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IMPROVING VOLTAGE STABILITY IN SUBTRANSMISSION THROUGH PV CURVES AND CRITICAL VOLTAGE BALANCE FOR PHOTOVOLTAIC COMPENSATION

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Abstract

The constant increase in energy demand and the need to reduce the carbon footprint on the environment has put countries in a race against time, looking for alternative resources or ways to supply this need. One of the main resources is solar radiation, which can be used to generate energy, initially on a small scale, but in recent years has been directed towards supplying large cities. The economic, political, and social investment must respond to planning and expansion criteria in order to generate feasible proposals. Through simulation of a real electrical system, the voltage instability was determined, which was corrected at software level by entering a photovoltaic solar plant, being this dimensioned from the PV curve obtained. Finally, the optimal location for the development of a solar photovoltaic plant among four possible scenarios was obtained through the application of an optimization algorithm. This approach was converted into an alternative applicable to different geographical locations.

Keywords: Stability, SEP, digsilent, collapse, PV, photovoltaic, energy, renewable, particles, optimization.

1. INTRODUCTION

One of the main indicators to establish or determine the economic and social growth of nations is the electricity sector [1]. Within this generation-demand exchange, it is imperative to have the capacity to satisfy the energy consumption, Electrical parameters as frequency, voltage, current and load are of primary importance for power supply and quality standards are of primary importance for power supply and power quality standards [2], starting from the electric generation, the realization of the respective study to determine the ideal place for its implementation usually presents a predominance of various factors among which we can mention the hydrographic, topographic, geographic, climatological, meteorological, climatic, among others ,but through the modeling and study of a power flow, it is possible for us to determine power flow it is possible for us to determine actions that allow us to control the active and reactive control the active and reactive power of the network that directly influence the stability of an SEP [3].

For our study, a photovoltaic power plant is analyzed in order to promote alternative sources in the field of electric power [4]. The choice of the site becomes a key determinant in terms of its generation efficiency, the environmental impact involved in the construction and commissioning of the generating plant. Which will also be decisive in terms of generation efficiency, the environmental impact of the the environmental impact involved in the construction and operation of the generating plant, and the generating plant and, after that, the environmental impact that the generation process itself demands [5].

For the purpose of this study, several possible scenarios have been developed based on their performance and will be validated by means of the optimization technique known as particle swarm or PSO, which seeks the optimal result within a space of possible outcomes [6].

This paper provides an introduction to the Electric Power System. The Ecuadorian electric sector is analyzed in order to give a general scenario of study including its regulations at the governmental level. Subsequent to the mentioned above, the cases of stability in a SEP are presented, with the objective of presenting the particular case of voltage stability.

The imperative of the administration of an electric power system is to offer the electric service guaranteeing its continuity in supply, quality and as economically as possible.

The same way, over the years, technology has improved in such a way that it is possible for "non-conventional renewable energies" to be incorporated to the production of energy on a large scale for the nations.

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From this point, having a clear idea of the energy reality of Ecuador, the readership is informed about the inclusion that renewable energies have had in the country under study and the solution is established in order to define, through the application of optimization algorithms, the ideal place in front of several study proposals.

2. MATERIALS AND METHODS

2.1. General introduction to the Electric Power System

The Power Electrical System (SEP) is generally composed of three fundamental areas of study: generation, transmission and distribution, providing the end user or load with adequate voltage levels and currents according to their needs [7]. From the technical point of view, a power system is represented by: sources, conductors and equipment required to supply electrical power [8].

It is common as in any real system, that losses occur mainly due to the distance between the generation plant and the consumer, being this the loss generally represented in the transmission lines and the gradual wear of the equipment that make up the SEP [9]. Within this generation-demand exchange, it is important that the energy supplier is fully capable of meeting the required consumption in the most economical way possible [10], [11].

2.2. Quality of electricity supply in Ecuador

The agency for regulation and control of electricity and non-renewable natural resources is the governmental entity of Ecuador, with the acronym ARCERNNR, in responsible for ensuring compliance with the quality of energy delivered to final consumers, either residential, industrial or commercial, through the legal figure of regulation 002/20, which indicates parameters related to the quality of the service of distribution and commercialization of electric energy [12], [13]. The ARCERNNR determines 3 important parameters concerning the quality of the electric service, which are:

1)Voltage levels. - To minimize the problems that may occur because of the losses, it is necessary to determine the permissible supply voltage limits [12], this may be calculated as follows:

$$\Delta V_k = \frac{V_k - V_N}{V_N} * 100\ \% \qquad (1)$$

Where ΔV_k is voltage difference supplied at a point k, with respect to a nominal reference voltage; V_k is voltage supplied at a point k of the network, this value is the average recorded in at least every three seconds during a time interval of 10 minutes; V_N is nominal voltage measured as a reference at a point k of the electrical network;

2)Admissible range of voltages. - The ARCERNNR defines a range of admissible network voltages, depending on the voltage level there are tolerable values [12], table 1 shows in detail these values:

Table 1. Admissible voltage limits according to the ARCERNNR 002-20 regulation

Level of voltage	Reference voltage	Admissible range
High Voltage. Group 1	> 138 kV	± 5.0 %
High Voltage. Group 2	> 40 kV & ≤ 138 kV	± 5.0 %
Medium Voltage	> 0,6 kV & ≤ 40 kV	± 6.0 %
Low Voltage	≥ 0,6 kV	± 8.0 %

Figure 1 below visualizes the structure of the electrical power system [14]:

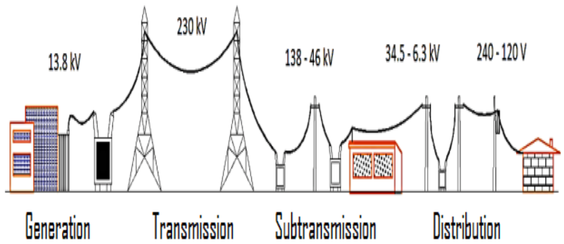

Fig. 1. Basic elements of a power system

3)Voltage unbalance. -In electric networks, voltage unbalance is one of the problems with the highest frequency rate, a consequence of the incorporation of loads into the network [15]. This unbalance can be determined as [12]:

$$Voltage\ Unbalance = \left|\frac{V^-}{V^+}\right| * 100\% \qquad (2)$$

Where V^- is negative sequence component, the average product of the measurements analyzed at least every three seconds over a period of ten minutes; V^+ is positive sequence component, the average product of the measurements analyzed at least every three seconds over a period of ten minutes.

2.3 Stability in electrical power systems and classification

Stability is the property of an SEP to operate in a steady state under normal operating conditions and its capacity to recover an acceptable steady state after being subjected to a perturbation [16], these phenomena could be classified as shown in Figure 2:

For the purpose of study of the present article, the main phenomena of voltage stability is analyzed, because it is the central focus of the specific objectives set out [17].

There are a number of main phenomena that cause voltage instability with a frequent recurrence rate:

1)Load increase. - Inside the main indicators to establish or determine the economic and social growing of the nations, is the electrical sector [1], the absence of SEP planning and the sudden entrance of load always creates a fluctuation in

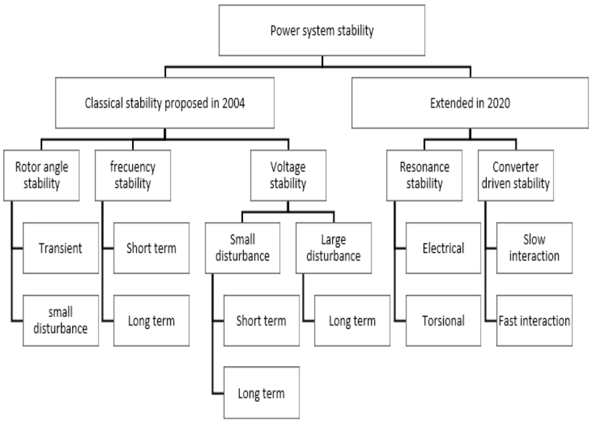

Fig. 2. Stability classification in electrical power systems

the voltage level [18], representing an inevitable factor due to the exponential increase of the energy demand caused by population increase and the improvement of the lifestyle [19].

2) Operation at the maximum limits of the machine. -The operating limits of a machine may be visualized in their respective capacity diagram, these values limit the equipment caused by magnetic saturation that leads to heating of both the ferromagnetic core and the windings of the machine [20], [21], the work of the machine caused by unplanned load increase causes stability problems [22].

The analysis of the PV curves is interpreted from their collapse point, while its active power demand is increasing, the voltage is decreasing, so the curve that is in the lower part of the "y" axes, corresponding to the coordinates of the voltages, will indicate which is the most critical bus of the network (see Figure 2) [23]. In the PV curve, it is indicated that P is the amount of active power being supplied by the bus and V is the change in voltage as the load begins to increase to reach the point of maximum transfer before reaching the voltage collapse, as shown in Figure 2 [24]. With the above 10 loads, the PV curves are obtained using DigSilent software. Each bus has different types of loads, so their angles, voltages and power changes, a curve was obtained for each bus to analyze and identify the point of collapse in the most critical bus of the study system [25].

3)Remote from the generation plants. - Transmission lines generate losses represented in voltage level drops on account of their impedance [9]. Strategies such as raising the voltage levels for transmission can in certain cases lead to not having the necessary voltage limits to guarantee the quality of service imposed by the ARCERNNR in its regulation 002/20 [12], [23].

When planning the implementation of a generation plant, the optimal location is a determining factor in addition to the type of generation system and the environmental impact, among other factors [24].

4)Very high inductive reactive power. - Along with the increase of the load, high reactive power components of inductive type are added to the electrical network, causing voltage and angle instability [25], [26].

2.4 Introduction of renewable energy in the electricity system

Several decades ago, the study of photovoltaic energy applications led to the development of technologies to supply homes and later industries [27] and with this, the concept of distributed generation was introduced, where generation is close to the load and is generally of an environmentally friendly type [28].

Currently, photovoltaic development has enabled the implementation of large-scale photovoltaic plants or parks in order to alleviate power grids and the environmental problems [29], the world nowadays has large generation parks which cover large areas of land, but which in turn benefit thousands of people [30].

2.5 Renewable energy in the Ecuadorian electricity

The Republic of Ecuador, whose current constitution dates from 2008, has taken as its main protagonist the change of its productive and energy matrix [31], focused on large emblematic projects, which are based on the creation and repowering of each sector that makes up the Ecuadorian electrical system [32] including green energy in generation, repowering at the transmission level (voltage increase to 500kV) [33] and the improvement of the energy received by end users [13].

The present electricity master plan, which initially covered the period 2018-2027 and has been extended until 2031 by the present government (2021-2025), with the purpose of attracting private capital to be invested in non-conventional renewable energy, indicates that as of 2018, Ecuador has an electricity service coverage or electrification coefficient of 97.05% [34] , which is analyzed every four years to verify and estimate compliance with the plan [35].

On April 16, 2016, Ecuador suffered an earthquake recognized as one of the biggest natural disasters in recent decades, with the epicenter located in the coastal province of Manabí, which affected mainly the canton of Pedernales [36], thus compromising electricity distribution and showing the deficiencies in terms of energy reliability [37], [38].

The introduction to the network of this type of system allows the optimization of active power losses [39].

2.6 Optimal location of the PV plant

This type of power plants, as mentioned above, in some cases involve large areas of land, making their optimal location a critical problem for the project planner, who must evaluate geographic, environmental, technical and economic criteria to determine the feasibility of the power plant [40], [41].

2.7 Options for minimizing power losses and quality problems

The most common techniques used to upgrade an electrical network are:

1. Reconfiguration of the network [42], illustrated in Figure 3;
2. Siting and dimensioning of distributed generation with storage systems [43].

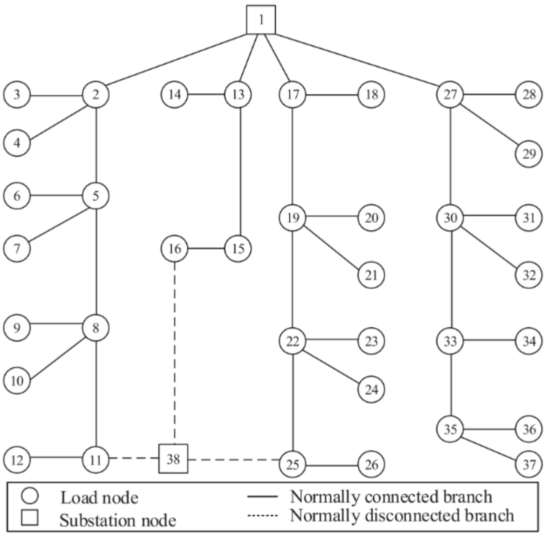

Fig. 3. Techniques to reduce power losses and voltage drops: Network reconfiguration. Described in "Analytical Reliability Assessment Method for Complex Distribution Networks Considering Post-Fault Network Reconfiguration" [44]

The central focus of this paper deals with the distributed generation technique applied to a power system, as shown in Figure 4.

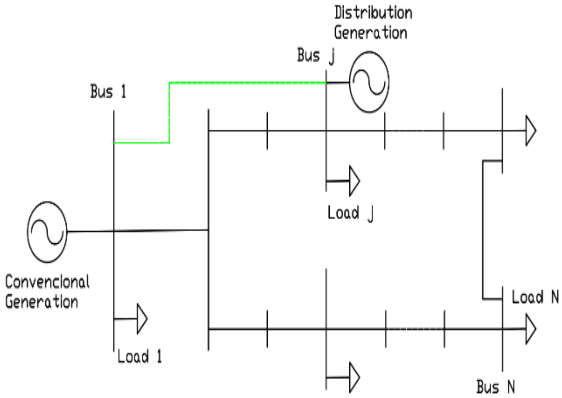

Fig. 4. Location of distributed generation on the grid. Credits Author

2.7 Definition of the algorithm to be applied

Every year, there is a significant increase in electricity demand, and with the increase in demand, problems begin to occur in the network [45] where generally there are mainly voltage drops, transformer overloads, overloaded lines, leading the user to begin to have problems related to power quality [13], [46].

2.8 Development challenges for optimization

The techniques mentioned are subject to restrictions that represent several challenges for network optimization, considering the complexity that might be present in the network topology [41], loss minimization, cost reduction, demand projection, geographic restrictions, and the incorporation of distributed generation with their respective storage system [47],[49]; however, this case study does not contemplate storage because it is a system incorporated to the network [50].

2.9 Particle Swarn Optimization

The Particle Swarm Optimization (PSO) algorithm is part of the metaheuristic algorithms [51]. For its application, this method considers the possible solutions within an analysis space, range or interval [14].

The mathematical modeling can be represented in terms of position and velocity [52], the movement of each particle of the system in the set or dimension D is related to its inertia, and to the cognitive and social components [53], as shown below:

$$X_i^{(t+1)} = X_i^{(t)} + v_i^{(t+1)} \tag{3}$$

$$v_i^{(t+1)} = \underbrace{\gamma * v_i^{(t)}}_{Inertia} + \underbrace{\alpha * r_1 * \left[\vartheta_i - X_i^{(t)}\right]}_{Cognitive\ behaviour} + \underbrace{\beta * r_2 * \left[\sigma - X_i^{(t)}\right]}_{Social\ behaviour} \tag{4}$$

Where X_i is position for each iteration as function of time (t); $v_i^{(t)}$is present velocity; ϑ_i is best known velocity of the particle; σ is best known position among all the particles of the study set; γ is weight or inertial factor. α is constant to calibrate the cognitive behavior. β is constant to calibrate the social behavior; $r_{1,2}$ is random values in the interval between 0 and 1.

At the start of the iterative optimization process the inertial factor γ can take values of 0.9 to explore a larger search area and consequently reduce to 0.4 and then adjust its search parameters [54].

Generally, the values of α and β oscillate between 1 and 2 with the purpose of increasing the local exploration or emphasize the importance of the optimum found by the set as a whole [55], generally 100 iterations are selected [56].

2.10 Optimal location of the PV plant

The Matlab algorithm considered for its application is the particle swarm, and the input of the parameters obtained in the PvSyst software was considered for its application. Among the parameters or variables entered, the following are detailed:

1) Name of scenarios;
2) Yields;
3) Annual production;
4) Specific production;

5) Inverter power;
6) Solar Fraction;
7) Energy used;
8) Design Power;
9) Number of modules;

The purpose is to determine a convenient location to install the renewable energy plant [57], considering that it must meet the characteristics of a SEP [10]. In our case, the objective function is performed seeking to maximize the weighted sum of the yields [58].

The restrictions are related to the variables with the previously obtained values, remembering that they must not be negative and must be less than or equal to unity [59].

The optimization function "Particle Swarm" or "particleswarm" is called, which, through iterations and loops, searches for an optimal solution between several candidates.

The graph presented in Figure 5, uses as example the objective function sine(x)+cos(x) with domain between -5 and 5, with 50 particles and 100 iterations. The values adopted for the constants are: 0.8 for γ , while α and β have a value of 2.

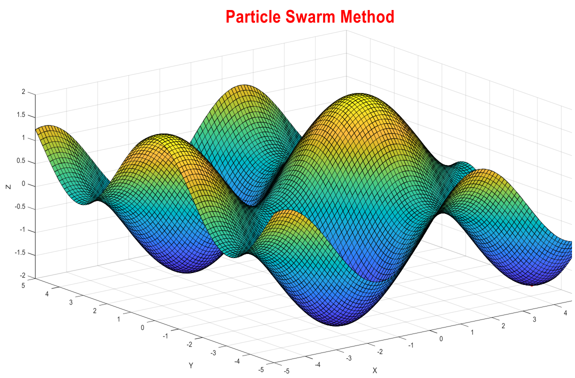

Fig. 5. Particle swarm applied to the objective function sine(x)+cosine. Source: Author

2.11 Softwares used in the study scenarios

1)Digsilent Power Factory application. - The development of computational software has allowed a more efficient study, planning and decision making regarding the operation of the electrical sector [60].

DigSilent Power Factory allows the modeling and simulation of an electrical system to be subsequently evaluated in various conditions to those that can be exposed such as power flows in steady state, fault analysis, coordination of protections, dynamic modeling, contingencies, among others [61],[62].

The use of this software for decision making at the electrical level has been implemented by both private and state companies such as the National Energy Center Corporation (Cenace) and the business entity Transelectric, in charge of energy transmission in the country [63].

2)Analysis of the solar potential-PVSYST. - this software is used in the study of the irradiance resource, which allows analyzing the irradiance behavior through a database [64] and at the same time has libraries with real elements that will be used in a photovoltaic installation [65].

3)Matlab. - Is extensively applied in the study and design of electrical power systems [66]. For our purpose, the data obtained were vectorized, comparing the initial results with those obtained after our work [67], in turn using the particle swarm algorithm, determines the optimal scenarios [68].

3. PV CURVE, POWER FLOW AND PHOTOVOLTAIC COMPENSATION SYSTEM

3.1 Electric power system in the province of Manabí

This network is conformed by the following elements:

- 28 busbars;
- 9 three-winding transformers;
- 13 two-winding transformers;
- 10 charging points;
- 4 three-phase transformer banks.

The network loads are connected at:

- Severino;
- Chone;
- St. Gregory;
- Quevedo;
- Lodana corners;
- 3 Portoviejo corners;
- 2 Manta.

The study of the effect of these loads will allow to determine the state of the network, allowing to analyze and observe the voltage stability by means of the PV curve.

The one-line diagram representing the electrical system may be observed in figure 9.

3.2 PV Curve

The PV curve represents the maximum load that can be placed on a bus or line without a voltage drop, which leads to voltage instability [69].

The behavior of the voltage can be observed in relation to the variation of the active power in the network [62]. The critical or collapse point occurs when increasing the power demand, the voltages decrease rapidly because of the requirement of an infinite amount of reactive power [70].

Figure 6 indicates that power systems should ideally operate in the upper part of the PV curve, at which point the system appears to be statically and dynamically steady [71].

For the study, using Digsilent software, an independent curve is obtained for each bus, allowing the identification of the collapse point and thus the most critical bus of the system, which will be intervened by distributed generation [73].

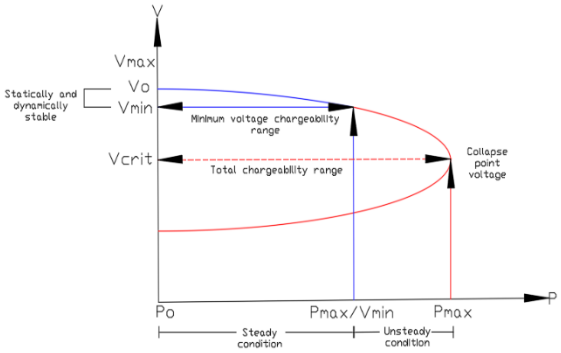

Fig. 6. Details of the PV curve [72]

3.3 Power flow and voltage stability

Through the use of the power flow we can define the voltage instability [74], observing the graph proposed in Figure 7.

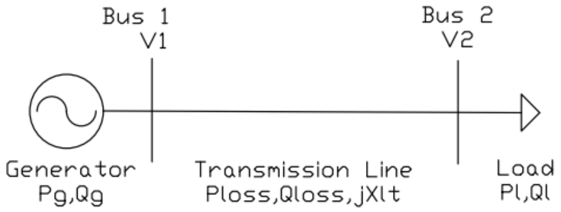

Fig. 7. Two-bar system

The voltage V2, in relation to the required power is determined as follows:

$$V_2 = \sqrt{\frac{(V_1^2 - 2Q_l X_{lt}) \pm \sqrt{V_1^4 - 4Q_l X_{lt} V_1^2 - 4P_l^2 X_{lt}}}{2}} \quad (5)$$

Where V_1 is voltage at bus 1; V_2 is voltage at bus 2. P_l is active power required by load; Q_l is reactive power requiered by load; X_{lt} is reactance of the transmission line.

The respective system of equations representing the power balance may be determined. It should be remembered that the system of equations is actually nonlinear, because the voltage V2 is internally expressed quadratically.

$$\begin{cases} P_g = P_l + P_{loss} \\ Q_g = Q_l + Q_{loss} \end{cases} \quad (6)$$

Where P_g is active power produced; P_l is active power required by load; P_{loss} is active power loss in the transmission line; Q_g is produced reactive power; Q_l is reactive power required by load; Q_{loss} is reactive power loss in the transmission line.

For solving this type of problem, the Newton-Raphson method [75] is used, which indicates:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (7)$$

Where $\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$ is vector of power variation, denoted ΔPot; $\begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}$ is Jacobian matrix, denoted J; $\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}$ is voltage stability matrix.

For determining the voltage variation, it is necessary to clear the voltage stability matrix:

$$\Delta V = J^{-1} \Delta Pot \quad (8)$$

Where ΔV is voltage variation; J^{-1} is inverted Jacobian matrix; ΔPot is power variation.

It must be remembered that, if the determinant of the Jacobian is zero, mathematically the matrix has no inverse and therefore in terms of power flow, it ceases to exist [76].

From the power system analysis point of view, it shows that the losses in the transmission line are excessively high and there is not enough generation to transfer energy.

3.4 Dimensioning of the photovoltaic compensation system

Manabí province bases its generation exclusively on thermal power plants, by the public company according to data obtained by ARCERNNR [77]; however, since it is a point of high demand, another photovoltaic project is being planned in this province, such as "El Aromo" [78].

The canton of Chone counts with four substations (S/E), which are mainly for distribution and transmission [77], the energy demand and the lack of generation at this point produce the stability problems analyzed by the authors Santillán and Peña [79].

Most of the distribution system in Ecuador is under the administration of the National Electricity Corporation, a state-owned company, abbreviated CNEL-EP, and subdivides its concession areas into business entities; the S/Es in the Chone canton are: Sesme of 69/34.5 kV , administered by the business entity CNEL-EP Santo Domingo, the S/E Chone and S/E Chone Subtransmision both of 69/13.8 kV which respond to CNEL-EP Manabí and the S/E Severino of 69/13.8kV which is of private financing [34].

In Figure 8, the arrangement of the substations in the canton Chone is presented and in Table 2. Chone

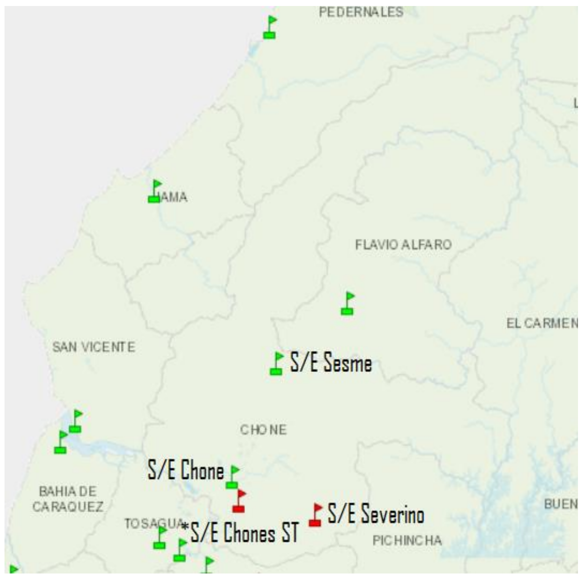

Fig. 8. Substations location located in Chone. Source: Geoportal

ST* is Chone subtransmisión. The geographic location of the substations or busbars considered for the analysis is presented in detail.

Table 2. Location of study sites.

	Sesme	Chone	Chone ST*	Severino
Latitude	-0.51 ˚S	-0.70 ˚S	-0.74 ˚S	-0.79 ˚S
Longitude	-80.04 ˚W	-79.94 ˚W	-80.11 ˚W	-79.94 ˚W
Altitude	176 m	12 m	56 m	482 m

4. ANALYSIS AND RESULTS

4.1 Manabí electric system and PV curve

The one-line diagram of the Manabí electrical system used for the analysis is presented in Figure 9.

Comparing the results obtained by the authors Santillán and Peña [79], which represented the starting point for this study; observing table 3, the 5 buses with the lowest critical values, we have the following.

Table 3. Results obtained from the PV curve by data export

Bus	Power drop p.u	Power MW
Chone 69 kV	0.595	639.006
Chone 138 kV	0.602	639.006
Portoviejo 69 kV	0.834	639.006
Montecristi 138 kV	0.894	639.006
St. Gregory 69 kV	0.897	638.928

The figure 10 indicates that the criticality is focused on the 69 kV Chone bus, the most critical sub-transmission bus is the 69 kV Chone bus, which has a voltage of 0.595 p.u. and supplies a power of 639.006 MW. It is interesting to note that at 69 kV the next critical bus is the 69 kV Portoviejo bus with a value of 0.834 p.u. and a power of 639.006 MW. It should be noted that the 138 kV Chone bus also presents a critical voltage of 0.602 p.u, making the city of Chone a considerable study point.

The values obtained indicate that at this point there is a surplus of active power demanded, so it is necessary to locate generation to compensate the system and stabilize the voltage drop.

Using the data exported through the trend curve option, we can determine the equation of the PV curve of the 69 kV Chone bus, which is a quadratic equation of fourth degree as can be seen in figure 11.

$$p.u = -2e^{-11}MW^4 + 2e^{-8}MW^3 - 8e^{-6}MW^2 - 0.0006MW + 1.0983 \quad (9)$$

Where p.u is voltage per unit; MW is the power demanded by the network.

This equation must be determined in order to obtain the power variation to design the photovoltaic system. Based on the work of the authors Li and Dong, using equation 10, the power variation is determined [80], [81].

Performing the respective clearing and evaluation of the equation in 0.9 p.u, the power point of 453.339 MW is reached.

$$P_{req} = P_{crit} - P_{eval} \quad (10)$$

$$P_{pv} = 639.006 - 453.339$$

$$P_{req} = 185.667\ MW$$

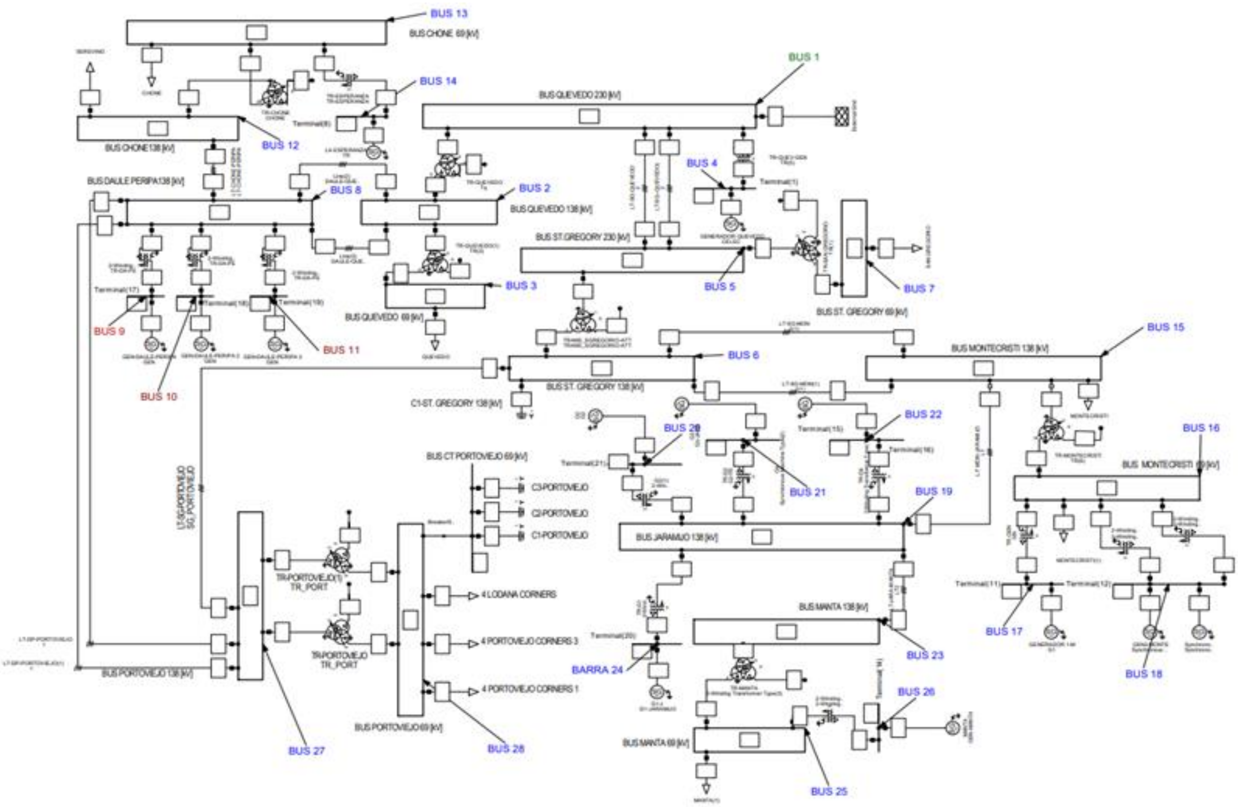

Fig. 9. Electrical system of the province of Manabí

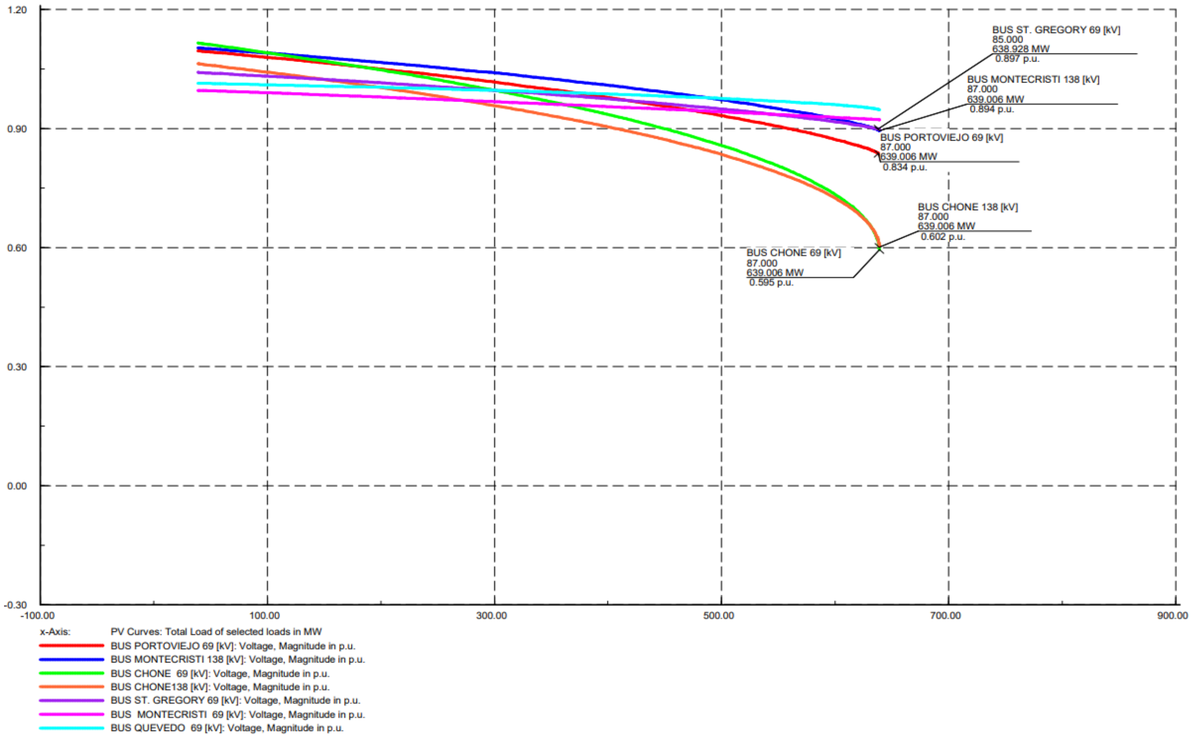

Fig. 10. PV curves of the Manabí electrical system

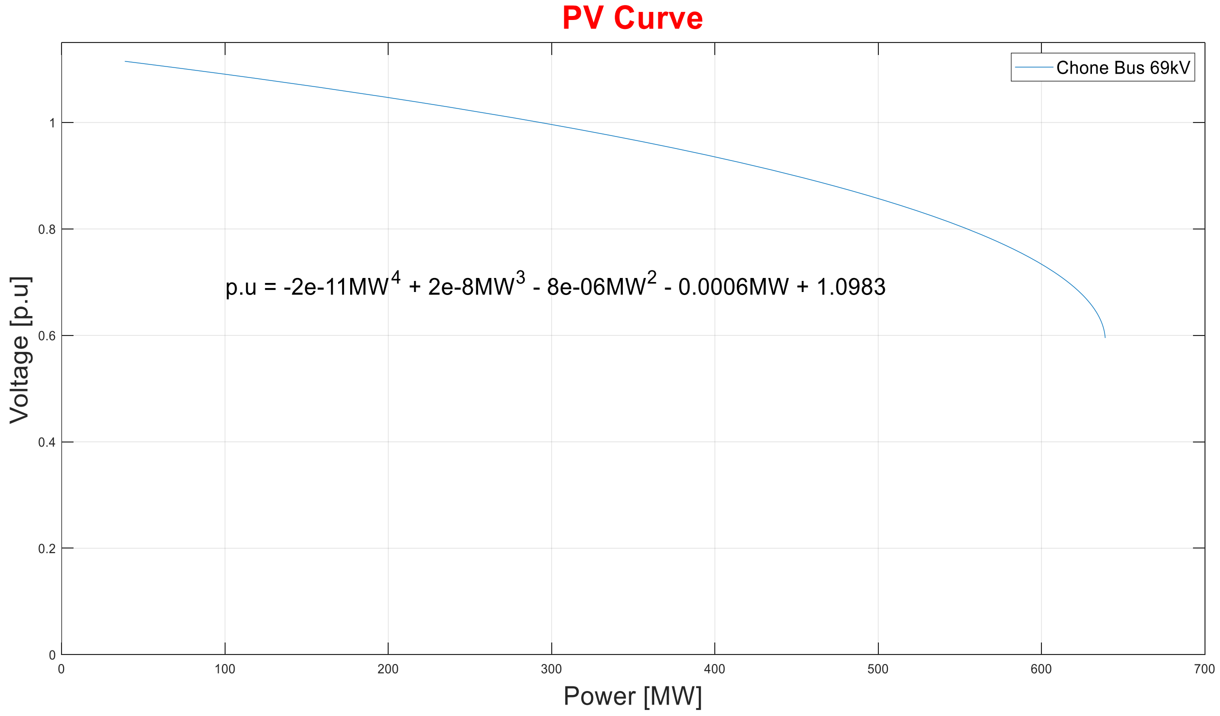

Fig. 11. PV Curve of the 69 kV Chone Bus

Where P_{req} is required power; P_{crit} is critical or maximum voltage unsteady power; P_{eval} is evaluated power. For our case study 0.9 or higher.

The critical curve, in this case the 69 kV Chone Bus, is presented in Figure 11:

Analysis results in a variation of 185.667 MW, it is possible to choose a range between 1.2 and even 1.5 of generation surplus, considering that this raises the cost of the installation [82]; for our case a range of 25% will be considered, therefore, the cost of the installation will be higher [83]:

$$P_{pv} = 1.25 * (P_{req}) \tag{11}$$

$$P_{pv} = 1.25 * 185.667\ MW$$

$$P_{pv} = 232.084\ [MW]$$

Where P_{pv} is photovoltaic Power and P_{req} is required power.

Assuming a unitary power factor with a purely resistive load, it is possible to move the critical power to 862.316 MW with a voltage value of 0.761 p.u., this value is obtained due to the little or almost null presence of reactive power, representing the reactive generation a fundamental part of the generation.

Nowadays power inverters have adaptive power factor functions, which can be configured by a trained user in order to manipulate the reactive injection in the network, this is due to its topology similar to the static reactive generators or SVG [84]. Two scenarios may be observed in Figure 12, it is necessary to evaluate the critical point of collapse in the "corrected" scenario by inserting the photovoltaic plant, where it is noticeable that the initial analysis point at 639.006 MW has a value of 0.595 p.u to 0.930 p.u, therefore the PV curve has been taken to a stable operating point in the case of the 69 kV Chone busbar.

It should be pointed out that the analysis of reactive compensation goes far beyond the scope of this study and will remain as future research to complement this article.

4.2 Photovoltaic power plant

Using the data obtained in Digsilent Power Factory, we proceeded to perform the photovoltaic dimensioning, using the same type of field and control equipment to observe the annual irradiance in the different geographical locations of Chone, with the results shown in Table 4.

For equipment selection, the criterion of minimizing the number of equipment to be installed were used, and those that fulfilled this requirement selected. It should be noted that the selection was made using the criterion of stationary panels at 8° in which the software reduced the losses to the maximum.

In Table 5, the results of the losses and the energy generated by each solar photovoltaic park are detailed.

The different geographic scenarios show the difference in production between the different points, resulting in a higher production in the Chone bar, product of the irradiance levels in its location.

Table 4. Summary of elements used in the photovoltaic solar park

	Sesme	Chone	Chone ST*	Severino
Installed peak power MWp	232.1	232.1	232.1	232.1
Inverter rated power MWca	178.7	178.7	177.8	178.7
Modules number	JKM585M-7RL4-V	JKM585M-7RL4-V	JKM585M-7RL4-V	JKM585M-7RL4-V
Number of PV modules	396725	396725	396725	396725
Inverters Model	Sunway Skid 8000-620	Sunway Skid 8000-620	Sunway Skid 8000-620	Sunway Skid 8000-620
Inverters Number	26	26	23	26

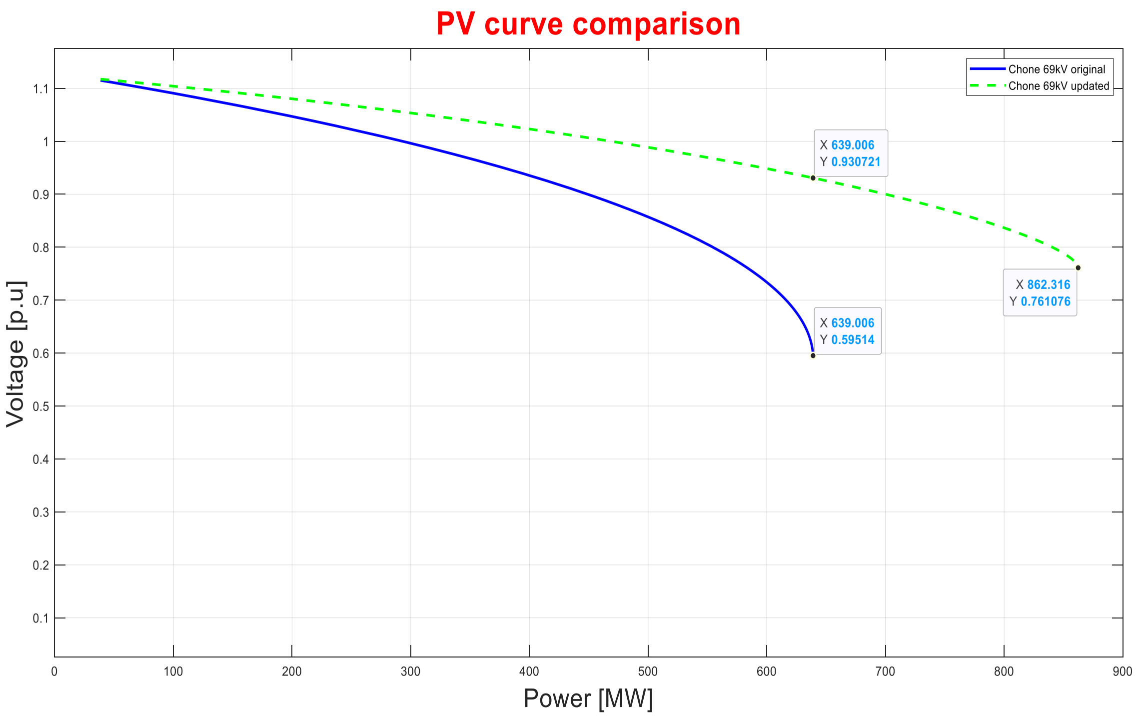

Fig. 12. Comparison of results at the 69 kV Chone Bus Station

Table 5. Results of production obtained in the four geographic scenarios

	Sesme	Chone	Chone ST*	Severino
Produced energy	298207806	300039575	290432517	291700756
Utilized energy	1301163096	1301163096	1301163096	1301163096
Specific production	1285	1293	1251	1257
Yield ratio %	80.43	80.41	78.18	80.97
Solar fraction %	22.52	22.69	21.99	21.89

Subsequently, the energy used remains theoretically the same because of the number of panels that conform the photovoltaic array and the equipment to be used.

The specific production of the plant is associated with the energy produced over the theoretical power at which it is dimensioned. The most important result obtained is the yield ratio, in which Severino's bar, according to their characteristics (location and irradiance), has a performance slightly higher than the one of the array under study.

Analysis is essential to visualize, as shown in Figure 13, The difference between monthly production during a year, with production peaks in the months of March, April and May, totally opposite to low production months such as August, September and October.

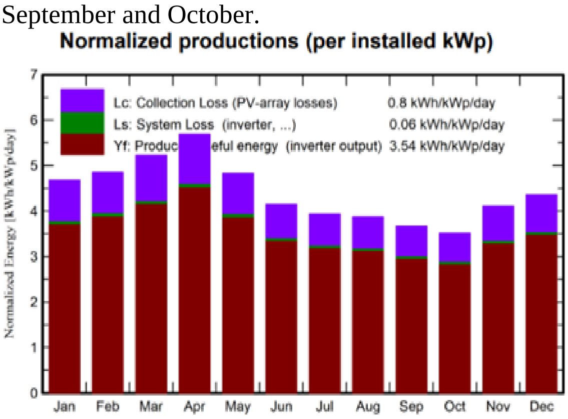

Fig. 13. Results of the Chone bar, which has the highest production of the scenarios analyzed

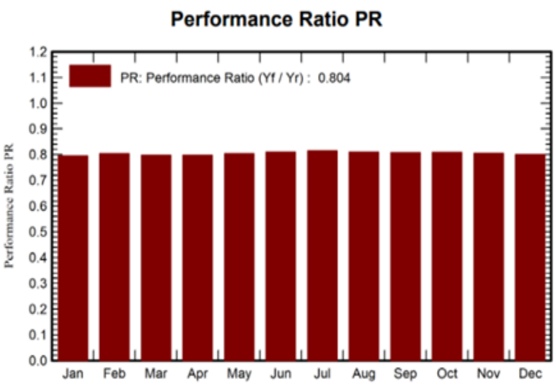

Fig. 14. System yield For Chone Bus Bar

Furthermore, Figure 14 shows the equity in yields during the months of the year for the Chone busbar

Although the highest energy production levels in all scenarios are in April and the lowest level is in September for Chone, Chone de Subtransmisión and Sesme, but in the case of the Severino substation it is in October.

The energy production results for the Chone sub-transmission busbar are shown in Figure 15.

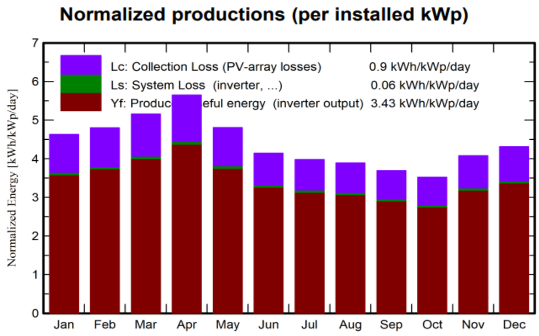

Fig. 15. Results of the Chone sub-transmission bus

Observing Figure 16, it becomes apparent that the system performance in this scenario is below 0.80, signifying its classification as the least favorable scenario.

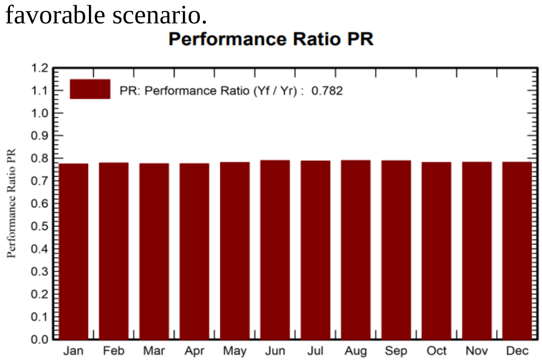

Fig. 16. Results of the Chone sub-transmission busbar

The results for the Sesme busbar are shown in Figure 17. In general terms, the Sesme busbar is the second ideal location for the implementation of the photovoltaic plant.

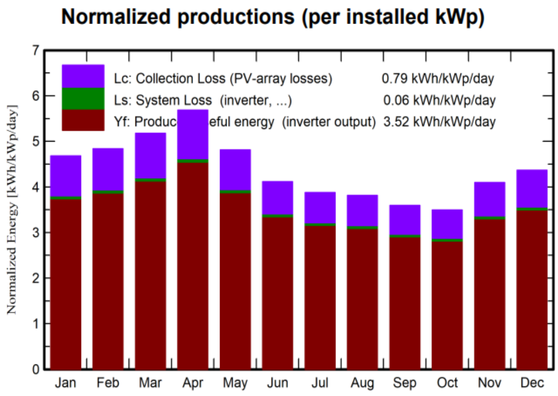

Fig. 17. Energy production results of the Sesme busbar

Figure 18 shows that the average yield for the Sesme bar is above 0.80 and shows a better balance in terms of monthly yield.

In Figure 19 we can appreciate the Severino busbar scenario, which represents through the particle swarm algorithm was determined to be the best option for the implementation of the photovoltaic park.

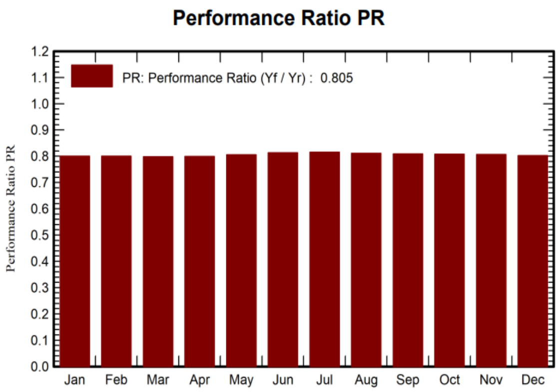

Fig. 18. Sesme busbar performance results

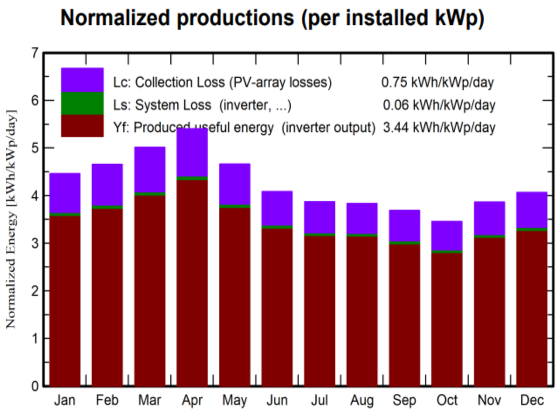

Fig. 19. Energy production results of the Severino busbar

As shown in Figure 20, the performance of the Severino scenario is superior to the other scenarios evaluated; therefore, the algorithm used indicates it as the best option for the implementation of the photovoltaic park.

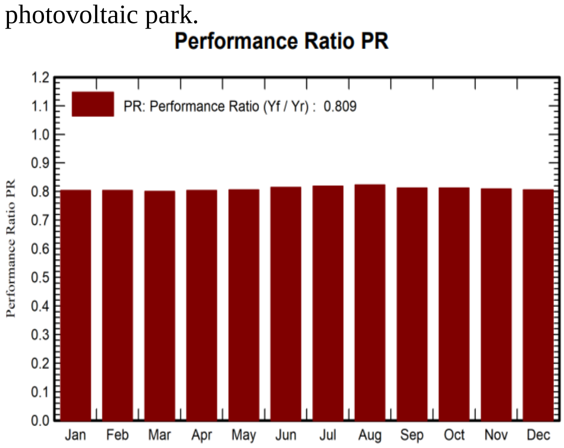

Fig. 20. Severino busbar performance results

Regarding the design, within the solar photovoltaic park there are variants ranging from 0.440kV to 13.8kV systems and its subsequent conversion to 69kV or directly from 13.8kV to 69kV, it is possible to have up to 20kV at the output of the inverter according to its model, therefore having to go through a conversion to 69kV [85], thus changing our injection point in the one-line diagram in Figure 21.

Groups or strings of the S/E Chone where the injection point might change depending on the type of design to be carried out. Considering the example of the Bhadla substation in India, substations could be built for each string or group [86], as shown in Figure 22, which could inject energy to the required busbar.

Considering the example of the Bhadla substation in India, substations could be built for each string or group [86], as shown in Figure 22, which could inject energy to the required busbar.

For this, the losses must be considered because of the transformer sets, calibrating the inverters with different levels of reactive compensation.

Considering the conductors, traditional copper can be used or transport technologies such as blindobars can be implemented [87], which demonstrate lower losses in terms of voltage drop, hysteresis and can be easily coupled to the needs of the PV park [88]. The use of a hybrid copper-aluminum transport technology is possible depending on the design [89].

4.3 Optimal location of the PV solar plant

Using the data entered in terms of performance and equipment, the algorithm determines that the optimal site is at the Severino substation. This confirms the idea that could be generated in the PvSyst software that this would be the most profitable site, due to its irradiation characteristics.

The power shown is the design power of the solar photovoltaic plants. The analysis of the candidates is

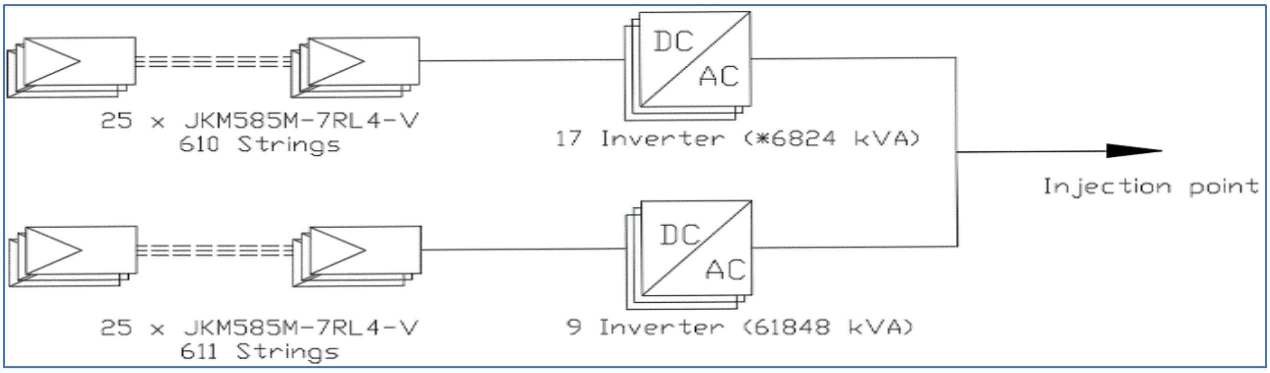

Fig. 21. Groups or strings of the S/E in general form

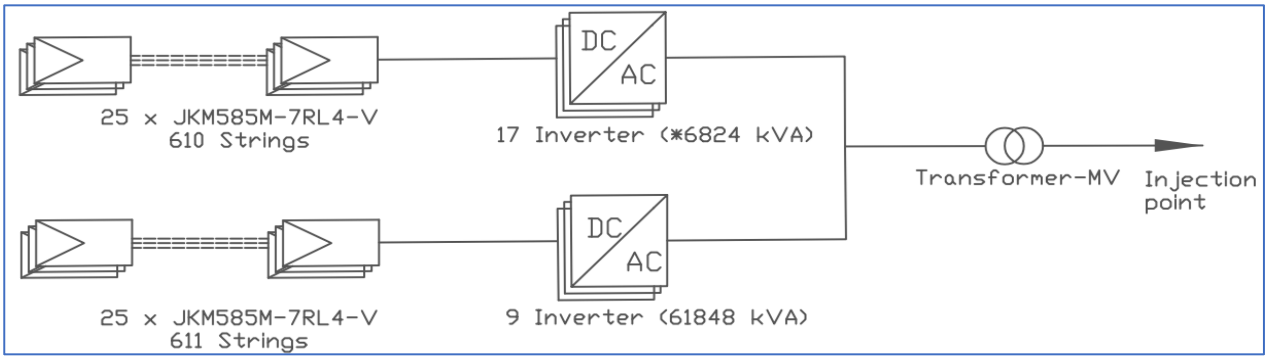

Fig. 22. Groups or strings of the S/E Sesme, including transformer for its subsequent transition to 69kV

```
Optimization ended: relative change in the objective value
over the last OPTIONS.MaxStallIterations iterations is less than OPTIONS.FunctionTolerance.
Scenario Sesme: Yield 80.43, Power 232.10 MW
Scenario Chone: Yield 80.41, Power 232.10 MW
Scenario Severino: Yield 80.97, Power 232.10 MW
Scenario Chone_ST: Yield 78.18, Power 232.10 MW
The optimal scenario is: Severino
```

Fig. 23. Matlab algorithm visualizing the optimal scenario. Severino substation

visualized in the command window, as shown in Figure 23, when the algorithm is executed.

In graphs 23 and 25, obtained by Matlab, the iterations performed by the particle swarm algorithm were obtained. The iterations were kept in a range between 0 and 22, performing variants from 0 to 21, however, the proposed number of iterations was 100, finding the optimal evaluation result much earlier, due to the extension of the problem.

The bar graph shown in Figure 24 highlights the optimal location found with a yield percentage of 80.97%. It is important to highlight that in the same way there is no difference greater than one unit in three of the scenarios analyzed, however, being Chone de Subtransmisión the one with the lowest performance rate, which is 78.18%.

We can visualize in the figure 25 the particle s warm graph, showing the different scenarios in comparison to the power, annual production and performance, where the Severino substation is the most important.

5. DISCUSSIONS

This article can be divided into three main topics: the electrical power system, renewable energy through photovoltaic systems and optimization to determine the ideal location.

The chosen scenarios were based on substations of the Manabí electrical system, which, having different levels of irradiance, gave the results obtained and can be replicated in other geographical locations, simulating its network to determine the lack of generation and the instability of the system, following the methodology used in this study.

Regarding the electric power system: It was possible to corroborate the results obtained by authors Santillán and Peña concerning the need to install a power plant in the critical bar of Chone. A study of the QV curve should be carried out, analyzing the impact of the power plant on Manabí's

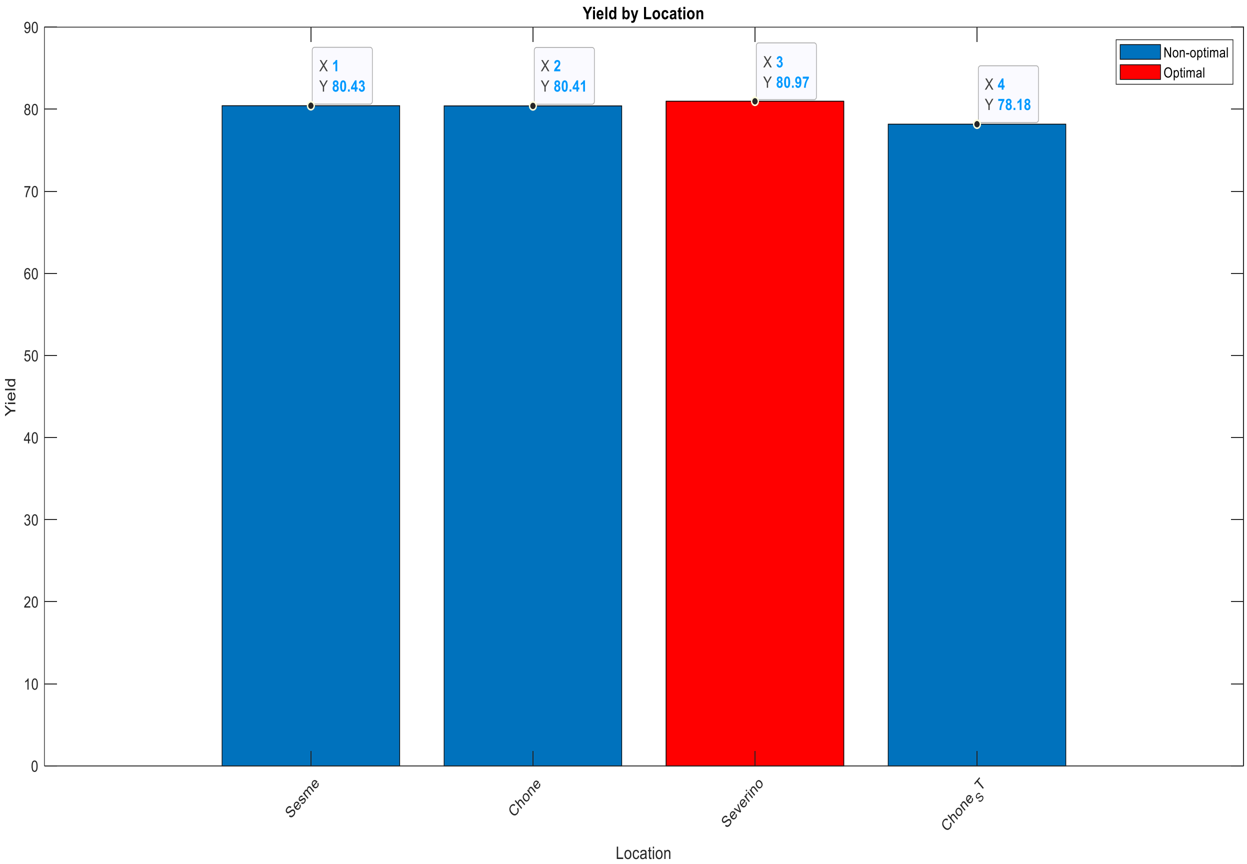

Fig.24. Yields of the scenarios, with the ideal scenario shown in red

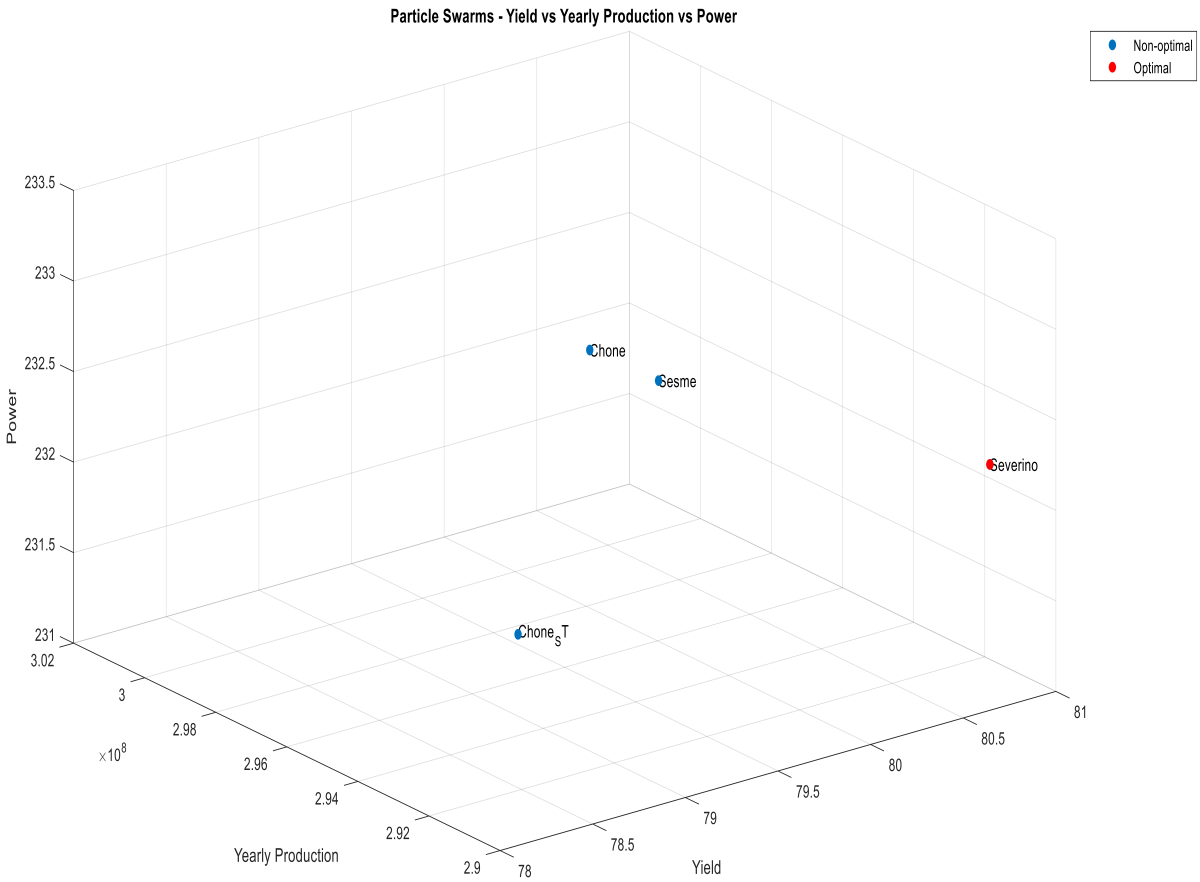

Fig. 25. Graph showing the evaluation of the parameters entered indicating that the Severino substation site is the optimal site

electric system. Similarly, the study of the insertion of capacitive and inductive reactors to the network that were not covered.

The photovoltaic analysis was performed with the same model of equipment, using the least number of them, however, the plates or panels used in the simulation were of monofacial type, but in recent years bifacial technology has been developed, which may allow us to save physical space and budget. It is possible to perform a technical-economic analysis on the implementation of the solar photovoltaic system, both monofacial and bifacial, within which parameters such as the geographic area to be occupied, cost and investment recovery would enter.

Similar situation of the previous paragraph is presented with the power inverters, it would be necessary to redesign the network with these new elements and make the comparative results taking the present study as a reference.

Furthermore, it is possible to reduce or increase our generation margin or surplus, which will allow us to minimize or maximize among several points: the number of equipment, project costs, geographic area of analysis, among others.

Considering the topics addressed in this section, with one of them focusing on the technical-economic analysis or evaluation of the equipment to be used, the possibility of field implementation of the stability study is opened. This process involves taking into account the significant economic investment required for the technical aspect, as well as other factors such as environmental, legal, administrative, export, and other relevant aspects.

The execution of the stability study entails a careful consideration of various aspects. Among them, the need for a detailed technical-economic analysis to assess the equipment to be used is emphasized. This step is crucial, especially given the magnitude of the economic investment required for technical implementation. In addition to the financial perspective, additional factors such as environmental, legal, administrative, and export aspects must be taken into account, all of which play an essential role in the success and viability of the project. We should also mention that the same analysis should be applied to the 138 kV Chone busbar. In our modeling of the Manabi province network, this bus occupies the second place in terms of the 'criticality' of its stability point. It has a voltage of 0.602 p.u with a collapse power of 639.006 MW. This situation opens a new case of analysis at another voltage level. The correction of these issues will significantly improve the stability of this province. It would represent a better use of energy transmission.

Based on the previous paragraph, it is important to mention the importance of the administrative part of these power plants, in which the timely management of maintenance will allow taking preventive actions regarding the preservation of the Power System components.

Within the field of electrical protections, it is of vital importance the correct coordination of the protections in the medium voltage switchgear to be used in the elevator type substation that is in charge of delivering the generated energy to the grid.

6. CONCLUSIONS

The present study has demonstrated that it is possible to insert a power plant or photovoltaic system in an operating power system, following the analysis and verification procedures by means of algorithms, measurements and simulations from which it has been possible to reach an optimal point in which it is possible to insert such plant, improving the stability of the system, when initially it had a critical power of 639.006 MW at 0.596 p.u, is taken to a new collapse point of 862.316 MW at 0.761 p.u; with the insertion of the photovoltaic plant the previous collapse point of 639.006 MW has a value of 0.930 p.u, being above 0.9 p.u, therefore the PV curve has been taken to a more stable operation site in the case study of the electric system of Manabi.

Based on this point it is possible to make new designs following the methodology of the present work of the elevation substations, as mentioned above, the substations of Chone can take values ranging from 0.440/13.8 kV and 13.8/69 kV or directly from 13.8/69kV. The number of strings proposed by the software indicates that the 20/69kV connection can be made. It provides several points of analysis that can cover: insulation coordination, transformer selection, instrumentation and metering, protections, grounding systems, etc.

The optimization has several points for its development that initially can change the variables by choosing another type of design or equipment, until using another type of optimization method or algorithm, which may require other study variables in the case of simulating new scenarios such as load points or using multi-objective optimization in the case of analyzing a specific distribution network.

The design shall depend on the needs or specifications of the SEP's and also on the budget or the purchasing or monetary capacity of the administrator of the power system under study, thus generating new lines of future research.

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