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A methodology to calculate maximum generation capacity in low voltage distribution feeders

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A B S T R A C T

The aim of this article is to present an easily applicable methodology to calculate maximum distributed generation (DG) capacity in radial low-voltage feeders. The methodology indicates the highest capacity that can be installed at a fixed point in the feeder for which the voltage is kept within the permissible limits in critical scenarios, i.e. high generation and low load. The concept is based on the main findings of previous studies identifying the points of connections where the voltage may be exceeded. The provisional voltage profile of a line is strongly related to the topology of DGs along the line. The methodology can be applied in any radial feeder with or without existing DG installations.

1. Introduction

One of the EU's biggest challenges towards 2050 is cutting greenhouse gas emissions by 80–95% [1]. The electricity generation sector is one of the main contributors to achieve this commitment by reaching near-complete decarbonisation [2]. In this context, renewable energy sources (RES), mainly wind and solar, will provide about half of the electricity generated in the EU by 2050 [3]. Moving towards a carbon-free society requires considerable effort to reach the target whilst maintaining the quality and security of supply high. The EU is launching funding mechanisms to support activities that push forward key policy priorities towards renewable energy generation, including the development of methods and tools for network integration of distributed renewable resources [4].

Maximum capacity of distributed generation (DG) sources is limited by line loading and by voltage rise—issues already tackled in literature [5,6]. One of the major challenges at high DG penetration is to secure uninterruptable energy supply. This can be problematic in critical scenarios of low demand and high generation, causing reverse power flows in the low voltage (LV) distribution feeders. In these scenarios, according to [7,8] the voltage limit can be exceeded, leading to disconnection of the generators. Thus, one of the key elements under high DG deployment is the increase of the hosting capacity of the lines. This can be realised by measurements such as grid reinforcement, reactive power provision, active power curtailment or limiting the feed in [9–12]. These measurements have been proven costly or inconvenient to the end users [13,14]. Thus the first decision making step should be the calculation of the maximum DG capacity [15]. A precise calculation of local hosting capacities has been addressed in [16]; however, this calculation should be feeder and topology specific [17,18], because the maximum capacity of a new DG is strongly depended on the point where is going to be connected along the feeder.

Recognising the importance in finding the maximum hosting capacity of a LV feeder, the present article introduces an easy applicable tool for a straightforward estimation with no need of complicated calculations, e.g. test and trial or neural networks [19,20]. The proposed methodology calculates the maximum DG capacity in a fixed point in radial LV feeders taking into account the properties of the line and the already connected DGs. The methodology is based on an analytical approach described in [21]. As research is focusing on the measures to increase the hosting capacity, the present article answers a very targeted question which should a priori been considered: What is the maximum capacity of a new DG to be installed considering (i) specific feeder characteristics, (ii) the installation point of the new DG and (iii) already installed DGs, which leads the line to exhaust its capacity and thus aforementioned measurements should be taken afterwards?

2. Methodology

The proposed methodology is developed to calculate maximum distributed generation (DG) capacity in low voltage (LV) feeders in

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a specific node. This will determine the maximum capacity of a new DG, which can be installed, keeping power quality of the feeder in the acceptable range. It is applied with the aid of an analytical approach presented in [21]. This calculation is performed for critical scenario, when there is high DG generation and low load. In critical scenario under high DG deployment voltage upper limit may be violated. Thus the proposed methodology ensures that the voltage is within the limits under these conditions. In any other condition, the voltage along the line is lower. A single-line LV feeder, as depicted in Fig. 1, is used to explain the methodology. The presence of loads and their values (household consumption) along the feeder does not change the procedure. To simplify the methodology, the maximum capacity of a new DG to be installed is assumed to refer to a DG operating in unity power factor. Reactive power of already connected DGs (if some or all of them operate in power factor other than one) is included in the methodology (see Eq. (1), $Q_{DG \cdot i}$). Lastly, after applying the methodology, the loading of the line with the calculated maximum capacity should be checked. In case the thermal limit of the feeder is exceeded, the calculated maximum capacity of the new DG should be recalculated as it will be explained later (Section 2.1).

In order to calculate the maximum capacity of the new DG in a specific node, i.e. $j+1$, of a LV feeder with N nodes, the following equation is obtained from Eq. (11) in [21]:

$$P_{DG \cdot max \cdot j+1} = \sum_{i=j+1}^{N} (P_{LOAD \cdot i}) - \sum_{i=j+2}^{N} (P_{DG \cdot i}) + \sum_{i=j+1}^{N-1} (P_{LOSS \cdot i,i+1}) - \frac{U_{j+1} \Delta U_{j,j+1} - L_{j,j+1} X' \left(\sum_{i=j+1}^{N} (Q_{LOAD \cdot i}) + \sum_{i=j+2}^{N} (Q_{DG \cdot i}) \right)}{L_{j,j+1} R'} \tag{1}$$

where node $j+1$ is the node in which the maximum capacity of the new DG is calculated, N is the total number of nodes, $P_{DG \cdot max \cdot j+1}$ is the maximum capacity that can be installed in the node $j+1$, $P_{LOAD \cdot i}$ is the active load at node i, $P_{DG \cdot i}$ is the rated active power of the DG systems already installed along the line, $P_{LOSS \cdot i,i+1}$ are the losses between nodes i and $i+1$, U_{j+1} is the voltage of the node $j+1$, $\Delta U_{j,j+1}$ is the difference of the voltage between the successive nodes j and $j+1$, $L_{j,j+1}$ is the distance between the successive nodes j and $j+1$, X', R' are the reactance and resistance of the LV line per meter, $Q_{LOAD \cdot i}$ is the reactive load at node i, $Q_{DG \cdot i}$, is the reactive power of the DG at node i in case DG operates in a power factor other than one. For the subject DG to be connected at the node $j+1$, the reactive power is considered zero.

In order to solve Eq. (1), the following assumptions are introduced:

- Losses, $P_{LOSS \cdot i,i+1}$, along the line are relatively small [21] and are ignored. The calculated capacity will be smaller but within safe limits.
- Since critical scenario conditions of low demand and high generation are considered, loads can be assumed as a minimum household consumption (e.g. the refrigerator: 0.2 kW/phase with $\cos\varphi = 0.7$ [21]) and that the DGs operate at their rated power, thus $P_{LOAD \cdot i}$, $P_{DG \cdot i}$, $Q_{LOAD \cdot i}$ and $Q_{DG \cdot i}$ are known.

Applying these assumptions Eq. (1) becomes three unknown parameters function:

$$P_{DG \cdot max \cdot j+1} + \left(\frac{1}{L_{j,j+1} R'} \right) U_{j+1} \Delta U_{j,j+1} = \sum_{i=j+1}^{N} (P_{LOAD \cdot i}) - \sum_{i=j+2}^{N} (P_{DG \cdot i}) + \frac{X' \left(\sum_{i=j+1}^{N} (Q_{LOAD \cdot i}) + \sum_{i=j+2}^{N} (Q_{DG \cdot i}) \right)}{R'} \tag{2}$$

Eq. (2) has the following form: $P_{DG \cdot max \cdot j+1} + a\ U_{j+1}\ \Delta U_{j,j+1} = b$,where $P_{DG \cdot max \cdot j+1}$, is the first unknown – the maximum capacity that can be connected at the node $j+1$, U_{j+1} is the second unknown – the voltage at the node $j+1$ after the new installation of $P_{DG \cdot max \cdot j+1}$, $\Delta U_{j,j+1}$ is the third unknown – the voltage difference between the nodes $j,j+1$ after the new installation of $P_{DG \cdot max \cdot j+1}$.

Thus the voltage at the subject node U_{j+1} and the voltage difference of the successive nodes $\Delta U_{j,j+1}$ need to be calculated. The challenge is to find a way to predict the voltage rise caused by the new DG. The assumption in all cases is that the maximum capacity to be installed is limited by the maximum voltage that will eventually appear in the line. This voltage defines the maximum DG. The node where the maximum voltage will appear depends on the topology of the line. Thus in a feeder where DGs are already connected the maximum voltage will appear in the last distant node with a significant DG capacity installed [5]. Significant DG is considered to be a capacity high enough to cause reverse energy flow i.e. from consumer to the step-down transformer, in critical conditions (high generation and low load). Thus the maximum voltage in the line can be found at the node where this DG is connected, beyond the $j+1$ node.

In order to solve Eq. (2), a distinction should be made between different feeder topologies, since already connected DG systems play a decisive role. Three scenarios are therefore identified as presented in Table 1. The methodology is developed accordingly.

- Scenario A: The new DG is the first DG to be connected along the line at a fixed node.
- Scenario B: The new DG system is to be connected at a fixed node. The line has no other DGs connected before the new DG, but at least one DG sited after.
- Scenario C: The new DG system is to be connected at a fixed node. The line has at least one DG connected before the new DG.

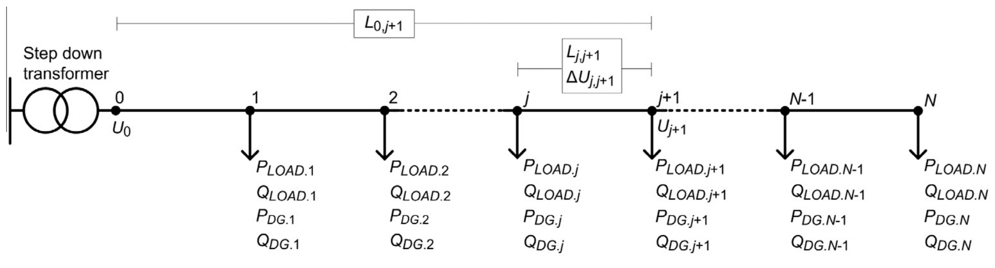

Fig. 1. Single-line diagram of a radial LV feeder.