Maximum hosting capacity of distributed generation in three-phase distribution systems: an approach based on an optimization model

Máxima capacidade de hospedagem de geração distribuída em sistemas de distribuição trifásicos: uma abordagem baseada em um modelo de otimização

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ABSTRACT
In this paper, an optimization problem is formulated with the main purpose of determining the maximum hosting capacity of distributed generation in three-phase electric power distribution systems. The objective function to be maximized is the sum of the active powers injected into the system buses in which distributed generation is considered. Inequality constraints are used to determine lower and upper bounds for voltage magnitudes, unbalance factor, reverse power flow at the substation bus and active power insertion. Power flow equations are modelled as equality constraints according to the three-phase current injection method. Simulations are performed using a modified IEEE 33-bus to show the effectiveness of the proposed methodology for determining the maximum hosting capacity in three-phase distribution feeders assuming dispersed generation previously allocated in the network. An index is proposed to calculate the maximum hosting capacity based on the response of the optimization problem. Additionally, daily load profiles are considered to test the proposed methodology assuming system load variation. The main contribution of this paper is the optimization model which assumes bounds for reverse power flow and unbalance factor in a systemic analysis based on the three-phase current injection method equations (TPCIM).

Keywords: hosting capacity, electric distribution systems, distributed generation, computational simulations.

RESUMO

Neste artigo, um problema de otimização é formulado com o principal objetivo de determinar a máxima capacidade de hospedagem de geração distribuída em sistemas elétricos de distribuição trifásicos. A função objetivo a ser maximizada é o somatório de potências ativas injetadas nas barras do sistema nas quais unidades de geração distribuída são consideradas. Restrições de desigualdade são usadas para se determinar limites mínimos e máximos para magnitudes de tensão, grau de desequilíbrio, fluxo reverso na subestação e inserção de potência ativa. Equações do fluxo de potência são modeladas como restrições de igualdade de acordo com o método de injeção de correntes trifásico. Simulações são realizadas usando um sistema de 33 barras modificado a fim de mostrar a eficiência do método proposto para determinar a máxima capacidade de hospedagem em alimentadores de distribuição trifásicos assumindo geração dispersa previamente alocada na rede. Um índice é proposto para calcular a máxima capacidade de hospedagem baseada na resposta do problema de otimização. Além disso, curvas diárias de carga são consideradas para testar o método proposto considerando variações da carga do sistema. A principal contribuição deste artigo é a modelagem do problema de otimização que assume limites para reversão de fluxo de potência e grau de desequilíbrio em uma análise sistêmica baseada nas equações do Método de Injeção de Correntes Trifásico (MICT).

Palavras-chave: capacidade de hospedagem, sistema de distribuição de energia elétrica, geração distribuída, simulações computacionais.

1 INTRODUCTION

Due to ever increasing use of renewable energy in power distribution networks, it is utterly important to verify their impacts on the system operation and planning by appropriate methodologies (Mulenga et al., 2020).

Distributed generation based on the use of diesel generators, photovoltaic (PV) systems and wind power parks are often considered within the context of smart grids environment. The benefits of their usage include voltage profile improvement, power losses reduction and increase of energy matrix variability (Almeida et al., 2020, Celli et al., 2018). However, some potential disadvantages may be associated to distributed generation due to their intermittent nature including occurrence of overvoltages, reverse power flows and power quality degradation (Mahroo-Bakhtiari et al., 2019).

As a consequence, it is important to determine the maximum amount of distributed generation (DG) which a system can accommodate without deteriorating its power quality in general terms. Maximum hosting capacity (MHC) corresponds to the determination of the maximum power generation associated to DGs assuming specified limits for parameters such as maximum and minimum voltage magnitudes (Quijano et al., 2017). In order to evaluate the maximum hosting capacity, three main approaches can be used according to the literature survey presented in Mulenga et al., 2020: (i) deterministic methods in which the hosting capacity is determined by analytical algorithms which provide the maximum amount of DG to be accommodated in the network. When using a deterministic method, the grid, customer and DG models are known. The distribution grid is modelled using active power, reactive power, series line impedances and constant impedance, current or power load models; (ii) stochastic methods which relies on statistical analysis considering a large number of different scenarios to be analyzed based on the assumption that DG can be allocated at any bus of the system and assuming the inherent intermittent nature of the DG units; (iii) time-series approach which assumes daily load variations and provide the maximum amount of DG to be inserted into the system in regular time intervals. Time-series based methods use historical data in the form of measured time series of solar photovoltaic production and customer power consumption in distribution grids.

Reference (Lakshmi and Ganguly, 2018) presents a multi-objective planning approach to optimally allocate open unified power quality conditioners by simultaneously optimizing the photovoltaic hosting capacity and energy losses of distribution systems. The limits on bus voltage magnitudes, line current flows, maximum generation capacity, and the percentage of voltage sag mitigated are considered to be the operational constraints of the optimization problem. The solution is provided by particle swarm optimization algorithm which is associated to disadvantageous computational time.

A stochastic assessment of distributed generation hosting capacity and energy efficiency in active distribution networks is presented in Quijano et al., 2017. A multi-period and multiobjective optimization algorithm, based on a linearized optimal power flow, is formulated. The results show that the photovoltaic deployment in distribution systems reduces the energy loss based on statistical analysis.

Abad et al., 2019 presents a probabilistic based framework to determine the maximum hosting of DGs considering the voltage rise due to their allocation.

In order to control the voltage, local volt/var control strategies absorb or inject reactive power, provoking an additional current to be injected or absorbed in the connection point of smart inverters. These control strategies are analyzed in Schultis, 2019 with the objective of evaluating their impact on the determination of hosting capacity. It is important to notice that, the strategy of using volt/var control based on the use of smart photovoltaic inverters helps to improve the voltage profile.

Multiple energy storage scenarios are assessed to increase renewable penetration in microgrids in Lee et al., 2020. The results prove that higher photovoltaic penetration can be achieved with substation control and automation.

In Wang et al., 2019, interval and affine arithmetic are both applied to deal with uncertainties related to load variability and also to DG generation. A practical 55-bus rural feeder in China is used to validate the method compared with the conventional method, and also to verify the value in decision-making of PV planning for utilities.

An optimization-based hosting capacity methodology is developed in Alturki et al., 2018 being the distribution grid power flow linearized to provide the results of maximum hosting capacity. Tests were carried out on a radial system considering a balanced single-phase power distribution grid.

Reference (Sahu and Ghosh, 2019) presents an optimization model to verify hosting capacity of distribution grids. The method is tested on the single phase IEEE 33-bus distribution system, whose reconfiguration is achieved by particle swarm optimization. Loss minimization is used as the objective function to be minimized. All the buses are considered as potential locations for DG units and the results provide the maximum hosting capacity evaluated for each bus of the test feeder in a systemic analysis which is very useful for future utilities planning.

In Fu and Chiang, 2018, a power distribution system reconfiguration is addressed considering the problem of maximizing the amount of DG to be inserted into the network.

Raja et al., 2018 presents a methodology to optimally determine the location of DGs and their hosting capacity. The performance of the developed method is evaluated using simulation of test network employing realistic time series data.

In de Oliveira et al., 2019, the concept of dynamic hosting capacity is introduced. In this case, the maximum hosting capacity is evaluated for different load scenarios in regular time intervals during a given period of time. The method is validated on a real test feeder of a federal university. However, the hosting capacity is evaluated based on a Thevenin equivalent for an unique measurement point in the network.

Based on the literature review, it is worth notice that there are a large number of recent papers aiming to analyse the hosting capacity in distribution systems. Different approaches are considered to determine the maximum amount of DG to be accommodated in the test systems considering different advantages and disadvantages of their installation. IEEE test feeders are generally used to validate the results provided by the proposed methodologies and single-phase approaches are commonly used.

In this paper, the maximum hosting capacity is determined by an optimization model formulation in which the objective function to be maximized is the sum of the active powers inserted by distributed generation at buses in which they are considered assuming unbalanced three-phase power systems to be evaluated. Inequality constraints are considered for voltage magnitudes, unbalance factor and reverse power flow. To test the proposed methodology, simulations are carried out using IEEE 33-bus test system for nominal load and also assuming daily load profiles. An index for calculating the hosting capacity is proposed based on the optimization problem solution.

This paper is subdivided into four main sections including this introductory one. In the second section, the proposed method is presented. Simulations are performed in the third section with presented results to validate the proposed methodology. Finally, conclusions are highlighted in the final section.

2 PROPOSED METHOD

2.1 OPTIMIZATION MODEL

The maximum hosting capacity is determined by an optimization model, described in this section. The objective function to be maximized is the sum of the injected active powers ($P_{k,G}^{s}$) by the DG units for all the k buses in which they are considered, as presented in equation (1) for all the three phases of the system ($s \in \{a,b,c\}$) in which N_{GD} represents the total number of distributed generation units.

The use of the three-phase current injection method (Garcia et al., 2000) equations for power flow calculation are expressed as equality constraints (4), (5), (6) and (7) in this work representing an important contribution. The advantage of their usage is that unbalanced three-phase power flows can be evaluated appropriately considering all their inherent characteristics as discussed in Garcia et al., 2000 such as unbalanced three-phase loads, mutual and self-impedances for all the system branches.

Additionally, inequalities (8), (9), (10), (11) and (12) are also incorporated to the optimization model. They represent lower/upper bounds for voltage magnitudes, active/reactive power generation at each bus in which DG is considered, unbalance factor and reverse power flow, respectively.

$$\max \sum_{s \in \{a,b,c\}} \sum_{k=1}^{N_{GD}} P_{k,G}^{s} \tag{1}$$

subject to:

$$P_k^{s,sch} = (P_{k,G}^s - P_{k,L}^s) \tag{2}$$
$$Q_k^{s,sch} = (Q_{k,G}^s - Q_{k,L}^s) \tag{3}$$

$$I_{re,k}^s = \frac{P_k^{s,sch}\, V_{re,k}^s + Q_k^{s,sch}\, V_{im,k}^s}{(V_{re,k}^s)^2 + (V_{im,k}^s)^2} \tag{4}$$

$$I_{im,k}^s = \frac{P_k^{s,sch}\, V_{im,k}^s - Q_k^{s,sch}\, V_{re,k}^s}{(V_{re,k}^s)^2 + (V_{im,k}^s)^2} \tag{5}$$

$$I_{re,k}^s - \sum_{m \in \Omega_k} \sum_{t \in \{a,b,c\}} \left(G_{km}^{st}\, V_{re,m}^s - B_{km}^{st}\, V_{im,m}^s\right) \tag{6}$$
$$I_{im,k}^s - \sum_{m \in \Omega_k} \sum_{t \in \{a,b,c\}} \left(G_{km}^{st}\, V_{im,m}^s + B_{km}^{st}\, V_{re,m}^s\right) \tag{7}$$

$$V_k^{s,min} \leq V_k^s \leq V_k^{s,max} \tag{8}$$

$$0 \leq P_{k,G}^s \leq P_{k,G}^{s,max} \tag{9}$$

$$-tg(cos^{-1}(fp_k)) \leq Q_{k,G}^s \leq tg(cos^{-1}(fp_k)) \tag{10}$$

$$0 \leq \delta_k \leq \delta_k^{max} \tag{11}$$

$$\sum_{s \in \{a,b,c\}} \sum_{k=1}^{N_{GD}} P_{k,G}^s \leq \sum_{s \in \{a,b,c\}} \sum_{k=1}^{N_{buses}} P_{k,L}^s \tag{12}$$

- $P_k^{s,sch}$, $P_{k,G}^s$, $P_{k,L}^s$ represent the scheduled, generated and load active powers, respectively;
- $Q_k^{s,sch}$, $Q_{k,G}^s$, $Q_{k,L}^s$ represent the scheduled, generated and load reactive powers, respectively;
- $I_{re,k}^s$ and $I_{im,k}^s$ are real and imaginary parts of the injected current at a given bus k specified in rectangular coordinates on a given phase s;
- $V_{re,k}^s$ and $V_{im,k}^s$ are real and imaginary parts of the voltage magnitude at a given bus k specified in rectangular coordinates on a given phase s;
- G_{km}^{st} and B_{km}^{st} are the conductance and susceptance of a given distribution line connecting bus k to m, for a given phase s and its corresponding mutual t;

- V_k^s; $V_k^{s,min}$; $V_k^{s,max}$ represent the actual, minimum and maximum value of the voltage magnitude at given k on phase s;
- $P_{k,G}^s$; $P_{k,G}^{s,max}$ represent the actual and maximum value of active power injected by a given DG unit;
- $Q_{k,G}^s$ is the reactive power of the DG units related to the minimum power factor (fp_k) allowed by international standards ($fp_k > 0.92$);
- N_{buses} is the total number of system buses;
- δ_k, δ_k^{max} are the actual and maximum values of the voltage unbalance factor.

The inequality constraint (11) is related to the voltage unbalance factor, which is calculated based on Equation (13), where α represents the phasor quantity (α = 1 $\angle 120°$). It is defined as the ratio of the modulus of the negative-sequence (V_{neg}) to the positive-sequence (V_{pos}) components of the voltage at fundamental frequency, expressed as a percentage, according to standard IEC 61000-3-14. For balanced systems, δ_k is equal to 0% and the maximum allowed value is generally lower than 1%.

$$\delta_k = \left(\frac{V_{neg}}{V_{pos}}\right).100\% = \left(\frac{\dot{V}_k^a + \alpha^2\,\dot{V}_k^b + \alpha\,\dot{V}_k^c}{\dot{V}_k^a + \alpha\,\dot{V}_k^b + \alpha^2\,\dot{V}_k^c}\right).100\% \tag{13}$$

Inequality constraint (12) is related to the reverse power flow which may occur at the substation bus due to the insertion of distributed generation. In this case, the power generated by the DGs must be equal or less than the total load of the distribution system. The incorporation of this constraint represents an important contribution of this work since it ensures that the maximum hosting capacity is determined with no reverse power flow. This feature avoids the power flow to be inserted into high voltage systems compromising the operation of protection schemes as discussed in Holguin et al., 2020 and Khani et al., 2018.

The response of the optimization problem is calculated based on the system variables which comprises all the voltages at each bus of the system and the outputs of the DGs. The proposed formulation is solved by interior point methodology according to reference (Oliveira et al., 2015) in which the safety barrier interior point method is presented.

2.2 PROPOSED INDEX

Based on the response of the optimization problem, it is possible to calculate the maximum hosting capacity, denoted by index η presented in equation (14). It determines the percentage value of distributed generation in reference to the loads demanded by the system buses, being Nb the total number of load buses in the network.

$$\eta\,(\%) = \left(\frac{\sum_{s\,\in\,\{a,b,c\}}\sum_{k=1}^{N_{GD}} P_{k,G}^{s}}{\sum_{s\,\in\,\{a,b,c\}}\sum_{k=1}^{N_{buses}} P_{k,L}^{s}}\right).100\% \qquad (14)$$

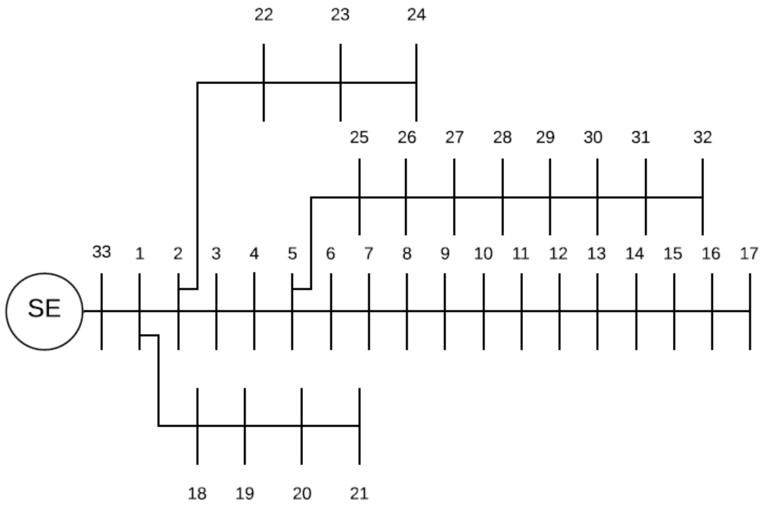
The proposed index in equation (14) is used in order to ease the presentation of the results obtained from the proposed methodology.

Note that the index computes the total amount of distributed generation to be accommodated with respect to the total amount of system load. In case of a reverse power flow, DG units would generate more than the total load of the system being higher than 100% in this situation. This is computed by the proposed index.

3 RESULTS AND DISCUSSION

In order to validate the results obtained from the proposed methodology, the 33-bus test system is used, being its single line diagram presented in Figure 1. It consists of 32 load buses and a substation bus (bus 33). This system is used in order to consider unbalanced three phase loads, being their nominal data defined for each phase a, b, c and all the system buses according to reference (Melo et al., 2017). Considering the nominal load demanded by the system, the substation bus provides a total amount of active generation equal to 7.68 MW on phase a, 6.82 MW on phase b and 8.63 MW on phase c once the system is unbalanced.

Figure 1- Single line diagram of the 33-bus test system



Once the focus of the analysis is not DG allocation, but the determination of maximum hosting capacity assuming different scenarios, simulations are conducted according to the following statements: (i) The proposed technique is tested assuming no DG unit installed into the grid. This simulation aims to evaluate the system state before the installation of DG units; (ii) Tests are conducted considering a single DG unit allocated into the system. In this case, the aim of the simulation is to evaluate the maximum hosting capacity to be accommodated in a single bus; (iii) The proposed formulation is subject to different scenarios including different number of buses with DG allocated in dispersed locations; (iv) The allocation of distributed generation in all the system load buses of the system is considered. This approach is important to determine the maximum hosting capacity at each bus systemically, being an useful tool for utilities planning within active distribution systems context, as discussed in Sahu and Ghosh, 2019; (v) Dynamic hosting capacity is calculated based on the proposed formulation assuming daily load variations with the objective of determining the MHC at each time interval in which the algorithm is executed. Once the system load varies along the day, it is expected that the η index to be different at each time interval.

In all the situations, the three-phase voltage magnitudes are evaluated as well as the unbalance factor associated to each bus. This feature is one of the main contributions of this work once the MHC is calculated considering the unbalance factor of the network to be below a threshold value specified by IEC 61000-3-14.

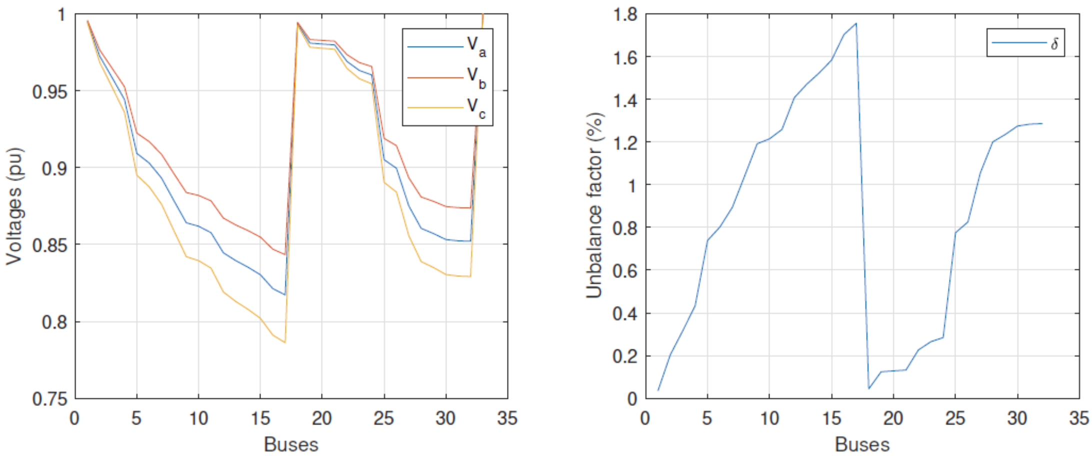
For the limits of the inequalities of the optimization model used in the proposed method, minimum and maximum values of voltage magnitudes are equal to 0.95 and 1.05, respectively. The unbalance factor maximum adopted value is 1%. The maximum allowable value of power generated by each DG unit is equal to the total system load data. Another important consideration is that the power factor of the DGs are set equal to the unitary value, meaning that only active power is provided.

The code of the proposed method was implemented using MATLAB software, using a computer IntelCoreTM i7-2600 CPU @ 3.40 GHz and 16 GB(RAM), with the operational system Windows-10.

3.1 BASE CASE

In order to prove the results of the simulation considering no DG unit previously installed into the test system, a three-phase power flow is executed according to reference (Garcia et al., 2000). Once the results of the power flow are obtained, it is possible to evaluate the system state before the installation of distributed generation units. Figure 2 presents the results of the voltage magnitudes calculated for each phase a, b and c.

Figure 2 - Voltage profile and unbalance factors for the base case



It can be noted that, the system voltage magnitudes are below 0.95 for a large number of buses. Additionally, the unbalance factor is higher than the threshold value 1%, indicating that when the system operates in nominal condition, undervoltage cases are observed and the unbalance factor is not according to the adopted limit.

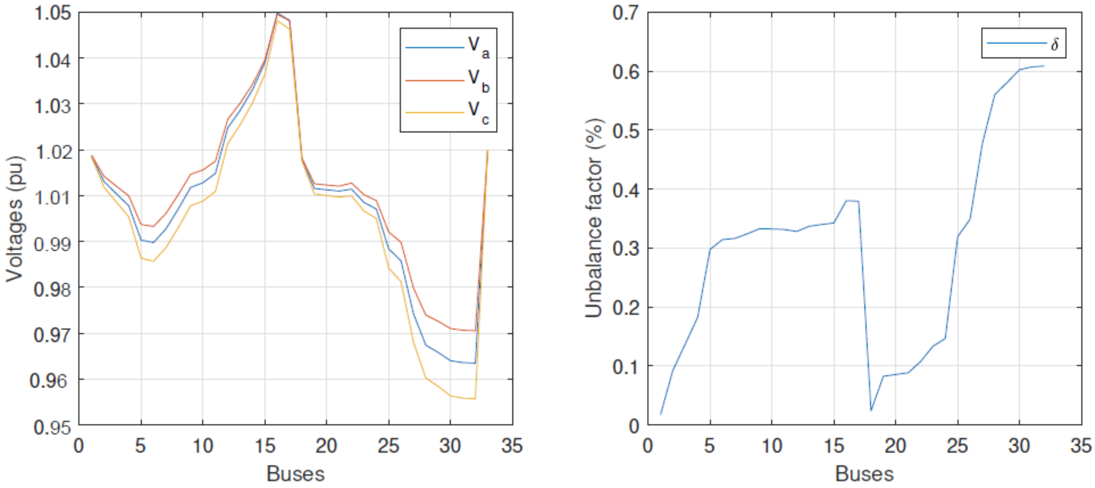
3.2 DG UNIT ALLOCATED AT BUS 16

In order to verify the effectiveness of the proposed method, the MHC index is calculated assuming a DG at bus 16. Figure 3 presents the results obtained for bus voltage magnitudes and unbalance factor. It can be noted that the maximum voltage of 1.05 is associated to bus 16 in which the DG is allocated.

All the unbalance factors are below the threshold value of 1%, according to the inequalities used in the proposed formulation.

Active power generated at bus 16 would be 3.54 MW, 3.20MW and 4.42MW on phases a, b and c respectively. In this case, the η index is equal to 48.23%. Note that, no reverse power flow occurs once the total amount of generation is about 48.23% of the total load demanded by the system buses.

Figure 3- Voltage magnitudes and unbalance factors for a single DG at bus 16

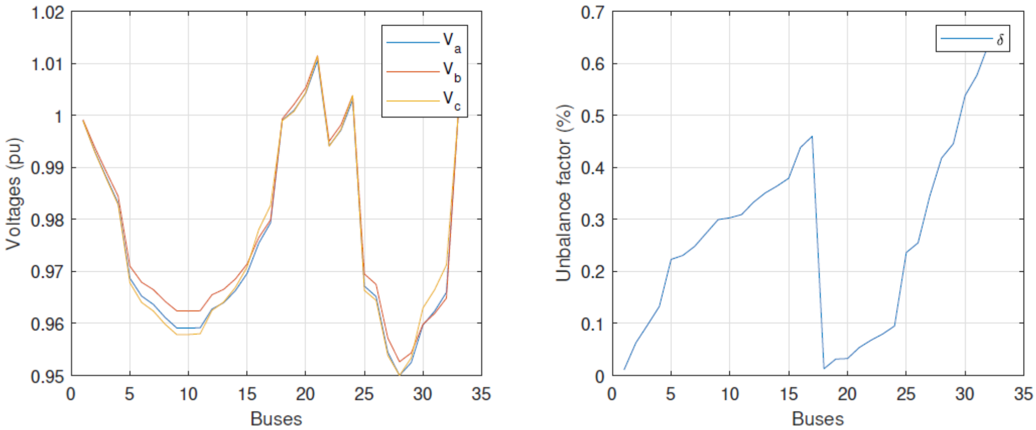


3.3 DG UNITS ALLOCATED AT END BUSES OF THE LATERAL FEEDERS

In this case, the simulations are performed according to the case presented in (Alturki et al., 2018). DGs are considered to be allocated at buses 17, 21, 24 and 32. These are the end buses of the lateral feeders of the 33-bus test system represented in Figure 1.

Figure 4 presents the results obtained for the voltage magnitudes and unbalance factors associated to each busbar of the 33-bus test system assuming the installation of DGs in the network.

Figure 4- Voltage magnitudes and unbalance factors for DG units at end buses



It can be noted that, by the use of the proposed technique, the unbalance factor is always below the threshold of 1% and the voltage magnitudes are within the proposed limits. It is also important to notice that, the installation of the DG units would be useful to reduce the unbalance factors of the power systems using the proposed method. It is very important for utilities planning considering future smart grids environment.

The maximum powers to be generated at the buses with DG units are presented in Table 1 for each phase a, b and c. The η index calculated for this case study is 92.73%. Based on these results, it is possible to conclude that more distributed generation can be accommodated into the power systems if they are dispersed along the distribution feeders. Although this conclusion may be obviously highlighted by a large number of papers, it can also be verified using the proposed method.

Table 1- Active power generated at each bus

Bus	$P^a_{g,i}$ (MW)	$P^b_{g,i}$ (MW)	$P^c_{g,i}$ (MW)
17	1.73	1.54	1.91
21	1.76	1.68	1.88
24	1.76	1.66	1.89
32	1.89	1.52	2.19

3.4 DG UNITS ALLOCATED AT SEVEN BUSES OF THE SYSTEM

To reinforce the conclusions obtained in the previous subsection, all the end buses (17, 21, 24 and 32) contain DG installed. Additionally, DGs are also allocated at buses 1, 2 and 5. In this scenario, a larger number of buses is considered as potential locations of distributed generation.

Figure 5 presents the results of voltage magnitudes and unbalance factors for all the system buses. It can be noted that all the voltage magnitudes are between acceptable limits and the unbalance factor has been reduced.

Figure 5- Voltage magnitudes and unbalance factors for seven DGs

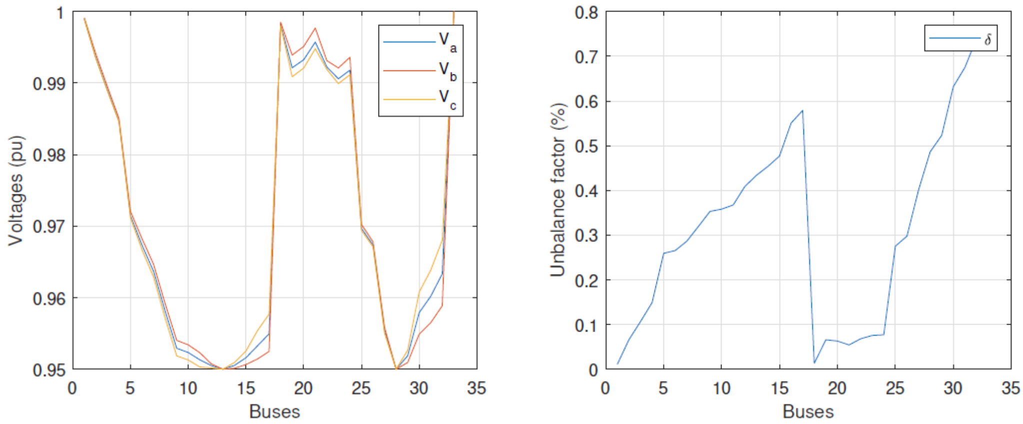


Table 2 presents the maximum powers to be generated at the buses with DG units for each phase a, b and c. The index η is 93.08% in this case study, reinforcing the conclusion that when the generation is dispersed throughout the power grid, the hosting capacity is higher than the case in which a DG is allocated at a single bus.

Table 2- Active powers generated at each bus

Bus	$P^a_{g,i}$ (MW)	$P^b_{g,i}$ (MW)	$P^c_{g,i}$ (MW)
1	0.7856	0.7813	0.8407
2	0.8209	0.8081	0.8803
5	0.9924	0.9244	1.0772
17	1.2205	1.0070	1.3837
21	0.7804	0.7779	0.8341
24	0.8170	0.8055	0.8755
32	1.6813	1.2683	1.9412

3.5 DG UNITS ALLOCATED AT ALL THE SYSTEM BUSES

As proposed in Sahu and Ghosh, 2019, a systemic analysis can be used to evaluate the maximum hosting capacity at each system bus. In this case study, DG units are considered to be allocated at all the system buses. When the proposed method is used for evaluating this case, it is also possible to determine voltage magnitudes and unbalance factors, as presented in Figure 6.

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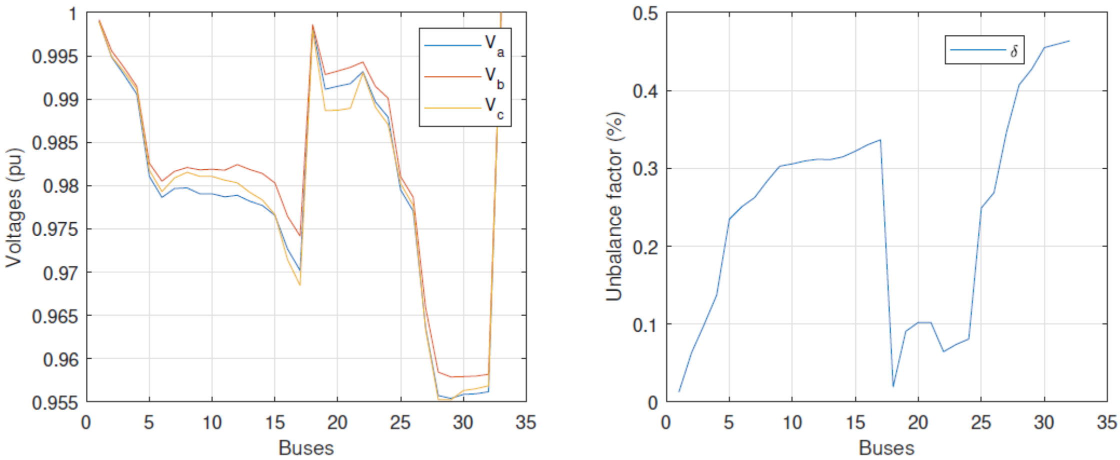
Note that, even for this case study, the proposed method is able to provide the maximum hosting capacity ensuring that the voltage magnitudes are within the limits and the unbalance factor is below 1% as determined by the constraints of the optimization model. The index η is equal to 91.59% in this case.

Figure 6- Voltage magnitudes and unbalance factors for all the system buses



3.6 COMPARATIVE RESULTS

Based on the results provided in the literature, it can be possible to evaluate the maximum hosting capacity, either considering the reverse power flow at substation bus or disregarding this situation.

This subsection presents a comparative analysis of the results provided by the proposed method when inequality constraint (12) is used (situation in which no reverse power flow is allowed) and when this inequality is neglected (situation in which the reverse power flow is allowed) to determine the maximum hosting capacity.

Table 3 presents these comparative results in which Case 1 is considering DG unit only at bus 16; Case-2 considers DG allocated at the end buses (17, 21, 24 and 32) and Case-3 considers DG units at all system buses for a systemic analysis.

It is possible to note that, when the inequality constraint (12) is disregarded, the reverse power flow is allowed. The consequence is higher values of η indicating that the hosting capacity is higher in this situation.

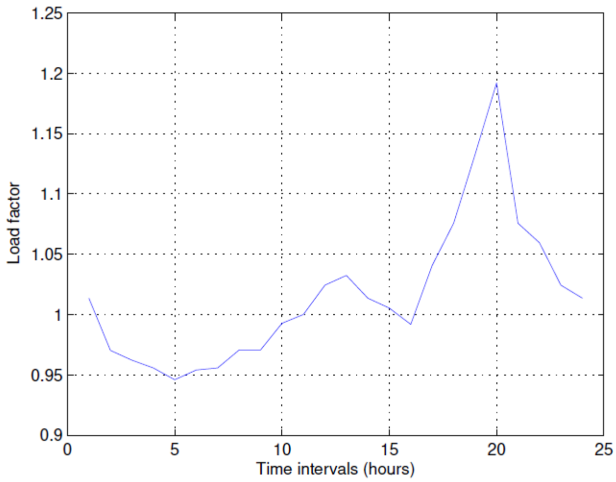
Table 3- Comparative results

Situation	Case 1	Case 2	Case 3
No reverse power flow	48.23 %	92.73 %	91.59 %
With reverse power flow	50.49 %	108.66 %	128.80 %

3.7 DYNAMIC HOSTING CAPACITY EVALUATION

In this subsection, the proposed method is tested considering load variations. A daily load profile is simulated according to data provided in reference (Melo et al., 2019) which are presented in Figure 7. Note that, in order to simulate the daily variation of the loads, they are multiplied by a factor which is equal to 1 for the nominal load. The load varies along a total period of 24 hours of a day.

Figure 7- Daily load curve

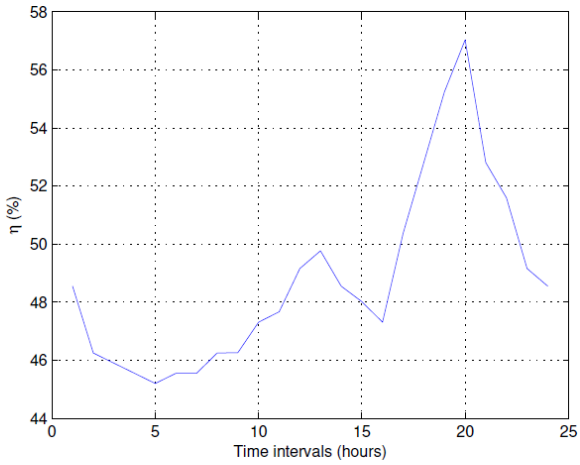


The results obtained from the proposed formulation is now provided in regular time intervals, determining the maximum hosting capacity along the day. This type of simulation is within the concept of dynamic hosting capacity in which the problem is evaluated for a given period of time.

Figure 8 presents the dynamic hosting capacity evaluated by the proposed index η when a single DG unit is considered to be installed at bus 16. It can be noted that η varies along 24 hours due to the loading conditions. It can be noted that η assumes higher values for higher load factors. As expected, in the peak loading (20:00 hours), η assumes the highest value.

When the load is below the nominal value, η assumes lower values. The load and maximum hosting capacity curves have a similar shape with little differences due to the inequalities imposed by the optimization model.

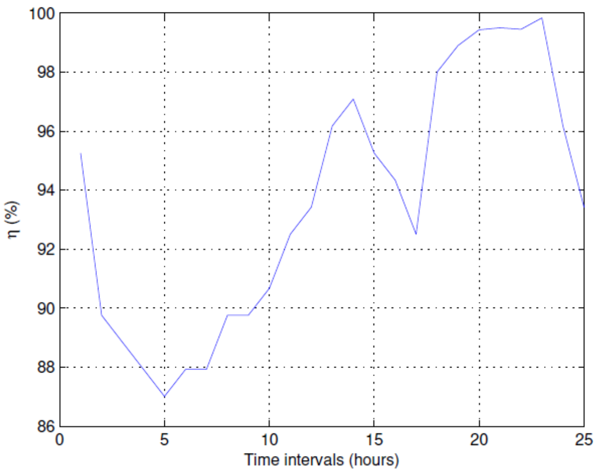
Figure 8-MHC index for a daily load curve



The proposed formulation considering all the system buses as potential locations for DGs to be inserted into the system is tested in the next case study. Note that, as presented in Figure 9, for the peak loading at 20:00 hours, the η index is below 100% once the proposed method does not allow the occurrence of reverse power flow nor unbalance factor to be higher than its corresponding threshold value adopted.

This feature impacts on the calculation of the maximum hosting capacity, validating the results for this situation.

Figure 9- Proposed index for the case study



4 CONCLUSIONS

This paper presented an optimization model to determine the maximum amount of generation to be accommodated in active power distribution systems. Inequality constraints are used to determine lower and upper bounds for voltage magnitudes, unbalance factor and reverse power flow at the substation bus. Additionally, an index is proposed to evaluate the maximum hosting capacity in this work.

The main contributions of this paper are: (i) the consideration of three-phase power networks assuming unbalanced loads; (ii) power flow equations are modelled as equality constraints according to the three-phase current injection method validating its use within the context of hosting capacity analysis; (iii) a proposed index is used for determining the dynamic hosting capacity of the system assuming daily load profiles.

A large number of scenarios are evaluated considering different number of DGs to be allocated in multiple locations. A systemic approach is used for determining the MHC considering the impact on system buses voltage magnitudes and unbalance factors.

The proposed formulation provides deterministic results which can be used for utilities planning considering future smart grids environment, regarding the problem of reverse power flow and voltage unbalance factor considering DG units.

REFERENCES

Abad MSS, Ma J, Han X (2019) Distribution systems hosting capacity assessment: Relaxation and linearization. In: Smart Power Distribution Systems, Elsevier, pp 555–586

Almeida D, Abeysinghe S, Ekanayake MP, Godaliyadda RI, Ekanayake J, Pasupuleti J (2020) Generalized approach to assess and characterise the impact of solar pv on lv networks. International Journal of Electrical Power & Energy Systems 121:106058

Alturki M, Khodaei A, Paaso A, Bahramirad S (2018) Optimization-based distribu- tion grid hosting capacity calculations. Applied Energy 219:350–360

Celli G, Chowdhury N, Pilo F, Soma GG, Troncia M, Gianinoni IM (2018) Multi- criteria analysis for decision making applied to active distribution network plan- ning. Electric Power Systems Research 164:103–111

Fu YY, Chiang HD (2018) Toward optimal multiperiod network reconfiguration for increasing the hosting capacity of distribution networks. IEEE Transactions on Power Delivery 33(5):2294–2304

Garcia PA, Pereira JLR, Carneiro S, Da Costa VM, Martins N (2000) Three-phase power flow calculations using the current injection method. IEEE Transactions on Power Systems 15(2):508–514.

Holguin JP, Rodriguez DFC, Ramos G (2020) Reverse power flow (rpf) detection and impact on protection coordination of distribution systems. IEEE Transactions on Industry Applications

Khani H, El-Taweel N, Farag HE (2018) Real-time optimal management of reverse power flow in integrated power and gas distribution grids under large renewable power penetration. IET Generation, Transmission & Distribution 12(10):2325– 2331

Lakshmi S, Ganguly S (2018) Simultaneous optimization of photovoltaic hosting capacity and energy loss of radial distribution networks with open unified power quality conditioner allocation. IET Renewable Power Generation 12(12):1382–1389

Lee J, Bérard JP, Razeghi G, Samuelsen S (2020) Maximizing pv hosting capacity of distribution feeder microgrid. Applied Energy 261:114400

Mahroo-Bakhtiari R, Izadi M, Safdarian A, Lehtonen M (2019) Distributed load management scheme to increase pv hosting capacity in lv feeders. IET Renewable Power Generation 14(1):125–133

Melo ID, Pereira JL, Variz AM, Garcia PA (2017) Harmonic state estimation for distribution networks using phasor measurement units. Electric Power Systems Research 147:133–144

Melo ID, Pereira JL, Ribeiro PF, Variz AM, Oliveira BC (2019) Harmonic state estimation for distribution systems based on optimization models considering daily load profiles. Electric Power Systems Research 170:303–316

Mulenga E, Bollen MH, Etherden N (2020) A review of hosting capacity quantifi- cation methods for photovoltaics in low-voltage distribution grids. International Journal of Electrical Power & Energy Systems 115:105445

de Oliveira C, Elias T, Bollen M, Ribeiro PF, de Carvalho P, Zambroni AC, Bon- atto BD (2019) The concept of dynamic hosting capacity for distributed energy resources: Analytics and practical considerations. Energies 12(13):2576

Oliveira EJ, Oliveira LW, Pereira J, Honório LM, Junior ICS, Marcato A (2015) An optimal power flow based on safety barrier interior point method. International Journal of Electrical Power & Energy Systems 64:977–985

Quijano DA, Wang J, Sarker MR, Padilha-Feltrin A (2017) Stochastic assessment of distributed generation hosting capacity and energy efficiency in active distribution networks. IET Generation, Transmission & Distribution 11(18):4617–4625

Raja AA, Mansoor M, Zahid F (2018) Optimal sitting of distributed generation based on hosting capacity approach. In: 2018 International Conference on Engineering and Emerging Technologies (ICEET), IEEE, pp 1–5

Sahu SK, Ghosh D (2019) Hosting capacity enhancement in distribution system in highly trenchant photo-voltaic environment: A hardware in loop approach. IEEE Access 8:14440–14451

Schultis DL (2019) Comparison of local volt/var control strategies for pv hosting capacity enhancement of low voltage feeders. Energies 12(8):1560

Wang S, Dong Y, Wu L, Yan B (2019) Interval overvoltage risk based pv hosting capacity evaluation considering pv and load uncertainties. IEEE Transactions on Smart Grid