# Evaluation of Solar Panel Integration in Power Control Distribution Networks

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**Abstract:** The reduction of greenhouse gases, such as $CO_2$, has led countries to adopt measures to reduce their environmental impact, according to the goals of the 2030 agenda. As a result, changes in the operation and planning of electricity systems and distribution networks are taking place, which have had to adapt to the incorporation of non-conventional renewable energies, such as photovoltaic. The integration of these technologies generated problems such as voltages outside the allowed limits, fluctuations, overloads, reverse flows, sympathetic tripping and an increase in fault currents, making it necessary to evaluate the percentage of renewable energies that can be safely integrated. This research evaluated the integration capacity of solar panels in the distribution network of primary and secondary lines using OpenDSS in the Chimbo feeder of the Guaranda substation of the Bolivar CNEL EP business unit. Two methodologies are presented: the first one evaluates the maximum input capacity of solar panels in percentage terms, and the second one implements a reactive power-voltage control using an optimization model. The results showed that, with the first methodology, the maximum integration limit was 48%, while the second methodology allowed the integration of 100% of the solar panels, without exceeding the power quality limits established by national regulations.

**Keywords**: Photovoltaic panels, voltage profile, electrical distribution, electrical demand, solar irradiation

# Evaluación de Integración de Paneles Solares en Redes de Distribución para Control de Potencia

**Resumen:** La reducción de gases de efecto invernadero, como el $CO_2$, ha llevado a los países a adoptar medidas para reducir su impacto ambiental, de acuerdo con los objetivos de la agenda 2030. Como consecuencia, se están produciendo cambios en la operación y planificación de los sistemas eléctricos y las redes de distribución, que han tenido que adaptarse a la incorporación de energías renovables no convencionales, como la fotovoltaica. La integración de estas tecnologías generó problemas como tensiones fuera de los límites permitidos, fluctuaciones, sobrecargas, flujos inversos, disparos por simpatía y aumento de las corrientes de falla, haciendo necesario evaluar el porcentaje de energías renovables que pueden ser integradas de forma segura. En esta investigación se evaluó la capacidad de integración de paneles solares en la red de distribución de líneas primarias y secundarias utilizando OpenDSS en el alimentador Chimbo de la subestación Guaranda de la unidad de negocio Bolívar CNEL EP. Se presentan dos metodologías: la primera, evalúa la capacidad máxima de aporte de los paneles solares en términos porcentuales, y la segunda implementa un control de potencia reactiva-tensión utilizando un modelo de optimización. Los resultados mostraron que, con la primera metodología, el límite máximo de integración era del 48%, mientras que la segunda metodología permitía la integración del 100% de los paneles solares, sin superar los límites de calidad de energía establecidos por la normativa nacional.

**Palabras clave:** Paneles fotovoltaicos, perfil de tensión, red de distribución, demanda eléctrica, irradiación solar

## 1. INTRODUCTION

The constant evolution of technology and the commitment to reduce greenhouse gas emissions to meet the 2030 diary (CEPAL, 2018), have made photovoltaic panels more efficient and economical. To start with, the Agency for the Regulation and Control of Non-Renewable Energy and Natural Resources ARCERNNR approves resolution No. ARCERNNR-001/2021 corresponding to the Regulatory Framework of Distributed Generation for self-supply of regulated consumers of electrical energy (ARCERNNR, 2021). Therefore, there is a high probability that regulated and non-regulated users

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install photovoltaic panels along the feeder and problems such as: overvoltage, unbalances, harmonics, flows in two directions, sympathetic tripping, increased levels appear. short circuit, among others.

Currently, this document evaluates the power input of photovoltaic panels through two methodologies that help the analysis of voltages in the nodes, power through the lines and currents in the electrical distribution network of the Guaranda-Chimbo feeder of the Guaranda substation belonging to CNEL EP BOLIVAR in order to control the massive input of photovoltaic panels in compliance with the integral regulation for the distribution and commercialization of electrical energy in the country No. ARCERNNR-002/20.

Through this study, it is intended to analyze in depth the problems that the electrical network has when there is a massive entry of photovoltaic panels into the Chimbo feeder, being renewable energies these help to protect the environment and its ecosystem, since, if distributed photovoltaic or conventional generation mainly thermal power plants will decrease and reduce greenhouse gas or $CO_2$ emissions, except for the introduction of solar cells, as well as help reduce technical losses in the electrical distribution network.

To address the problem of massive entry of photovoltaic generators into the electrical grid, they carry out a hosting capacity theorem to determine the amount of photovoltaic generation capacity distributed for each client with security and protection (Khomarudin et al. 2022), this Capacity Methodology Lodging consists of installing Photovoltaic in client to client with the maximum capacity without exceeding the limit of the system. However, as the photovoltaic panels depend on the solar irradiation that is variable during the day and weather conditions in Kahrobaee et al. (2020) proposes a probabilistic approach to determine the impact of the reduction of photovoltaic energy on the improvement of the accommodation capacity of a distribution circuit in different integration locations.

Today, there are efforts by electric distribution companies to determine the accommodation capacity in their networks in Niederhuemer et al. (2015) they carry out a probabilistic planning approach that increases the accommodation capacity of photovoltaic energy while accepting an active power reduction, performed with the P(U) control of the photovoltaic inverter, for short periods of time. Ebe et al. (2017) compare different methods for assigning future photovoltaic capacity based on analysis of solar potential at the distribution system level. Rule-based methods are developed and compared with a probabilistic method, which is repeated several times as a Monte Carlo analysis.

Likewise, to determine the allocation of photovoltaic power to the grid nodes, Bhusal et al. (2019) propose a stochastic method to calculate the distributed generation accommodation capacity for photovoltaic panels while guaranteeing that no voltage requirements are violated, the proposed method takes electric vehicle charges into account. As photovoltaic panels power electronics as an interface to connect to the electrical network in Nakhodchi et al. (2021) proposes a new approach to estimate a safe accommodation capacity in terms of harmonic distortion, considering standard limits for harmonic voltages and currents. It is shown that triple harmonics and seven harmonics are the harmonic orders that determine the total accommodation capacity. Likewise, electrical distribution networks consist of primary and secondary networks. Navarro et al. (2021) developed a methodology to determine the photovoltaic solar energy hosting capacity of a distribution network, considering the interactions between medium-voltage (MV) and low-voltage (LV) networks at different voltage levels. Their approach included detailed LV network modeling features for a comprehensive analysis. A novel solution to calculate hosting capacity based on network congestion risk. In addition to the classical voltage and current constraints, the proposed approach also integrates the stochastic allocation of distributed generation and separately assesses its impact on the value of hosting capacity. In Ezzeddine et al. (2021) he proposes a topology agnostic estimation method for the PV hosting capacity of distribution networks, this method uses the strength of the direct path from the slack bus to the customer and an assumed topology to avoid a complete knowledge about the network topology. Using an assumed topology, an estimate of the minimum surge carrying capacity for each penetration level and the transformer surge carrying capacity is obtained for any combination of customers having PV panels. The inclusion of solar panels requires mathematical optimization models or in this sense in Alrushoud et al. (2020) proposes a PV allocation method based on the optimal capacity to evaluate the PV hosting capacity, Firstly, we use the load allocation method to assign realistic load profiles to each charging node up to each household, instead of randomly assigning the PV installed capacity to each household, secondly, the optimal PV size for each household is calculated. based on annual load profiles.

Wang et al. (2016) propose a maximum accommodation capacity evaluation method taking into account the optimal and robust operation of on-load tap changers (OLTC) and static var compensators in the uncertain context of power outputs from distributed generation and load consumption. In Hassan et al. (2022) a new multi-stage algorithm is developed based on an analytical approach and an optimal power flow for the evaluation of the hosting capacity of distributed renewable generation. In the first stage, the optimal locations of the distributed renewable generation are determined analytically, and the second stage involves the calculation of the optimal sizes of the distributed renewable generation for the evaluation of the optimal accommodation capacity.

The reviewed investigations do not address the control strategies of inverters and voltage regulators for the large-scale integration of renewable energy sources into electrical distribution networks. The entrance of the photovoltaic panels to the electrical distribution network is of a random nature due to the variability of the primary energy and the uncertain knowledge of the installation of the users. This causes the analysis to be performed using stochastic methods.

Regarding our investigation, it is proposed to evaluate the state variables of the system with the entry of photovoltaic panels using the random method of load profiles and solar irradiation and after that a strategy is carried out control in the voltage power inverter with a method of mathematical optimization. For this, the OpenDSS software will be used, which allows modeling the electrical distribution network (Ochoa, 2015) and the python platform for the interface and data management (Hariri, 2017) together with Pyomo and the solver knitro.

The rest of this document is organized as follows. Then, it presents the general data of the Guranda - Chimbo feeder of the company CNEL - BOLIVAR is presented. Subsequently, the methodology used is explained. Then the results and discussion are presented. Finally, additional information to be considered is detailed, after which conclusions and recommendations are presented.

## 2. METHOD

This research adopts a quantitative and explanatory approach to analyze the state variables of the electrical distribution network before the entry of photovoltaic panels. To achieve this, the deductive method that helps to obtain knowledge by developing applications or concrete consequences from general principles was taken.

### *2.1 Methodology 1*

The integration of photovoltaic panels for each user is evaluated stochastically using the Monte Carlo method to assess the maximum power capacity injected into the network. The implemented methodology is illustrated in Figure 1.

This figure explains the methodology for the entry of photovoltaic panels into the electrical distribution network. As a first step, the modeling of the primary and secondary lines, transformers, demand, fuses, etc. This is done in the openDSS format, for which we have the map in ArcGIS of the Guaranda - Chimbo feeder.

Previously, the python vs openDSS interface is created, for them a master.dss file is created that contains all the network modeling and the ODSSfunction file which includes all the functions required for the interface and execution from Jupyter. Once the two previous steps have been completed, we proceed to execute the power flow to see if the program is modeled correctly, if this is the case, we proceed to verify the voltages, if not, we proceed to verify the modeling in openDSS.

This step is important because the voltages must match those of the real system. Once it has been verified that the implemented system is the same as real and that the voltages are within the range of +- 10%, 25% of the photovoltaic panels are entered into the feeder, this is to randomly install 1721 users of the total number of 6887, successively with each percentage.

Once again, the power flow is executed and it is verified if it complies with the lower and upper voltage limits, if it complies, the process is finished, otherwise the state variables are verified, that is, voltage in the nodes, currents in the lines, over voltages in the transformers.

This process is repeated for each integration percentage, as illustrated in Figure 1. Using the proposed methodology, the amount of distributed energy resources from photovoltaic panels that can be connected to the grid without causing instability in the system or violating security regulations is determined.

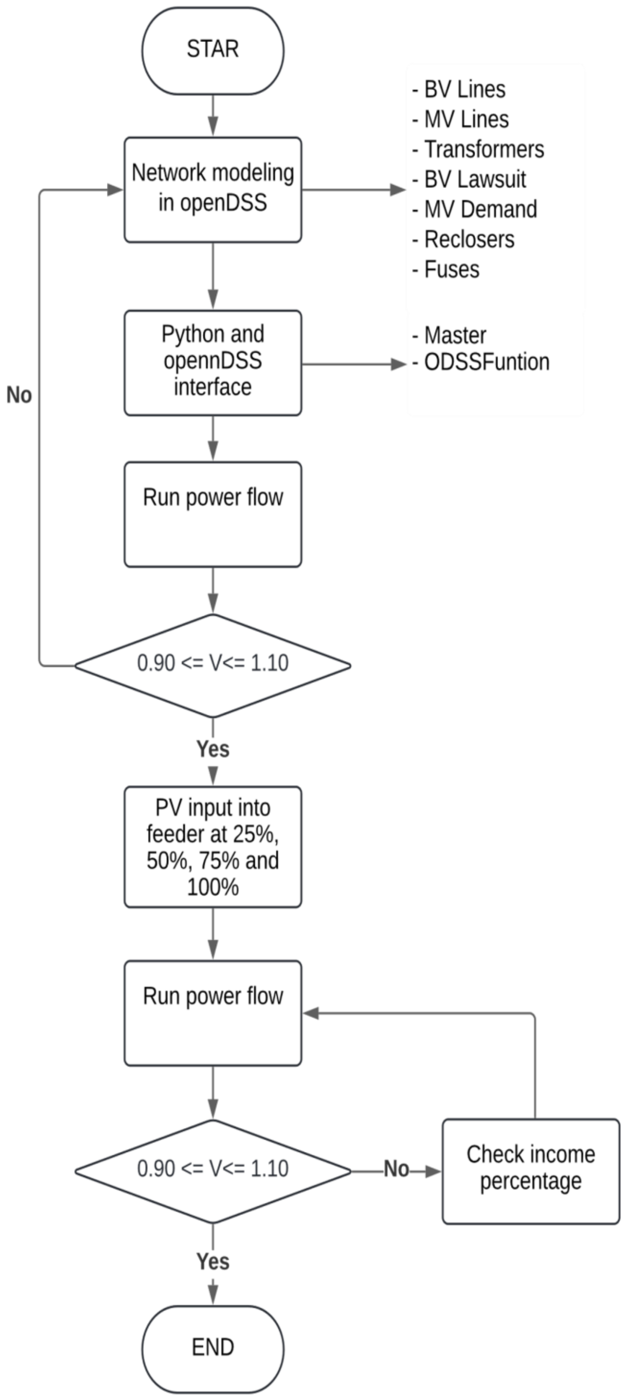


**Figure 1.** Methodology 1

### *2.2 Methodology 2*

Renewable energy sources, such as photovoltaic generation and small run-of-the-river hydroelectric plants, use power converters to connect to the grid and extract maximum power.

However, there are three types of control modes for managing the energy generated by the photovoltaic panel, these modes depend on the characteristics of the electrical distribution network.

- Centralized control
- Distributed cooperative control
- Decentralized control.

The centralized control and the distributed cooperative use communication networks with a large bandwidth to be able to control from a control room which makes it unfeasible in practical applications due to cost. On the other hand, the decentralized control is local and dispatches power in each photovoltaic inverter based on instantaneous local measurements (Cheng, 2020). Therefore, due to its cost-effectiveness and benefits, we will propose decentralized control.

The following Equations are used to control the active power and reactive power in the inverter of each photovoltaic panel through a nonlinear optimization model:

$$\text{minz: } \sum_{t\in T}\sum_{pv\in pvs} -P_{\text{conpvt}} + \frac{1}{\alpha}\tan(\phi)_{\text{conpvt}} \qquad (1)$$

Subject to:

$$p_i^s = g_{ii}v_i^2 + \sum_{i\neq j} g_{ij}v_iv_j\cos(\delta_{ij}) + \sum_{i\neq j} b_{ij}v_iv_j\sin(\delta_{ij}) \qquad (2)$$

$$q_i^s = -b_{ii}v_i^2 + \sum_{i\neq j} g_{ij}v_iv_j\sin(\delta_{ij}) - \sum_{i\neq j} b_{ij}v_iv_j\cos(\delta_{ij}) \qquad (3)$$

$$p_i^s = P_{gpv}^s - \left[p_{zj}^s\left(\frac{v_i^s}{v_{nomi}}\right)^2 + p_{Ii}^s\left(\frac{v_i^s}{v_{nomi}}\right) + p_{pi}^s\right] \qquad (4)$$

$$q_i^s = Q_{gpv}^s - \left[q_{zj}^s\left(\frac{v_i^s}{v_{nomi}}\right)^2 + q_{Ii}^s\left(\frac{v_i^s}{v_{\text{nomi}}}\right) + q_{pi}^s\right] \qquad (4)$$

$$P_{gpv}^s = P_{sppv}P_{con_{pv}} \qquad (5)$$

$$Q_{gpv}^s = P_{gpv}^s\tan(\phi)_{conpv} \qquad (6)$$

$$-\tan(\text{acos}(\phi_m in)) \leq \tan(\phi)_{\text{conpv}} \leq 0 \qquad (7)$$

$$\sqrt{P_{gpv}^2 + Q_{gpv}^2} \leq S_{invpv} \qquad (8)$$

$$v_{\text{mini}} \leq v_i^s \leq v_{\text{max}i} \qquad (9)$$

Where:
$s \in \Omega$ belongs to the set of phases *(a, b, c)*.
$i, j \in \sigma$ belongs to the set of nodes.
$t \in T$ belongs to simulation time.
$p_i^s$ is the active power injected for each of the phases.
$q_i^s$ is the reactive power injected for each of the phases.
$P_{gpv}^s$ is the active power of the photovoltaic panel for each of the phases.
$Q_{gpv}^s$ is the reactive power of the photovoltaic panel for each of the phases.
$p_{zj}^s$ is the constant impedance active demand for each of the phases.
$q_{zj}^s$ is the constant impedance reactive demand for each of the phases.
$p_{Ii}^s$ is the active constant current demand for each of the phases.
$q_{Ii}^s$ is the constant current reactive demand for each of the phases.
$p_{pi}^s$ is the constant active power demand for each of the phases.
$q_{pi}^s$ is the constant reactive power demand for each of the phases.
$P_{sppv}$ is the solar power profile obtained through solar irradiation.
$P_{con_{pv}}$ active power control variable of the photovoltaic panel.
$\tan(\phi)_{conpv}$ reactive power control variable of the photovoltaic panel.
$\alpha$ factor for reactive power control that must be greater than 1.

## 3. RESULTS

The evaluation of the methodological proposal detailed in Section II is conducted on the Guaranda–Chimbo feeder, which belongs to CNEL-BOLIVAR.

### *3.1 Results and discussion of methodology 1*

Methodology 1 is ideal for studying the integration of photovoltaic panels into the electrical distribution network. This approach does not include voltage regulation control, allowing an evaluation of the maximum percentage of integration the network can accommodate without exceeding upper voltage limits.

Therefore, it is carried out in the Guranda Chimbo feeder, which consists of 6887 users, the loads of each user are taken as a ZIP polynomial model, and they were modeled in a monophasic way because they are unbalanced loads. However, the demand profile and solar irradiation enter randomly in the declared loads. Therefore, being a large system, it is not possible to graph all the nodes, so only 30 random nodes shrink. The simulation is carried out for 30 days.

Figure 2 shows the voltage profile with 48% integration of photovoltaic panels for day 2, revealing that some nodes exceed the upper voltage limit. This means that no photovoltaic panels can be entered in those nodes that exceed the voltage limits. In the same way, the Figure 3 on day 12 presents higher voltages in some nodes for that charge and irradiation profile. However, for the remaining days they present similar characteristics.

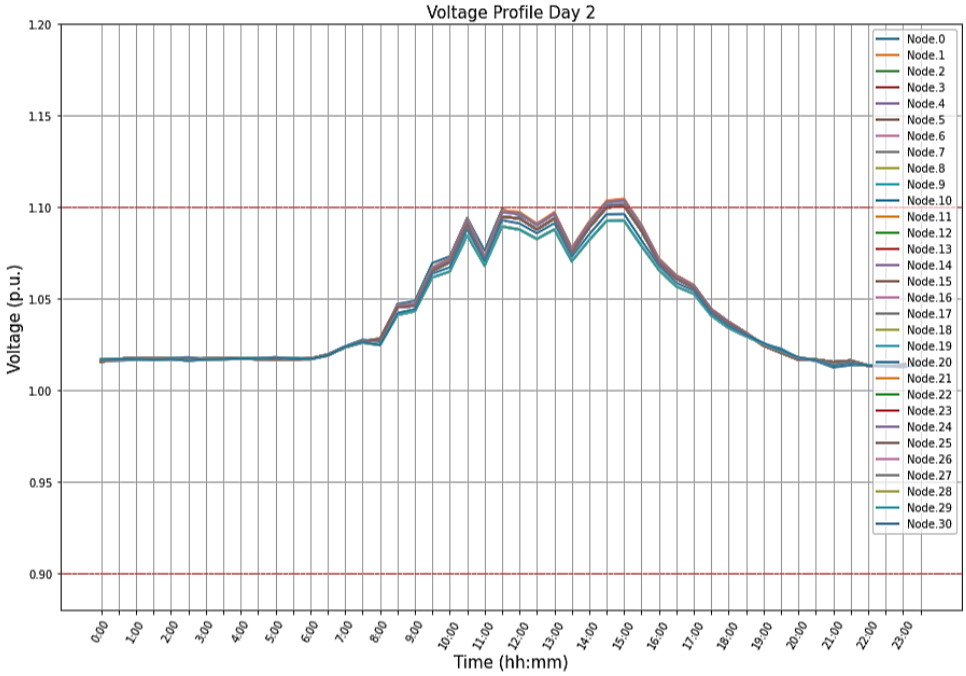


**Figure 2.** Voltage profile with photovoltaic panels at 48%

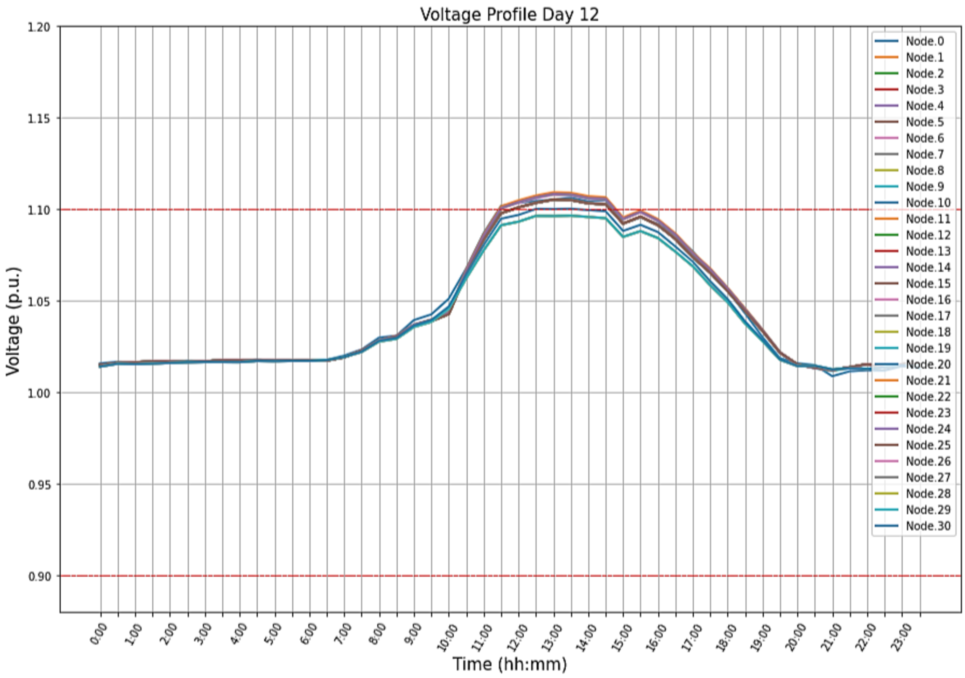


**Figure 3.** Voltage profile with photovoltaic panels

### *3.2 Methodology 2 feeder Guaranda Chimbo*

With Methodology 2, 100% of photovoltaic solar panels can be entered and the voltage can be controlled to a maximum of 1.10 in per unit using the previously presented mathematical optimization model. This mathematical model contains 77232 variables and 104352 constraints. It is solved with the knitro solver that is used to solve non-linear problems such as unbalanced power flow in electrical distribution networks.

Figure 4 illustrates the integration of photovoltaic panels at 100%, showing that the voltages remain within the limits allowed by the regulations. Figure 5 shows the current of the three phases at the beginning of the substation, where it shows us that the current is also limited when the reactive power-voltage control is carried out.

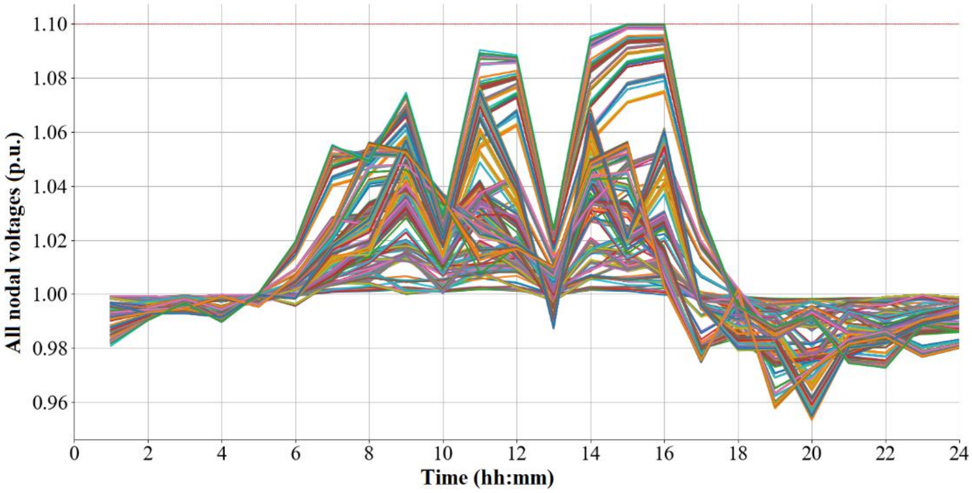


**Figure 4.** Entry of photovoltaic panels at 100% and the voltages

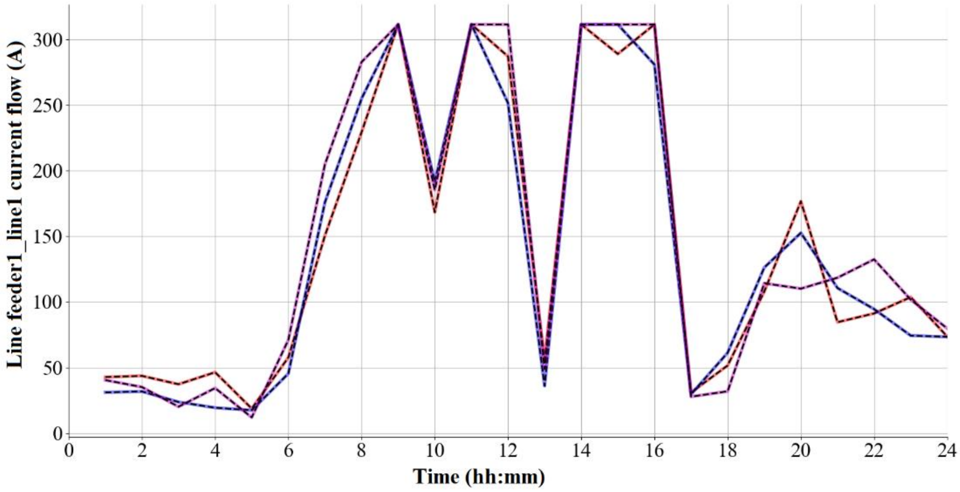


**Figure 5.** Current flow in the network

Figure 6 illustrates the power flow through the line near the Guaranda substation. During hours of high solar incidence, the flow becomes negative, meaning that power flows from the photovoltaic panels toward the substation. Conversely, during hours of low solar incidence, the flow moves from the substation toward the loads.

Figure 7 illustrates the power control performed by the optimizer, which operates from 9:00 a.m. to 4:00 p.m. when solar incidence limits the delivery of additional power to the network, ensuring compliance with the voltage profile within regulatory standards.

Finally, Figure 8 illustrates the reactive power control variable of the photovoltaic panel tan($\phi$), this helps to keep the voltage within the allowed limit +- 10%.

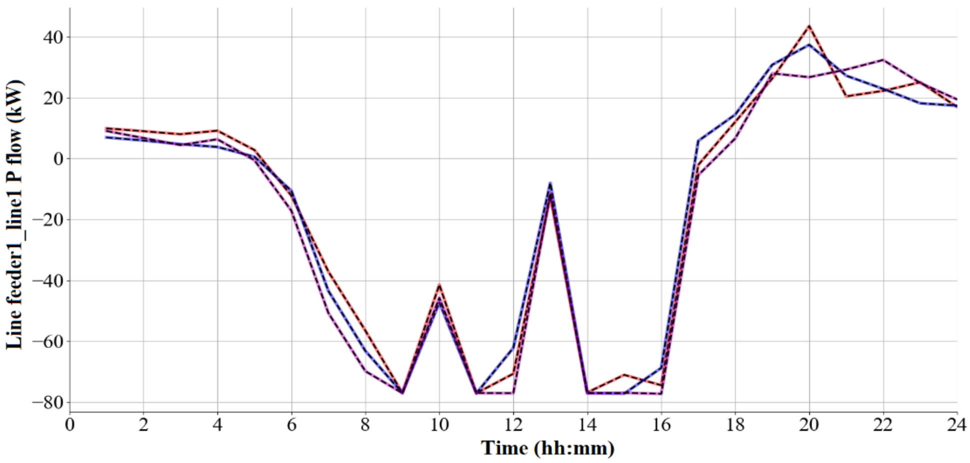


**Figure 6.** Power flow network

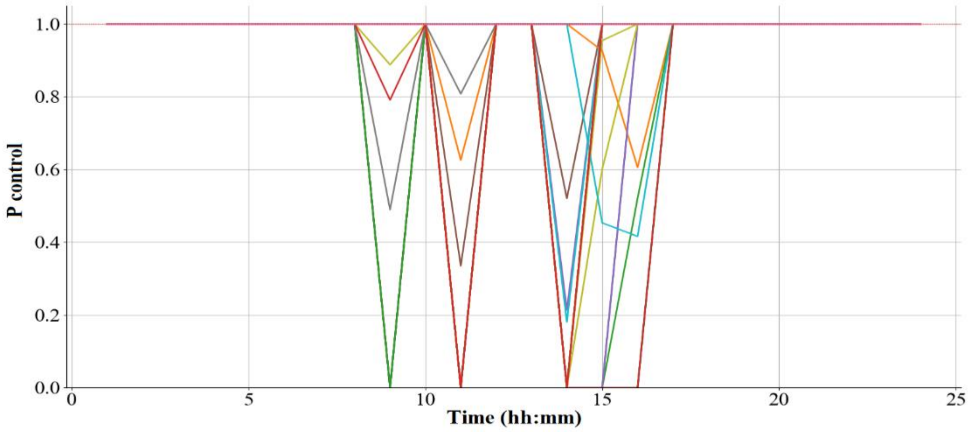


**Figure 7.** Power control

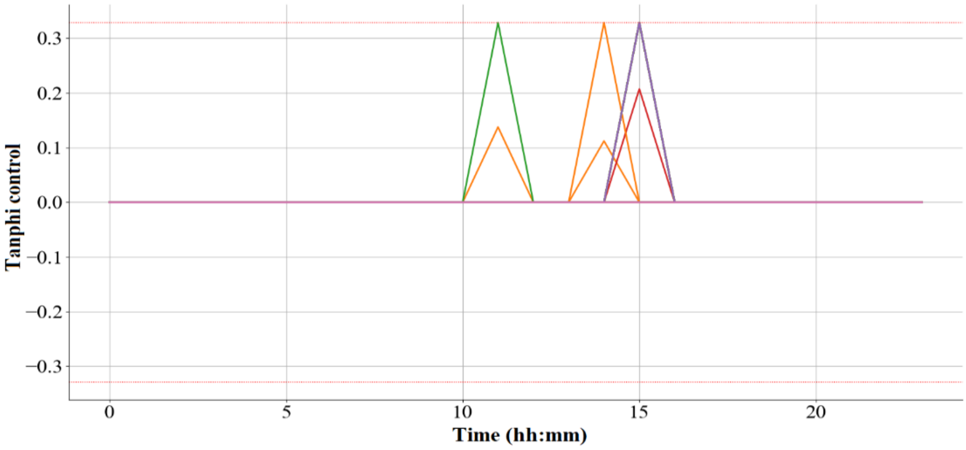


**Figure 8.** Reactive power control variable of the photovoltaic panel tan(ϕ)

## 4. CONCLUSION

Methodology 1 is deemed adequate for assessing the integration of photovoltaic panels into the unbalanced electrical distribution network, facilitating an understanding of the permissible penetration percentage that can be accommodated within this network while adhering to energy quality regulations. Consequently, the upper integration limit for the Guaranda–Chimbo feeder is determined to be 48%.

To achieve elevated percentages, we employ Methodology 2, which effectively minimizes reactive power while simultaneously maximizing the active power output of each photovoltaic panel, all in accordance with the constraints imposed by power balance, as well as the minimum and maximum operational parameters of the electrical system and photovoltaic panels in conjunction with their respective inverter. Through the application of this methodology, it has been feasible to integrate 100% compliance with the stipulated voltage profile. Nevertheless, the occurrence of reverse power flow has been noted, which results in the inappropriate activation of protective mechanisms within the electrical feeder system.

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