Voltage Quality Index Based Method to Quantify the Advantages of Optimal DG Placement

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***Abstract*—This paper presents the advantages of the optimal DG placement during the operation stage of the radial distribution system. The method taken for optimal DG placement (ODGP) is considered from our previous work, which gives optimal locations based on Load Concentration Factor (LCF). Various cases of random DG placement (RDGP) are considered which are divided into two main categories. In first, the locations are varied and in second DG sizes are rotated on same locations found by LCF method. In all these cases, the total active power delivered by the DGs is kept same as for the case of ODGP. The load growth in network is considered to correspond to the future operational stage. A novel Voltage Quality Index (VQI) is proposed in this work which provides a straightforward method for quantifying the system's voltage quality status. Furthermore, two different scenarios, with and without a centralized voltage control algorithm, are considered for the comparison purpose. The advantages of ODGP in all these cases are highlighted by comparing the active power loss reduction, and voltage profile and quality improvement. The results showed that, in case of voltage problem, algorithm could improve voltage to a better limit, while keeping the losses reduced, in case of ODGP than RDGP cases.**

***Index Terms*—distributed generation, analytical expressions, simultaneous optimal sizing, load growth, voltage quality index, voltage profile, active power loss**

I. Introduction

Increasing interest in renewable energy sources have changed the entire energy system in today's world. This has converted the conventional centralized generation and bulk power transmission to the smaller generating units i.e., Distributed Generations (DGs) which are directly connected near the loads to the distribution system [1].

Penetration of ever increasing number of DGs has made the power system operators to face new challenges such as reliability issues, increased line flows and congestion, power quality problems, increased power loss and other similar issues in power system. Similarly, increased harmonics are voltage variation beyond permissible band are also crucial. Keeping in view the scenario where the DGs are being added in the system on regular basis, tremendous amount of focus is given to the problem of optimal DG placement (ODGP). This is due to the fact that ODGP aims to increase the environmental, economical and technical benefits to the maximum, not only for the customers but also for the energy suppliers [2]. ODGP is beneficial for all the partners in the power systems including consumers and utilities.

The huge number of studies that highlight the usefulness of ODGP provide a convincing reason to adopt it in real world scenarios. For example, the ODGP improves reliability of power system, decreases the investment and operational costs and mitigates harmful environmental effects [3]. Despite this fact, the solution to ODGP problem is usually considered as theoretical, especially in systems with unbundled regulations. In order to further highlight the benefits of ODGP, a study to quantify its advantages in operational phase is highly needed. In this regards, this work presents convincing results by considering the case of growing load over the period of time and studying the active power loss and voltage quality of the network with ODGP and Randomly Placed DGs (RDGP). Moreover, based on a simple Voltage Control Algorithm (VCA), is is shown that the network with ODGP is easier to control in case of voltage problems.

For the purpose of ODGP, there have been several studies with various methods including meta-heuristic, analytical and classical approaches. All these methods have respective pros and cons. For example, meta -heuristic methods, which are most common choices for solving ODGP problem, can converge to a local optima [4]. Similarly, analytical technique are good in finding exact solution, these are usually hard coded and hence, generalizing their solution to any network is usually difficult [5]. MOreover, analytical methods are usually iterative for finding the optimal location, such as given in [6] and [7], hence these may consume more time in finding the solution. The simulation time becomes even more if placement of multiple DGs is needed because, in such case, the same procedure needs to be repeated for several times, depending upon the number of DGs to be placed. Example of such methods include [8].

To minimize this impact, a new analytical method was proposed in [9], yet the method for selecting optimal locations for DG placement was not given. Moreover, the usefulness of the method was highlighted for meshed networks. The results for radial networks to show loss minimization are presented in [10]. In recent researches such as in [11], it is showed that splitting the whole optimization problem into separate parts can reduce the simulation time and produce better results. Due to such reasons, the method for ODGP has been extended in [12], where the Load Concentration Factor (LCF) method is presented for optimal location selection. The results presented show an improvement in the voltage profile of the system along with reducing the loss considerably. The method for selection of a operational power factor capable of further reducing the losses and improving the voltage profile is also given.

The authors in [13] proposed a voltage stability index for identifying the most sensitive buses in a radial system. The focus of their index derivation is voltage collapse, and is based on the active and reactive power transferred over the distribution line. In an attempt to quantify the benefits of DGs, authors in [14] proposed voltage profile improvement index. This index is a ratio of voltage profile of the system with and without DGs for same load conditions. As the ratio cannot provide enough information about the exact magnitude of the numbers (for which ratio is being taken), the usefulness of this index is limited. Another voltage stability index is proposed in [15] which identifies the buses near the voltage collapse. This index is based on the line voltage of two directly connected buses via a line with certain values of R and X. This helps in providing the information about specific region in the system. To get the overall impact about the system voltage condition, the value of index for all the buses is needed. Such an approach becomes complicated when the scenario of load growth with various load iterations is considered due to huge amount of data to be scanned for getting exact information.

This paper attempts to extend the usability of method developed earlier by considering the load growth. In case of any voltage problem due to load growth, a centralized Voltage Control Algorithm (VCA) takes corrective action by changing the reactive power demand from the DGs as suggested in [16] as one of the methods for increasing DG penetration whereby keeping the voltage within required limits. Both these phenomenon (load growth and VCA) are implemented to represent the future scenario and effectiveness of the ODGP in operational stage of the system. As a usual practice, the ODGP is done for some reference load conditions, but in case of load growth, same results may not be exactly applicable. Moreover, different control actions are needed in operation of the system due to number of reasons. It is proved with the experiments that the LCF based analytical method produced better results in loss minimization along with the better voltage quality.

Rest of the paper is organized as: Section II details the base case i.e., ODGP for the comparison purpose along with the different RDGP cases considered. The centralized VCA and VQI are explained in Section III, which also contains very brief overview of the simulation setup. The results and discussion is given in Section IV, followed by the conclusion in Section V.

II. Overview of Different DG Placement Cases

A. Optimal DG Placement

In this work, the standard IEEE 37 Node radial network is considered where total of four DGs are placed. For ODGP, the method presented in [12] is used. This method splits the optimal location selection and optimal size selection into parts, former based on LCF whereas as analytical expressions for simultaneous sizing of multiple DGs are utilized for the later. The operational power factor, proposed in this method is utilized which suggested the power of 0.97 for this network. The locations and sizes of DGs, based on this method, are given in the Table I

TABLE I
ODGP with Analytical Method

Bus Number	Active Power (kW)	Reactive Power (kVar)
12	0.6	0.1504
18	0.6	0.1504
22	0.9	0.2256
32	1.475	0.3697

B. Random DG Placement

Optimal DG placement is usually considered as a theoretical study due to different reasons but its advantages can neither be ignored nor denied. In this work it is attempted to provide a reason for optimal DG placement in a different way. To achieve this, total of eight different cases are considered with different locations of DGs. In order to make the considered RDGP cases comparable to the ODGP case up to certain degree, total output power from DGs is kept similar in both cases. However, their locations are changed. Based on this location variation, two different categories are made. First category groups the cases where the locations can be anywhere in the network while having the sizes similar to those given in Table I. This category contains 5 different cases corresponding to the different sets of locations. In second category, the locations are kept same as those for ODGP case (found by LCF method) but the sizes are rotated such that all ODGP locations do not have exactly similar size of DG in this category of RDGP. The Table II provides the details of these categories.

The load growth considered in this work correspond to the total of 26.5% increase from the base load condition of 5.25 MVA. Load growth is considered in order to manipulate the scenario where the system demand is increased beyond the value for which the ODGP was done. As the optimal DG sizes found in ODGP problem are the function of system variable such as power demand and network losses, the found sizes will no longer remain optimal for case with changed system variables. Despite this fact, the ODGP has proved advantageous as shown in the Section. IV.

III. Description of Operational Stage

A. Centralized Voltage Control Algorithm

In this work, the operational phase is considered by increasing the load up to a maximum value in the network. For base case network, with ODGP and without load growth, no voltage problems are observed. After step by step increment in the load (S_{load}) up to the maximum load value ($S_{load_{max}}$), the bus voltage reading is taken for all n nodes in the system

TABLE II
RDGP CASES

Cat - 1	Case - 1	Bus Number	10	13	24	27
		DG Size (kW)	1.475	0.6	0.9	0.6
	Case - 2	Bus Number	9	20	21	26
		DG Size (kW)	1.475	0.6	0.9	0.6
	Case - 3	Bus Number	8	17	23	36
		DG Size (kW)	1.475	0.6	0.9	0.6
	Case - 4	Bus Number	8	17	23	30
		DG Size (kW)	1.475	0.6	0.9	0.6
	Case - 5	Bus Number	8	17	23	27
		DG Size (kW)	0.6	0.6	0.9	1.475
Cat - 2	Case - 6	Bus Number	12	18	22	32
		DG Size (kW)	1.475	0.9	0.6	0.6
	Case - 7	Bus Number	12	18	22	32
		DG Size (kW)	0.9	1.475	0.6	0.6
	Case - 8	Bus Number	12	18	22	32
		DG Size (kW)	0.9	0.6	1.475	0.6

and stored as $V_{bus_1}, V_{bus_2}, V_{bus_3}...V_{bus_n}$. In case of voltage problem at any node, the reactive power output of the DGs (Q_{DG}) is changed sequentially. The sequence is controlled based on the priority set by the sensitivity (Sen_{ij}) of the buses with DGs with respect to the bus(es) with voltage problem. Higher the sensitivity value (Sen_{ij}), higher is the priority of respective DG for adjusting reactive power and attempting to mitigate the voltage problem. If the voltage problem persists after the top ranked DG in the network delivers or absorbs the reactive power up to its maximum limit $Q_{i_{max}}$, the next DG in the list provides as per similar rule and so on. The voltage control action stops if either the voltage at all buses changes back to the permissible limits or the total reactive power capacity of all the generators is fully exhausted. The maximum number of DGs is specified by i_{max}. This whole algorithm is summarized in Algorithm 1 for the case of problem of low voltage. Same algorithm can be modified for voltage rise problems with minor changes corresponding the the flow of reactive power from DG. As given in [17], the upper and lower voltage limits taken in this work are 0.94 and 1.06 p.u. The maximum allowable reactive power dispatch from DGs in this work corresponds to the DG's power factor of 0.89. The sensitivity of bus i containing DG with respect to the bus j having the voltage problem is given as:

$$Sen_{ij} = \frac{\partial V_j}{\partial Q_i} \tag{1}$$

The sensitivity can be found using the power flow solution of the system. In real power flow calculations, the partial derivative given in Eq. (1) can be replaced with delta (Δ) for simplification of calculations and easy assessment of the required value of reactive power [18]. The value of reactive power needed from DG at i_{th} bus in case of voltage problem can be calculated as:

$$\Delta Q_i = \frac{\Delta V_j}{Sen_{ij}} \tag{2}$$

$$\left.\begin{aligned} \Delta V_j &= |V_{j_{current}} - V_{min}| \\ \Delta V_j &= |V_{j_{current}} - V_{max}| \end{aligned}\right\} \tag{3}$$

$$\Delta Q_i = Q_{DG} - Q_{i_{new}}$$

$$Q_{i_{new}} = Q_{DG} - \frac{\Delta V_j}{Sen_{ij}} \tag{4}$$

The value of reactive power needed from DG can be computed using Eq. (4), where the current value of reactive power output from DG (Q_{DG}) is already known.

Algorithm 1: Centralized voltage control algorithm with load growth

```
Initialization;
Calculate Load Flow Sensitivity;
Build Sensitivity Table for Buses with DGs (Sen_ij[]);
Sort Descending Sen_ij[];
while (S_load < S_load_max) do
    Run Load Flow;
    V = Min(V_bus1, V_bus2, V_bus3...V_busn);
    i = 1;
    while (V < 0.94) and (i ≠ i_max) do
        Get Sen_ij;
        Calculate Q_i_new using Eq. 4;
        if (Q_i_new => Q_i_max) then
            i = i + 1;
        else
            set Q_DG = Q_i_new;
            calculate load flow, get V_new;
            V = V_new;
        end
    end
    Next S_load;
end
```

The purpose of implementing the voltage control algorithm is to show the ease and efficiency of performing corrective actions in case of voltage problem in different considered cases. Detailed discussion about this is given in Section. IV.

B. Voltage Quality Index

An important objective of power system control is not only to maintain the voltage inside the permissible range (±6 % of nominal voltage in this work) but also to maintain the voltage variation as low as possible during the case of any changes in the system such as load variations. In order to explain the impact of load growth and voltage control action in a better quantifiable way, Voltage Quality Index (VQI) is proposed in this work. For any load condition i, this is given by the following relation.

$$VQI_i = \left[V_{nom} - \frac{V_{max_i} - V_{min_i}}{V_{max_i}} \right] 100\% \tag{5}$$

Where, V_{nom} is the nominal bus voltage in p.u. and is taken to be unity in our case; V_{max_i} and V_{min_i} are the respective maximum and minimum voltages in the network at ith load condition.

In power systems, it is always desired to keep the difference between V_{max_i} and V_{min_i} as low as possible for a better quality because it depicts that, for specific load condition, the system voltage remains nearly uniform. Therefore, higher value of VQI_i corresponds to the better voltage quality in the system. The utilization of VQI_i provides a better insight into the system with discrete numeric results which help in quantifying the system voltage condition and possibility of comparison among different cases.

Another advantage of using this factor is that, for a similar difference between V_{max_i} and V_{min_i}, it gives higher value output for higher value of these variables. For example, if V_{max_i} and V_{min_i} are 1.01 and 0.98 respectively, the resulted VQI_i would be 97.03% whereas, for a similar difference in case of 0.95 and 0.92 respectively, the resulted VQI_i would be 96.84%. On basis of this, the VQI_i is also helpful in giving information about the actual bus voltages in a system for specific load condition.

To further explain the usefulness of the proposed VQI_i, three different cases are compared.

1. $V_{max_i} - V_{min_i} = 0.03$. This correspond to VQI_1
2. $V_{max_i} - V_{min_i} = 0.05$. This correspond to VQI_2
3. $V_{max_i} - V_{min_i} = 0.08$. This correspond to VQI_3

This comparison shows that, for the same value of V_{min_i}, VQI_i reduced as the value of V_{max_i} is increased. This impact is indicative of the fact that the system has higher difference in bus voltage for specific load condition in different part of the network.

All these useful features of proposed VQI_i are summed up in Fig. 1 for the indicative values given in Table III. It can be seen that, for higher difference between V_{max_i} and V_{min_i}, the value of VQI_i is lower. Such advantages make the proposed VQI_i a useful index which can help in better understanding of system voltage conditions with a single overview.

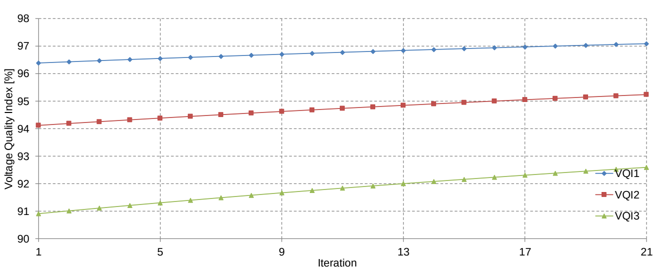

Fig. 1. Evolution of Voltage Quality Index at Different Loading Conditions

TABLE III
COMPARISON OF DIFFERENT VOLTAGE QUALITY INDEX

Iter	V_{min_i}	V_{max1}	V_{max2}	V_{max3}	VQI_1	VQI_2	VQI_3
1	0.8	0.83	0.85	0.88	96.39	94.12	90.91
2	0.81	0.84	0.86	0.89	96.43	94.19	91.01
3	0.82	0.85	0.87	0.9	96.47	94.25	91.11
4	0.83	0.86	0.88	0.91	96.51	94.32	91.21
5	0.84	0.87	0.89	0.92	96.55	94.38	91.30
6	0.85	0.88	0.9	0.93	96.59	94.44	91.40
7	0.86	0.89	0.91	0.94	96.63	94.51	91.49
8	0.87	0.9	0.92	0.95	96.67	94.57	91.58
9	0.88	0.91	0.93	0.96	96.70	94.62	91.67
10	0.89	0.92	0.94	0.97	96.74	94.68	91.75
11	0.9	0.93	0.95	0.98	96.77	94.74	91.84
12	0.91	0.94	0.96	0.99	96.81	94.79	91.92
13	0.92	0.95	0.97	1	96.84	94.85	92.00
14	0.93	0.96	0.98	1.01	96.88	94.90	92.08
15	0.94	0.97	0.99	1.02	96.91	94.95	92.16
16	0.95	0.98	1	1.03	96.94	95.00	92.23
17	0.96	0.99	1.01	1.04	96.97	95.05	92.31
18	0.97	1	1.02	1.05	97.00	95.10	92.38
19	0.98	1.01	1.03	1.06	97.03	95.15	92.45
20	0.99	1.02	1.04	1.07	97.06	95.19	92.52
21	1	1.03	1.05	1.08	97.09	95.24	92.59

C. Simulation Setup

In order to implement the proposed method, coupling of DIgSILENT PowerFactory (DSPF) [19] and Python is used. DSPF is a powerful simulation tool which provides the options of modelling and simulating variety of power systems. It also has the capability of exporting or importing the models in different formats. On the other hand, Python is a versatile programming language with various advantages ranging from ease of use up to the handling of complex data easily. Using Python, it is easily possible to access DSPF as an object and control it from inside Python. Based on such reasons, this pair of tools is preferred over other tools and coupling methods. Few other examples of tool coupling can be found in [20] which proposes coupling of DSPF with Matlab. For presented work, IEEE 37 node network is implement in DSPF using the data given in [21], and all the coding related to implementation of proposed algorithm and getting results is implemented in Python. The network configuration is given in Fig. 2.

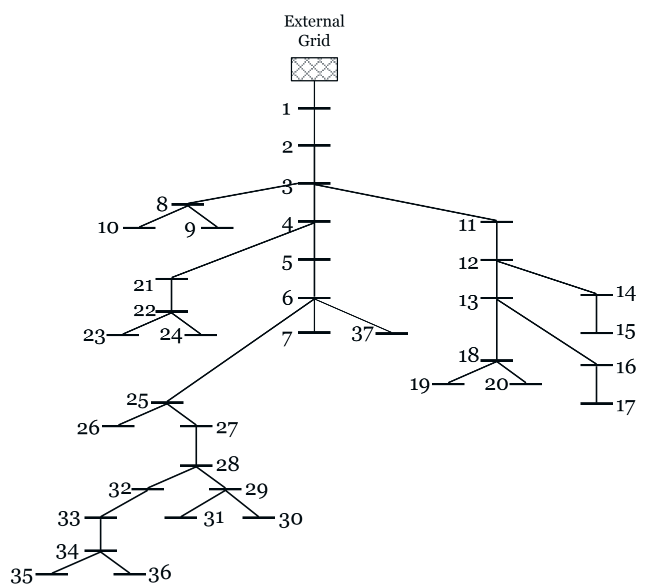

Fig. 2. IEEE 37 Node Radial System

IV. Results and Discussion

In this work, the important variables to be discussed are active power loss and system voltage which is represented by the index VQI. The results for these two variables are given in the Fig. 3 - Fig. 6, respectively.

A. Active Power Loss

The Fig. 3 and Fig. 4 provide comparison of active power loss reduction with load growth in different studied cases. It is clear from these figures that the loss was reduced to the maximum in case of ODGP. The observed values were 11.91 kW and 118.28 kW without Voltage Control Algorithm (VCA), and 11.91 kW and 102.28 kW with VCA, at minimum and maximum considered loads, respectively. The nearest competitor is the case - 5 in which the minimum and maximum values of loss, with VCA, are appeared to be 36.46 kW and 161.08 kW, respectively. The worst performance was observed in case - 2. For this case, with VCA, loss with minimum load condition was recorded to be equivalent the value of loss with maximum load of ODGP. Moreover, the highest value of loss was observed in this case at maximum considered load with a value of 324.01 kW without VCA and 310.44 kW with VCA.

Another important information in Fig. 4 is about the voltage control action which was taken by the centralized VCA in case of voltage reduction. As the case of increasing load is considered and output from DGs is supposed to be constant, voltage rise problem was not observed in this study. In case of voltage drop problem, the indication of corrective action of the control algorithm appeared at the iteration 99 for ODGP case. For all other cases, the need of corrective action was felt earlier in comparison to the ODGP case. In ODGP case, after iteration 113, total reactive power capability of the system was exhausted therefore further correction was not possible. Once again, a nearest competitor is case - 5 in which the first corrective action was taken after iteration 84 whereas total reactive power capability was exhausted after iteration 98 hence corrective action was not possible.

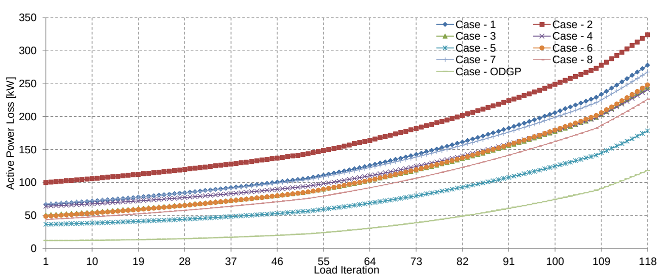

Fig. 3. Active Power Loss without Voltage Control Algorithm

B. System Voltage - Voltage Quality Index

Voltage quality index results are presented in Fig. 5 and Fig. 6. The case of ODGP outperformed all other possible cases considered in this study too and a trend similar to the active power loss case is observed. The highest value of VQI is observed in case of ODGP at load iteration 10. This value

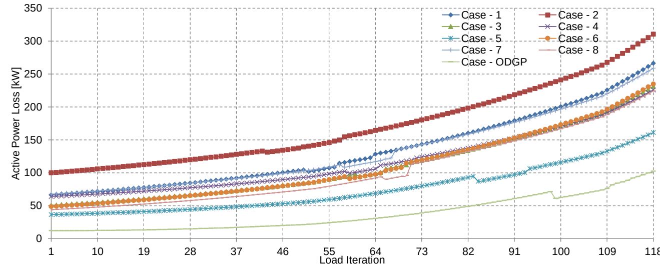

Fig. 4. Active Power Loss with Voltage Control Algorithm

is 98.83% for both cases i.e., without and with VCA. For this case, the least VQI is reported at last iteration which is equal to 88.30% and 98.43% without and with VCA, respectively. The reason for similar value of peak VQI is that it appeared at the load iteration when no voltage control action is needed. Almost 10% of improvement in VQI is observed in minimum value of VQI in case with VCA. For case - 5, highest and lowest value of VQI were 97.86% and 92.09% which appeared at first and last iterations, respectively in case with VCA.

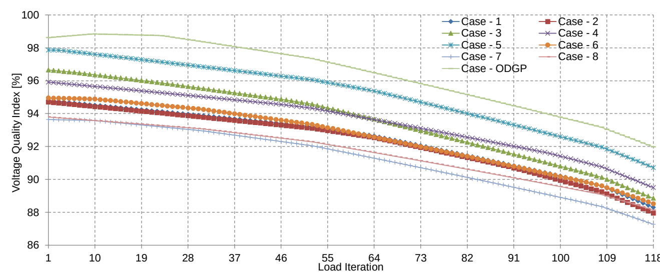

Fig. 5. Voltage Quality Index without Voltage Control Algorithm

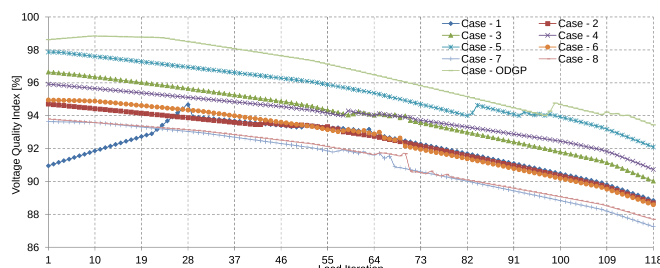

Fig. 6. Voltage Quality Index with Voltage Control Algorithm

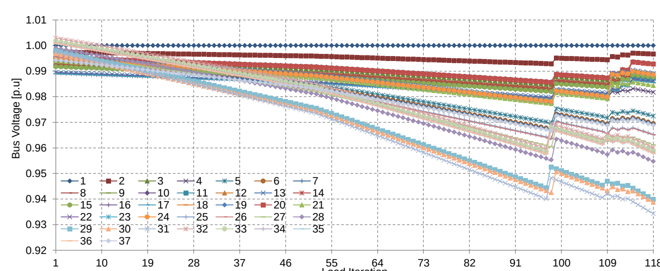

Fig. 7. Voltage Profile with Voltage Control Algorithm - ODGP Case

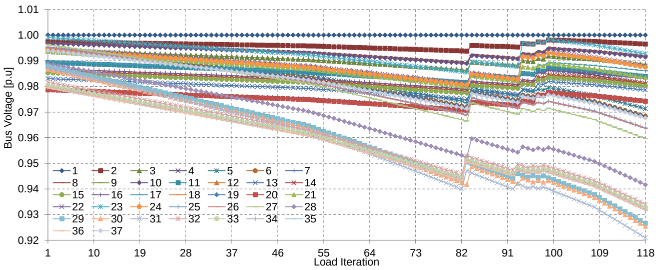

Fig. 8. Voltage Profile with Voltage Control Algorithm - Case 5

For the purpose of further clear explanation, the voltage profiles of all the buses for the ODGP case and case - 5 (being nearest competitor to the ODGP case), with VCA, are given in Fig. 7 and Fig. 8, respectively. It is obvious from these figures that the corrective action by VCA is implemented successfully but after increasing the load beyond certain limit, the corrective action is not possible. This is because of the reason that permissible reactive power limits for all the DGs in the system are reached. An interesting comparison is about the iteration at which this limit appeared. For ODGP case, it is after the iteration 113 whereas for case - 5, it was after iteration 98. This means that with the ODGP, the system can handle more load without violating the bus voltage limits in network. Finally, the important result is about the number of buses with voltage problem when the total reactive power reserve is exhausted. This number is only 2 for ODGP case but it is 8 for case - 5.

V. Conclusion

This paper thoroughly discusses the advantages of ODGP in comparison to RDGP and highlights them in terms of better loss reduction and voltage quality over the term of load growth in the system. For ODGP, analytical method for sizing and LCF base location selection from previous work are considered. To explain the network's voltage quality in different cases, VQI is proposed which provides a straightforward method to quantify system's voltage quality status. With the help of results, it is proved that the ODGP is beneficial in reducing the losses and gives better voltage quality in the network. In case of voltage problem due to load growth, the voltage control action is implemented via VCA. The results also show that the network's capacity to withstand more load without violating permissible voltage limits increased in ODGP case. Moreover, the number of buses experiencing voltage problem is reduced significantly with ODGP and implemented VCA.

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