ON THE DER HOSTING CAPACITY OF DISTRIBUTION FEEDERS

Nikos Hatziargyriou
NTUA – Greece
nh@power.ece.ntua.gr

Evangelos Karfopoulos
NTUA – Greece
ekarf@power.ece.ntua.gr

Achilleas Tsitsimelis
NTUA - Greece
atsitsimelis@power.ece.ntua.gr

Despina Koukoula
NTUA – Greece
kdespina@power.ece.ntua.gr

Marco Rossi
RSE – Italy
marco.rossi@rse-web.it

Viganò Giacomo
RSE - ITALY
giacomo.vigano@rse-web.it

ABSTRACT

In the last two decades, there is significant increase in the grid connected distributed energy resources (DER) worldwide. At the distribution level, a high DER penetration provides a number of challenges for the Distribution system operators (DSOs) concerning the operation and planning of their electricity networks. Despite these operational problems, DSOs are often faced with high political pressures to increase DER installations by investors driven by significant economic incentives. There is a clear need to adopt an objective metric that can define, at the planning stage, the limits of electricity grids for hosting DER without violating operational constraints. This paper reviews the methods and regulations currently used in several countries, it proves analytically the maximum allowable capacity for DER hosting in the worst case scenario and examines its possible increase by applying smart control solutions.

I. INTRODUCTION

Ambitious national targets for Renewable Energy Resources (RES) have been applied by providing significant economic incentives (i.e. feed in tariff support schemes, tax exemptions etc.) to motivate a large integration of Distributed Energy Resources (DER) into distribution networks. A high penetration of DER however, can significantly affect the network operation in a number of ways. The main operational issues, as identified by [1][2], are:

- **Violation of thermal limits:** The integration of DER modifies the current flows, which can lead to the violation of thermal limits of network elements.
- **Voltage Regulation:** High DER production combined with low consumption may lead to overvoltage problems at remote nodes of the lines. Even though voltage regulation is achieved through on-load tap changers (OLTC) and step voltage regulators (VR), voltage control is complicated when lines with different characteristics are supplied from the same transformer.
- **Fault level**: DER contribution to fault currents may result in exceeding the short capacity of the network.
- **Power Quality**: Power electronic interfaced DER provides harmonic emissions.
- **Reverse Power Flow**: Distribution networks are designed on the assumption of unidirectional power flows. Under minimum demand and maximum DER generation conditions, reversal of power flows affects certain types of tap changers and the operation of voltage control and protection schemes.

Due to these adverse effects on distribution network operation, DSOs adopt conservative measures and are reluctant to increase DER penetration. On the other hand, they are subjected to increasing pressures by private investors to increase DER penetration. It is clear that an objective measure or metric is needed to define the maximum DER capacity that can be installed without provoking any technical problems. This is defined as the "DER Hosting Capacity".

The European energy regulators [3] and the European grid operators [4] have proposed the concept of Hosting Capacity (HC) as a metric of future electricity grids (the "Smart Grid"). It was examined within the EU project EU-DEEP (European Distributed Energy Partnership) aiming to determine the allowable grid deployment of distributed generation [5][6]. In the context of this paper the following definition holds:

Definition: DER hosting capacity is the network index indicating the maximum power capacity of distributed energy resources that can be integrated in a distribution network above which one or a combination of specific network parameters (i.e. bus voltage, line thermal limit, network losses, fault current, feeder power flow) exceed the pre-defined limits.

There is no common evaluation approach for the determination of the DER hosting capacity. Diverse evaluation criteria are applied by different DSOs, aiming to define the optimal DG siting and sizing, as overviewed in [7]. The common basis of all methods is the implementation of power quality indices [8] for assessing the HC. The first study on the HC published in 2004 [9] was followed by a number of publications [5][6] and [10]-[18], that deal with various effects of DER connections. For example in [11], the DC injection from the power electronic interfaces connecting DER with the grid is examined. In [12], dynamic simulations are performed to assess the risks of degraded performances of classic protection systems in the presence of significant penetration of DER. In [13], three aspects of power quality concerning DER are examined: voltage quality, current quality and network reliability/stability due to DER tripping on voltage dips or frequency swings. In [14], the optimal design of the distribution infrastructure is examined considering DER deployment. In [15], the DER hosting capacity is assessed implementing voltage criteria and considering that DER are integrated under the "plug-and-play" concept. In [16], deterministic and stochastic approaches are introduced to evaluate the DER impact on the voltage profile

(overvoltage risks). Probabilistic load flow techniques have been proposed for an objective assessment of this impact already in [17]. In [18], the impact of DG deployment on the frequency control during normal and emergency operational conditions is analysed.
This paper provides an overview of common practices for the determination of the DER hosting capacity applied worldwide. It defines the "Worst Case Hosting Capacity" metric and examines the effects of applying smart control solutions. These methods are applied to the model of an actual MV rural distribution feeder and the results are analysed and compared.

II. DER HC EVALUATION CRITERIA AND PRACTICES

This section provides an overview of the practical guidelines adopted by DSO in order to define the limits of distribution networks for hosting DER. The analysis is based on the work described in the technical brochure of CIGRE WG C6-24 called *"Capacity distribution feeders for hosting DER"* [1].
Although there is no common evaluation method for the determination of the DER hosting capacity, these can be classified into four main categories [1]:

Category A: *Criteria based on the capacity of the existing network infrastructures*

The maximum DER hosting capacity is defined as a percentage of the installed transformer capacity of HV/MV and MV/LV substations and the thermal limits of the MV and LV feeders. Concerning the HV/MV and MV/LV substation limits, this percentage usually lies between 50% and 75% as for example in Spain, Canada, Italy, South Africa etc. On the contrary, in a few countries, this percentage limit can be rather loose reaching up to 90% (i.e Czech) or even 100% (i.e. Belgium, South Korea). The aforementioned criteria can become even more strict when additional constraints are applied, such as reverse power flow and *N*-1 conditions. Indicative countries, where such constraints are applied, are Canada, Belgium, China, Czech Republic.

Category B: *Criteria related to voltage regulation limits*

The upper median voltage and the voltage variation limits reduce the DER deployment level in a distrubution network. In most countries, the voltage regulation is based on the EN 50160 standard for MV networks and EN 50549 standards for LV network. Even though the standard allowable voltage variaton is 10% from the nominal one, most DSO's practical operational limits are more strict and vary between 5÷8%. The voltage variation around the median value should not exceed 3÷4% ensuring that the final service voltage to LV users remains within statutory limits.
To evaluate the voltage criteria, load flow analysis are performed considering two extreme network operational conditions. For instance, for a given node *i*, maximum load/minimum generation for the calculation of minimum voltage $V_{min,i}$ and minimum load/maximum generation for the maximum voltage $V_{max,i}$. The median and deviation voltage performance indicators ($V_{m,i}$ and ΔV_i respectively) can be defined by:

$$V_{m,i(\%)} = \frac{\frac{V_{max,i} + V_{min,i}}{2} - V_n}{V_n} \cdot 100\% \quad (1)$$

$$\Delta V_{i(\%)} = \frac{V_{max,i} - V_{min,i}}{2V_n} \cdot 100\% \quad (2)$$

wherein V_n corresponds to the network's nominal voltage.

Category C: *Criteria based on the load-to-generation ratio*

In some countries, criteria based on the load-to-generation ratio are applied either from islanding prevention considerations or voltage regulation problems. For instance in Canada, the maximum allowable generation to be connected to a distribution system should not exceed 7÷10% of the annual feeder peak load. In South Africa, this percentage limit is almost doubled. In USA, the aggregated nominal power of the DER on a distribution line must be less that 100% of the minimum line load and up to 5% of the total annual peak load. Unless these criteria are met, a detailed evaluation procedure is required.

Category D: *Criteria related to the short circuit capacity*

The short circuit criteria ensures that the fault level of the network, after considering DER penetration, remains below the designed short circuit capacity (SCC) of the network and the short circuit withstand capabilities of individual equipment. For safety reasons, DSOs apply stricter criteria, since the aggregate nominal power of the connected DER must be lower than a small percentage (15÷25%) of the SCC at the point of common coupling. The most conservative percentage (i.e. 10%) is applied in China and Spain, while the highest one exists in USA.

III. UNCONTROLLED DER HC

The following analysis considers MV rural distribution lines, where DER integration is limited by voltage rise. Voltage rise depends on the dispersion of DER and load among the nodes of the feeder. In this section, the DER hosting capacity of a distribution feeder is examined assuming that the whole installed DER and the load are concentrated in a single node. For each network node, the DER installed capacity is increased until its voltage exceeds the maximum admissible value (+5% of the nominal value). It is assumed that the DER operates at unity power factor. The output of this analysis is a set of maximum DER installed capacities at each network bus $U = \{P_{max,1}, \ldots P_{max,i}, \ldots, P_{max,N}\}$, where N is the number of network buses. The worst case hosting capacity is defined as the minimum value of the defined set U:

$\min\{P_{max,1}, \ldots P_{max,i}, \ldots, P_{max,N}\}$.
The highest voltage rise occurs when DER is connected at the node with the largest electrical distance from the feeder origin. As proven in the Appendix, any distribution of the same DER capacity cannot provide higher voltage rises than the worst possible case defined previously. In this case, the calculated DER hosting capacity is termed the '*Worst Case Hosting Capacity*'. This is compared later with other criteria applied in practice. It is clear that the HC depends on the assumed load and that the worst case occurs at minimum load.

IV. CONTROLLED DER HC

DER hosting capacity can be substantially increased applying voltage controls. Two voltage regulation practices are examined: the on-line adjustment of the OLTC operational settings and the reactive DER output power control.

On-Load-Tap Changer control

The On-Load-Tap-Changer (OLTC) adjusts the feeder's voltage in order to maintain the bus voltages within acceptable limits. One common practice to operate the voltage regulator is based on the following expression:

$$\Delta V_e = \frac{\sum_{k=1}^{n} \Delta V_k S_k}{\sum_{k=1}^{n} S_k} \tag{3}$$

where ΔV_k is the voltage drop from the origin, S_k is the load in each network bus. The voltage at the MV bus of the in-feeding substation is fixed by the controller as follows:

$$V_{feed} = \begin{cases} 0.95 & \text{if } \Delta V_e > +0.05 \\ 1.0 - \Delta V_e & \text{if } |\Delta V_e| < 0.05 \\ 1.05 & \text{if } \Delta V_e < -0.05 \end{cases} \quad [\text{p.u.}] \tag{4}$$

In case a voltage violation occurs due to the large share of DER, the transformer tap compensates the secondary voltage rise (the OLTC is on the primary winding).

DER reactive power control

DER units can operate at lagging power factor absorbing reactive power from the grid. The absorption of reactive power can partially compensate the voltage rise at the buses where DER are connected. The effects of DER reactive power control on DER hosting capacity are then examined. It is assumed that the power factor of DER operation cannot be lower than 0.9 and that the reactive power exchange between the DER units and the grid is expressed by the fixed $Q(V)$ control curve of Fig. 1. Unless there is violation of the voltage deviation due to the DER integration, the reactive power exchange is zero or constant and the installed DER capacity at the specific bus under study further increases in a stepwise way.

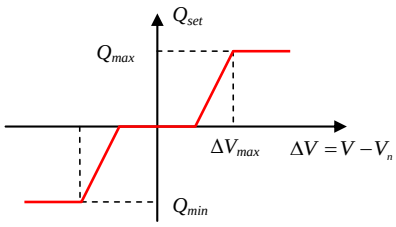

Fig. 1: Q(V) control curve for DER bus

V. STUDY CASE

A model of an actual MV rural distribution feeder of Sperhiada, in Central Greece is simulated in order to quantify the DER hosting capacity. The distribution feeder comprises a 150/(15.75-21) kV, 40/50 MVA transformer and 101 MV/LV substations. The peak load is approximately 7.5 MW and 2.98 MVAr. The minimum load is approximately 3 MW and 0.085 MVAr.

Common HC evaluation practices

In the next paragraphs, the practical criteria for calculating the DER hosting capacity classified in Section II are applied.

Category A:
The maximum DER hosting capacity is defined as percentage (50%÷100%) of the installed transformer capacity of HV/MV and MV/LV substations and the thermal limits of the MV and LV feeders. According to this, the maximum DER hosting capacity in Sperhiada case ranges between 2.36 MW and 4.71 MW bounded by the lowest line thermal limit. A more analytical approach based on the network capacity is to concentrate DER on a single bus and increase its installed power until violation of the network limits occurs in the configuration of minimum network load. Under these conditions, the DER hosting capacity varies between 2.4 MW and 4.8 MW.

Category B:
In order to calculate the voltage deviation defined by (2), V_{min} is calculated at the peak load with minimum DER generation, while V_{max} at the minimum load with maximum DER generation. For these criteria the siting and sizing of DER is crucial. DER sites are maintained at the actual connecting buses. In the minimum load configuration, the total DER installed capacity is increased and it is allocated proportionally to the initial DER distribution, until the voltage limits are violated. Under this assumption, the HC is 5.4 MW.

Category C:
According to this criterion, the DER hosting capacity ranges between 0.53 MW and 0.75 MW, when defined as percentage (7÷10%) of the network peak load, or 3 MW when considering minimum network load.

Category D:
The SCC is defined by the following formula:

$$\mathrm{SCC} \cong \frac{S_{base}}{Z + S_{base}/MVA_{trans}} \tag{5}$$

where Z is the p.u. impedance of the electrically most distant node from the origin, MVA_{trans} is the nominal capacity of the primary HV/MV transformer and S_{base} is the power base. The DER hosting capacity defined as percentage of the SCC (10÷25%) ranges between 1.42 MW and 3.54 MW.
It should be noticed that the criteria of category C and D are mostly applicable for urban lines serving higher concentration of loads, while for longer rural lines the criteria of category B are mostly relevant.

Uncontrolled Worst Case Hosting Capacity

Fig. 2 shows that the installed DER capacity decreases exponentially as a function of the electric distance from the feeder origin, when all DERs and load is assumed concentrated at a single node. The worst case hosting capacity, obtained at the most distant node, is 4.8 MW.

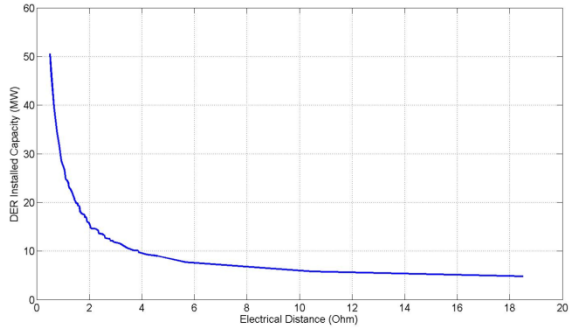

Fig. 2: The HC – Buses Electric Distance relationship

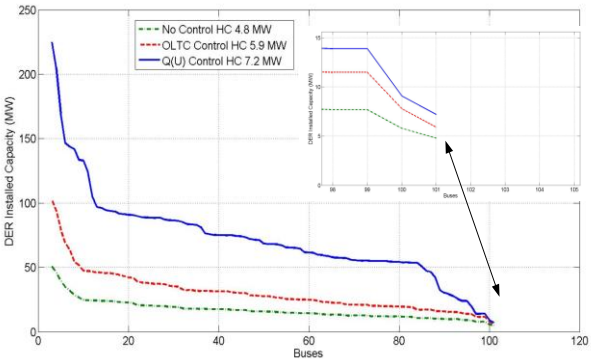

Fig. 3: The HC – Buses relationship

Controlled Worst Case Hosting Capacity

The basic characteristics of the adopted OLTC controller are reference voltage 1 p.u., control range +7.5/-12.5%, 17 tap positions (6 positive + 0 + 10 negative steps) and 1.25% change per step. Fig. 3 illustrates the effect of OLTC when the DER and load are assumed concentrated at each node. Results show that the HC value has increased to 5.9 MW. Thus, the implementation of the OLTC increases the HC to almost 23% compared to the uncontrolled case. Moreover, Fig. 3 displays also the increase of HC along the feeder, when the DER reactive power control is activated, as shown in Fig.1. The HC is now 7.2 MW, which is an increase of approximately 22% compared to the case of OLTC implementation.

Analysis of the results

Table I summarizes the results for the DER hosting capacity of the examined MV rural distribution network focusing on voltage related criteria. It can be seen that all practical methods provide results admirably close to the worst case HC. The implementation of control mechanisms for voltage compensation (OLTC and DER reactive power control) significantly increases the maximum DER capacity by 23% and 50%, respectively.

Table I: DER HC based on different evaluation criteria

Criteria for calculating DER Hosting Capacity	**DER HC** [MW]
Practical Category A Criteria - Line loading	2.4 - 4.8
Practical Category B Criteria - Voltage Variation	5.4
Practical Category C Criteria - Load-Gen. ratio	3.0
Practical Category D Criteria - Short Circuit	1.4 - 3.5
Worst case HC - Uncontrolled	4.8
Worst case HC -Controlled - OLTC	5.9
Worst case HC - Controlled - DER $Q(V)$	7.2

VI. CONCLUSIONS

This paper provides an overview of common practices for the determination of the DER hosting capacity applied worldwide. It defines the "*Worst Case Hosting Capacity*" metric and examines the effects of voltage control solutions. Comparison among the different HC evaluation practices shows that, in MV rural distribution networks, the practical criteria applied provide mostly conservative results, similar to the ones obtained by the application of the worst case HC metrics. It is shown that simple grid or DER control schemes (i.e OLTC or DER reactive power control) can significantly increase the allowable DER hosting capacity.

APPENDIX

Let's assume a radial feeder with n nodes (in which n is the most remote bus). The voltage at node k is:

$$V_k = V_0 + \sum_{h=1}^{n} z_{kh} I_h \tag{A.1}$$

where V_0 = 1 p.u. is the voltage at the MV feeder origin, I_h is the total injected current in the h-th node (DER unit current minus the current absorbed by the load) and z_{kh} is defined as follows:

$$z_{kh} = \begin{cases} \sum_{l \in path(k)} z_b(l) & \text{for } k = h \\ \sum_{l \in path(k) \cap path(h)} z_b(l) & \text{for } k \neq h \end{cases} \tag{A.2}$$

where $path(k)$ is the sequence of nodes which create a path from the feeder origin until the k-th node. Having

assumed injections of constant power S_h, unitary power factor and voltages close to 1 p.u., it can be reasonably stated that:

$$I_h = S_h^* / V_h^* \cong P_h \quad \text{[p.u.]} \qquad \text{(A.3)}$$

where V_h^* is the complex conjugate of the voltage and P_h is the injected active power, both related to the h-th bus. Assuming that all DERs and loads are connected to a generic node k, (A.1) becomes:

$$V_k = V_0 + z_{kk} \sum_{h=1}^{n} P_h \quad \text{[p.u.]} \qquad \text{(A.4)}$$

According to (A.2), z_{kk} is the total impedance of the path between the feeder origin and the selected bus k. By comparing (A.1) and (A.4), it is possible to notice that:

$$z_{kk} \sum_{h=1}^{n} P_h \geq \sum_{h=1}^{n} z_{kh} P_h \quad \text{only for } k = n \qquad \text{(A.5)}$$

Since n is the most remote node of the network (with the largest self-impedance $z_{kk} = z_{nn}$), it is possible to demonstrate that, having considered (A.4):

$$V_n \geq V_k \quad \text{for any } k \qquad \text{(A.6)}$$

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