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Estabilidad de tensión en una red de 115 kV con integración de generación fotovoltaica

Voltage stability in a 115kV network with the integration of PV generation

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Resumen

Este artículo tiene como finalidad modelar el sistema de potencia de la Electrificadora del Meta (EMSA), analizar eventos ocurridos durante la integración de generación distribuida y realizar un estudio de estabilidad de tensión en estado estacionario con Digsilent PowerFactory. Para modelar el sistema se tomaron datos de equipos y eventos proporcionados por la entidad administradora del mercado eléctrico y datos internos de la electrificadora. Se realiza el estudio de estabilidad utilizando las curvas P-V y Q-V que limitan la demanda en el sistema de potencia. Los resultados permiten concluir que el factor más importante en la implementación de generación fotovoltaica a gran escala es la regulación de voltaje por parte del generador y es indispensable generar un manual de operación para coordinar la inyección o consumo de potencia reactiva, teniendo en cuenta la curva de capacidad declarada para minimizar las variaciones de tensión que sufren los clientes.

Palabras clave: DigSilent PowerFactory, estabilidad de tensión, generación fotovoltaica, variaciones de tensión, generación distribuida.

Abstract

The purpose of this article is to model the power system of the *Electrificadora del Meta* (EMSA), analyze events that occurred during the integration of distributed generation, and perform a stationary voltage stability study with DigSilent PowerFactory. To model the power system, data from equipment and events is collected from the electricity market administrators and the utility's internal information. The stability study is performed employing the P-V and Q-V curves that limit the demand in the power system. Results lead to the conclusion that the primary factor influencing the implementation of large-scale PV generation is the generator's voltage regulation and it is essential to have an operation manual to coordinate the injection or consumption of reactive power, considering the declared capacity curve to minimize the voltage variations experienced by clients.

Keywords: DigSilent PowerFactory, distributed generation, voltage stability, photovoltaic generation; voltage variations.

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1. Introduction

The increment in the penetration of PV generation can lead to alterations in the voltage magnitudes in transmission systems. Furthermore, the impacts of high levels of PV penetration on the stability of transmission systems depend on multiple factors as the system topology, the power demand and the perturbations studied [1], [2].

In Colombia, many network operators are investing in renewable generation projects to improve service quality or reach non-connected zones with access difficulties [3]. These investments represent a sustainable solution for decreasing the stress of the interconnected power system. Currently, with the projects that are in place and others already approved by the *Unidad de Planeación Minero-Energética* (UPME), renewable generation tends to cover the totality of the power demand in some regions.

The *Electrificadora del Meta* (EMSA) is a network operator in charge of transmission, distribution and commercialization of electric energy in the Meta Department, Colombia. Currently, EMSA's PV generation represents approximately 44 % of the Department's power demand and an expansion is projected given the projects approved by the UPME. Since the integration of PV generation at a large scale some negative events have been evidenced in EMSA's power system: transmission lines and transformers overloading, low voltage reported by non-regulated clients, voltage variations correlated with weather variations, and variations in power flows.

This article presents an evaluation of the impacts generated by the integration of large-scale PV generation in the EMSA's power system, aiming to provide the network operator with criteria to mitigate negative events such as changes in the power flows [4], voltage instability [5], [6], protection incorrect triggers [7] and power quality issues in general. In such a way guarantee that the system variables are within the technical limits, which leads to an appropriate operation and improvement of the power quality in the region.

A series of events that took place in EMSA's power system related to voltage stability are analyzed by recreating them through simulations, providing possible causes and prevention for future secure operation. Furthermore, a methodology for assessing the stationary voltage stability is applied where the load margin and the reactive power are evaluated at each bus when generation and load vary according to a pattern [8]. This process allows establishing criteria for evaluating the connection of new renewable generation projects and mitigating voltage variation events that generate sustained interruptions, to improve the quality of the power supplied.

2. Methodology

The methodology of the study consisted of three main stages that comprise the collection of the data from the power system for developing its model on Digsilent PowerFactory, the analysis of events related to voltage stability, and the assessment of stationary stability. Figure 1 shows a general flowchart for the methodology.

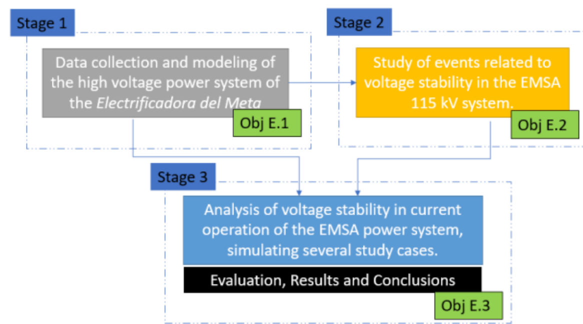

Figure 1. General flowchart of methodology. Source: Authors.

2.1. Data collection and modeling

The data from transmission lines, transformers, PV generation and other equipment was collected from XM's *Paratec* [9] and EMSA directly on site. The average and maximum power demand data employed was collected in 2022. The regional transmission system (STR) is modeled mainly at 115 kV.

2.2. Analysis of events related to voltage stability

The analysis is based on reproducing events that lead to sustained service interruptions or voltage variations. This information was collected from the historical logs of interruptions and events from the SCADA for local events, and the events in the STR are collected from XM's *Herope* [10].

2.3. Assessment of stationary voltage stability

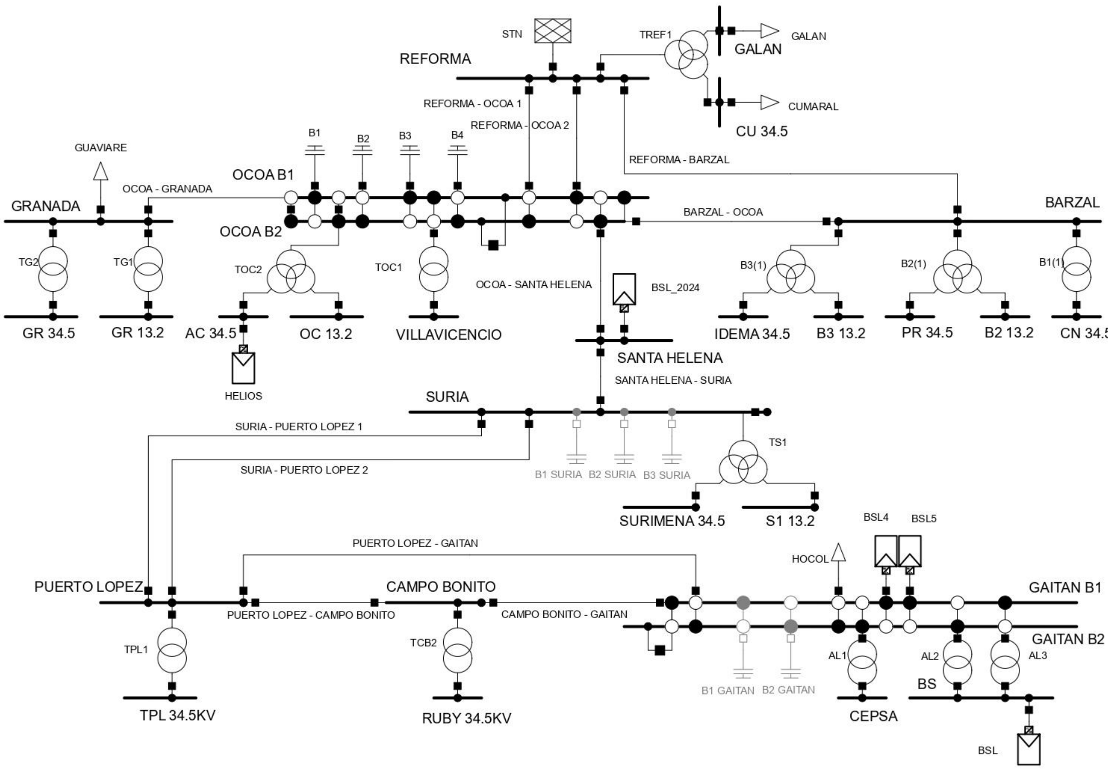

Figure 2. EMSA's power system one-line diagram in 115 kV. Source: Authors.

The assessment is based on the relationship between the nature of the load and active power flows in the power system, which affects the voltage at the buses. With the PV curves, we determine the maximum active power that can be delivered by transmission lines, the critical node and the load limit to operate without losing voltage stability in steady state. Next, we evaluate the reactive power at transmission lines and its relationship with the voltages in the power system.

DigSilent PowerFactory allows obtaining the PV and QV curves for each node in the power system in a particular operating condition, then the critical node and the operating limits are evaluated in steady state and after a perturbation. The curves are evaluated in terms of the criteria for tension stability $\left(\frac{dQ}{dV}, \frac{dE}{dV}\ y\ \frac{dQ_S}{dQ_L}\right)$ [6], and the results are compared with real scenarios.

Finally, with the results of the case study, we provide a set of premises for guaranteeing EMSA's operation under the voltage limits and avoiding situations that can lead to instability. We also provide recommendations for acting over undesired events to improve the time for service recovery.

3. Case study

In this section, a general description of EMSA's power system is provided as well as the particular events that have been caused by the integration of PV distributed generation. These events include voltage variations, changes in power flows, and reactive power consumptions (and injections) by generation. Finally, the scenarios for the voltage stability study are defined considering the load of the power system, the future expansion of the distributed generation, and contingency analysis.

3.1. Description of EMSA's power system

EMSA's power system has nine substations in 115 kV, as shown in Figure 2, and Table 1 shows a summary of the elements that were considered for the case study. The Reforma substation is the point of connection to the Colombian National Transmission System (STN), from there, three transmission lines come out, two lines go to the Ocoa substation, and one to the Barzal substation.

Table 1. EMSA's Power System Overview.

Element	High Voltage (115 kV)	Medium Voltage (34,5/13,2 kV)
Transmission Lines	11	136
Nodes	9	40

Power Transformers	14	43
PV Generation	2	2
Loads	2	94
Capacitors	9	0

Source: Authors.

Reforma substation has a 30 MVA three-winding transformer that supplies power in 13.2 kV and 34.5 kV. Barzal substation has two 40 MVA power transformers that supply power in 13.2 kV and 34.5 kV as well. Ocoa substation (double bus) has two 40 MVA power transformers and four capacitor banks, with 12.5 MVAr each. These three substations form the Reforma-Barzal-Ocoa ring.

Ocoa is connected through transmission lines with Granada and Santa Helena substations. Granada has two power transformers (30 MVA and 20 MVA), that supply power to Guaviare Department. Santa Helena is currently connected with the Suria substation and it is projected to connect with the STN. Suria substation has a 30 MVA three-winding transformer and three capacitor banks with 12.5 MVAr each, and it is connected with the Puerto López substation through a couple of lines.

Puerto López substation has a 13.75 MVA power transformer that supplies power in 34.5 kV, and it is connected with the Campo Bonito substation through a transmission line. Campo Bonito has two power transformers, with 45 MVA (currently out of service) and 13.75 MVA, and it is connected to the Gaitán substation. These three substations conform the ring Puerto López – Campo Bonito – Gaitán. Finally, the Gaitán substation (double bus) has two compensation banks with 5 MVAr each, and two parallel 30 MVA transformers that intake PV generation and supply power in 34.5 kV.

3.2. PV distributed generation in EMSA's power system

Currently, at the Gaitán substation, there are three 20 MW PV fields connected in 34.5 kV (BSL), and two 20 MW PV fields connected in 115 kV (BSL4 and BSL5), that is a total of 100 MW, the operator of these PV plants is Trinasolar. Helios PV plant with 10 MW is connected to the Ocoa substation at 34.5 kV, and it is projected to increase its installed power to 30 MW. Furthermore, the PV generation plant Catama is projected to have 100 MW installed at the Suria substation in 2024.

3.3. Events caused by the integration of distributed generation in EMSA's power system

In the following, several recent events that have occurred in EMSA's power system since the entry of PV generation are presented to predict the circumstances that can affect the voltage in the system and define analysis scenarios.

3.3.1. Voltage variation events

Voltage variations are the most common events in the presence of PV generation. Figure 3 shows an example of the voltage signals at the Gaitán substation, where the variations are evident. During the hours with PV generation, there is voltage control only on the a-b phase, and in the second peak of the power demand there is a voltage drop. Some of the registries of the most important events are described in the following:

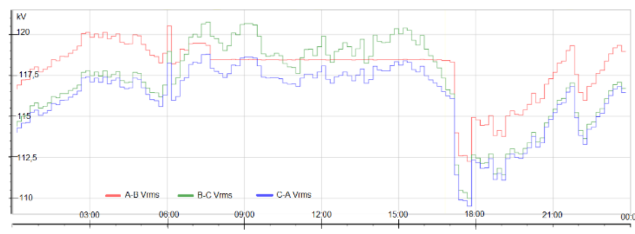

Figure 3. Line-to-line voltage signal at Gaitán Substation. Source: EMSA SCADA registry.

January 6, 2022: Generation in 115kV at Gaitán caused a drop in voltage below 0.9 p.u. Afterward, the National Dispatch Center (CND) commanded to connect compensation bank 1 at Gaitán and compensation bank 3 at Suria at 115 kV to raise the voltage profile in the zone. Minutes later, PV generation power increased to nearly 100 MW causing an increase in voltage over 1.1 p.u. and leading to disconnect the compensation bank 2 at Gaitán given the overvoltage.

August 18, 2022: Clients at Gaitán reported voltage fluctuations at 10:30 am, the day was sunny and the PV fields were generating 20 MW each with a power factor close to 1. The voltage at the Gaitán substation was 121 kV but the variation detected was approximately 2 kV.

September 29, 2022: The generation was at its maximum, and voltage variations were detected at Gaitán between 107 and 122 kV. The reactive power consumed by the PV generation was variable between 1 and 5 MVAr.

Voltage control implemented for each of the BSL4 and BSL5 plants

The BSL4 and BSL5 plants in the S/E Gaitán have implemented three control modes: Voltage, reactive power and Power factor [11], through the Plant Controller (PPC), currently voltage control by voltage is implemented.

- Only one control mode can be active
- Each control mode receives a voltage value as a reference which the plant will follow and maintain by injection or absorption of reactive power, once the respective control mode is enabled.
- The control of the plants (PPC) takes as reference the phase-phase measurement Vab from the commercial frontier meters.
- The injection of reactive power and active power is carried out in a three-phase balanced manner for each plant, but based on the amount of reactants required to maintain the setting of voltage with reference to the phase voltage indicated by the OR.
- The plants have declared the injection/absorption capacity curves of reactive power to CNO and CND, and these are approved according to agreements CNO-1599 [12] and CNO-1600 [13]. Relevantly, it is indicated that for operating voltages between 0.95 and 1.05 p.u. the plants will be obliged to deliver up to 6.567 MVAr for node voltage control purposes.

3.3.2. Power flow fluctuations

September 22, 2022. During a maneuver planned by the CND, the Campo Bonito–Puerto Gaitán transmission line bay in 115 kV should be disconnected and cleared. The PV generation was at its maximum, at the moment of opening the circuit breaker, two overcurrent events triggered the circuit breaker at the 115 kV busbar connection.

3.3.3. Reactive power consumption by PV generation

October 4, 2022. At 5:30 a.m. PV generation was 0MW, and voltage below 99 kV (0.86 p.u.) was detected at the Gaitán substation. A revision of system variables showed that PV plants BSL4 and BSL5 connected at 115 kV were consuming 10 MVAr each. Capacitor banks 1 and 2 at Gaitán were connected to regulate voltage; however, the reactive power consumption at BSL4 and BSL5 increased to 13 MVar each, leaving the voltage at the substation at 100 kV. Then capacitor bank 2 was connected at the Suria substation and the voltage decreased to 104 kV. Suddenly, Trinasolar disconnected BSL4 and BSL5 without coordinating with the CND or EMSA which caused an overvoltage at Gaitán that reached 126 kV. Finally, 115 kV capacitor bank 2 at Suria was disconnected and the voltage at Gaitán was regulated to 120 kV (1.04 p.u.).

3.4. Description of scenarios for the stability study

This Section describes the different scenarios for the voltage regulation and stability analysis. The selected scenarios consider peak generation and demand during the normal operation of the system, future entry of additional PV generation and contingencies.

3.4.1. Peak of PV generation

This scenario takes place at the first peak of power demand with the PV generation at its maximum. Helios PV plant generates 16 MW and Trinasolar generates 100 MW at the Gaitán substation. For simulating this scenario, the power demand is considered to be the average at noon, and four 12.5 MVAr capacitor banks are connected at the Ocoa substation (Normal operation instructed by the CND).

3.4.2. No PV generation available

This scenario is placed at the second power demand peak (6:00 p.m.), with the highest power consumption by the clients and no PV generation by Helios and Trinasolar. Given the configuration of the system, this scenario has the most loaded transmission lines and transformers, and the lowest voltages downstream. Also, four 12.5 MVAr capacitor banks at the Ocoa substation and two 5 MVAr capacitor banks at Gaitán are connected (Normal operation instructed by the CND).

3.4.3. Future expansion of PV generation

This scenario consists of projecting the entry of 100 MW of PV generation at Suria substation which is expected to happen in 2024. The simulation considers an average power demand at noon and four 12.5 MVAr capacitor banks connected at Ocoa.

3.4.4. Contingency analysis

This simulation considers the maximum PV generation and the average power demand. It evaluates events at each transmission line of the power systems, reducing the impedance to find the active and reactive power limits at the critical nodes to operate facing an N-1 event without losing voltage stability.

4. Simulation and analysis of events in EMSA’s power system

Some of the events described in Section 3.3 were simulated using DigSilent Powerfactory to analyze the behavior of the power system under realistic conditions affecting voltage regulation.

4.1. Simulation of voltage variation events

Initially, the simulation considers a sunny day with normal operation, four 12.5 MVAr capacitor banks connected at Ocoa, and voltage controlled at BSL in 35.2 kV. The voltage at Gaitán is 117 kV, the load of transmission lines does not exceed 30% and on average the load of transformers is 80%. However, the 30 MVA transformer AL2 at Gaitán is overloaded at 115% by the transference of PV power generated at BSL (Figure 4). This condition is not adequate since it can generate damage to the transformer.

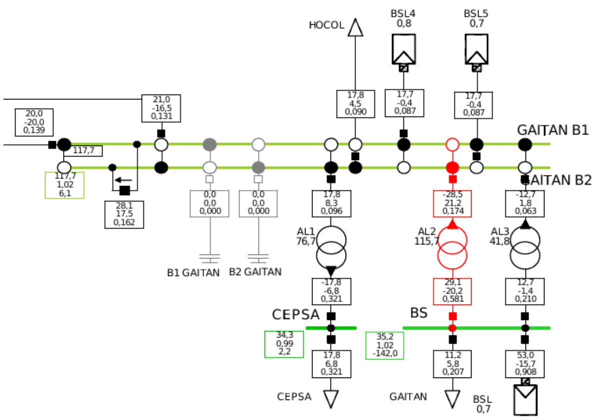

Figure 4. Power flows at Gaitán Substation during voltage variation event. Source: Authors.

Afterward, the same simulation is carried out without the PV generation and Ocoa's capacitor banks, keeping the voltage control at BSL. As shown in Figure 5, the voltage decreases to 110 kV (0.96 p.u.) but is still within the regulatory limits. Ocoa - Santa Helena transmission line reaches 60% of its capacity, and transformer TOC2 at Ocoa reaches 98.1%.

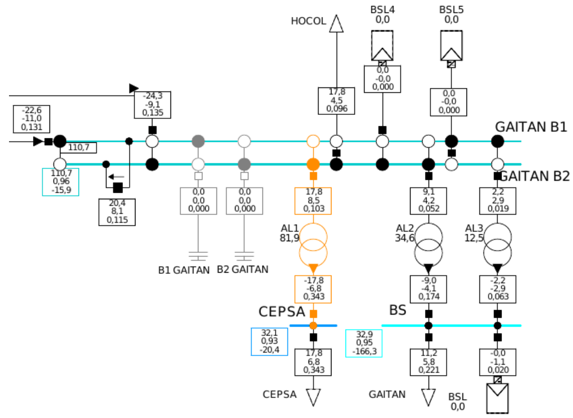

Figure 5. Power flows at the Gaitán substation without PV generation. Source: Authors.

When the same simulation is performed without voltage control at BSL, the voltage exceeds the regulatory limits, reaching 1.2 p.u. at Gaitán, and causing the disconnection of capacitor bank B1 by overvoltage (Figure 6). In addition, protection coordination triggers other loads connected to Gaitán (Hocol and Cepsa).

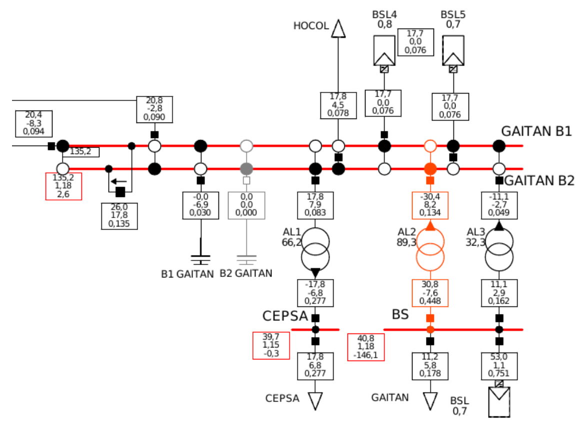

Figure 6. Power flows at the Gaitán substation without voltage control at BSL. Source: Authors.

The fluctuations in irradiance and by consequence in PV generation affect the voltage regulation, Figure 7 shows how the substation with the highest PV generation installed capacity, i.e. Gaitán, has the largest voltage variation. In the studied scenarios the voltage peak goes from 110 kV to 135 kV, surpassing the regulatory limit.

In this sense, it was necessary to establish voltage regulation guidelines for TrinaSolar. The guidelines implement a voltage control based on magnitude [11]. EMSA determines a reference voltage to be followed by the PV plant. The plant controller measures the a-b line-to-line voltage, and the injection of reactive power is done in the three phases. Also, the PV plants declare reactive power injection/absorption curves before the CNO and CND [12] [13]. The plant controller must guarantee the reference voltage even in periods with low PV power availability.

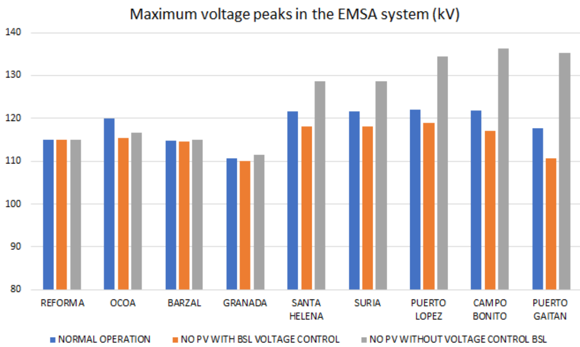

Figure 7. Maximum voltage in each simulated scenario. Source: Authors

4.2. Power flow fluctuations

A maneuver planned by the CND requires turning off and disconnecting the Campo Bonito – Gaitán transmission line as shown in Figure 8. The power generated at BSL4 and BSL5 should pass through the Gaitán substation transference switch. In this case, the current (178 A) surpassed the setting of the protection (170 A), since these power flow changes were not considered previously, which led to the trigger of the switch. Bus 1 at Gaitán was cleared disconnecting BSL4 and BSL5 and leaving loads Hocol and Cepsa without power. This event stresses the importance of considering the power flow fluctuations in the PV generation in the protection coordination.

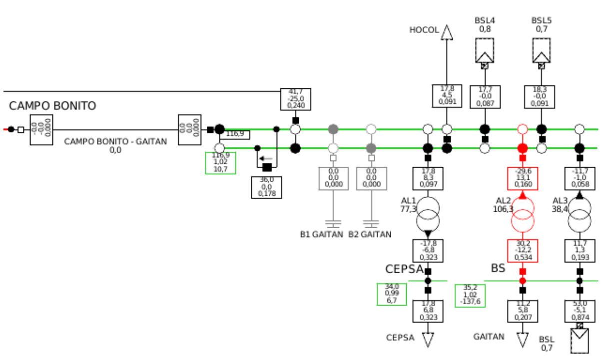

Figure 8. Power flows during the maneuver planned by the CND. Source: Authors.

4.3. Reactive power consumption by PV generation

With the PV generation in 0 MW, BSL4 and BSL5 operate as an inductor consuming 10 MVAr each. Figure 9 shows the voltage decreasing to 99 kV (0.86 p.u.) which is the low-voltage limit for the 115 kV buses.

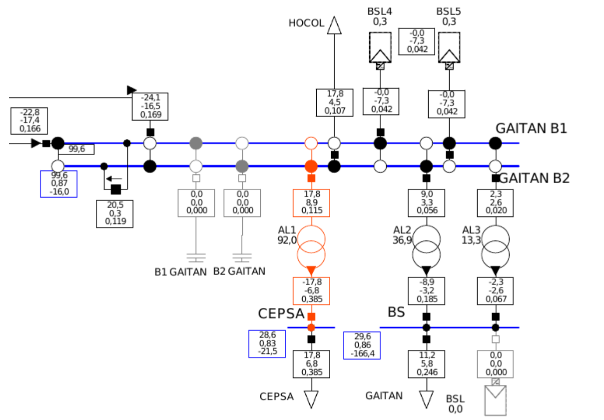

Figure 9. Reactive power consumption by BSL4 and BSL5. Source: Authors.

In this situation, the CND instructed to connect compensation banks B1 and B2 at Gaitán and B3 at Suria, which improved the voltage profile reaching 105 kV at Gaitán.

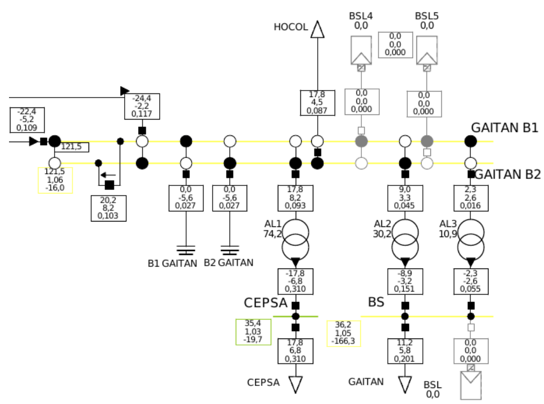

Figure 10. Disconnection of BSL4 and BSL5 by Trinasolar. Source: Authors.

However, an opening command was executed by Trinasolar disconnecting BSL4 and BSL5, which led to an overvoltage reaching 125.8 kV AT Puerto López substation. This situation led to the disconnection of the compensation banks at Suria and Gaitán with the CND. Given the lack of coordination between Trinasolar, EMSA and the CND, the clients connected to Hocol and Cepsa suffered an interruption in the service as shown in Figure 10. In this scenario, the PV generation operator must not allow the plant to consume reactive power from the power system to avoid voltage drops in the substation of connection.

5. Steady state stability study in EMSA's Power System

In this section, the P-V and Q-V curves of the power system are analyzed for the scenarios described in Section 3.4.

5.1. Analysis of P-V curves

The P-V curve is employed to find the maximum active power load that can be connected before exceeding the critical voltage stability point at a specific bus when the generation and load vary according to a pattern [6].

5.1.1. Analysis with peak PV generation

The P-V curves are determined for the scenario with the highest PV generation; in this case, the critical node is a 13.2 kV bus at the Ocoa substation and the active power stability limit is 498,1 MW with 0.52 p.u. voltage, as it is shown in Figure 11. In steady state, with approximately 0.9 p.u. voltage it is possible to handle 240 MW to observe the regulatory limits in terms of voltage. However, the power flow at this node is limited by the 40 MVA three-winding transformer TOC2. The next node with critical voltage is the 34.5 kV bus at the Ocoa substation with 0.67 p.u. and 497 MW, but its power flow is also limited by the upstream transmission lines and substation. Therefore, if the operating limits and ratings of transformers are observed, the power system is far from exceeding the stability limits under conditions of high PV generation available with the current installed power.

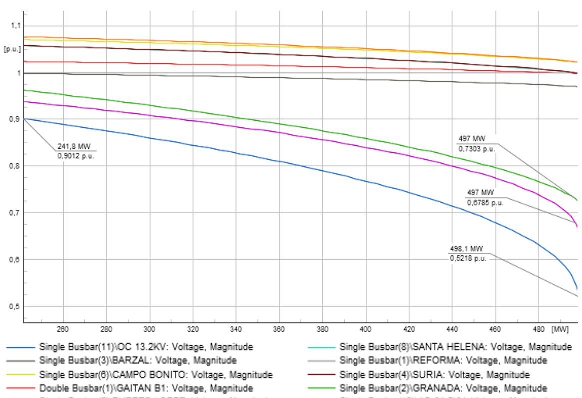

Figure 11. EMSA's power system P-V curves with PV generation. Source: Authors.

5.1.2. Analysis with no PV generation available

The P-V curves were determined again for the scenario with the maximum power demand and no PV generation available. It is evidenced that the behavior of the critical nodes changes decreasing the limits of active power (Figure 12). The critical node is located at Gaitán's 115 kV side, and the active power demand limit is 346.3 MW at 0.71 p.u. voltage, which is considerably lower than the previous scenario. This limit is similar at Suria, Puerto López, and Campo Bonito.

5.1.3. Analysis considering the future expansion of PV generation

When the future expansion of PV generation is considered, the P-V curves are similar to the scenario with peak PV generation. The critical node in this case is located at the Granada substation with 0.76 p.u. voltage and 501.8 MW, as shown in Figure 13. The power demand limit is increased by 2 MW approximately thanks to the additional PV generation.

5.1.4. Contingency analysis

The contingency analysis consisted of simulating failures in each transmission line of EMSA's power system and determining the critical power while clearing such failures. Table 2 shows the results of the critical node and critical power for each contingency. Results indicate that under contingency events, the Gaitán substation is in most cases the critical node.

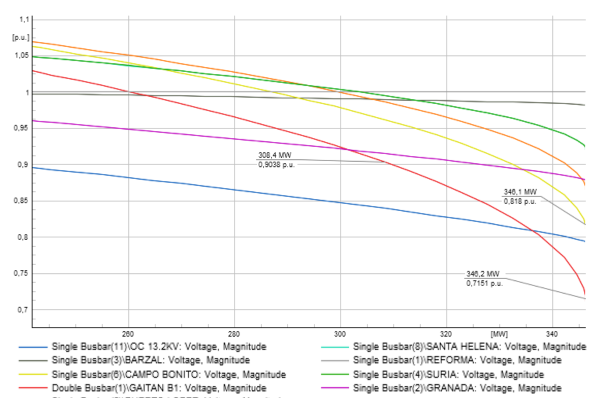

Figure 12. EMSA's power system P-V curves without PV generation. Source: Authors.

The worst-case scenario happens when the failure is located at the Puerto López – Campo Bonito transmission line, where the critical power reduces to 249.37 MW. Figure 14 shows the P-V curves before and during the failure, where the change given the new impedance of the power system during the failure is evident.

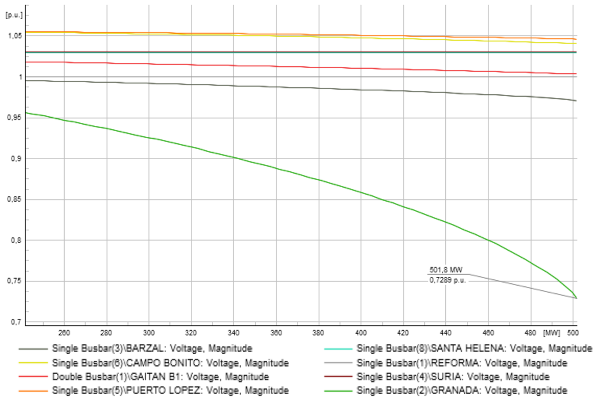

Figure 13. EMSA's power system P-V curves with the future increment in PV generation. Source: Authors.

According to all the P-V curves obtained from the simulation, Gaitán and Granada substations are critical nodes to guarantee steady state stability, depending on the studied scenario, Source: Authors.

Table 3 shows the summary of results from P-V curves.

When the PV generation is maximum, the Gaitán substation has a considerable capacity to supply load, therefore its active power limit is higher and the critical node is located at Granada. However, when there is no PV generation available and during simulated failures, the Gaitán substation is critical because it has the biggest voltage variation compared with the STN.

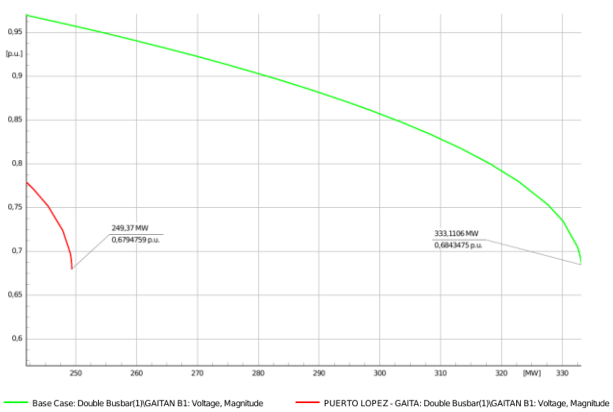

Figure 14. EMSA's power system P-V curves with PV generation for the most critical failure. Source: Authors.

Table 2. Critical node and power according to the failure event resulting from P-V curves in EMSA's Power system.

Contingency	Critical node	Critical power [MW]
Puerto López-Campo Bonito 115 kV	Gaitán	249.40
Puerto López-Gaitán 115 kV	Gaitán	306.90
Campo Bonito-Gaitán 115 kV	Gaitán	313.50
Suria-Puerto López 2 11 kV	Gaitán	321.40
Ocoa-Granada 115 kV	Gaitán	324.20
Suria-Puerto López 1 11 kV	Gaitán	324.60
Ocoa-Santa Helena 115 kV	Ocoa	351.70
Santa Helena-Suria 115 kV	Ocoa	353.10
Reforma-Barzal 115 kV	Gaitán	369.30
Reforma-Ocoa 2 115 kV	Gaitán	371.50
Reforma-Ocoa 1 115 kV	Gaitán	372.60
Barzal-Ocoa 115 kV	Gaitán	380.70

Source: Authors.

Table 3. Summary of results of P-V curves for different scenarios in EMSA's power system.

Scenario	Critical Node	Critical Power [MW]	Critical Voltage [Vp.u.]
Maximum PV generation	Granada	497.8	0.73
No PV generation available	Gaitán	346.3	0.71
Future expansion	Granada	501.1	0.76
Contingency analysis	Gaitán	249.4	0.67

Source: Authors.

Considering the regulatory limits for the voltage variation (±10%) [14], and the average power demand of EMSA's power system, there is a wide range for increasing the demand without exceeding the steady-state stability. Moreover, the ratings of transmission lines and transformers limit the power flow with a margin under the limits of active power determined by the P-V curves.

5.2. Analysis of Q-V curves

Q-V curve defines the reactive power capacity of a bus when subjected to voltage variations [15]. These curves were determined for the scenario defined in Section 3.4.

5.2.1. Q-V curves with peak PV generation

Initially, the scenario with the highest PV generation is considered for the calculation of the Q-V curves. Figure

15 shows some of the Q-V curves at medium voltage for this scenario, where the B3 node at the Barzal substation (13.2 kV) has the lowest reactive power capacity with 11.48 MVAr at 0.5 p.u. voltage. Nevertheless, the rating of the transformer that supplies this node is 10 MVA at the corresponding winding, which limits the reactive power capacity, and the maximum reactive power demand is 2 MVAr.

After analyzing the Q-V curves, the critical node is the BS node at the Gaitán substation (34.5 kV) given the reactive power that delivers and the behavior of the Q-V curve, with 24.8 MVAr of critical reactive power at 0.68 p.u. of voltage. The reactive power at this node depends on the power curve established by the CNO to regulate the voltage at the PV generation (Currently a minimum of 6.56 MVAr).

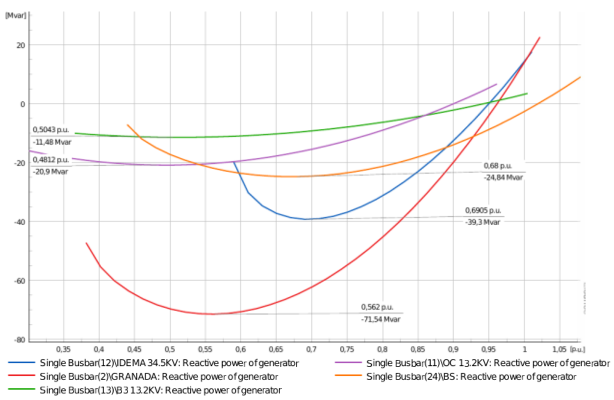

Figure 15. Q-V curves for the scenario with the peak PV generation. Source. Authors.

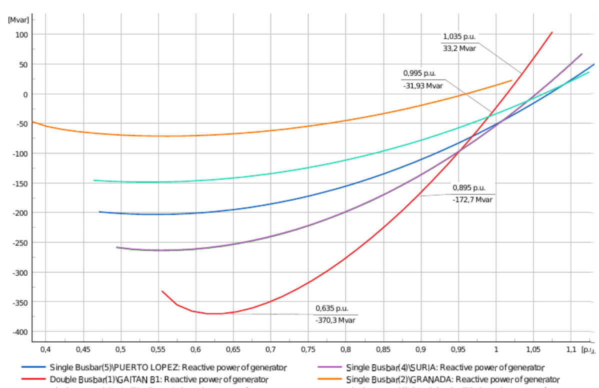

Figure 16. Q-V curves for the scenario with the peak PV generation at 115 kV. Source: the authors

Although the node Idema at Barzal substation (34.5 kV) presents a steeper change in the reactive power capacity, it is important to note that its load curve is residential with an average consumption of 6.8 MVAr and the rating of the transformer that supplies it (B3) is 30 MVA at the corresponding winding.

Figure 16 describes the behavior of the Q-V curves at 115 kV nodes, which is important to study given the entry of future PV generation projects and the presence of compensation banks that can affect the voltage stability. It is noted that the Granada substation is critical with 75 MVAr of reactive power capacity at 0.55 p.u. of voltage and the Gaitán substation has the highest reactive power capacity with 370.3 MVAr at 0.63 p.u. of voltage. This shows there is a wide range of reactive capacity in the 115 kV transmission system.

5.2.2. Q-V curves with no PV generation available

In the scenario with no PV generation available at 6 p.m., the Q-V curves are considerably different than the ones obtained with peak PV generation as can be seen in Figure 17. The reactive power capacity at the Gaitán substation (115 kV) decreased to 32.09 MVAr at 0.69 p.u. voltage, considering the PV connected to this node and two 5MVAr capacitor banks, it is considered critical at EMSA's power system with no availability of PV generation.

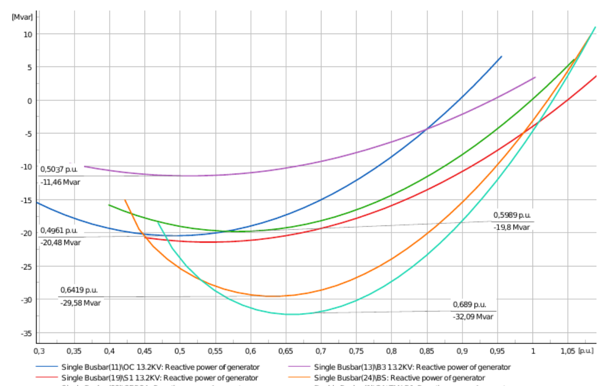

Figure 17. Q-V curves with no PV generation available. Source: Authors.

5.2.3. Q-V curves with the future expansion of PV generation

The Q-V curves were determined under the scenario that considers the installation of 100 MV of PV generation at the Suria substation. The curves (Figure 18) tend to remain unchanged (Compared with Figure 15) at the nodes upstream of where the PV generation is installed, for instance, the critical node at the Granada substation has a reactive power limit of -71.02 MVAr. However, the node BS at Gaitán increases its reactive power limit from 24.80 to 46.91 MVAr.

5.2.4. Analysis of Q-V curves under contingencies

After performing the analysis of Q-V curves under contingencies in the lines of the power system, the failure at the Campo Bonito – Gaitán transmission line produces a critical reactive power of -2.28 MVAr at Gaitán with 0.66 p.u. of voltage as it is shown in Figure 19. This critical behavior is caused by the change in the impedance of the power system after clearing the failure.

In addition, Figure 20 shows the Q-V curves at node BS and other medium voltage nodes, considering that CNO guidelines for voltage regulation establish the injection of 6.56 MVAr at Gaitán, this is below the critical reactive power at BS (8.86 MVAr).

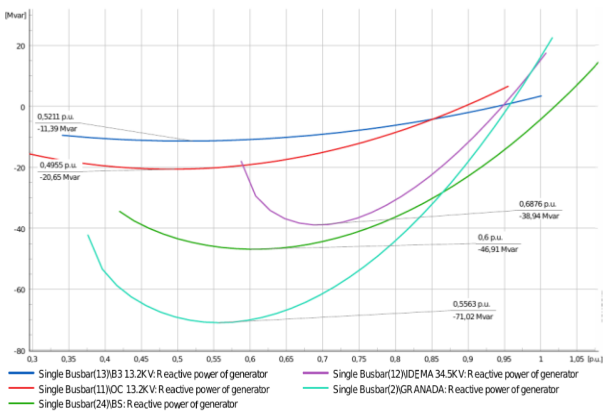

Figure 18. Q-V curves with the installation of future PV generation. Source: Authors.

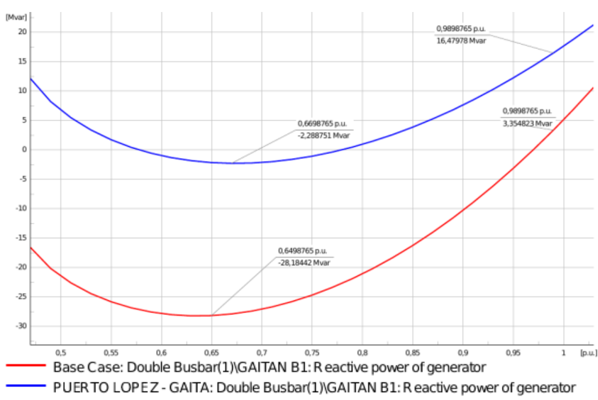

Figure 19. Q-V curves during the Campo Bonito – Gaitán failure at 115 kV. Source: Authors.

In summary, the critical nodes for all the studied scenarios are shown in Table 4. The selection of the critical node took into consideration the behavior of the load curve, the type of demand and the reactive injections, given that most of the load is residential and some of the nodes have exclusively residential load. It was noted that when increasing the PV generation at a node, the reactive power steady state stability limit in the nodes upstream is not affected, but this limit decreases in the connection node depending on the amount of generation and increases in the nodes downstream of such node.

The voltage stability limit at the Gaitán substation with no PV generation available decreases when the Campo Bonito – Gaitán transmission line fails, leaving an operating limit of 16.4 MVAr over 0.9 p.u. Considering that the reactive power that each BSL can deliver is 6.56 MVar [16], there is a possibility of a voltage instability event, under the following conditions: (a) Campo Bonito – Gaitán transmission line is offline and (b) the compensation banks at Gaitán substation are connected injecting more than 16.4 MVAr.

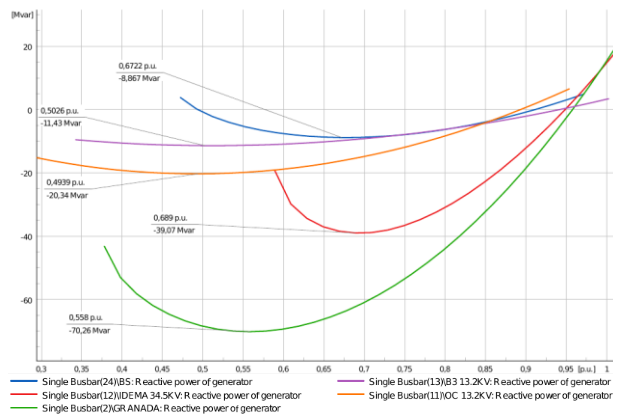

Figure 20. Q-V curves at 34.5 kV and 13.2 kV nodes during the failure at Campo Bonito – Gaitán with 6.56 MVAr at BS. Source: Authors.

Table 4. Summary of critical nodes resulting from the Q-V curve analysis.

Q-V Curves	Critical bus	Critical Power [MVAr]	Critical Voltage [Vp.u.]
Maximum PV generation	BS	-21.84	0.68
No PV generation available	Gaitán	-32.69	0.69
Future expansion	Granada	-71.00	0.55
Contingency analysis	Gaitán	-2.28	0.66

Source: Authors.

Therefore, it is recommended that the network operator keeps the voltage low at Gaitán during the rainy season without connecting the capacitor banks, and depending on the irradiance, coordinate with Trinasolar to keep the injections of reactive power at BSL4 and BSL5 under 10 MVAr.

6. Conclusions

Considering the events related to voltage stability simulated in EMSA's power system, it is concluded that there are technical aspects that must be considered in the integration of PV generation. Among them, are the inversion of the power flows, the coordination of protections, and the transmission lines and transformers capacity. These simulations are helpful to avoid interruptions, improving the power quality delivered to the users. Also, it is recommended to perform power flows in different cases when there are maneuvers at the points of connection of PV generation.

The results show how the voltage stability of the power systems is affected when there is an increase in the PV generation connected to the system. The entry of PV generation to a power system at 115 kV can decrease the inertia; however, it can increase the steady stability margins of active and reactive power.

One of the most relevant factors in the integration of large-scale PV generation is the voltage regulation by the generator. It is fundamental that the network operator and the generation are coordinated for the injection or consumption of reactive power, and comply with the regulatory bodies, such as the CNO.

7. Acknowledgement

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