Assessment of Maximum Permissible Capacity of Distributed Generations Connected to a Distribution Grid with Feeder Voltage Control Equipment

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Abstract
The primary purpose of this study is to assess the maximum permissible capacity of distributed generations (DGs) connected to distribution systems with feeder voltage control equipment using the dual genetic algorithm (DGA), in Taiwan. The DGA is adopted to address uncertainty problems of distribution system operating states. The DGA can be subdivided into two genetic algorithm (GA) stages. In the first stage, the chromosome is used to consider the configurations of the system network of interest; those are the impedance-sensitive factors. In the second stage, the chromosome is used to consider the operating statuses of the system loads and voltage control equipment; these chromosomes are the current-sensitive factors. The existing approaches overlook the system operation conditions that may yield incorrect results and hence lead to wrong decisions in practical applications. Therefore, a maximum permissible DG capacity evaluation approach based on the DGA is proposed. The conclusions from this study are beneficial for a fast screening process for grid interconnection applications in DGs and their promotion in Taiwan.

Keywords: Distributed Generation, Voltage Control, Genetic Algorithm

I. Introduction

With the rapid growth of distributed generations (DGs), feeder voltage control equipment have become critical in ensuring that bus voltages operate in a specific range (0.95–1.03 p.u.). Even though such equipment have been installed in distribution systems, good voltage regulation still needs to be ensured [1-5]. Some studies [6-10] have used the dual genetic algorithm (DGA) to evaluate the maximum permissible capacity of DGs. However, the voltage control equipment was not considered. It is difficult to maintain voltage level by operators in practice.

In this study, the DGA is used to determine the relationship between the maximum permissible capacity of DGs and the short-circuit capacity of the distribution system; additionally, the feeder voltage control equipment is considered. The topologies of the system networks and the operating conditions of the system loads with the voltage control equipment are evaluated in the first and second chromosomes of the GA, respectively. The simulation results can be used to accelerate grid interconnection applications in DGs by screening the capacity of DGs where the short-circuit capacity of a point of common coupling is under the lower limit from a distribution system operator's perspective.

II. Proposed Algorithm

To include most scenarios in practical distribution systems, the feasible ranges of the system parameters and the operation conditions for Taipower distribution systems are considered. In this study, the DGA is used to search the boundaries of the maximum permissible DG capacity.

2.1 DGA

The DGA can be subdivided into two GA stages. In the first stage, the topologies and parameters of the networks are regarded as impedance-sensitive control variables. In the second stage, the operating conditions of the system loads are regarded as current-sensitive control variables. The DGA is combined with the Pareto optimality to search the boundaries of the maximum permissible DG capacity.

(1) Objective function for the first GA

In the first GA stage, the topologies of the system networks are determined. The objective function for this stage is represented as (1). The constraint for the feasible ranges of the steady-state voltage deviations is defined as (2). The equality constraint for the operating power factor of the DGs is defined as (3). The inequality constraints for the feasible ranges of the operating impedance-sensitive and current-sensitive control variables are defined as (4) to (11).

Minimize

$$f_{1,i} = w_1 \left(\sqrt{\sum_{j=1}^{k} (P_i(S_{MVA_j}))}^{\,2} \right)^{-1} + w_2 \left(\sqrt{\sum_{j=1}^{k} (P_i(S_{MVA_j}))^2} \right) \tag{1}$$

where w_1 and w_2 are the weighting factors, and $w_1 + w_2 = 1$. If $w_1 = 1$ and $w_2 = 0$, the objective function (1) is used to search the upper boundary of the maximum permissible DG capacity. If $w_1 = 0$ and $w_2 = 1$, the objective function (1) is used to

search the lower boundary of the maximum permissible capacity.
In (1), i is the ith chromosome, j is the jth short-circuit capacity, k is the total number of short-circuit capacities, P is the maximum permissible DG capacity, and S_{MVA} is the short capacity MVA at the interconnected point of the DGs.

$$d_i \in d_{\max} \cup \mathrm{d}_{\min} \tag{2}$$
$$\cos\theta_i = \cos\theta_{spec} \tag{3}$$
$$SSCC_{\min} \le SSCC_i \le SSCC_{\max} \tag{4}$$
$$XREI_{\min} \le XREI_i \le XREI_{\max} \tag{5}$$
$$VLP_{\min} \le VLP_i \le VLP_{\max} \tag{6}$$
$$RCST_{\min} \le RCST_i \le RCST_{\max} \tag{7}$$
$$PIST_{\min} \le PIST_i \le PIST_{\max} \tag{8}$$
$$XRST_{\min} \le XRST_i \le XRST_{\max} \tag{9}$$
$$SPFC_{\min} \le SPFC_i \le SPFC_{\max} \tag{10}$$
$$LPF_{\min} \le LPF_i \le LPF_{\max} \tag{11}$$

where d is the steady-state voltage deviation owing to DG interconnection; $\cos\theta$ is the power factor of the DGs; max is the upper boundary of the constraint; min is the lower boundary of the constraint; $spec$ is the specified value; $SSCC$ is the system short-circuit capacity at the primary side of substation transformer; $XREI$ is the X/R ratio of the system equivalent impedance; VLP is the voltage level of the primary distribution network; $RCST$ is the rated capacity of the substation transformer; $PIST$ is the percent impedance of the substation transformer; $XRST$ is the X/R ratio of the substation transformer; $SPFC$ is the size of the primary feeder conductor; LPF is the length of the primary feeder.

(2) Objective function for the second GA
In the second GA stage, the operating conditions of the system loads are determined. The objective function for this stage is represented as (12). The constraint for the feasible ranges of the steady-state voltage deviations is defined as (13). The equality constraint for the operating power factor of the DGs is defined as (14). The inequality constraints for the feasible ranges of the operating impedance-sensitive and current-sensitive control variables are defined as (15) to (21).

$$\text{Minimize} \quad f_{2,\mathrm{i}} = w_1 (P_{\mathrm{i}}(\mathrm{S}_{\mathrm{MVA}_\mathrm{j}}))^{-1} + w_2 P_i(\mathrm{S}_{\mathrm{MVA}_\mathrm{j}}) \tag{12}$$

where the definitions of w_1 and w_2 are the same as those defined in the preceding section.

$$d_i \in d_{\max} \cup \mathrm{d}_{\min} \tag{13}$$
$$\cos\theta_i = \cos\theta_{spec} \tag{14}$$
$$V_{\min} \le V_k \le V_{\max} \ , \forall k \in \{1, 2, ..., n\} \tag{15}$$
$$Tap_{\min} \le Tap_i \le Tap_{\max} \tag{16}$$
$$SC_{\min} \le SC_i \le SC_{\max} \tag{17}$$
$$TLPF_{\min} \le TLPF_i \le TLPF_{\max} \tag{18}$$
$$PFFL_{\min} \le PFFL_i \le PFFL_{\max} \tag{19}$$
$$DDFL_{\min} \le DDFL_i \le DDFL_{\max} \tag{20}$$

$$TLF_{\min} \le TLF_i \le TLF_{\max} \qquad (21)$$

where V_k is the voltage at the *k*th bus; *n* is the total number of buses; Tap is the tap position of the on-load tap-charger (OLTC) transformer; SC is the number of shunt capacitor banks; $TLPF$ is the total load along the primary feeder; $PFFL$ is the power factor of the feeder loads; $DDFL$ is the distribution of discrete feeder loads; TLF is the total load of other feeders supplied by the same substation transformer.

(3) Optimal solution by the proposed DGA method

A flowchart of the proposed DGA method for evaluating the maximum permissible DG capacity is shown in Figure 1. The procedure of the proposed DGA method is as follows: (1) Input the feasible ranges of the system topologies and system load conditions, (2) translate the system topologies and system load conditions into the corresponding gene model, (3) set the sizes of the populations, and the probabilities of mutations and crossovers, (4) initialize the populations of the DGA, (5) implement the iteration procedure until the stopping rules are satisfied, and (6) output the optimal results obtained by the DGA.

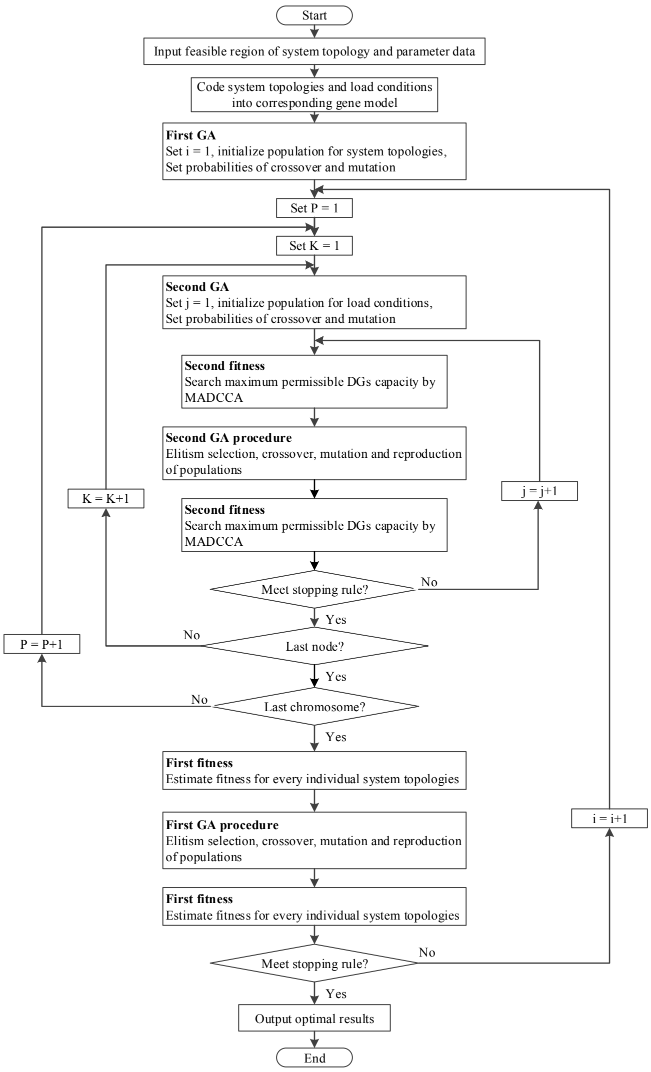

Figure 1: Flowchart of the proposed DGA method for evaluating maximum permissible DG capacity.

III Test Cases and Results

The feasible ranges for the system parameters in the Taipower distribution systems are listed in Table 1. To predetermine the range of solution sets of the maximum permissible capacity of the DGs, the operating impedance-sensitive and current-sensitive control variables for 69/11.4-, 161/11.4-, and 161/22.8-kV distribution systems (DSs) are generated randomly.

Table 1: Feasible ranges of system parameters

Factor	Feasible range for system parameters
System short-circuit capacity	800 MVA in 69/11.4-kV DSs 2,000 MVA in 161/11.4-kV DSs
Voltage level of primary feeder	11.4 kV
Rated capacity of substation transformer	12.5 MVA or 25 MVA in 69/11.4-kV DSs 30 MVA or 60 MVA in 161/11.4-kV DSs
Percent impedance of substation transformer	15%
Size of primary feeder	477 AAC with 0.131 + j0.364 Ω/km
Length of primary feeder	12 km
Peak demand at the heavy loading feeder	3 MW
Peak demand at the light loading feeder	600 kW
Total loads of other feeders	9 MW
Power factor of feeder loads	0.8 lagging
DG capacity	3 MW or 6 MW
Power factor of DG	1.0
Location of DG	Middle of feeder (6 km from substation) or end of feeder (12 km from substation)

3.1 69/11.4-kV distribution systems

(1) DG with P.F. 1.0

For 69/11.4-kV distribution systems, the case where the DGs are operated at a power factor (P.F.) of 1.0 and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 2. As shown, the system short-circuit capacity is proportional to the maximum permissible DG capacity. That is, the larger the system short-circuit capacity, the higher are the maximum DG capacities allowed. Generally, the maximum permissible capacities of the DGs are restricted by the limitations of steady-state voltage deviation owing to the DGs and the maximum continuous operation currents of the feeders and transformers. If the system short-circuit capacity is larger than 60 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (6 MVA).

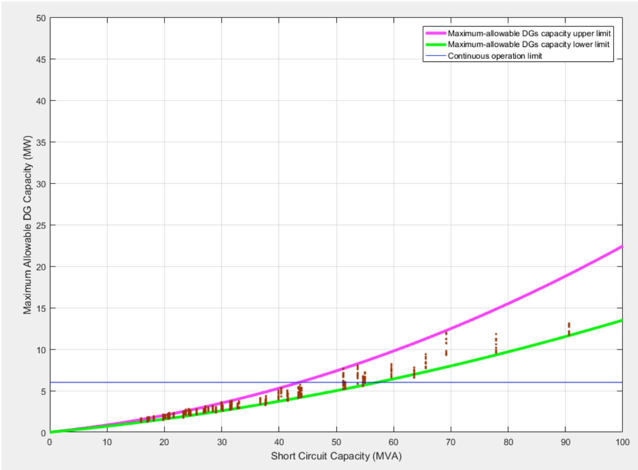

Figure 2: Maximum permissible DG capacity versus short-circuit capacity at the connection point of DG for 69/11.4-kV distribution systems (DG P.F. = 1.0 and d% = 3%)

(2) DG with P.F. 0.9 lagging

For 69/11.4-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 lagging and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 3. If the DGs are operated at P.F. lagging, the reactive power is produced by the DGs. Therefore, the voltage drops along the feeder are improved. The voltage magnitudes at the nodes along the considered feeder are increased proportionally. That is, the steady-state voltage deviations owing to the DGs are greater than the specified steady-state voltage deviation limitation. With the same system short-circuit capacity, the maximum permissible capacity of the DGs with a P.F. of 0.9 lagging is less than that of 1.0.

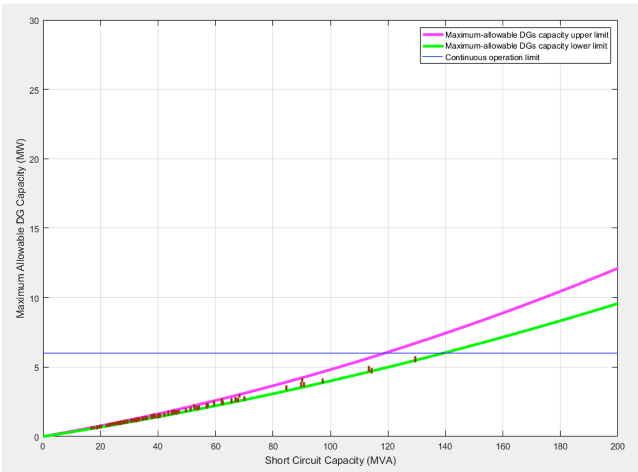

Figure 3: Maximum permissible DG capacity versus short-circuit capacity at the connection point of DG for 69/11.4-kV distribution systems (DG P.F. = 0.9 lagging and d% = 3%)

(3) DG with P.F. 0.9 leading

For 69/11.4-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 leading and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 4. As shown, the maximum permissible capacity of the DGs with a P.F. of 0.9 leading is larger than that of 1.0. If the system short-circuit capacity is larger than 55 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (6 MVA). Therefore, the operating power factor of the DGs exhibit significant effects on the steady-state voltage deviations along the feeders.

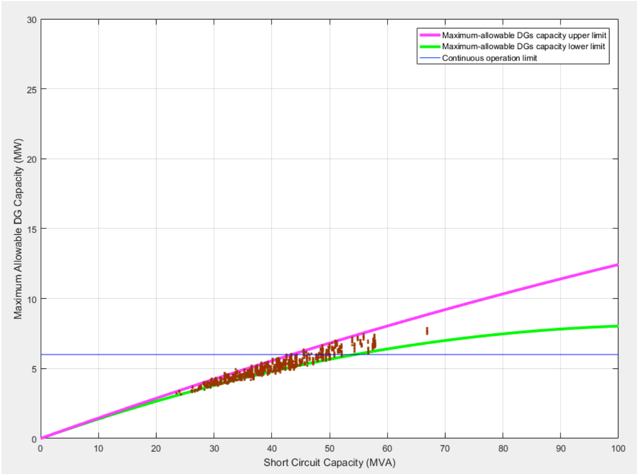

Figure 4: Maximum permissible DG capacity versus short-circuit capacity at the connection point of DG for 69/11.4-kV distribution systems (DG P.F. = 0.9 leading and d% = 3%)

3.2 161/11.4-kV distribution systems

(1) DG with P.F. 1.0

For 161/11.4-kV distribution systems, the case where the DGs are operated at a P.F. of 1.0 and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 5. If the system short-circuit capacity is larger than 65 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (6 MVA).

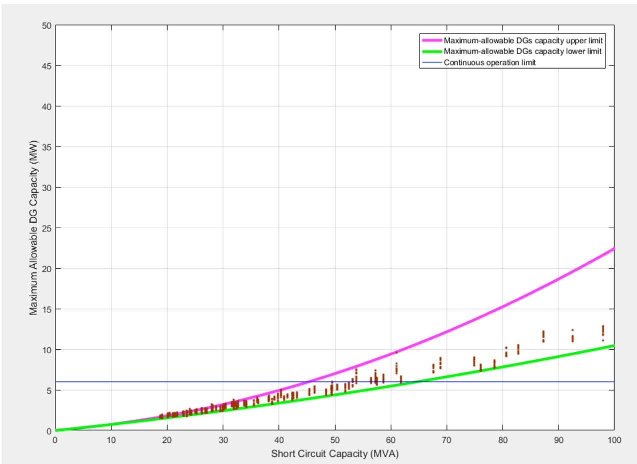

Figure 5: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/11.4-kV distribution systems (DG P.F. = 1.0 and d% = 3%)

(2) DG with P.F. 0.9 lagging

For 161/11.4-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 lagging and the steady-state voltage deviations owing to DGs are limited to 3%

is shown in Figure 6. If the system short-circuit capacity is larger than 150 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (6 MVA).

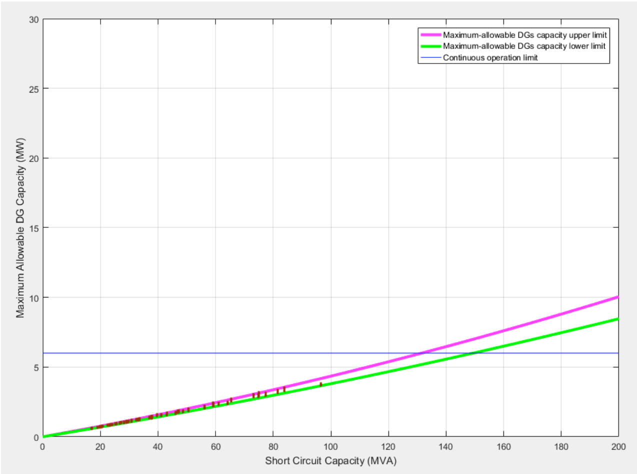

Figure 6: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/11.4-kV distribution systems (DG P.F. = 0.9 lagging and d% = 3%)

(3) DG with P.F. 0.9 leading

For 161/11.4-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 leading and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 7. If the system short-circuit capacity is larger than 55 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (6 MVA).

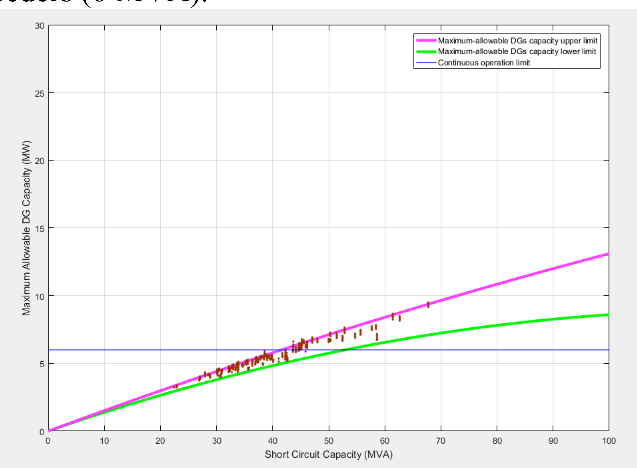

Figure 7: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/11.4-kV distribution systems (DG P.F. = 0.9 leading and d% = 3%)

3.3 161/22.8 kV distribution systems

(1) DG with P.F. 1.0

For 161/22.8-kV distribution systems, the case where the DGs are operated at a P.F. of 1.0 and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 8. If the system short-circuit capacity is larger than 230 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (12 MVA).

(2) DG with P.F. 0.9 lagging

For 161/22.8-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 lagging and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 9.

(3) DG with P.F. 0.9 leading

For 161/22.8-kV distribution systems, the case where the DGs are operated at a P.F. of 0.9 leading and the steady-state voltage deviations owing to DGs are limited to 3% is shown in Figure 10. If the system short-circuit capacity is larger than 100 MVA, the maximum permissible capacity of the DGs is restricted by the maximum thermal limitation of the feeders (12 MVA).

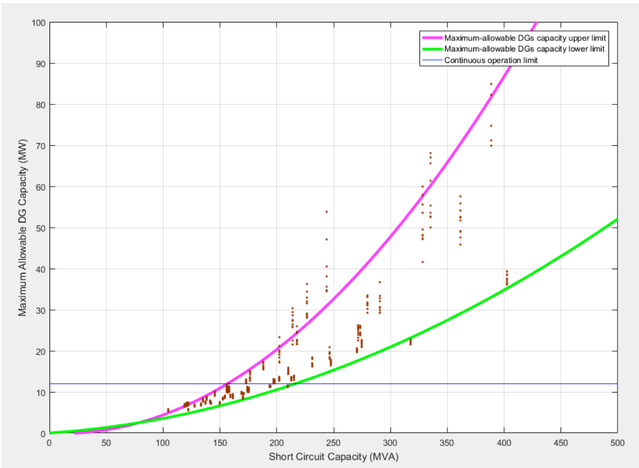

Figure 8: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/22.8-kV distribution systems (DG P.F. = 1.0 and d% = 3%)

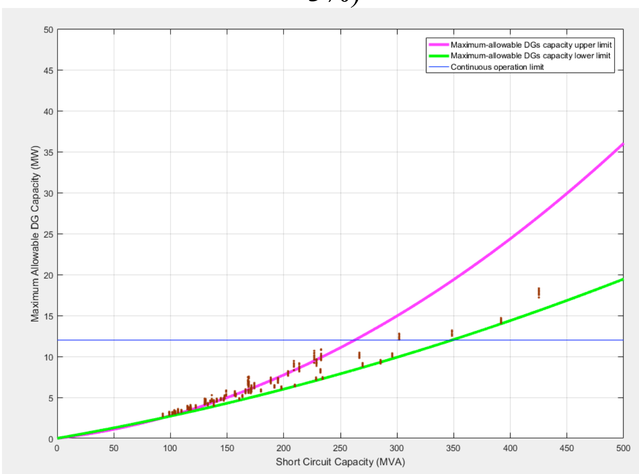

Figure 9: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/22.8-kV distribution systems (DG P.F. = 0.9 lagging and d% = 3%)

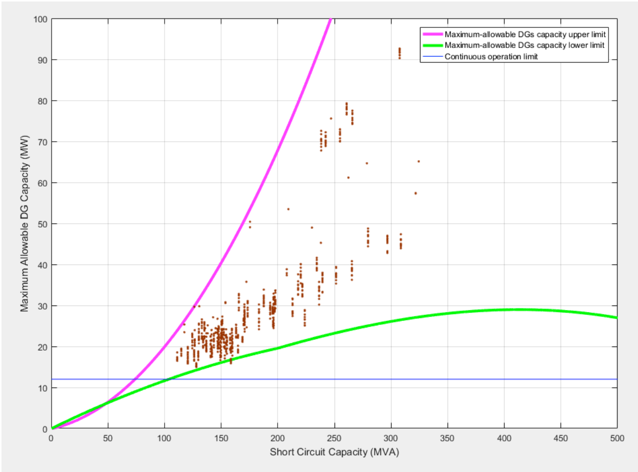

Figure 10: Maximum permissible DGs capacity versus short-circuit capacity at the connection point of DG for 161/22.8-kV distribution systems (DG P.F. = 0.9 leading and d% = 3%)

IV Conclusion

In this study, various system-planning-based factors affecting the maximum permissible DG capacity were investigated. The primary factors that affected the maximum permissible DG capacity were (1) the system short-circuit capacity at the primary side of the substation transformer, (2) the X/R ratio of the system equivalent impedance, (3) the voltage level of the primary distribution network, (4) the rated capacity of the substation transformer, (5) the percent impedance of the substation transformer, (6) the X/R ratio of the substation transformer, (7) the size of the primary feeder conductor, (8) the length of the primary feeder, (9) the tap position of the OLTC transformer, (10) the number of capacitor banks, (11) the total load along the primary feeder, (12) the power factor of the feeder loads, (13) the distribution of discrete feeder loads, (14) the total loads of other feeders supplied by the same substation transformer, (15) the power factor of the DGs. The results of this study indicated that the operating power factors of the loads and DGs majorly affected the maximum permissible DG capacity, among the primary factors listed above. Hence, the application of voltage and reactive power compensation techniques may be effective for increasing the maximum permissible capacity of DGs.

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