Discussion on the Existing Deterministic Approaches for Evaluating the Voltage Deviation due to Distributed Generation

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Abstract: - This paper investigates uncertainties in the existing deterministic approaches for evaluating steady-state voltage deviation due to distributed generation. Nowadays, deterministic approaches are widely adopted by the persons proposing the interconnection of distributed generation. However, the existing deterministic approaches overlook some operation conditions that may give rise to incorrect results and lead to wrong decisions in practical applications. In this paper, the interconnection rules for distributed generations and the existing deterministic approaches for evaluating steady-state voltage deviations are introduced first. Then, various factors effecting steady-state voltage deviation and the determination of maximum allowable DG capacity are discussed. Finally, the uncertainties of the existing deterministic approaches are discussed. It is intended for reference by utility engineers processing distributed generation interconnection applications.

Key-Words: - Distributed generation, Distribution system, Power flow analysis, Power quality, Voltage deviations, Wind power.

1 Introduction

The Kyoto Protocol went into effect on February 16, 2005. The need to reduce greenhouse gases has led to growing worldwide interest in renewable energy generation, especially wind power. Due to the desire for more renewable energy, many small power sources have been hooked up to distribution systems. The penetration of distributed generation (DG) is fast increasing in distribution networks throughout the world, especially in Europe. It is predicted that DG will account for more than 25% of new generation being installed by 2010 [1]-[2]. The major part of the increasing DGs should be covered by wind power. Wind energy is a type of clean energy, produces no air pollution, and therefore has rapidly become the most competitive energy resource among the renewable energy resources. Wind Force 12 points out that 12% of the world's electricity needs will be from wind power by 2020 [3].

IEC 61400 series standards are an important basis providing reliable certification processes and acceptance criteria for standards related to the design of wind turbines in Europe. In addition, rules for measurement and assessment of power quality characteristics of grid connected wind turbines are included in IEC 61400-21 [4]. IEEE-1547 is the standard for interconnecting distributed resources (DRs) with electric power systems, nationwide in the United States of America [5]. IEEE-1547 offers a way to more efficiently manage energy resources, and ensure the reliability of the power system.

The reduction of distribution network power loss, release of transmission capacity, and enhancements of system continuity and reliability are some of the advantages of DG applications. In contrast, the parallel operations of DG with the power grid alters the traditional operating rules of the latter and poses new issues regarding power quality, e.g. voltage deviations, flicker, harmonic, frequency, etc.

However, the most critical impact of DG on the distribution grid is the steady-state voltage deviation (or slow voltage variation). Hence, a simply applicable deterministic approach to steady-state voltage deviations becomes imperative. For that reason, some evaluation methods of steady-state voltage deviations have been proposed [6]-[9]. In [6]-[7], some concepts of deterministic approaches were presented. Slow and fast voltage deviations, flicker and harmonic emissions evaluation methodologies were considered in [8]-[9].

In recent years, energy efficiency improvement and greenhouse gas emission reduction are hot subjects in numerous fields. Therefore, many studies that can be used to improve system efficiency and reduce the carbon dioxide emissions have been presented. In [10], a comprehensive unified energy and environmental model for cooling generation assessment was presented. In [11], the influence of energy consumption and CO_2 emission by different building methods during all the process from the producing of material to completion of construction was discussed.

Many studies on the maximum allowable DG capacity that can be connected to a distribution system without problems have been presented. In [12], the influences of several distribution voltage control methods on maximum capacity of distributed generators were discussed. In [13], [14], a general formula to calculate the range of the maximum DG capacity per feeder was presented. In this general formula, many parameters, such as the length of the feeder and the power factor of DG were taken into account. In [15], a method for placement of DG units in distribution networks has been presented. This method is based on the analysis of power flow continuation and determination of buses most sensitive to voltage collapse.

For a future integration in a Micro-Grid and Virtual Power Plant (VPP) method, a multi-objective approach to support selecting the location and size of DG in distribution networks was presented in [16]. This approach is based on a Soft System Methodology (SSM) for structuring the problem of DG planning and Genetic Algorithms (GA) to compute non-dominated solutions to the multi-objective programming model. In [17], an engineering algorithm to place DGs in strategic locations as a solution of the system problem when subjecting to a severe disturbance was presented. This algorithm is adopted to minimize the operation cost taking into consideration the system operation constraints when applying either installing DG units or shedding loads.

Many maximum power point tracking (MPPT) techniques for photovoltaic systems have been developed to maximize the produced energy. However, these techniques may vary in many aspects as: simplicity, convergence speed, sensors required, cost, digital or analogical implementation, range of effectiveness etc. In [18], a comparative study of ten widely-adopted MPPT algorithms was presented.

The paper is organized as follows: the introduction of the interconnection rules for distributed generations, the existing deterministic approaches to steady-state voltage deviation, the factors affecting steady-state voltage deviations, determination of maximum allowable DG capacity, comparison of the solution sets by power flow analysis with the evaluative results by the existing deterministic approaches, followed by a concise conclusion.

2 Interconnection Rules for Distributed Generations

Table 1 outlines the requirements for the steady-state voltage deviation caused by DG grid-connection in the US, Germany, and Denmark. IEEE Std. 1547 states that the DR (distributed resource) unit shall parallel with the area electrical power system (Area EPS) without causing a voltage fluctuation at the point of common coupling (PCC) greater than ±5% of the prevailing voltage level of the Area EPS at the PCC, and meet the flicker requirements. The cumulative influence of the existing DR units parallel with the same Area EPS must be taken into account in the evaluated value of the voltage variation. The relevant codes of Germany and Denmark were established by considering single wind turbines and whole wind farms separately to bound the voltage variation at the PCC. Although the system characteristics, voltage levels and considerations are different from country to country, the requirements of maximum permissible steady-state voltage deviation caused by DG grid-connection are commonly bounded within 1 to 5% [19]-[23].

Table 1. Overview of common requirements for voltage deviation

	Area, Regulation and Scope		Voltage Deviation
US	IEEE Std. 1547		± 5 %
Germany	VDEW	Medium Voltage Network	< 2 %
	VDN	Individual generating unit (wind turbine)	≤ 0.5 %
	VDN	Entire plant (wind farm)	≤ 2 %
	VDN	System faults	≤ 5 %
Denmark	DEFU	10 ~ 20kV grid	≤ 1 %
	Eltra Transmission grid	General constraint (wind farm)	< 3 %
		Until a freaquency of 10 per hour (wind farm)	< 2.5 %
		Until a freauency of 100 per hour (wind farm)	< 1.5 %
	Eltra Distribution grid	10 ~ 20kV grid (wind turbine)	≤ 4 %
		50 ~ 60kV grid (wind turbine)	≤ 3 %

3 Existing Steady-State Voltage Deviation Deterministic Approaches

For the most part, (1) and (2) are usually used to assess steady-state voltage deviations due to DG interconnection with the distribution network [6]-[9].

$$d\% = \frac{R \cdot P_\phi + X \cdot Q_\phi}{\left|U_{DG(w/o)}\right|^2} \times 100\% \tag{1}$$

where d% denotes the steady-state voltage deviation as a percentage of the nominal voltage; $U_{DG(w/o)}$ is the nominal line-to-line voltage (in kV) without DG output; R and X represent the equivalent resistance and inductive reactance at the DG-connected point respectively (in Ohms); and P_ϕ and Q_ϕ stand for the maximum active and reactive power produced by DG (in MW and Mvar) respectively.

$$d\% = \frac{S_G}{S_{S.C.}} \cos(\phi + \theta) \times 100\% \tag{2}$$

where d% denotes the steady-state voltage deviation as a percentage of the nominal voltage; $S_{S.C.}$ is the network short circuit capacity at the point of DG connection; S_G stands for the rated apparent power of DG at 1-min. time interval; and ϕ and θ represent the phase angle of the grid driving-point impedance and the phase angle between the output voltage and current of DG, respectively. Network short-circuit capacity and grid driving-point impedance angle are the parameters that describe the strength and characteristic of the grid at the point of DG connection.

Although deterministic approaches are widely adopted to evaluate the steady-state voltage deviation due to DG grid-connection, the existing deterministic approaches are too simplified to take into account all the system operating conditions in real situations. Therefore, deterministic approaches are not always valid to confirm that the steady-state voltage deviations caused by DG interconnection satisfy the requirements of the rules in IEC 61400-21.

More, the above evaluation methods are generally not suitable for two or more DGs interconnected to a feeder. In such cases, the results of the voltage deviations are caused by all DGs and the discrete loads along the feeder. Hence, power flow calculations are commonly required, and the actual network configuration and loads must be taken into account.

3 Factors Affecting Steady-State Voltage Deviations

Even though the most rigorous way for determining the steady-state voltage deviations of DG grid-connection is power flow analysis, transparent evaluation methods for voltage deviations are imperative. DG models are like other electric devices having both steady-state and dynamic models. In this paper, the steady-state DG model was adopted for evaluating the steady-state voltage deviations due to DG interconnection to the distribution network.

In general, the major factors that affect steady-state voltage deviations due to DG interconnection are the power factor of DG, the system short-circuit capacity, the rated capacity of the main transformer, the percent impedance of the main transformer, the size of the feeder main conductor, the length of the primary feeder, the discrete loads along the feeder, the power factors of feeder loads, the distribution of feeder loads, the voltage level of the primary feeder, etc. In the major factors listed above, the power factor of DG is the most significant one. Hence, the power factor of DG is considered separate from other factors.

3.1 System short-circuit capacity

In this paper, the system short-circuit capacity stands for the short-circuit capacity at the high-voltage side of the main transformer. The driving-point impedance (the equivalent impedance view into the system) at the high-voltage side of the main transformer, denoted as system driving-point impedance, is inversely proportional to the system short-circuit capacity. The driving-point impedance at the point of DG connection is therefore varied with the system short-circuit capacity. Usually, if the system short-circuit capacity is larger than 2000 MVA, the system driving-point impedance will be much smaller than the impedance of the main transformer. Therefore, the effects of the system driving-point impedance (or the system short-circuit capacity) on the voltage deviation will be less significant than the impedance of the main transformer, and may be neglected.

3.2 Rated capacity of main transformer

The per-unit impedance of the main transformer is inversely proportional to its rated capacity. Hence, the driving-point impedance at the point of DG connection is also inversely proportional to the rated capacity of the main transformer. That is, the larger the transformer capacity is, the less voltage deviation arises.

3.3 Percent impedance of main transformer

The percent impedance of the main transformer is the key factor affecting the network equivalent impedance or the short-circuit capacity at the secondary side of the main transformer. Hence, the driving-point impedance at the point of DG-connection is also proportional to the percent impedance of the main transformer. The typical percent impedances of main transformers in distribution systems of Taiwan Power Company (Taipower) are between 5 and 15%. Hence, the larger the transformer impedance is, the more voltage deviation occurs.

3.4 Size of primary feeder conductor
If the DG connection point is located nearer to the feeder end, the effect of the feeder impedance on the driving-point impedance at the DG-connection point becomes larger. In that case, if the length of the primary feeder is not short, the size of the feeder may have a significant effect on the voltage deviation.

3.5 Length of primary feeder
The feeder impedance is linearly proportional to the feeder length. Hence, the feeder length also has a significant effect on the driving-point impedance at the DG-connection point, as well as the voltage deviation.

3.6 Loads on primary feeder
The currents in feeder segments are functions of the loads distributed along the primary feeder. Although the current will not affect the driving-point impedance of the DG-connection point, it does affect the voltage deviation.

3.7 Power factors of feeder loads
The power factors of feeder loads along the feeder play a key part in voltage deviation on a feeder, therefore, should be taken into account when evaluating the voltage deviation due to DG.

3.8 Distribution of discrete feeder loads
It is not easy to analyze the effects of distributed loads accurately in real situations. In general, the distributions of discrete feeder loads can be classified into three typical groups: increasingly distributed, decreasingly distributed, and uniformly distributed loads. The different load distributions may cause different current flows inside the feeder segments. The load distributions also play a key part in voltage deviation of a feeder. However, the load distribution is not considered in the existing deterministic approaches. That makes the existing deterministic approaches inaccurate inherently.

3.9 Voltage level of primary feeder
With the same loading conditions, the higher the voltage level of the primary feeder, the less feeder current flows. On the other hand, if the same conductor size is used, the higher voltage level will allow more power to be delivered. For example, for an 11.4 kV Taipower open-loop distribution system the typical maximum continuous operation current limit of a primary feeder is 300A. That is, the maximum power that can be delivered by a feeder is about 6 MVA. If the feeder voltage level is upgraded from 11.4 kV up to 22.8 kV, the maximum power delivered is increased from 6 MVA to 12 MVA. Besides, on the same feeder loadings, if the voltage level is increased, the load currents will be decreased proportionally, and the voltage deviation will decrease as well. This factor is not taken into account in the existing deterministic approaches either.

The factors described above can be classified in two groups: the impedance-sensitive factors and the current-sensitive factors. The system short-circuit capacity, the rated capacity of the main transformer, the percent impedance of the main transformer, the size of the feeder conductor, and the length of the primary feeder belong to the first group, the impedance-sensitive factors. The loads on the primary feeder, the power factors of feeder loads, the distribution of discrete feeder loads and the voltage level of the primary feeder are included in the second group, the current-sensitive factors. These two kinds of factors have less or more effect on voltage deviation, case by case.

In general, the existing deterministic approaches only consider the impedance-sensitive factors and two of the current-sensitive factors, that are the loads on the primary feeder and the power factor of feeder loads. In other words, the existing deterministic approaches consider the short-circuit capacity at the point of DG connection and the total active and reactive power consumptions of the feeder loads. Therefore, imprecision is not prevented in the evaluation results by supplied the existing deterministic approaches.

4 Determination of Maximum Allowable DG Capacity
To overcome the uncertainties of the existing extreme values deterministic approaches, performing computations for every possible

combination of bus loads, power productions of DGs is necessary. Therefore, the possible combinations within the feasible ranges of parameters in interest distribution systems are taken into account.

In the proposed algorithm, a maximum allowable DGs capacity calculation algorithm (MADCCA) is necessary to search the maximum allowable DGs capacity for the every individual system state. Fig. 1 shows the flowchart of the maximum allowable DGs capacity calculation. The maximum allowable DGs capacity of a given connection point is calculated by a pair of given voltage limits, and a given power factor of DGs. The bisection search method is used to calculate the maximum allowable DG capacity. The calculation procedure is described below, step by step:

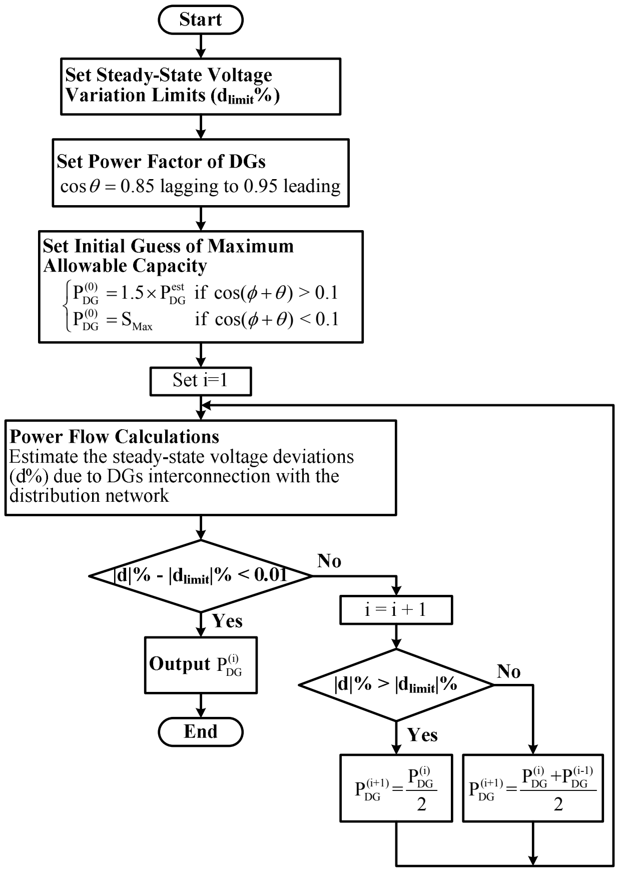

Fig. 1. Flowchart of maximum allowable DGs capacity calculation algorithm

(1) Set steady-state voltage deviation limitations: The maximum allowable DGs capacity in a distribution system should be restricted by a pair of steady-state voltage deviation limitations according to national electrical codes and local regulations.

(2) Assign a Power Factor for DGs: In every evaluation of maximum allowable DGs capacity, the power factor of DGs should be assigned first. In Taiwan, the DGs should be operated in the power factor range of 0.85 lagging to 0.95 leading.

(3) Initial Guess of Maximum Allowable DGs Capacity: If the $\cos(\phi+\theta)$, as shown in (2), is larger than 0.1, the initial value of maximum allowable DGs capacity can be obtained by (2). In this step, P_{DG}^{est} denotes the estimated value of maximum allowable DGs capacity by (2). However, if $\cos(\phi+\theta)$ is smaller than 0.1, the existing deterministic approaches become invalid. Equation (2) cannot be applied to obtain the estimated value of maximum allowable DGs capacity. In this case, a related larger value will be used as the initial value of maximum allowable DGs capacity. In this paper, 15 MW is selected by considering the Taipower distribution system.

(4) Power Flow Calculation: The power flow calculations are required to find the voltage profiles of the entire distribution network under given conditions mentioned above.

(5) Judgment of voltage deviation by the specified Voltage Limitations: The steady-state voltage deviation at the point of DG connection obtained by a power flow calculation is judged according to the given pair of limitations. If the difference between calculated voltage deviation and given limitation is within the given small value ε (0.01, in this paper), $P_{DG}^{(i)}$ is the maximum allowable DGs capacity at that point under the given conditions. The search procedure will be finished after producing the search result. If it is not the case, the search procedure goes into step (6).

(6) Modify Maximum Allowable DGs Capacity for Next Trail Values: If the steady-state voltage deviation at the point of DG connection exceeds the limitations of the steady-state voltage deviation, $P_{DG}^{(i)}/2$ is selected as the next trail value of the maximum allowable DGs capacity. Otherwise $(P_{DG}^{(i)} + P_{DG}^{(i-1)})/2$ is selected.

Therefore, the maximum allowable DGs capacity obtained as a calculation result satisfies a pair of the steady-state voltage deviation limitations.

A flow chart of evaluation algorithm of maximum allowable DG capacity connected to a distribution system is illustrated in Fig. 2. The first step in execution of the application program is to input the feasible regions of the system topology and system load conditions. In the second step, the possible combinations of the system topologies and the system load states in the feasible regions of the interest distribution systems are generated. In the third step, a series of power flow solutions for every probable combination of bus loads and system topologies is implemented. In the last step, the solution sets by power flow analyses are output by two polynomials of degree 2, that is, the upper and lower limits by the power flow solutions.

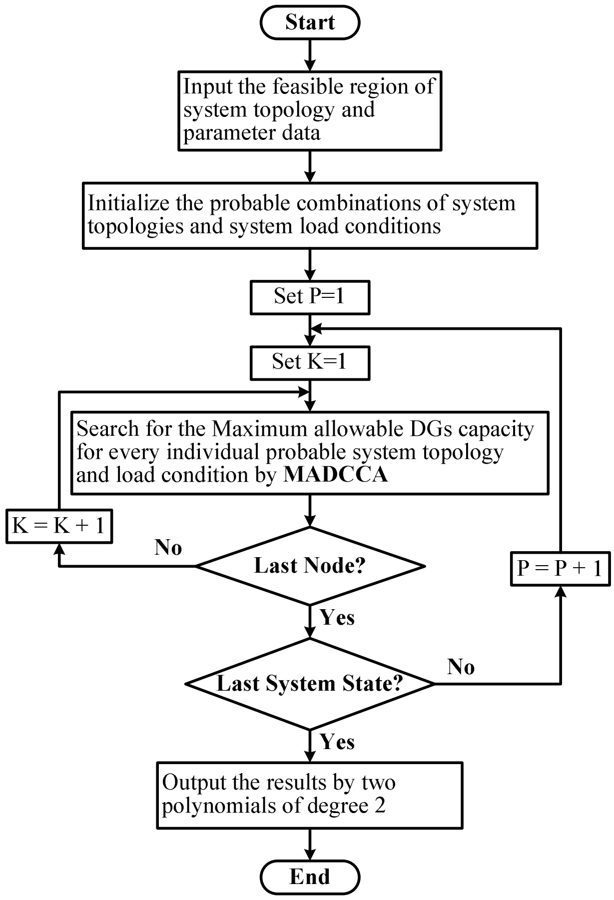

Fig. 2. Flowchart of the proposed algorithm

5 Test Cases and Results

A 13-bus distribution system shown in Fig. 3 is adopted as a sample system to discuss the uncertainties of the existing extreme possible values deterministic approaches. In Fig. 3, each dot denotes a load tapped-off point with loads lumped at that location. The lumped load is assumed to be three-phase balanced.

The feasible ranges of system parameters in practical Taipower distribution systems are listed as follows:

(1) The system short circuit capacities at the primary side of the substation transformers are typically between 400 and 2000 MVA.
(2) The voltage levels of the primary distribution network are 11.4 or 22.8 kV.
(3) The X/R ratios of the equivalent impedance viewed into high-voltage transmission network from the primary side of the substation transformer are typically between 6.0 and 6.5.
(4) The rated capacities of the substation transformer are 25, 30 or 60 MVA.
(5) The percent impedances of the substation transformer are typically from 5% to 15%.
(6) The X/R ratios of the substation transformer are typically between 10 and 20.
(7) The circuits in the Taipower distribution systems typically have main feeders of 5 to 20 km in length with various three-phase and single-phase branches from the three-phase feeder main. Moreover, in the program, the lengths of line segments of this radial-type feeder are generated randomly.
(8) The feeder conductor in the Taipower distribution system is 477 AAC overhead lines or 500 MCM underground cables, with unit length impedances of 0.131 + j 0.364 and 0.1469 + j 0.1325 ohms per km respectively.
(9) The total of a given feeder are between 600 kW and 3 MW, and the power factors of all loads are assumed between 0.8 lagging and unity. In the search process, three types of load distributions: increasingly distributed, decreasingly distributed, and uniformly distributed are all applied.
(10) The total loads of other feeders supplied by the same substation transformer are between 2 and 9 MW, and represented by a lumped load connected to the bus of the secondary side of the substation transformer. The power factor of this lumped load is assumed to be unity because the power factor is mostly corrected to near unity in Taipower distribution systems.

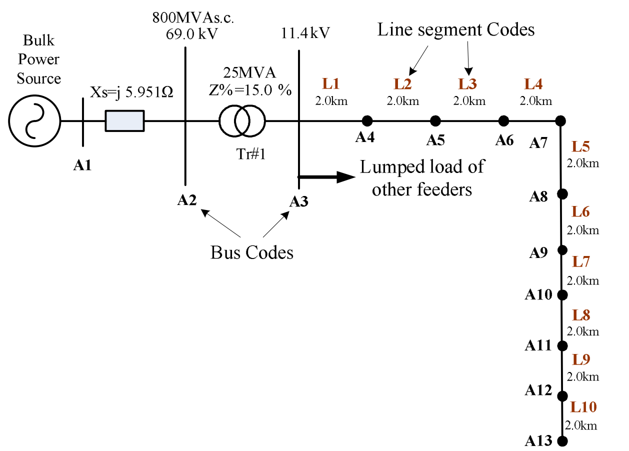

Fig. 3. Sample system

Fig. 4 illustrates the comparisons of the solution sets by power flow analysis with the evaluated solutions by existing extreme values deterministic approaches. The DGs are assumed to operate at unity power factor and the steady-state voltage deviations due to DG are limited to 2.5%, as a percentage of the nominal voltage.

Fig. 4 indicates that the maximum allowable DG capacity versus the short-circuit capacity at the connection point of DG is not unique. The simulation results reveal that the solutions for the existing deterministic approaches are located between the upper and lower limits by the power flow solutions, because the maximum allowable capacities of DG are determined by the actual network configurations and features, as well as the load conditions. Thus, the evaluation results of existing extreme values deterministic approaches will be full of uncertainties because of various system operating conditions in real situations. This makes the person processing the DG interconnection lose confidence in making judgments on the interconnection application with only the results from deterministic approaches.

Generally, the maximum allowable capacities of DGs to be installed are restricted by the limitation of steady-state voltage deviation ruled by interconnection codes and maximum continuous operation current of feeder according to the network configuration.

Fig. 5 shows the case that the DGs are operated at a power factor 0.95 leading. The results indicate that the solutions by the existing deterministic approaches dramatically diverge from the solution region obtained by power flow analysis because in these cases the $\cos(\phi+\theta)$ is smaller than 0.1. That makes the existing deterministic approaches invalid. Hence, the applicable range of the existing deterministic approaches is restricted to $\cos(\phi+\theta) > 0.1$. So, existing deterministic approaches are limited by this condition, as well as the DG operating conditions.

Fig. 6 shows the case that the DGs are operated at a power factor 0.85 lagging. And, the steady-state voltage deviations due to DG are limited to 2.5%, as a percentage of the nominal voltage. The simulation results show that the solutions for the existing deterministic approaches are above the upper and lower limits by the power flow solutions, that is, the maximum allowable DG capacities are overestimated by the existing extreme values deterministic approaches. Therefore, the existing deterministic approaches will yield uncertain results due to various distribution system operating conditions.

If all the system parameters of a system are within the ranges given in the sample system, the steady-state voltage deviations should be located between the lower and upper limit curves shown in Fig. 4. The error of the deterministic approaches will be limited. More, Fig. 4 will be of value to quickly process the interconnection application. If the parameters do not fit, the Fig. 4 cannot be applied. For example, if the length of a feeder is longer than 20 km. Hence, if the ranges of the system parameters can cover typical distribution circuit parameters of a utility or portions of utility distribution systems, a Fig., which looks like Fig. 4, can be obtained and be applied to most interconnection cases. However, a lot of power flows should be analyzed to obtain a Fig. like Fig. 4.

To perform fast screening process for the interconnection applications of DGs, the Fig. 4 is redrawn to Fig. 7. In the same way, Figs. 5 and 6 can be redrawn to Figs. 8 and 9 respectively. Figs. 8 and 9 show the case that the DGs are operated at power factor of 0.95 leading and 0.85 lagging respectively. The solution sets of the maximum allowable DGs capacity connected to a distribution system by the proposed algorithm, shown in Figs. 7, 8, and 9, can be distinguished into four regions.

(1) Region I: If the cases located above the upper limit curve and below the maximum continuous operation limit line, the steady-state voltage deviations due to DG will be greater than ±2.5%. However, the operation currents due to DG may fit the maximum continuous operation limitation.
(2) Region II: If the cases located between the lower and upper limit curves, and below the maximum continuous operation limit line, the operation currents due to DG may fit the maximum continuous operation limitation. However, the steady-state voltage deviations due to DG cannot be determined because they may vary with the actual network configurations and features, as well as the load conditions. Therefore, if the case located at this region, the supplement review is required.
(3) Region III: If the cases located below the lower limit curve and the maximum continuous operation limit line, the steady-state voltage deviations due to DG will be limited to ±2.5% and the operation currents due to DG may fit the maximum continuous operation limitation. Therefore, the case located at this region will both pass the steady-state voltage deviation limitation and the maximum continuous operation current limitation in a fast screening process for DG interconnection.
(4) Region IV: If the cases located above the maximum continuous operation limit line, the operation currents due to DG will not satisfy the

maximum continuous operation limitation, the security limit.

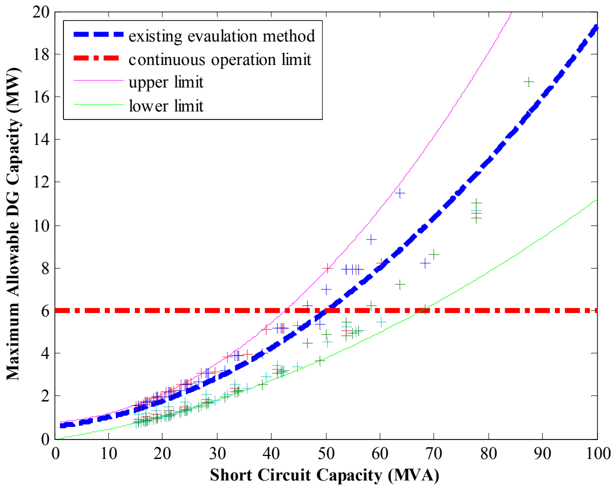

Fig. 4. Comparison of the solution sets by power flow analysis with the extreme values by deterministic approaches (DG P.F. = 1.0 and d% = 2.5%)

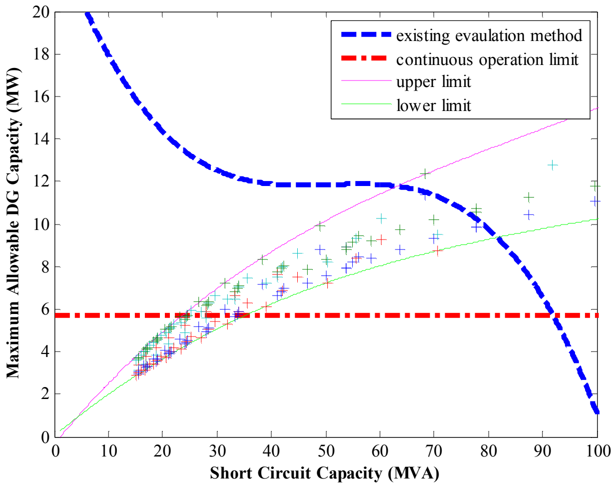

Fig. 5. Comparison of the solution sets by power flow analysis and the extreme values by the deterministic approaches (DG P.F. = 0.95 leading and d = 2.5%)

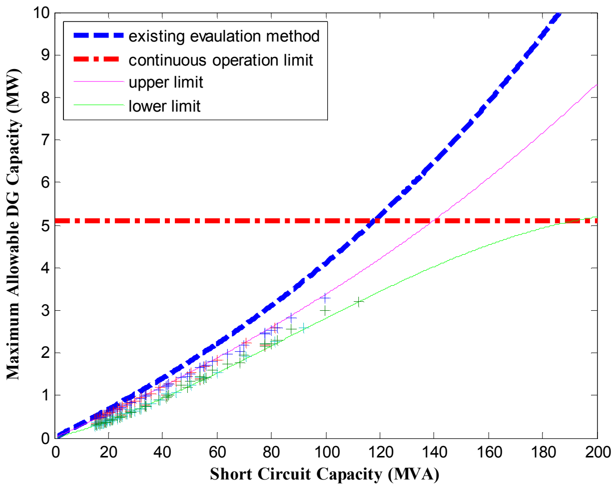

Fig. 6. Comparison of the solution sets by power flow analysis and the extreme values by the deterministic approaches (DG P.F. = 0.85 lagging and d = 2.5%)

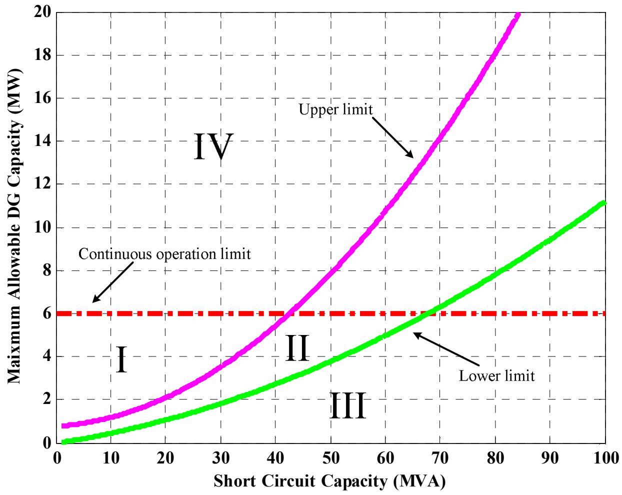

Fig. 7. Maximum allowable DGs capacity versus short-circuit capacity at the connection point of DG (DG P.F. = 1.0 and d% = 2.5%)

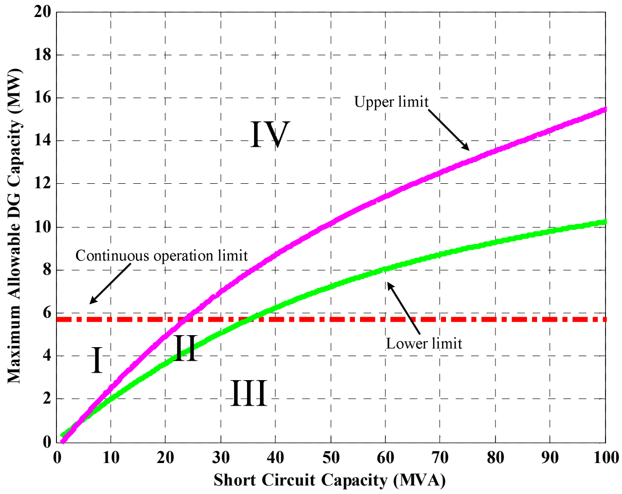

Fig. 8. Maximum allowable DGs capacity versus short-circuit capacity at the connection point of DG (DG P.F. = 0.95 leading and d% = 2.5%)

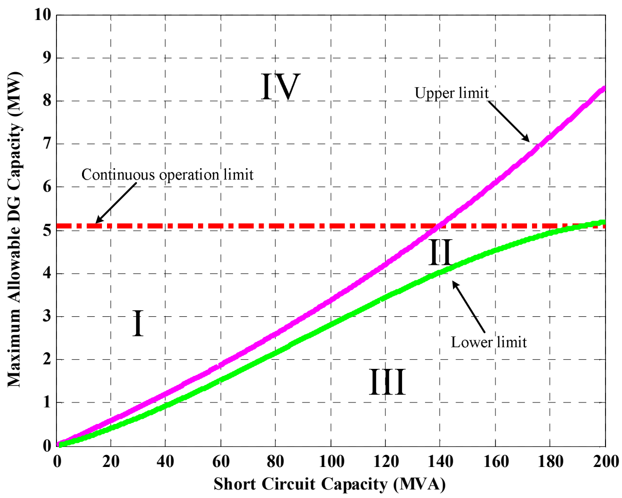

Fig. 9. Maximum allowable DGs capacity versus short-

circuit capacity at the connection point of DG (DG P.F. = 0.85 lagging and d% = 2.5%)

6 Conclusion

The findings of this paper indicate that the existing deterministic approaches will yield uncertain results due to various distribution system operating conditions in real situations. Cases located between lower and upper limits may lead to mistaken decisions concerning interconnections.

To resolve the problem, stochastic techniques can be adopted to deal with the uncertainty problems of distribution system operating states [24]-[25]. The probabilistic power flow also can be used to assess the solution sets for every possible system state [26]-[27]. However, performing computations for every probable combination of bus loads, power productions of DGs, and network topologies is impractical due to the large computation efforts required. New approaches should be proposed to remedy this difficulty.

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