Static Voltage Stability Analysis with the Integration of Distributed Generation: An Albanian Case Study

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Abstract: - Modern power networks face significant operational uncertainties that can threaten the stability of the power grid, due to the rising integration of distributed generation (DG), particularly from renewable energy sources, such as photovoltaic plants. The integration of distributed generation (DG) into power systems has become a pivotal factor in enhancing the efficiency and sustainability of electricity supply. This paper presents a detailed static voltage stability analysis of the Albanian power grid, focused on the effects of the Karavasta Photovoltaic Park, one of Albania's largest renewable energy projects. Using a combination of P-V and Q-V curves, V-Q sensitivity analysis, and modal analysis, the study reveals significant improvements in the system's voltage stability following the integration of the PV plant. The NEPLAN software is used for voltage stability analysis. Particularly, the reactive power margin at the critical node Nst. Babice increased considerably from -82.009 MVAr to -1061.2 MVAr, while the system's loading margin improved from 99.08% to 101.97%, demonstrating that the integration of large-scale PV generation enhances voltage stability by providing additional reactive power support and improving the grid's resilience to voltage collapse. Furthermore, the modal analysis identified the Bistrice-Delvine-Sarande buses as the system's weakest points, highlighting areas where additional reinforcement is required. As more renewable energy has to be integrated into the grid, the study also emphasizes the importance of making targeted interventions at critical buses and branches to ensure long-term stability. The results of this research are essential for Albania's energy transition as the country seeks to diversify its energy sources, especially solar power. More generally, the methodologies and results in this paper provide a suggestion for maintaining power system voltage stability with increased renewable energy penetration.

Key-Words: - Photovoltaic Plant, Distributed Generation, Voltage stability, Neplan, Comparison, Static methods.

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1 Introduction

The traditional electricity system is undergoing a tremendous revolution that is happening rapidly changing how it is controlled and operated. Historically, the traditional power system—especially in Albania—has mostly depended on a large number of synchronous generators to keep the grid's voltage and frequency stable. However, the operation and control of power systems are changing with the introduction of renewable energy sources, such as converter-based generators, [1], necessitating the development of new services, such as frequency control reserves, to ensure efficient and secure operation of power systems, and that presents challenges due to their impact on grid voltage levels [2]. Distribution and transmission system operators need to cooperate to fully understand the integration of renewable energy sources into the power system. Photovoltaic plants, installed in the presence of loads, can improve the quality and security of energy supply, reducing losses in transmission and distribution networks. Albania has great potential for this due to the high number of sunny hours per year, approximately 2700 hours/year. According to an IRENA study, by 2030, it is forecasted that photovoltaic plants with a capacity of 1074 MW will be installed, with an annual production of 1697 GWh, [3]. However, it is important to highlight that the inverters used for connecting photovoltaic plants have a low inertia constant, making them sensitive to network fluctuations, [1].

Distributed Generation (DG) is typically considered as electricity produced closer to the end point of use. DG units have been widely installed in demand systems and directly connected to distribution networks due to the fast development of DG technologies, [4], [5]. These systems can reduce power losses and delay investment in distribution and transmission expansion. Adequate size and optimal location are essential to achieving it, [6]. However, there are advantages and disadvantages to the DG connection in terms of environmental, technical, and economic aspects, [7]. A high level of DG penetration may affect the control and operation of the whole system, leading to technical consequences that must be determined, [8], [9]. Therefore, to avoid instability issues and guarantee an acceptable system voltage, such aspects need to be examined.

Problems related to voltage stability in power systems are one of the major concerns in power system planning and operation, [10]. Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all nodes in the system under normal conditions and after being subject to a disturbance, [11]. The electrical system is in a state of voltage instability, when there is a continuous and uncontrolled decrease in voltages at voltage buses, due to disturbances. This phenomenon is known as voltage collapse.

Voltage instability issues are examined through a variety of both static and dynamic analytical methods. The P–V and Q–V curves are widely employed tools for evaluating the static voltage stability limits of a power system [12], [13], and [14]. References [15] and [16] utilized the minimum eigenvalue of the power flow Jacobian matrix as an indicator of the proximity to voltage collapse. The concept of the energy function is employed in [17], [18] to establish a voltage stability index. Additionally, references [19], [20], [21], and [22] used a simplified equivalent circuit, derived from the Thevenin theorem, to evaluate the voltage stability limit of a power system. Although stability studies generally require a dynamic model of the electrical system, this paper focuses on analyzing voltage behavior through static techniques, which are commonly used in voltage stability assessments, [23].

The literature [24] gives a review of bus and line stability indices to monitor the level of voltage stability in the electric network. In [25] it is used MVSI indicator to identify the weak areas of electric power systems and predict the voltage collapse for different load conditions.

This paper is organized into seven sections. The second section provides a detailed explanation of the voltage stability static methods utilized in the case study. The third section presents an overview of the Albanian power system. The fourth section presents the case study itself. The fifth and sixth sections delve into results and discussions. Lastly, the seventh section presents the conclusions.

2 Static Methods

There are several methods to assess the voltage instability issue, and they can be generally divided into two groups: static and dynamic. The voltage stability methods that will be used in the examination of the Albanian power system are discussed in this section.

2.1 The P-V and Q-V Curves Methods

P-V and V-Q curves are generated through continuous load flow calculations. Prior to the calculation, several selections must be made: a group of loads and generators whose power will change during the calculation process within predefined limits, a group of bus voltages to be recorded, the loading rate at the beginning of the simulation, and the loading rate at the end of the simulation if the process is to be stopped before voltage collapse occurs, [26]. These methods fail to give useful information about the causes of voltage instability and it is not possible to precisely know the collapse point, [23].

2.1.1 The P-V Curves Methods

The P-V curves are the most commonly employed method for Voltage Stability Assessment. P-V curve analysis illustrates the relationship between active power transfer from a source to a load and its impact on load voltages. P-V curves are generated through a parametric study involving a series of AC load flow calculations, systematically monitoring changes in one set of load flow variables relative to another. This process determines transfer limits, accounting for voltage and reactive power flow effects. These curves are instrumental in identifying the loading margin of a power system, where the margin between the voltage collapse point and the current operating point serves as a voltage stability criterion. Figure 1 is depicted a P-V curve. As the load is gradually increased, there are computed power flows until reaches the P-V curve’s nose. At the nose point, additional load growth gives no feasible operating voltage magnitude, and it is the point when voltage collapse often occurs, [11], [27].

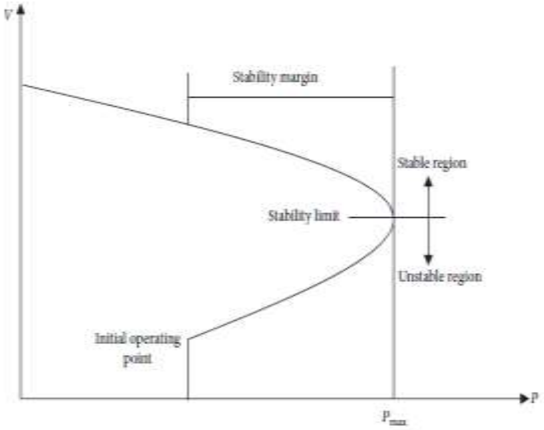


Fig. 1: P-V curve, [23]

For a P-V curve, the distance of active power from the operating point to the nose point of the curve is called the active power margin and is calculated below:

$$LM(P) = P_{critical} - P_{operating} \tag{1}$$

Where:
- $P_{critical}$ – the value of the active power of the P-V curve at the nose point
- $P_{operating}$ – the value of the active power of the P-V curve at the operating point

The voltage stability margin (VSM) of a bus is known as the distance between the initial voltage point and the voltage collapse point and can be calculated as below:

$$VSM = \frac{V_{initial} - V_{critical}}{V_{critical}} \tag{2}$$

Where:
- $V_{initial}$ – the initial bus operating voltage
- $V_{critical}$ – the bus voltage at the collapse point

2.1.2 The Q-V Curves Methods

By the Q-V curve method is possible to know the maximum reactive power that can be achieved or added to the weakest bus before reaching the minimum voltage limit. The Q-V curve can be used as an index for voltage instability. The point where dQ/dV is zero is defined as the point of voltage stability limit, [18]. Figure 2 depicts a Q-V curve. The operating point is where the curve intersects the x-axis, and the y-axis displays the amount of reactive power that must be injected or absorbed for a bus to operate at a specific voltage. A reactive power deficiency is indicated if the minimum point is above the horizontal axis, and more reactive power sources are required to avoid a voltage collapse situation [11], [27]. VSM is calculated as the equation (2).

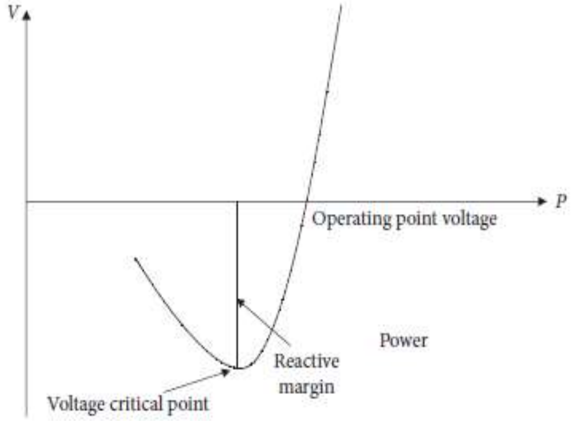


Fig. 2: Q-V curve, [23]

For a Q-V curve, the reactive power margin is the distance from the operating point to the nose point of the curve and is calculated as below:

$$LM(Q) = Q_{critical} - Q_{operating} \tag{3}$$

Where:
- $Q_{critical}$ – the value of the reactive power of the Q-V curve at the nose point
- $Q_{operating}$ – the value of the reactive power of the Q-V curve at the operating point

2.2 The V-Q Sensitivity Analysis Method

The V-Q sensitivity of a bus is the slope of its Q-V curve at a given operating point and can be determined much more swiftly than performing a full Q-V curve calculation. V-Q sensitivity analysis evaluates the relationship between voltage variations and changes in reactive power. The classical reduced Jacobian matrix provides extensive information regarding V-Q sensitivity, [11].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \cdot \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{4}$$

$\Delta P, \Delta Q$ – the mismatch of active and reactive power,
$\Delta \delta, \Delta V$ – the incremental changes in the bus voltage angle and magnitude,
$[J] = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix}$ – the Jacobian matrix.

The ith diagonal element of the matrix [J_{QV}] represents the VQ sensitivity of the load bus *i* when considering changes happen in active and reactive power. Letting $\Delta P = 0$, equation (4) becomes as below:

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = [J] \cdot \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{5}$$

$$\Delta Q = J_R \cdot \Delta V \tag{6}$$

$$J_R = \left[J_{QV} - J_{Q\delta} {J_{P\delta}}^{-1} J_{PV}\right] \quad (7)$$

where J_R is the reduced Jacobian matrix of the system.

So, in this way we can take the bellowed equation:

$$\Delta V = {J_R}^{-1} \cdot \Delta Q \quad (8)$$

The ${J_R}^{-1}$ is the inverse of the reduced Jacobian matrix and its elements represent the V-Q sensitivities. The self-sensitivities coefficients are the diagonal $\partial V_i/\partial Q_i$, and the mutual sensitivities are the non-diagonal ones $\partial V_k/\partial Q_i$ of the reduced Jacobian matrix. The signs of the sensitivity coefficients are used to assess system stability. If the sensitivity coefficients are positive, the system is considered to be voltage stable. Sensitivity coefficients indicate system stability, with smaller coefficients indicating stability. As magnitude increases, stability decreases, reaching infinite at the stability limit. Negative coefficients indicate voltage instability, [11]. For voltage-controlled buses, the sensitivity coefficients are zero, [11]. The limitations of this approach are that the linear characteristics of this method are not good, especially for complex power systems; hence, it cannot accurately reflect the critical state of a system, [23].

2.3 The Modal Analysis Method

The assessment of the system's voltage stability can be evaluated by calculating the smallest eigenvalues and their corresponding vectors of the reduced Jacobian matrix (7). Eigenvalues are related to voltage and reactive power variation mode. If all eigenvalues are positive, the system is considered stable in terms of voltage. The system's closeness to voltage collapse can be determined by measuring the magnitude of the smallest eigenvalues, [11]. It is represented by eigenvector matrices as shown in the following equation, [11]:

$$J_R = \zeta \cdot \Delta \eta \quad (9)$$

where ζ is the right eigenvector matrix of J_R, η is the left eigenvector matrix of J_R, and Δ is the diagonal eigenvalue matrix of J_R. From equation (9), the reduced Jacobian matrix J_R can be expressed as below:

$${J_R}^{-1} = \zeta\eta\ \Delta^{-1} \quad (10)$$

By calculating the bus participation factors, we can pinpoint areas of voltage weakness or instability. These factors indicate the amount that a bus contributes to a particular mode of instability, highlighting the potential effectiveness of countermeasures at that bus in stabilizing the mode. The bus participation factors reveal which areas are closest to voltage instability for all small eigenvalues. These factors help in identifying the voltage stability weakest areas and provide valuable information into the mechanisms underlying the loss of stability.

$$P_{ki} = \zeta_{ik} \cdot \eta_{\ ki} \quad (11)$$

The bus participation factor determines the contribution of λ_i to the V-Q sensitivity at bus k. A high value of P_{ki} at bus k for mode i means this bus is close to voltage instability in this mode.

The branch participation factors show which branches, in response to small variations in reactive load, absorb the most reactive power. High participation factor branches are typically weak or heavily loaded. The relative participation of branch j in mode i is given as below, [11]:

$$P_{ji} = \frac{\Delta Q_{loss}\, for\ branch\ j}{max\ \Delta Q_{loss}\, for\ all\ branches} \quad (12)$$

Generator participation factors illustrate which generators, in response to small variations in system reactive loading, provide the most reactive power. The relative participation of generator g in mode i is given as below, [11]:

$$G_i = \frac{\Delta Q_g^i}{\max \Delta Q_g^i} \quad (13)$$

Thus, these factors are crucial for understanding the distribution of reactive power reserves among generators, to maintain an adequate margin for voltage stability. The advantage of this approach is that it gives information about voltage stability status and the mechanism of instability. The limitation of this method is that eigenvalues do not provide an absolute measure of the proximity to voltage collapse, [23].

3 Albanian Power System Overview

The main challenge dealing with Albania's electric power system is that the production is based only on hydropower and the fast-rising demand for electricity. Figure 3 illustrates the energy demand and production from 2009 to 2022. We can see that the production of electric energy is strongly influenced by the hydrologic year. Meanwhile, during this period, the total annual consumption changed from 6,592 GWh in 2009 to 7,923 GWh in 2022, while the total annual production changed from 5,158 GWh in 2009 to 7,002 GWh in 2022 [28].

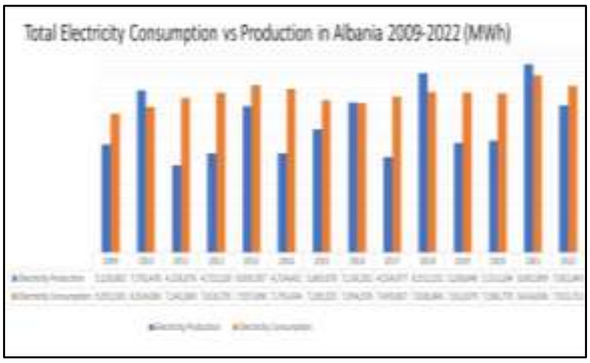


Fig. 3: Total electricity consumption and production in the country throughout the years

Due to the power sector's struggles to meet the increasing demand, transmission lines, and transformers are frequently overloaded, which can cause voltage dips or fluctuations, necessitating improvements in electricity consumption and production, the expansion of international connections and exchanges, and a more accurate reasoning for the development of new system infrastructure. The Albanian government granted concessions for the construction of small and medium private hydropower plants (HPPs) to meet the increasing electricity demand. These HPPs generated 3583.28 GWh in 2023, or approximately 40.7% of total production [28].

It is important to emphasize that, unlike other European countries that are promoting the use of renewable energy sources (RES) to replace traditional generation, Albania produces 100% of its electricity from renewable sources. Albania's electricity generation is heavily reliant on hydropower, contributing around 95% of the total electricity supply [28]. This reliance makes the power grid vulnerable to seasonal fluctuations in water availability, leading to variable power generation.

Figure 4 shows the comparison of monthly net production with monthly net consumption throughout the months of 2022 in Albania. The monthly maximum production of electricity for 2022, is marked in March with 649,844 MWh, while the minimum production was during September with 314,360 MWh. The monthly maximum consumption for 2022, is marked in January with 751,950 MWh, while the minimum consumption of electricity during 2022 was during October with 470,160 MWh [28].

From Figure 4, we observe that load surpasses the production throughout the entire year, except the months of April and May.

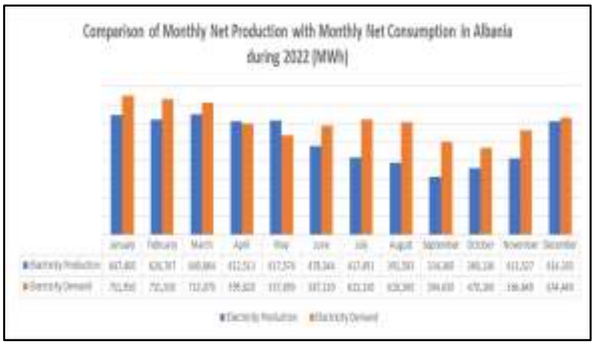


Fig. 4: Comparison of monthly net production with monthly net consumption in Albania during 2022

During dry seasons or droughts, the reduced hydropower output can strain the grid and affect voltage stability. The limited diversification in energy means there is little backup during periods of low hydropower production, exacerbating voltage instability. Due to this reason, Albanian's National Energy Strategy sets ambitious targets for expanding solar capacity in Albania, with plans to develop more large-scale solar parks and promote small-scale installations across the country. The Albanian government has introduced various incentives to attract investment in solar energy, including feed-in tariffs for small PV plants, competitive auctions for larger projects, and long-term power purchase agreements (PPAs). The PV plants that have signed connection agreements in 2022, with a total installed capacity of 255.2 MW, are expected to be energized during the 2022-2023 period, demonstrating the government's proactive approach to expanding solar energy, [28]. Alongside large-scale projects, there has been a growing trend in small-scale PV installations across Albania. These include rooftop solar panels on residential, commercial, and industrial buildings.

4 Case Study

In this paper, the Albanian power system has been analyzed. The hydropower plants constructed in Albania's north, such as the HPP of Koman, Vau Dejes, and Fierza, are the biggest and meet the most energy demand. The high nominal voltages that are present in this system are 400 kV, 220 kV, 154 kV, and 110 kV. Up to now, it has only been supplied by the synchronous generators of the hydropower plants. Because of this heavy reliance on water flows from snowfall and rainfall, it might be challenging to meet the demand for energy throughout the summer.

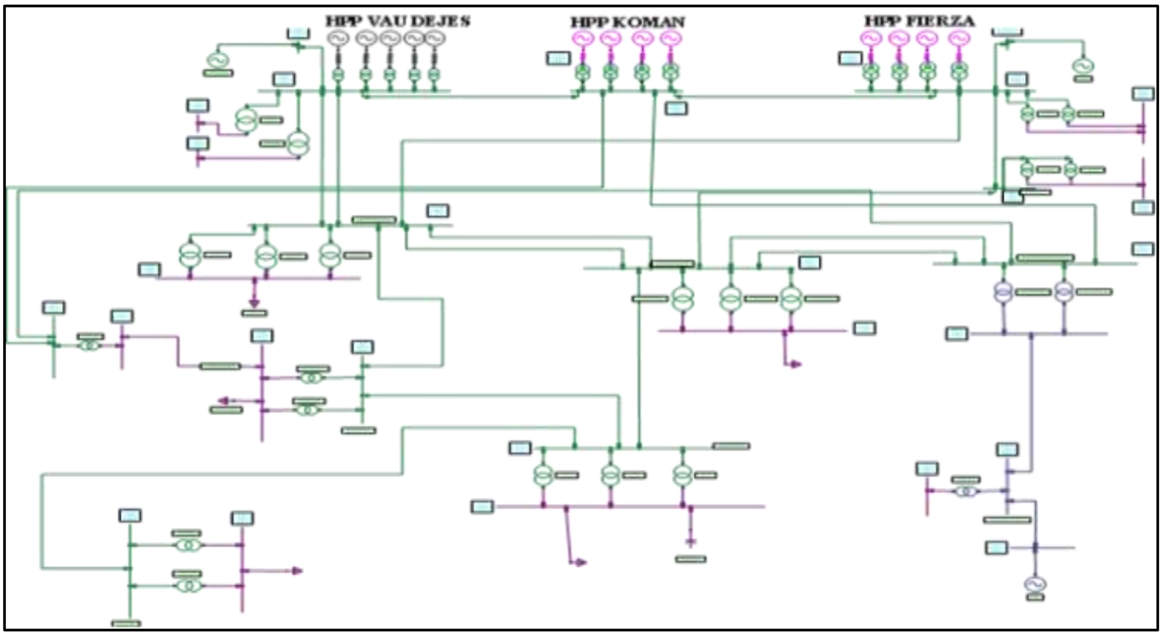


Fig. 5: Schematic design of the Albanian Power System

In addition to small and medium hydropower plants, which have contributed to the energy balance [29], new wind and PV plants are going to be constructed in the next years.

The Karavasta photovoltaic plant (140 MW or approximately 9,08% of peak load) is an energy source that has started producing in the last few years. The impact of this PV plant will be analyzed in this paper.

The maximum regime for the year 2023 will be taken as the base case analysis. In this scenario, the generation is 1409.942 MW active power and 405.435 MVAr reactive power, also the imported is 92.942 MW and 120.129 MVAr.

In this paper, we have conducted the Voltage Stability Analysis in the condition of PV penetration and small and medium HPPs. Two case studies have been analyzed:

- Base case
- PV penetration

Figure 5 shows a schematic representation of the electricity system of Albania, but the system under consideration with several voltage levels consists of many layers built into Neplan software.

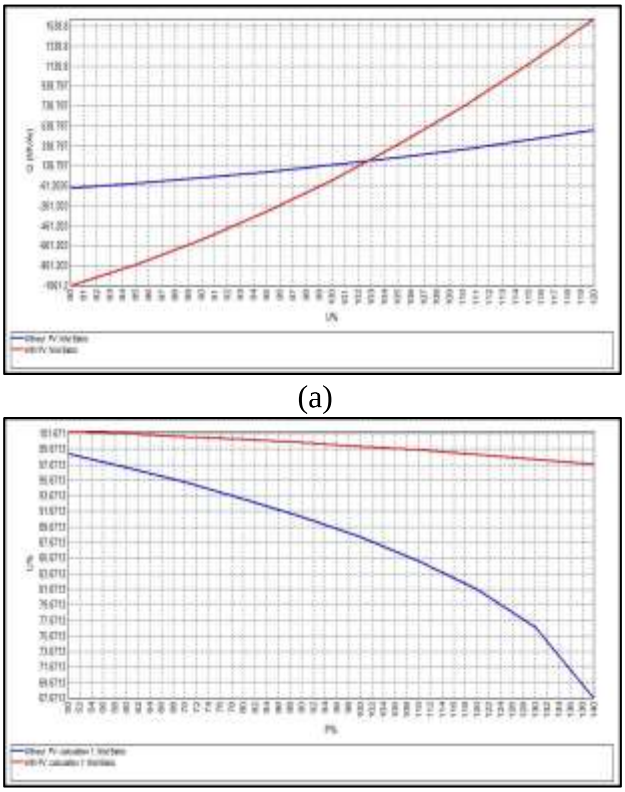
5 Results and Analysis

In the following we have analyzed Voltage Stability for Albanian power system, using P-V and Q-V curves, Q-V sensitivity analysis, and modal analysis. Analyzing P-V and Q-V curves, we have identified the critical node.

5.1 P-V and Q-V curves

In Figure 6 are shown the P-V and Q-V curves obtained for the Nst. Babice node, which is considered the critical node, for the base case, with the lowest active and reactive power reserves.

In Figure 6(a), are presented Q-V curves of Nst. Babice for both study cases, where we can see the improvement of reactive power margin after the integration of PV plant, respectively from -82.009 MVAr to -1061.2 MVAr. We can do the same analysis, by observing the P-V curves in Figure 4(b). The margin between the voltage collapse point and the current operating point is used as voltage stability criterion. In Figure 6(b), are presented P-V curves of Nst. Babice for both study cases, where we can see the improvement of loading margin with 2,89 %, respectively from 99.08 % to 101,97 %. Equations (1) and (3) are used to evaluate the loading margin. After the integration of the Karavasta photovoltaic plant, there has been a noticeable increase in both active and reactive power reserves. This positive impact is attributed to the increased reactive power support provided by the PV plant which reduces grid strain and lowers the possibility of voltage dips, especially in weak areas in the system.



(a)

(b)

Fig. 6: Q-V a) and P-V b) curves

5.2 Q-V Sensitivity Analysis

Table 1 presents the V-Q sensitivity coefficients for both scenarios: without the integration of the Karavasta photovoltaic plant and with its integration. In both instances, the system is observed to be voltage stable, indicated by the positive coefficients. Additionally, there is a noticeable decrease in the coefficients after the integration of the photovoltaic plant. Smaller coefficients signify enhanced voltage stability in the system. A decrease in V-Q sensitivity coefficients for the critical node, Nst, was observed. Babice, specifically from 0.0649 to 0.0351.

Table 1. V-Q sensitivity coefficients

Node	**V-Q sensitivity coefficients (%/MVAr)**	
	With PV	*Without PV*
Nst. Tirana 2	0.0243	0.0536
Nst. Babicë	0.0351	0.0649
Nst. Fier	0.0396	0.0507

5.3 Modal Analysis

Modal analysis has an advantage over other methods by providing detailed insights into the mechanisms of instability. To investigate static voltage stability through this analysis, it is essential to calculate eigenvalues, node participation factors, branch participation factors, and generator participation factors. Using Neplan software for simulation, the eigenvalues for both scenarios have been computed and are illustrated in Figure 7.

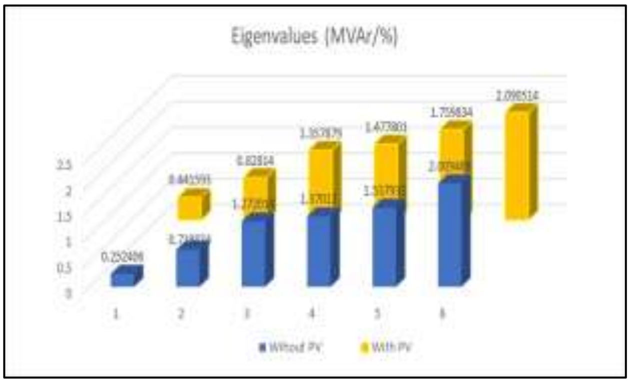


Fig. 7: Eigenvalues (MVAr/%)

In Figure 7, the system remains stable in both scenarios, indicated by the positive coefficients. However, the smaller the eigenvalue, the closer the voltage is to instability. The magnitude of the eigenvalue serves as a measure of the system's proximity to instability. A recalculation of the system's eigenvalues identifies an increase in the smallest eigenvalue, specifically from 0.252 to 0.442.

The subsequent results will focus exclusively on the smallest eigenvalue under conditions where the limit of mutual sensitivity or participation factors exceeds 20%. This implies that the analysis is conducted for those eigenvalues where the node, branch, and generator participation factors have the most significant impact on the assessment of voltage stability.

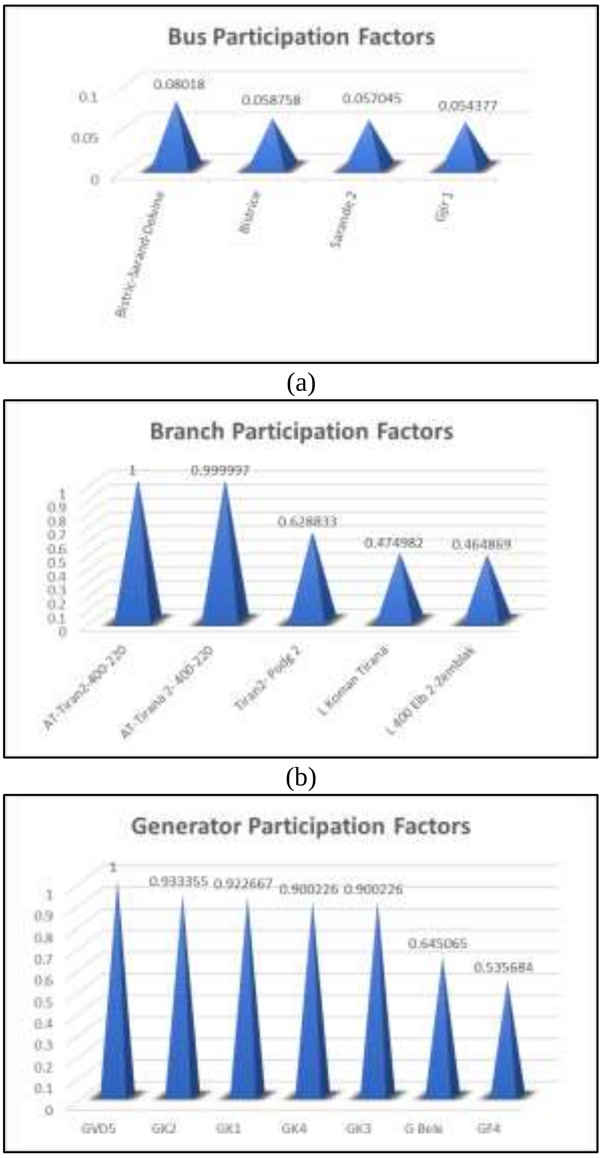
5.3.1 Participation Factors

In the following, we have presented which buses, branches, and generators and to what extent they influence the system so that appropriate measures can be taken to improve the situation, using the smallest Eigenvalue. Equations (11)-(13) are used to evaluate the participation factors. Referring to Figure 7, we see that the smallest Eigenvalue is 0.252.

In Figure 8(a), are shown the buses which have the most influence for the smallest Eigenvalue. We see, that the Bistrice-Delvine-Sarande is the closest node to voltage instability. To prevent a voltage collapse, this node needs to be continuously monitored and corrective measures (such as reactive power compensation) should be taken.

Figure 8(b) illustrates the branches that are proximate to instability or experiencing overload.

These branches are identified as those absorbing the highest amounts of reactive power, corresponding to the smallest eigenvalue. In Figure 8(b), we observe that AT-Tirana 2 is the branch absorbing the most reactive power, highlighted as the most vulnerable to becoming overloaded. The results obtained provide important information regarding the identification of the critical branches of the network, those branches with the highest participation factors. These elements consume more reactive power during a small increase in load. This is valuable information that can be used by system operators, who classify branches with the highest participation factors that should be disconnected during a fault. Disconnecting these branches from the network could cause a loss of voltage stability.



(a)

(b)

(c)

Fig. 8: Bus Participation Factors a) Branch Participation Factors b) Generator Participation Factors c) for the smallest Eigenvalue

Figure 8(c) presents the generator participation factors. The reactive power generated changes drastically with the increase in load. These generators need to provide reactive power reserves to maintain the static voltage stability of the power system. However, not all generators provide reactive power in the same amount, and some might be more effective in stabilizing the system than others. The ability of these generators to provide reactive power becomes even more crucial in preventing voltage collapse when they are located nearby to critical nodes. Observing Figure 8(c), GVD5 results as the most effective generator for maintaining voltage stability by providing reactive power reserves.

Overall, participation factors are crucial in pinpointing the exact locations within the power grid that are most vulnerable to voltage instability. They allow operators to prioritize interventions, monitor key branches, and optimize generator control.

6 Discussions

The analysis conducted in this paper emphasizes that the integration of DG, particularly PV plants, into traditional power systems presents both opportunities and challenges for voltage stability. Through static methods, this research has highlighted key results that are relevant for both technical advancement and practical implementation. These methods demonstrated that the integration of the 140 MW PV plant significantly enhances the voltage stability of the Albanian power grid. In particular, significant improvements were found at critical nodes, such as Nst. Babice, based on the examination of P-V and Q-V curves. The reactive power margin increased from -82.009 MVAr to -1061.2 MVAr following PV integration, while the loading margin improved from 99.08% to 101.97%. This positive impact is attributed to the increased reactive power support provided by the PV plant which reduces grid strain and lowers the possibility of voltage dips, especially in weak areas in the system. The degree of improvement is highly dependent on the specific characteristics of the system, as demonstrated by the unique challenges faced by the Albanian power system dominated by hydropower plants.

The bus participation factors identified the Bistrice-Delvine-Sarande buses as the most critical. Similarly, critical transmission lines, which absorb the greatest reactive power and are vulnerable to overloading during periods of high load demand, were identified using the branch participation factors. Moreover, modal analysis suggests that the system is still close to its stability limits in certain areas, despite the improvements by the 140 MW Karavasta PV plant.

The results from this study have several practical implications for system operators. Using a combination of static analysis techniques, this paper addresses the impact of integrating a large PV plant into the voltage stability of the Albanian power grid, which is historically reliant on hydropower. Firstly, the improvements in voltage and the reactive power, generated by transmission lines, indicate that the future incorporation of renewable energy, such as wind or PV plants, could continue to enhance the grid's voltage stability. However, this also requires careful management of the system's weakest points, which have been identified through participation factor analysis. The other contribution of this paper is that using modal analysis, identified the critical components of the power system. In scenarios with high load demand or low generation, targeted interventions at critical buses, branches, and generators will be necessary to avoid voltage collapse. While the study focuses on the Albanian power grid, its approach and results are relevant to any power system, which is integrating renewable energy sources into the system.

Despite the comprehensive insights into voltage stability provided by this study, there are some limitations that should be considered. Initially, the investigation concentrated primarily on static voltage stability techniques, which are valuable but do not fully capture the dynamic behavior of the system in the presence of external disturbances. To evaluate how the grid reacts to more complex and transient events, further study could expand on this by analyzing dynamic stability, including time-domain simulations. Furthermore, the analysis assumes a constant PV-generating output, but solar power can be highly variable due to weather variations, so stochastic models that simulate the variations in sun irradiance and how they affect voltage stability might offer more accurate insights into the system's performance under fluctuating renewable generation.

Finally, future research could investigate the effects of combining PV plants with other renewable energy sources, including wind power. This would offer an expanded awareness of how multi-source renewable energy systems affect the stability of the grid and interact with it.

7 Conclusions

This paper presents the impact of the integration of PV generators on voltage stability. The static voltage stability analysis used various techniques: P-V and Q-V curves, V-Q sensitivities, and modal analysis. Using a combination of these methods, this study provided a detailed assessment of how large-scale PV plant integration affects the stability of a power system that is traditionally dominated by hydropower. Following the integration of the PV plant, the P-V and Q-V curve methods showed improvements both in voltage and reactive power margin at the critical node, indicating increased grid resilience against possible voltage collapse. The reactive power margin was increased from 82.009 MVAr to -1061.2 MVAr, while the loading margin from 99.08% to 101.97%, in this way lowering the risk of voltage collapse. Also, the V-Q sensitivity analysis demonstrated a decrease in sensitivity coefficients after PV integration, indicating enhanced voltage stability throughout the system.

Among the methods used, modal analysis turned out to be the most effective in locating the areas, that are vulnerable to voltage instability, providing detailed information about the weakest buses, generators, and branches, allowing for countermeasures. In this way, helps the system's operators prioritize interventions, optimize production control, and monitor critical branches.

Overall, the Albanian power grid's voltage stability is improved with the integration of the Karavasta Photovoltaic Plant. The results from this study serve as a valuable guide for operators and policymakers as they seek to integrate more renewable energy sources into the grid while maintaining reliability and stability, but with careful planning and targeted interventions, the voltage stability can be enhanced. This research underscores the importance of a balanced energy mix and the strategic placement of distributed generation to support voltage stability.

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Contribution of Individual Authors to the Creation of a Scientific Article

- Viktor Rrotani conducted the literature review, conceptualized and formulated the case study, modeled the power system in Neplan, carried out the simulations, and analyzed the results.
- Rajmonda Bualoti has carried out the Static Methods, developed the mathematical models, contributed to the discussions and conclusions sections, and provided revisions and advice.
- Marialis Celo has carried out the Albanian Power System Overview, analyzed the results obtained from the simulations, contributed to the discussions section, and drew the conclusions.

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Conflic of Interest

The authors have no conflicts of interest to declare.

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