A deterministic method of distributed generation hosting capacity calculation: case study of underground distribution grid in Morocco

Soukaina Naciri, Ismail Moufid, Hassan El Moussaoui, Tijani Lamhamdi, Hassane El Markhi
SIGER, Intelligent Systems, Georesources, and Renewable Energies Laboratory, Faculty of Sciences and Techniques, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Article Info

Article history:

Received Jan 5, 2022
Revised Aug 10, 2022
Accepted Aug 20, 2022

Keywords:

Distributed generation
Distribution grid
Grid reconfiguration
Hosting capacity
Load flow analysis

ABSTRACT

Global warming has become a significant concern over the past decades. As a result, governments have shifted their policies toward renewable energy sources and environmentally friendly industries. This approach requires a renewal of the electrical networks to accommodate this new intermittent generation (from solar and wind sources) while remaining stable and reliable. In this vision, the notion of hosting capacity has been introduced to define the amount of new distributed generation that an electrical network can host without affecting its stability and reliability. This study proposes a deterministic method based on the π model of cables to estimate the underground feeder's hosting capacity. This method considers reverse power flow, overvoltage, reconfiguration, overloading, and the physical characteristics of lines. It is applied to the Moroccan medium voltage underground radial feeder. Through DIgSILENT power factory software, the power flow analysis is carried out to validate its effectiveness in overcoming overvoltage and cable overload problems. The results validate the relevance of our method, its reliability, its fluidity of application, and its ability to maintain performance indices within the acceptable range.

Corresponding Author:

Soukaina Naciri
SIGER, Intelligent Systems, Georesources, and Renewable Energies Laboratory, Faculty of Sciences and Techniques, Sidi Mohamed Ben Abdellah University
PO. Box 2202, Fez 30050, Morocco
Email: soukaina.naciri@usmba.ac.ma

1. INTRODUCTION

The portion of renewable energies electricity production increased to 29% in 2020, against 27% in 2019 around the world. Thus, the consumption of renewable energies increased by 3% in 2020. The main driver has been almost 7% growth in electricity production from renewable sources. The liberalization of the electricity market, long-term contracts, and the continued installation of new power plants have contributed to the growth of renewable energy integration despite declining demand for electricity, construction delays, and lack of clear regulations in many parts of the world [1].

Morocco has become leading in the energy sector after the launch of its energy strategy in 2009, which aims to get 52% of electricity production from renewable energies (REs) by 2030 [2]. In this context, ambitious energy projects have seen the light, such as the Moroccan solar energy programme (NOOR) solar complex in Ouarzazate City. Along with these large projects, the strategy focused on small-decentralized generation, which is gaining more popularity with the liberalization of the electricity market. The law (No. 13-09) [3] of renewable energy legalizes and promotes the production of energy from renewable sources, its market, and its export by public or private entities. Moreover, it also provides for the right for an operator or prosumer to produce electricity from renewable energy sources on behalf of a consumer or a group of consumers connected to the national electricity grid of medium voltage (MV), high voltage (HV), and very high voltage (VHV).

The HV and VHV grids injection has already seen the light with different projects. However, no project has been launched for medium voltage, although legally, this injection is authorized. That is generally due to the lack of intelligible regulation between distributed generation (DG) owners and distribution system operators (DSOs). Elsewhere, it is due to the proximity of the renewable energy sources to the customer.

Distributed generation is defined as electricity production via renewable energy sources (especially wind and solar sources) close to customer sites [4]–[8]. It is connected to the distribution network, reducing transmission losses and minimizing environmental issues [9], [10]. However, integrating new production plants in an already existing power system may modify the system configuration and lead to several problems; overvoltage, equipment overloading, reverse power flow, protection, and power quality issues [8]. For these reasons, the distribution system operators are asked to take sufficient time for a detailed study to refuse or accept any injection request.

Up to this point, the penetration of DG is expected to rise quickly. A significant connection of DG in a network not designed to receive production plants has a critical impact on grid reliability, security, regulation, and quality of service [11]–[15]. For a distribution power system, the shifting from no DG utilities to a very high DG penetration can be done through different levels. Namely: level 1 corresponds to low to medium DG integration; in this case, the energy produced remains lower than the energy consumed, and network parameters are under control. Level 2 corresponds to high DG integration; the generation starts exceeding the consumption, making the grid bidirectional. Finally, level 3 corresponds to very high DG integration; the production is higher than the load's demand. Many technical problems can appear at this level, and the performance indices can reach their limits.

The frequent issue with excessive penetration of DGs at the point of common coupling (PCC) and its surroundings is overvoltage. In addition, serious problems such as thermal overload of network equipment, inadequate performance of protective equipment, and the risk of exceeding short-circuit capacity are also present [16]. Therefore, it is necessary to assess the ability of the network to support these new arrivals without exceeding the limits of the operational parameters.

With the liberalization of the electrical market, the DG investors can inject their production into the distribution grid. However, a conflict of interest can exist between DG owners and DSOs. While the DSOs are worried about the excessive DG penetration problems, investors aspire to increase the integration of their DG plants into the electrical network. In this context, the hosting capacity approach was introduced [16]. The hosting capacity (HC) is generally defined as the maximum injected power that a distribution network can support [7], [13], [17]–[20]. In this context, several types of research have been done recently, especially on HC calculation and improvement methods. Ismael *et al.* [16] presented a comprehensive review of the research, limitations, developments, assessment techniques, and enhancement technologies of HC in power systems. In another review, Mulenga *et al.* [6] discussed and compared the HC calculation methods (deterministic, stochastic, and time series) for photovoltaic systems in low-voltage distribution grids.

Different methods are used to quantify the HC, and many criteria are considered. Murthy *et al.* [10] proposed a mathematical model to determine the maximum power of DG to be connected in a distribution network. This model is based on the power flow equation considering loads, existing production, and overvoltage. In another work [21], the linearization of the power flow equation is performed to determine the DG maximum generation in a practical case. Their results showed that the value obtained of HC is the same as using conventional methods; however, the proposed method outperforms them in terms of computational time. Papaioannou and Purvins [11] presented a methodology for calculating the maximum DG in low voltage radial feeders based on an analytical approach. According to the authors, the methodology can be used with or without existing DG installations. de Oliveira *et al.* explored, in addition to the voltage criteria, harmonics to evaluate the HC [22] and dynamic HC [23] of photovoltaic panels connected to the LV distribution network of a university campus. In Lennerhag *et al.* [24], measurements at various locations for a given grid are used to increase the accuracy of the HC; however, Qi *et al.* [25] used the medium voltage direct current link to increase HC.

Many studies considered only the overhead lines for hosting capacity calculation; however, most distribution grids are underground. That presents the primary motivation of the present study; thus, a method of calculating hosting capacity adequate to this kind of grid is developed. This study determines the hosting capacity of underground distribution feeders by considering several parameters, namely reverse power flow, overvoltage, reconfiguration, thermal overloading and feeder parameters. It aims to maximize the amount of DG without adversely impacting grid operation. The proposed approach can be applied to both overhead and underground feeders.

This paper is divided into four main parts. Section 2 presents an overview of the hosting capacity approach. In section 3, the mathematical models of hosting capacity proposed in the literature are discussed. In section 4, the mathematical model is developed and applied to a 39 buses radial distribution feeder under different cases. Then, the model efficacy is discussed in light of the results obtained from the cases study. In conclusion, remarks and outlooks are highlighted.

2. HOSTING CAPACITY

2.1. Hosting capacity approach

In computer sciences, the term hosting capacity refers to the ability of a Web server to host numerous access requests. Since 2004, this term has been explored in electrical applications. Endré Even took the lead to evaluate the integration of renewable resources based on the hosting capacity notion [26]. Then, many investigations have been done in this new field.

For a DG, the hosting capacity approach offers a fair and open discussion between investors and DSOs to assure a transparent balancing between their interests [24]. The hosting capacity refers to the maximum amount of DG connected to a given grid without causing any technical problem in a part of or the entire distribution network, as illustrated in Figure 1. Moreover, the introduction of DG will affect power system performances. Every change in power generation and loads can affect the performance indicators. Hence, the performance indices will be the primary tools that quantify the impact of DG on the power system. Connecting a power supply unit in a distribution network is a two-sided coin; it can improve the system's operation as it can deteriorate it. Therefore, system operation degradation is always acceptable if the performance indices are still within their boundaries [16].

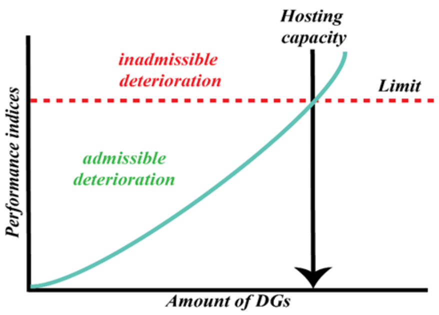

Figure 1. Hosting capacity concept

2.2. Technical criteria limiting DG hosting capacity

The process of calculating HC requires the definition of suitable performance indices. The choice of indices and limits has a significant impact on its value. Thus, the precision of network data is obligatory when planning a DG connection. In general, the process begins with the choice of limiting factors. The most technical limiting factors that the DSOs are based on to assess the HC of a given feeder for DG connection decision are listed in [5]:

- Voltage criteria: contains voltage drop, voltage unbalance, and overvoltage. Overvoltage is the frequent criterion used in HC assessment.
- Thermal rating criteria: during high generation and minimum load, excess power generated by DG plants flows back to substations through lines and transformers. Both lines and transformers have a maximum current that they can support. Violating its limit causes overheating of these types of equipment.
- Protection criteria: the DG interconnection can modify the fault current that the protection devices detect. Therefore, resizing the circuit breakers is required.
- Power quality criteria: wind and solar sources are intermittent, resulting in power quality issues such as voltage fluctuations. Thus, these technologies are connected to the network through electronic power devices, leading to harmonic voltage and current.

Because of the issues above-mentioned, DSOs are hesitant to promote new DG connections, except detailed studies are performed. However, such studies delay the DG integration process and make DG owners complain. Hence, simplified methodologies allow DSOs to assess the HC network quickly but reliably. DG planning studies can be classified into different categories without in-depth studies according to the approaches adopted. The HC capacity approach is one of these categories. It aims to size DGs that can be connected to the grid while assuring the quality of service.

2.3. Hosting capacity calculation process

Successful integration of DG requires expressing interconnection requirements clearly. Therefore, the calculation of HC is based on several steps to formulate these requirements mathematically. Generally, the calculation of HC proceeds as: i) selection of one or more hosting capacity criteria (already mentioned above); ii) specifying a limit for each performance index according to national rules and or international standards; iii) developing a mathematical model based on the selected performance index/indices; iv) calculating the maximum power that can be injected at a given point; v) checking the limit of the performance index/indices. If it is violated, redevelop the model. Otherwise, validate it; and vi) obtaining the HC capacity.

2.4. Mathematical models state of art

DG planning studies can be classified into different categories according to adopted approaches. The HC capacity approach is one of these categories. It aims to size DGs that can be connected to the grid while assuring the quality of service. In these studies, the voltage rise is the frequent criterion considered. This issue may occur when the generation exceeds the local loads. As DGs are connected close to customers' sites, overvoltage will cause significant problems for customers and the whole system [7].

For this reason, studies that adopt the HC approach examine this issue to find the suitable DG capacity that avoids it. In relation, authors in [27] proposed a mathematical model given by (1) to calculate the maximum photovoltaic (PV) power injected into an MV Turkish feeder. The feeder is modelled using a simple single diagram, as shown in Figure 2. The selected criterion is overvoltage, the feeder parameters are taken uniformly along the feeder, and the cable capacity is neglected.

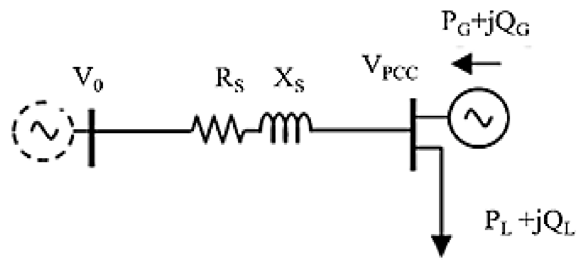

Figure 2. Single diagram of the feeder with DG

$$P_{DGmax} = V_{max}V_o\left[V_{max}V_oG - V_oY\cos\left(\sin^{-1}\left(\frac{V_{max}B}{-Y}\right)\right)\right] \quad (1)$$

Where P_{DGmax} is the maximum active power of DG, V_o and V_{max} are voltages of swing and DG connected point respectively, and $Y = \left|\frac{1}{R_S+jX_S}\right| = |G + jB|$ presents the total admittance of the line.

Authors have taken different assumptions during the formulation process. For example, cables and overhead lines capacitances and loads are ignored. Besides, the authors supposed that the injected PV power has a unity power factor, which is unrealistic since PV panels are connected to the network via inverters that inject or absorb reactive power. Therefore, assumptions make the expression simple and easy to apply but can lead to an under or overestimation of HC. In the same context, the authors of [28] presented a detailed analysis of the sensitivity of photovoltaic HC to several network factors. The model is developed to avoid overvoltage complications when production is more significant than consumption, as shown in (2):

$$P_{DGmax} = \frac{V_{PCCmax}(V_{PCCmax}-V_0)}{R_S(1+\tan(\varphi)\frac{X_S}{R_S})} + P_{Lmin} \quad (2)$$

where V_{PCCmax} and V_0 are respectively the voltage at the PV integrated point and the maximum voltage of the swing bus. R_S and X_S are respectively the resistance and reactance of the Thevenin equivalent impedance at the point of common coupling (PCC). φ is the angle at the PCC. P_{Lmin} the minimum power of the load.

Power electronic devices and nonlinear loads are predicted to inject harmonic currents. As long as PV panels are connected to the grid via inverters that inject harmonic currents, voltage wave deformation will happen, and, consequently, voltage rise is expected. The harmonic impact on HC is not addressed in the models mentioned above. However, de Oliveira *et al.* [23] related the hosting capacity concept to voltage harmonic distortion by introducing the harmonic orders in HC expression. Their model was based on replacing the maximum voltage at PCC with its root mean square (RMS) in (2). The RMS is generally defined as the root square of the sum of squares of each harmonic voltage. They have supposed that loads have an insignificant harmonic impact; (2) can be rewritten as flow:

$$P_{DGmax} = \frac{1}{R_S}\sum_{h=1}^{51}\frac{V_{PCCmax}^{h}(V_{PCCmax}^{h}-V_o^{h})}{(1+tan(\varphi)\frac{hX_S}{R_S})} \quad (3)$$

where the V_{PCCmax}^{h} is the voltage magnitude permissible for harmonic order h. Referring to international standards, the individual voltage distortion is required to be below 5% for $h \geq 2$ and below 105% for $h = 1$. The authors have addressed harmonic impact in addition to overvoltage in HC calculation. They have shown t significant risks to applying simple models in HC determination. Therefore, system's HC analysis requires more limiting factors to be considered.

To facilitate the integration of the intermittent (solar and wind), a more general equation was proposed in [6]. This model takes into account the loads and DG generators already connected to the network in the calculation. The model is obtained by applying the reduction method applied to the load flow matrix.

$$P'_{max} = P_{max} + \left|S''_{scDG}\right| \left(\sum_{1}^{n}\frac{\left|S''_{SLn}\right|}{\left|S''_{scPCCn}\right|}.cos(\theta_{PCC}-\theta_{DG}+\varphi_n) - \left(\sum_{1}^{k}\frac{|S_{DGk}|}{\left|S''_{SCDGk}\right|}.cos\ (\theta_{DGn}-\theta_{DG}+\varphi_{DGk})\right)\right) \quad (4)$$

P'_{max} denote the final maximum DG capacity, $P_{max}$is the maximum capacity of DG for unloaded case; $\left|S''_{SLn}\right|/\left|S''_{scPCCn}\right|$ is the ratio of the short-circuit powers at the integration point and at the point where the load and DG unit have common coupling, and θ and φ are the phase angle of DG.

In all these examples, mathematical models are developed for DGs programmed to be at the end of the feeder. Voltage is selected as the primary criterion for developing the models to avoid overvoltage or the voltage rises due to the harmonics. The thermal criteria are ignored in these cases. Thus, they are based on a single diagram containing only the line's impedance since line capacitance is ignored to simplify the calculation. In addition, the characteristics of the single line diagram are uniformly taken. However, it is not the case for a real feeder, in which branches do not necessarily have the same characteristics. Neglecting this point may lead to more technical complexions, most likely thermal overload.

3. SYSTEM MODELLING

3.1. Case study

Deterministic hosting capacity studies aim to find the maximum distributed generation capacities that can be connected without influencing network performance. All these studies are based on mathematical modelling of technical criteria making HC assessment possible and easy. In most related publications, voltage rise is the critical event considered, and the goal is getting the maximum power that will not cause this event. Focusing on one criterion and assumptions in HC calculation may lead to grave problems after DG integrations like thermal overloading. Therefore, HC estimation requires more limiting factors to be considered.

Almost all distribution grids are underground. According to the reviewing articles, no study addresses the hosting capacity of underground feeders. As their maintenance is complex, their HC determination requires deep analysis. For analyzing the situation related to the subject and obtaining an HC method that takes more limiting factors, an MV feeder of Morocco is addressed for developing the mathematical model. The examined underground network is slightly complex [12]. For economic reasons, the cables used do not possess the same physical characteristics along the feeder. The feeder contains 40 buses, as depicted in Figure 3. They are connected using three different types of underground cables (green, blue, orange): i) the blue has an impedance Z1=0.145+j0.1 Ω/km, a capacitance of C1=400 nF/km, and support 400 A as maximum current; ii) the green has an impedance Z2=0.239+j0.11 Ω/km, a capacitance of C2=300 nF/km, and support 300 A as maximum current; and iii) the orange cable impedance is Z3=0.372+j0.13 Ω/km, its capacitance is equal to C3=300 nF/km, and its maximum current is 225 A.

The π diagram is an approximation of the cable model. This approximation remains correct as long as the cable is not too long. Consequently, the studied feeder is modelled by a single-line diagram in which all the parameters are expressed per unit (p.u). The cables are modelled using the π model, which in the series impedance of the cables is positioned in the middle of half capacitance, as shown in Figure 4.

As underground networks are potentially subject to long downtimes in the damage event (several tens of hours), the integration of DG in this type of network can lead to more loaded cables and contributes to the fault current supply. Therefore, grave damages may happen and require more repairing time. In the next section, a mathematical model is proposed to estimate the maximum permissible DG power injected at a given point of this grid and avoid these problems. The calculation considers the overloading of cables/transformers, overvoltage, minimum loads, and revers power flow.

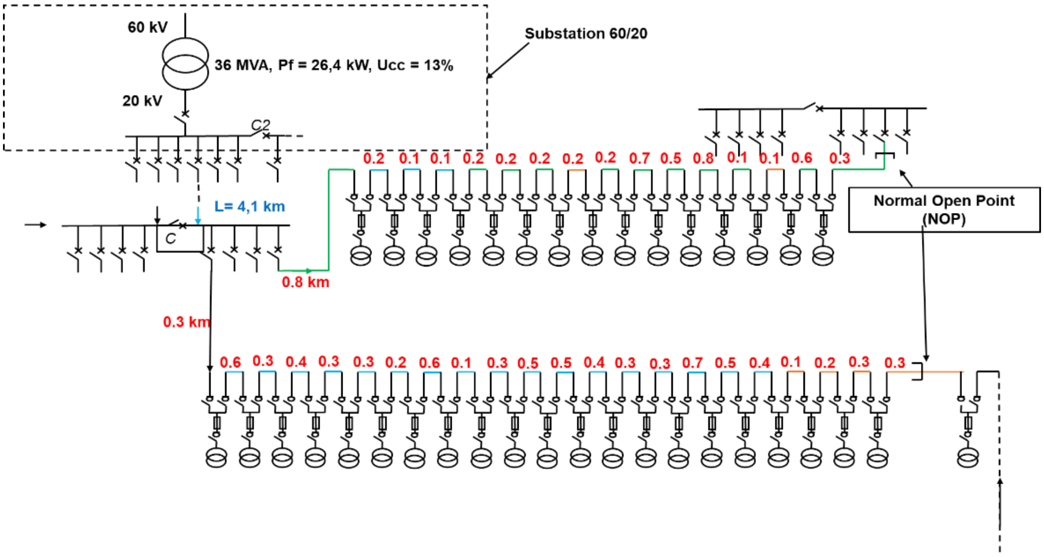

Figure 3. Studied Moroccan feeder

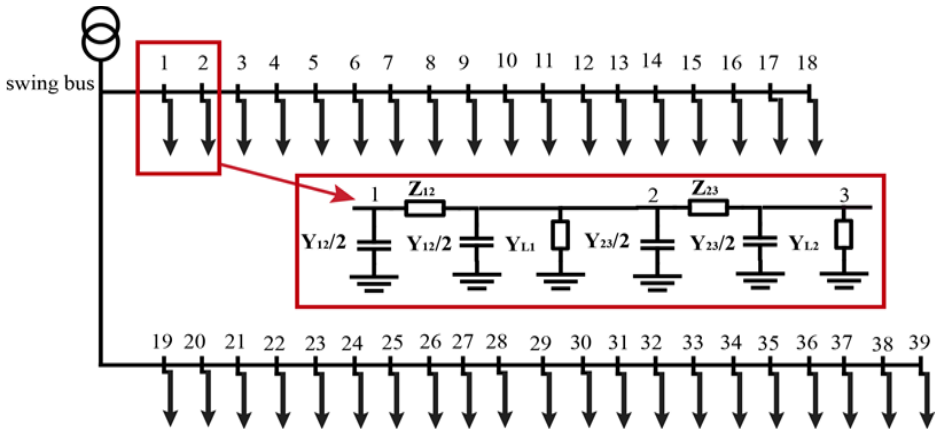

Figure 4. The single line diagram of the studied system

3.2. Hosting capacity calculation

The maximum electrical power injection in a given feeder can be formulated considering the feeder parameters and the selected HC criteria. In the model processing, the assumptions are taken as flow: i) the feeder physical parameters are irregularly distributed along with the studied departure; ii) the capacitances of the cables are considered in the calculation; iii) reversing power could occur in the worst-case scenario, the maximum generation and minimum loads. Thus, the connection of DG to a given bus can supply all the ascending and descending loads of that bus; iv) the normal opening point (NOP) is moved for grid reconfiguration to show its effect on the HC; and v) the criterion retained for this model is overvoltage; its limit was 10% of the standard voltage and the overload of the transformer and the cables.

According to Figure 5, the branches are presented as a cascade association of the model in a π of cables and loads. The matrix associated with the π model for the first branch is given by (5), which V_1, I_1, V_2, and I_2 are the voltages and currents at the input and output of the model respectively. Z_{12} is the impedance between buses 1 and 2, $Y_{12} = jC\omega/2$ and is the linear transverse admittance where C is the capacitance of the cables.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \frac{Z_{12}Y_{12}}{2} + 1 & Z_{12} \\ Y_{12}(1 + \frac{Z_{12}Y_{12}}{4}) & \frac{Z_{12}Y_{12}}{2} + 1 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{5}$$

To formulate the mathematical model, the DG is planned to be connected to bus 3. As shown in Figure 4, the DG current circulates to supply the loads upstream and downstream of bus 3. The current injected by DG at bus 3 is formulated as (6):

$$I_{DG3} = I_3' + I_3'' + I_{L3} \tag{6}$$

where, I_3' is the current flowing downstream of the injection bus (bus 3), I_3'' is the current flowing upstream of the injection bus (bus 3), and I_{L3} is the load current on bus 3.

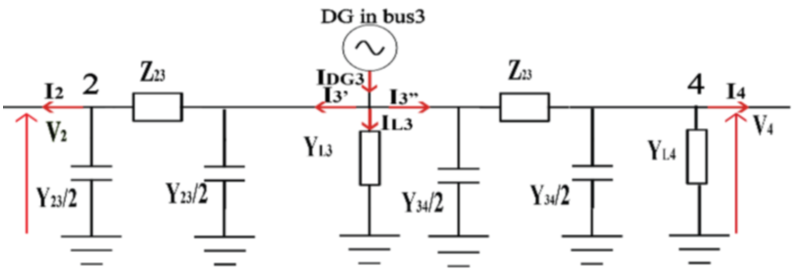

Figure 5. Reverse power flow after DG integration to bus 3

Depending on the matrix given by (5), the currents upstream and downstream the bus 3 can be written as (7):

$$\begin{bmatrix} V_3 \\ I_3'' \end{bmatrix} = B_1 \begin{bmatrix} V_4 \\ I_4 \end{bmatrix} \tag{7}$$

where B_1 is expressed as (8), (9):

$$B_1 = \begin{bmatrix} Z_{34}\left(\frac{Y_{34}}{2} + Y_{L4}\right) + 1 & Z_{34} \\ \frac{Z_{34}Y_{34}^2}{4} + Y_{34} + Y_{34}\left(\frac{Z_{34}Y_{34}}{2} + 1\right) & \frac{Z_{34}Y_{34}}{2} + 1 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} V_3 \\ I_3' \end{bmatrix} = T_1 \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{9}$$

where T_1 is expressed as (10):

$$T_1 = \begin{bmatrix} Z_{23}\left(\frac{Y_{23}}{2} + Y_{L2}\right) + 1 & Z_{34} \\ \frac{Z_{23}Y_{23}^2}{4} + Y_{23} + Y_{23}\left(\frac{Z_{23}Y_{23}}{2} + 1\right) & \frac{Z_{23}Y_{23}}{2} + 1 \end{bmatrix} \tag{10}$$

Current and voltage at Bus 2 can be expressed as a function of the current and voltage of the last bus. Likewise, the current and voltage at bus 4 can be described as a function of the current and voltage of the bus that follows it. Accordingly, (7) and (9) can be written as (11), (12):

$$\begin{bmatrix} V_3 \\ I_3'' \end{bmatrix} = \prod_{i=1}^{15} B_i \begin{bmatrix} V_{18} \\ I_{18} \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} V_3 \\ I_3' \end{bmatrix} = \prod_{i=1}^{24} T_i \begin{bmatrix} V_{39} \\ I_{39} \end{bmatrix} \tag{12}$$

where, V_{39}, I_{18}, and I_{39} are the voltages and currents at the end of departures 1 and 2, respectively. To generalize the mathematical model, let j take the integration bus number of DG. n, and m are successively the numbers of branches existing upstream and downstream of the bus j. The feeder ends can change status when the NOP is displaced. Hence, bus voltage and current the ends are denoted by V_{end_k} and I_{end_k}, where k can take 1 or 2 to represent the line number. The (11), (12), and (6) become:

$$\begin{bmatrix} V_j \\ I_j^{"} \end{bmatrix} = \prod_{i=1}^{n} B_i \begin{bmatrix} V_{end_1} \\ I_{end_1} \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} V_j \\ I_j' \end{bmatrix} = \prod_{i=1}^{m} T_i \begin{bmatrix} V_{end_2} \\ I_{end_2} \end{bmatrix} \tag{14}$$

$$I_{DGj} = I_j' + I_j^{"} + I_{Lj} \tag{15}$$

The value of the current flowing through each element of the network (line, cable, or transformer) must not exceed the current ratings of these components. The calculation of the current flow should not exceed these values. Excessive current values can lead to overheating of features and even rupture. So, I_{DGj} must be less than current ratings. As the studied system contains branches with different current ratings, the rating current is taken as the lesser maximum current of the three cables, 225 A.

$$S_{DGj} = V_{max_j}.I_{DG_j}^* \tag{16}$$

In (17) represents the maximum power that can be injected in bus j when the generation is higher than the consumption. This scenario can cause a high voltage at the injection bus and surroundings. The permissible overvoltage is 1.1 $p.u$, can be rewritten as (17):

$$S_{DGj} = 1.1 I_{DG_j}^* \tag{17}$$

4. RESULTS AND DISCUSSION

First, the maximum power of DG is calculated using the proposed mathematical model as shown in (17) and those existing in the literature (1) to (4) for different locations. DG locations are chosen at the start, middle, and end of the feeders, and the worst scenario (maximum generation minimum load) is addressed. The buses considered are 1, 8, 17, 28, and 39. Models given by (1) to (4) are developed for the DGs, which will be integrated at the end of the feeder. Therefore, these models are not applicable for bus 1, which is at the start of the feeder. However, for the buses located in the middle (buses 8 and 28), the HC is calculated by considering only the branches and the loads up to buses 8 and 28. The line capacitance is ignored in these models. However, the proposed model takes into account all the characteristics of the cables and shows the impact of the capacity on the HC obtained, as shown in Table 1.

In particular, the cable's capacitance in the calculation increases the HC values for all studied buses, which is around 1.3 MVA increases for some buses. The HC value depends essentially on the criteria used and the location of the DG. It differs from one model to the other based on the assumptions and constraints taken. However, our proposed model addresses the problems of overvoltage, cable and transformer overloading, and reverse power flow. For this reason, the HC obtained by our proposed model has the lowest values compared to the others. Therefore, the more criteria studied, the minimum value of HC will be. Power flow analysis is performed using DIgSILENT power factory software to test the effectiveness of the proposed model. The overvoltage and overloading of cable have been cheeked for both cases: connecting the DG and in its absence. The two cases were performed over all the predefined locations for all resulting values of HC given in Table 1. The bus voltages before and after DG integration are presented in Figure 5. Before DG integration, the bus voltages (red line) decrease from the substation to the end of the feeders. Whereas after its integration, the voltage for all DG capacities obtained in Table 1 is raised, especially at the bus where DG is integrated and around it. Consequently, the higher the value of the DG power, the greater the voltage rise.

Voltage for different busses in Figures 6(a) and 6(b) has not reached the overvoltage limit after DG with capacities calculated using the proposed model. The voltage is increased by 4% after connecting DG, which allows more DG integration. However, the rise of voltage in Figures 6(c) to 6(f) is significant for DG units performed with capacities gotten from the models existing in the literature. The voltage deviation reaches 10% in Figure 6(c). So, overvoltage problems are expected if the network under study operates under other conditions (minimum load) or hosts new DG units. All models have respected the overvoltage constraint, but a risk of violating this constraint will probably occur when calculating the HC with those existing in the literature.

Table 1. Obtained HC using the proposed model and the existing mathematical model in MW

DG location		Bus 1	Bus 8	Bus 17	Bus 28	Bus 39
The proposed model	With capacitance	6.9912	7.3727	7.2123	14.8597	12.8088
	Without capacitance	6.1602	6.5897	6.3836	14.2712	12.2508
(1)		-	23.9159	24.5539	37.7483	23.0480
(2)		-	14.8134	15.2300	19.5148	12.9754
(3)		-	14.5528	14.9701	18.0946	12.3726
(4)		-	15.2379	18.1361	15.5742	16.8307

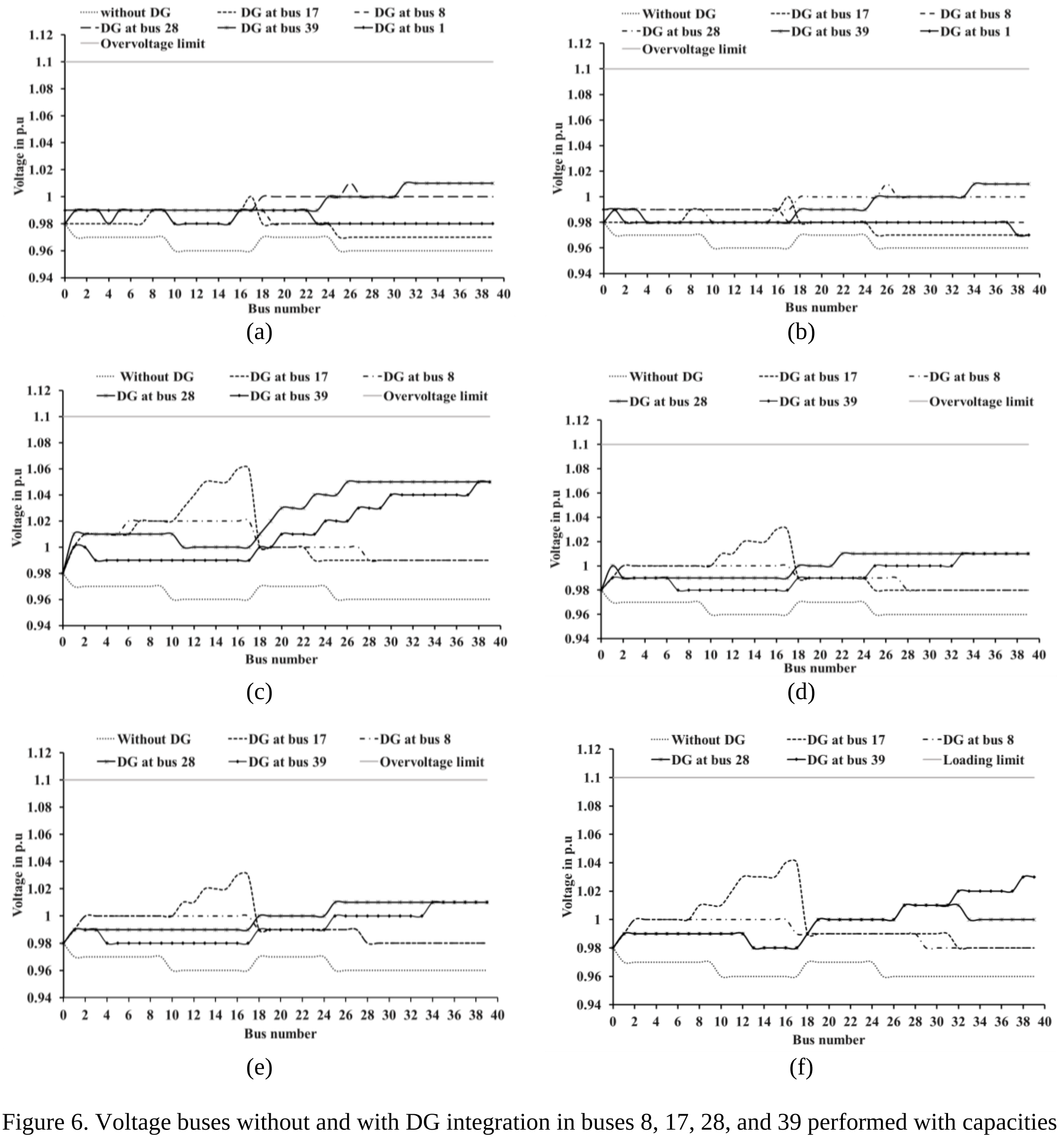

Figure 6. Voltage buses without and with DG integration in buses 8, 17, 28, and 39 performed with capacities calculated using the proposed model (a) considering the cable capacitance, (b) ignoring cable the capacitance (c) (1), (d) (2), (e) (3), and (f) (4)

Being the most common problem after DG integration, the surge has been the most considered constraint when determining a network's ability to accommodate new energy sources. Besides this problem, cable overload can occur, especially as the current increases after connecting the DG. As well as, underground cables failure is costly and time-consuming to fix. Protection systems are designed to protect cables from high current levels present under fault conditions. However, the rise in temperature due to prolonged overload conditions is just as likely to cause cable failure. Thus, introducing DG in an already existing grid may aggravate this failure. Therefore, cable overload becomes a primary constraint to be taken into account during the HC calculation process. However, researchers have always overlooked this problem, even though its effects on the network are significant. As shown in Figure 7, cable loading increases after connecting DG at the studied locations. The DG performed with capacities calculated with the proposed model in Figures 7(a) and 7(b) respect this limit in all cables. Contrariwise, Figures 7(c) to 7(f) show that cables loading exceeds its limit for DGs performed with capacities calculated using the model existing in the literature. Thus, taking into account the reverse flow helps avoid overloading the cables.

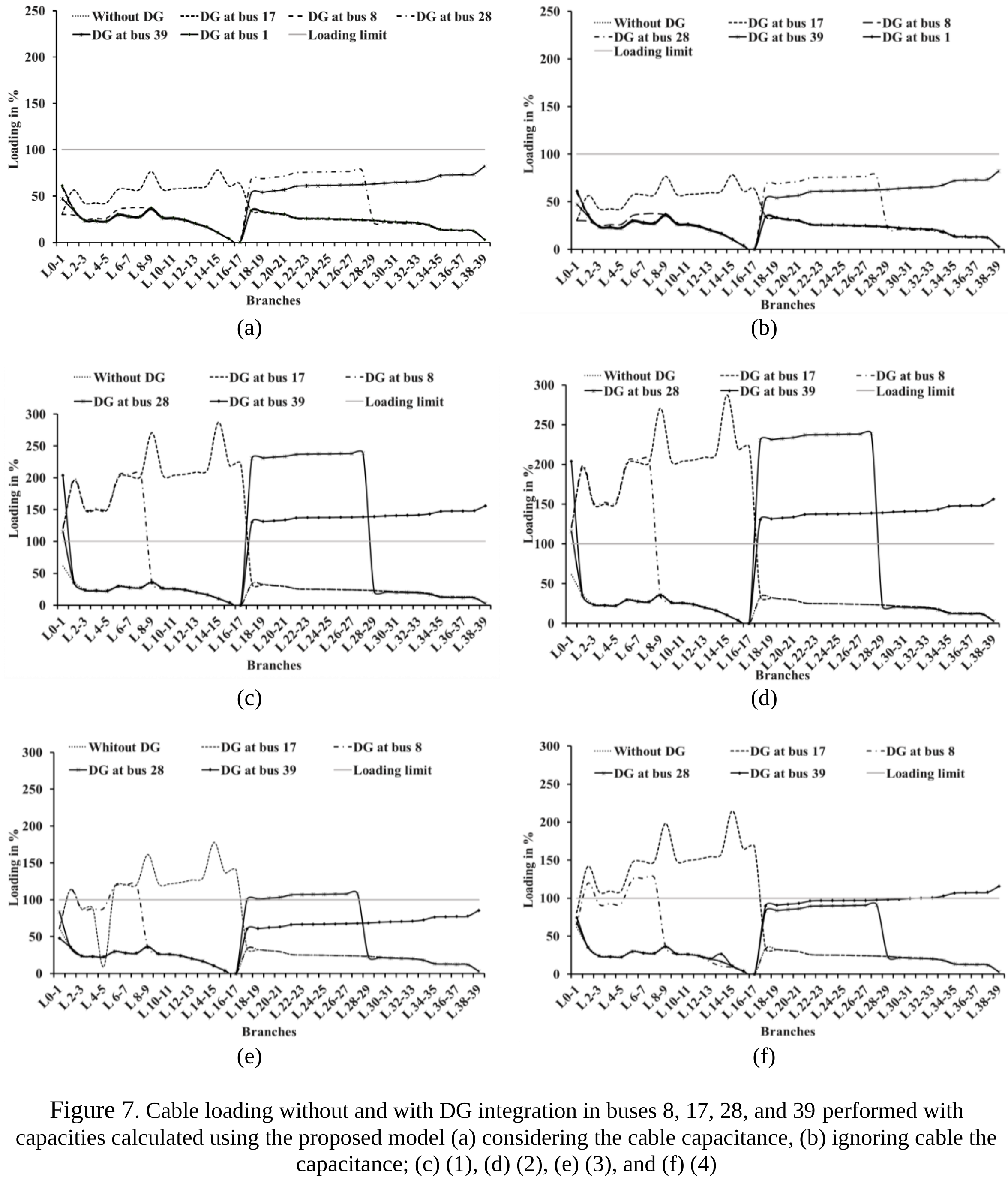

Figure 7. Cable loading without and with DG integration in buses 8, 17, 28, and 39 performed with capacities calculated using the proposed model (a) considering the cable capacitance, (b) ignoring cable the capacitance; (c) (1), (d) (2), (e) (3), and (f) (4)

The proposed model shows its effectiveness in respecting the constraints of hosting capacity. It is noteworthy that the more criteria are taken, the minimum HC will be, but the safely DG integration will be. Overvoltage is the most considered constraint when determining a network's ability to accommodate new energy sources, for a reason being the most common problem after DG integration. Besides this problem, cable overload can occur, especially as the current increases after connecting the DG. As well as, underground cables failure is costly and time-consuming to fix. Protection systems are designed to protect cables from high current levels present under fault conditions. However, the rise in temperature due to prolonged overload conditions is likely to cause cable failure. Thus, introducing DG in an already existing grid may aggravate this failure.

One of the techniques for optimizing the configuration of a radial network is changing the location of NOPs. Network reconfiguration has several advantages, such as minimizing power loss, minimizing overload cases to reduce the number of overloaded equipment, and others. Consequently, the proposed mathematical model succeeds in associating the hosting capacity approach with the reconfiguration of the studied system to facilitate the application of smart grids in future applications.

The NOP of the studied feeder is moved to different places to show its impact on the hosting capacity value. The hosting capacity is calculated using the proposed model at buses 17, 8, and 28 for four cases as:

a. Case 1: NOP is placed between buses 18 and 39 (normal place)
b. Case 2: NOP is placed on buses 10 and 11
c. Case 3: NOP is placed on buses 28 and 29.

Table 2 presents the resulting DG power after applying the mathematical model we developed for the three cases. The hosting capacity depends on the DG and NOP locations. As shown in the Table 2, the DG power of bus 8 has a higher value (13.2384 Mw) when NOP is placed between buses 28 and 29 (case 3).

Table 2. Obtained HC using the proposed model for cases 1, 2, and 3 in MW

DG location	Bus 8	Bus 17	Bus 28
Case 1	7.3727	7.2123	14.8597
Case 2	5.0176	15.1064	16.4115
Case 3	13.2384	12.8471	7.5378

DG at bus 17 has a maximum value (15.1064) when NOP is between buses 10 and 11. While the HC for bus 28 is higher (16.4115) when NOP is placed between buses 10 and 11 (case 2). When changing the location of the NOP, the grid configuration also changes. Consequently, the length of the feeder can be increased or decreased, which explains the various values obtained of HC for the same bus. Therefore, such a study will be helpful for the optimization of DG sizing and location studies and network reconfiguration.

Overvoltage and cables overload are again examined for cases 1, 2, and 3. For all DG locations (bus 8, 17, and 28) and NOP locations, the voltage profiles respect the upper voltage limit, which is 1.1 p.u, as illustrated in Figures 8(a) to 8(c). Thus, the results again confirm the effectiveness of our proposed model to avoid overvoltage problems. Grid reconfiguration via changing NOP emplacement can increase the hosting capacity of the grid as long as the optimal location is selected. The optimal location of NOP can be chosen according to respecting HC constraints. So, cable loading can increase or decrease according to DG and NOP locations. The results in Figures 9(a) to 9(c) show that loading for all cables is still under the limit for all cases.

Our proposed model showed its efficiency in respecting overvoltage and overloading constraints. Moreover, our model is inclusive and easier to apply, and it considers more than one criterion, unlike the existing one in literature. It also considers the reconfiguration of the network to respond to the smart grid transition. Therefore, considering more constraints during HC calculation reduces its value but guarantees more secure DG integration in a given distribution grid. Finally, our model was applied to a real feeder of Morocco, where we studied the variation of the location of NOP and DG impact on the HC. Our results show a significant dependency of HC on the DG and NOP locations.

The integration of DG at three locations with three NOP locations results in voltage profiles and cables loading below their thresholds even for the worst-case (minimum load with maximum generation). The main key to our model efficiency is the voltage maintenance and loading under their limits. However, the maximum power values obtained by the proposed model may not always be exact owing to assumptions made on unknown parameters such as voltage and loads consumption during the modelling stage. Therefore, the hosting capacities obtained should be approximate values. The time variable and real-time generation and load data are required for greater accuracy.

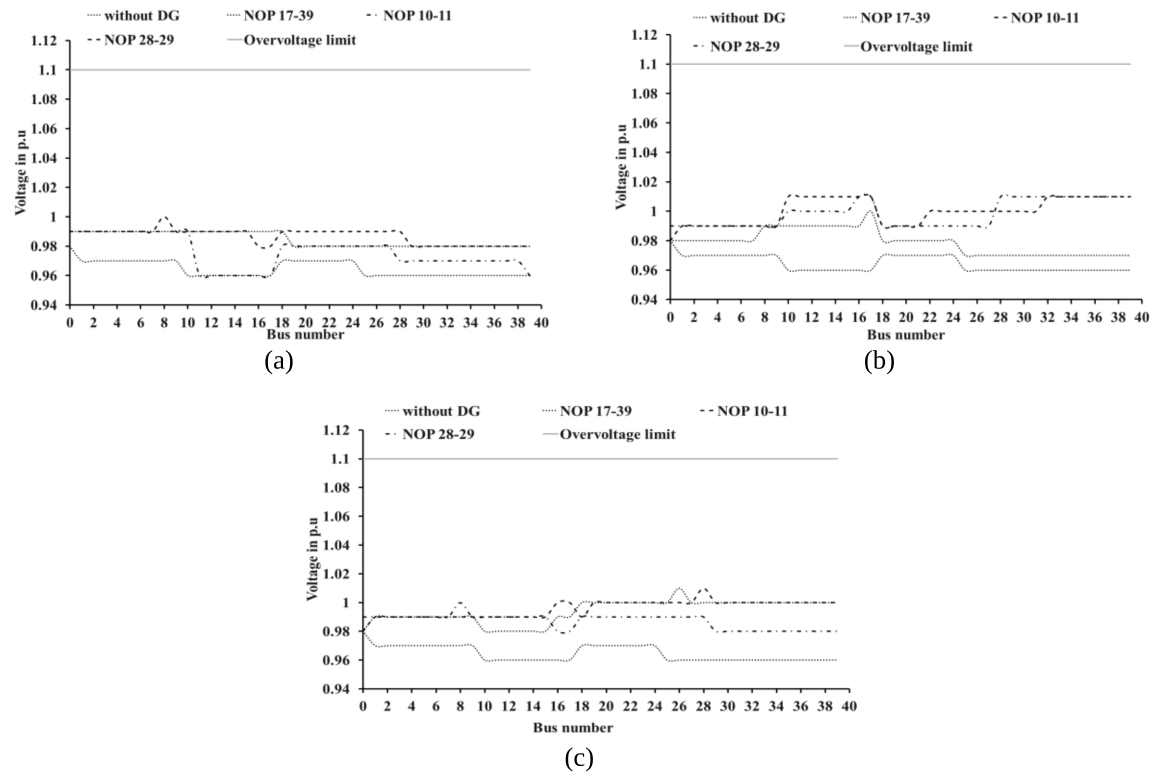

Figure 8. Impact of NOP on bus voltages after DG integration performed with capacities calculated at buses (a) bus 8, (b) bus 17, and (c) bus 28

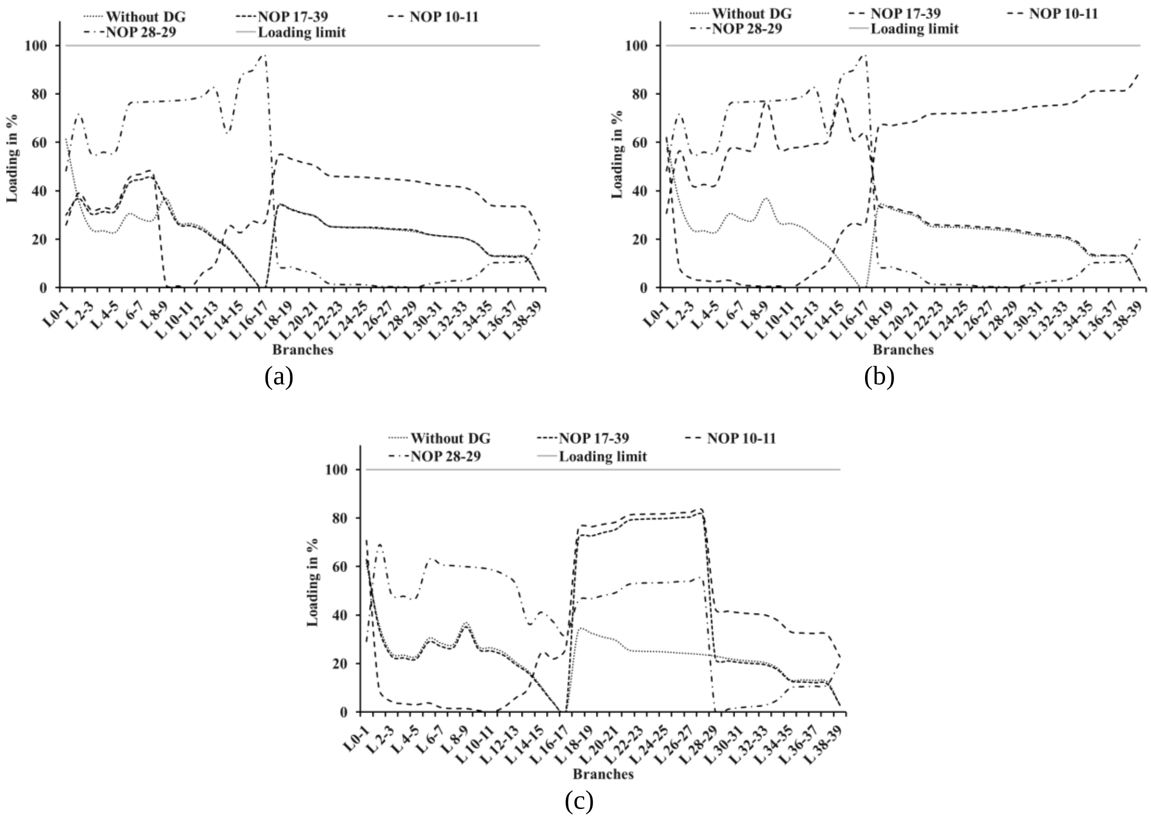

Figure 9. Impact of NOP on cable loading after DG integration performed with capacities calculated at buses (a) bus 8, (b) bus 17; and (c) bus 28

5. CONCLUSION

In this paper, a mathematical model is developed to estimate the hosting capacity of a DG planned to be integrated into a given grid point. This study aims to get a more comprehensive model that considers overvoltage, reverse power flow, overloading of the cables, grid reconfiguration, and the real parameters of the system under study. The proposed model is based on a real Moroccan underground grid of 39 buses.

The proposed mathematical model shows its efficiency compared to others existing in the literature. It is more inclusive and easier to apply. Unlike the existing ones, it considers more than one criterion. Thus, it is more realistic because it is developed from a real feeder of Morocco. The proposed model also considers the reconfiguration of the network to meet the integration of smart grid technologies. The results show a significant dependency of HC on the DG and NOP locations. The integration of DG at three locations with three NOP locations results in voltage profiles below the upper voltage limit during maximum generation and minimum loads case. Maintaining the voltage and loading of the studied system under their limits during the scenario mentioned above proves the efficiency of the proposed model. For all studied cases, the voltage of grid busses and cable loading are within their limits during the high generation and low loads (worst case). Therefore, considering more constraints during HC calculation diminishes its value but guarantees more secure DG integration in a given distribution grid. However, the maximum power values obtained by the proposed model may not always be exact. While the modelling stage, various assumptions were made on unknown parameters such as voltage and loads consumption. Therefore, the hosting capacities obtained should be approximate values. The time variable and real-time generation and load data are required for greater accuracy.

REFERENCES

[1] IEA, "Renewables bucked the trend in 2020," *Global Energy Review*. pp. 1–36, 2021, Accessed: Dec. 14, 2021. [Online]. Available: https://www.iea.org/reports/global-energy-review-2021/renewables.

[2] M. Azeroual, A. El Makrini, H. El Moussaoui, and H. El Markhi, "Renewable energy potential and available capacity for wind and solar power in Morocco towards 2030," *Journal of Engineering Science and Technology Review*, vol. 11, no. 1, pp. 189–198, Feb. 2018, doi: 10.25103/jestr.111.23.

[3] "Regulatory texts." (in French), Minister for Energy Transition and Sustainable Development Accessed: Dec. 14, 2021. [Online]. Available: https://www.mem.gov.ma/pages/textesreglementaires.aspx.

[4] P. Schavemaker and L. Van der Sluis, *Electrical power system essentials*, 2nd ed. 2017.

[5] M. S. S. Abad, J. Ma, D. Zhang, A. S. Ahmadyar, and H. Marzooghi, "Sensitivity of hosting capacity to data resolution and uncertainty modeling," in *Australasian Universities Power Engineering Conference (AUPEC)*, Nov. 2018, pp. 1–6, doi: 10.1109/AUPEC.2018.8757980.

[6] E. Mulenga, M. H. J. Bollen, and N. Etherden, "A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids," *International Journal of Electrical Power and Energy Systems*, vol. 115, 2020, doi: 10.1016/j.ijepes.2019.105445.

[7] J. Lee, J.-P. Bérard, G. Razeghi, and S. Samuelsen, "Maximizing PV hosting capacity of distribution feeder microgrid," *Applied Energy*, vol. 261, Mar. 2020, doi: 10.1016/j.apenergy.2019.114400.

[8] K. Doğanşahin, B. Kekezoğlu, R. Yumurtaci, O. Erdinç, and J. P. S. Catalão, "Maximum permissible integration capacity of renewable DG units based on system loads," *Energies*, vol. 11, no. 1, pp. 1–16, 2018, doi: 10.3390/en11010255.

[9] I. Moufid, S. Naciri, H. E. L. Moussaoui, T. Lamhamdi, and H. El Markhi, "Power loss minimization using the integration of DGs and reconfiguration of distribution system: applied on real distribution feeder of urbain areas of Kenitra City in Morroco," *Advances in Science, Technology and Engineering Systems Journal*, vol. 5, no. 5, pp. 74–79, 2020, doi: 10.25046/aj050511.

[10] G. V. K. Murthy, C. H. V Suresh, K. Sowjankumar, and B. Hanumantharao, "Impact of distributed generation on unbalanced radial distribution system," *International Journal of Scientific and Technology Research*, vol. 8, no. 9, pp. 539–542, 2019.

[11] I. T. Papaioannou and A. Purvins, "A methodology to calculate maximum generation capacity in low voltage distribution feeders," *International Journal of Electrical Power and Energy Systems*, vol. 57, pp. 141–147, 2014, doi: 10.1016/j.ijepes.2013.11.047.

[12] A. K. Jain *et al.*, "Dynamic hosting capacity analysis for distributed photovoltaic resources—framework and case study," *Applied Energy*, vol. 280, Dec. 2020, doi: 10.1016/j.apenergy.2020.115633.

[13] N. Soukaina, E. Hassane, E. M. Hassan, and L. Tijani, "Hosting capacity estimation of underground distribution feeder in Urbain Areas," in *International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*, Apr. 2019, pp. 1–5, doi: 10.1109/WITS.2019.8723822.

[14] E. Mulenga, M. H. J. Bollen, and N. Etherden, "Distribution networks measured background voltage variations, probability distributions characterization and solar PV hosting capacity estimations," *Electric Power Systems Research*, vol. 192, Mar. 2021, doi: 10.1016/j.epsr.2020.106979.

[15] A. F. Zobaa, S. H. E. A. Aleem, S. M. Ismael, and P. F. Ribeiro, *Hosting capacity for smart power grids*. Springer Cham, 2020.

[16] S. M. Ismael, S. H. E. A. Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," *Renewable Energy*, vol. 130, pp. 1002–1020, Jan. 2019, doi: 10.1016/j.renene.2018.07.008.

[17] M. S. S. Abad, J. Ma, A. S. Ahmadyar, and H. Marzooghi, "Distributionally robust distributed generation hosting capacity assessment in distribution systems," *Energies*, vol. 11, no. 11, pp. 1–19, 2018, doi: 10.3390/en11112981.

[18] K. Nigim, "Integration of distributed generation with electrical power system," in *Power Electronics in Smart Electrical Energy Networks*, vol. 34, London: Springer London, 2008, pp. 203–228.

[19] J. F. B. Sousa, C. L. T. Borges, and J. Mitra, "PV hosting capacity of LV distribution networks using smart inverters and storage systems: A practical margin," *IET Renewable Power Generation*, vol. 14, no. 8, pp. 1332–1339, 2020, doi: 10.1049/iet-rpg.2019.1054.

[20] R. Cépedes, C. Gallego, H. Smit, and A. Gómez, "Improving distribution network hosting capacity," *Neplan*, pp. 1–5, 2019.

[21] M. Alturki, A. Khodaei, A. Paaso, and S. Bahramirad, "Optimization-based distribution grid hosting capacity calculations," *Applied Energy*, vol. 219, pp. 350–360, Jun. 2018, doi: 10.1016/j.apenergy.2017.10.127.

[22] T. E. C. de Oliveira, M. Bollen, P. F. Ribeiro, P. M. S. de Carvalho, A. C. Zambroni, and B. D. Bonatto, "The concept of dynamic hosting capacity for distributed energy resources: analytics and practical considerations," *Energies*, vol. 12, no. 13, pp. 1–18, 2019, doi: 10.3390/en12132576.

[23] T. E. C. De Oliveira, P. M. S. Carvalho, P. F. Ribeiro, and B. D. Bonatto, "PV hosting capacity dependence on harmonic voltage distortion in low-voltage grids: Model validation with experimental data," *Energies*, vol. 11, no. 2, 2018, doi: 10.3390/en11020465.

[24] O. Lennerhag, S. Ackeby, M. H. J. Bollen, G. Foskolos, and T. Gafurov, "Using measurements to increase the accuracy of hosting capacity calculations," *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1, pp. 2041–2044, 2017, doi: 10.1049/oap-cired.2017.0316.

[25] Q. Qi, C. Long, J. Wu, K. Smith, A. Moon, and J. Yu, "Using an MVDC link to increase DG hosting capacity of a distribution network," *Energy Procedia*, vol. 142, pp. 2224–2229, 2017, doi: 10.1016/j.egypro.2017.12.622.

[26] C. Schwaegerl, M. H. J. Bollen, K. Karoui, and A. Yagmur, "Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources," *IEE Conference Publication*, vol. 4, no. 2005–11034, pp. 153–157, 2005, doi: 10.1049/cp:20051229.

[27] M. Altin, E. U. Oguz, E. Bizkevelci, and B. Simsek, "Distributed generation hosting capacity calculation of MV distribution feeders in Turkey," *IEEE PES Innovative Smart Grid Technologies Conference Europe*, pp. 1–7, 2015, doi: 10.1109/ISGTEurope.2014.7028776.

[28] A. Dubey and S. Santoso, "On estimation and sensitivity analysis of distribution circuit's photovoltaic hosting capacity," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2779–2789, 2017, doi: 10.1109/TPWRS.2016.2622286.

BIOGRAPHIES OF AUTHORS

Soukaina Naciri received the master degree in electrical engineering option Electronics, Signals, and Automated Systems from the faculty of science and technologies of Sidi Mohammed Ben Abdallah University She is now a Ph.D. student at Intelligent Systems Georessources and Renewable Energy Laboratory (SIGER) of the faculty of science and technologies of Sidi Mohammed Ben Abdallah University. Her research interests include power electronics, motor drives, and renewable energy. She can be contacted at email: soukaina.naciri@usmba.ac.ma.

Ismail Moufid is a Ph.D. student at Intelligent Systems Georessources and Renewable Energy Laboratory (SIGER) of the faculty of science and technologies of Sidi Mohammed Ben Abdallah University. His Research interests include reduction of power loss in distribution network, power electronics, motor drives, and renewable energy. Ismail had a Master degree in Electronics, Signals and Automated Systems from the faculty of science and technologies of Sidi Mohammed Ben Abdallah University of Fez. He can be contacted at email: ismail.moufid@usmba.ac.ma.

Hassan El Moussaoui received the the master degree in Industrial electronics from University of Quebec at Trois-Rivières, Quebec, Canada. He received his Ph.D. Degree in the impact of wind energy integration on the national electricity grid from Sidi Mohamed Ben Abdellah University, Fez in 2015. He is currently a professor in the Department of Electrical Engineering with Faculty of Science and Technology, Fez (Morocco). His main research interests include smart grid, renewable energy, energy management and, artificial intelligence. He can be contacted at email: hassan.elmoussaoui@usmba.ac.ma.

Tijani Lamhamdi received the Master degree in nuclear physics from Mohamed V University, Rabat in 1988. He received his first Ph.D. Degree in Design and implementation of a gain and time stability control system for all NEMO detectors from University Louis Pasteur Strasbourg France. He received his second Ph.D. Degree in NEMO 3 experiment - Study of the background noise and measurement of the double beta decay period of 150Nd from Sidi Mohamed Ben Abdellah University, Fez in 2007. He is currently a professor in the Department of Electrical Engineering with Faculty of Science and Technology, Fez (Morocco). His main research interests include smart grid, artificial intelligence and renewable energy systems. He can be contacted at email: tijani.lamhamdi@usmba.ac.ma.

Hassane El Markhi received the Engineer degree in electrical engineering from Hassan II University, Casablanca in 1995. He received his Ph.D. degree in fault location in electrical power distribution systems and improvement of a grid-integrated DFIG based wind turbine system from Sidi Mohamed Ben Abdellah University, Fez in 2015. He is currently a professor in the Department of Electrical Engineering with Faculty of Science and Technology, Fez (Morocco). His main research interests include smart grid, fault location, and renewable energy systems. He can be contacted at email: Hassane.elmarkhi@usmba.ac.ma.