International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 2, June 2026, pp. 760~769
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i2.pp760-769

Impact of synchronous condensers on voltage stability in systems with high renewable energy penetration

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Article Info

Article history:

Received Jun 11, 2025
Revised Jan 27, 2026
Accepted Mar 12, 2026

Keywords:

Loadability margin
Point estimate method
Renewable energy sources
Synchronous condenser
Voltage stability

ABSTRACT

The rapid integration of renewable energy sources (RES) poses significant challenges to power system reliability, particularly regarding voltage stability and reduced loadability margins. This study investigates the impact of synchronous condensers as a mitigation strategy to enhance stability in grids with high renewable penetration. The research objective is to evaluate how these devices influence loadability margins while considering the inherent stochastic nature of RES. The methodology employs PV curves for static voltage stability assessment, utilizing the 2m+1 point estimate method (PEM) to model uncertainty with high computational efficiency. This approach allows for the calculation of statistical indicators, including mean values, standard deviations, and confidence intervals for loadability margins. Simulations were conducted on the IEEE reliability test system (RTS) using NEPLAN360 software. The results demonstrate that the deployment of synchronous condensers (SCs) significantly improves voltage stability by increasing load margins and reducing the standard deviation of uncertainty. Conclusions indicate that these devices are effective reactive power compensators that provide a more robust operational environment against RES variability. Future research will focus on the optimal sizing and placement of these compensators to further maximize grid security.

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1. INTRODUCTION

The increasing integration of renewable energy sources (RES) has significantly transformed the operation and planning of modern power systems [1]. While these technologies contribute to sustainability and energy diversification, they also introduce technical challenges that must be addressed to ensure system reliability. Among the most critical issues are low short-circuit capacity [2], reduced system inertia [3], and transient stability concerns [4], all of which can compromise the secure operation of the grid. One of the most pressing challenges, and the focus of this study, is voltage stability [5], [6].

Voltage stability refers to the ability of a power system to maintain acceptable voltage levels under normal operating conditions and after disturbances [7]. This capability is constrained by the maximum power that can be transferred through the network without causing voltage collapse [8]. Several studies have shown that systems with high-RES penetration are more susceptible to voltage instability, which reduces their loadability margins and increases the risk of voltage-related failures [9]-[12].

To assess voltage stability, various analytical methods have been developed, including both dynamic and static approaches [5], [13]. Among the static methods, P-V and Q-V curves are widely used to evaluate loadability margins, which represent the maximum power that can be transmitted before voltage instability occurs [5]. These techniques have been applied to study the impact of RES on system performance, revealing a consistent reduction in voltage stability margins as renewable penetration increases [14]-[17].

Given the stochastic nature of RES, it is essential to incorporate uncertainty into voltage stability assessments. Probabilistic methods such as Monte Carlo simulations offer high accuracy but are computationally intensive [18]. A more efficient alternative is the point estimate method (PEM), which captures uncertainty with significantly lower computational effort. PEM has been successfully applied in power flow studies involving correlated random variables, making it a suitable tool for analyzing systems with high RES variability [19]-[21].

In this context, it is essential to explore solutions that mitigate the voltage stability issues associated with the integration. One such solution, examined in this study, is the use of synchronous condensers (SCs). These devices are selected due to their inherent capability as reactive power compensators. Previous studies have demonstrated that reactive power management has a direct impact on voltage stability margins [22], [23]. Moreover, SCs have proven to be an effective solution to several challenges introduced by RES in power systems [24]. Their dynamic performance has even been shown to surpass that of other compensators, such as static var compensators (SVCs) [25], [26]. In addition to their application in systems with high renewable penetration, they are also beneficial in other low-inertia environments, such as high voltage direct current (HVDC) connection points [27], [28].

This paper presents an analysis of the impact of synchronous condensers on voltage stability in power systems with high penetration of RES. The assessment of loadability margins is carried out using PV curves, while uncertainty in renewable generation is addressed through the 2m+1 point estimate method. The IEEE reliability test system (RTS) is used as the test case, and simulations are performed using the NEPLAN360 software. The analysis compares multiple system scenarios and highlights the benefits of incorporating synchronous condensers to enhance voltage stability.

2. METHOD

The analysis of the impact of synchronous condensers on voltage stability in power systems with high renewable energy penetration requires a comprehensive framework. This framework includes several key components: the method used for voltage stability analysis, the probabilistic approach to account for uncertainty, and the sizing criteria for both RES and synchronous condensers. Each of these elements plays a critical role in accurately assessing system behavior under varying operational conditions.

This section details the key components required for analysis. It begins with an explanation of P-V curves and two loadability margins used to assess voltage stability. Next, the 2m + 1 point estimate method, originally proposed by Hong [29], is introduced and adapted to the context of power systems. The section then clarifies the criteria used for sizing RES, referencing relevant Colombian regulations. Finally, it presents the approach for sizing SCs, including a brief description of their placement within the system.

2.1. PV curves and load margins

The P-V curve is a static stability analysis method used for voltage stability, which represents the relation between the voltage (V) and the active power (P). This curve is obtained by computing different power flows where the load changes [30]. This forms a “nose” shaped curve in which the nose is called the critical point [5]. After this critical point the system is in voltage instability. From this curve, two loadability margins can be defined. The first one is the difference between the tip of the curve and the rated power of the system’s load. The second one is proposed in this document and is defined as the difference between the active power at a minimum voltage value and the rated power of the system’s load. These two margins are named in this document as the maximum load margin (λ_{max}) and minimum voltage load margin (λ_v) respectively. In Figure 1, these two margins are illustrated in the P-V curve.

2.2. Point estimate method (PEM)

A 2m+1 point estimate method is used to obtain these load margins for considering the uncertainty of the RES. This method was developed by Hong [29], where m is the number of random variables that are used for the analysis (in this case, the number of RES). This method requires the knowledge of the four central moments of each random variable ($\mu_{pl}, \sigma_{pl}, \lambda_{pl,3}, \lambda_{pl,4}$), where μ_{pl} is the mean value, σ_{pl} the standard deviation, $\lambda_{pl,3}$ is the skewness and $\lambda_{pl,4}$ is the kurtosis [31] of the random variable (the injected power by a renewable power plant).

Let Z be a random variable function (for example, the load margins) that depends on the random variables X (RES power injection), so $Z = f(X_1, \ldots, X_m)$. Then the average value and the standard deviation of this function can be obtained as (1)-(3) [31].

$$\mu_z = \sum_{i=1}^{2m+1} w_{l,k} f(x_{l,k}) \tag{1}$$

$$E(Z^2) = \sum_{i=1}^{2m+1} w_{l,k} f^2(x_{l,k}) \tag{2}$$

$$\sigma_Z = \sqrt{E(Z^2) - \mu_Z^2} \tag{3}$$

For this study, the random variable function Z is the two load margins, and each random variable X is the active power produced by each RES. Each w_i represents the weight factor of a concentration point that is computed using the PEM formulation. Each concentration point computes a value for Z in a scenario of the random variable X, $f(x_{l,k})$. The values for $x_{l,k}$ and $w_{l,k}$ are computed as (4)-(6) [31].

$$x_{l,k} = \mu_{pl} + \xi_{l,k}\sigma_{pl} \tag{4}$$

$$w_{l,k} = \begin{cases} \frac{(-1)^{3-k}}{\xi_{l,k}(\xi_{l,1}-\xi_{l,2})}, & k = 1,2 \\ \frac{1}{m} - \frac{1}{\lambda_{pl,4}-\lambda_{pl,3}^2}, & k = 3 \end{cases} \tag{5}$$

$$\xi_{l,k} = \begin{cases} \frac{\lambda_{pl,3}}{2} + (-1)^{3-k}\sqrt{\lambda_{pl,4} - \frac{3\lambda_{pl,3}^2}{4}}, & k = 1,2 \\ 0, & k = 3 \end{cases} \tag{6}$$

There are 3 concentration points for each random variable, hence making it 3m concentration points. However, when k=3 all concentration points share the same equation making them 2m+1 concentration points. This method is used for independent random variables, but if this is not the case, the correlated random variables are decorrelated based on fictitious variables. This is done by using a Cholesky transformation as it is presented in [31]. In this document, the random variables are assumed to be independent, so there is no need to use this procedure.

Now with this procedure, 2m+1 generation scenarios are obtained. These scenarios represent the active power that is produced in each of the RES ($p_{l,k}$). With these values, 2m+1 PV curves are computed, and all the load margins are obtained. With each respective weight, the mean value and the standard deviation of the load margins are calculated with (1), (2), and (3).

2.3. Confidence intervals

As stated before, using (1), (2), and (3), the mean value and the standard deviation of the load margins are calculated. With these two values an interval with a confidence level of 95% can be obtained. In (7) the lower value of the confidence interval is shown, where τ takes the value of 1.96 for 95% confidence; defined as (7) [12].

$$CI_{min} = [\mu_\lambda - \tau\sigma_\lambda] \tag{7}$$

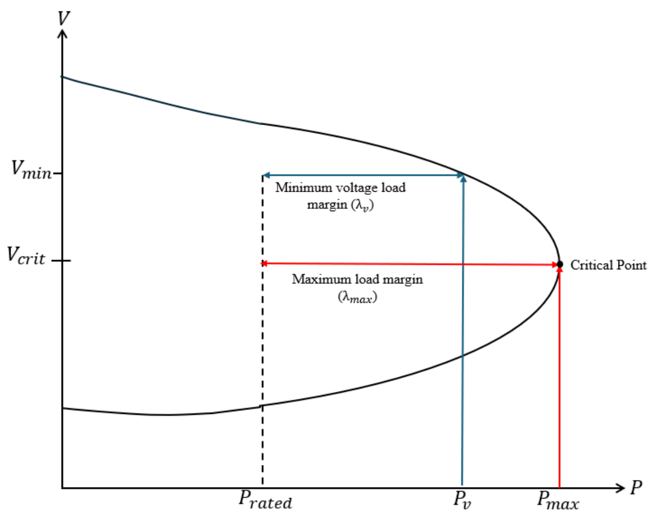

Figure 1. PV curve with the defined load margins

2.4. Reactive power limits for RES

Like it is stated in [30], PV curves are computed using multiple power flows. It is critical to establish the power limits RES have. In this document, the Colombian regulation is used as a reference for the restriction renewable energies have. The energy and gas regulatory commission (CREG) establishes in the 090 law of 2019 that renewable energies should have at least a 0.95 power factor to inject and absorb reactive power into the national grid [32].

Using these reactive limits, RES are configured as a PV element for power flow calculation, with the active power configured depending on the generation scenario calculated with PEM. This configuration is used when there are no synchronous condensers connected to the same bus as the RES. On the other hand, when synchronous condensers are used in the same bus as the renewable energy source, the configuration changes. Now they are established as a PQ, where their active power depends on the generation scenario, and the Q is fixed based on the values obtained from a power flow with no synchronous condensers.

2.5. Synchronous condensers sizing

A synchronous condenser (SC) is a synchronous machine that operates without a prime mover or mechanical load. By controlling its excitation field, it can generate or absorb reactive power. They have been used since 1930 as reactive power compensators in transmission and sub-transmission systems [7]. In recent years, synchronous condensers have begun to rise again because of the inclusion of renewable energy. In China, their excellent performance is reflected in strong voltage support and overload capacity, and there is a lot of improvement in order aspects of the power systems [33].

As a reactive power compensator, it is necessary to establish the capacity of these devices. In this document, they are used as a reactive compensator for renewable energy sources whose power factor takes the value of 0.95. A new power factor is the objective to be achieved using synchronous condensers. In (8) it is shown the equation used to determine the reactive power of the synchronous condensers.

$$Q_{SC} = Q_{rated} - P_{rated}(\tan(\cos^{-1}(pf))) \tag{8}$$

The location of the synchronous condenser in this study is established to be the same as RES. This is also a choice made by different studies like [6].

3. RESULTS AND DISCUSSION

This section presents the study system and the variations that are made to it, to include RES and synchronous condensers. Also, the results of the different cases of study are presented. First, a mean generation scenario is studied to conclude about the effect of synchronous condensers. After this, two analyses with and without synchronous condensers are presented using PEM to capture the uncertainty and conclude based on confidence intervals. The power factor used for RES is established in 0.95 and the voltage criteria for the margin (λ_v) is 95%.

3.1. Test system

The system used for this study is the IEEE-RTS system that has 24 buses [26]. The electrical single-line diagram of the system is shown in Figure 2. For this system the bus selected as slack is the equivalent generator on bus 23. Finally, an economic dispatch is performed based on the variable cost of synchronous machines of the system to perform a power flow. All the parameters of the system are included in original document [34].

3.2. Renewable energy information

As a study case for testing the proposed methodology, some coal-based synchronous generation is replaced by renewable energy generation. The two thermic plants with a capacity of 76 MW connected to nodes 1 and 2, for a total of 4 machines, get replaced by two wind power parks (WPP) rated with 200 MW. Also in node 16, the 155 MW coal thermic plant is replaced by a 300 MW WPP. With these replacements, the system ends up with a 24% renewable energy penetration. Figure 3 shows the changes made to the IEEE-RTS system.

The application of the PEM requires to know the statistical information of these three wind power parks. In Table 1, the four statistical central moments of the three WPP are shown; these are normalized to the rated power of each WPP. This information can be obtained through Monte Carlo simulations to characterize RES, as shown [35]. Also, the capacity of the synchronous condensers is calculated to achieve a 0.85 power factor in the point of connection of the RES. These values are shown in Table 2, where the information of the reactive limits of the WPP is also available.

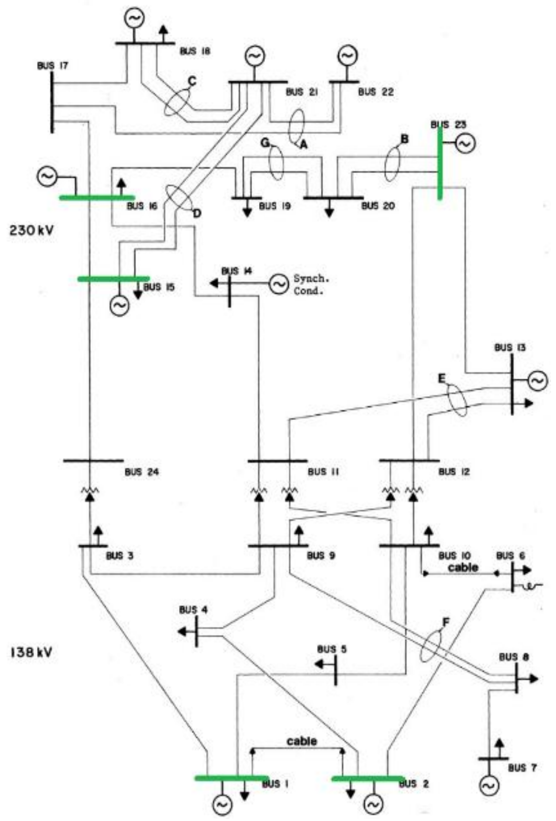

Figure 2. IEEE RTS system [34]

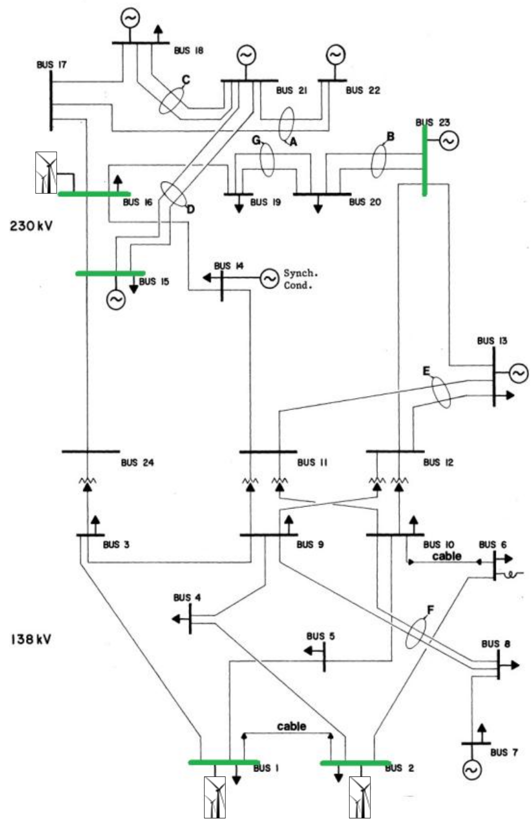

Figure 3. IEEE-RTS system with the renewable replacements

Table 1. Statistical information of the WPP

Central moment	WPP_{Bus1}	WPP_{Bus2}	WPP_{Bus16}
μ_{pl}/P_{rated}	0.3018	0.3018	0.2949
σ_{pl}/μ_{pl}	1.0096	1.0096	0.5255
$\lambda_{pl,3}$	0.8490	0.8490	-0.3573
$\lambda_{pl,4}$	2.4270	2.4270	1.8357

Table 2. Reactive limits for the WPP and SC

Wind p[ark	P_{rated} [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]	SC Q_{max} [Mvar]	SC Q_{min} [Mvar]
WPP_{Bus1}	200	66	-66	58	-58
WPP_{Bus2}	200	66	-66	58	-58
WPP_{Bus16}	300	99	-99	87	-87

3.3. Voltage stability results in an average generation scenario

In this subsection, P-V curves are computed for a deterministic average generation scenario. The active power generated in this case is 60.36 MW for the two WPPs connected to buses 1 and 2 and 80.47 MW for the WPP connected to bus 16. From this scenario, load margins are obtained for three different systems. First, for the test system without RES and synchronous condensers. Second, for the system with the inclusion of RES but without synchronous condensers. And finally, for the system with RES and synchronous condensers. Also, for the three results obtained, Figure 4 shows a comparative curve of the nodes that reach the minimum voltage, which in this case is 95%, used to calculate the minimum voltage load margin (λ_v). All nodes of the system share the same value for the maximum load margin (λ_{max}). Table 3 presents all the results obtained for this average scenario.

The synchronous condenser has a positive effect on voltage stability. The effect was so significant that it even surpassed the system that only has synchronous generation. Also, the congestion bus of the system changed from node 4 to node 6 thanks to the synchronous condensers.

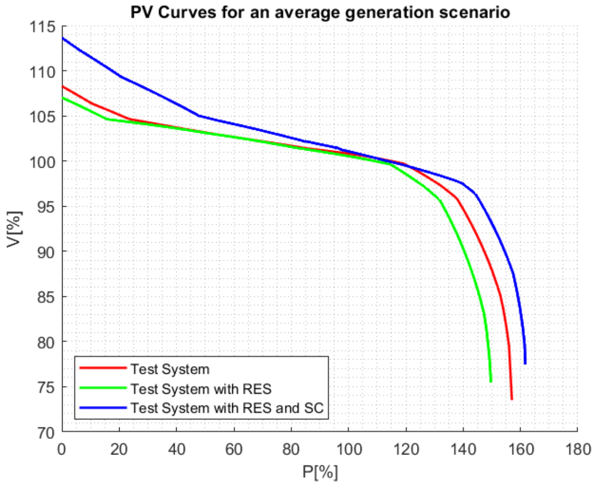

Figure 4. PV curves for the average generation scenario

Table 3. Load margins obtained for the average generation scenario

Loadability margins	Test system	Test system with RES	Test system with RES and SC
λ_v [%]	40.0	33.0	47.0
λ_{max} [%]	57.0	49.5	61.5
λ_v [MW]	1140.0	940.5	1339.5
λ_{max} [MW]	1624.5	1410.0	1752.8
Minimum voltage bus	(4)	(4)	(6)

3.4. Results for the PEM analysis in the test system with RG without CS

Now the results for the PEM analysis are presented for the system with Renewable energy sources without implementing synchronous condensers. First, all the concentration points are calculated for the 3 WPP, which leads to 7 concentration points. In Table 4, all the concentration points are presented, including the weight of each point and the respective active power generation. It should be noted that all the weight factors add up to 1.

With the concentration points, seven PV curves were computed to acquire the mean and the standard deviation of the load margins. It is worth mentioning that the concentration point W0 is the average generation scenario analyzed above. Table 5 presents the load margins in %, while Table 6 presents the same margins in MW. Finally, Table 7 presents the mean value and the standard deviation in MW and % for the test system with renewable energy sources without synchronous condensers. This table also has information on the coefficient of variation (σ /μ) and the low value (minimum value) of the confidence interval (CI_{min}).

Table 4. Concentration points calculated for the 3 WPP

Concentration point	WPP_{Bus1} [MW]	WPP_{Bus2} [MW]	WPP_{Bus16} [MW]	Weight factor
w0	60.36	60.36	88.47	-0.7577
w1	169.93	60.36	88.47	0.2025
w2	2.53	60.36	88.47	0.3836
w3	60.36	169.93	88.47	0.2025
w4	60.36	2.53	88.47	0.3836
w5	60.36	60.36	141.49	0.3324
w6	60.36	60.36	18.84	0.2531

Table 5. Load margins in % for the test system with RES without SC

Concentration point	λ_v [%]	λ_{max} [%]
w0	33.00	49.65
w1	43.60	59.25
w2	26.10	43.50
w3	43.60	59.20
w4	26.00	43.60
w5	33.40	50.20
w6	32.50	48.85

Table 6. Load margins in MW for the test system with RES without SC

Concentration point	λ_v [MW]	λ_{max} [MW]
w0	940.50	1415.03
w1	1242.60	1688.63
w2	743.85	1239.75
w3	1242.60	1687.20
w4	741.00	1242.60
w5	951.90	1430.70
w6	926.25	1392.23

Table 7. Statistical information of the load margins for the test system with RES without SC

Statistics	[%]	[MW]
μ (λ_v)	31.97	911.08
μ (λ_{max})	48.83	1391.63
σ (λ_v)	9.03	257.47
σ (λ_{max})	8.08	230.24
σ (λ_v) / μ (λ_v)	0.28	0.28
σ (λ_{max}) / μ (λ_{max})	0.17	0.17
CI_{min} (λ_v)	14.26	406.44
CI_{min} (λ_{max})	32.99	940.35

3.5. Results for the PEM analysis in the test system with RES and SC

After studying the impact of including renewable energy sources on voltage stability, this section presents the results of the effect that synchronous condensers have. Because both situations share the same random variables, the concentration points shown in Table 4 are shared in these two cases. Similarly to the results presented above, Table 8 presents the load margins in % while Table 9 presents the load margins in MW both for the system with RES and SC. Following the analysis, the mean value, standard deviation, the coefficient of variation, and the bottom level of the confidence interval is presented on Table 10. From these results, it can be observed that the medium values are significantly higher when synchronous condensers are included in the system, mitigating the effect the renewable energy sources have on voltage stability. Similarly, including synchronous condensers reduces the standard deviation of the load margins, reducing the uncertainty these values have in the confidence interval.

Table 8. Load margins in % for the test system with RES and SC

Concentration point	λ_v [%]	λ_{max} [%]
w0	46.80	61.65
w1	55.10	70.20
w2	40.80	56.20
w3	55.60	70.20
w4	40.80	56.25
w5	47.40	62.40
w6	46.00	60.65

Table 9. Load margins in MW for the test system with RES and SC

Concentration point	λ_v [MW]	λ_{max} [MW]
w0	940.50	1415.03
w1	1242.60	1688.63
w2	743.85	1239.75
w3	1242.60	1687.20
w4	741.00	1242.60
w5	951.90	1430.70
w6	926.25	1392.23

Table 10. Statistical information of the load margins for the test system with RES and SC

Statistics	[%]	[MW]
μ (λ_v)	45.66	1301.23
μ (λ_{max})	60.95	1737.01
σ (λ_v)	7.50	213.70
σ (λ_{max})	7.22	205.77
σ (λ_v) / μ (λ_v)	0.16	0.16
σ (λ_{max}) / μ (λ_{max})	0.12	0.12
CI_{min} (λ_v)	30.96	882.38
CI_{min} (λ_{max})	46.80	1333.70

3.6. Comparison of the results obtained

To facilitate comparison of the results, Table 11 presents the mean load margin values for each test system scenario. The mean value corresponding to the system without RES and SCs matches the one obtained under the average generation scenario. All values are expressed both as percentages and in megawatts (MW), as indicated in the table.

Based on the results, the integration of synchronous condensers into systems with RES leads to a significant increase in load margins. This improvement is so substantial that even the average margins surpass those of the base system without RES. These findings provide valuable insights into the planning and operation of power systems, particularly in scenarios where RES integration poses challenges to voltage stability.

Table 11. Comparative of the load margins for the three system variations

Statistics	Test system	Test system with RES	Test system with RES and SC
μ (λ_v) [%]	40.0	31.97	45.66
μ (λ_{max}) [%]	57.0	48.83	60.95
μ (λ_v) [MW]	1140.0	911.08	1301.23
μ (λ_{max}) [MW]	1624.5	1391.63	1737.01

4. CONCLUSION

This document presented a method to study the impact of synchronous condensers on voltage stability based on PV curves and the computation of the lower loadability margins based on uncertainty analysis. This uncertainty analysis is based on the point estimate method, which allows the computation of statistical information such as the mean value, the standard deviation, the coefficient of variation, and a confidence interval of the loadability margins that can help to plan and operate power systems.

For a specific case study, in the 24-node IEEE RTS system, including renewable energy penetration of 24% of the total system capacity, it could be identified the positive effect synchronous condensers had on the voltage stability. It was observed that the load margins increased, and the standard deviation decreased, reducing the uncertainty renewable energy sources have. Future work can study the optimal location and sizing of these devices to improve voltage stability. Finally, a comparison can be made of the stability effect of other compensation devices, such as SVC versus synchronous condensers, when renewable energy sources are present in a power system.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mario A. Rios		✓	✓	✓	✓	✓		✓	✓	✓			✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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