Analysis of the Impact of Distributed Generation Placement on Voltage Profile in Distribution Systems

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***Abstract*— This paper analyzes the impact of distributed generation (DG) placement on voltage profile under certain penetration level in low-voltage (LV) distribution networks. DGs are allocated via different probabilistic approaches to account for uncertainties of DG installation in the future. The main contribution of this paper is in understanding how to apply proper probability distribution functions (PDFs) and constraints for DG placement location to prevent under- and over-voltage problems or unexpected load disconnections. The results prove that the developed approach can reduce the probability of having load voltage violations, which means the network may have more DGs accommodated. Such techniques can be considered as a tool for the network planning engineer to facilitate the installation of DGs in the future.**

***Index Terms*--Distributed generation (DG); DG placement; low-voltage secondary network; voltage profile; voltage quality.**

I. Introduction

Currently, the usage of distributed generation (DG) is increasing significantly. Despite the high cost, the installation of DGs in the modern power grid provides electricity near the customers comparing to the traditional radial supply of power from a distant generator. Other benefits of DG include the system loss reduction, improvement of voltage profile across the feeder, benefits to the environment, etc. However, there are numbers of challenges that DG pose to the safe and reliable operation in the distribution system [1]–[9].

Several papers reported on different techniques for DG allocation in the radial distribution systems using the probabilistic approach [10], [11]. The operation strategies of radial and meshed systems are pretty different from each other, and the flow of reverse power from the low-voltage (LV) network to the medium-voltage (MV) feeders is not expected. For the safety reasons, the protection at the secondary side of transformer is designed to trip when reverse power is sensed, which implies that the requirements for the unidirectional active power flow in the secondary networks imposes additional constraints that are not present in meshed systems [12], [13]. While there are studies reporting the advantage and disadvantages of DGs in the radial distribution systems [14]-[20], a literature review revealed that there are no systematic studies reporting the effects of the impacts on voltage profile by applying various PDFs to DG allocations in secondary networks.

In [12], the possible impacts to load voltages are studied by applying one set of PDFs under different DG penetrations. It is understood that if customers are allowed to freely install DGs on their premises and DGs become widespread, it is possible that the load violations may occur under small DG penetration [12]. In our analysis, we focus on how to decrease the probability of having voltage violation. The goal is to design proper PDFs and constraints considering type, size, and location of DGs together with the network topology under certain DG penetration, so that the network may allow more DGs to be installed and the maximum DG penetration is greater. This planning tool is quite effective if DG penetration driven by the customer follows a certain trend described by the probabilistic approach used in this study.

This paper starts with a background of the study set-up, in Section II, continues with the fundamentals of the PDF design in Section III and ends with simulation results in Section IV.

II. Background

A. *Description of the Test Network*

Details of a typical LV meshed network are described in [21]-[23]. The test LV meshed network including all system components is modeled in the Alternative Transients Program (ATP) shown in Fig. 1. Important components of an LV secondary network are the secondary network protections [21]-[25]. The protection is installed on the secondary side of the network transformers so that they can be disconnected automatically when the power starts to flow in the reverse direction.

The test network is a meshed distribution network designed by the authors from the experience. The test network includes 74 secondary cable sections, 26 aggregated loads, 6 transformers, and 6 protection elements. The network operates at 13.8 kV from the area substation through the primary feeder sections where the distribution transformers are connected to step-down the voltage to 460 V for the customers. The load flow results converges for the light load and peak load base cases. The aggregated loads are represented as constant impedances. Nodes 1 to 26 are where the aggregated loads are.

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The total light load is about 8.2 MW, and the total peak load is about 32.8 MW.

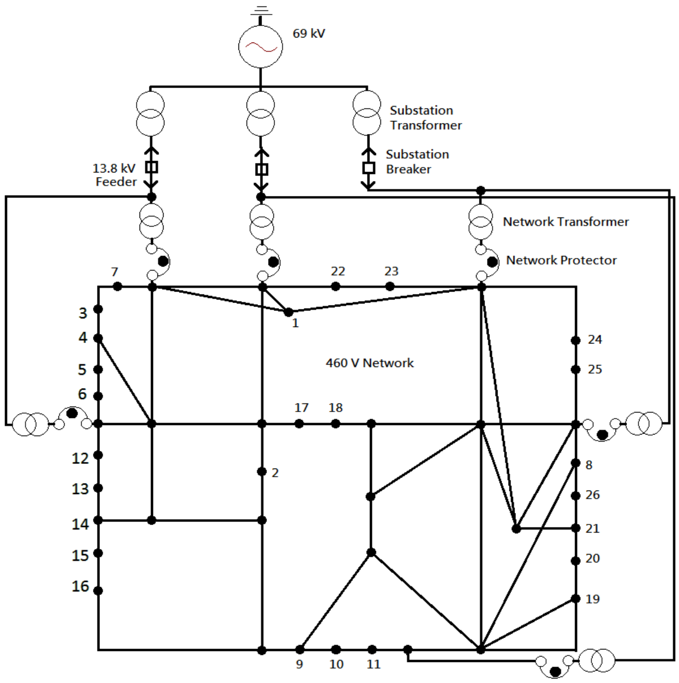

Figure 1. The test network.

B. Overview of DG Characteristics

To investigate the impact of DG placement, the type, size, and location of DG are considered in this study. It is unrealistic to design a PDF for each load and each size of DG, so the loads are classified into groups based on the power demand as shown in Table I. The different type and rating of DGs are also classified in groups for the placement selection purpose. The simulations and analyses are based on explicit representation of each load and each rating of DG. The types of DG used in this study are: inverter-based, induction types and synchronous generators. According to utility regulations, the selection of DG for a particular location has a direct relationship to the output-power range of the generator [12]. The output range of inverter-based DG, inductive and synchronous generator types are 0.02 kW to 2 MW, 0.01 kW to 2 MW, and 1 kW to 2 MW, respectively. The ratings of DG are also divided into different group corresponded to different load groups.

C. Gibbs Sampler and Monte Carlo Method

Similar to [12], in this paper, the Gibbs sampler [26], [27] is applied to generate three key parameters for the placement of the nondeterministic DGs: type, size, and location. The Gibbs sampler algorithm is one of the Markov Chain Monte Carlo methods. The method is commonly applied for the generation of random variables from a marginal distribution directly without having to calculate the probability density via integration. An important advantage of the Gibbs sampler as a tool for the statistical study of DG penetration is that it enables low-dimensional conditional distributions (avoiding the use of a complicated multivariate distribution). In addition, more parameters for DGs can be added easily, for example, the cost of DG. Due to the space constraints, the details of Gibbs Sampler will not be discussed here but may be found in [12], [26], [27].

TABLE I. LOAD GROUP BASED ON POWER DEMAND.

Group Location	Power Demand Range
Very Large Load	Larger than 3 MW
Large Load	600 kW - 3 MW
Medium Load	150 kW - 600 kW
Small Load	30 kW - 150 kW
Very Small Load	0 kW - 30 kW

D. Overview of the Study Procedure

An overview of the study procedure is described in Fig. 2. We focus on the situation when the DGs are placed under certain penetration level on the light (minimum) load conditions. A translator is written so that the netlist generation process has been automated for this study [24]. The output of this translator is a complete ATP netlist which can be automatically loaded into the ATP to perform simulations. An ATP Results Analysis algorithm is also developed to collect and analyze the data from ATP. An overview of the DG Allocator algorithm is shown in Fig. 3 [12]. The non-deterministic DG units are generated from the PDFs and can be placed at the particular location only when none of the constraints is violated. The DG is allocated one-by-one which follows how DG penetration is done by the customer.

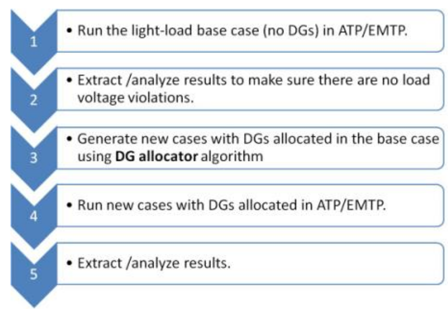

Figure 2. An overview of the study procedure.

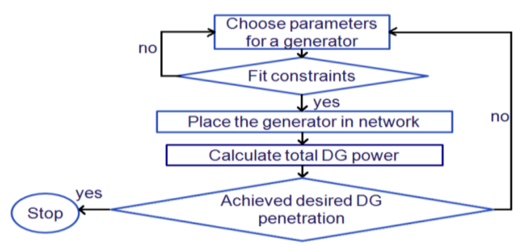

Figure 3. Allocation algorithm for non-deterministic DG units. .

III. DESIGN OF PROPER PDFS TO ALLOCATE DGS

In this paper, all the DGs are referred to as non-deterministic DGs [12], which means that the location, type, and size of DGs are not known parameters. DGs are probabilistically allocated at the customer loads to perform the analysis of different hypothetical scenarios [12].

The selected conditional probability functions to allocate nondeterministic DGs were designed in accordance with: a) the IEEE standard for interconnecting distributed resources with electric power systems [28], b) local utility requirements [29], [30], and c) physical conditions of the selected distribution network. Generally, the probability of choosing a particular DG type and its rated output power for installation at any customer location depends on the power demand at this location. It is more likely that customers will choose the rating of the DGs in accordance with the power consumption. Thus, for a DG unit having a particular large rating, the probability of being installed at locations with large demand is higher.

When DG units are installed at the undesirable location, even with very small DG penetration level, which still could be a large size DG unit, the impact may be unacceptably low or high voltages at certain loads [12]. In [12], the possible impact on load voltages are studied by applying one particular set of PDFs under different DG penetrations. In this paper, we focus on how to design the proper PDFs and constraints considering type, rating, and location of DGs together with the network topology under certain DG penetration. For instance, DGs allocated via the uniform distribution may cause more voltage violation problems than the ones placed using different set of PDFs [12] because a large rating DG has a smaller probability to be allocated at a small load by design. To avoid such a situation, our approach is to design a set of proper PDFs that will assure more realistic placement strategy for DGs. This implies that the DGs should have relatively small ratings when applying the PDFs designed using the proposed allocation method.

A. Challenges

Designing a proper set of PDFs requires multiple factors to be taken into account:

1) Characteristic and topology of network: The characteristic and topology of the network is unique for every secondary network (i.e. load capacity, number of subnetworks and spot networks), which implies that the additional constraints are different. For instance, in [32] there are two secondary networks Sutton and Flushing. In Sutton network, there are 311 low voltage loads and the total light load is 49.13 MW. In Flushing network, there are 6918 low voltage loads and the total light load is 241.95 MW. Comparing two networks, there is 22 times large number of loads in Flushing than in Sutton, but the amount of total light load is only 5 times more in Flushing than in Sutton. This implies there are more possible loads for DG allocation in Flushing, so we can conclude that if the PDF applied to Sutton in [12] is applied to Flushing, then the load voltage violation problems will be less.

2) Additional Constraints: The additional constraints are necessary for the secondary network. In this paper, the following constraints [12] are considered to be control variables for the allocation of the DGs: 1) a DG can only be installed at customer locations; 2) a DG unit cannot exceed 2 MW output power; 3) only one type of the DG is allowed per location; and 4) each location may have multiple DG units of the same type. These constraints are based on regulatory requirements and physical limitations of the distribution networks in the metropolitan areas, so these constraints could vary for every secondary network under study. With increasing demand for DGs, there should be requirements designed for a large DG penetration level in the current market. The newly connected DG should follow the philosophy “connect and forget”, so that the designed constraints must ensure the continuity and reliability.

3) Rating groups of DGs: It is also important that the rating of a DG group corresponding to the load groups is carefully considered. The design principle is that for every load group, at least one DG rating group must be available for every type of DG. Otherwise there will be some loads which cannot have any DGs allocated.

B. Design Principle for PDFs and constraints

The outcome from the DG allocator (outcome from step 3 in Fig. 2) will not be exactly the same as designed PDFs because of the constraints and the group classification of load demand and DG rating. For instance, if the uniform distribution is applied to DG allocation, then one may expect that the DG power ratio between three types is approximately the same. However, the results show that the synchronous type DG has a larger ratio. The reason is that there are more large size induction types DG than the other two types.

From the studies and experience, the authors suggest the following method of designing proper PDFs: look at the output from DG Allocator and perform some number of cases in EMTP to see how the PDFs and constraints reflect to the results. If the geographical coordinates are available, one can plot the map [12] to see the placement of DG in conjunction with the results obtained from EMTP. The following examples illustrate the point.

- If one sees that the large size induction type DGs have caused too much voltage drops, then one may apply an additional constraint which states that the induction type DG rating may not be greater than the light load for every load.
- If one sees that the constraint “the DG units at a load cannot exceed 100 % peak load demand for that load” has caused some load voltage violations because the constraint allows a large DG to be possibly allocated at a small load, then one may lower the percentage, say to 85% of the peak load, to decrease the probability of having load voltage violations.
- If one sees on the geographical map that there are mostly large DGs allocated and the results show there are load voltage violations, then one can adjust the PDFs or apply the aforementioned method.

IV. Simulation Results

The most important information to be extracted from the simulated cases is the voltage profiles at the loads and primary side of transformer, together with the status of the network protection. A review of the light load network voltage profile has been performed (steps 1 and 2 in Fig. 2) to ensure the selected network is stable and suitable for the study prior to the installation of DGs. The obtained results confirmed that there are no network protections open in the light-load base case and no load voltage violation exists. A voltage violation is defined as a load having a voltage deviation larger than 5% from its rated voltage for normal operating conditions [28], [31].

The PDFs and the constraint "the DG units at a load cannot exceed a certain percentage of the peak load demand for that load" are considered to be the independent variables where all other constraints are control variables. One can observe that in all simulations, the input voltage for the transformers is always within the acceptable range. Therefore, the voltage profile analysis in this paper is based on the number of loads having voltage violations applying different independent variables in DG Allocator algorithm. The total number of simulated cases is given in Table II, where the DG penetration level of all cases is 50 %. The method for determination of number of necessary cases is presented in [12].

Proposed Distribution 1 is the same set of the proposed distributions for DG penetration used in the study reported in [12]. Proposed Distribution 2 is adjusted from proposed Distribution 1 so that the output ratio of three types of DG is modified as shown in Table III. Both proposed Distributions 1 and 2 are designed based on the principle that the large customer will have large demand and vice versa (not Uniform Distribution).

TABLE II. NUMBER OF CASES WITH DIFFERENT INDEPENDENT VARIABLES (DG PENETRATION LEVEL: 50 %).

Groups	PDFs	Maximum DG At A Load	Number Of Cases
1	Uniform Distribution	100 % peak load	40
2	Uniform Distribution	85 % peak load	40
3	Proposed Distribution 1	100 % peak load	40
4	Proposed Distribution 1	85 % peak load	40
5	Proposed Distribution 2	100 % peak load	40
6	Proposed Distribution 2	85 % peak load	40

TABLE III. AN AVERAGE OUTPUT RAITO OF THREE TYPE OF DGS

PDFs	Inverter [%]	Induction [%]	Synchronous [%]
Uniform Distribution	24.3	14.5	61.2
Proposed Distribution 1	44.2	14.6	41.2
Proposed Distribution 2	19.7	10.2	70.1

Fig. 4 summarizes the results of hundreds of simulations aimed at finding the potential voltage profile problems. The probability of having voltage violation versus the number of loads with violation problem is plotted for different groups for penetration level being 50 % of the light load. One can see that as the designed distribution and constraints change, the probability of having voltage violations also changes. Looking at Fig. 4, one can see that the probability of having at least 1 load having voltage violation is 48 % for Group 1, but 30 % for Group 6. Fig. 4 clearly shows that 1) probability of having load violation problems is decreased when the maximum DG power decreases and 2) Proposed Distribution 2 gives the best results (less probability of having load voltage violations) and Uniform Distribution gives the worst ones. In other words, the probability of having at least 1 load voltage violation is reduced by 18 % under 50 % DG penetration.

The average percent of loads with voltage violations together with the obtained standard deviations is given in Fig. 5. A small standard deviation indicates that the data points tend to be close to the average value. In contrast, a large standard deviation indicates that data are spread over a wide range of values. One can see that the Group 1 has the largest number of load voltage violations and standard deviation where the Group 6 has the smallest.

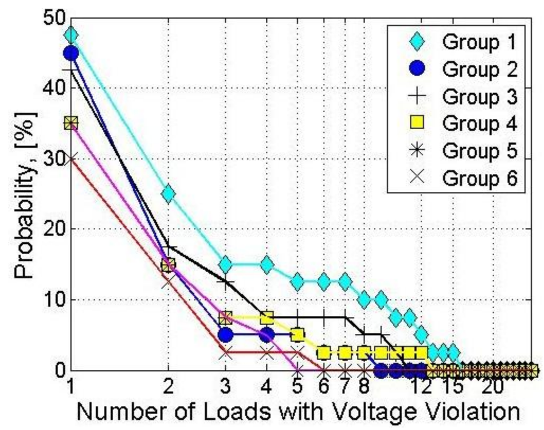

Figure 4. Probability of having voltage violations of more than ±5 % versus the number of loads with violation.

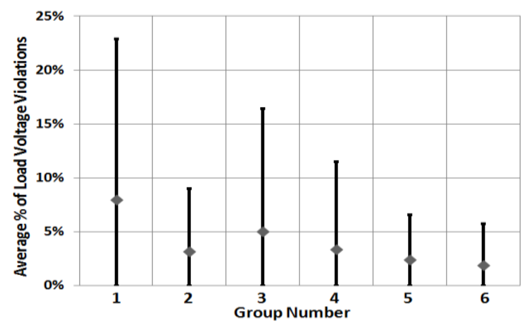

Figure 5. Average percent of loads having voltage violations versus the group number.

By applying Uniform Distribution, it is possible that a large rating DG is allocated at a small load, so the probability of having load voltage violation is high. By applying proposed Distribution 1, we see that when a large size induction type DG unit is installed at a load point, the under-voltage problem occurs on multiple loads in the vicinity of the load. Table IV shows such a situation where multiple induction type DGs caused more than three load voltage violations in some areas. Generally, one can include an additional constraint to limit the rating of induction type DG at loads as aforementioned. In this paper, we apply another approach which is to adjust the PDFs so that the ratio of synchronous type DG is increased to avoid such a situation.

V. CONCLUSIONS

This paper made several contributions:

- It has presented a method to effectively decrease the probability of having load voltage violation problems by applying different probabilistic approach to DG placement

- The example where the DGs are allocated under certain penetration level under the light load conditions shows the trend (the probabilistic approach) the customer should follow if they would like to have the DG installed.
- The proposed simulation set-up can be considered as a tool for the network planning engineer to facilitate the installation of DGs in the future.

TABLE IV. PERCENTAGE OF CASES HAVING MORE THAN THREE LOAD VOLTAGE VIOLATIONS WHILE MULTIPLE INDUCTION TYPE DGS ARE ALLOCATED CLOSE TO EACH OTHER.

Groups	Percentage [%]
1	17.5
2	5
3	12.5
4	7.5
5	7.5
6	2.5

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