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Research Article

Impacts on Medium-Voltage Industries due to the PV Generation in Low-Voltage Networks

Tiago Pinheiro Ribeiro[1], Paulo Roberto Duailibe Monteiro[1], Thiago Trezza Borges[1], Marcio Zamboti Fortes[1,*], Cintia Machado de Oliveira[2], Leticia Fritz Henrique[3] and Maria Fernanda Lopes Almeida[1]

[1]Fluminense Federal University, Brazil asso da Patria St., 156, E-431, São Domingos, Niteroi – RJ, Brazil
[2]Celso Suckow da Fonseca Federal Center for Technological Education, Brazil
[3]Juiz de Fora Federal University, Brazil

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Abstract

As investments in photovoltaic distributed generations (PVDG) become more attractive, medium and low-voltage networks may be impacted by this intermittent source. In this sense, power quality studies are essential to ensure continuity and reliability in power supply, especially in priority loads, such as industries connected to the medium-voltage network. This paper aims to analyze the impacts on power quality of industries fed in medium-voltage (MV) for different penetration levels of intermittent PV generation installed in low-voltage (LV) networks. Two industries were modeled in different buses on IEEE 8500-node test system, simulated in the OpenDSS program. The analysis parameters are based on steady-state voltage, power factor, and voltage imbalance for each industry. The results show violation in steady-state voltage starting in 5.5 MW and 27.5 MW of PVDG penetration in the MV and LV buses, for both industries, respectively. In addition, voltage imbalance problems are seen in 100 % of PVDG penetration for the industry at the end of the feeder.

Keywords: Distributed generation; Photovoltaic power generation; Load flow; PV intermittence; Power quality.

1. Introduction

The need to promote sustainable development imposes changes in the electrical matrix aiming at low-carbon emissions, through the strong participation of clean energies in its composition. In this context, added to the need to diversify the electrical matrix, the photovoltaic distributed generation (PVDG) has been widely implemented in several developed countries and establishing an important role in the electricity energy sectors by contributing with electricity energy supply [1-2].

In Brazil, PVDG has been employed by a few consumers, despite the growth potential for the coming years. This expectation is due to the reduction of acquisition, installation and maintenance costs. Besides, Brazil has a privileged geographical location that confers a high solar incidence with good uniformity [3].

The PVDG penetration brings major changes in conventional distribution networks, causing power flow from the load to the grid [4]. Besides, PVDG may bring possible inconveniences due to its unpredictable and fluctuating generation characteristics [5-6].

Furthermore, there is a growing number of low-voltage (LV) consumers, who are installing PVDGs on their properties. This effect increases the amount of generated power injected in this voltage level. In consequence, this large amount of generation can reflect impacts for LV and medium-voltage (MV) consumers, such as industries.

In the light of this new context, studies are needed to assess the impacts that the high penetration of energy from a large number of PVDGs connected to LV grids may cause to the MV grids that have the role of distributing energy to various consumers, including industrial consumers. Furthermore, several studies in the literature perform analyses with PVDGs, however, these works do not consider the unpredictable behavior of photovoltaic sources or even adapt the photovoltaic output in order to simplify its implementation [7], inferring results that do not portray reality.

To contribute to the literature, this study proposes to investigate the impacts that PVDG penetration allocated in LV network causes at the connection point of industrial loads in the MV network, as well as to evaluate the effects of the generation output intermittency according to the electric power quality (PQ) parameters. In this study, the PQ is contextualized and evaluated through normative parameters of the Brazilian electrical sector. Thus, the objective of this paper is to analyze the impacts on the PQ of two industries installed in the MV grid of the IEEE 8500-buses test feeder due to the massive presence of PVDGs in the LV grid, considering an intermittent and a flat generation profile (GP). One of the industries is modeled at the beginning of the grid, close to the substation, and another one at the end of the grid. The test case is simulated in the OpenDSS computational tool with the variation of the PVDG penetration level in 5 scenarios. The analyzed PQ parameters are the steady-state voltage, power factor and voltage imbalance.

The following organization is considered for the rest of the paper. Section II presents a review of photovoltaic generation and the Brazilian scenario, including PQ parameters analyzed according to Brazilian standards. Section III addresses the system modeled in the OpenDSS

*E-mail address: mzamboti@id.uff.br
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software. Section IV presents and analyzes the simulation results. Finally, the conclusions are discussed in section V.

2. **Photovoltaic generation and Brazilian context review**

The use of solar photovoltaic energy (SPE) worldwide has imposed the need for new studies and research to make clear the effects of its use, advantages and disadvantages. In addition, there are incentives at work for mitigating measures to the drawbacks that are intrinsic to SPE, such as intermittency.

It is important to note that the study of SPE is quite broad and can involve many technical aspects, depending on the technology used by the photovoltaic system, installation location, PVDGs generation power, grid topology, and protection strategies of the power grid. On the other hand, monetary aspects should also be considered, such as investment costs, maintenance, return on investment, among others.

To understand how some of these aspects are being addressed in the literature, Tab. 1 presents relevant studies that address PVDG. Some of these studies have been conducted through temporal analysis, which may be static-series or time-series, with data varying or not at different instants of time.

Tab. 1 proves that several parameters have been the subject of research in recent years concerning PVDG. On the other hand, Tab. 1 also reveals that few studies have explored intermittency until this moment.

Table 1. Relevant work on photovoltaic distributed generation.

Authors	Network	PV Profile (Flat or Intermittent)	Analysis Technique	Main Conclusions
Garfi et al. [7]	33-bus IEEE test feeder	Flat	Time-series	The photovoltaic integration enhances the voltage profile and reduces power losses and active power production.
Smith et al. [8]	Real feeder	-	Time-series (OpenDSS)	The photovoltaic character changes buses voltages daily profiles and the power production plan.
Tonkoski et al. [9]	Hypothetical network	-	Static-series (PSCAD)	Unbalance conditions are reduced near the substation but increased towards the end of the feeder, due to the location of the PVDG on the grid.
Santos [10]	Real feeder	-	Time-series (PV*SOL)	The addition of PVDG to the system provides an amount of voltage rise throughout the daylight hours.
Gabdullin et al. [11]	Real feeder	Intermittent	Static-series (OpenDSS)	The feeder impedance, the feeder length and the transformer impedance play important roles in determining the voltage rise rate.
Afonso [12]	Real feeder	-	Static-series (ATPDraw)	Long feeders are more likely to experience voltage rise problems, which increases the feeder impedance values.

2.1. Intermittence

The SPE generation is not regular overtime, as the solar radiation level varies with the rotational and translational movements of the planet. In addition, the flow of solar radiation on the photovoltaic panel is unpredictable due to interposition of obstacles such as clouds and dust. In [7] two examples of GP are presented, one is a GP real and intermittent, while another is a flat GP, obtained through the hourly average of the values measured in the intermittent profile.

The presence of this type of source in the energy matrix increases the participation of intermittency and randomness in the energy injected into the electrical system. This effect can directly impact the number of grid control actions depending on the level of injected power. In addition, SPE generation can be characterized as non-dispatchable and extemporaneous, since power system operators cannot control PVDG outputs, making it difficult to grid management and the system energy balance as a whole [7]. Besides, the current distribution systems were not designed considering the power generation by the final consumers. In this sense, the distribution network has its protection designed to act in a radial scheme and unidirectional power flow [12].

In this context, the large-scale connection of photovoltaic sources has brought impacts on the electrical systems of several countries, searching for the reduction of these impacts an important object of study [13]. Concerning Brazil, this scenario is no different. According to [14], the connection of intermittent generation systems has increased the costs related to changing the operation strategy of traditional plants.

2.2. Brazilian Regulation

A few years ago, the National Agency of Electrical Energy (ANEEL) began negotiations to reduce the barriers that limited the installation of small distributed generators in the electrical grid. In this sense, the negotiation regarding the regulation of PVDG was very important, once there was the involvement of several agents of the electric sector [15].

Subsequently, two normative resolutions were formulated that dealt with the connection of PVDG in the electric system. In [16] an 80 % rebate was defined in the tariffs for the use of distribution and transmission services for enterprises built until 2017 that use SPE, in their first ten years of operation. In [17] the general conditions for connecting distributed micro-generation (up to 75 kW) and mini-generation (from 75 kW to 5 MW) to the distribution systems were established.

Especially for photovoltaic systems, the Brazilian Association of Technical Standards (ABNT) has also established some standards that should be observed regarding interface requirements [18], equipment testing procedures [19], and anti-islanding prevention measures for photovoltaic systems [20].

2.3. Power Quality Parameters

With the modernization of equipment connected to the grid, the importance of PQ and preservation of reliability and good operation of the electrical system is verified. In this study, the evaluation of the PQ considered the aspects of steady-state voltage, power factor and voltage imbalance, defined in [21]. These parameters are used to analyze the supply of electricity services to industries located in the MV network when the LV network has PVDG penetration.

Tab. 2 presents the steady-state voltage limits (Vn) for the evaluation of the LV buses, while Tab. 3 presents the limits for the MV buses [21].

Table 2. Connection points at rated voltage equal to or lower than 1 kV.

Service Voltage	Voltage Tolerance Boundary (pu)
Appropriate	(0.92 ≤ Vn ≤ 1.05) (0.92 ≤ Vn ≤ 1.05)
Precarious	(0.87 ≤ Vn < 0.92 or 1.05 < Vn ≤ 1.06) (0.87 ≤ Vn < 0.92 or 1.05 < Vn ≤ 1.06)
Critical	(Vn < 0.87 or Vn > 1.06) (Vn < 0.87 or Vn > 1.06)

For the power factor, [21] establishes that the reference values should be between 0.92 and 1.00, inductive or capacitive. The voltage imbalance should not exceed 3 % for systems with a nominal voltage equal to or less than 1 kV, and 2 % for systems with a nominal voltage between 1 kV and 230 kV, according to [21].

Table 3. Connection points at rated voltage higher than 1 kV and lower than 69 kV.

Service Voltage	Voltage Tolerance Boundary (pu)
Appropriate	(0.93 ≤ Vn ≤ 1.05)
Precarious	(0.90 ≤ Vn < 0.93)
Critical	(Vn < 0.90 ou Vn > 1.05)

3. **Case Study**

The network under study, shown in Fig. 1, is the IEEE 8500-buses test system. This is a real distribution network with MV and LV feeders coexisting in the same system and total nominal load of about 16.6 MW. The system voltage is 12.47 kV at MV and 120/208 V at LV. The substation transformer is rated at 27.5 MVA. Two 1.549 MW industries were modeled in the MV grid, one at the beginning, close to the substation, and the other at the end of the grid, whose data are presented in section 3.2. The LV distribution network consists of a radial circuit with 1,177 LV two-phase consumers, considered in this work as an imbalanced system.

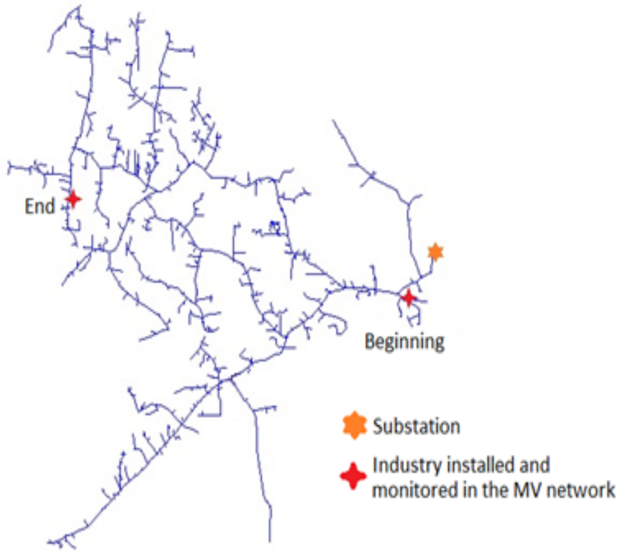

Fig. 1. IEEE 8500-bus distribution system.

To study the grid in its default state, the voltage regulation control was disabled. This modification allows distribution system operators to develop control and protection studies and adjustments in the scenario that suits them, aiming to ensure reliability and optimization of the number of control actions [22].

3.1. Distributed Generation

The PVDG modeling is composed of two profiles: intermittent, representing real data, and flat, portraying approximations in energy production.

The intermittent profile's data was measured in a real photovoltaic plant located in Rio Grande do Norte - Brazil. The measurements considered the time interval from 5:00:00 to 18:30:00, with a data resolution of 30 seconds. Fig. 2 shows the normalized intermittent profile.

The flat profile, shown in Fig. 3, was obtained by interpolating the data from Fig. 2. This method is one of the approximate ways to find the generation curve of photovoltaic panels.

For the PVDG allocation in the LV network, this study considered the installation in consumers that have nominal power equal to or greater than 2 kW, totaling 1,164 consumers.

To portray existing loads in the network over time, 6 normalized load profiles [23-26], with an hourly resolution, were randomly distributed, as shown in Fig. 4. It is noteworthy that the resolution of these curves is hourly.

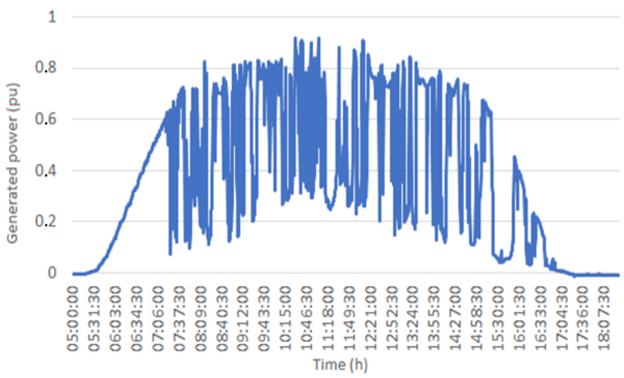

Fig. 2. Intermittent generation profile.

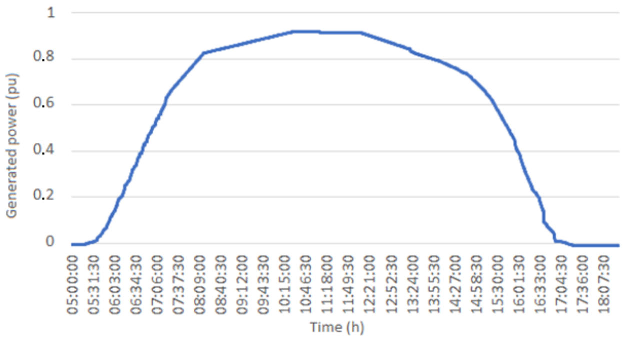

Fig. 3. Flat generation profile.

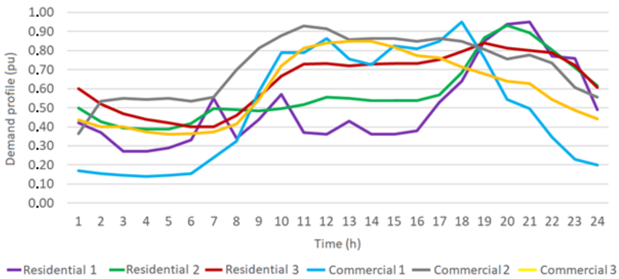

Fig. 4. Load profiles of consumers in the LV grid, adapted from [23-26].

3.2. Industries Installed in MV Network

The industries were installed in two different points of the network, one at the beginning and the another one at the end, respectively, in the MV grid. The industries were considered equal and modeled based on the electrical system presented in [27], modeled in the computer program ETAP (Electrical Power System Analysis Software), comprising the MV/LV transformer and the LV loads.

The electrical system considered consists of a 2 MVA transformer and its loads. Concerning that proposed in [27], the input voltage of the MV/LV transformer was changed from 13.8 kV to 12.47 kV, keeping its power at 2 MVA. The LV loads were replaced by a nominal equivalent load of 1,549 MW. Fig. 5 presents the normalized load profile adopted for the industries [23], with hourly data resolution.

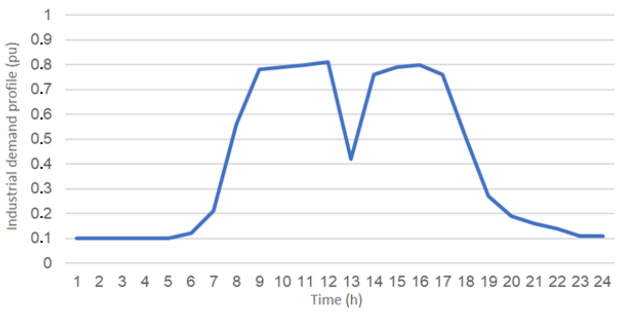

Fig. 5. Industrial demand profile, adapted from [23].

The PVDG modeling is composed of two profiles: intermittent, representing real data, and flat, portraying approximations in energy production.

3.3. Studied Scenarios

This study addresses the electric system analysis of the industries in the MV grid, considering the simulation of the PVDGs exclusively in the LV grid consumers. First, the network base case was simulated without the PVDG. Then, scenarios were simulated, classified by GP, intermittent and flat, and penetration level of the PVDGs in the grid, ranging from 20 % to 100 % in relation to the main substation transformer, totaling 5 scenarios for each profile plus the base case. Fig. 6 presents the aspects that make up the scenarios.

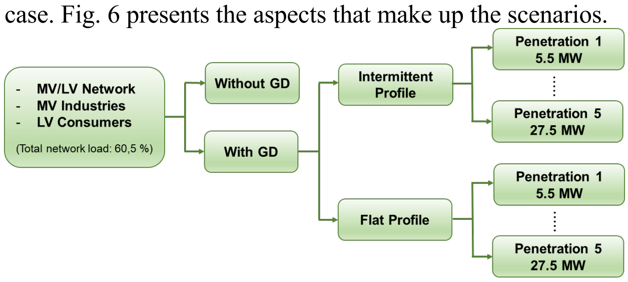

Fig. 6. Diagram of analyzed scenarios.

4. Results

This section carries out the assessments of 5 scenarios for each GP (intermittent and flat) compared to the base case, i.e., without any PVDG, totalizing 11 scenarios. The simulations were performed in OpenDSS with VBA, from 5:00:00 to 18:30:00 with 30 seconds resolution.

In sequence, the results of the behavior of PQ parameters are presented and analyzed according to [21].

4.1. Industry at the beginning of the grid

Fig. 7 and 8 present the relative frequency of times that the bus of the industry at the beginning of the grid reaches a specific voltage value. These figures classified the voltage levels observed throughout the day in six ranges, starting at 0.96 pu to values above 1.05 pu. In Fig. 7 and Fig. 8, the scenarios of PVDGs penetration considering the intermittent and flat GP are represented, respectively, in addition to the base case.

The base case simulation indicates the steady-state voltage of the MV and LV buses at adequate levels, according to Tab. 2 and Tab. 3. With the PVDGs connection, there is a voltage shift towards increasingly larger ranges due to the increase in generation in each scenario.

Critical violations, above 1.05 pu, started to appear in the MV buses from the 5.5 MW scenario. In the LV buses, precarious violations, between 1.05 and 1.06 pu, emerged from the 11 MW scenario and reached critical levels in the 27.5 MW scenario, with records above 1.06 pu. Given this situation, with voltage levels outside the PQ limits (Tab. 2 and Tab. 3), the equipment becomes more susceptible to damage, including compromising the systems in which they are installed, making them less reliable and subject to operational disturbances.

Fig. 9 presents the comparative voltage profile throughout the day, observed in one of the MV and LV phases of the industry at the beginning of the grid, considering the 27.5 MW scenario, which presented the most severe results in relation to the voltage limits established by [21]. The other phases were not represented, since the voltage behavior was similar.

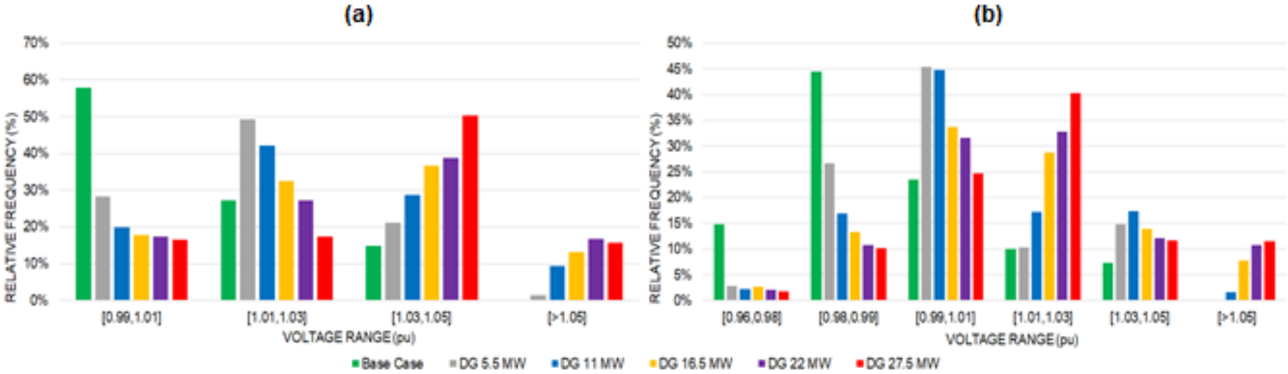

Fig. 7. Steady-state voltage of the industry at the beginning of the grid (intermittent profile): (a) MV buses; (b) LV buses.

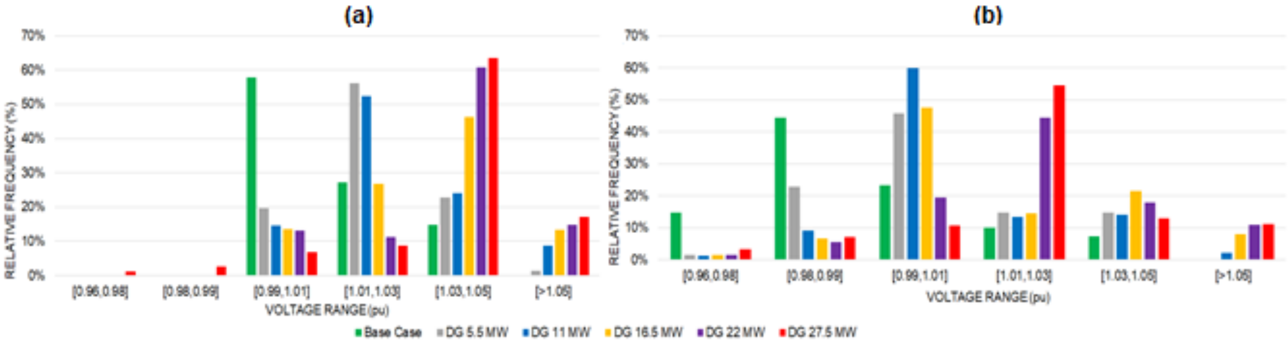

Fig. 8. Steady-state voltage of the industry at the beginning of the grid (flat profile): (a) MV buses; (b) LV buses.

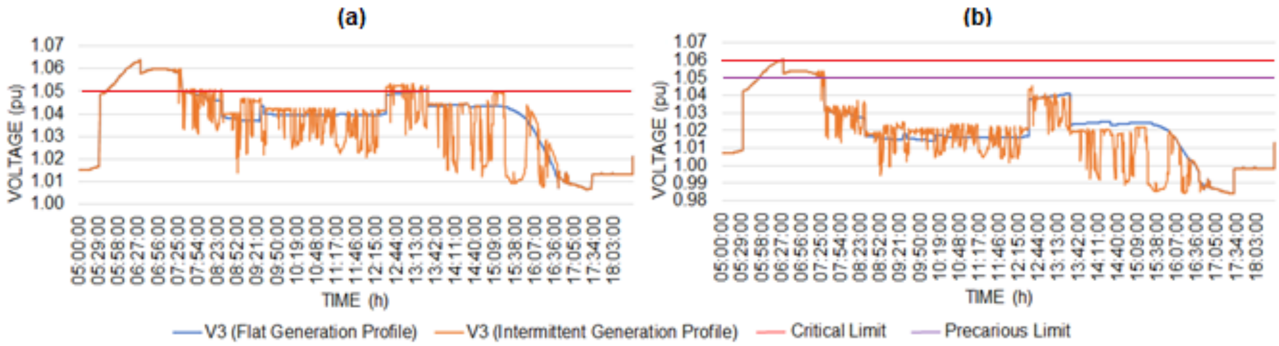

Fig. 9. Voltage profile of the industry at the beginning of the grid: (a) MV bus; (b) LV bus.

It can be seen in Fig. 9 that the intermittent generation profile of the PVDGs caused a high variability in the voltage levels of the industry's electrical system. This fact can be even more grave due to the financial limitations that smaller industries have to invest in resources to mitigate this occurrence.

Furthermore, in certain periods of the day the voltage exceeds 1.05 pu and then returns to operate at adequate levels. This fact is due to the correlation between the energy produced by PVDG in the LV grid and the load profile of the industry. The industry load profile a reduced demand until around 7:25:00 and between 12:30:00 and 13:30:00.

Fig. 10 and 11 present the voltage imbalance in the MV and LV buses of the industry as a function of the PVDGs penetration levels and considering intermittent and flat GP. For each scenario, the data dispersion recorded in the simulations is represented.

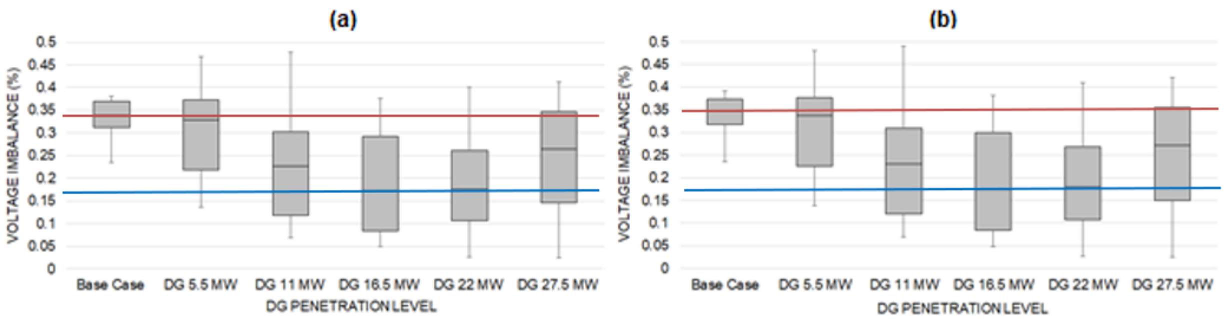

Fig. 10. Voltage imbalance of the industry at the beginning of the grid (intermittent profile): (a) MV buses; (b) LV buses.

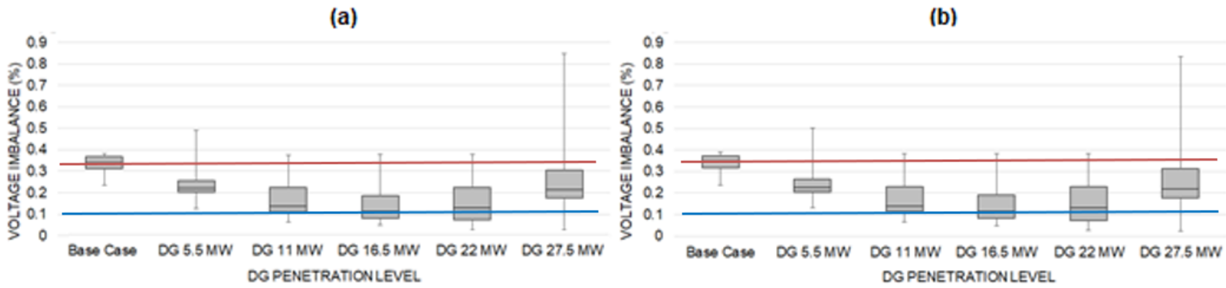

Fig. 11. Voltage imbalance of the industry at the beginning of the grid (flat profile): (a) MV buses; (b) LV buses.

Fig. 10 and 11 indicate that the average voltage imbalance showed a decreasing trend in each scenario compared to the base case, due to the generation level of PVDGs in the LV grid consumers. In Fig. 10 the average decreased to 0.18 % in the 16.5 MW scenario compared to 0.34 % in both buses in the base case. In Fig. 11 the average decreased to 0.11 % in the 16.5 MW scenario, compared to 0.34 % in both buses in the base case.

This downward trend occurs due to the contribution of the PVDGs allocated in the phases with higher demand in the LV consumers, causing a synergy between demand and generation level at some instants of the day. In consequence, this synergy reduces the imbalance in the LV grid and in the industry installed in the MV grid. However, increasing PVDGs at levels that significantly relieve the demand of the loads, a new voltage imbalance starts to be observed in the system due to the injection of excess energy into the grid. This fact can be seen in the 27.5 MW scenario in Fig. 11, where voltage imbalance was recorded above the average of the other scenarios, and which was reflected in the voltage drop observed for the same scenario in Fig. 8, reaching 0.96 pu.

It can also be seen that the intermittent GP has an influence on the data dispersion in the interquartile ranges throughout the scenarios compared to the flat GP. Thus, for the intermittent GP, the voltage imbalance is greater throughout the day. However, there were no violations of this parameter in any of the simulated scenarios.

Concerning the power factor, there was no violation in the measurements taken, being always above 0.92 independent of the GP (intermittent and flat) and the penetration level of the PVDGs.

4.2. Industry at the end of the grid

Fig. 12 and 13 show the relative frequency of times that the voltages in the buses were at the voltage levels indicated on the abscissa axis, from values less than 0.93 pu to values greater than 1.05 pu.

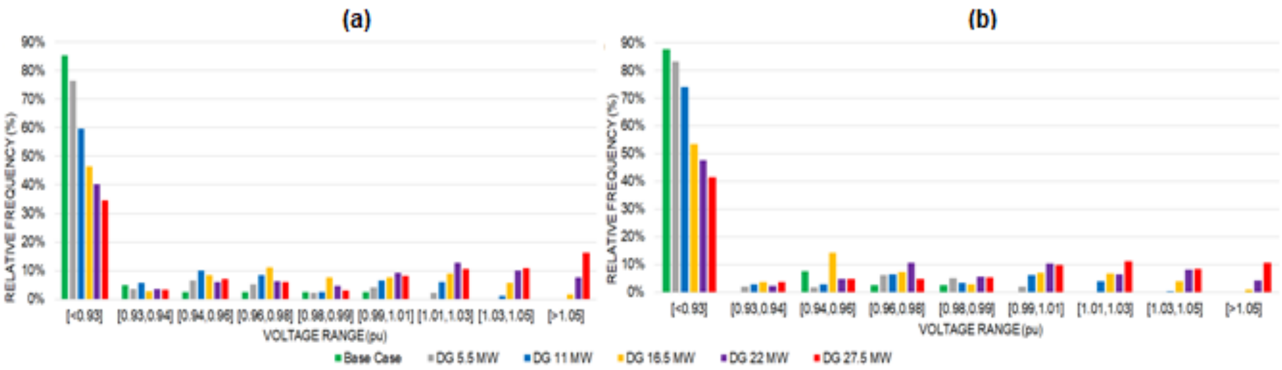

Fig. 12. Steady-state voltage of the industry at the end of the grid (intermittent profile): (a) MV buses; (b) LV buses.

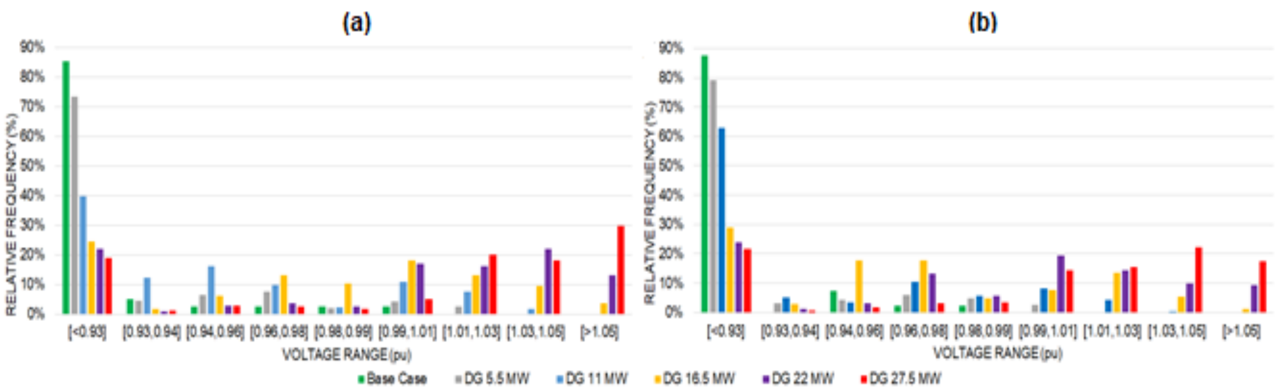

Fig. 13. Steady-state voltage of the industry at the end of the grid (flat profile): (a) MV buses; (b) LV buses.

Fig. 12 and 13 indicate that steady-state voltage levels of the base case present undervoltage problems, below 0.90 pu in the MV bus and below 0.87 pu in the LV bus. This effect occurs due to the voltage drop across the feeder, causing a voltage reduction in the buses at the end of the network.

With the connection of the PVDGs, the voltage levels raised. However, some critical violations, above 1.05 pu and 1.06 pu, started to appear in the MV and LV buses, respectively, from the 16.5 MW scenario, reaching even higher levels in the 27.5 MW scenario, with records above 1.06 pu. At this point, the equipment of the industry at the end of the grid becomes highly susceptible to the effects of the voltage when it is out of the limits established in Tab. 2 and Tab. 3. In this sense, these types of equipment can be damaged by overvoltage or even stop working due to undervoltage.

Fig. 14 presents the comparative voltage profile throughout the day, observed in one of the MV and LV phases of the industry at the end of the grid, considering the 27.5 MW scenario, in relation to the voltage limits established by [21].

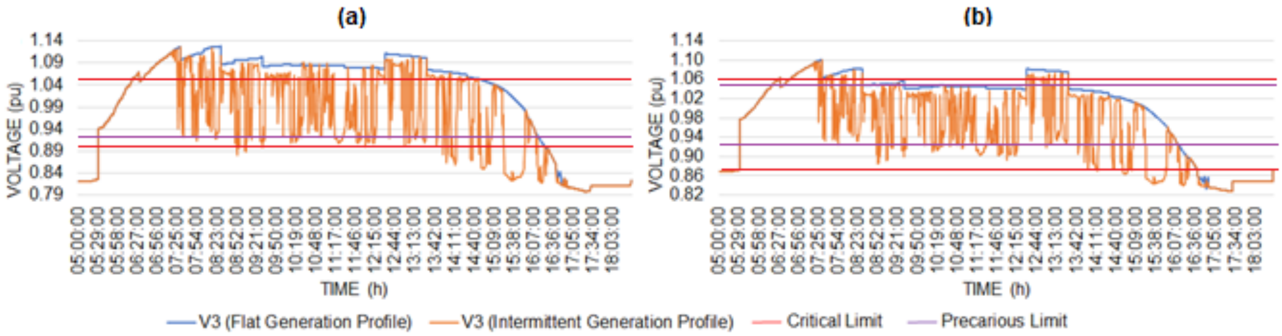

Fig. 14. Voltage profile of the industry at the beginning of the grid: (a) MV bus; (b) LV bus.

For the industry installed at the end of the grid, it is evident the great difference that the intermittent and flat GP of PVDG brings to the voltage levels, including the network itself. It can be seen that at 8:52:00 and 15:38:00 there were some lower voltage violations considered critical, below 0.90 pu, which did not occur with the flat GP. In addition, the industry was also impacted with more severe overvoltage levels, above 1.05 pu in many times during the day, corroborating with the results observed in Fig. 12 and Fig. 13.

Fig. 15 and 16 present the voltage imbalance in the MV and LV buses of the industry as a function of the penetration levels of PVDGs, considering intermittent and flat GP.

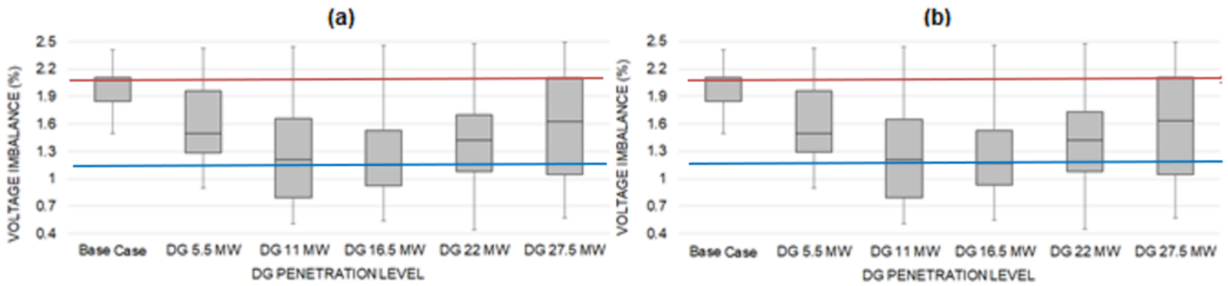

Fig. 15. Voltage imbalance of the industry at the end of the grid (intermittent profile): (a) MV buses; (b) LV buses.

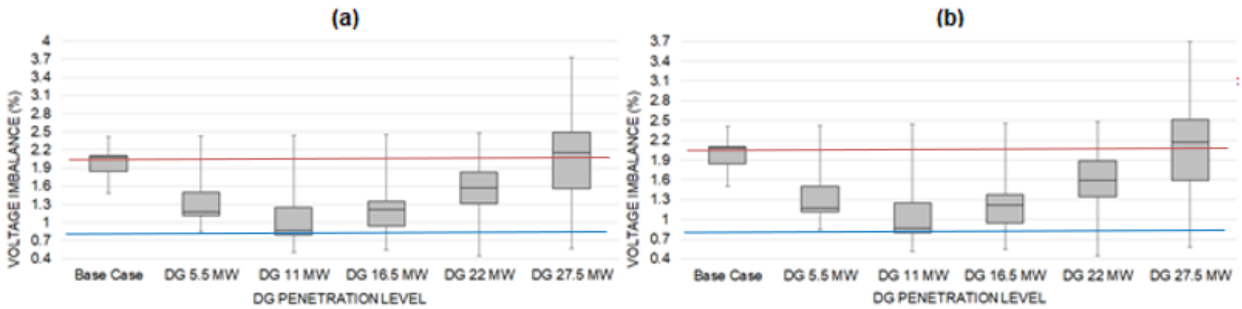

Fig. 16. Voltage imbalance of the industry at the end of the grid (flat profile): (a) MV buses; (b) LV buses.

Fig. 15 and 16 points that the average voltage imbalance showed a decreasing trend in each scenario compared to the base case. In Fig. 15 the average decreased to 1.15 % in the 16.5 MW scenario compared to 2.1 % in both buses in the base case. In Fig. 16 the average decreased to 0.85 % in the 16.5 MW scenario, compared to 2.1 % in both buses in the base case.

In all simulated scenarios, considering the intermittent GP of PVDGs, there was a voltage imbalance violation in the MV bus, with records above 2 % in many times of the day. This fact was also verified with the flat GP, including LV bus violations in the 27.5 MW scenario, with an imbalance above 3%.

Furthermore, the analysis of voltage imbalance for both industries indicates that the imbalance will increase as far as the industry is installed away from the substation. This situation requires a particular concern for three-phase motors due to the circulation of imbalanced currents that cause losses, temperature rise, and reduced lifetime.

It is also possible to observe the influence of the intermittent GP on the data dispersion in the interquartile ranges throughout the scenarios, increasing the voltage imbalance throughout the day.

In addition, for the industry at the end of the grid, the power factor showed no violations, regardless of the GP (intermittent and flat) and the PVDGs penetration level, with all measurements remaining above 0.92.

5. Conclusion

This work analyzed the impacts that PVDGs allocated in the LV grid cause on industries located in the MV grid regarding PQ. Five scenarios were simulated for two GPs (intermittent and flat), totaling 11 scenarios that were compared to the base case. The simulations had their results analyzed according to the location of the two industries, at the beginning and end of the grid, to verify the behavior of the steady-state voltage, power factor and voltage imbalance.

The results show that PVDGs present in the LV grid brought impacts to the PQ of the electric system, in particular to the industries in the MV grid. The steady-state voltage of both industries showed increasing levels of overvoltage as PVDG penetration in each scenario. This effect was aggravated in the industry at the end of the grid. On the other hand, there was a decreasing trend of the voltage imbalance levels throughout the day as a function of the generation level from PVDGs. However, the results point to several violations occurring throughout the day in the voltage imbalance parameter. The voltage imbalance level in the industry at the end of the grid was much higher than in the industry at the beginning of the grid. Regarding the power factor, there were no violations for both industries, independent of the GP considered and the PVDGs penetration level. Concerning the intermittent GP, its influence on the voltage imbalance for the two industries was verified, presenting higher levels than the flat GP, causing high variability in the voltage levels for both industries throughout the day, having presented more severe occurrences of undervoltages and overvoltages in the industry at the end of the network. Such a situation directly impacts the equipment operations and weakens the systems where they are installed, even more for those smaller industries that have limited resources to mitigate such occurrence.

Further work can be done considering a control system suited to one of the scenarios presented for the industries. Finally, a methodology for optimizing the number of protection and control actions can be performed for the studied scenarios.

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