

A Short-Circuit Analysis Based Method for Estimating Distributed Generation Hosting Capacity

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Abstract—The rapid growth of solar photovoltaic (PV) distributed generation (DG) connections combined with the limited capacity of distribution networks to accommodate such generation poses challenges to distribution utilities in connecting new PV systems. In this context, hosting capacity (HC) analysis is becoming a valuable tool. This paper proposes a method for estimating DG HC through a simple equation based on short-circuit analysis. Case studies conducted on test feeders demonstrate that the method can estimate the real HC with minor errors, being a good approach to fast and easily estimate the HC in applications such as first screening studies.

Keywords—Distributed power generation, hosting capacity, load flow, power distribution, short-circuit analysis.

I. INTRODUCTION

The world is experiencing rapid growth in renewables, particularly from solar photovoltaic (PV) sources. According to the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS), the global installed capacity of solar generation increased dramatically over the past decade, rising from 140.3 GW at the end of 2013 to 1,642 GW by the end of 2023—representing a compound annual growth rate of 28% [1]. Of this total, 44% is connected as distributed generation (DG), ranging from rooftop PV systems to small solar farms of a few MW [1].

Despite the significant benefits that solar PV can offer to a country's energy mix—such as reducing dependence on fossil fuels and mitigating the impact of changing hydrological conditions, particularly in countries heavily reliant on hydroelectric generation—there are still major technical challenges to overcome. Many of these PV systems are connected to distribution networks that were not originally designed to accommodate a significant amount of generation.

While there are regional differences in the characteristics of distribution networks, this segment of electric power systems shares key features that explain the challenges to hosting a great number of generators, such as their radial topology, the lower voltage levels (up to dozens of kV) and feature conductor impedances with a significant resistance component [2]. In contrast, transmission systems operate at high voltages (hundreds of kV) in meshed grids primarily characterized by reactance [3]. The combination of these characteristics along with the reverse power flow from DG installations (back toward distribution substations) can lead to

technical issues in network operation such as steady-state voltage rise, cable overloads, and potential stress on other equipment such as voltage regulators (VRs) and On-Load Tap Changers (OLTCs) [4], [5].

In this context, the concept of DG hosting capacity (HC) refers to the maximum amount of DG that can be integrated into a distribution network without negatively impacting the grid's reliable operation or necessitating substantial upgrades to the existing infrastructure. Due to the limited capacity of distribution networks to accommodate DG and the rapid growth of DG installations in many countries the remaining HC is decreasing quickly in numerous areas.

Among the various factors limiting a distribution system's capacity to host DG, one of the most significant is the equivalent impedance at the point of common coupling (PCC) with DG, known as the short-circuit or Thévenin's impedance. In distribution systems, this impedance is relatively high due to the radial topology and conductor characteristics (section area and arrangement geometry). This is closely related to the concept of system stiffness or weakness, as defined by the stiffness ratio in IEEE Std 1547.7™-2013 [6], where a higher equivalent impedance corresponds to a lower short-circuit capacity at the connection point.

The objective of this paper is to present a simplified equation-based method, derived from short-circuit analysis, for estimating the HC of DG on lightly unbalanced feeders, focusing on the overvoltage potentially caused by the connection of such generators as the main impact [4], [5]. Through computational simulation case studies, the paper also evaluates the practical applicability of this method for estimating the HC at specific PCCs in medium voltage (MV) feeders. The paper is organized as follows: Section II details the proposed method; Section III presents a case study applying the method to three distribution test feeders, along with a discussion of the results; and Section IV provides the main conclusions drawn from this work.

II. A SHORT-CIRCUIT ANALYSIS BASED METHOD

The method presented in this section is aimed to be applied in assessing the HC of three-phase DG connections of up to a few MW in lightly unbalanced primary distribution feeders with nominal voltage of a few dozens kV. Because of this objective, the formulation presented in this section considers a positive sequence network [7]. Additionally, the method is developed on the premise that the entire interconnected power system at a given point of common coupling can be represented through a voltage source behind an impedance, as in the classical short-circuit analysis [3], based on the

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Thévenin's theorem of electric circuits [8], as schematized in Fig. 1.

In Fig. 1 the gray $\times$ represents the PCC of the DG (also in gray) and the entire power systems within the dashed gray area in (a) are substituted by the equivalent in (b). On the equivalent, as stated in Thevenin's Theorem [3], [8], $\hat{V}_P$ is the voltage at the bus P , the PCC, $\hat{V}_S$ is the voltage behind the impedance, which corresponds to the voltage at the PCC under open circuit conditions, i.e., before the connection of the DG, $Z_1 = R_1 + jX_1$ is the (positive sequence) Thevenin's impedance (or short-circuit impedance), composed by the real (R_1) and imaginary (X_1) parts and $\hat{I}$ is the current injected by the DG into the power system.

The circuit represented in Fig. 1 (b) can be described by the following equation:

$$\hat{V}_P = \hat{V}_S + (R_1 + jX_1) \cdot \hat{I} \quad (1)$$

Because the complex power injected into bus P is given by $S = P + jQ = \hat{V}_P \cdot \hat{I}^*$, (1) can be expanded to:

$$\Delta\hat{V} = \hat{V}_P - \hat{V}_S = (R_1 \cdot P + X_1 \cdot Q + j(X_1 \cdot P - R_1 \cdot Q)) \cdot \left(\frac{1}{\hat{V}_P}\right) \quad (2)$$

Equation (2) can be simplified if the following assumptions are considered:

- If the angular difference between $\hat{V}_P$ and $\hat{V}_S$ is small, i.e., if $\theta_P \approx \theta_S$ then $\Delta\hat{V} \approx \text{Re}\{\Delta\hat{V}\}$, meaning that the imaginary part of $\Delta\hat{V}$ in (2) is approximately 0, and $\hat{V}_P \approx V_P$. This hypothesis is reasonable for distribution feeders due to the fact that distribution feeders are shorter and with lower X/R ratio compared to high voltage transmission lines, where the angular difference can be much higher [2], [3]
- If the DG operates with unity power factor, i.e., injecting only active power, which is the most common operating mode [4], [6], then the value of Q is 0

With the first assumption, (2) becomes

$$\Delta V \approx V_P - V_S \approx (R_1 \cdot P + X_1 \cdot Q) \cdot (1/V_P) \quad (3)$$

whilst with the second one (3) can be simplified into:

$$\Delta V \approx V_P - V_S \approx R_1 \cdot P / V_P \quad (4)$$

Equation (4) can be rewritten in per unit considering a base voltage V_{BASE} :

$$(V_P - V_S) / V_{BASE} \approx R_1 \cdot P / (V_P \cdot V_{BASE})$$

$$v_P - v_S \approx R_1 \cdot P / (v_P \cdot V_{BASE}^2) \quad (5)$$

For HC assessment, v_P can be replaced by the maximum accepted level in voltage quality standards such as ANSI C84.1 in North America [9] or PRODIST Módulo 8 in Brazil [10]. According to both references, the limit is 5% above the nominal level (1.05 pu). If the power P is to be expressed in kW and V_{BASE} in kV, then:

$$P \approx V_{BASE}^2 \cdot 1,050 \cdot (1.05 - v_S) \cdot \frac{1}{R_1} \quad (6)$$

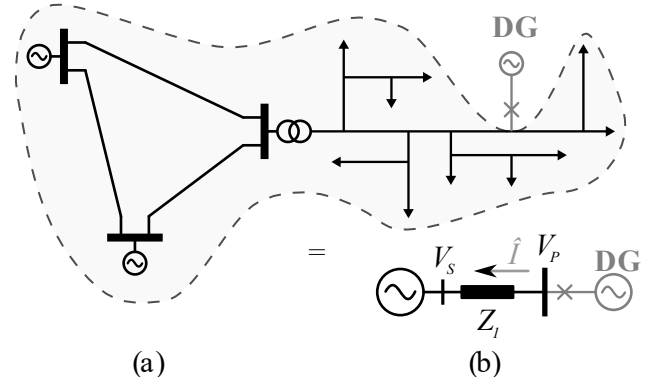


Fig. 1. Representation of (a) an entire power system through its (b) equivalent for short-circuit analysis.

Therefore, the idea of the remaining of this paper is to investigate the validity of applying (6) to calculate the DG HC of a given node (PCC) of a distribution feeder, i.e., the maximum power that a DG can inject into that node before the voltage quality limits are violated. This validity will be assessed based on the error (ε) between the analytic estimation of the DG HC (P_{AN}), given by (6), and the actual DG HC given by the results of power flow studies (P_{PF}).

$$\varepsilon = (P_{AN} - P_{PF}) / P_{PF} \cdot 100\% \quad (7)$$

For practical applications, if the error is sufficiently small, then the analytical equation can be used instead of the need for more costly power flow studies. Even better if the error is negative, i.e., the DG hosting capacity estimated by the analytical approach is smaller than the one calculated by power flow studies, because this means that the proposed approach is conservative.

It is worth mentioning that the approach proposed in this paper, i.e., the analytical equation expressed in (6), can estimate the HC only if the voltage at the PCC between the distribution system and the connecting DG is the most restrictive aspect, i.e., if the voltage rise at this point is the impact that limits the increase of the DG capacity. From a practical perspective, however, this is the value that utilities are normally interested in since the steady-state overvoltage is the most restrictive impact on the increase of DG penetration in most Brazilian distribution feeders [4], [5].

In the following sections of this paper, the robustness of the proposed method is shown through case studies with numerical simulations of typical distribution test feeders. The impact of the variations in the parameters of these feeders will also be assessed and then a discussion of the applicability of the method described in this section will be presented.

III. CASE STUDY

This section presents some case studies where the proposed method is applied. Initially, in subsection III.A, the hosting capacity of a 2-node feeder is investigated to illustrate the method. Then, in subsection III.B, a more realistic feeder with loads and other generators previously connected is used to further demonstrate the robustness of the approach. In subsection III.C, the method is used to analyze IEEE 34 node test feeder and finally subsection III.D briefly discusses the method and further applications.

A. 2-Node Feeder

1) *System and Study Description.* The first distribution feeder to be used in the case study is a simple 2-node feeder presented in Fig. 2. This could represent any simplified radial distribution circuit where the source is the distribution substation. Its rated voltage is 12.47 kV, and it has no load, but whilst this is not realistic, it approaches a common practice of distribution utilities in DG integration studies to be conservative and initially considers the worst-case scenario of a connection in a feeder lightly loaded.

For this simple feeder, (6) can be written in terms of the distance between the two nodes (d) and the resistance per unit of length (r_1). Also, the voltage at the PCC when the DG is not connected to the circuit, i.e., v_s in (6), is equal to the voltage at the bus S, V_{SUB} , representing a distribution substation busbar.

$$P \approx \frac{V_{BASE}^2 \cdot 1,050 \cdot (1.05 - V_{SUB})}{r_1} \cdot \frac{1}{d} \quad (8)$$

Therefore, for this 2-node feeder, it is worth mentioning that, as in (8), the DG hosting capacity is affected by the circuit nominal voltage, the value of the voltage at the substation busbar (normally regulated by OLTCs and close to the maximum allowable levels), the resistivity of the distribution cable, and the distance of the DG PCC relative to the substation.

2) *Results.* The DG hosting capacity of the PCC as a function of its distance is presented in Fig. 3 for different values of V_{SUB} (1.00, 1.01, 1.02, 1.03, 1.04 pu) considering the feeder conductor is 1/0 AWG all-aluminum cable (AAC). The distances started with 2 miles because closer distances result in HC higher than a few MW, which is the most common limit of individual DGs at MV levels [11]–[13]. The solid gray line corresponds to the values obtained by (8) while the dashed black lines correspond to the values obtained by successive power flow solutions run in OpenDSS/DSS Extensions [14]. The values obtained by both approaches match, with a maximum error of -1.4% (for $d=2$ mi and $V_{SUB}=1.0$ pu, with $P_{AN}=4.3$ MW and $P_{PF}=4.4$ MW). As shown in Fig. 3, the proposed method can capture the maximum power that can be injected into the PCC despite the distance of this point and the voltage at the substation busbar.

If the voltage at the substation busbar is kept constant (regulated) at 1.02 pu and different conductors are used—4 AWG ($X/R=0.32$), 2 AWG ($X/R=0.48$), 1/0 AWG ($X/R=0.74$), 3/0 AWG ($X/R=1.12$), 4/0 AWG ($X/R=1.39$), and 336.4 MCM ($X/R=2.09$) [15]—the results of HC as function of the distance is presented in Fig. 4. The higher the X/R relation at the PCC, the worse is (8) in estimating the HC. Nonetheless, the worst errors observed are smaller (in magnitude) than -7% when the conductor used is 336.4 MCM.

In all the cases presented in this subsection, the error using (6) was small and negative, i.e., the HC estimated through the method is slightly smaller than the real value, obtained through power flow solutions. Therefore, the method is shown to be slightly conservative for zero load conditions, which is positive for an approach intended to be a first screening for the HC analysis.

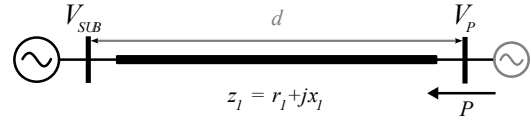


Fig. 2. 2-node feeder.

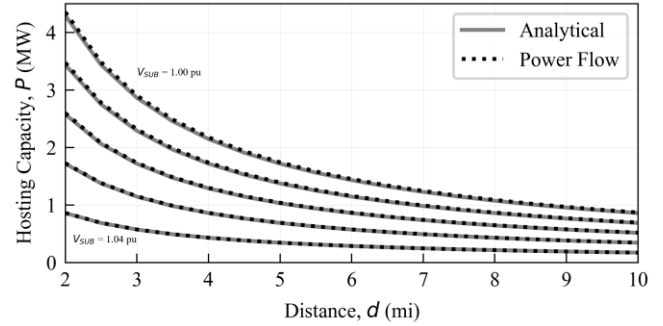


Fig. 3. DG hosting capacity as function of the distance of the PCC for different values of V_{SUB} using 1/0 AWG AAC in the 2-nodes feeder.

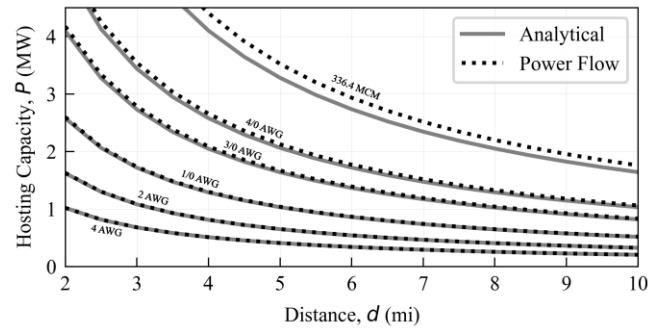


Fig. 4. DG hosting capacity as function of the distance of the PCC for different conductor arrangements using $V_{SUB}=1.02$ pu in the 2-nodes feeder.

B. 5-Node Feeder

1) *System and Study Description.* The second distribution feeder used in the case study is a progression of the previous system, a more complex and realistic yet simple feeder presented in Fig. 5. The previous 2-node feeder is useful for a didactical demonstration, but it lacks important elements in a real feeder, such as the loads and other DGs. To better investigate the effects of such elements (up and downstream loads and other upstream generation) in the accuracy of the proposed method, this subsection uses the 5-node feeder described here.

In the case study of this subsection, more than 1 million simulations were performed in the 5-node feeder considering a random variation of its parameters in the respective ranges as described:

- Nominal voltage, V_{BASE} (chosen among 11.4, 13.8, or 23.1 kV with equal probability)
- Operation voltage at the substation busbar (node S), V_{SUB} (uniformly between 1.00 and 1.04 pu)
- Overhead line cables (4, 2, 1/0, 3/0, 4/0 AWG, and 336.4 MCM bare aluminum cables; 35 (~2 AWG), 70 (~2/0 AWG), or 185 mm² (~365 MCM) (XLPE covered cables)
- Relative distances between the upstream load bus, downstream load bus, and the previously connected DG (being the most distant element, the downstream load bus, between 1 and 10 miles from the substation)

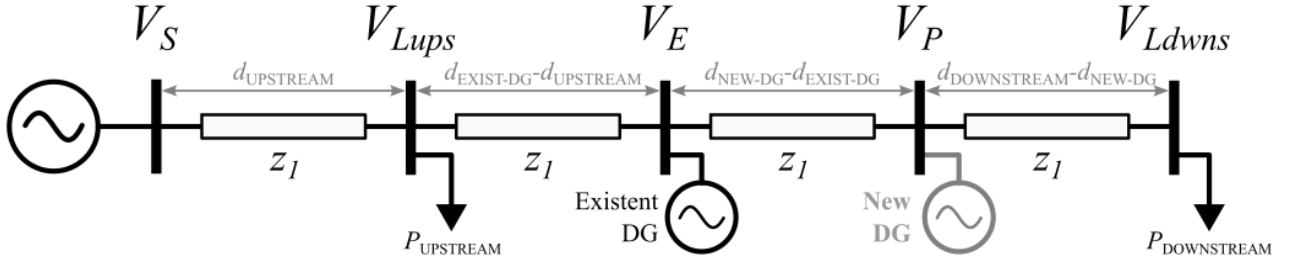


Fig. 5. 5-node feeder.

- Active power demand of the loads (between 0 and 2 MW)
- Loads power factor (between 0.85 lag and 1.0)
- Previously connected DG power injection (between 0 and 2 MW, unity power factor)

Random combinations of those parameters can sometimes result in unrealistic operating conditions within the feeder. For example, a combination of a lower nominal voltage (11.4 kV), a moderate substation busbar voltage (near 1.0 pu), a low-capacity conductor (4 AWG), greater load distance (about 10 miles), closer proximity of existing DG (around 1 mile), high load demand (about 2 MW), minimal power injection from existing DG (near 0 MW), and a lower power factor (0.85) can lead to unrealistically low voltage levels at the PCC (bus P) before connecting the new DG. Conversely, a different combination—such as a lower nominal voltage (11.4 kV), a slightly higher substation voltage (1.04 pu), a low-capacity conductor (4 AWG), shorter load distance (1 mile), greater DG distance (10 miles), minimal load demand (near 0 MW), higher power injection from existing DG (about 2 MW), and a higher power factor (1.0)—can lead to unrealistically high voltage levels at the PCC before the new DG connection.

Since the method is intended for practical applications, where feeder voltages should remain within the range of 0.95–1.05 pu, any scenarios with maximum voltages above 1.05 pu or minimum voltages below 0.95 pu were discarded and replaced with new, randomly generated scenarios. Additionally, scenarios yielding HC values above 5 MW were excluded and replaced by scenarios with HC values up to 5 MW, as the method in this paper focuses on assessing HC in MV feeders for DG capacities up to a few MW—typical of connections at MV levels. This process was repeated until the desired number of valid scenarios was achieved.

2) *Results.* 1 million randomly selected scenarios were evaluated. In each of these scenarios, the values of the parameters described in subsection III.B.1) were randomly selected within the given ranges. For instance, scenario #1 consists of $V_{BASE} = 11.4$ kV, $V_{SUB} = 1.016$ pu, 4/0 AWG, $d_{UPSTREAM} = 0.385$ mi, $d_{DOWNSTREAM} = 6.900$ mi, $d_{EXIST-DG} = 3.011$ mi, $d_{NEW-DG} = 3.787$ mi, $P_{UPSTREAM} = 1,667$ kW, $P_{DOWNSTREAM} = 904$ kW, $PF_{LOAD} = 0.981$. On the other hand, scenario #2 consists of $V_{BASE} = 23.1$ kV, $V_{SUB} = 1.028$ pu, 3/0 AWG, $d_{UPSTREAM} = 8.744$ mi, $d_{DOWNSTREAM} = 9.745$ mi, $d_{EXIST-DG} = 6.645$ mi, $d_{NEW-DG} = 9.439$ mi, $P_{UPSTREAM} = 1,475$ kW, $P_{DOWNSTREAM} = 255$ kW, $PF_{LOAD} = 0.944$, and so on. For each scenario, the HC of the node P was calculated using (6) (P_{AN}) and through successive power flow solutions run in OpenDSS/DSS Extensions [14] (P_{PF}) and the results

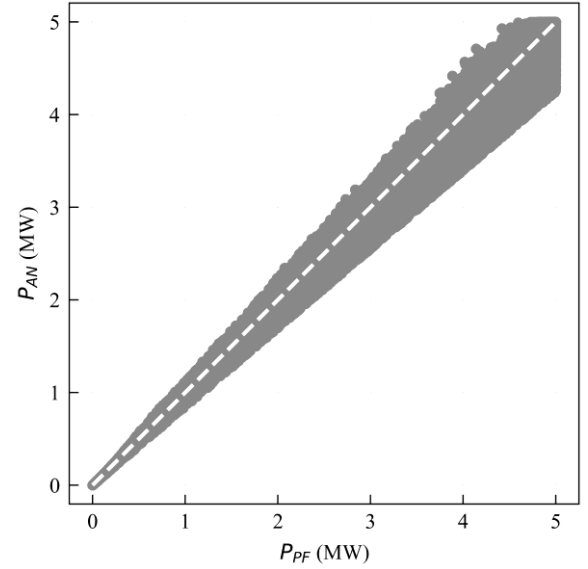


Fig. 6. Analytical and power flow HC values across 1 million scenarios.

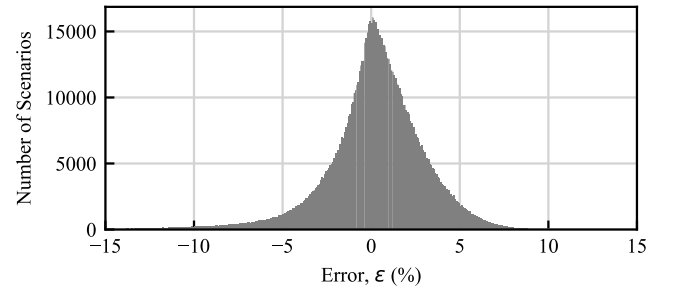


Fig. 7. Distribution of errors across 1 million scenarios.

TABLE I. STATISTICS OF DISTRIBUTION OF ERRORS ACROSS 1 MILLION SCENARIOS SIMULATED IN THE 5-NODE FEEDER

Error, ϵ	Probability (%)
[-5 and +5%]	92.252
[-10 and +10%]	99.032
[-15 and +15%]	99.855
[-5.84% and +5.84%]	95.000
[-9.91% and +9.91%]	99.000
[-15.94% and +15.94%]	99.900

are presented in Fig. 6. The error, given by (7), was obtained for each one of the 1 million scenarios and its histogram is presented in Fig. 7.

As one can note, for practical applications, i.e., considering only realistic operating points, the error of the HC given by (6) is small. The statistics of the distribution of those errors are presented in Table I. A share of 92.25% of the simulated scenarios have errors between $-/+5\%$, with 99.03% of the simulated scenarios with errors limited to $-/+10\%$. For 95% of the simulated scenarios, the error of assessing the HC

through (6) are between -5.84% and +5.84%, while for 99%, it lies in the range $\pm 9.91\%$. Those numbers mean that if (6) is adopted to assess the HC of a distribution feeder operating under realistic conditions before the connection of a new DG (up to 5 MW) up to 10 miles distant from the substation, HC with errors ranging from $\pm 5\%$ is more than 92% of the cases, indicating that the use of such equation provides reasonably accurate estimation of the real HC value.

Compared to the case presented in subsection III.A, where the system load was neglected and (6) resulted in a conservative value of the HC, the results for the system with non-zero load presented in this section are not always conservative, since roughly half of the scenarios presented a positive error (i.e., $P_{AN} > P_{PF}$). For practical applications, it is better if the simplified approach given by (6) was always conservative. If this conservativeness is important for the calculation, one can either neglect the system load or apply a 5-10% rebate in the value of the HC obtained through (6).

C. IEEE 34 Node Feeder

1) *System and Study Description.* The previous case studies are useful for understanding the proposed method, but it is also important to test it in more realistic feeders. For this purpose, the IEEE 34 Node Test Feeder presented in Fig. 8 [16], [17] was chosen because it is commonly used for DER integration studies due to its voltage regulation challenges [16].

The following modifications were done in the original data before the method was applied: (a) the lines were made ideally transposed and from the original 3×3 Z matrix it was obtained the proper, mutual and positive sequence impedance; (b) the single-line laterals were made three-phase and the unbalanced loads were balanced to reduce the feeder voltage unbalance, and (c) the OLTC voltage at the busbar 800 was reduced to 1.035 pu to better accommodate DG connections. With those changes, the power flow at the head of the feeder is $2,042.4 + j215.7$ kVA, close to the original result ($2,042.9 + j290.3$ kVA). The main difference is the reactive power flow, due to the capacitors, which are constant power in the original feeder and constant impedances in this case. The losses in the simulated circuit are 268.7 kW against 273 kW from the original feeder. The HC was assessed only for the nodes upstream of the first VR since this portion of the feeder is long enough to evaluate the errors of the proposed method (~ 19.65 miles). This portion (configuration 300) uses 1/0 AWG ACSR cables with $Z_l = 1.1201 + j0.8333 \Omega/\text{mi}$.

2) *Results.* The results obtained are presented in Table II. The power flow results (PPF) were obtained through OpenDSS/DSS Extensions [14] and corresponds to the maximum power that can be injected into the given node before its voltages reach the upper limit of 1.05 pu. For the analytical ones (P_{AN}), (6) was evaluated for the values of V_{BASE} , v_s , and R_l provided, with R_l resulting from the product between $1.2101 \Omega/\text{mi}$ and the distance d also presented in the table. Buses 808m, 812m, and 814m correspond to the middle of the segment between buses 806-808, 808-812, and 812-814. The results indicate that in practical approaches, it is possible to evaluate the HC for a DG connection using the (6) with errors smaller than 8% with distances between the PCC and the substation of up to 19.65 miles, which is a relatively long distance for DG connections.

TABLE II. RESULTS OF THE CASE STUDY IN IEEE 34-NODE TEST FEEDER

Bus	V_{BASE} (kV)	v_s (pu)	d (mi)	R_l (Ω)	P_{AN} (kW)	P_{PF} (kW)	ϵ (%)
802	24.9	1.0331	0.49	0.55	19,984	20,100	-0.58
806	24.9	1.0319	0.82	0.92	12,812	12,869	-0.44
808m	24.9	1.0206	3.87	4.36	4,396	4,354	0.97
808	24.9	1.0092	6.92	7.80	3,406	3,326	2.42
812m	24.9	0.9961	10.47	11.8	2,973	2,867	3.69
812	24.9	0.9830	14.02	15.8	2,759	2,613	5.60
814m	24.9	0.9727	16.84	19.0	2,654	2,483	6.90
814	24.9	0.9623	19.65	22.1	2,579	2,392	7.83

D. Discussion

It is worth noting that the simplifications underlying the approach in Section II—such as higher R/X ratios, light load conditions, and unity power factor—are essential for the method accuracy but are also conditions commonly adopted by distribution utilities when evaluating HC for their feeders. These assumptions enable the effective application of (6), resulting in the low errors demonstrated in this paper. The method is particularly accurate when estimating DG capacities up to a few megawatts, which is enough for practical applications.

IV. CONCLUSIONS

This paper proposes a practical and straightforward method to assess the distributed generation (DG) hosting capacity (HC) at a specific point in a medium voltage (MV) feeder using an equation derived from classical short-circuit analysis. The method involves calculating the short-circuit impedance at a given DG point of common coupling (PCC) and the voltage at this point prior to DG connection. These values are then applied to a simple equation to estimate the maximum power that can be injected into the system without exceeding the upper steady-state voltage limit, typically the most restrictive factor in HC.

Case studies using test feeders showed that the method provides accurate HC estimates, with acceptable errors compared to values obtained through power flow studies. Although the method can slightly overestimate HC, practical recommendations are offered for applying it in preliminary screening studies where quick and simple analysis is required. Future work will focus on expanding the method to cope with unbalanced DG connections within unbalanced networks and with the connection of multiple DGs.

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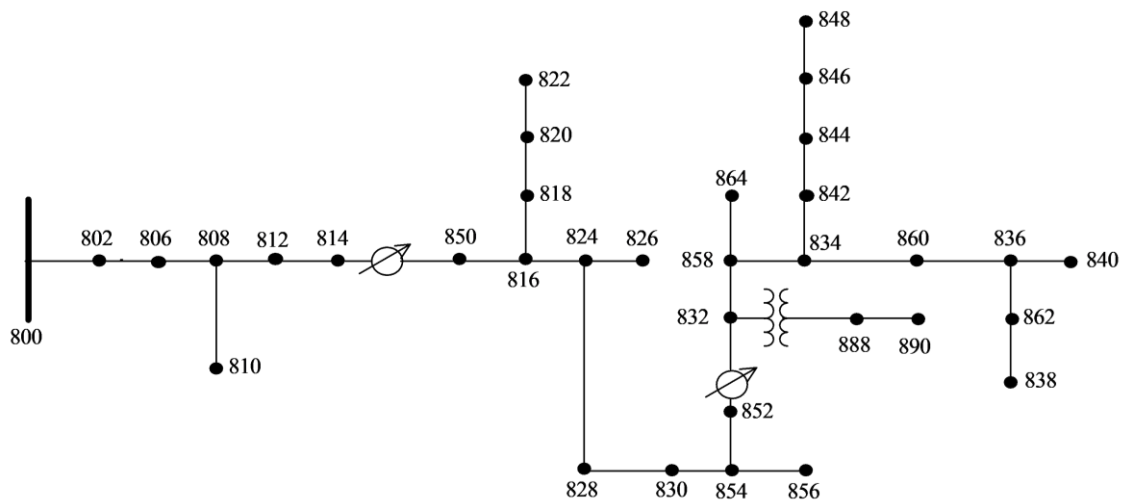


Fig. 8. IEEE 34 node test feeder.

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