factor also affected the voltage profile positively and resulting voltage profile was within less than 3% of desired 1 p.u value. As the optimal reactive power output from DG is function of the calculated optimal active power output, the DGs with no active power output could not help the voltage profile to improve significantly. The results for the most and the minimum voltage with specific type of DGs connected in the system are summarized in the Table II. Almost similar trend was followed in case when the DG locations were chosen region-wise i.e., case 2. DG sizes in use case 3 are also given in Table I, whereas maximum and minimum values of voltages are given in Table II. It can be concluded from results presented in this table that the voltage profile improvement is nearly same in use case 2 and 3.

TABLE I. Optimal DG Sizes with Static Load

Use Case 1			Use Case 2			Use Case 3	
DG Loc	PDG (kW)	QDG (kVar)	DG Loc	PDG (kW)	QDG (kVar)	PDG (kW)	QDG (kVar)
12	1.731	0.554	8	0.910	0.291	0.17	0.08
18	0.768	0.246	18	1.271	0.407	1.808	0.34
22	0.858	0.275	22	0.865	0.277	0.93	0.185
32	1.222	0.391	32	1.222	0.391	1.269	0.347

TABLE II. Voltage Limits with Static Load

	No DG	DG pf = 1	DG pf = 0.95	DG pf = 0.95 Lag	PDG = 0 QDG = Value
Overall System as Single Region - Use Case 1					
Max Vol. (p.u)	1.0000	1.0045	1.0227	1.0000	1.0000
Min Vol. (p.u)	0.8780	0.9774	0.9981	0.9528	0.9036
Region-wise Locations - Use Case 2					
Max Vol. (p.u)	1.0000	1.0038	1.0209	1.0000	1.0000
Min Vol. (p.u)	0.8780	0.9767	0.9962	0.9530	0.9027
Region-wise Locations - Use Case 3					
Max Vol. (p.u)	1.0000	1.0199	1.0326	1.0067	1.0000
Min Vol. (p.u)	0.8780	0.9793	0.9929	0.9649	0.8954

The detailed overview of the voltage profile at all the given scenarios is shown in Fig. 2, 3 and 4. An important result from these graphs is that the region-wise placement has less deviation from 1 p.u value for most of the buses, especially when DG power factor is 0.95 leading. This also highlights the need of considering multiple geographically apart regions.

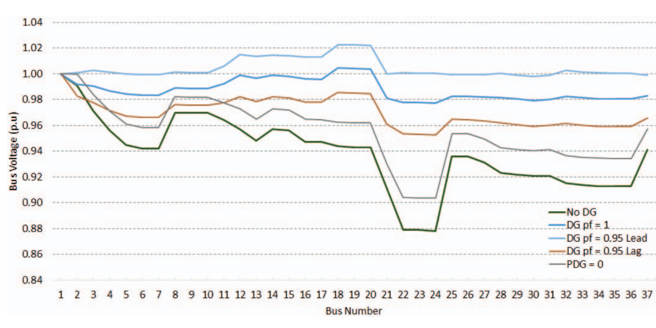

Fig. 2. Voltage Profile with Static Load - Use Case 1

2) Time Varying Load: Using same method as previous, the optimal DG sizes were found. There had been two different approaches for comparison and validation of the method; one with fixed DG sizes as were found for static loads and other when DG sizes were calculated for every time step of load variation. Half hour step over the period of a day are considered in this work. It is worth mentioning that the static load condition is a single value chosen near 80% of peak load

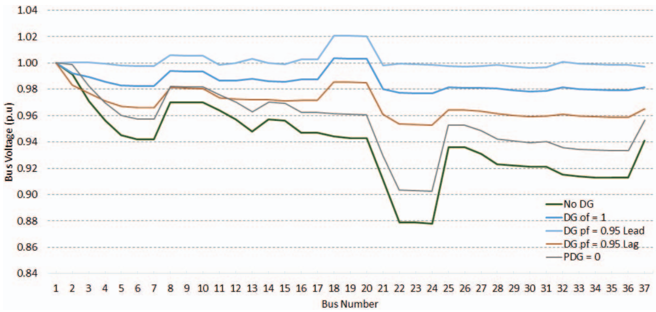

Fig. 3. Voltage Profile with Static Load - Use Case 2

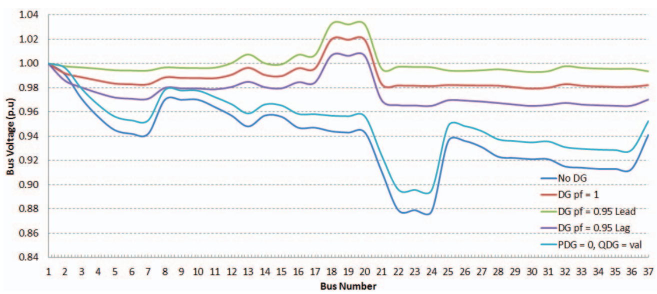

Fig. 4. Voltage Profile with Static Load - Use Case 3

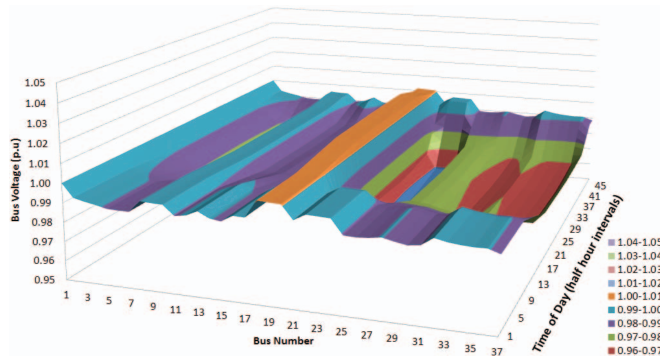

Fig. 5. Voltage Profile with Time Varying Load at pf = 1 - Use Case 2

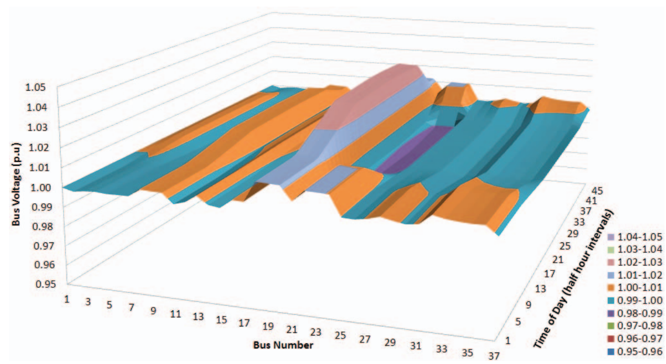

Fig. 6. Voltage Profile with Time Varying Load at pf = 0.95 - Use Case 2

in time varying load. Therefore, the optimal sizes were similar to those of static case in case of this first approach. For the second approach, the DGs sizes were varying.

The maximum and minimum values of the voltage on any bus in the system over the complete profile are summarized in the Table III. It can be seen from this table that region-wise placement has produced better results when optimal sizes were calculated simultaneously using the analytical expressions. For other cases, the improvement is seen w.r.t the case of no DGs but it is still out of boundary of $\pm$ 5%. Moreover, some researches suggest the minimum limit in distribution networks to be 0.90 p.u. as given in [20]. It is also important to mention that the reason for being not so useful in case 1 is that it has few instances when the load is higher than that of nominal load value for which the optimal sizes were calculated.

Further overview about the voltage profile is shown in Fig. 5 and 6. Only graphs for the cases with best improvement i.e., with power factor of 0.95 and unity in case 2 are given here. Time of day is taken from 00:00 as tic 1 until 23:30 as tic 48.

TABLE III. VOLTAGE LIMITS WITH TIME VARYING LOAD

	No DG	DG pf = 1	DG pf = 0.95	DG pf = 0.95 Lag	PDG = 0 QDG = Value
Overall System as Single Region - Use Case 1					
Max. Vol. (p.u)	1.0000	1.0003	1.0217	1.0000	1.0000
Min. Vol. (p.u)	0.7910	0.9021	0.9179	0.8851	0.8245
Region-wise Locations - Use Case 2					
Max. Vol. (p.u)	1.0000	1.0061	1.0298	1.0000	1.0000
Min. Vol. (p.u)	0.7910	0.9542	0.9862	0.9185	0.8305
Region-wise Locations - Use Case 3					
Max. Vol. (p.u)	1.0000	1.0199	1.0326	1.0067	1.0000
Min. Vol. (p.u)	0.7910	0.9160	0.9328	0.8981	0.8107

V. Conclusion

This paper focuses mostly on improving the voltage profile in radial distribution network by placing optimally sized DGs at given locations. IEEE 37 node radial feeder, with minor modifications was used as a test system. The electrical network was implemented in PowerFactory whereas the optimal sizes and other controlling was done through interface with Python. It is observed that if the locations were chosen on separate feeders (region-wise) the voltage profile improvement was better than that of placing more DGs on single feeder. Furthermore, power factor of the DG also influenced the amount of improvement in voltage profile. Another important observation was that the proposed analytical expression found better sizes for DGs in case of static load which was about 80% of peak load in time varying load case.

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