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Voltage stability investigation: enabling large-scale renewable energy integration in Tamil Nadu's grid

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ABSTRACT

The integration of renewable energy sources (RES) such as wind and solar, characterized by their inherent intermittency and variability, poses notable challenges to the stability and reliability of power systems. This research addresses these challenges by conducting a detailed load flow, voltage sensitivity and stability analysis at a significant extra high voltage (EHV) pooling station under high-RES penetration. Employing advanced simulation methodologies, the study evaluates the effects of RES integration on voltage profiles and the system's capacity to sustain equilibrium under steady-state operations. The findings highlight that substantial RES integration induces considerable voltage fluctuations and reactive power disparities. To counter these effects, static var compensators (SVCs) were deployed, demonstrating their efficacy in enhancing voltage stability and providing essential reactive power support. The study confirms the pivotal role of SVCs in alleviating voltage sensitivity to RES fluctuations, thereby promoting a more stable and reliable power supply. This research underscores the importance of strategic reactive power management devices in enabling a seamless transition towards a renewable-dominant energy landscape.

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1. INTRODUCTION

The increasing integration of renewable energy sources (RES), particularly wind and solar, has become a global imperative to combat climate change and reduce dependency on fossil fuels. However, their inherent intermittency and variability introduce significant challenges in maintaining power system stability and reliability. These challenges become even more pronounced in regions experiencing high-RES penetration, where fluctuations in generation can lead to issues such as voltage instability, frequency deviations and reactive power imbalances.

Tamil Nadu, India, presents a unique case study due to its ambitious renewable energy targets and extensive integration of wind and solar power [1]. With an installed capacity of over 43,132 MW as of March 2025 [2], the state is one of India's largest electricity producers, with RES accounting for a significant share of its power generation mix (Figure 1). The Tamil Nadu government has implemented progressive policies, including the Tamil Nadu solar energy policy, to accelerate RES deployment. However, as RES penetration increases, maintaining grid stability and voltage regulation has become a growing concern, particularly at the extra high voltage (EHV) pooling stations that serve as critical nodes in the transmission network.

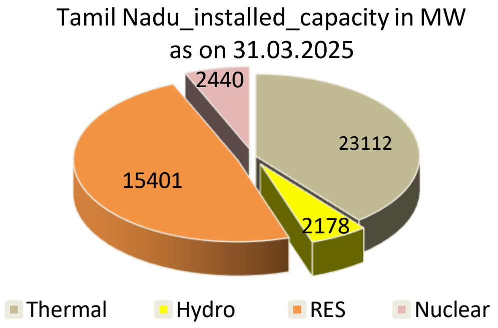


Figure 1. Tamil Nadu's total installed capacity as of March 31, 2025

Several studies [3]-[5] have explored the integration of RES into power grids, with a focus on stability enhancement using flexible AC transmission systems (FACTS) devices, such as STATCOM and SVC. Prior research has demonstrated that these devices can provide dynamic voltage support and reactive power compensation, helping to mitigate the voltage fluctuations associated with RES integration. However, many existing studies lack a real-time system-based approach tailored to high-RES penetration scenarios in Tamil Nadu's EHV transmission infrastructure. Furthermore, optimal deployment strategies for FACTS devices to enhance voltage stability in large-scale renewable grids remain an open research area.

This research aims to address these gaps by conducting a detailed voltage stability investigation at a key 400 kV EHV pooling station in Tamil Nadu's grid. The main objectives are:

- To analyze the impact of high-RES penetration on voltage stability using load flow and voltage sensitivity studies.
- To evaluate the effectiveness of static var compensator (SVC) in maintaining voltage stability and managing reactive power under varying load conditions.
- To develop an optimized strategy for reactive power management, ensuring improved system reliability and seamless RES integration.

The study employs real-time operational data and advanced simulations using ETAP, making it one of the first comprehensive assessments of Tamil Nadu's high-RES grid infrastructure at the transmission level. The findings contribute to the development of resilient power networks capable of accommodating higher RES shares while ensuring stability and reliability.

2. LITERATURE SURVEY

The integration of large-scale RES into modern power systems presents substantial technical and operational challenges, particularly in regions such as Tamil Nadu, where wind and solar potentials are high. Several studies have addressed these complexities, focusing on grid reliability, voltage stability and effective control strategies to manage fluctuating generation and demand conditions.

Rose *et al.* [6] examined the evolution of Tamil Nadu's electric power sector, projecting a shift by 2030 toward a diversified energy portfolio dominated by wind, solar and battery storage and reduced reliance on coal, hydro and nuclear sources. Sreedevi *et al.* [7] conducted a detailed case study on the impact of large-scale wind power integration on grid stability, revealing that up to 29.3% of wind generation could be accommodated without compromising system performance. Percis *et al.* [8] addressed the large-scale energy integration requirements, emphasizing the coordination required for stable and economic grid operation. At a national level, Palchak *et al.* [9] discussed India's potential to integrate 175 GW of renewable energy, concluding that such a scale of deployment was feasible with minimal curtailment, provided appropriate infrastructure planning is undertaken.

On the international front, several works provide insights into challenges arising from inverter-based resources and high penetration of RES. Sajadi *et al.* [10] explored the interaction between inverter-based generation and conventional grids, emphasizing the importance of control mechanisms. Syranidou *et al.* [11] employed a pan-European dispatch model to investigate curtailment risks due to transmission limitations under high VRES scenarios. Holjevac *et al.* [12] evaluated the Croatian grid's adaptability to high-RES growth, focusing on voltage and frequency deviations and inertia reduction. Hoody *et al.* [13] examined energy transition scenarios in Antigua and Barbuda, stressing economic and technological factors in achieving 100% RES targets.

Voltage regulation and reactive power support continue to be core research themes. Al-Majali and Zobaa [14] proposed an optimal STATCOM allocation framework to enhance voltage stability across power networks. Hosseinpour and Ben-Idris [15] carried out sensitivity analyses for inverter-based systems using direct methods and simulations. Hurtado *et al.* [16] offered a system operator's viewpoint on stability assessments in low-inertia networks, while Jalalat *et al.* [17] introduced a computationally efficient STATCOM placement method. Teskeredzic et al. [18] applied dynamic phasor simulations to analyze the behavior of high inverter-based resource systems and Gan *et al.* [19] provided a broader perspective on renewable energy's role in global sustainability efforts.

Several studies have also addressed oscillatory behavior and optimization techniques in RES-dominated grids. Su An *et al.* [20] analyzed wideband oscillations, emphasizing detection and mitigation strategies. Hassan *et al.* [21] developed an improved optimal power flow algorithm incorporating FACTS devices and RES, while Sabo *et al.* [22] studied PV-induced oscillation center shifts based on plant location. Brestan *et al.* [23] evaluated the influence of grid-connected converters on power system stability and protection. Comprehensive surveys by Mastoi *et al.* [24] and Erdiwansyah *et al.* [25] further highlighted the integration challenges of wind and variable RES, respectively, focusing on control techniques, grid stability and infrastructure adaptability.

This review presents key developments in renewable energy integration in Tamil Nadu, starting with studies [6]-[11] that assess the region's capacity for solar and wind utilization. These works establish the foundation for understanding local RES potential and planning needs. Subsequent research [12]-[26] shifts focus to the technical challenges of integrating variable RES into existing grid infrastructure, offering critical insights into operational stability, voltage regulation and dispatch coordination.

A consistent theme across these studies is the emphasis on maintaining system resilience amid rising RES penetration. Notably, several works highlight the role of FACTS devices, particularly SVCs, in supporting grid stability. SVCs provide fast-acting, continuous reactive power compensation, enabling effective voltage control under dynamic conditions. As shown in Figure 2, their compact and modular design, wide operating range and adaptability to constrained spaces make them well-suited for modern transmission systems. Moreover, their low maintenance requirements contribute to long-term cost efficiency. By synthesizing these findings, the review outlines a framework for resilient, high-RES power systems-supporting both grid modernization and sustainable energy policy.

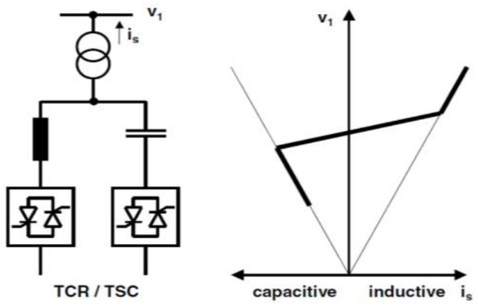


Figure 2. SVC-basic construction with V-I Characteristics

This research delves into methodologies tailored to address the challenges of integrating large-scale RES into power systems. The findings enrich the field of power system resilience and renewable energy integration, offering insights that can inform policy decisions and drive global technological advancements. This study contributes to shaping the future landscape of sustainable and resilient energy networks on an international scale.

3. RESEARCH METHODOLOGY ADOPTED

This study is based on the 400 kV Kayathar EHV transmission substation in Tamil Nadu, a key renewable energy pooling station. The model was developed using real-time operational data captured during varying wind conditions and simulated in ETAP software [26]. The substation includes eight 400 kV, eleven 230 kV and three 110 kV feeders, supported by two 315 MVA (230 kV) and one 200 MVA (110 kV) auto-transformers, as shown in Figure 3 and is structured to enable high-capacity renewable integration.

Drawing on detailed grid data-fault levels, generator specs, transformer ratings and feeder impedance-the model replicates system behavior under real operating conditions. It includes 820 MW of wind power from seven wind farm clusters and a 50 MW solar plant connected at both 230 kV and 110 kV levels. Each wind farm feeder is simulated as an induction generator with step-up transformers, reflecting the dynamic nature of renewable generation.

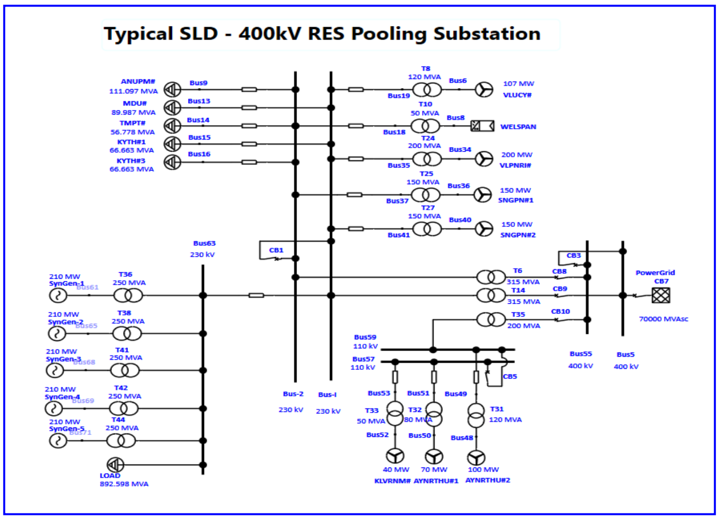


Figure 3. Typical SLD–400 kV RES pooling substation

The model supports detailed load flow, voltage sensitivity and stability analyses to evaluate the substation's performance across different load scenarios. These assessments are vital for understanding RES integration impacts and ensuring consistent grid reliability and voltage stability under diverse operating conditions.

4. RESULTS AND DISCUSSION

4.1. Load flow analysis

The load flow analysis in ETAP is performed using the adaptive Newton-Raphson method, an advanced iterative numerical technique designed to solve nonlinear algebraic equations. This essential method is based on the Taylor series expansion of the power balance equations and carefully updates the voltage at each bus during each iteration. The algorithm stops when the power mismatch at all buses falls within a specified tolerance. The adaptive Newton-Raphson method in ETAP enhances the convergence properties and overall efficiency of the standard Newton-Raphson method.

4.1.1. Test case-I

The load flow studies are conducted to align with the real-time system operating conditions. In test case I, 20% of wind generation and solar generation are considered for injection into the network in order to observe the system behaviour with minimum RES contribution. The details of generation and load are (Tables 1 and 2) as follows:

Table 1. Details of generation considered for test case-I & II

Generation details	Line type	Distance in kM	Max rating	Test case–I		Test case–II	
				MW	%Gen	MW	% Gen
PowerGrid	-	-	20000 MVA	231.95	-	-181.55	
SynGen-5x210 MW	Zebra	56.24	1050 MW	748.50	71.3	648.48	61.8
230 kV Wind #1	Zebra	20.13	107 MW	21.40	20	85.60	80
230 kV Solar #	Zebra	5.56	50 MW	10.00	20	40.00	80
230 kV Wind #2	Zebra	11.5	200 MW	40.00	20	160.00	80
230 kV Wind #3	Zebra	26.3	150 MW	30.00	20	120.00	80
230 kV Wind #4	Zebra	26.3	150 MW	30.00	20	120.00	80
110 kV Wind #1	Panther	35	40 MW	8.00	20	32.00	80
110 kV Wind #2	Panther	2	70 MW	14.00	20	56.00	80
110 kV Wind #3	Panther	2	100 MW	20.00	20	80.00	80
Total				**1153.85**		**1160.53**	

Table 2. Details of load demand considered for test case–I & II

Load details	Line type	per kM impedance	Distance in KM	MW	MVAr	% PF
230 kV Feeder #1	Zebra	0.08+0.4i	65	100	47.86	90
230 kV Feeder #2	Zebra	0.08+0.4i	125	81	38	90
230 kV Feeder #3	Zebra	0.08+0.4i	22	51	25	90
230 kV Feeder #4	Zebra	0.08+0.4i	12	60	29	90
230 kV Feeder #5	Zebra	0.08+0.4i	12	60	29	90
230 kV Feeder #6	Zebra	0.08+0.4i	56.24	800	396	90
Total				**1152**	**564.86**	

The total generation in the system for test case I is 1154 MW, comprising 980 MW from conventional sources and 164 MW from wind generation and 10 MW from Solar generation which represents 20% of the total installed RES capacity. To ensure that the bus voltages remain within permissible limits, a reactive power compensation of 1150 MVAr is added at different voltage level.

In this test case, the pooling station is handling a minimum amount of power generated from RES, resulting in a deficit of power, which is then supplemented from the 400 kV side of the power grid. This necessitates a 71.3% generation requirement from the 5×210 MW synchronous generators to fulfill the demand on the 230 kV side. This situation highlights the reliance on conventional generation sources when renewable energy generation is at a minimum. The RES capacity penetration for the test case-I is calculated as follows:

$$RES\ Capacity\ Penetration\ (in\ \%)\ =\ RES\ Gen.(in\ MW)/Total\ Gen.(in\ MW) \qquad (1)$$
$$=\ 174/1154\ =\ 15.07\%$$

4.1.2. Test case-II

In test case II, the contribution of RES generationsis ramped up from 20% to 80% is considered for integration to analyze the system behaviour with maximum RES participation. Now, the total generation in the system for test case II is 1160 MW, comprising 648 MW from conventional sources and 654 MW from wind generation and 40 MW from Solar generation which represents 80% of the total installed RES capacity. To ensure that the bus voltages remain within permissible limits, further reactive power compensation of 100 MVAr is added at different voltage level.

In this scenario, the pooling station is managing a maximum generation of RES, resulting in a surplus of power being supplied to the 400 kV side of the Power Grid. This surplus not only aids in reducing the generation requirement from the 5×210 MW synchronous generators from 71.3% to 61.8%, but it also sufficiently meets the demand on the 230 kV side. This optimization helps in better utilizing renewable sources and reducing reliance on conventional generation, which is crucial for creating a more sustainable and efficient power system. The RES capacity penetration for the test case-II is calculated as follows:

$$RES\ Capacity\ Penetration\ (in\ \%)\ =\ RES\ Gen.(in\ MW)/Total\ Gen.(in\ MW) \qquad (2)$$
$$=\ 694/1160\ =\ 59.82\%$$

Load flow results from Test case-II show that the pooling station can integrate up to 80% of the installed RES capacity while maintaining voltage within acceptable limits. This highlights the network’s readiness for high renewable penetration, a vital insight for future planning. An additional 100 MVAr of reactive power compensation was required to stabilize bus voltages, underscoring its importance in voltage control, system reliability, power flow optimization and overall power quality under high RES scenarios.

4.2. Voltage sensitivity and stability analysis

The 400 kV Kayathar Pooling Substation which is characterized by a mix of conventional 5x210MW Synchronous Generators and substantial renewable energy generation, presents an ideal case for assessing the efficacy of SVCs in stabilizing the grid under diverse loading conditions. It evaluates how the integration of SVCs influences the grid’s ability to maintain voltage stability and manage reactive power demands, especially during high renewable energy output and under various grid disturbances. This study carefully analyzes the voltage profile of the 230kV Main Bus which is critical node for the connected loads and major RES additions in the network. Also, observes how the SVCs respond to changes in load and generation patterns.

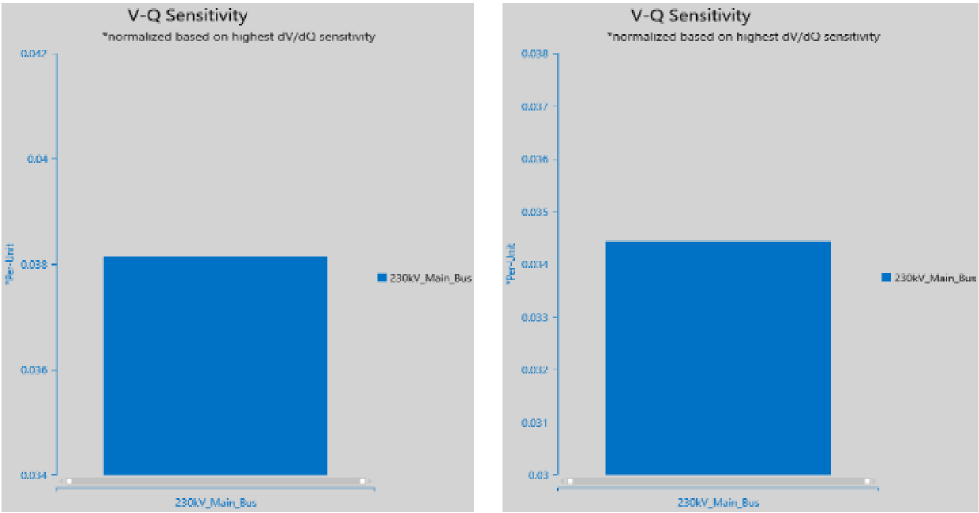
4.2.1. Voltage sensitivity

Voltage sensitivity analysis involves examining how voltage levels at different nodes in a power system are affected by changes in other system parameters, notably the reactive power injections or loads. This analysis is crucial for understanding the behavior of the system under varying load conditions and for planning reactive power compensation strategies. This factor is used to assess how sensitive the voltage at a particular bus is to changes in reactive power. It is given by:

$$dV/dQ$$

where, dV represents a small change in voltage and dQ represents a small change in reactive power.

This V-Q sensitivity can be used as an indicator of the margin of stability. A higher value which is closer to zero but not negative typically means more stability margin. The value of 0.0381 p.u observed from the base case without SVC influence, indicates that the voltage at the node is higher sensitivity to reactive power changes compared with the value of 0.0345 p.u obtained from SVC case as shown in Figure 4. A small change in reactive power will result in a very small change in voltage, suggesting a more stable condition at that node. Figure 4(a) V-Q sensitivity analysis with base case and Figure 4(b) with SVC.



(a) (b)

Figure 4. V-Q sensitivity analysis (a) base case and (b) with SVC

4.2.2. Voltage stability analysis

Voltage stability analysis aims to determine the power system's ability to maintain acceptable voltage levels at all buses under normal and contingency conditions. It involves assessing the system's response to various disturbances, including changes in load demand and generation. Power-voltage (P-V) and Q-V curves represent the relationship between power (P or Q) and voltage (V) and are used to assess the proximity of the system to voltage instability. Maximum power transfer theorem can be used to understand voltage stability limits.

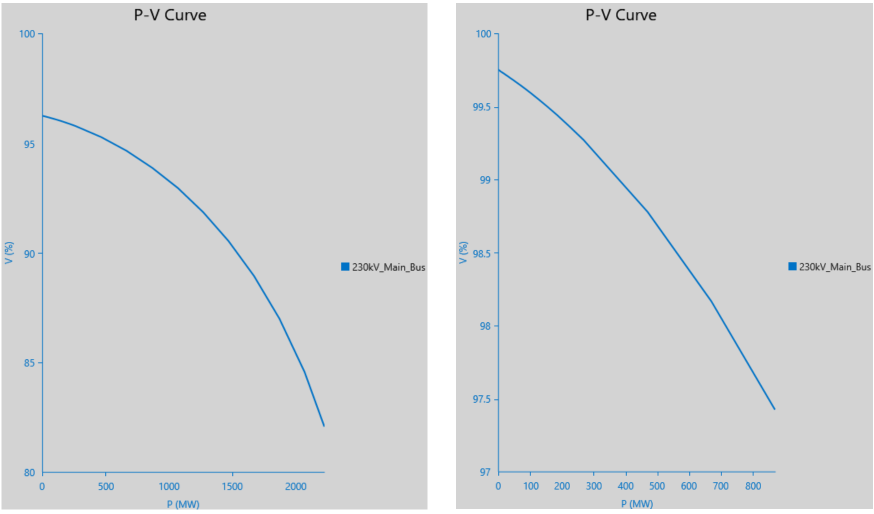
$$P_{max} = V2/X$$

Where, Pmax is the maximum power transferable, V is the voltage and X is the reactance.

A. Observation of P-V curve

Based on the study results, P-V analysis results with base case scenario without SVC impact, it can be see that the voltage percentage starts at 96.233% with no load and progressively decreases as the load increment increases. At a load increment of 1.20%, the voltage slightly drops to 96.231%, indicating a small initial voltage drop with increased load. As the load continues to increase, the voltage decrease becomes more pronounced. At higher load increments, the voltage drop is more significant. The voltage percentage decreases to 82.055% at the highest load increment provided, which shows a significant voltage drop under heavy loading conditions, indicating potential voltage stability issues without external VAR support.

In the SVC scenario, the voltage percentage starts at a higher value of 99.750% with no load, which is noticeably better compared to the base case as highlighted Figure 5. The voltage remains more stable as the load increases, with a voltage percentage of 99.721% even at a load increment of 19.80%. The SVC appears to be effectively mitigating the voltage drop. Even at high load increments, the voltage percentage stays higher compared to the base case. At the highest load increment provided, the voltage percentage is 97.422%, which is significantly higher than in the base case without SVC, showcasing the SVC's effectiveness in maintaining voltage stability. Figure 5(a) P-V curve analysis with base case and Figure 5(b) with SVC.

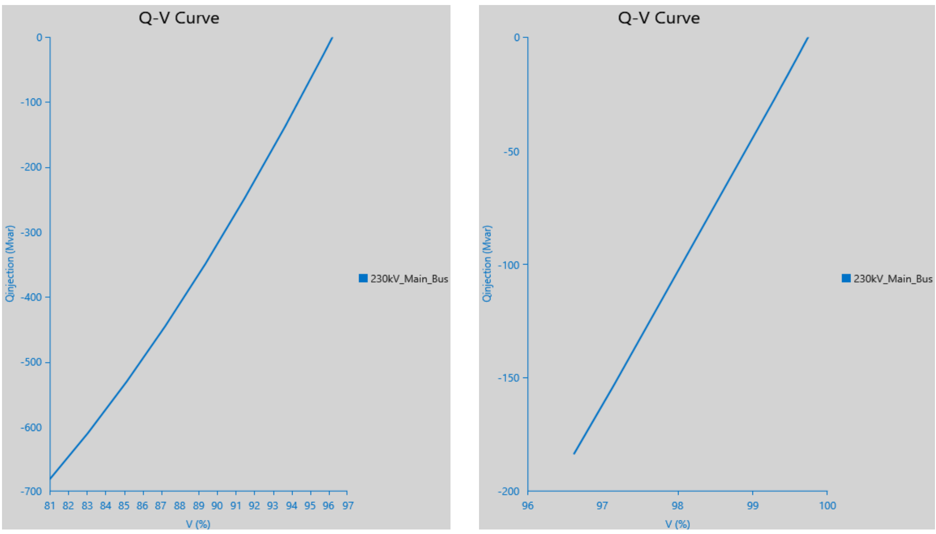


(a) (b)

Figure 5. P-V curve analysis (a) base case and (b) with SVC

B. Observation of Q-V curve

It is observed from the base case scenario without SVC inclusion, the reactive power (Q) starts at -92.609 MVAr with no load increment and becomes less negative as the load increment increases, indicating that the system is absorbing less reactive power from the bus. The V% decreases as the reactive power absorption decreases, which is expected as the voltage typically drops when reactive power support is reduced. There is a transition point where the Q value becomes positive, indicating the system is generating reactive power. As the Q values become more positive, the voltage continues to drop significantly, reaching as low as 81.017% at the highest load increment of 655.46% as indicated Figure 6.



(a) (b)

Figure 6. Q-V curve analysis (a) base case and (b) with SVC

With SVC in operation, reactive power begins at a more negative value of -298.508 MVAr under no-load conditions, indicating stronger initial voltage support. As load increases, the voltage drop is minimal, demonstrating enhanced stability. The SVC continues to absorb reactive power even at higher load increments, maintaining voltage above 96% up to a 165.55% load increase. This consistent support confirms SVC's effectiveness in stabilizing voltage across varying load conditions. The summarized results in Table 3 present a comparative overview of voltage sensitivity and stability performance across different scenarios.

Table 3. Summary of voltage sensitivity and stability analysis

Parameter	Base case (Without SVC)	With SVC	Improvement (%)
Voltage sensitivity (V-Q)	0.0381 p.u. (high sensitivity)	0.0345 p.u. (lower sensitivity)	9.45% reduction
Voltage drop (P-V curve)	96.23% (initial) → 82.05% (peak load)	99.75% (initial) → 97.42% (peak load)	Stability maintained
Reactive power (Q-V curve)	-92.6 MVAr (unstable at high loads)	-298.5 MVAr (better reactive power absorption)	Better reactive support

Overall, the presence of SVC significantly improves voltage sensitivity and stability in the studied network, especially during high load scenarios. Its role is critical in grids with high renewable penetration, such as wind power, where managing reactive power and voltage fluctuations is essential for reliable system operation

5. CONCLUSION

This work has examined the impact of high renewable energy source (RES) penetration on voltage stability at the 400 kV Kayathar EHV pooling station in Tamil Nadu. The analysis shows that large-scale RES integration can significantly affect system voltage performance, highlighting the need for effective stability enhancement measures. The study demonstrates that Static Var Compensator (SVC) technology plays a vital role in improving system resilience by providing fast-acting reactive power support, reducing voltage fluctuations, and maintaining reliable operation across diverse load and generation conditions. Its integration strengthens the grid's ability to accommodate higher shares of renewable energy without compromising operational stability.

The outcomes provide valuable guidance for planners, operators, and policymakers in shaping strategies that balance sustainability with reliability. Moreover, the findings establish a foundation for future research into advanced FACTS-based solutions and coordinated control mechanisms aimed at further enhancing stability in renewable-rich power networks.

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AUTHOR CONTRIBUTIONS STATEMENT

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

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Chelladurai Chandarahasan	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Edwin Sheeba Percis		✓		✓		✓		✓		✓	✓	✓	✓	

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.

INFORMED CONSENT

Not applicable. This study did not involve human participants or personal data.

ETHICAL APPROVAL

Not applicable. This study did not involve human participants or animals.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author (C.C.) upon reasonable request. Certain data used in this study were obtained from State Utility operational records and are subject to confidentiality restrictions.

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