Analysis of Voltage Stability Issues with Distributed Generation Penetration in Distribution Networks

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***Abstract*—This paper presents an overall analysis of how the penetration of distributed generation in low-voltage secondary distribution networks affects voltage stability. It is critical that the voltage collapse point be carefully studied under different system operating points to prevent degradation of service. System components have been sophisticatedly modeled in ATP/EMTP. DGs are allocated in a probabilistic fashion to account for uncertainties in future allocation. A large number of experiments under both light and peak load conditions have been carried out to provide realistic results. Results indicate that voltage stability is positively correlated with penetration of DG, but large induction type DG may lower the voltage stability margin.**

***Index Terms*--Distributed power generation, power systems, power system stability, reactive power, smart grids.**

I. INTRODUCTION

Distributed generation (DG) has become an increasingly important source in the modern power grid. Although the cost of installation is high, DG benefits the customers by providing electricity endemic to the customer rather than at a distant generator. Therefore, DG can help to reduce the demand at peak times so that power congestion may be minimized preventing degradation of service. Yet, research efforts reveal that there are challenges that DG poses to the safe and reliable operation of distribution systems [1]–[16].

To provide optimal reliability to customers, in case of multiple contingencies, the meshed low-voltage (LV) secondary networks are applied to major metropolitan areas and business districts. There is more effort involved in interconnecting DG with meshed networks compared to radial ones since the operation strategies are different [17], [18]. For instance, in meshed networks the reverse power flow from LV networks to medium-voltage (MV) networks is forbidden, which means the network protection will be tripped if the power flows from secondary side to primary side. Significant research effort has been invested in elucidating the advantages and disadvantages of DG for radial networks [19]-[24], but there is a very limited amount of work in meshed networks [16], [25]-[27].

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Several papers reported on different techniques for DG allocation in radial distribution systems using probabilistic techniques [28], [29]. However, because of the characteristics and constraints of mesh networks, it would be difficult to implement certain optimization strategies for DG allocation. Therefore, a probabilistic approach is proposed based on the relationship between customer demand and DG parameters (type, size, and location) [26], [27]. In this paper, a probabilistic approach to allocation will be applied.

In the 1990s the voltage stability problem became an interesting topic for transmission networks and was extensively studied [30]-[32]. Recently, with the advent of new DG technology, voltage stability studies have been extended to distribution networks [33]. In this paper the long-term voltage stability will be considered to reveal the the system's ability to maintain steady voltage profiles following small disturbances experienced through continuous variations in load [34]-[36].

In this paper, we present a comprehensive analysis of how the penetration of DG may affect the voltage stability of the system in a LV secondary meshed network. A large number of experiments have been conducted under both light and peak load conditions. We have discovered that the voltage stability margin (*VSM*) is strongly correlated with penetration of DG. Our results reveal that generally the penetration of DG has a positive impact on the *VSM*, but negative impact may occur in cases where large induction type DG lowers the *VSM*.

II. PRELIMINARIES

A. Secondary Network Under Study

Details of typical LV meshed networks are described in [18], [37], and [38]. In order to provide the highest level of reliability (the ability to survive multiple contingences), all the secondary sides of network transformer are tied together with loads to form a meshed grid [24]. This design maximizes the reliability of the grid.

An important component of LV networks is secondary network protection [38]-[41] which prevents the power flow from the secondary side to the primary side. This restriction induces additional constraints and challenges for DG allocation. For example, if the total power provided by DG units is greater than the loads inside a spot network, all the network protections will trip and the loads will be disconnected.

The test network shown in Fig. 1 is a simplification of a real system, designed to reveal the relationship between voltage profile and stability. All system components are modeled in detail in the Alternative Transient Program (ATP) [42]. The network has 15 transformers, 15 network protections, and 26 aggregated loads. These loads correspond to 25 loads (Load 2 to Load 26) in the meshed network at 208 V and one spot network load at 460 V. The DGs may potentially be connected at 26 loads.

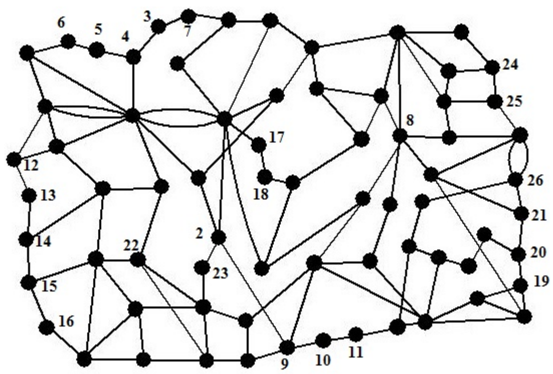

Fig. 1 One-line diagram of test network.

B. Gibbs Sampler and Monte Carlo Method

For DG allocation purposes the Gibbs sampling algorithm [43]-[45] is applied. This kind of allocation allows us to analyze non-deterministic DGs, meaning that the parameters of DG are not known in advance. Three important parameters of DG taken into consideration are their type, size, and location.

The Gibbs sampler is a Markov Chain Monte Carlo (MCMC) method, used for directly generating samples from a target distribution. Applying the Gibbs sampler enables description of future DG allocation using low-dimensional conditional distributions, avoiding the use of complicated multivariate distributions. As a tool for the statistical study of DG penetration, more parameters for DGs can be easily added, for example, the cost of DG. The details of Gibbs sampler may be found in [43]-[45].

C. Overview of DG Characteristics

To study the impact of DG penetration on the *VSM*, three parameters of DG are considered. In practice there will be a large number of loads and various parameters related to DG units, so it is unrealistic to design a particular distribution for each load and each size of DG unit. Therefore, different types and ratings of DGs, and different power ranges of load, are classified in groups for allocation purposes. Based on the regulations of local utility, the possible installation of DG considered by a customer is most likely dependent on the output-power range of DG [17]. The output range and types of DG considered in this study are listed in Table I, and the size of load is listed in Table II. The types of DG are classified according to the connection between the DGs and the grid.

D. Non-deterministic DG Allocation and Constraints

Generally, a series of proposed conditional probability functions utilized for non-deterministic DG allocation should obey the following requirements: (1) the IEEE standard [46]; (2) requirements from local utilities (see examples in [47] and [48]); (3) physical conditions of the selected distribution network. The relationship between type, size, and location of DG are taken into consideration. In this paper, we follow the conditional probabilities and constraints suggested by [26].

TABLE I. TYPES AND RATINGS OF DG.

Types of DG	Output Range of DG	Power Factor
Inverter-based	0.02 kW to 2 MW	1
Induction	0.01 kW to 2 MW	0.9
Synchronous	1 kW to 2 MW	0.85

TABLE II. 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

III. VOLTAGE STABILITY OF MESHED NETWORK

Voltage stability is related to the overall loadability of the system [30]-[32]. It is possible that the entire system is operated on the border of the voltage instability region while the voltage profiles of the system are still within the normal operating margins.

Fig. 2 demonstrates the relationship between the load bus voltage magnitude and load demand, which is also known as the P-V curve. The distance from the current operating point to the voltage collapse point ('Knee' point) renders the measurement of the voltage stability margin (*VSM*). At this point, the load demand is the same as the maximum deliverable power. The *VSM* discussed in this paper is an estimation of long-term voltage stability [49] of the entire system.

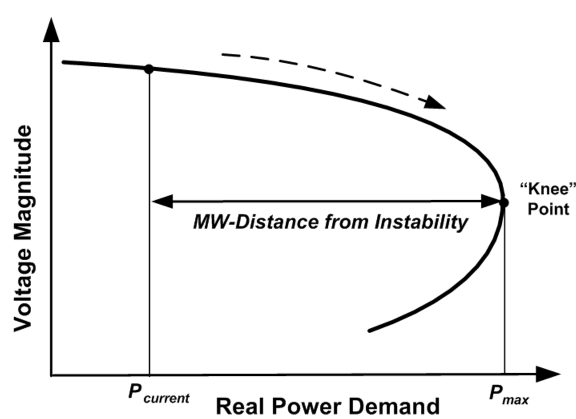

Fig. 2. P-V curve.

The *VSM* can be established by searching for the voltage collapse point on the P-V curve [49]. Before the collapse point is reached, the network *VSM* may be expressed as:

$$VSM = P_{\max} - P_{current} \,, \quad (1)$$

where P_{max} is the maximum deliverable power, $P_{current}$ is the load active power demand at current operating point (OP), and *VSM* represents the MW-distance between current OP and the collapse point [50].

The continuation power flow (CPF) method [35] is applied to estimate the stability margin. While the load power factor is assumed to be constant, the load demand is increased in small increments so that the operating point will be pushed from the base case towards the collapse point along the P-V curve. The voltage collapse point is obtained when the load flow Jacobian becomes singular.

IV. DG Penetration Study

In this work, all the scenarios were simulated in time and frequency domains in ATP. Every system component is represented within detailed models. The reasons for performing the studies in ATP are as follows [26], [27]: 1) network protection cannot be represented by commercial load-flow tools; 2) the mechanisms of switching and protective devices cannot be properly modeled in other tools (under- and over-voltage protection of DGs); 3) the DG model is not as detailed in other tools as those in ATP. The DG and load models are represented explicitly in ATP simulations. The loads are represented as constant impedances and the DGs are represented using steady-state model [51].

The simulation time is set to be sufficient enough to reach the steady-state in time-domain simulations (time step 80 µs). For cases under light load conditions, we used 800 ms, which is 10,000 time steps overall. For cases under peak load conditions, we used 1200 ms, which is 15,000 time steps overall. To obtain results of possible outcomes of allocation, the penetration level of DGs is increased in increments of 10% under both light and peak load conditions. The precision level of *VSM* is 0.1%.

An overview of the study procedure is illustrated in Fig. 3. We focused on the two situations: when the DGs are placed with a certain penetration level under light (minimum) and peak (maximum) load conditions. First, the VSM of base cases was obtained. Then DGs were added in the base case and the VSM with allocated DGs was obtained.

The DG allocation procedure is shown in Fig. 4 [26], [27]. The parameters of DG are discussed in Section II-C and the constraints are discussed in Section II-D. The non-deterministic DG units were generated from the PDFs using Gibbs sampler (Section II-B) and placed at a particular location only when none of the constraints are violated [26], [27]. The DG is allocated one-by-one, mimicking how DG allocation is performed by customers.

The details of how to obtain the VSM are shown in Fig. 5. After running the time-domain steady-state cases in ATP, we obtained the results and created the load-flow files of cases with DG allocated. Then, we ran load flow using the load flow function in ATP to obtain the VSM.

V. Results and Analysis

Prior to the DG penetration study, we examined the network voltage profiles under light and peak load base cases to ensure the test network is suitable and stable. The obtained results show the voltages at primary sides of transformer and at loads are within ±5% range from the nominal voltage. For all other simulation cases in this paper, the voltage profiles of the transformers are always within ±5% range from the nominal voltage.

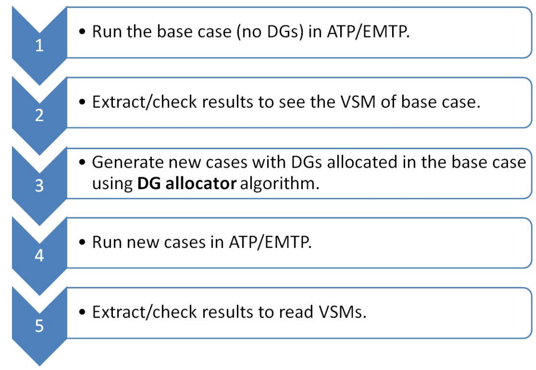

Fig. 3. Overall Study Procedure.

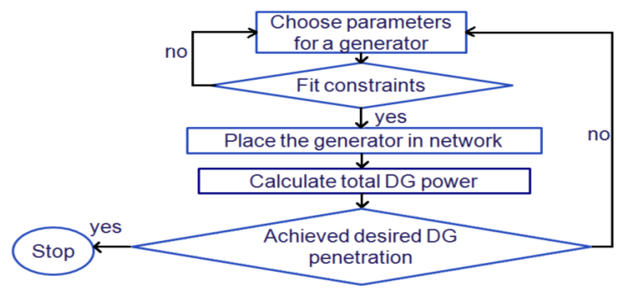

Fig. 4. DG allocation procedure.

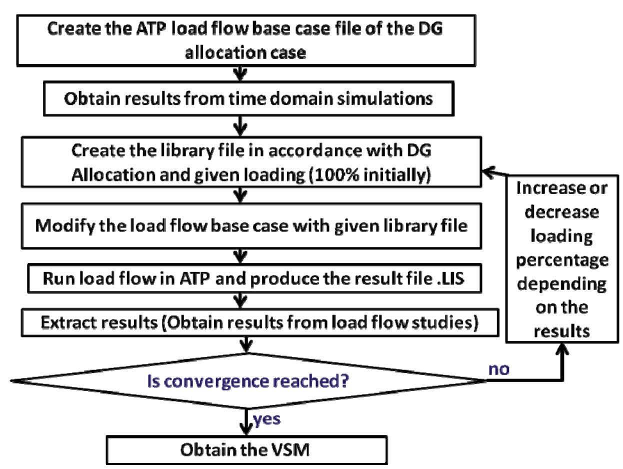

Fig. 5. Procedure of obtaining the *VSM*.

Figs. 6 and 7 summarize the results of this study, which demonstrate DG real power output versus the *VSM* under light and peak load conditions, respectively. It can be observed from Figs. 6 and 7 that there are more data points under higher penetration at the upper right hand corner, which means DG has a positive impact on the *VSM* in general. This has been further illustrated in Table III, where the average *VSM*s are shown under light and peak load conditions.

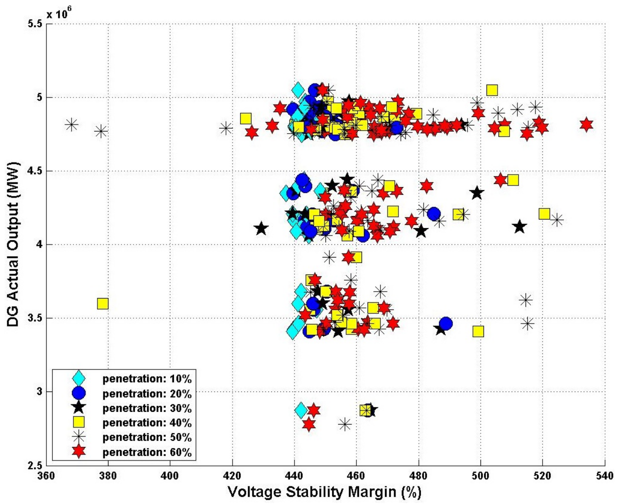

Fig. 6. DG real power output verses the *VSM* under light load conditions.

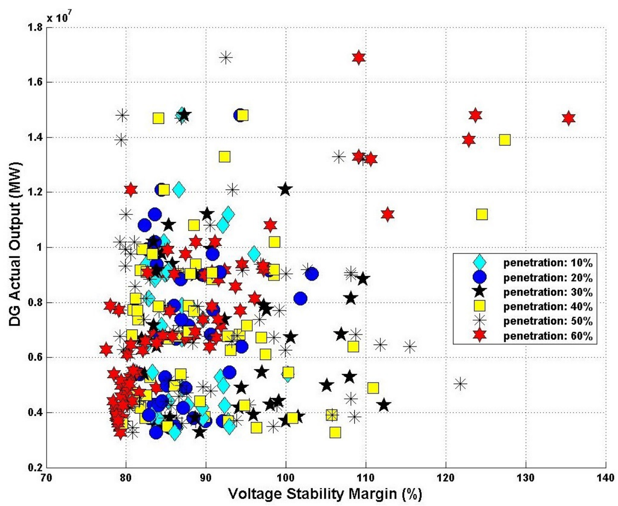

Fig. 7. DG real power ourtput verses the *VSM* under peak load conditions.

TABLE III. *VSM* UNDER LIGHT AND PEAK LOAD CONDITIONS WITH NON-DETERMINISTIC DGS

DG Penetration (%)	Average *VSM* under Light Load Conditions with Non-deterministic DG (%)	Average *VSM* under Peak Load Conditions with Non-deterministic DG (%)
0	438.6	81.8
10	442.1	87.4
20	450.4	87.7
30	454.7	92.8
40	459.1	90.5
50	462.2	90.0
60	467.4	87.3

However, such phenomena are more distinct in Fig. 6 than in Fig. 7. In Fig. 7, a large number of cases (data points) under higher DG penetration, which have similar *VSM*s with those under lower DG penetration, are located at lower left hand corner instead of upper right hand corner. This indicates that these cases with initial (desired) high DG penetration eventually cannot produce the desired real power , and they lead to small *VSM*s. Table IV shows the final penetration of DG which is not the same as (or close to) the desired penetration under peak load conditions. One may also see the average final penetration under peak load conditions is about 20%, even when the desired penetration of DG is 60%. The reason for this is that the *VSM* of the network is very small under peak load conditions and the DG protections are open in these scenarios.

TABLE IV. TYPES AND RATINGS OF DG INITIAL AND AVERAGE FINAL DG PENETRATION LEVEL OF RUNNING CASES

Initial (desired) Penetration (%)	Average Final (after DG protections open) Penetration (%): Light Load Conditions	Average Final (after DG protections open) Penetration (%): Peak Load Conditions
10	9.24	7.45
20	19.31	11.00
30	29.30	16.98
40	38.44	18.61
50	46.86	20.29
60	53.89	21.73

Tables V and VI demonstrate (1) the number of total cases simulated, (2) the number of cases where the *VSM*s are smaller than the *VSM*s in the base cases (no DG allocated), and (3) the percentage of these cases under light and peak load conditions, respectively. For instance, in Table V under 10% DG penetration, there is one case out of 40 cases (2.5%) where the *VSM* is smaller than the one in the base case, which means the *VSM* actually decreases with DG allocated. The method for determining the number of necessary cases is presented in [26].

TABLE V. NUMBER OF CASES FOR DIFFERENT DG PENETRATION UNDER LIGHT LOAD CONDITIONS

DG Penetration [%]	Number of Total Cases	Number of Cases Having Smaller *VSM* than the Base Case	Percentage of Cases Having Smaller *VSM* than the Base Case of All Cases [%]
10	40	1	2.5
20	40	0	0.0
30	40	1	2.5
40	60	2	3.3
50	80	3	3.8
60	80	3	3.8

In Tables V and VI, the cases where the *VSM*s are smaller than the *VSM*s in the base cases (no DG allocated) are represented as data points at the left hand side in Figs. 6 and 7, where those data points having smaller *VSM* than 438.6% (*VSM* under light load base case) in Fig. 6 and 81.8% (*VSM* under peak load base case) in Fig. 7. In Table V, there are only a few cases where DG has a negative impact on *VSM*s under light load conditions. In Table VI there are more cases where DG has negative impact to *VSM*s under peak load conditions than those under light load conditions. Therefore, this situation, where DG has negative impact on *VSM*s, becomes more significant under higher DG penetration and in peak load cases, which deserve more attention. The reason is that the *VSM* is very small under peak load conditions, and the induction type DG which absorbs reactive power may easily lower the *VSM*. DG protections are open because of over- or under-voltage problems, which results in the variation of *VSM*. Therefore, we may conclude that the *VSM* problem should be analyzed jointly with the voltage quality problem to study the behavior of the network with DG allocated.

TABLE VI. NUMBER OF CASES FOR DIFFERENT DG PENETRATION UNDER PEAK LOAD CONDITIONS

DG Penetration [%]	Number of Total Cases	Number of Cases Having Smaller *VSM* than the Base Case	Percentage of Cases Having Smaller *VSM* than the Base Case of Total Cases [%]
10	40	0	0.0
20	40	1	2.5
30	40	0	0.0
40	60	10	16.7
50	80	22	27.5
60	80	34	42.5

VI. CONCLUSIONS

This paper makes several contributions:

- It has presented an overall analysis of the influence of the penetration levels of DG on the network under peak and light load conditions. DG has been allocated probabilistically to account for the future installation in the network. A large number of simulations have been performed to reach conclusions.
- The network may not sustain a high level of DG penetration because of the critical *VSM* under peak load conditions. In this study, the network can only sustain up to 20% DG penetration even though the desired penetration is 60%.
- In general, DG has positive impact to the *VSM*. However, such impact could be negative under peak load conditions and high level of DG penetration, since DG protections are open due to the voltage quality problem and this condition may affect the *VSM*. Also, the induction type DG may lower the *VSM*. Therefore, the voltage stability problem should be studied together with the voltage quality problem to maximize the penetration level of DG.

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