Integration of renewable energy into San Andres Island electrical grid

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ABSTRACT

Renewable energy (RE) sources integration in electrical grids is changing the dynamics of planning and operation. Overvoltage, overcurrent, and malfunction of protection schemes are some effects if it is limits are not controlled. This article presents a methodology based on the hosting capacity (HC) concept to estimate performance indexes by considering stochastic methods and systematic simulation taking as study case the grid of San Andres Island. RE is of special interest in islands where diesel generators produce energy with a high footprint and security of supply is low as there is a high dependence on fossil fuels and their transport regime. The simulations are carried out in DigSilent PowerFactory integrated with Python to automate the iterations over different penetration levels. The most limiting factor found is transformer rating. Voltage rise is a factor to be monitored at the end of the circuits. Emissions are reduced with the introduction of renewable energies, but variability needs to be controlled as it could require fast start-up of generators; this modifies monitoring and control schemes to maintain stability. The limit found is higher than the established regulation for non-interconnected zones (NIZ) in Colombia, showing the capability of the grid to integrate RE.

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1. INTRODUCTION

Sources of renewable energy (RE) have a growing participation in electrical grids. In Colombia, it has been promoted by Laws 1715 of 2014 and 2099 of 2021, which establish rules for the integration into the National Interconnected System (SIN) and non-interconnected zones (NIZ) to reduce gas emissions, diversify the energy matrix, and promote sustainable economic development [1], [2]. There are some specific areas called exclusive service areas such as San Andres Island, where diesel generators mainly feed the power grid and there are national government subsidies that reached more than 57 billion Colombian pesos in the first semester of 2023 [3], [4]. The price per kWh is also one of the highest in the country. An energy transition is necessary in these areas to reduce costs and make the energy market more sustainable. The energetic transformation mission raises the need to introduce new technologies agilely without compromising reliability [5]. Some of the benefits introduced by RE are security against shortages of fossil fuels, reduction of power losses and congestion at the transmission level, dynamization of the electrical market as there are new agents and reduction of greenhouse gasses emission [6], [7].

The integration of RE also poses challenges for the grid operator such as the dynamic or non-linear behavior of grid parameters, which should be studied under penetration levels and grid topology [8]. Some of the changes introduced by RE are voltage level rise, thermal overload, risk of exceeding short circuit capacity, and wrong operation of protection equipment [9]. Voltage rise can damage appliances, and voltage fluctuations, due to intermittency of sources, can accelerate the usage of load tap changers and regulators [10]. Voltage unbalance is another problem studied, as many residential photovoltaic (PV) systems installed are single-phased. High voltage unbalance increases voltage levels [11]. Other consequences are flickers, and increasing power losses [12]. Methodologies have been developed to study the integration of RE in electrical grids with its effects on performance indexes and the limits to maintaining power quality.

Since 2004, hosting capacity (HC) has been used to refer to the total capacity of distributed generation above which network performance becomes unacceptable. It indicates the limit of integration of RE into a grid and must be calculated for each indicator of interest for the grid operator [12]. There are several approaches used in the calculation of HC that can be classified into three main categories: deterministic, stochastic, and time-series.

Traditional network planning and operation used deterministic load flows that do not consider the variability of natural resources involved in RE such as irradiance and wind. The deterministic approach typically considers the worst-case scenario, usually with minimum demand and maximum generation. In time-series approaches, there are profiles of the dynamic components of the grid, and load flows are calculated for the shortest possible time interval. Several parameters, like location, size, or number of RE generators, are adjusted until the HC is obtained [13].

Stochastic methods are the most used as they consider uncertainty. One approach is to calculate the cumulative distribution of overvoltage and overcurrent by considering distributed energy resources (DER) location [14]. Other works use the terms best and worst HC [15]. The probability of each consumer acquiring solar installations is studied through a Bass model to calculate the year in which they will reach the feeder's limit and the transformers with a higher probability of having overvoltage problems [16]. Other studies consider the concepts of time of the day and time of the year with higher production probability to make calculations less extensive [17].

A data-driven HC framework and active learning algorithms are developed taking into account factors like socioeconomic behaviors and how DERs are managed and controlled showing that interpretation and results are subject to these factors [18]. Some methods combine detailed assessment based on power flows or short-circuit studies with streamlined assessment that uses direct calculations creating hybrid assessment focused on steady-state voltage and thermal metrics, reducing time calculation [19]. Algorithms such as particle swarm optimization (PSO), genetic algorithm (GA), and differential evolution (DE) are used for HC analysis to determine the optimal location and maximum penetration level considering land availability which is a constrain for solar photovoltaic integration to the grid, finding for the study case mid-feeder location is optimal compared to head or end feeder [20].

Stochastic methods are based on probabilistic load flows (PLF) creating random scenarios for DER number, capacity, and location. These random scenarios are created through methods like the dispersed grid technique and quasi-Monte Carlo [13]. Monte Carlo simulation technique is used to create scenarios with mechanisms like the roulette wheel and the application of scenario reduction [21]. Combined with Gaussian mixture model it is also used to characterize stochastic variables such as irradiance and demand, and power flow results concerning currents, voltages, and power factors are analyzed to determine hosting capacity [22]. Monte Carlo is the most popular numeric approach. Although it requires a great computational capacity, it provides grid operators with a straightforward approach to understanding the HC and applying it in decision-making.

This study evaluates the integration of RE through the HC concept by calculating indicators that guide grid planning and operation. The model of the grid of San Andres Island is used as a study case with valuable points that provide insights into the effects and limits of the penetration of RE in the grid. It is relevant in the context of San Andres Island as energy transition is a reality for all electrical grids, and more so for a region considered a biosphere reserve in need of better security of supply and less dependence on fossil fuels.

2. HOSTING CAPACITY

Some of the performance indexes evaluated are mentioned below. In terms of current, the rating of lines and transformers is the first variable monitored, taking the maximum rating for each penetration level, as defined by (1).

$$C_k^x = \frac{I_k^x}{I_{max}} \tag{1}$$

where I_k^x is the maximum current registered in the line for each penetration level. Change in rating is also monitored and is defined by (2) [6]:

$$\Delta C_k^x = C_k^x - C_0^x \quad (2)$$

where ΔC_k^x is the maximum change in rating of line k for a determined penetration level, C_k^x is rating index defined by (1), and C_0^x is the line rating without RE sources integration.

Voltage variation with uncertainty and instantaneous changes in RE generation sources is considered one of the most limiting factors. The equation (3) defines HC related to overvoltage [23]. According to Colombian regulations, voltage for distribution grids must range between 90% and 110% of nominal voltage for periods longer than one minute [24].

$$VHC = \min\{\sum_{i=1}^{N_{pv}} P_{pv} | (P_r[V_{max}^n \geq V_{lim}])\} \quad (3)$$

Losses are recorded through the (4):

$$P_{loss} = \sum_{i=1}^{N} I_i^2 R_i \quad (4)$$

where I is the current flowing through the line and R is the resistance.

3. METHOD

Figure 1 shows the electrical grid of San Andres Island used as the study case. It has a radial configuration consisting of three generation busbars at 13.8 kV, with a total of ten generators and 64.9 MW installed capacity as shown in Table 1. The energy produced is carried through the transmission lines at 34.5 kV to the substations of School House and Bight with loads of 7.21 and 12.68 MW, respectively, for a total load of 19.89 MW as shown in Table 2. The School House substation feeds five circuits and the Bight substation feeds eight circuits, one of which is modeled according to the available information to evaluate the integration of RE in low voltage.

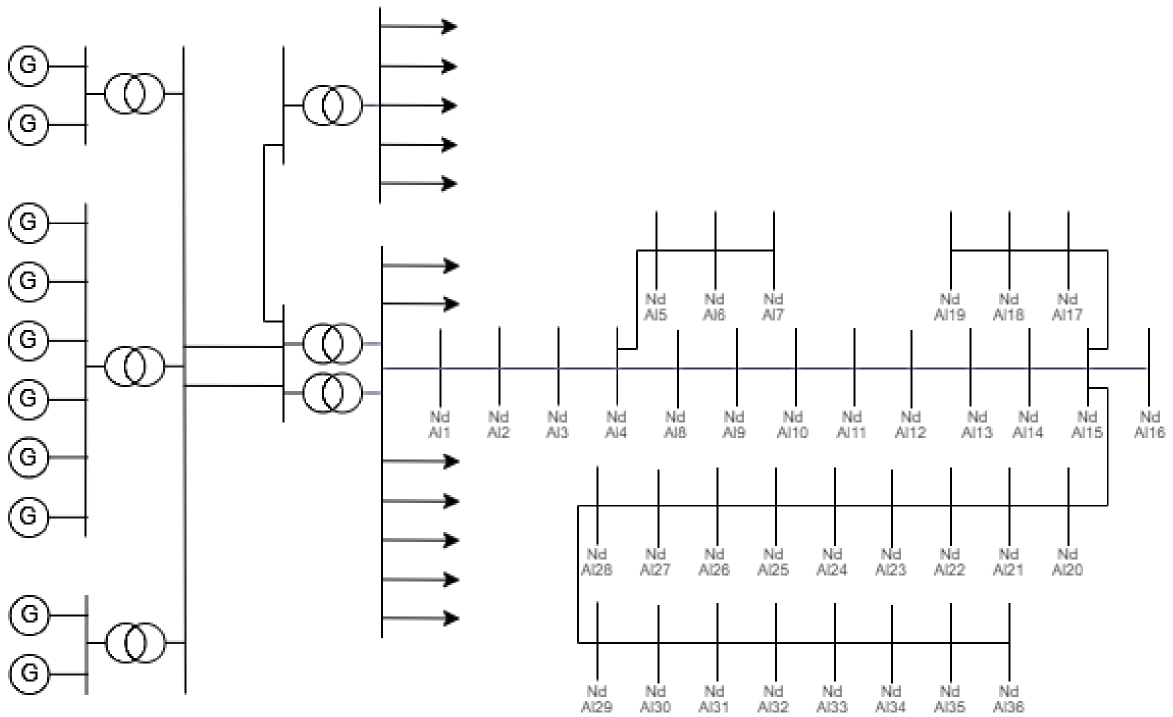

Figure 1. Diagram of San Andres Island electrical grid with Almendros circuit

Figure 2 shows the simulation flowchart. Through the integration of DigSilent PowerFactory with Python, the Monte Carlo method is used to set 25 increasing penetration levels to be evaluated in the simulations. For each penetration level, 1,000 iterations are performed and RE sources are located at the low-level nodes based on a uniform probability function. The capacity of each generator is assigned according to a fixed percentage that depends on the transformer capacity until the penetration level for each iteration is reached.

Table 1. Diesel centralized generation plants capacity

Group	Unit name	Installed capacity (MW)
A	Mirrlees Blackstone 1	9.6
A	Mirrlees Blackstone 2	9.6
B	GM-EMD L16-710G4b 9	2.85
B	GM-EMD L16-710G4b 10	2.85
B	GM-EMD L16-710G4b 11	2.85
B	GM-EMD L16-710G4b 12	2.85
B	GM-EMD L16-710G4b 13	2.85
B	GM-EMD L16-710G4b 14	2.85
C	MAN 1	14.30
C	MAN 2	14.30
A	Mirrlees Blackstone 1	9.6
A	Mirrlees Blackstone 2	9.6
B	GM-EMD L16-710G4b 9	2.85
B	GM-EMD L16-710G4b 10	2.85
B	GM-EMD L16-710G4b 11	2.85
B	GM-EMD L16-710G4b 12	2.85
B	GM-EMD L16-710G4b 13	2.85
B	GM-EMD L16-710G4b 14	2.85
C	MAN 1	14.30
C	MAN 2	14.30

Table 2. Circuits load

Substation	Circuit	Power (MW)	Power factor
El Bight	20 de Julio	1.46	0.92
El Bight	Back Road	0.54	0.93
El Bight	Juan XXIII	1.53	0.91
El Bight	Hospital	0.24	0.83
El Bight	Fragata	1.38	0.93
El Bight	Almendros	2.77	0.94
El Bight	Loma	1.81	0.94
El Bight	San Luis	2.95	0.94
El Bight	20 de Julio	1.46	0.92
El Bight	Back Road	0.54	0.93
El Bight	Juan XXIII	1.53	0.91
El Bight	Hospital	0.24	0.83
El Bight	Fragata	1.38	0.93
El Bight	Almendros	2.77	0.94
El Bight	Loma	1.81	0.94
El Bight	San Luis	2.95	0.94
School House	Natania	1.87	0.92
School House	Swamp Ground	0.46	0.99
School House	Boulevard	2.54	0.95
School House	Americas	0.78	0.95
School House	Colombia	1.54	0.93

Hourly irradiance historical data measured at the airport of San Andres Island by the *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM) are used to calculate the probability density function of solar generators. For each iteration, a random number is achieved from the probability density function for every solar generator and multiplied by its assigned capacity to consider the related uncertainty. A load flow is carried out for each iteration and voltage levels, rating of feeders and transformers, and losses are recorded to evaluate HC. The maximum and minimum voltage registered for nodes in each penetration level is obtained to assess regulation. Active power loss behavior is modeled concerning RE integration by an equation to observe improvements and some other characteristics can be found through boxplots. Maximum rating of lines and transformers is also obtained to observe possible limits and emissions reduction is seen as an important indicator for the island, considered a biosphere reserve.

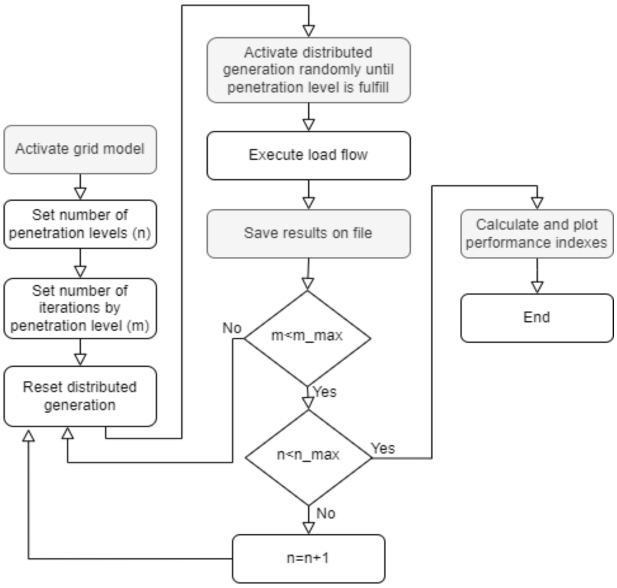

Figure 2. Simulation flowchart

4. RESULTS AND DISCUSSION

This section presents the results from the simulation. Different performance indexes are evaluated to assess the HC and to give some recommendations. Data is presented in graphics that resume the findings for each performance index.

4.1. Voltage

As expected, RE integration into the grid involves an increase in voltage levels. Figure 3 shows the minimum registered voltage for some of the main nodes in each penetration level. Without RE, the end of the circuit is near minimum voltage regulation and experiment voltage rises with higher penetration levels, which is positive for the case studied.

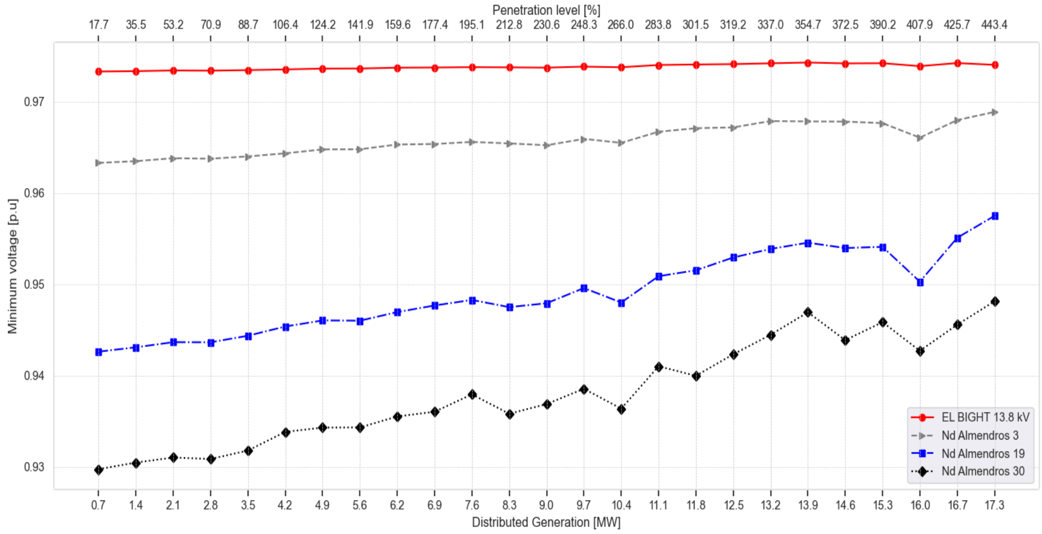

Figure 3. Minimum voltage in nodes

Figure 4 shows the maximum registered voltage for some of the main nodes in each penetration level. According to the results, regarding the minimum voltage, nodes in the tail of the circuit show greater variation. For the study case, voltage levels do not exceed regulation, so there is no HC associated with voltage. At a penetration level equivalent to 200% of the load connected to the circuit, the voltage increase obtained reaches 10% in circuit tails. Voltage variation needs to be considered for adequate protection schemes as it can compromise the grid's stability.

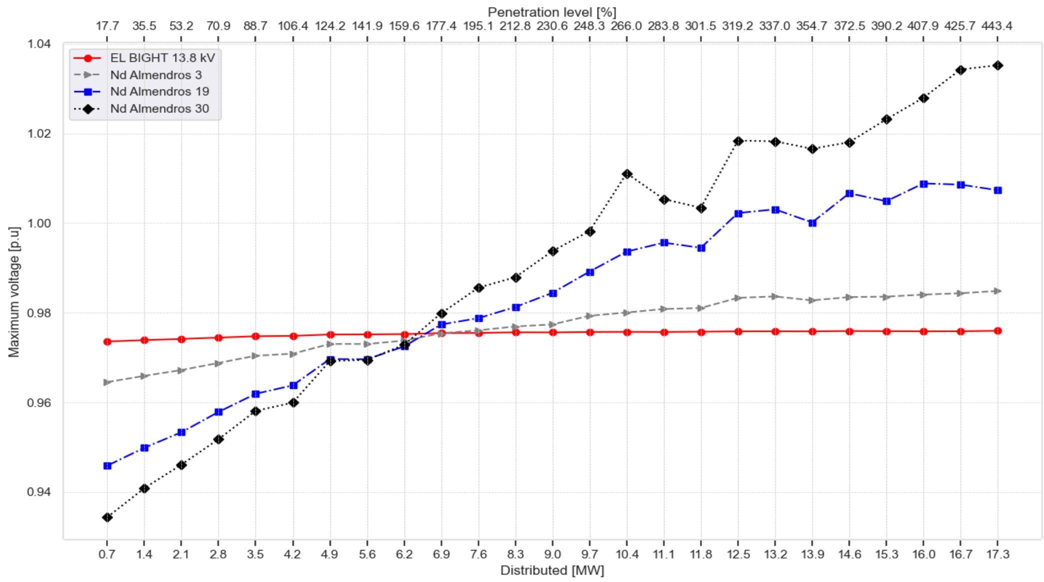

Figure 4. Maximum voltage in nodes

4.2. Losses

Total active power losses were saved for each iteration. Figure 5 shows the average power losses for each penetration level. There is a minimum of losses for the circuit when generation meets load level. In the study case, this is true for all the loads connected to the substation as the circuit is not isolated from the other connected loads.

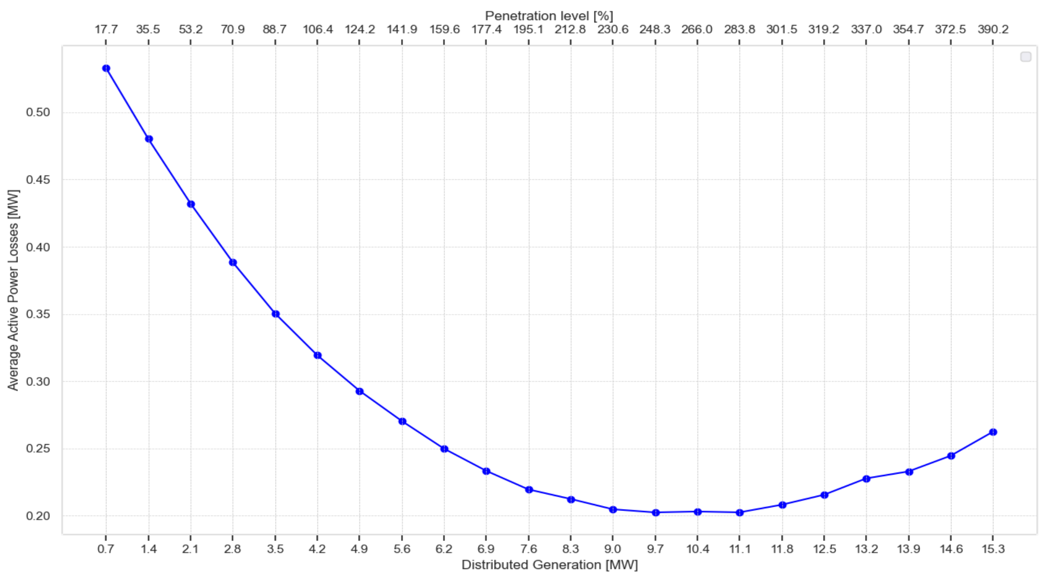

Figure 5. Average active power losses in the circuit

It is possible to find the function associating RE integration with losses through regression models. For the study case, it was found there is an average loss reduction of 3.33% per MW of solar energy installed. The function that describes losses for the Almendros circuit is the following:

$$l = -5{,}932e^{-6}x^3 + 9{,}634e^{-4}x^2 - 1{,}982e^{-2}x + 0{,}273 \quad (5)$$

where l are the losses as a function of RE integration (x) in MW.

The increase in RE makes the results more variable as shown in Figure 6. The system becomes less predictable and needs to have available generators to be switched on. In this sense, operation costs can be increased so the grid operator needs to establish prediction and control schemes to optimize the variability associated with RE uncertainty. The system stability can be affected by turbine generation change ramps.

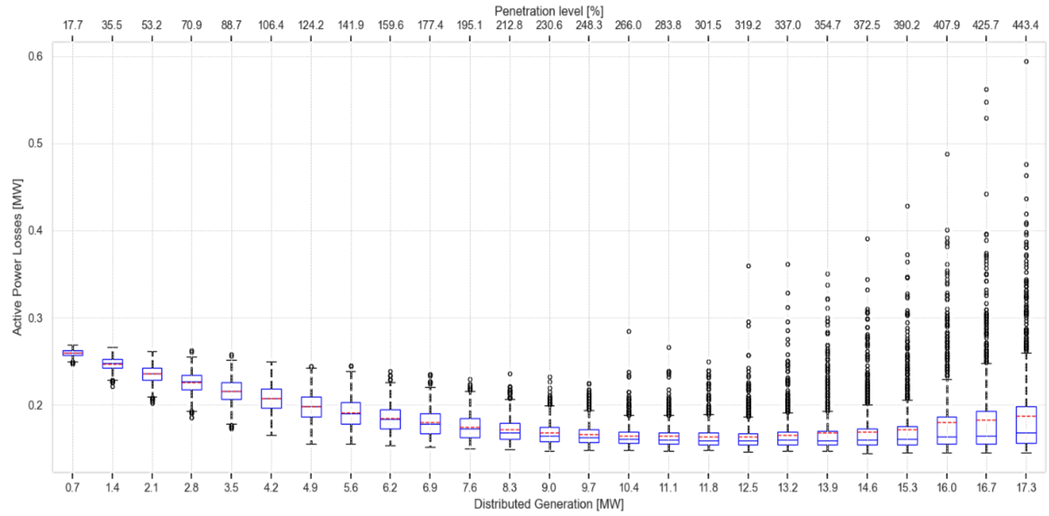

Figure 6. Active power losses

4.3. Rating

Figure 7 shows the maximum rating for lines registered in each penetration level. Lines have a lot of spare capacity to hold distributed generation. The capacity of the lines at the beginning of the circuit is reduced with RE integration. rating increases the most in lines located in the middle of the circuit, whereas it increases the least in lines located at the end of the circuit.

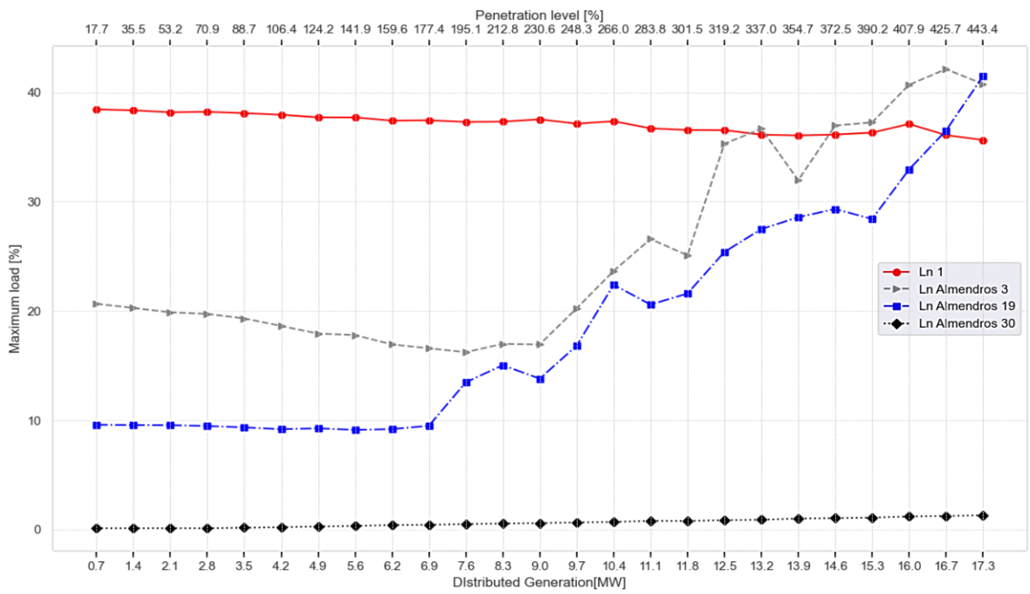

Figure 7. Maximum rating in lines

For the circuit evaluated, transformer rating is the most limiting factor as shown in Figure 8. The HC associated with transformer rating can be found at approximately double the load connected to the circuit. At this point, transformers have 100% reverse flow.

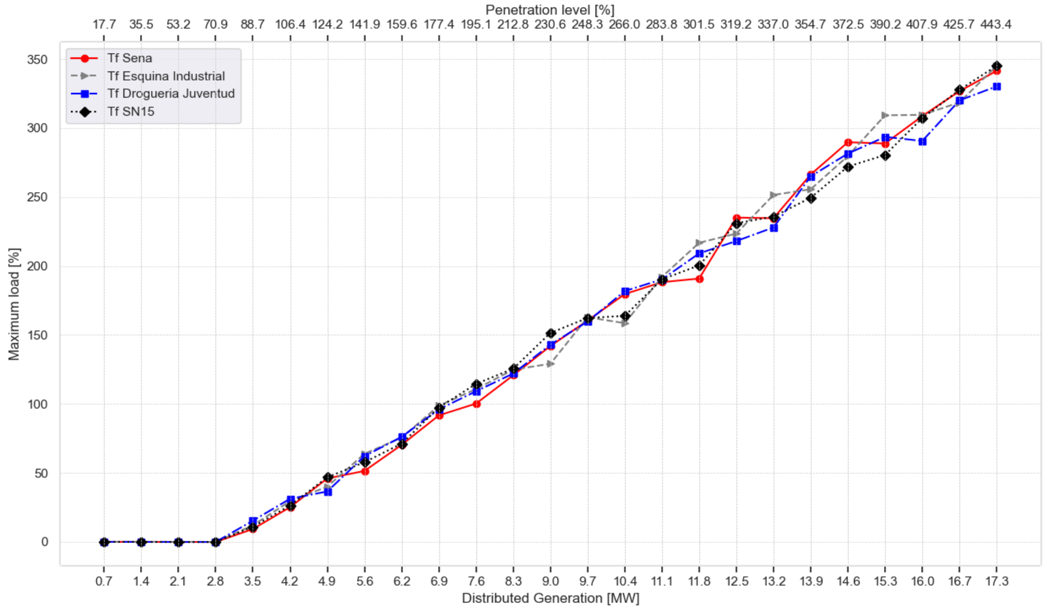

Figure 8. Maximum rating in transformers of Almendros circuit

4.4. CO_2 emissions

With the increase in renewable energy sources in the grid, CO_2 emissions are lowered as shown in Figure 9. In the scenario of an average load with a penetration level of 5.55 MW, an average of 0.87 tons of CO_2 is saved in an hour of generation. The amount of emissions savings also depends on the variability of the renewable energy sources.

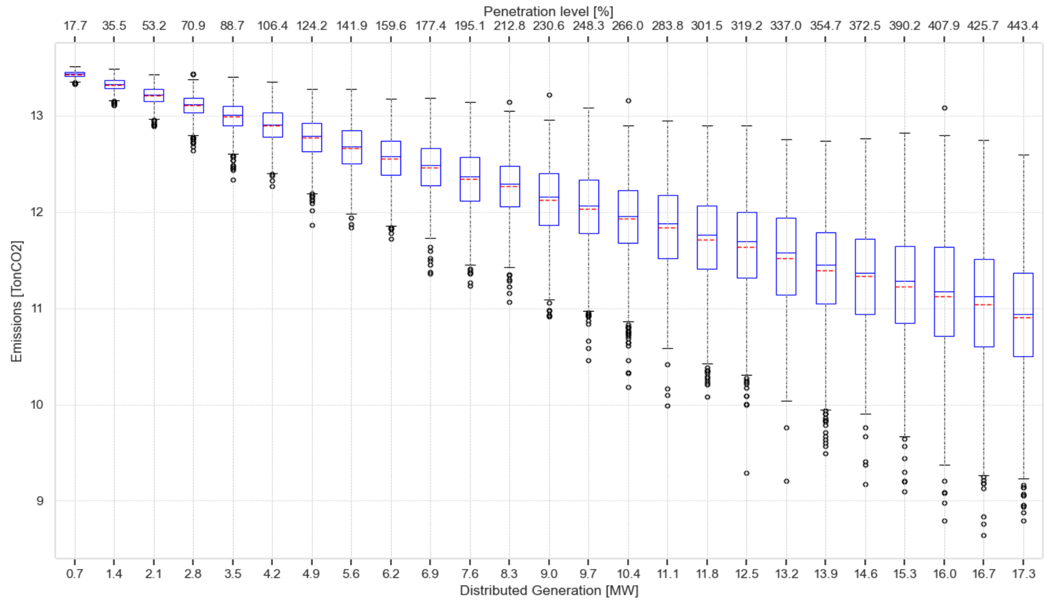

Figure 9. CO_2 emissions

From the performance indexes evaluated it is conceivable that for the grid of San Andres Island studied, the limit of 15% of the circuit capacity, transformer, or substation to which the connection is requested, established by Resolution 038 of 2018 [25] for Non-Interconnected zones, would not have a negative impact on the grid operation. Increasing it would reduce gas emissions and generation costs.

5. CONCLUSION

A methodology based on Monte Carlo simulation integrated with DigSilent PowerFactory and Python is developed. This methodology makes it possible to evaluate performance indexes and to find the HC of an electrical grid. HC depends on the topology and asset characteristics. It is necessary to model low voltage circuits so that the effect in the tails of the circuit can be observed, as it shows greater variations. The integration of RE changes operating parameters by introducing voltage rise and increases in lines and transformer rating. For the studied grid, transformer rating is the most limiting factor with an HC equivalent of approximately twice the circuit load, resulting in 100% reverse flow for some transformers. It was found that nodes in the tail of the circuit can have up to 10% voltage rise, which can alter the protection schemes, Grid operators need to have more observability of the system and should adjust scheme protection based on new operational parameters. The introduction of RE results in lower power losses. For the study case, an average of 3.33% of power losses is reduced for each MW of RE installed. Results show that the optimum for power losses is when distributed generation capacity meets demand levels. In conclusion, for the San Andres Island grid study case, the maximum penetration level of 15% as established by actual regulation for non-interconnected zones, could be increased with aims of reducing gas emissions and lowering production costs.

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