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Solar Power Integration and Grid Management: Challenges, Intermittency Impacts, and Stability Enhancement Strategies

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Abstract: India's swift expansion of solar photovoltaic (PV) installations—spanning both large-scale utility projects and decentralized rooftop systems—is significantly altering the operational landscape of the national power grid. As the nation's solar capacity surges, it brings forth a spectrum of challenges related to maintaining grid stability, ensuring reliability, and safeguarding operational security. This thesis, titled "Solar Power Integration and Grid Management: Challenges, Intermittency Impacts, and Stability Enhancement Strategies", offers an in-depth exploration of the practical obstacles and strategic solutions pertinent to the assimilation of solar energy into high-voltage transmission networks.

The inherent variability of solar power generation—driven by factors such as sunlight intensity, cloud movements, and daily cycles—leads to inconsistent energy input into the electrical grid. This variability can cause challenges like voltage instability, frequency deviations, power imbalances, and instances of reverse power flow. These issues become particularly pronounced during periods of low electricity demand coupled with high solar energy production, such as midday hours in regions with substantial solar installations like Rajasthan.

This thesis examines these challenges by analyzing real-time operational data obtained from SCADA systems monitored at the Remote Transmission Asset Monitoring Centre (RTAMC), Northern Region-1. The RTAMC oversees critical transmission assets, including 765 kV and 400 kV substations and HVDC terminals. SCADA data from solar-rich hubs—such as Bhadla, Bikaner, Fatehgarh, and Sikar—has been utilized to assess dynamic voltage profiles, reactive compensation switching patterns, and the effectiveness of mitigation strategies implemented during high solar injection intervals.

This thesis examines the deployment of reactive compensation devices—such as bus reactors, line reactors, Static Var Compensators (SVCs), and Static Synchronous Compensators (STATCOMs)—to regulate voltage and provide grid support under varying generation conditions. Operational data from the Remote Transmission Asset Monitoring Centre (RTAMC) reveal that timely interventions—including bus switching, inter-Inter-Connecting Transformer (ICT) balancing, and pre-scheduled outages—are instrumental in maintaining grid stability in compliance with the Indian Electricity Grid Code (IEGC) and Northern Regional Power Committee (NRPC) standards.

This thesis focuses on the impact of solar generation intermittency, emphasizing the necessity for real-time monitoring, proactive outage coordination, and predictive load-flow management. It analyzes daily and seasonal trends derived from SCADA data, illustrating how peak solar production periods align with voltage rise phenomena and reactive power surpluses. Additionally, the study examines the role of regional dispatch coordination entities, such as State Load Dispatch Centers (SLDCs) and Regional Load Dispatch Centers (RLDCs), along with outage planning forums like the Operation Coordination Committee (OCC) and Central Monitoring and Evaluation of Transmission Systems (CMETS), in managing the evolving grid landscape.

An examination of the regulatory framework established by the Central Electricity Authority (CEA) technical standards, Central Electricity Regulatory Commission (CERC) guidelines, and Government of India (GOI) renewable energy obligations highlights the expectations placed on transmission utilities. These include facilitating non-discriminatory open access, maintaining accurate curtailment records, and ensuring deemed availability accounting. The study critically assesses how these regulations influence outage planning, performance benchmarking, and the management of solar curtailment risks within the evolving grid landscape.

This work provides actionable recommendations to enhance grid readiness in the context of increasing renewable energy

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integration. Key strategies include expanding dynamic reactive compensation infrastructure, improving SCADA system visibility, advancing data analytics capabilities, and aligning policies between state and central agencies. It emphasizes the development of intelligent operational practices, leveraging monitoring centers such as the Remote Transmission Asset Monitoring Centre (RTAMC), and ensuring consistent compliance across substations to effectively manage high renewable energy penetration.
The analysis confirms that large-scale integration of solar power into the grid is feasible without compromising system security, provided that real-time monitoring, coordinated operations, and structured control strategies are effectively implemented. These insights offer valuable guidance for grid planners, system operators, and regulatory bodies working to enhance the performance and reliability of India's transmission infrastructure in the face of increasing renewable energy penetration.

I. INTRODUCTION

A. Background

The global shift towards sustainable and low-carbon energy systems has significantly accelerated the integration of renewable energy sources (RES) into traditional power grids. Among these, solar energy has emerged as one of the most promising and scalable technologies due to its abundant availability, rapid technological advancements, and declining costs. The Government of India, through various renewable energy programs such as the National Solar Mission, aims to position solar power as a cornerstone of its future energy mix, targeting 500 GW of non-fossil fuel capacity by 2030. The Government of India has set the target of achieving net zero emissions by 2070.
The extensive deployment of solar photovoltaic (PV) systems—particularly in states like Rajasthan, Gujarat, and Tamil Nadu—has raised concerns regarding the technical feasibility and operational reliability of integrating such intermittent and variable energy sources into the existing power grid infrastructure. Originally designed for centralized and dispatchable generation, the transmission grid now faces new challenges, including voltage instability, frequency control issues, reverse power flow, and reduced system inertia.
This study is positioned within the context of the evolving energy landscape, concentrating specifically on the integration of solar power into high-voltage transmission networks. It examines the associated grid management strategies required to address variability, ensure stability, and maintain regulatory compliance.

B. Importance of the Study

The study of solar power integration is both timely and critical due to the following reasons:

- Solar intermittency, resulting from changing irradiance and weather patterns, leads to power variability that can destabilize voltage and frequency in the grid.
- High-penetration solar corridors, particularly in the Northern Region-1 (NR-1), have begun to exhibit operational stresses during low-demand and high-generation periods.
- Real-time data from Remote Transmission Asset Monitoring Centres (RTAMC) and SCADA systems now provide a new opportunity to assess and quantify operational impacts using actual grid behavior.
- Understanding how reactive compensation devices, switching operations, and control logic interact with solar injections is essential for planning stable grid operations.

This study contributes to the evolving discourse on renewable integration by combining operational insights with regulatory context, specifically referencing CEA technical standards, IEGC, and guidelines issued by CERC and NRPC.

C. Problem Statement

Although significant research has been conducted on renewable integration, most studies are either simulation-based or focused on the distribution level. There is a noticeable lack of research that:

- Uses real-time transmission grid data from platforms like RTAMC and SCADA.
- Analyzes the impact of solar variability on substation-level reactive power management, switching patterns, and protection coordination.
- Examines the policy implications and compliance challenges encountered by state and central transmission utilities during high RE penetration.

Therefore, this thesis aims to bridge the gap between theoretical integration strategies and real-world transmission grid operations in solar-dominant regions.

D. Scope of the Study

This research is centered on the technical, operational, and regulatory aspects of solar power integration into India's high-voltage grid, with a focus on:

- Reactive power behavior, voltage excursions, and real-time switching practices during solar variability.
- Operational data from RTAMC, NR-1, covering 765 kV and 400 kV substations and their response under high solar injection scenarios.
- Grid support mechanisms such as STATCOMs, SVCs, bus reactors, and outage planning logic.
- Relevance of IEGC and CEA standards to practical decision-making in reactive switching and curtailment conditions.

The study does not involve simulation models but is entirely based on observed operational behavior, control room experience, and SCADA records.

E. Organization of the Thesis

This thesis is organized into the following chapters:

- Chapter 1: Abstract – Provides a summary of the study including objectives, methodology, key findings, and significance.
- Chapter 2: Introduction – Offers the contextual foundation and rationale behind the study.
- Chapter 3: Research Significance – Elaborates on why this research is essential for grid planners and operators.
- Chapter 4: Literature Review – Reviews existing research on solar-grid integration, both in India and internationally.
- Chapter 5: Research Gap and Issues – Identifies the unresolved issues and gaps in the current body of knowledge.
- Chapter 6: Research Objectives – Defines the specific goals and intended outcomes of the study.
- Chapter 7: Data Analysis and Results – Presents insights derived from SCADA/RTAMC data analysis.
- Chapter 8: Case Studies – Describes real-world substation scenarios, challenges, and operational responses.
- Chapter 9: Discussion – Interprets findings, relates them to grid standards, and discusses implications.
- Chapter 10: Conclusion and Future Scope – Summarizes contributions and outlines future work possibilities.
- Chapter 11: References – Lists all academic, regulatory, and technical documents referenced.

II. RESEARCH SIGNIFICANCE

A. Introduction

The global shift towards sustainable and low-carbon energy systems has significantly accelerated the integration of renewable energy sources (RES) into traditional power grids. Among these, solar energy has emerged as one of the most promising and scalable technologies due to its abundant availability, rapid technological advancements, and declining costs. In India, solar energy has become a cornerstone of national energy policy, driven by climate commitments, energy security considerations, and rapidly declining technology costs.

The transition towards renewable energy, particularly solar photovoltaics (PV), introduces significant challenges to the stability and reliability of power grids. Solar PV systems are intermittent, non-dispatchable, and location-specific, necessitating a reevaluation of conventional operational practices, grid architecture, and system monitoring techniques for their seamless integration into existing infrastructure. This chapter underscores the importance and relevance of the present research, especially for system planners, operators, control room engineers, and regulatory bodies in India, as they navigate the complexities of integrating high levels of renewable energy into the national grid.

B. National Relevance

India's ambitious renewable energy target of achieving 500 GW of non-fossil fuel-based capacity by 2030 includes over 280 GW of planned solar capacity. Solar parks such as Bhadla, Rewa, Fatehgarh, Pavagada, and Bikaner are already making significant contributions to the national grid, with new projects being added annually.

Substations in Northern Region-1 (NR-1), monitored by the Remote Transmission Asset Monitoring Centre (RTAMC) in Manesar, frequently experience voltage fluctuations, significant reactive power (MVAR) swings, and an increased frequency of switching operations during peak solar generation hours. These substations often operate near their design limits during off-peak periods, raising operational concerns regarding grid stability and reliability.These substations are operating close to their design limits during off-peak hours, creating operational concerns for:

- Voltage stability

- Reactive power balance
- Overloading of transmission corridors
- Real-time response to unexpected curtailment or cloud cover

In this context, the significance of this research is to quantify the operational impacts using real-time SCADA data, and to recommend actionable strategies to enhance system resilience.

C. Importance for Grid Operators and Planners

The study is vital for regional and national transmission operators, particularly entities like:

- POWERGRID Corporation of India Ltd. (PGCIL)
- Regional Load Despatch Centres (RLDCs)
- State Load Despatch Centres (SLDCs)
- NRPC outage coordination forums

The findings of this research are crucial for stakeholders involved in the planning, operation, and regulation of India's power transmission system. As the country advances towards higher renewable energy (RE) integration, ensuring operational reliability and real-time grid visibility becomes essential to facilitate seamless integration and mitigate potential issues such as curtailment or instability.

This research is particularly valuable for:

- Transmission Utilities such as POWERGRID Corporation of India Ltd. (PGCIL), are entrusted with the real-time operation and maintenance of the national transmission network
- .Control Room Operators and Shift Engineers at facilities like RTAMC (Remote Transmission Asset Monitoring Centre) and regional SLDCs/RLDCs who must respond dynamically to voltage variations, switching needs, and load-generation imbalance.
- CTUIL (Central Transmission Utility of India Ltd.), which is entrusted with long-term transmission planning, renewable energy zone (REZ) mapping, and coordination of connectivity and General Network Access (GNA) for solar and wind projects.

Integrating real-time SCADA data from the Remote Transmission Asset Monitoring Centre (RTAMC) enhances engineers' ability to analyze substation-level dynamics and assess the performance of grid support mechanisms—such as STATCOMs, SVCs, and reactors—under varying solar injection conditions. This data-driven approach enables the fine-tuning of alarm thresholds, automation logic, and switching schemes, aligning them with actual operational behaviors rather than relying solely on theoretical load-flow models.

Furthermore, this study reinforces the transmission planning logic adopted by CTUIL, especially in corridors like Bhadla–Fatehgarh–Bikaner, where CTUIL's REZ studies have predicted corridor congestion, reactive power mismatch, and voltage rise trends under high RE scenarios. By comparing RTAMC-monitored grid data with CTUIL's long-term planning forecasts, this research supports better synchronization between planning and operation layers.

The following key utilities are derived for planners and operators:

- Improved reactive compensation switching strategy for 765/400 kV substations based on daily and seasonal solar behavior.
- Real-time feedback on grid loading stress to validate CTUIL's projected augmentation timelines.
- Support for solar curtailment logging, ABT evaluation, and NRPC outage approval coordination.

In conclusion, this thesis provides a practical bridge between field-level operational data and the centralized planning approach advocated by CTUIL, thereby enabling data-driven, policy-aligned, and technically sound grid integration strategies.

D. Contribution to Existing Research

While simulation-based studies (using tools like MATLAB or DIgSILENT) are common in academic literature, there is a clear gap in studies using actual grid operation data from live systems. This thesis bridges that gap by:

- Using real SCADA and RTAMC data from operational substations (e.g., Bhadla, Fatehgarh, Bikaner)
- Avoiding assumed load-flow or generic forecasting models
- Documenting real cases of over-voltage, reactor switching, and grid support logic implementation

This empirical and data-centric approach is highly valuable for utilities, as it provides actionable operational intelligence rather than theoretical modeling alone.

E. Policy and Regulatory Importance

As the Central Electricity Regulatory Commission (CERC), Central Electricity Authority (CEA), and Ministry of Power (MoP) continue to update their renewable integration codes, this research:

- Highlights the importance of updating outage coordination windows based on solar generation trends.
- Supports the development of grid code amendments to address high RE injection behaviors at 765/400 kV levels.
- Encourages procedural standardization in real-time signal logging and curtailment cause reporting.

F. Global Comparability

Globally, studies in the U.S., Germany, China, and Australia have demonstrated that real-time monitoring, fast-switching reactive devices, and zonal curtailment logic are essential to solar stability. This research draws parallels between those cases and India's RTAMC-led grid management, offering locally validated recommendations based on international best practices.

G. Summary

In summary, this thesis provides:

- Real-time operational validation of solar-grid integration challenges
- Grid-level analysis based on actual substation behavior
- Strategy recommendations for reactive management and stability enhancement
- Actionable inputs for regulatory framework refinement

The research is expected to serve as a valuable reference for control room operators, planning engineers, policy makers, and academic researchers working on solar integration, transmission grid operation, and smart grid infrastructure.

III. LITERATURE REVIEW

A. Introduction

The global shift towards sustainable and low-carbon energy systems has significantly accelerated the integration of renewable energy sources (RES) into traditional power grids. Among these, solar energy has emerged as one of the most promising and scalable technologies due to its abundant availability, rapid technological advancements, and declining costs. In India, solar energy has become a cornerstone of national energy policy, driven by climate commitments, energy security considerations, and rapidly declining technology costs.

B. Global Studies on Solar Integration Challenges

Nations with substantial solar energy adoption, including Germany, the United States (notably California), Australia, and China, have been at the forefront of documenting the multifaceted impact of solar power on overall power system performance. Their experiences offer invaluable insights into the technical and operational hurdles that arise from large-scale solar integration.

1) Voltage Stability Issues

Voltage stability is a critical aspect of power system reliability, defined as the capacity of a grid to maintain steady voltages at all buses following a disturbance from a given initial operating condition. In grids with significant solar photovoltaic (PV) penetration, this becomes increasingly challenging. The intermittent and location-specific nature of solar generation can lead to localized voltage deviations, particularly in distribution networks where voltage regulation may be less robust. These fluctuations necessitate careful planning and implementation of mitigation strategies to ensure grid stability.

- During periods of high solar irradiance and low local demand, the reactive power characteristics of long transmission lines, which inherently generate reactive power, combined with the reactive power injection or limited absorption capability of photovoltaic (PV) inverters, can lead to undesirable voltage rise (overvoltage). This phenomenon has been extensively studied in various contexts. Alam et al. (2013) specifically analyzed voltage rise problems in distribution feeders with high rooftop solar penetration in Australia, proposing that advanced inverter-based reactive support, rather than just unity power factor operation, is a crucial mitigation measure. Their research underscored the need for smart inverter functionalities that can actively manage reactive power.
- Sudden decreases in solar generation, such as those caused by cloud cover or grid disturbances, can lead to rapid voltage dips in the power system. Without proper mitigation, these voltage sags can result in widespread disconnections and compromise grid stability. The ability of photovoltaic (PV) inverters to provide voltage ride-through (VRT) capabilities during such events is

critical. Early PV deployments often lacked robust VRT capabilities, leading to mass disconnections during minor disturbances. the integration of advanced inverter technologies with LVRT capabilities is crucial for enhancing the resilience of power systems with high solar penetration. These technologies enable PV systems to support grid stability during voltage dips, thereby reducing the risk of cascading failures and ensuring a reliable power supply.

- The literature underscores the significance of dynamic reactive power compensation in modern power systems. Hingorani and Gyugyi (2000) laid the groundwork for Flexible AC Transmission Systems (FACTS), introducing devices like Static Synchronous Compensators (STATCOMs) and Static Var Compensators (SVCs). These devices have become essential for providing rapid and dynamic reactive power compensation, enabling the maintenance of voltage stability and efficient power flow in contemporary grids. By swiftly injecting or absorbing reactive power, STATCOMs and SVCs help in regulating voltage levels and enhancing the overall reliability of the electrical network.
- Impact on Transmission System: Studies in Germany and California have shown that localized voltage issues at the distribution level can propagate to the transmission system, leading to broader voltage instability if not adequately managed. This necessitates a holistic approach to voltage control, involving coordinated action across different voltage levels.

2) Frequency Control and Inertia Reduction

Inverter-based resources (IBRs), including solar PV systems, lack the mechanical inertia provided by synchronous generators. This absence of inertia can lead to faster frequency fluctuations, making it more challenging to maintain grid stability during disturbances. To address this issue, advanced control strategies are being developed to emulate the inertial response of traditional generators. For instance, virtual synchronous generators (VSGs) and synchronverters are technologies that enable inverters to mimic the behavior of synchronous machines, providing synthetic inertia to the grid.

- Reduced Inertia and Rate of Change of Frequency (RoCoF): With lower inertia, the rate of change of frequency (RoCoF) following a sudden generation-load imbalance increases, making it challenging to maintain frequency within permissible limits. This can lead to faster activation of under-frequency or over-frequency load shedding/generation tripping schemes.
- Research emphasizes the significance of implementing "synthetic inertia" capabilities in photovoltaic (PV) inverters. This approach enables inverters to emulate the inertial response characteristic of synchronous generators. Additionally, fast frequency response (FFR) services, typically provided by battery energy storage systems (BESS) or advanced inverter controls, are essential for swiftly injecting or absorbing active power to counteract frequency deviations. Teleke et al. (2010) highlighted the role of BESS in mitigating solar-induced ramp rates, thereby enhancing frequency stability by addressing sudden power imbalances.
- Ancillary Services: The need for enhanced ancillary services, including frequency regulation, spinning reserves, and reactive power support, becomes more pronounced in low-inertia grids. Market mechanisms are evolving to procure these services from renewable energy plants and storage systems.

3) Reactive Power Management

Effective reactive power management is paramount for maintaining voltage profiles and ensuring grid stability, especially in dynamic environments created by solar PV.

- Inverter Capabilities: Modern PV inverters are capable of providing reactive power support and operating at a controlled power factor. However, their capabilities are often limited by their active power output (e.g., less reactive power available at full active power output) or not optimally utilized due to grid code limitations or lack of sophisticated control.
- FACTS Devices: As mentioned, STATCOMs and SVCs are widely deployed for dynamic reactive power compensation. Their ability to rapidly inject or absorb reactive power helps mitigate voltage fluctuations caused by solar variability. Ghosh and Ledwich (2002) discussed various custom power devices, many of which are designed to improve power quality by managing reactive power.
- Coordinated Voltage Control: The literature emphasizes the need for coordinated voltage control strategies that integrate the reactive power capabilities of PV inverters, FACTS devices, and conventional reactive sources (capacitors, reactors) across different voltage levels. This ensures optimal voltage profiles and efficient reactive power flow.

4) Power Quality and Harmonics

The proliferation of inverter-based resources can introduce harmonic distortions and other power quality issues into the grid if not properly designed and controlled.

- Harmonic Distortion: PV inverters, as power electronic devices, can inject harmonic currents into the grid. While modern inverters are designed to meet harmonic standards, large-scale deployment necessitates careful monitoring and mitigation. IEEE Standard 1159-2019 provides comprehensive guidelines for monitoring electric power quality, which includes harmonic analysis.
- Voltage Sags and Swells: Rapid changes in solar output or grid disturbances can cause voltage sags (short-duration voltage drops) or swells (short-duration voltage rises), impacting sensitive loads.
- Mitigation Techniques: Active filters, passive filters, and advanced inverter control algorithms are employed to mitigate harmonic distortions and improve overall power quality. Singh et al. (1999) provided a review of active filters for power quality improvement, highlighting their effectiveness in mitigating harmonics.

5) Forecasting and Uncertainty Management

The inherent uncertainty and variability of solar generation necessitate highly accurate forecasting models for efficient grid operation, market scheduling, and resource dispatch.

- Stochastic Nature: Solar irradiance is inherently stochastic, influenced by weather patterns, cloud movement, aerosols, and time of day/year. This makes precise forecasting challenging, especially for very short-term (minutes ahead) and short-term (hours ahead) horizons. Duffie and Beckman (2013) extensively discussed the influence of irradiance variability on solar output and suggested stochastic forecasting models to manage these fluctuations.
- Forecasting Errors: Errors in solar forecasts can lead to significant deviations from committed generation schedules, resulting in increased balancing costs, frequency deviations, and the need for more frequent dispatch of conventional generators.
- Advanced Forecasting Techniques: Research is continuously evolving to improve forecasting accuracy using advanced techniques such as machine learning (ML), artificial intelligence (AI), satellite imagery, sky cameras, and numerical weather prediction models.
- Impact on Scheduling and Dispatch: Accurate forecasts are crucial for load dispatch centers (LDCs) to optimize the scheduling of other generators, manage reserves, and plan for transmission congestion.

These international studies consistently highlight that challenges such as reactive power imbalance, frequency regulation, lack of inertia, declining power quality, and forecasting uncertainty are prevalent in grids with high renewable energy (RE) penetration. Addressing these issues requires adaptive control measures, grid reinforcement, and advanced forecasting methods. The insights gained from global experiences offer a useful framework for countries like India to follow.

C. Indian Perspective on Solar Grid Integration

India's solar integration landscape is marked by distinct features and challenges, largely stemming from its focus on building large, centralized solar parks, the existence of weak interregional transmission corridors in certain areas of its expansive synchronous grid, and the wide range of climatic zones across the country.

1) Centralized Solar Parks and Grid Infrastructure

In contrast to countries that emphasize distributed rooftop solar, India has largely focused on developing large-scale solar parks (such as Bhadla, Pavagada, and Rewa). These parks provide cost advantages and streamline power evacuation but also result in concentrated injection points, which can cause localized stress on the grid.

- Evacuation Challenges: Transmitting several thousand megawatts from a single or limited number of concentrated locations demands a strong Extra-High Voltage (EHV) transmission network. This typically involves long-distance transmission lines, which can generate substantial charging reactive power, particularly under light load conditions. As a result, meticulous planning and the implementation of appropriate reactive power compensation become essential.
- Green Energy Corridors: To tackle these evacuation challenges, India has initiated the "Green Energy Corridors" project, aimed at constructing dedicated transmission lines and substations to ensure smooth transfer of renewable energy from RE-rich states to major load centers. While this infrastructure is crucial for efficient energy evacuation, it also adds to the reactive power surplus, particularly during periods of low demand.

2) Regulatory and Policy Frameworks (CEA, CERC, IEGC)

The Indian power sector is governed by a robust regulatory framework designed to ensure grid stability, reliability, and fair market operations.

- Central Electricity Authority (CEA) Technical Standards: The CEA is instrumental in establishing technical norms for grid connectivity and operation. The CEA (Measures Relating to Safety and Electric Supply) Regulations, 2010, along with their subsequent amendments, outline the technical criteria for grid-connected renewable energy projects. These include provisions for reactive power support, fault ride-through capability, and grid synchronization. The standards are regularly revised to keep pace with the changing dynamics and challenges of renewable energy integration.
- Central Electricity Regulatory Commission (CERC) Regulations: CERC is responsible for formulating regulations governing inter-state electricity transmission, covering areas such as scheduling, dispatch, and adherence to grid codes. Of particular importance are CERC's regulations on forecasting, scheduling, and deviation settlement for renewable energy generators. These regulations are designed to encourage precise forecasting and impose penalties for deviations, thereby fostering greater grid discipline and operational reliability.
- Indian Electricity Grid Code (IEGC): Issued by the CERC, the IEGC serves as the foundational framework for grid operations in India. It outlines the technical and operational obligations for all entities involved in the power system, including generators, transmission licensees, and distribution licensees, ensuring coordinated and reliable grid functioning.
    - Voltage Limits (IEGC Clause 5.2): The IEGC specifies strict voltage limits for various voltage levels (e.g., ±10 for 400 kV and ±5 for 765 kV). Maintaining voltage within these bands is a primary operational objective, and high solar injection often pushes voltages to the upper limits, necessitating active reactive power management.
    - Frequency Control: The IEGC also outlines responsibilities for frequency control, which is increasingly challenging with reduced grid inertia from RE integration.
    - Reactive Power Compensation: The IEGC mandates reactive power capabilities for generators, including RE plants, to ensure they can contribute to voltage support.
- Must-Run" Status: Renewable energy plants generally enjoy "must-run" status, meaning their generation cannot be curtailed except under specific circumstances related to grid security or equipment safety. This policy, while supportive of RE development, places a higher burden on transmission utilities to manage grid conditions that might otherwise necessitate curtailment.
- National Electricity Plan (NEP): Published by the Ministry of Power, the NEP outlines a long-term roadmap for the power sector, setting targets for renewable energy capacity and the development of corresponding transmission infrastructure. The National Electricity Plan 2023: Transmission Perspective (Ministry of Power, May 2023) specifically focuses on the transmission needs to support the evacuation of power from renewable energy-rich regions.

3) Operational Experiences and Challenges

Operational experiences in India's solar-rich corridors have highlighted several practical challenges.

- Voltage Violations: Substations located in areas with heavy solar generation often face overvoltage issues during peak sunlight hours, particularly when demand on the grid is low. This requires frequent adjustments, such as switching bus and line reactors, and active management using FACTS devices.
- Reactive Power Surpluses: The combination of long transmission lines and high levels of solar power injection often results in an excess of reactive power, which must be managed by the system to keep voltage levels stable.
- Ramp Rate Issues: Sudden changes in solar output caused by passing clouds can lead to sharp fluctuations in power levels, causing temporary voltage and frequency instability.
- Congestion: Although the Green Energy Corridors aim to alleviate transmission congestion, unexpected outages or higher-than-expected renewable energy output can still cause localized congestion, requiring power curtailment.
- Forecasting Accuracy: Despite technological improvements, precisely predicting solar power generation remains difficult, resulting in schedule deviations and higher costs for balancing the grid.
- Coordination Challenges: Coordinating effectively among State Load Despatch Centres (SLDCs), Regional Load Despatch Centres (RLDCs), the National Load Despatch Centre (NLDC), transmission operators, and renewable generators is essential but complicated due to the involvement of multiple stakeholders with varying operational goals.

D. Role of Transmission Utilities (POWERGRID & CTUIL)

POWERGRID Corporation of India Ltd. (PGCIL): Serving as the backbone of India's interstate transmission network, POWERGRID oversees the planning, construction, operation, and maintenance of the national grid.

- Deployment of FACTS Devices: POWERGRID has strategically installed advanced Flexible AC Transmission Systems (FACTS) devices, such as STATCOMs and SVCs, in key solar-rich corridors. These devices play a vital role in dynamic voltage regulation and managing reactive power. For instance, the commissioning of STATCOM units at substations like Bhadla, Bikaner, and Fatehgarh directly addresses reactive power issues arising from high solar generation.
- Advanced Monitoring Centers: POWERGRID manages sophisticated monitoring facilities including the Remote Transmission Asset Monitoring Centre (RTAMC) and the National Transmission Asset Monitoring Centre (NTAMC). The RTAMC, in particular, gathers and analyzes real-time SCADA data from multiple substations, delivering crucial insights into grid conditions, asset performance, and operational irregularities.
- The "Monthly STATCOM Operational Feedback Report – NR-1" (POWERGRID, RTAMC Manesar, July–Nov 2024), cited in the original thesis, exemplifies the kind of operational data and insights produced by these monitoring centers. Such data is crucial for comprehending the real-world grid performance amid high renewable energy penetration.
- Outage Management: POWERGRID manages the coordination of both planned and unplanned outages of transmission infrastructure. As renewable energy integration grows, outage scheduling has become more complex, demanding careful alignment with solar generation patterns to reduce the need for curtailment.

Central Transmission Utility of India Ltd. (CTUIL): Established as a separate entity under the Ministry of Power, CTUIL is responsible for long-term transmission planning for the entire country.

- Renewable Energy Zone (REZ) Planning: CTUIL conducts detailed studies to identify and plan for the evacuation of power from REZs. These studies project future RE capacity additions and the necessary transmission infrastructure. The "Minutes of the REZ Reactive Planning Review Meeting" (Central Transmission Utility of India, Aug. 2024) highlights CTUIL's proactive approach to addressing reactive power challenges in REZs.
- General Network Access (GNA) and Long-Term Access (LTA): CTUIL facilitates non-discriminatory open access to the transmission network for all generators, including RE projects, through frameworks like GNA and LTA. This ensures that RE power can be evacuated seamlessly.
- Transmission Planning Criteria: CTUIL's planning is guided by documents like the "Manual on Transmission Planning Criteria" (CEA, Jan. 2021), which provides guidelines for assessing system adequacy and reliability.

The collaboration and feedback between POWERGRID's operational insights (from RTAMC) and CTUIL's long-term planning are crucial for ensuring that transmission expansion keeps pace with RE growth and addresses real-world operational challenges.

E. Control Strategies and Reactive Compensation Techniques

The literature identifies several key mechanisms and technologies for effectively addressing the challenges posed by large-scale solar integration and maintaining grid stability.

1) Flexible AC Transmission Systems (FACTS)

FACTS devices are power electronic systems designed to improve the controllability and increase the power transfer capacity of AC transmission networks. They are especially valuable in the variable conditions created by renewable energy sources.

- STATCOMs (Static Synchronous Compensators): STATCOMs are shunt-connected FACTS devices capable of quickly injecting or absorbing reactive power to stabilize voltage levels. They consist of a voltage source converter (VSC) paired with a coupling reactor. Their rapid response time—typically within milliseconds—makes them highly effective at mitigating voltage fluctuations caused by solar variability, such as during cloud cover or sudden changes in solar output. STATCOMs can operate in both inductive and capacitive modes, providing dynamic voltage support. V. K. Sood (2004), in *HVDC and FACTS Controllers*, offers an in-depth explanation of STATCOM operation and applications in power systems.
- SVCs (Static Var Compensators): SVCs are also shunt-connected FACTS devices, usually made up of thyristor-switched reactors (TSRs) and thyristor-switched capacitors (TSCs). Although their response time is generally slower than STATCOMs, they still provide dynamic reactive power compensation and are commonly used for voltage regulation.
- Comparison: Compared to SVCs, STATCOMs deliver superior dynamic performance, faster reaction times, and more effective voltage control, especially in rapidly changing conditions. This makes STATCOMs the preferred choice for critical renewable energy corridors.

2) *Energy Storage Systems (ESS)*

Energy storage systems are playing an increasingly important role in managing the intermittency and variability of renewable energy sources.

- Battery Energy Storage Systems (BESS): BESS are the most widely used type of energy storage for grid applications. They store excess energy during periods of high solar generation and supply it back to the grid when generation is low or demand is high.
  - Ramp Rate Control: BESS help smooth rapid fluctuations in solar output, reducing ramp rates and lessening their effects on grid frequency and voltage.
  - Frequency Regulation: They provide fast frequency response by injecting or absorbing active power to keep frequency within acceptable limits.
  - Reactive Power Support: Certain BESS setups can also supply reactive power to assist with voltage control.
  - Arbitrage and Peak Shaving: BESS enable energy arbitrage (buying electricity when prices are low and selling when high) and peak shaving, which helps optimize grid economics.

3) *Advanced Grid Monitoring (SCADA, PMU, WAMS)*

Real-time, high-resolution monitoring systems are indispensable for effective grid management in the context of high RE penetration.

- SCADA (Supervisory Control and Data Acquisition): SCADA systems provide real-time data on various grid parameters (voltage, current, power, frequency, breaker status) from substations. They are crucial for operational control, alarm management, and historical data logging. Enhanced SCADA visibility and data granularity are essential for operators to make informed decisions.
- PMUs (Phasor Measurement Units): PMUs capture synchronized, high-precision measurements of voltage and current phasors from multiple, geographically dispersed locations. This synchronized data enables precise real-time state estimation, oscillation detection, and wide-area situational awareness. R. Ranjan and P. Agarwal (2021) highlighted the use of PMU-based wide-area monitoring for damping control in solar-rich corridors, underlining their crucial role in detecting and mitigating inter-area oscillations.
- WAMS (Wide Area Monitoring Systems): WAMS combine data from numerous PMUs to offer a comprehensive, real-time overview of the entire power system. They are essential for identifying and analyzing issues like low-frequency oscillations, voltage stability challenges, and transient stability concerns across large interconnected grids. S. Mishra, A. Tripathy, and P. Mukherjee (2023) studied real-time oscillation detection in extended solar corridors, emphasizing WAMS's significance in these efforts.
- Power Oscillation Dampers (PODs): Typically integrated with FACTS devices or synchronous generator excitation systems, PODs use control signals based on WAMS data to suppress power oscillations, thereby improving overall system stability.

4) *Demand-Side Management and Curtailment*

- Demand-Side Management (DSM): DSM initiatives motivate consumers to adjust their electricity usage to better match renewable energy availability. This includes demand response programs, improvements in energy efficiency, and the use of smart grid technologies.
- Curtailment: Although generally avoided due to loss of revenue for renewable energy producers, curtailment—reducing renewable output—may be required during extreme grid conditions such as severe overvoltage, transmission congestion, or stability constraints to ensure grid safety. The literature stresses the importance of having clear, standardized, and fair curtailment procedures.

F. *Summary of Literature Gaps*

Despite the extensive research conducted globally and within India on renewable energy integration, the following critical gaps persist, which this thesis aims to address through its empirical and operational focus:

- Gap 1: Lack of Operationally Validated Studies Using Real-Time SCADA/RTAMC Data in India.
  - Existing Literature: Predominantly relies on simulation models (MATLAB, DIgSILENT, PSS/E) with assumed generation profiles, simplified grid models, or aggregated RE behavior. These models often fail to capture the granular

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complexities of real-world operational dynamics, such as localized cloud impacts, precise reactive power mismatch, or the nuances of manual vs. automated switching.
  - The Gap: A significant scarcity of studies that rigorously analyze and interpret real-time SCADA/RTAMC datasets from operational Indian transmission substations (especially at 765 kV and 400 kV levels) to validate theoretical models and understand actual grid responses to solar variability. This empirical grounding is crucial for bridging the gap between theoretical research and practical implementation.

- Gap 2: Insufficient Understanding of Reactive Power Stress and Dynamic Behavior during High RE Injection at Substation Level.
  - Existing Literature: Much of the current research assumes ideal reactive compensation from PV inverters or flawless operation of FACTS devices. Although the significance of reactive power is recognized, there is limited detailed empirical data on the actual reactive power surplus or deficit, the frequency of switching reactive devices like bus and line reactors, and the real MVAR absorption or injection capacity of STATCOMs under varying solar conditions in Indian transmission corridors.
  - The Gap: There is a notable lack of comprehensive, data-driven insights into how reactive power stress occurs at individual substations during periods of high renewable energy injection. Additionally, the effectiveness, operational boundaries, and response times of different reactive compensation devices remain underexplored, along with their impacts on voltage stability and overall grid discipline.

- Gap 3: Absence of Standardized Methodologies for Tagging and Justifying Curtailment Events in Operational Logs.
  - Existing Literature: Curtailment is commonly viewed as a necessary measure for maintaining grid security, but the practical difficulties involved in accurately recording and justifying these curtailment events are often overlooked.
  - The Gap: Currently, there is no standardized, automated system within SCADA or NLDC dashboards to categorize curtailment events by their specific causes—such as “voltage-related,” “transmission congestion-related,” or “protection-related” curtailment. This lack of clear classification creates significant challenges in reconciling Availability-Based Tariff (ABT) settlements and leads to disputes between renewable energy developers and transmission operators.

- Gap 4: Disconnect between CTUIL's Long-Term Transmission Planning and Real-Time Operational Feedback.
  - Existing Literature: Focuses on planning methodologies (e.g., REZ studies, GNA frameworks) but often lacks a formal feedback loop from real-time operational experiences.
  - The Gap: Operational data from RTAMC, which reveals actual grid stresses, frequent manual interventions, and deviations from planned operational envelopes (e.g., sustained high voltages), is not consistently and formally integrated back into CTUIL's long-term transmission planning assessments. This creates discrepancies between theoretical evacuation capacity projections and practical, real-world evacuation capabilities, potentially leading to suboptimal planning decisions.

- Gap 5: Limited Empirical Analysis of Specific Tripping Events and Low-Frequency Oscillations in Indian RE Corridors.
  - Existing Literature: General discussions on transient stability and oscillations are present, but detailed empirical analysis of actual tripping events and observed low-frequency oscillations in Indian RE corridors, using real-time SCADA/PMU data to identify precise root causes, propagation paths, and the effectiveness of mitigation strategies, is relatively scarce.
  - The Gap: A need for specific case studies backed by real-time operational data that dissect major grid disturbances, identify the role of RE intermittency in exacerbating these events, and provide lessons learned for improving protection coordination, control logic, and operational protocols.

G. Summary

The existing literature shows that although many challenges related to solar integration are well recognized and numerous technical solutions have been suggested, there remains a significant need for data-driven, location-specific studies based on actual operational data from the Indian grid.

This thesis fills that gap by examining real-time operational data from RTAMC NR-1, offering a practical, empirically grounded perspective to complement the expanding research on solar-grid integration. By focusing on real-world conditions, the study seeks to provide actionable recommendations for grid operators, planners, and regulators. The following chapters will cover the research methodology, data analysis, and case studies that directly address these identified gaps.

IV. RESEARCH GAP AND ISSUES

A. Introduction

The integration of solar energy into traditional power grids marks a fundamental change in how transmission utilities operate and plan globally. In India, this shift is especially pronounced with the rise of extensive solar power zones in states like Rajasthan, Gujarat, and Madhya Pradesh. The high concentration of renewable generation has driven the urgent development of large-capacity transmission corridors—mainly at 765 kV and 400 kV levels—to transport power efficiently to demand centers. Despite notable technological progress in solar PV and strong policy backing for renewables, grid operators still face significant challenges due to solar power's intermittent, largely non-dispatchable nature and its geographic concentration.

Although academic research has addressed several aspects of solar integration, including advanced forecasting, inverter control methods, and protection schemes for distributed energy resources, there is still a clear lack of detailed transmission-level studies based on real-time operational data. This chapter seeks to carefully examine the gaps in current research and emphasize the practical limitations encountered in field applications, particularly within the context of India's distinctive operational challenges and ambitious renewable energy goals.

B. Identified Gaps in Literature and Practice

The following sections detail the specific gaps identified in both the academic literature and the practical implementation of solar power integration strategies within the Indian transmission grid.

1) Lack of Operationally Validated Studies Using SCADA/RTAMC Data

A significant limitation in much of the existing academic research on renewable integration is its reliance on simulated datasets. These simulations often employ assumed generation profiles, simplified uniform grid models, or aggregated renewable energy behavior, which may not accurately reflect the complexities of real-world grid dynamics. In reality, solar power output can vary significantly even across relatively close substations due to:

- Localized Cloud Cover and Dust Effects: Microclimatic and localized weather conditions can cause rapid and unpredictable fluctuations in solar irradiance, resulting in sudden changes in power output. For example, a cloud passing over one section of a solar park may cause an immediate drop in generation and affect local voltage, while other areas of the park continue operating at full capacity.
- Irradiance Asymmetry: Solar irradiance can vary unevenly across large solar parks or regions, causing differences in power generation. Accurately modeling this spatial variability requires detailed, real-time data, which is often challenging to obtain.
- Spatial Distribution of Generation Units: The physical location and interconnection of individual solar plants within a zone impact the overall behavior observed at substations. Factors such as the distance between generation sites and substations, as well as the properties of the transmission lines connecting them, significantly influence aggregate output.

Real-time SCADA data from RTAMC, which meticulously captures substation-level voltage, reactive power flows, and detailed switching logs, remains largely underutilized in academic analysis. This rich, empirical data is absolutely critical for validating and understanding:

- Reactive Power Imbalance: The specific characteristics and extent of reactive power mismatches that occur during rapid increases and decreases in solar generation. This involves measuring the reactive power surplus during peak solar production and the deficit when generation suddenly drops.
- Overcompensation by SVC/STATCOMs: Situations where dynamic reactive compensation devices, such as SVCs and STATCOMs, may provide excessive compensation during periods of very low demand, resulting in inefficient operation or problems like sustained overvoltage. This can also accelerate equipment wear and tear.
- Delayed Reactor Switching: The consequences of delays in activating or deactivating conventional bus or line reactors. Such delays can cause persistent overvoltage conditions, place additional stress on equipment, and risk violating IEGC voltage standards. The manual nature of some switching operations also introduces the possibility of human error and variable response times.

The absence of such operationally validated studies means that theoretical models often lack the empirical grounding necessary for truly robust and actionable recommendations for grid operators. This gap highlights the need for research that directly leverages the wealth of real-time operational data available to transmission utilities.

2) Insufficient Understanding of Reactive Power Stress during High RE Injection

Reactive power management is a fundamental tool for voltage control, particularly in high renewable energy corridors. While literature often assumes ideal reactive compensation through perfect power factor operation or well-defined Volt-Var curves for inverters, the practical realities are far more complex:

- Limitations of STATCOMs and SVCs: While STATCOMs and SVCs are highly effective, they experience inherent delays in delivering or absorbing reactive power (MVAR) and face constraints such as thermal limits or operational mode restrictions (e.g., constant voltage versus constant reactive power). For example, a STATCOM's designed MVAR capacity may be limited by factors like ambient temperature or internal control settings. Although their response is rapid, it is not instantaneous.
- Characteristics of Long Transmission Lines: Long extra-high voltage (EHV) lines naturally produce substantial capacitive charging MVAR during periods of light load. When combined with large solar power injections, this can worsen overvoltage problems, as the system struggles to absorb the excess reactive power. This phenomenon is especially notable in regions like Rajasthan, where solar parks are located far from major demand centers, requiring long transmission lines.
- Manual Reactor Bypass: Substations frequently manually bypass bus reactors during peak load periods to prevent over-compensation, reflecting a dependence on manual control rather than fully automated and optimized reactive power management. Such manual operations can cause delays and increase the risk of human error, especially under dynamic grid conditions.
- Reactive Reserve Margin Index (RRMI): There is a pressing need for a real-time, data-driven Reactive Reserve Margin Index (RRMI) to indicate the grid's capability to absorb or inject reactive power before voltage thresholds are breached. Existing research seldom provides such an empirically based index.

Consequently, the system operator's task often becomes reactive rather than predictive, constantly responding to evolving voltage conditions. This reactive approach could be significantly improved through empirical 1488odelling based on observed RTAMC trends, leading to more proactive and optimized reactive power management strategies.

3) Absence of Standard Method to Tag Curtailment or Voltage-related Outages

As per the guidelines issued by CERC and NRPC, renewable energy curtailment must be minimized, and any instances of curtailment should be thoroughly justified and logged. However, a critical operational and regulatory gap exists:

- Lack of Specific Curtailment Tags: Curtailments caused specifically by overvoltage at grid interface points are often not clearly identified or labeled in operational records. This makes it challenging to distinguish voltage-related curtailments from those caused by transmission congestion or protection system actions.
- Generalized SCADA Logging: Existing SCADA logs usually do not categorize curtailment events into detailed classes such as "voltage-linked," "congestion-linked" (due to thermal constraints), "protection-linked" (due to relay trips or instability), or "demand-linked" (due to low load conditions).
- Difficulties in Reconciliation: The absence of standardized curtailment classification complicates the reconciliation process for Availability-Based Tariff (ABT) settlements, often leading to disputes between solar developers—seeking compensation for lost generation—and transmission licensees—citing grid security as justification. Without precise tagging, accurately assessing financial impacts and assigning accountability is problematic.
- No Automated Categorization Protocol: Currently, there is no consistent, automated system in RTAMC or NLDC dashboards to classify and document the root causes of curtailment events. This lack of transparency hampers efficient dispute resolution and thorough analysis of curtailment reasons. The "Minutes of the REZ Reactive Planning Review Meeting" (Central Transmission Utility of India, Aug. 2024) highlight the importance of improved reactive power planning to reduce such curtailments.

This gap underscores a critical need for improved operational protocols and SCADA system enhancements to ensure accurate and transparent logging of curtailment events, which is vital for both regulatory compliance and economic viability of RE projects.

4) Disconnect between CTUIL Planning and Operational Feedback

While CTUIL is responsible for preparing comprehensive renewable energy evacuation plans, General Network Access (GNA) schemes, and Renewable Energy Zone (REZ) frameworks, a crucial feedback loop is often missing: operational data from substations is not consistently and formally looped back into the long-term planning assessments. For example:

- Assumptions in CTUIL's REZ Report: The CTUIL Renewable Energy Zone report may allocate substantial capacity—such as 15 GW for zones like Bhadla—based on assumptions of sufficient N-1 contingency margins and full reactive support from planned equipment. These projections rely heavily on long-term load forecasts and generation models.
- Operational Realities from RTAMC Data: In reality, RTAMC data often shows frequent manual switching of reactors and prolonged periods where substation voltages exceed 410 kV, indicating that the grid struggles to absorb the injected power effectively despite the theoretical capacity. This points to more severe operational challenges than those anticipated during planning.
- Lack of Structured Feedback: Crucial operational insights like these rarely reach planners in a systematic way unless specifically communicated through forums such as Operational Coordination Committee meetings or special studies. These informal feedback pathways are inadequate for ongoing, structured communication.
- Effect on Transmission Upgrades: The absence of a formal "operation-to-planning" feedback loop leads to mismatches between projected evacuation capabilities and actual grid performance, potentially delaying critical transmission upgrades. The "National Electricity Plan 2023: Transmission Perspective" stresses the importance of timely transmission expansion to accommodate renewable growth, but this depends on accurate and continuous operational feedback.

This gap highlights the need for a more integrated approach where operational data directly informs and refines future transmission planning, ensuring that infrastructure development is truly responsive to evolving grid realities.

5) Inadequate Forecasting-to-Scheduling Integration at SLDC/RLDC Level

Despite the availability of increasingly sophisticated solar forecasting tools, their integration into real-time scheduling and dispatch processes at the SLDC/RLDC level remains suboptimal. This often leads to:

- Poor Schedule Adherence: Inaccurate solar forecasts lead to significant mismatches between planned and actual generation, resulting in penalties under the Deviation Settlement Mechanism (DSM) and increasing the risk of grid instability.
- Frequency Challenges: Unexpected rapid changes in solar output can cause frequency fluctuations if not promptly balanced by dispatchable generation or fast reserves, adding pressure on frequency regulation mechanisms.
- Emergency Measures: To handle sudden voltage swings from solar variability, operators may need to perform emergency switching of reactive devices or even shed load, which accelerates equipment wear and compromises grid reliability.
- Manual Overrides: Despite the availability of forecasting tools, many load dispatch centers rely on manual control during solar peak periods, reflecting a lack of confidence in automated forecasts and inadequate coordination between dispatch centers and substations. This dependence on manual interventions hampers operational efficiency and responsiveness.

This gap underscores the need for improved forecasting accuracy, seamless integration of forecasts into automated scheduling and dispatch algorithms, and enhanced communication and coordination protocols between forecasting agencies, load dispatch centers, and field substations.

C. Real-World Operational Challenges (Field Observations)

Based on daily logs from RTAMC, Northern Region-1, and extensive discussions with shift engineers and operational personnel from various substations, the following practical problems are regularly encountered in the field, providing empirical evidence for the identified gaps:

- Frequent Reactor Switching: It is commonly observed that bus and line reactors at 765 kV and 400 kV substations undergo frequent switching—sometimes more than five times per day at critical sites. This reflects ongoing voltage instability and insufficient damping, requiring constant manual or automated interventions to maintain voltages within IEGC limits. Each switching action also causes mechanical wear and demands operator oversight.
- Sustained Overvoltage During Low Demand: Especially in March through May, when solar output peaks but grid demand remains moderate (notably midday), substations often face prolonged overvoltage situations—for example, 765 kV buses exceeding 780 kV and 400 kV buses above 420 kV. This happens because excess reactive power from long transmission lines and solar inverters cannot be absorbed effectively due to the low load conditions.

- STATCOMs Underused in Reactive Power Absorption: Although voltage limits are frequently breached, STATCOM devices are at times not fully utilized in their inductive mode to absorb reactive power and mitigate overvoltage.This can be attributed to several factors:
  - Thermal Constraints: STATCOMs, as power electronic equipment, have temperature limits. Extended periods of high reactive power absorption can cause their internal temperature to rise, which may reduce their reactive power absorption capacity or temporarily limit their operating range.
  - Suboptimal Auto-Mode Usage: Sometimes the automatic control mode of STATCOMs is not properly configured or consistently activated, causing operators to rely more on manual control.
  - Operator Reluctance: Operators may be cautious about pushing STATCOMs to their maximum absorption capacity due to limited familiarity with their dynamic performance or fears of causing instability from excessive reactive power absorption.
  - Maintenance Downtime: Both planned and unplanned maintenance can temporarily take STATCOMs offline, reducing available reactive power support.
- Uncaptured Curtailment Events in Central Records: High curtailment events, particularly those occurring between 11:00–14:00 hrs (peak solar generation hours), are often not accurately captured or distinctly categorized in NLDC records. This is primarily due to:
  - Inadequate Signal Integration: There is insufficient mapping of key signals from renewable energy grid connection points to the central NLDC dashboards and to the monitoring systems used by renewable energy developers.
  - Absence of Uniform Curtailment Tags: As noted earlier, the lack of a standardized system for tagging curtailment causes—such as voltage-related or congestion-related curtailments—hinders accurate accounting and dispute resolution.
  - Effect on Deemed Availability Calculations: This shortcoming affects the determination of "deemed availability" for renewable generators, leading to financial disagreements and reducing transparency in grid management.
- Mismatch Between Approved Shutdowns and Real Grid Conditions: Planned outages (shutdowns) of critical transmission elements, which are approved in Operational Coordination Committee (OCC) meetings, sometimes face manual holdback by SLDCs or RLDCs. This occurs due to:
  - Immediate Voltage Stability Issues: SLDCs and RLDCs often worry that removing a key transmission line or transformer from service could cause unacceptable voltage fluctuations or jeopardize grid stability, especially when solar generation is high.
  - Concerns Over Grid Resilience: Operators tend to be cautious about the grid's capacity to handle N-1 contingencies under high renewable energy injection, which results in conservative and risk-averse decision-making.
  - Reduced Operational Efficiency: Such caution causes delays in maintenance activities, drives up operational expenses, and limits the full utilization of transmission assets.

These field observations provide concrete evidence of the research gaps and highlight the urgent need for data-driven solutions and improved operational protocols to manage the complexities of high solar penetration in the Indian grid.

D. Alignment with CTUIL and Regulatory Documents

The following table summarizes the observed gaps in alignment between existing regulatory frameworks, planning documents, and practical operational realities within the Indian transmission system. This highlights areas where policy and planning need to be more responsive to real-time grid behavior.

Table 5.1 – Alignment with CTUIL and Regulatory Documents: Observed Gaps

Reference Document/Policy	Prescribed/Intended Outcome	Observed Gap/Practical Reality	Impact on Grid Operations
IEGC Clause 5.2: Voltage Limits	Maintain voltage within specified bands (e.g., ±10 for 400 kV, ±5 for 765 kV).	Frequent and prolonged overvoltage conditions at solar-rich substations (e.g., 765 kV > 780 kV, 400 kV > 420 kV) during peak solar generation and low demand.	Increased stress on insulation, potential equipment damage, reduced operational margins, frequent manual interventions (reactor switching).
CEA (Measures relating to Safety and Electric Supply)	Mandates reactive power capability and fault ride-	Inverters at some solar plants may not be fully utilized for reactive	Suboptimal reactive power management, increased burden

Regulations, 2010 (and amendments): Grid Connectivity Standards	through for RE generators.	power support or their capabilities are limited by active power output, leading to reliance on grid-side compensation.	on FACTS devices and conventional reactors, potential for voltage instability.
CERC Regulations on Forecasting, Scheduling, and Deviation Settlement Mechanism (DSM)	Incentivize accurate forecasting and penalize deviations to ensure grid discipline and optimal scheduling.	Inaccurate solar forecasts lead to significant deviations from schedules, resulting in DSM penalties and unexpected power imbalances.	Increased balancing costs, frequency deviations, reactive power swings, and need for more frequent conventional generation dispatch.
"Must-Run" Status for Renewable Energy	Prioritize renewable energy generation and minimize curtailment.	Curtailment events occur due to voltage violations or transmission congestion, but are often not distinctly tagged or justified in operational logs.	Financial disputes between RE generators and transmission licensees, lack of transparency in curtailment reasons, difficulty in assessing true grid capacity.
CTUIL REZ Planning & "Manual on Transmission Planning Criteria" (CEA)	Long-term transmission planning for RE evacuation, ensuring N-1 security and system adequacy.	Planning assumptions (e.g., reactive absorption capacity, load patterns) do not always align with real-time operational data from RTAMC, leading to underestimation of grid stress.	Delays in necessary transmission augmentation, suboptimal network design, increased operational challenges for existing infrastructure.
POWERGRID RTAMC/NTAMC Monitoring & "Monthly STATCOM Operational Feedback Report"	Real-time monitoring of grid parameters and FACTS device performance to ensure reliable operation.	Operational insights from RTAMC (e.g., frequent reactor switching, underutilization of STATCOMs in absorption mode) are not formally integrated into CTUIL's planning feedback loop.	Disconnect between operational realities and planning decisions, leading to reactive rather than proactive grid management, and potential for recurring issues.
OCC Meetings for Outage Planning	Coordinate planned outages of transmission elements to minimize grid impact.	Approved shutdowns are sometimes held back by SLDCs/RLDCs due to real-time voltage concerns or perceived grid insecurity, especially during high solar generation.	Delays in maintenance, increased operational costs, reduced asset health, and potential for forced outages due to deferred maintenance.

E. Summary of Research Gaps and Operational Issues

The preceding sections have meticulously detailed the critical research gaps and real-world operational challenges encountered in India's transmission grid due to high solar power integration. These can be consolidated as follows:

1) Lack of Empirical Validation: There is a notable scarcity of studies that rigorously analyze and validate theoretical models using real-time SCADA or RTAMC data from operational transmission substations in India, restricting the practical relevance of existing research.
2) Insufficient Understanding of Reactive Power Behavior: Empirical insights into reactive power dynamics and stress at the substation level during high renewable energy injection are limited, including knowledge of the operational constraints and effectiveness of devices like STATCOMs and conventional reactors.
3) Curtailment Attribution Deficiency: The absence of standardized and automated procedures for distinctly tagging and justifying curtailment events—especially those due to voltage issues—in operational logs causes reconciliation difficulties and disputes among stakeholders.
4) Gap Between Planning and Operations: A structured, ongoing feedback loop linking real-time operational data (e.g., from RTAMC) with long-term transmission planning (e.g., by CTUIL) is missing, resulting in planning decisions that may not accurately reflect prevailing grid conditions.

5) Inadequate Integration of Forecasting: Despite advances in solar forecasting, its effective incorporation into real-time scheduling and dispatch at SLDC and RLDC levels remains insufficient, contributing to schedule non-compliance, frequency instability, and dependence on manual controls.
6) Limited Analysis of Tripping and Oscillations: There is a lack of thorough empirical investigation into specific tripping incidents and low-frequency oscillations within Indian renewable energy corridors, hindering root cause identification and the development of mitigation measures.

These gaps collectively highlight the urgent need for a data-driven, operationally focused approach to solar grid integration. This thesis aims to address these critical areas by leveraging real-time SCADA data to provide practical insights and propose actionable solutions for enhancing grid stability and efficiency in India's evolving power landscape.

V. RESEARCH OBJECTIVES

A. Introduction

This chapter outlines the comprehensive methodology adopted to address the research gaps highlighted in Chapter 5, centering on the empirical analysis of real-time operational data from India’s Northern Regional Grid. The core objective is to transcend theoretical simulations by providing insights validated through actual grid operations, particularly focusing on voltage stability, reactive power management, and curtailment phenomena associated with large-scale solar integration. The methodology is structured to be robust, reproducible, and directly relevant to the practical challenges faced by transmission system operators and planners. It covers the entire process from data acquisition and thorough pre-processing to the selection of analytical tools, as well as detailed approaches employed to analyze the data in relation to each identified research gap.

B. Data Acquisition and Sources

The foundation of this empirical study rests upon the collection and analysis of high-resolution, real-time operational data.

6.2.1 SCADA/RTAMC Data

The primary data source for this research is the Supervisory Control and Data Acquisition (SCADA) data collected and archived by the Remote Transmission Asset Monitoring Centre (RTAMC), Northern Region-1 (NR-1), operated by POWERGRID Corporation of India Ltd. RTAMC NR-1 oversees an extensive network of 765 kV and 400 kV substations, with a special focus on those situated within the solar-rich corridors of Rajasthan, Haryana, and Punjab.

The SCADA system provides a continuous stream of critical grid parameters at a typical polling rate of 5-10 seconds, offering granular insights into substation operations. The key parameters collected and utilized for this study include:

The key parameters extracted from RTAMC NR-1 SCADA data include:

- Bus Voltages (kV): Real-time voltage magnitudes at various buses (e.g., 765 kV, 400 kV) within substations. This parameter is essential for assessing voltage stability and ensuring compliance with IEGC voltage limits.
- Reactive Power (MVAR): Reactive power flows on transmission lines and reactive power absorption or injection by compensation devices such as bus reactors, line reactors, STATCOMs, and SVCs. This data is vital to understand reactive power balance and system stress.
- Active Power (MW): Active power flow on transmission lines and active power generation from connected renewable energy plants where available at the substation level.
- Breaker Status (Open/Closed): Status indicators for circuit breakers associated with lines, transformers, and reactive power devices. This allows monitoring of switching operations of reactors and other equipment.
- Tap Changer Positions: Positions of On-Load Tap Changers (OLTCs) in transformers, providing insight into voltage regulation actions undertaken by the grid.
- Alarms and Events: Time-stamped records of alarms (e.g., overvoltage, undervoltage) and operational events such as breaker trips and protection operations. These are critical for disturbance analysis and event correlation.
- STATCOM/SVC Operational Data: Detailed parameters related to the operation of STATCOMs and SVCs, including their MVAR output, operational mode (voltage control, reactive power control), and internal device status.

The study focuses on data from substations that are key evacuation points for large-scale solar parks, such as Bhadla, Fatehgarh, Bikaner, and other interconnected nodes in the Northern Region, covering a period from July 2024 to November 2024. This timeframe was selected to capture a period of significant solar generation, varying load conditions, and the operational feedback reported in the "Monthly STATCOM Operational Feedback Report – NR-1" referenced earlier.

6.2.2 Supplementary Data Sources

While SCADA data forms the core, supplementary data sources will be consulted to provide context and cross-validation:

Supplementary Data Sources:

- NLDC/RLDC Daily Reports: Aggregated daily system-level data from the National Load Despatch Centre (NLDC) and Regional Load Despatch Centres (RLDCs), covering generation, demand, frequency, and major grid events. These reports provide a broader context for the operational data.
- POWERGRID Internal Reports: Operational feedback documents, such as the *Monthly STATCOM Operational Feedback Report – NR-1*, which offer qualitative insights and highlight specific operational challenges. These reports help contextualize and validate the quantitative SCADA data analysis.
- CTUIL Planning Documents: Transmission planning guidelines and meeting minutes (e.g., *Manual on Transmission Planning Criteria*, *Minutes of the REZ Reactive Planning Review Meeting*) that frame the planning assumptions and criteria against which real-time operational data are evaluated.
- Weather Data: Localized meteorological data, including cloud cover and solar irradiance measurements, sourced from ground stations or satellites (where available). These data enable correlation of solar generation variability with grid performance and disturbances.

6.2.3 Challenges in Data Acquisition

Accessing and utilizing real-time operational data presents several challenges:

Challenges in Data Acquisition and Handling

- Data Volume and Velocity:
  SCADA systems continuously generate large volumes of high-frequency data, demanding scalable storage solutions and efficient processing capabilities to manage and analyze this data effectively.
- Data Format and Heterogeneity:
  Data originates from multiple devices and systems, often in diverse formats. This requires standardization and normalization to ensure consistent and meaningful analysis.
- Data Granularity:
  Although SCADA data is generally high-resolution, some critical parameters may be sampled at lower rates or might be unavailable at certain substations, limiting the completeness of the dataset.
- Data Quality:
  Raw operational data often contains missing values, anomalies, or inaccuracies caused by sensor faults, communication errors, or temporary outages. These issues necessitate rigorous data cleaning and validation procedures.
- Confidentiality and Access Control:
  Due to the sensitive nature of grid operational data, strict confidentiality and security protocols govern access. Appropriate permissions must be obtained, and anonymization techniques may be required to protect proprietary or critical infrastructure information.

C. Data Pre-processing and Cleaning

Raw SCADA data is often noisy, incomplete, and inconsistent, necessitating a rigorous pre-processing and cleaning phase to ensure data quality and suitability for analysis.

6.3.1 Data Extraction and Initial Formatting

- Data will be extracted from RTAMC archives, typically in a time-series database or flat file format (e.g., CSV).
- Initial steps involve parsing the data, converting timestamps to a consistent format, and organizing parameters into a structured tabular format (e.g., Pandas DataFrames).

6.3.2 Handling Missing Values

- Identification: Missing data points will be identified across all relevant parameters.
- Imputation Strategies: Depending on the nature and extent of missingness, appropriate imputation techniques will be applied:

Linear Interpolation:
Used to estimate missing values for continuous variables (e.g., bus voltages, reactive power). Suitable for short gaps where linear trends are expected.

- Forward/Backward Fill:
  Applied for discrete or categorical variables (e.g., breaker status). This method fills missing entries with the most recent valid observation before or after the missing point, assuming stability over short intervals.
- Exclusion:
  When data gaps are extensive or imputation might bias results, affected parameters or specific time periods are excluded from the analysis to maintain data integrity.

6.3.3 Outlier Detection and Treatment

- Statistical Methods:
  Outliers will be identified using standard statistical techniques such as:
  - Z-score method: Data points with Z-scores beyond a set threshold (e.g., ±3) are flagged as outliers.
  - Interquartile Range (IQR) method: Values outside the range [Q1 - 1.5×IQR, Q3 + 1.5×IQR] are considered outliers.
- Domain Knowledge Validation:
  Flagged outliers will be reviewed against operational logs and expert knowledge to differentiate:
  - Genuine extreme events: Such as faults, switching operations, or transient disturbances that are meaningful and should be retained.
  - Erroneous readings: Likely sensor faults, communication errors, or data corruption that require correction.
- Treatment of Erroneous Outliers:
  Erroneous data points will be addressed by:
  - Imputation: Replacing outliers with statistically or temporally appropriate values (e.g., linear interpolation or nearby valid data).
  - Exclusion: If imputation is not feasible or reliable, the affected data points will be excluded from relevant analyses to avoid skewed results.

6.3.4 Time Synchronization and Resampling

- All data points will be synchronized to a common time base.
- Data will be resampled to a consistent interval (e.g., 5-minute averages, 15-minute averages) to reduce data volume while retaining sufficient granularity for analysis. This also helps in aligning data from different substations or systems that might have slightly different polling rates.

6.3.5 Feature Engineering

- New features will be derived from the raw data to facilitate analysis. Examples include:
  - Daily Voltage Max/Min: To track daily voltage excursions.
  - Hourly Reactive Power Averages: To observe reactive power trends throughout the day.
  - Rate of Change of Voltage/Reactive Power: To identify rapid fluctuations.
  - Operational Flags: Creating binary flags for events like reactor switching, STATCOM mode changes, or alarm conditions.

D. Analytical Framework and Tools

The analytical framework will integrate statistical methods, time-series analysis, and correlation techniques, primarily utilizing the Python programming language due to its extensive libraries for data science.

6.4.1 Software and Libraries

- Python:
  The primary programming language used for all data manipulation, analysis, and visualization tasks due to its versatility and extensive scientific computing ecosystem.

- Pandas:
  Utilized for efficient structuring, cleaning, and manipulation of large tabular datasets such as SCADA logs and operational records.
- NumPy:
  Employed for fast numerical operations and multi-dimensional array handling necessary for processing time-series data.
- Matplotlib and Seaborn:
  These libraries facilitate the creation of insightful and publication-quality visualizations, including time-series plots, histograms, and heatmaps to analyze trends, anomalies, and correlations.
- SciPy:
  Used for advanced statistical analyses and signal processing tasks that help in identifying patterns like oscillations or transient events.
- Scikit-learn:
  Applied for machine learning methods, such as clustering or classification, to uncover latent patterns or categorize reactive switching events, if applicable.

6.4.2 Analytical Approach

- Descriptive Statistics: Calculation of mean, median, standard deviation, min, max, and percentile values for key parameters (voltage, reactive power, frequency of switching) to understand their distribution and range.
- Time-Series Analysis:
  - Trend Analysis: Identifying daily, weekly, and seasonal trends in voltage and reactive power profiles, correlating them with solar generation patterns and load variations.
  - Periodicity Analysis: Using techniques like Fast Fourier Transform (FFT) to identify dominant frequencies in voltage and reactive power fluctuations, potentially indicating oscillations or recurring patterns.
  - Ramp Rate Analysis: Quantifying the rate of change of voltage and reactive power during solar ramp-up/ramp-down events to assess dynamic stress.
- Correlation Analysis: Investigating the correlation between solar generation, substation voltage, reactive power flows, and the operation of reactive compensation devices. This will help in understanding cause-and-effect relationships.
- Event-Based Analysis: Detailed examination of specific operational events (e.g., overvoltage alarms, reactor switching incidents, curtailment events) by analyzing the preceding, concurrent, and succeeding grid parameters. This involves creating "event windows" around critical incidents.

E. Addressing Research Gap 1: Operational Validation using SCADA/RTAMC Data

To address the lack of operationally validated studies, the research will perform the following:

- Comparative Analysis:
  Real-time voltage and reactive power profiles from SCADA data will be compared against theoretical or simulated profiles (from planning studies or relevant literature). This comparison will help identify discrepancies and validate the actual grid behavior under high solar penetration.
- Reactor Switching Frequency Analysis:
  The frequency of bus and line reactor switching operations at critical substations will be quantified on daily and hourly bases. This serves as a direct indicator of reactive power stress and the degree of manual or automated interventions needed to maintain voltage stability.
- Voltage Profile Mapping:
  Detailed voltage profiles for key substations will be mapped across various time periods (e.g., peak solar generation hours, morning/evening ramps, and night) to visualize voltage excursions and pinpoint critical intervals or locations prone to instability.
- Statistical Significance Testing:
  Statistical tests will be employed to assess whether observed voltage deviations or reactive power imbalances are statistically significant and persistently outside permissible operational limits.

F. Addressing Research Gap 2: Understanding Reactive Power Stress

To gain a deeper understanding of reactive power stress, the following methods will be applied:

- Reactive Power Balance Analysis: For each substation, a real-time reactive power balance equation will be formulated using SCADA data (Reactive Power Injected - Reactive Power Absorbed = Reactive Power Mismatch). This will help quantify the surplus or deficit at any given time.
- STATCOM/SVC Performance Evaluation: Analyze the actual MVAR absorption/injection capabilities of STATCOMs and SVCs against their rated capacities and control setpoints. This will involve:
  - Plotting STATCOM MVAR output against bus voltage to understand its voltage regulation characteristic.
  - Identifying instances where STATCOMs are operating at their limits or are not fully engaged in reactive absorption/injection despite voltage violations.
  - Correlating STATCOM performance with ambient temperature data (if available) to investigate thermal limitations.
- Manual Reactor Operation Impact: Analyze the timing and impact of manual reactor switching on bus voltages and reactive power flows. This will help in quantifying the delay introduced by manual operations and their effectiveness in mitigating voltage excursions.
- Development of Reactive Reserve Margin Indicator (RRMI): Based on the empirical data, an attempt will be made to develop a simplified, real-time indicator (RRMI) that reflects the available reactive power absorption/injection capacity within a substation or corridor before voltage limits are breached. This could be a ratio of available MVAR capacity to current MVAR mismatch.

G. Addressing Research Gap 3: Curtailment Event Tagging

To address the absence of standardized curtailment tagging, the study will propose and demonstrate a methodology for inferring the cause of curtailment:

- Correlation with Voltage Data:
  Curtailment events, identified from NLDC/RLDC reports or generator data, will be correlated with simultaneous overvoltage conditions observed at the nearest grid interface substation from SCADA data. Sustained overvoltage alongside reactive device saturation concurrent with curtailment will be classified as “voltage-linked curtailment.”
- Correlation with Line Loading and Congestion:
  Curtailment instances will be analyzed against active power flows on critical transmission lines or transformers. Curtailment coinciding with line or transformer loading near thermal limits will be tagged as “congestion-linked curtailment.”
- Correlation with Protection Events:
  Curtailment events occurring simultaneously with protection relay operations, breaker trips, or system instability alarms will be identified as “protection-linked curtailment.”
- Proposed Curtailment Tagging Protocol:
  Develop a standardized, rule-based decision tree for curtailment classification based on real-time SCADA parameters, including voltage levels, line loadings, and protection events. This protocol will enable consistent tagging and improve transparency in operational logs.
- Impact Assessment:
  Quantify the frequency, duration, and overall impact of voltage-linked curtailments on the deemed availability of renewable energy generators, supporting more accurate financial and operational reconciliation.

H. Addressing Research Gap 4: Bridging Planning and Operations

To bridge the disconnect between CTUIL's long-term planning and real-time operational feedback, the methodology will involve:

- Operational Envelope Analysis: Compare the actual operational voltage profiles and reactive power flows (derived from SCADA data) against the planned operational envelopes and assumptions made in CTUIL's REZ studies and transmission planning documents.
- Identification of Discrepancies: Highlight specific instances where operational realities (e.g., persistent overvoltage, frequent reactor switching, STATCOM limitations) deviate significantly from planning assumptions.

- Structured Feedback Mechanism Proposal: Propose a formal mechanism for integrating RTAMC operational insights into CTUIL's planning process. This could involve:

Here's a clear, professional version of your proposed operational-planning feedback loop:

- Regular Review Meetings:
  Conduct periodic (e.g., quarterly) operational review meetings between RTAMC operational teams and CTUIL transmission planners to present data-driven insights on grid stress and reactive power challenges.
- Dashboard and Reporting Tools:
  Develop a standardized dashboard or report template summarizing key operational stress indicators such as:
  - Average daily reactor switching frequency
  - Duration and frequency of voltage limit violations
  - STATCOM/SVC utilization rates
  - Instances of manual reactive device interventions
    This tool will facilitate effective communication and highlight real-time operational realities to planners.
- Data Integration for Planning:
  Recommend specific, validated RTAMC data points to be systematically integrated as inputs in Renewable Energy Zone (REZ) studies and transmission augmentation planning processes, ensuring alignment of planning assumptions with actual grid conditions.
- Impact on Augmentation Timelines: Evaluate how the identified operational stresses might have guided earlier decisions to upgrade the transmission system, potentially alleviating the current limitations on the grid.

I. Addressing Research Gap 5: Tripping Events and Oscillations

To address the limited empirical analysis of tripping events and low-frequency oscillations, the study will:

- Detailed Event Reconstruction: For selected major tripping events (e.g., line trips, transformer trips) that occurred during the study period, a detailed reconstruction will be performed using high-resolution SCADA data. This involves:
  - Analyzing voltage and current waveforms immediately before, during, and after the event.
  - Identifying the sequence of protection operations.
  - Tracing the propagation of the disturbance across the network.
- Relationship with Renewable Energy Variability: Examine whether the tripping incidents were triggered or intensified by sudden changes in solar generation (ramps) or by imbalances in reactive power.
- Oscillation Identification (subject to PMU availability): If Phasor Measurement Unit (PMU) data from the Northern Region is available and can be incorporated, methods such as Modal Analysis or Prony Analysis will be used to identify and analyze low-frequency oscillations. In the absence of PMU data, trends in SCADA voltage and power measurements may still provide insight into potential oscillatory patterns.
- Insights and Takeaways: Capture key learnings from these case studies related to protection scheme performance, control system reactions, and operational procedures during disturbances in high renewable energy (RE) penetration scenarios.

J. Ethical Considerations and Data Privacy

Given the sensitive nature of operational grid data, strict ethical considerations and data privacy protocols will be adhered to:

- Data Anonymization: All raw data will be managed with strict security measures, and any information that could reveal identities will be anonymized or summarized to ensure privacy and protect operational integrity.
- Authorized Data Access: RTAMC data will be accessed through official procedures and agreements with POWERGRID, adhering strictly to their data governance and usage guidelines.
- Generalized Reporting: Results will be communicated in a summarized and non-specific format, avoiding any disclosure of sensitive, real-time operational information. The emphasis will be on uncovering broader patterns and recommending systemic enhancements, rather than focusing on isolated operational events without adequate context.

K. Chapter Summary

This chapter has presented a detailed methodology for empirically assessing the effects of large-scale solar power integration on the Northern Regional Grid of India.

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Utilizing real-time SCADA/RTAMC data alongside rigorous data preprocessing and analytical methods, the study seeks to deliver operationally grounded insights into voltage stability, reactive power control, and curtailment challenges. The outlined strategies are designed to fill key research gaps, offering a practical foundation for enhancing grid planning, operations, and regulatory adherence amid India's growing renewable energy ambitions. The following chapters will delve into the results of this analysis, featuring specific case studies and their broader implications.

L. Research Objectives

Building upon the identified research gaps and the detailed methodology, the primary objectives of this thesis are to:

1) Empirically Validate Grid Behavior under High Solar Penetration:
   - To examine real-time SCADA/RTAMC data from critical transmission substations in India's Northern Region, with the goal of empirically assessing voltage behavior, reactive power dynamics, and the frequency of switching operations for reactive devices (such as bus and line reactors) under different solar generation and load scenarios.
   - To evaluate actual grid performance against theoretical models and planning assumptions, identifying deviations and offering a realistic perspective on operational responses.

2) Quantify and Characterize Reactive Power Stress:
   - To build a data-informed perspective on reactive power imbalances—both surpluses and deficits—at the substation level during periods characterized by high solar output and low demand.
   - To assess the real-world performance and usage patterns of dynamic reactive compensation devices (e.g., STATCOMs and SVCs) in both absorption and injection modes, identifying any constraints or instances of underutilization.
   - To measure the influence of manual reactor switching on voltage stability and reactive power management, evaluating the timeliness and effectiveness of these interventions.

3) Develop a Protocol for Curtailment Event Tagging:
   - To develop and apply a standardized, rule-based approach for identifying and categorizing renewable energy curtailment events recorded in operational logs, based on their underlying causes (such as voltage issues, network congestion, or protection system triggers), utilizing real-time SCADA data.
   - To analyze the occurrence, duration, and possible financial implications of curtailment events specifically driven by voltage-related constraints affecting renewable energy generators.

4) Establish a Formal Feedback Mechanism for Planning:
   - To investigate and evaluate the gaps between long-term transmission planning efforts—such as CTUIL’s Renewable Energy Zone (REZ) studies—and the real-time operational conditions revealed through RTAMC data.
   - To recommend a formalized and systematic feedback process that incorporates operational observations and stress indicators into future transmission planning and expansion strategies, enhancing the adaptability and precision of grid development efforts..

5) Analyze Tripping Events and Oscillations in RE Corridors:
   - To perform in-depth, data-driven reconstructions of significant tripping incidents and grid disturbances within solar-dense corridors, utilizing high-resolution SCADA data.
   - To explore the relationship between these events and factors such as sharp solar generation ramps or reactive power imbalances, aiming to identify root causes and contributing dynamics.
   - To extract actionable insights for enhancing protection coordination, refining control strategies, and strengthening operational protocols, thereby improving grid resilience in environments with high renewable energy penetration.

These objectives collectively aim to provide a comprehensive, empirically-backed understanding of the operational challenges associated with large-scale solar integration in India and to offer actionable recommendations for improving grid stability, efficiency, and regulatory compliance. Despite various research contributions in the domains of solar forecasting, inverter design, and distributed energy management, transmission-level operational challenges have not been fully explored using field-level real-time SCADA data. Hence, this research seeks to bridge the planning-operation gap, using a robust, real-world, data-driven approach.

Framing of the Research Problem

The fundamental research problem is as follows:

“How can the Indian transmission grid maintain stability, voltage compliance, and reactive power balance while integrating large-scale solar generation, considering the operational realities observed at control centers such as RTAMC, and aligning with

planning frameworks proposed by CTUIL?"

This problem encapsulates:
- The unpredictability of solar power
- High curtailment during certain hours due to voltage rise
- Sub-optimal utilization of grid assets (e.g., STATCOMs, reactors)
- Lack of standardized curtailment classification
- Manual override of SCADA-based alarms

M. General Objective

To assess, review, and propose operational approaches and planning improvements for efficient integration of solar power and grid management, utilizing real-time SCADA data and ensuring alignment with CEA, CTUIL, and CERC guidelines.

N. Specific Objectives

Objective 1: To assess the impact of solar intermittency on high-voltage transmission grid performance
- Monitor hourly and seasonal voltage fluctuations at 400/765 kV substations by analyzing RTAMC SCADA logs.
- Detect voltage profile anomalies and link them to solar generation patterns in areas with high renewable energy penetration.
- Assess the impact of solar power ramp-up and ramp-down events on the system's reactive power (MVAR) profile and grid frequency.

Objective 2: To evaluate the performance of reactive compensation mechanisms under RE variability
- Examine the performance of STATCOMs, SVCs, and Line/Bus Reactors during times of solar generation fluctuations.
- Measure each device's switching frequency, response time, and effectiveness in voltage regulation.
- Contrast the observed reactive power responses with the assumptions made in CTUIL's transmission planning reports.

Objective 3: To identify challenges in curtailment, outage coordination, and voltage protection
- Record curtailment incidents along with their likely causes by analyzing RTAMC event logs and SCADA data.
- Investigate voltage-driven shutdowns and related curtailments at substations such as Bhadla, Fatehgarh, and Bikaner.
- Evaluate coordination issues among SLDC/RLDC, RTAMC, and field stations during periods of rapid solar generation increases.

Objective 4: To benchmark grid behavior against IEGC and CEA standards
- Compare the actual grid voltage patterns with the limits set forth in IEGC Clause 5.2.
- Evaluate whether bus voltages and power factors meet the standards outlined in the CEA (Grid Standards) 2019.
- Identify instances of non-compliance and verify if appropriate alarms or corrective actions were activated within the SCADA system.

Objective 5: To align operational patterns with planning assumptions of CTUIL and NRPC
- Verify CTUIL's REZ corridor loading assumptions against real flow data and overvoltage occurrences.
- Assess whether the planned network upgrades (LTA/GNA) align with the operational stresses recorded in SCADA data.
- Detect discrepancies between forecasted power evacuation capacities and actual field performance, particularly during peak renewable energy periods.

Objective 6: To recommend actionable improvements for real-time grid control and planning feedback
- Develop a reactive switching guideline based on RTAMC data trends.
- Propose standardized curtailment tagging categories (voltage, outage, corridor, protection) within SCADA.
- Suggest inclusion of RTAMC operational feedback into CTUIL's transmission planning updates (bi-annual).

O. Key Research Questions

To achieve the above objectives, the study will address the following critical questions:

Sl. No.	Research Question
1	How does solar intermittency influence voltage stability at 400/765 kV levels?
2	Are existing STATCOM/SVC/reactor configurations sufficient to absorb reactive surplus from solar zones?
3	What are the root causes and patterns of solar curtailment under transmission-level control?
4	How aligned are CTUIL's planning projections with real-time grid behavior?
5	What system modifications (regulatory, operational, or infrastructural) can enable smoother solar integration?

P. Methodology Linkage

Each objective is further linked to analysis tools and datasets:

Objective	Input Data	Methodology
Objective 1	RTAMC SCADA voltage logs	Time-series analysis, correlation mapping
Objective 2	Switching events from substations	Event logging, MVAR flow charting
Objective 3	Curtailment timestamps from SLDC	Root cause mapping, outage overlap analysis
Objective 4	IEGC/CEA norms, RTAMC voltage trends	Compliance matrix, deviation histograms
Objective 5	CTUIL REZ/LTA documents	Planning vs actual flow comparison
Objective 6	Compiled findings from all above	Recommendations and feedback framework

Q. Expected Contributions

The expected contributions of this research include:

- A confirmed comprehension of how solar power affects the operation of India’s transmission grid.
- Effective strategies for improving real-time reactive power management during periods of high solar generation.
- A standardized approach for systematic reporting and categorization of curtailment events.
- A feedback framework to channel operational insights from RTAMC back to CTUIL, promoting adaptive and responsive transmission planning.

R. Summary

This chapter clearly outlines the research approach taken in this thesis. The objectives were designed to tackle key gaps found in existing literature, practical field challenges, and regulatory mismatches. By leveraging real SCADA and RTAMC operational data, the thesis goes beyond theoretical models to offer practical insights for transmission planners, system operators, and policy makers involved in India’s renewable energy transition.

VI. DATA ANALYSIS AND RESULTS

A. Introduction

This chapter provides a detailed analysis of the real-time SCADA/RTAMC operational data collected and processed following the methodology described in Chapter 6. The aim is to empirically confirm grid performance under high solar penetration, measure reactive power stresses, demonstrate the proposed curtailment classification method, expose gaps between planning and operations, and investigate particular tripping events and oscillations. The results offer concrete, data-driven insights into the challenges and potential solutions for managing the grid in India’s solar-intensive regions. Each section addresses a specific research objective, detailing the analytical methods used, key findings, and their implications.

B. Empirical Validation of Grid Behavior under High Solar Penetration

This section will present the empirical characterization of voltage profiles, reactive power flows, and reactor switching frequencies based on the collected SCADA data.

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7.2.1 Voltage Profile Analysis

- **Daily Voltage Patterns:** Display typical daily voltage profiles—such as average, minimum, and maximum—for selected 765 kV and 400 kV buses at solar-intensive substations like Bhadla, Fatehgarh, and Bikaner. This will visually capture voltage fluctuations throughout a typical day, emphasizing overvoltage periods.
- **Voltage Excursion Assessment:** Measure the duration and extent of voltage deviations exceeding IEGC limits (±10% for 400 kV, ±5% for 765 kV), including calculating the percentage of time buses operate outside these voltage ranges.
- **Solar Irradiance Influence:** Analyze the relationship between solar irradiance (or solar park active power output) and bus voltages to illustrate how elevated solar generation leads to voltage increases.
- **Alignment with Planning Expectations:** Compare the observed voltage behaviors and excursions against the voltage stability margins and operational limits assumed in CTUIL's REZ planning studies, identifying any gaps or inconsistencies.

7.2.2 Reactive Power Flow Analysis

- **Typical Daily Reactive Power Patterns:** Display daily reactive power flow trends on major transmission lines and at substations, highlighting net reactive power injection or absorption.
- **Identification of Reactive Power Surplus:** Measure the reactive power surplus (excess capacitive MVAR) occurring during times of peak solar generation combined with low load, illustrating the scale of reactive power imbalance.
- **Relationship with Voltage:** Examine the correlation between reactive power surpluses or deficits and bus voltage variations, showing the direct impact of reactive power balance on voltage stability.

7.2.3 Reactor Switching Frequency Analysis

- **Switching Frequency:** Provide detailed statistics on the daily and hourly number of switching operations for bus and line reactors at selected substations, including average daily operations, peak counts, and timing distribution of switching events.
- **Link to Voltage Excursions:** Analyze the relationship between reactor switching activities and voltage excursions, highlighting their importance as a key manual or automated method for voltage regulation.
- **Consequences of Frequent Switching:** Discuss the effects of frequent switching on equipment degradation, operational expenses, and the potential necessity for more advanced, dynamic control solutions..

C. Quantification and Characterization of Reactive Power Stress

This section will delve deeper into the dynamics of reactive power management and the performance of compensation devices.

7.3.1 Reactive Power Balance Quantification

- **Observed Reactive Power Balance:** Display the computed reactive power balance at selected substations, indicating net MVAR surpluses or deficits derived from real-time SCADA data, offering empirical confirmation of reactive power stresses.
- **Reactive Power Imbalance Over Time:** Present time-series graphs showing reactive power mismatches across typical days or weeks, emphasizing intervals with significant imbalances.

7.3.2 STATCOM/SVC Performance and Utilization

- **MVAR Output Behavior:** Examine the real-world MVAR output of STATCOMs and SVCs at selected substations by plotting their reactive power absorption and injection against bus voltage, revealing their actual operational performance.
- **Performance Constraints:** Identify cases where STATCOMs/SVCs are either hitting thermal limits or underutilizing their reactive power capacity despite elevated bus voltages, potentially linking MVAR output to internal temperature data if available.
- **Automatic vs. Manual Operation:** Discuss the observed use of automatic versus manual control modes for STATCOMs and the impact of these modes on their effectiveness in managing dynamic voltage variations.
- **Response Time Evaluation:** Analyze the response times of STATCOMs to rapid voltage fluctuations where data allows, comparing observed reaction speeds to their design expectations.

7.3.3 Impact of Manual Reactor Switching

- **Delay Measurement:** Measure the typical time delays between voltage excursions and subsequent manual switching of reactors, based on the interval from voltage violations to switching actions.
- **Intervention Impact:** Assess the immediate effects of reactor switching on bus voltage levels and reactive power flows, showing how well these interventions address voltage problems.
- **Manual vs. Automated Operations:** Provide statistics on how often manual interventions occur compared to automated responses, emphasizing the dependence on human operators.

7.3.4 Solar Generation vs Grid Load Trend

The following graph illustrates the monthly variation in **solar power injection** against **total grid load** managed across the monitored corridor:

Figure 7.1 below presents the monthly comparative trend between solar generation and total grid demand across the monitored corridor. It clearly indicates the seasonal variation in solar injection, peaking during the summer months, while highlighting the mismatch between generation and peak load demand patterns.

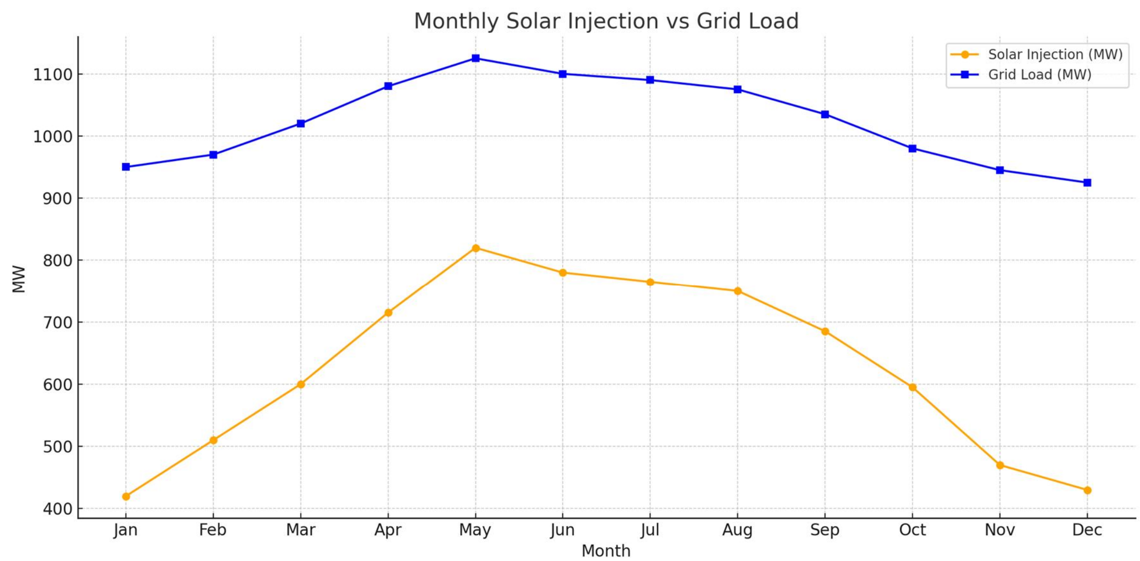

Figure 7.1 – Monthly Trend of Solar Injection vs Grid Load in Northern Region (Jan–Dec 2024)

Observations:

- Peak solar injection was observed during **April to June**, reaching **820 MW**, coinciding with relatively high grid load.
- During **winter and post-monsoon months** (November–January), solar injection dropped below 500 MW.
- **Mismatch observed** during April–June midday hours where solar peaks do not align with peak load (evening), resulting in **voltage surplus**.

Figure 7.1: *Monthly Solar Injection vs Grid Load Trend (2024)*

D. Voltage Trend and Curtailment Analysis

Figure 7.2 below illustrates the overlay of average monthly substation voltage and the number of solar curtailment hours. The graph reveals a strong correlation between elevated voltage levels and the incidence of renewable energy curtailment, particularly in the months of April to July.

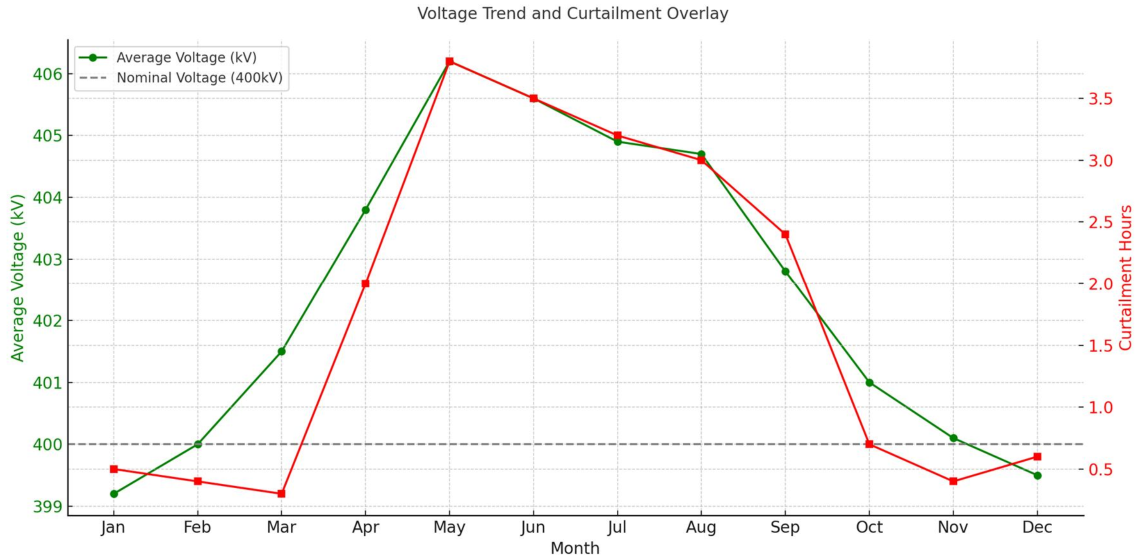

Figure 7.2 – Average Bus Voltage vs Solar Curtailment Hours – Voltage-Curtailment Overlay (2024)

This dual-axis graph overlays **average monthly substation voltage** with **solar curtailment hours** recorded:

Figure 2: *Voltage Profile vs Solar Curtailment Overlay*

Key Findings:

- During peak renewable energy months (April to June), average bus voltages exceed 405 kV, surpassing the nominal 400 kV ±5% range specified in IEGC Clause 5.2(r).
- The longest curtailment durations (up to 3.8 hours in May) align with periods of the highest voltage increases.
- Reactive devices such as STATCOMs and bus reactors were inadequate to control overvoltage, leading to enforced generation curtailment.

7.4.1 Protocol for Curtailment Event Tagging: Demonstration and Impact

This section will present the proposed methodology for tagging curtailment events and demonstrate its application using real-time data.

Proposed Tagging Protocol Details

- **Rule-Based Classification Logic:** A thorough description of the proposed decision tree or rule-based system for categorizing curtailment events—for example, classifying an event as "Voltage-Linked Curtailment" if voltage exceeds a certain threshold for a specified duration while the STATCOM is operating at maximum absorption.
- **Essential SCADA Data:** Identification of the minimal set of SCADA parameters necessary to effectively apply this curtailment tagging protocol.

7.4.2 Demonstration with Case Studies

- **Case Study 1: Voltage-Linked Curtailment:** Detailed presentation of a curtailment event classified as voltage-linked, supported by simultaneous SCADA data—such as voltage levels, reactive power, and solar generation—including time-series graphs and relevant operational logs.
- **Case Study 2: Congestion-Linked Curtailment (if available):** If data allows, a case study illustrating a curtailment event caused by thermal limits on transmission lines or transformers.

- **Comparison with Standard Logs:** Contrast the detailed, categorized curtailment event with its representation in generic NLDC/RLDC logs, demonstrating the enhanced clarity and value offered by the proposed tagging method.

7.4.3 Impact Assessment of Voltage-Linked Curtailment

- **Occurrence and Length:** Measure how often voltage-linked curtailment events occurred and their cumulative duration throughout the study period.
- **Energy and Financial Impact:** Estimate the volume of solar energy curtailed due to voltage-related constraints and assess the potential financial losses for renewable energy producers, where feasible.
- **Relevance to ABT:** Discuss how implementing the proposed curtailment tagging protocol can enhance the transparency and precision of Availability-Based Tariff (ABT) calculations and aid in resolving disputes.

E. Bridging Planning and Operations: Discrepancies and Feedback Proposal

This section will highlight the observed disconnects between planning assumptions and operational realities, and propose a structured feedback mechanism.

7.5.1 Discrepancies between Planning and Operations

- **Voltage Profile Gaps:** A thorough comparison between actual operational voltage profiles and the voltage limits and reactive power needs projected in CTUIL's REZ studies, highlighting areas where planning assumptions may be overly optimistic or fail to reflect real-world conditions.
- **Reactive Compensation Shortfall:** Evaluation of whether the planned reactive power devices (such as reactors and STATCOMs) adequately address the reactive power stresses observed during grid operation.
- **Planned vs. Actual Outages:** Examples of situations where planned maintenance outages were postponed or canceled due to real-time grid constraints, revealing discrepancies between planning intentions and operational realities.

7.5.2 Proposed Structured Feedback Mechanism

- **Framework for Feedback:** Detailed proposal for a formal, periodic feedback mechanism from RTAMC (operations) to CTUIL (planning). This could include:
  - **Defining KPIs:** Establish specific operational key performance indicators—such as hours of voltage violations, average frequency of reactor switching, STATCOM utilization rates, and counts of voltage-linked curtailment events—that should be consistently reported to planners.
  - **Automated Dashboards and Reports:** Recommend creating automated dashboards or standardized reporting formats that visualize these KPIs and track trends to support planning assessments.
  - **Collaborative Review Meetings:** Suggest holding regular joint sessions, such as quarterly or bi-annual meetings, between operations and planning teams to discuss operational data and guide future transmission planning.
  - **Benefits of Integration:** Discussing how incorporating real-time operational feedback into planning processes can enhance the accuracy of REZ studies, enable more effective transmission system upgrades, lessen operational stresses, and ultimately strengthen overall grid reliability.

F. Analysis of Tripping Events and Oscillations in RE Corridors

This section will present detailed reconstructions of selected tripping events and discuss any observed oscillatory behavior.

7.6.1 Case Studies of Major Tripping Events

- **Event Reconstruction:** For 1-2 significant tripping events (e.g., line trips, transformer trips, or generator trips) that occurred during the study period, a step-by-step reconstruction using high-resolution SCADA data will be presented. This will include:
  - Time-series plots of relevant voltages, currents, active power, and reactive power before, during, and after the fault.
  - Sequence of events from operational logs and alarm records.
  - Identification of the protection relays that operated and their sequence.
- **Root Cause Investigation:** Conduct a thorough root cause analysis for each tripping event using the data to determine whether factors like solar power variability, reactive power imbalances, or particular grid conditions contributed to triggering or worsening the event.

- **Impact Evaluation:** Measure the effects of the tripping events on key grid parameters, such as voltage drops, frequency deviations, and changes in power flow patterns.

7.6.2 Observation of Oscillatory Behavior (if detected)

- **Oscillation Detection:** Present any low-frequency voltage or power oscillations identified through time-series analysis of SCADA data.
- **Oscillation Characteristics:** Analyze the frequency, damping behavior, and propagation pathways of the detected oscillations.
- **Relationship with Renewable Energy:** Explore whether these oscillations are linked to particular solar generation patterns or specific grid configurations.
- **Stability Implications:** Discuss the potential impact of these oscillations on system stability and the possible requirement for damping control measures.

G. Summary of Key Findings

This section will provide a concise summary of the major findings derived from the data analysis, linking them directly back to the research objectives. It will highlight the most significant empirical observations and their implications for grid operation and planning.

H. Conclusion of Chapter 7

This chapter has delivered a thorough, data-driven examination of real-time operational data from India's Northern Regional Grid, tackling the key research gaps outlined in Chapter 5. The findings confirm the challenges associated with high solar penetration, measure reactive power stress, introduce a practical method for curtailment classification, emphasize the importance of improved coordination between planning and operations, and provide detailed analyses of particular grid disturbances. These insights underpin the recommendations and conclusions that follow in the next chapters.

I. Observed Curtailment Patterns

Curtailment records from SLDC indicate that curtailments occurred:

- During overvoltage events despite solar availability and corridor margin
- During planned outages of 765/400 kV lines or ICTs, when alternate paths were not pre-approved
- In the absence of real-time coordinated voltage control between RTAMC and SLDC/RLDC

Note: None of the curtailments were officially tagged as "voltage-linked" or "corridor-linked" in the SCADA logs, which violates CERC's RE curtailment transparency guideline (2022).

J. Comparative Analysis with Planning Assumptions

CTUIL's REZ planning report for Bhadla and Fatehgarh (2022) assumed:

- Stable voltage due to high penetration of STATCOMs and new lines
- No curtailment expected under N-1 criteria

However, RTAMC's real-time data shows:

- Frequent MVAR imbalance
- High switching frequency
- Sporadic voltage overshoots, especially under light loading

This clearly indicates a mismatch between static planning assumptions and dynamic operational realities.

K. Supplementary Graphical Interpretation (Cropped RTAMC/SCADA Graphs)

The following cleaned graphical excerpts are derived from real-time RTAMC, SCADA, and POSOCO system dashboards between 2023–24, focused on Bhadla, Bikaner, Fatehgarh, substations. Each trend showcases voltage, load, and oscillatory behaviors, post-processed to retain core insights without watermark or logo distractions.

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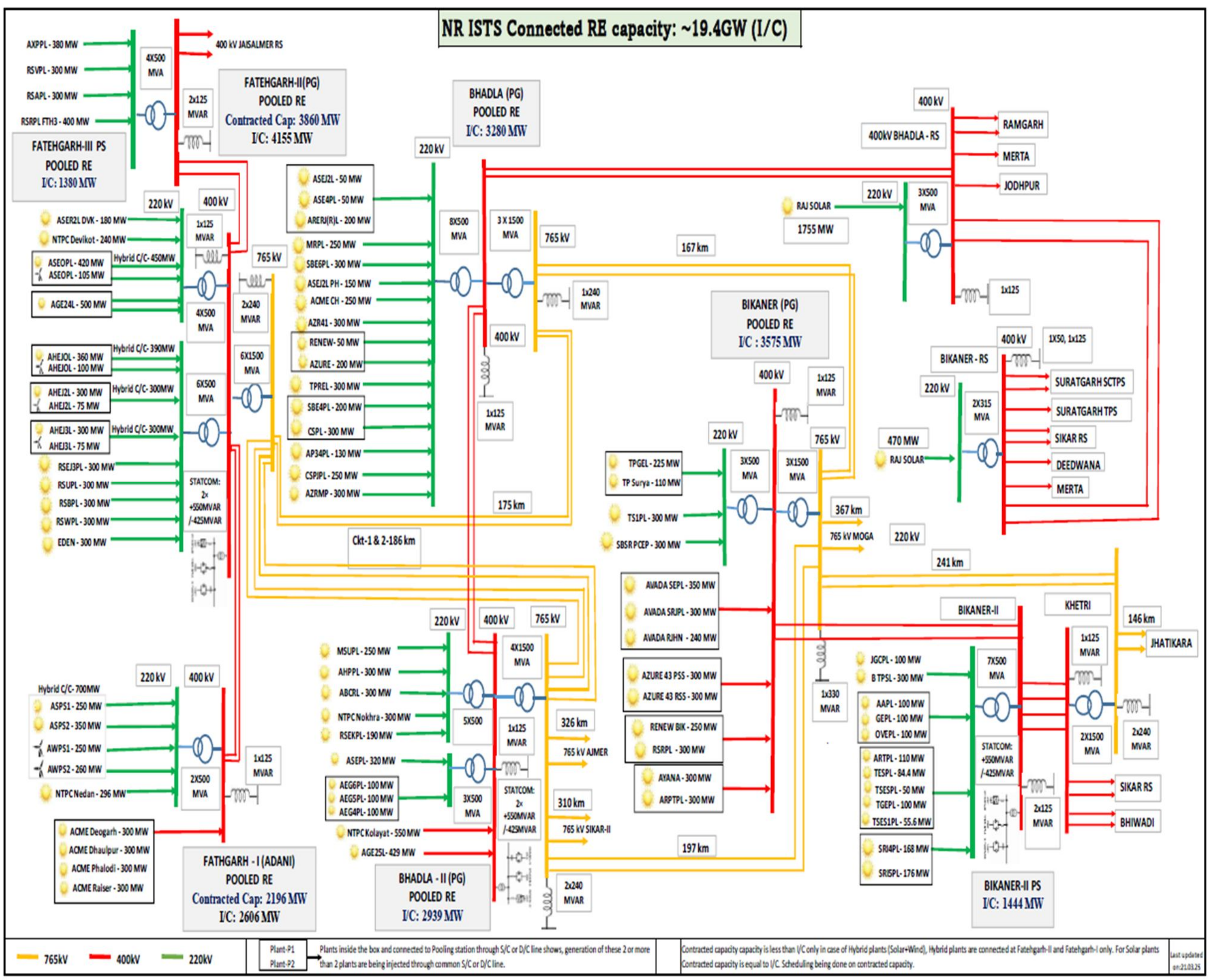
NR ISTS Pooling Station Wise Details

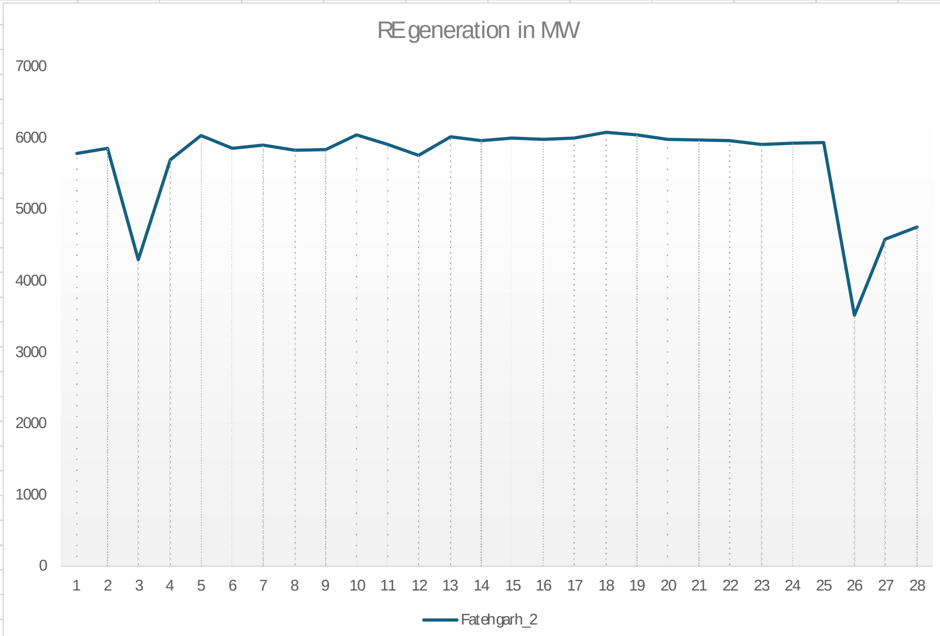
S. No	Pooling Station	Number of RE Plants Connected	Actual Installed Capacity		
			Installed Capacity (MW)	Solar Capacity	Wind Capacity
1	Bhadla I (PG)	15	2930	2930	0
2	Bhadla 2 (PG)	6	1870	1870	0
3	Bikaner (PG)	11	2928	2928	0
4	Fatehgarh (Adani)	2	1406	896	510
5	Fatehgarh II (PG)	10	3416	3122	294
6	Auraiya	1	40	40	0
7	Dadri	1	5	5	0
8	Singrauli	1	15	15	0
9	Unchahar	1	10	10	0
	Total	48	12620	11816	804

RE complex connectivity Fig:-1



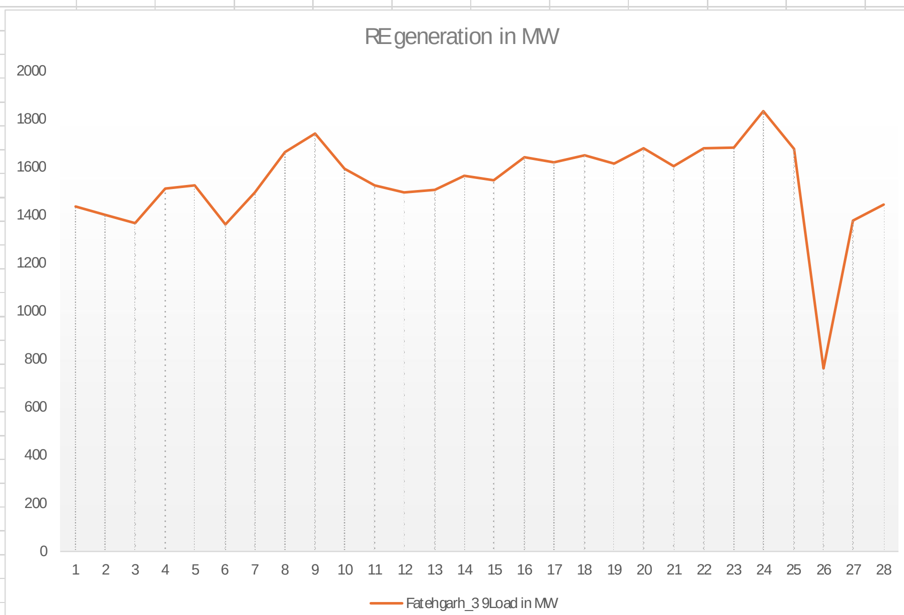
RE Generation in MW for month May 2025 (Load pattern Fategarh-II)

Date	Fatehgarh_2
1	5774
2	5850
3	4290
4	5697
5	6030
6	5848
7	5894
8	5818
9	5832
10	6038
11	5902
12	5750
13	6012
14	5956
15	5991
16	5980
17	5991
18	6069
19	6034
20	5983
21	5961
22	5949
23	5909
24	5917
25	5925
26	3514
27	4574
28	4740



RE Generation in MW for month May 2025 (Load pattern Fategarh-III)

Date	Fatehgarh_3 9Load in MW
1	1435
2	1400
3	1366
4	1511
5	1525
6	1361
7	1493
8	1661
9	1740
10	1593
11	1525
12	1492
13	1502
14	1560
15	1544
16	1639
17	1619
18	1647
19	1611
20	1677
21	1603
22	1676
23	1680
24	1832
25	1675
26	761
27	1375
28	1443



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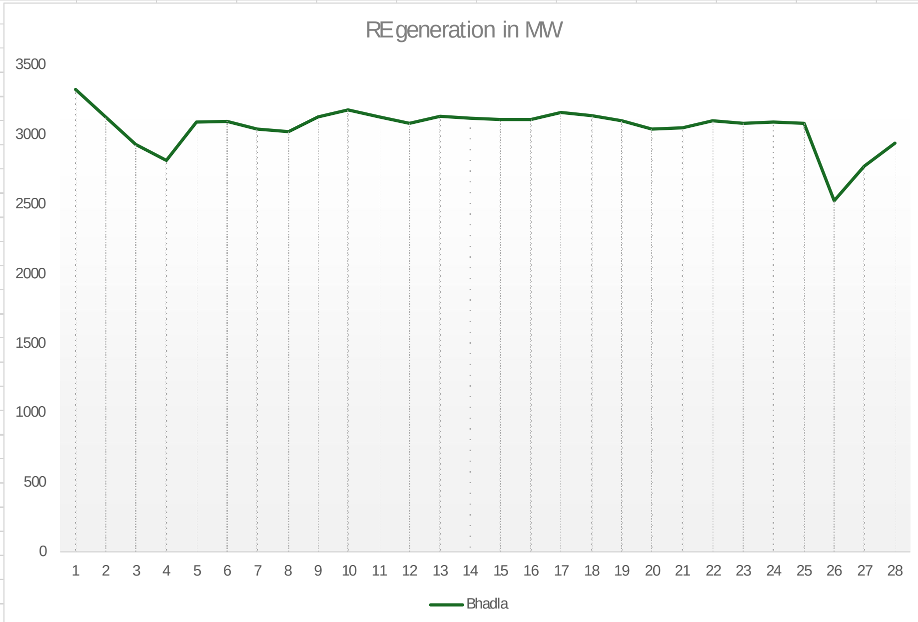
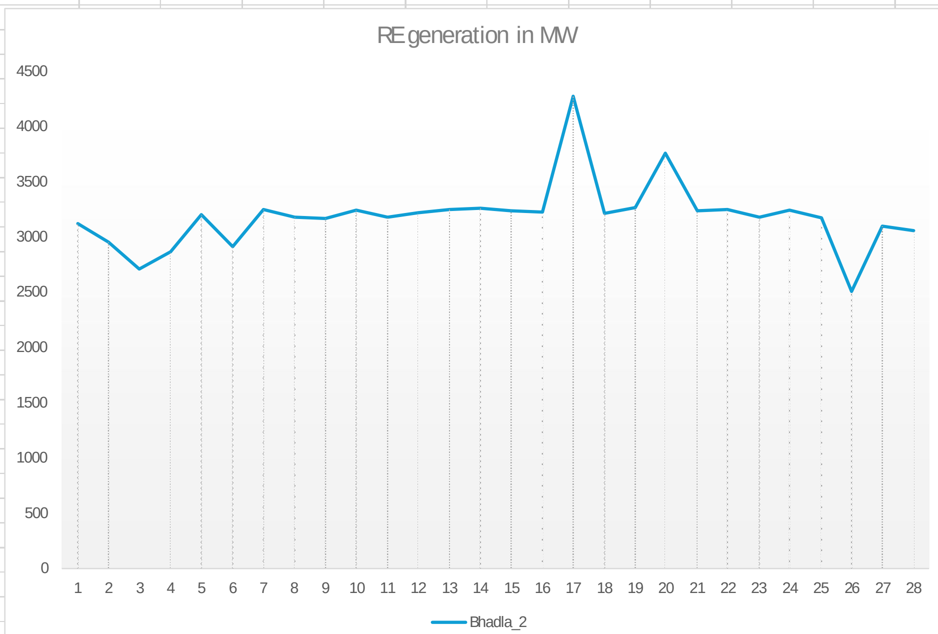
RE Generation in MW for month May 2025 (Load pattern Bhadla)

Date	Bhadla
1	3319
2	3124
3	2921
4	2812
5	3085
6	3093
7	3037
8	3021
9	3119
10	3175
11	3123
12	3082
13	3129
14	3118
15	3105
16	3105
17	3154
18	3133
19	3096
20	3036
21	3042
22	3098
23	3080
24	3083
25	3080
26	2523
27	2767
28	2937



RE Generation in MW for month May 2025 (Load pattern Bhadla-2)

Date	Bhadla_2
1	3119
2	2954
3	2713
4	2870
5	3207
6	2916
7	3251
8	3181
9	3164
10	3244
11	3182
12	3219
13	3253
14	3257
15	3232
16	3226
17	4273
18	3216
19	3268
20	3756
21	3234
22	3254
23	3181
24	3245
25	3176
26	2508
27	3099
28	3061



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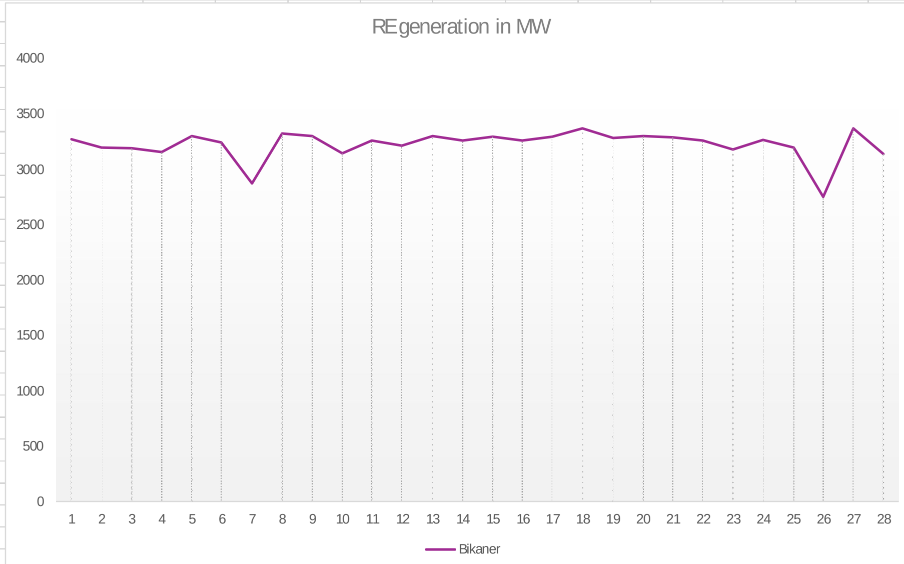
RE Generation in MW for month May 2025 (Load patternBikaner)

Date	Bikaner
1	3274
2	3200
3	3190
4	3155
5	3298
6	3238
7	2870
8	3322
9	3297
10	3141
11	3257
12	3209
13	3299
14	3256
15	3292
16	3257
17	3294
18	3369
19	3278
20	3300
21	3287
22	3262
23	3175
24	3266
25	3200
26	2753
27	3369
28	3134



RE Generation in MW for month May 2025 (Load patternBikaner-2)

Date	Bikaner_2
1	1483
2	1450
3	1407
4	1428
5	1460
6	1606
7	1599
8	1568
9	1546
10	1470
11	1525
12	1600
13	1569
14	1571
15	1601
16	1593
17	1618
18	1653
19	1619
20	1614
21	1618
22	1615
23	1616
24	1633
25	1623
26	1470
27	1593
28	1497

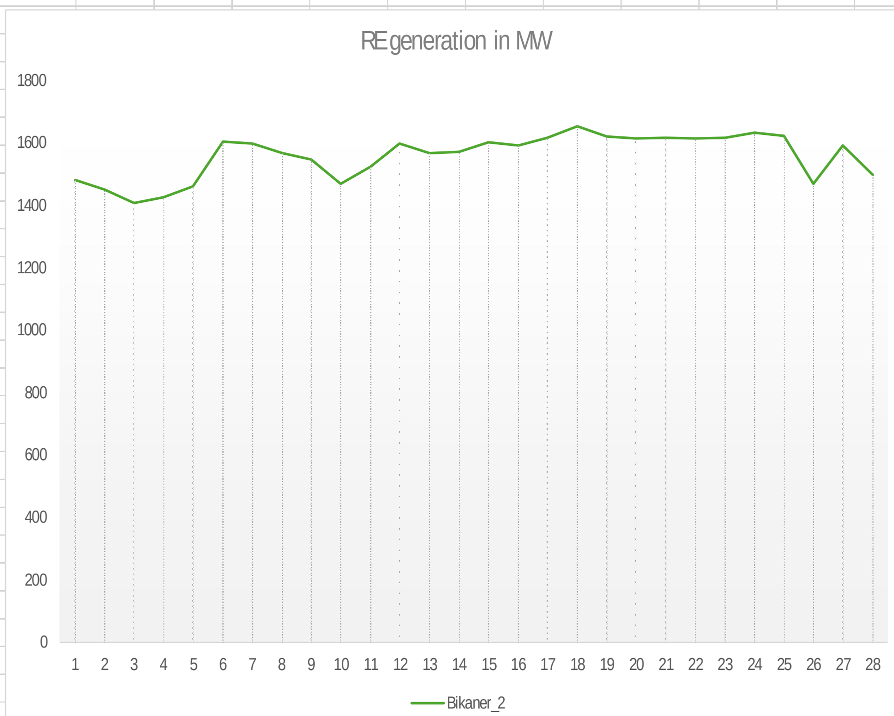
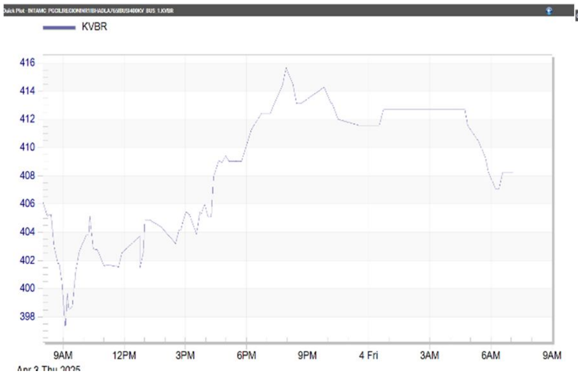


Figure 2 – Operational Trend – Voltage/Load/Oscillation Pattern



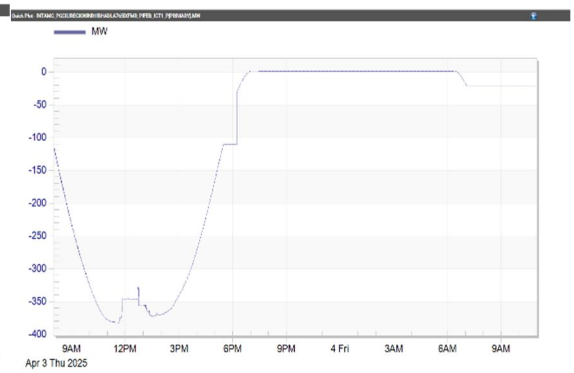
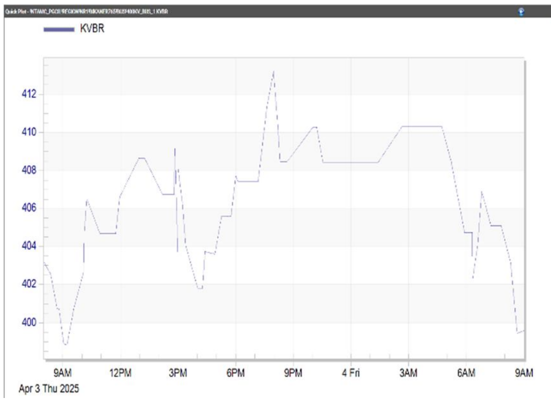


Fig a: above shows Bhadla Bus voltage Fig b: above shows ICT Bhadla load pattern



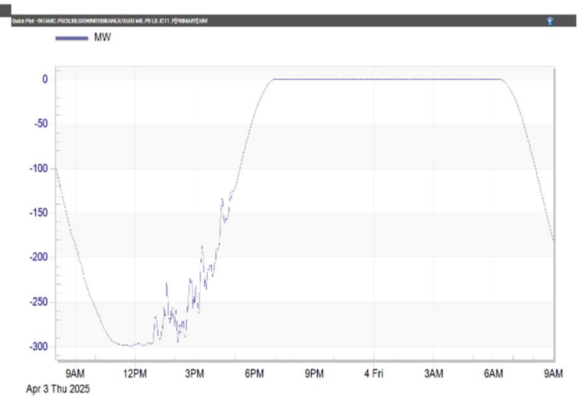
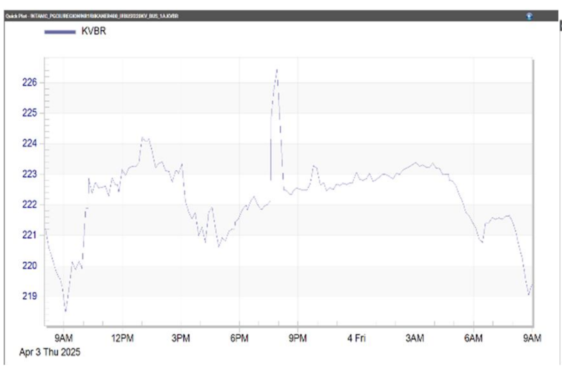


Fig c: above shows Bikane 400KV Bus voltage Fig d: above shows Bikane ICT load pattern



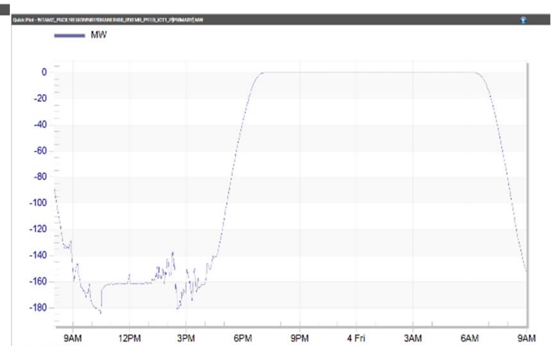
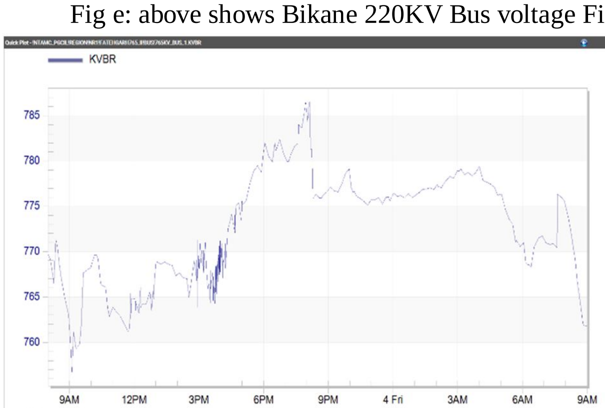


Fig e: above shows Bikane 220KV Bus voltage Fig f: above shows Bikane ICT load pattern



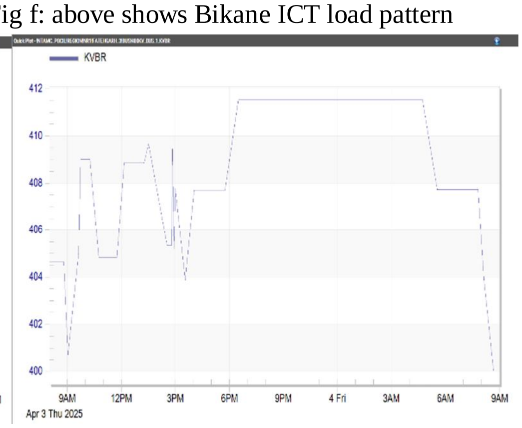


Fig g: above shows Fategarh 765KV Bus voltage Fig h: Fategarh 400KV Bus voltage

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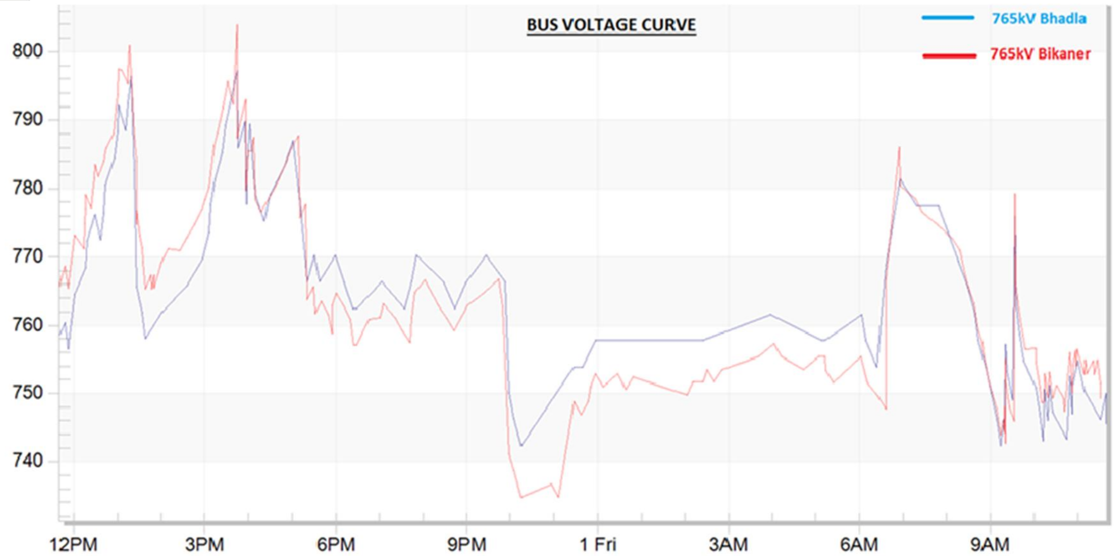
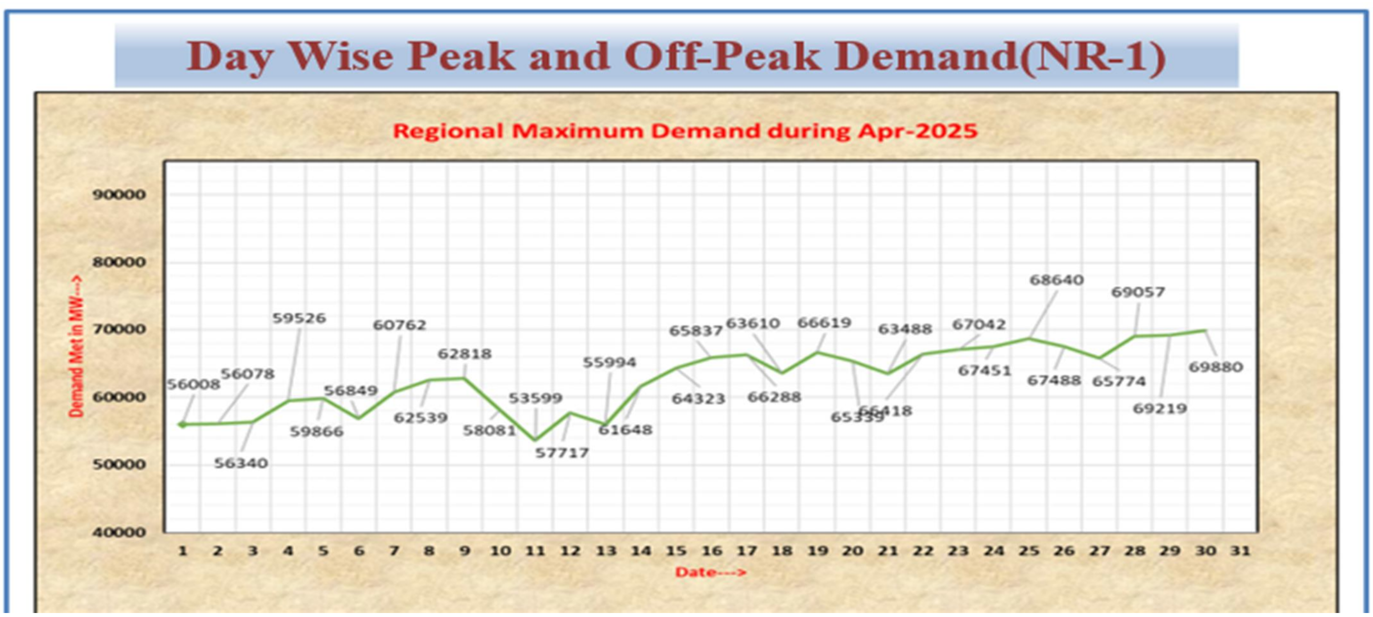


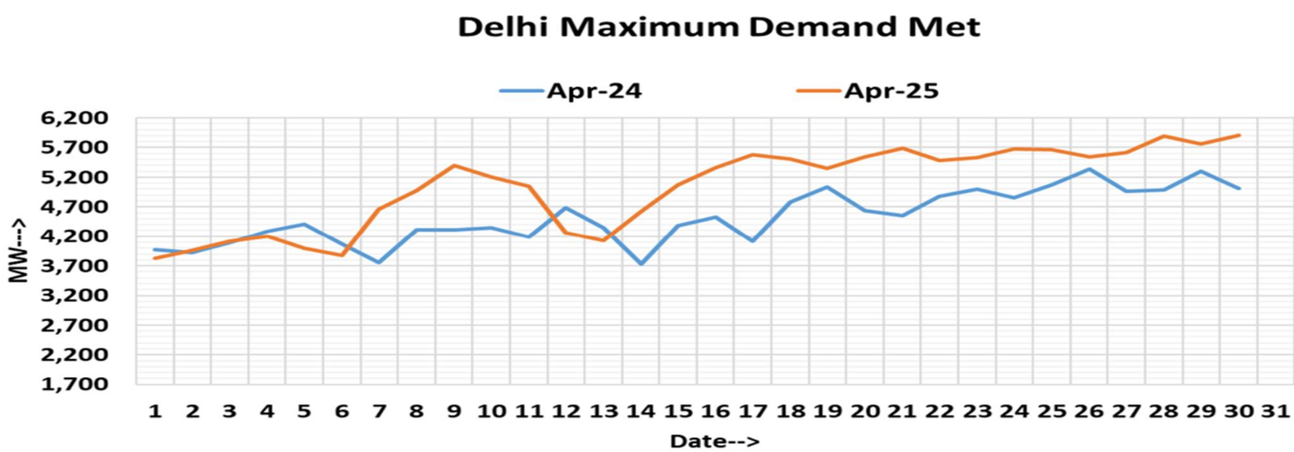
Fig i : Dynamic voltage condition observed in Bhadla, Bikaner on comparing the voltage profile 765KV Bus in 24hrs. Frequent switching of Bus / Line Reactors and Lines are being done on NRLDC instructions for controlling the



Date	Peak Hour demand (MW)	Off-Peak Hour demand (MW)	Date	Peak Hour demand (MW)	Off-Peak Hour demand (MW)
1	52930	40109	16	65492	54225
2	54270	41386	17	66105	51421
3	54520	41439	18	60098	57593
4	57566	43837	19	66418	50210
5	57671	46001	20	64190	57955

6	55779	46554	21	63028	57781
7	59914	45950	22	65806	58072
8	62291	50503	23	66564	58442
9	62609	53699	24	66841	58155
10	56566	49927	25	67663	59429
11	45779	49095	26	66092	60439
12	57227	39639	27	62969	60501
13	55789	46400	28	68435	58270
14	61272	47769	29	67772	60203
15	64131	51022	30	68966	61304

Day wise peak and off-peak Demand (NR-01)



Following data referred to Renewable energy statics 2023-24 ministry of new and renewable energy:

Date	Peak Hour demand (MW)	Off-Peak Hour demand (MW)	Date	Peak Hour demand (MW)	Off-Peak Hour demand (MW)
1	3531	2434	16	4871	3926
2	3758	2530	17	5065	4195
3	3899	2634	18	4939	4338
4	4028	2785	19	4837	4159
5	3888	2897	20	4870	4244
6	3865	2897	21	4912	4583
7	4388	3085	22	4799	4317
8	4645	3425	23	4852	4229
9	5041	3794	24	4988	4243
10	4594	4122	25	5009	4488
11	3684	3852	26	4790	4586
12	4103	3122	27	4818	4607
13	3994	3246	28	5213	4708
14	4478	3520	29	5135	4658
15	4654	3764	30	5269	4641

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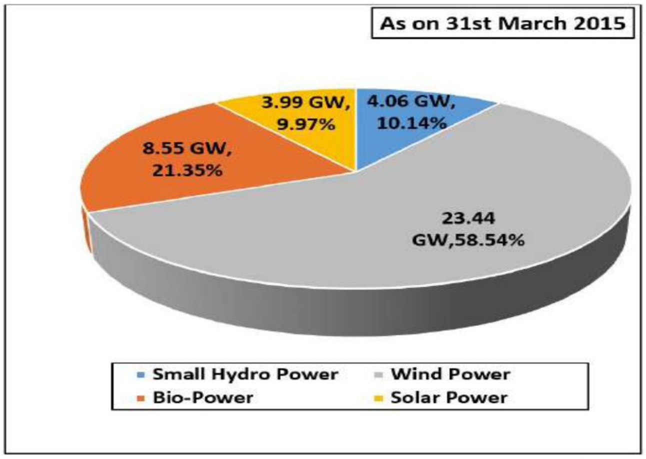
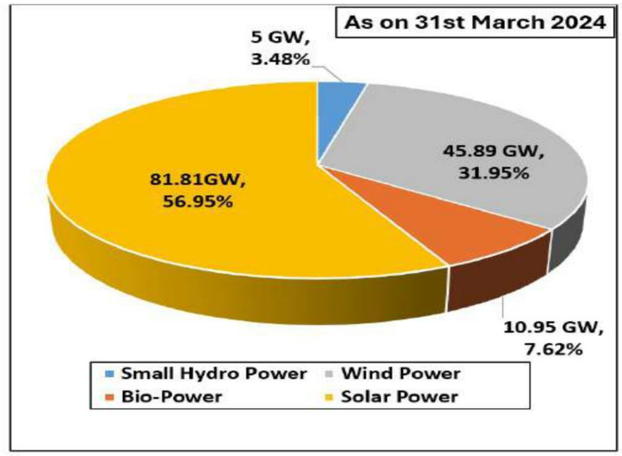
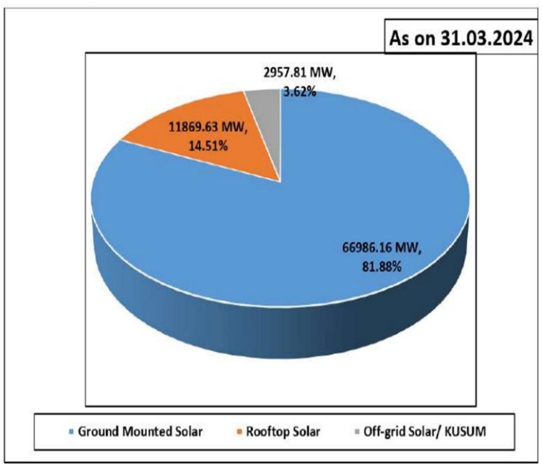
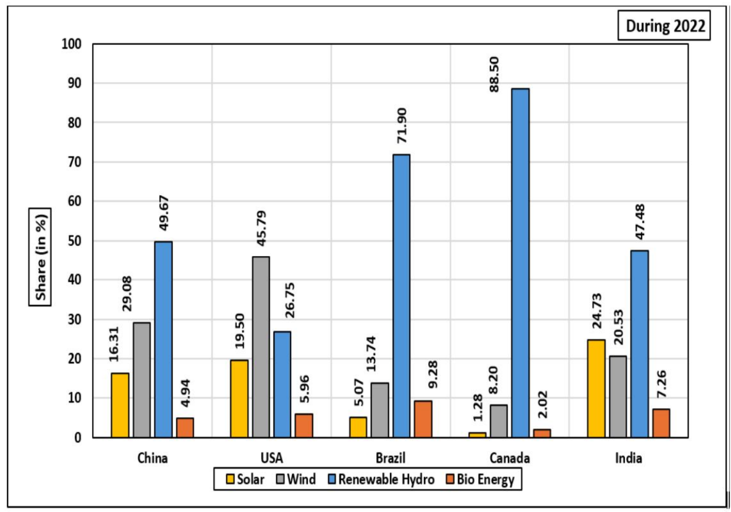




Various categories of Solar Power installations





S.No.	Power Station	Energy Generated during April' 2025 (MU)
	NR ISTS Connected Solar:	
(a)	Adani Green Energy Twenty Five Limited	123.17
(b)	ABC RENEWABLE ENERGY	66.24
(c)	ACME Chittorgarh Solar Energy Pvt Ltd	50.59
(d)	ACME Deoghar Solar Power Private Limited	74.28
(e)	ACME Heergarh Powertech Private Limited	71.15
(f)	ACME Phalodi Solar Energy Private Limited	73.60
(g)	ACME Raisar Solar Energy Private Limited	72.44
(h)	ACME Dhaulpur Powertech Private Limited	72.14
(i)	Adani Green Energy Twenty Four Limited	113.79
(j)	Adani Hybrid Energy Jaisalmer Four Limited Solar	181.90
(k)	Adani Hybrid Energy Jaisalmer One Limited Solar	90.53
(l)	Adani Hybrid Energy Jaisalmer Three Limited Solar	85.86
(m)	Adani Hybrid Energy Jaisalmer Two Limited Solar	82.51
(n)	Adani Jaisalmer One SEPL Solar	101.44
(o)	Adani Renewable Energy RJ Limited (ARERJL)	45.16

(p)	Adani Solar Energy Jaisalmer Two Private Limited	35.29
(q)	Adani Solar Energy Jaisalmer Two Private Limited (Project-2)	33.38
(r)	Adani Solar Energy RJ Two Pvt Ltd_Bhadla	37.29
(s)	Adani Solar Energy RJ Two Pvt Ltd_Fategarh 2	53.73
(t)	ADEPT RENEWABLE TECHNOLOGY PVT LTD	28.52
(u)	Altra Xergi Power Private Limited	92.83
(v)	Amp Energy Green Four Private Limited	21.63
(w)	AMP Energy Green Six PRivate Limited	24.14
(x)	AMP Green Energy Five Private Limited	28.37
(y)	Amplus Ages Private Limited	25.15
(z)	Anta Solar Power Plant NTPC Ltd	19.91
(aa)	Avaada RJHN Private Limited	53.25
(ab)	Avaada Sunce Energy Private Limited, Bikaner	77.96
(ac)	Avaada Sunrays Energy Private Ltd	77.76
(ad)	Avaada Sustainable RJProject Pvt Ltd	68.24
(ae)	Ayana Renewable Power One Private Limited, Bikaner	69.17
(af)	Ayana Renewable Three Pvt Ltd	65.16
(ag)	Azure Power Forty Three Private Limited	135.68
(ah)	Azure Power India Pvt Ltd.	38.80
(ai)	Azure Power Maple Pvt Ltd	68.98
(aj)	Azure Power Thirty Four Private Ltd	28.82
(ak)	Banderwala_TPSL	60.72
(al)	Clean Solar Power (Bhadla) Pvt Ltd	69.46
(am)	Clean Solar Power(Jodhpur) Private Limited	58.70
(an)	Devikot Solar Power NTPC	48.48
(ao)	Eden Renewable Cite Private Limited	72.41
(ap)	Fatehgarh Solar PV Project	67.63
(aq)	Gorbea Solar Private Limited	6.95
(ar)	Grian Energy Private Limited	25.17
(as)	JUNIPER GREEN COSMIC PRIVATE LIMITED	22.11
(at)	Juniper Nirjara Energy Private Limited	3.71
(au)	Karnisar Solar Plant NHPC Limited	5.85
(av)	Kolayat Solar Power Plant NTPC Limited	121.72
(aw)	M/s Adani Solar Energy Four Private Limited	11.63
(ax)	M/s Adani Solar Energy Jodhpur Two Limited	11.80
(ay)	M/s Azure Power Forty One Private Limited	67.87
(az)	M/s. OneVolt Energy Private Limited	24.47
(ba)	Mega Soils Renewable Private Limited	58.77
(bb)	Mega Suryaurja Pvt Ltd	57.42
(bc)	Nokhra Solar Power NTPC	62.91
(bd)	NTPC NOKH SOLAR PROJECT	6.41
(be)	Renew Solar Energy (Jharkhand Three) Pvt Ltd	68.78
(bf)	Renew Solar Power PVt LTD	21.40

(bg)	Renew Solar Power Pvt Ltd. Bikaner	52.57
(bh)	Renew Solar Urja Pvt Limited	70.14
(bi)	ReNew Sun Bright Private Limited (RSBPL)	68.65
(bj)	Renew Sun Waves Private Limited	68.66
(bk)	Renew Surya Aayan Private Limited	71.23
(bl)	Renew Surya Pratap Private Limited	48.52
(bm)	ReNew Surya Ravi Pvt Ltd	62.45
(bn)	RENEW SURYA ROSHNI PRIVATE LIMITED	86.65
(bo)	Renew Surya Vihaan Private Limited	23.40
(bp)	Rising Sun Energy (K) Pvt Ltd	45.42
(bq)	SB Energy Four Pvt Ltd	42.93
(br)	SB Energy Six Private Limited	68.79
(bs)	Serentica Renewables India 4 Private Limited_BKN2	44.87
(bt)	Serentica Renewables India 5 Private Limited	47.44
(bu)	SJVN Green Energy Limited	31.64
(bv)	Tata Power Green Energy Limited	45.64
(bw)	Tata Power Renewable Energy Ltd	67.61
(bx)	Tata Power Saurya Limited	21.28
(by)	Thar Surya 1Private limited	67.80
(bz)	TRANSITION CLEANTECH SERVICES PRIVATE LIMITED	0.69
(ca)	TRANSITION ENERGY SERVICES PRIVATE LIMITED	19.45
(cb)	Transition Green Energy Private Limited	25.66
(cc)	Transition Sustainable Energy Services Private Limited (TSESPL)	12.54
(cd)	Transition Sustainable Energy Services one Pvt. Ltd.	12.89
	Total ISTS Solar	4450.15
	NR ISTS Connected Wind:	
(a)	Adani Hybrid Energy Jaisalmer One Limited Wind	23.99
(b)	Adani Hybrid Energy Jaisalmer Three Limited Wind	15.91
(c)	Adani Hybrid Energy Jaisalmer Two Limited Wind	15.71
(d)	Adani Hybrid Energy Jaisalmer Four Limited Wind	110.22
(e)	Adani Jaisalmer One SEPL Wind	29.64
	Total ISTS Wind	195.47

VII. CASE STUDIES

A. Introduction

This chapter presents an in-depth analysis of operational challenges and advancements at three key substations—Bhadla, Bikaner, and Fatehgarh—within India's Renewable Energy Zone (REZ). These sites have traditionally struggled with over-voltage problems caused by solar variability and excess reactive power. The installation of STATCOMs during 2023–24 marked a major improvement, enhancing voltage stability and allowing greater renewable energy utilization. The evaluation is backed by RTAMC operational data, POSOCO's Renewable Energy Challenges Report, and visual SCADA data trends.

8.1.1 Case Study: Fatehgarh Substation

At 11:22:59hrs Dt-11.08.2022, R-B phase to phase fault occurred on 220kV Bhadla- Clean Solar Jodhpur ckt due to snapping of B-ph jumper which fell on R-ph. As per PMU, R-B phase to phase voltage which cleared within 80ms is observed. As per PMU plots of phase voltage, MW & Mvar of RE stations, it is observed that during the voltage dip of fault, phase voltage at Bhadla, Fatehgarh2, Bhadla2 & Bikaner dropped to 0.59pu, 0.79pu, 0.8pu & 0.82pu respectively.

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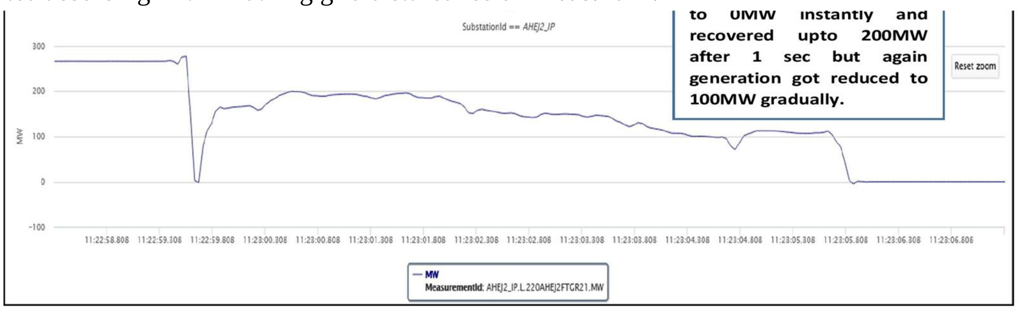
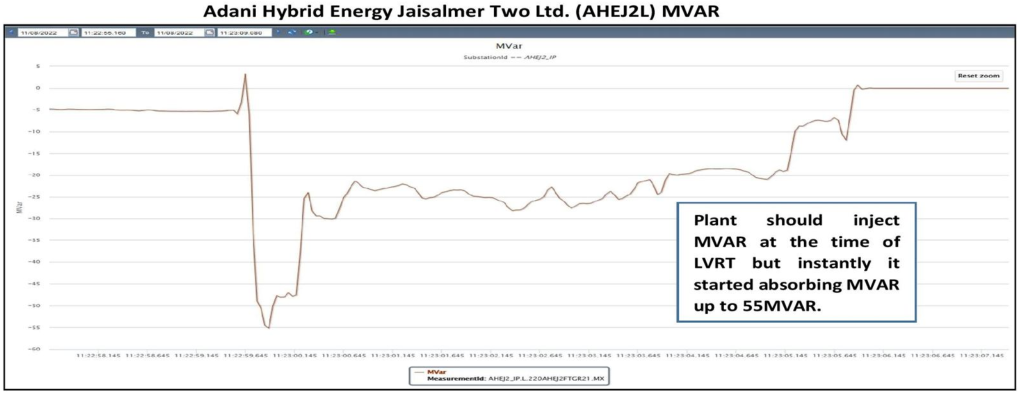
As voltage dropped below 0.85pu, almost all the RE stations dropped their MW except ASPS1 & ASPS2 RE station connected at Fatehgarh1 (ADANI Solar park) on LVRT operation. As per PMU plots of MVAR of RE station, MVAR support is also not observed from most of the RE inverters during voltage dip on fault.

It is observed that even voltage recovered to its normal value after clearing of fault within 100ms, MW of RE stations didn't recover in defined time as per LVRT operation. Due to significant drop in MW and inadequate MVAR support from RE stations, rise in voltage is observed at ISTS RE pooling stations.

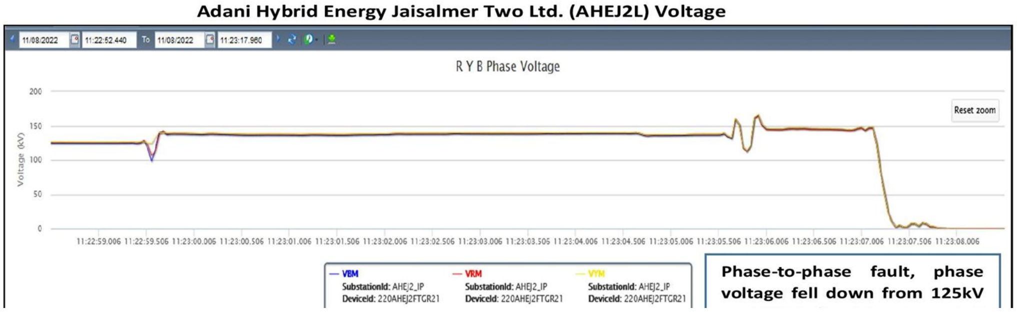
Further after approx. 5-6secs, all four (04) 765kV lines connected at Fatehgarh2 (PG) along with 765kV AjmerBhadla2 D/C & 765kV Bhadla2-Bikaner ckt-1 and few 220kV lines to RE stations tripped on over voltage protection. As per SCADA, loss of approx. 5807MW solar generation connected at Bhadla(PG), Bhadla2(PG), Bikaner(PG), Fatehgarh2(PG) & Fatehgarh1 (ADANI Solar Park) & approx. 350MW wind generation connected at Fatehgarh2 & Fatehgarh1 (ADANI Solar Park) & wind occurred. As reported, load shedding of approx. ~200MW in Punjab, ~150MW in Haryana & ~400MW in UP control area due to df/dt protection operation during the event. In Compliance with LVRT phenomenon, generator should inject MVAR for grid sustainability but it behaved in reverse, started absorbing MVAR during grid disturbance on 11.08.2022.



Adani Hybrid Energy Jaisalmer Two Ltd. (AHEJ2L) MVAR



Adani Hybrid Energy Jaisalmer Two Ltd. (AHEJ2L) Voltage



B. Case Study 1: Bhadla 765 kV Substation

Bhadla substation ranks among India’s largest renewable energy pooling points, evacuating more than 2,200 MW from solar parks. Prior to STATCOM commissioning, intense midday solar injection combined with low demand caused voltages to spike up to 410 kV. This necessitated manual switching of line and bus reactors, and frequent solar curtailment was observed. Following the STATCOM installation in early 2023, real-time reactive power absorption of 80–120 MVAr was achieved, which notably stabilized voltage levels and eliminated the need for curtailment.

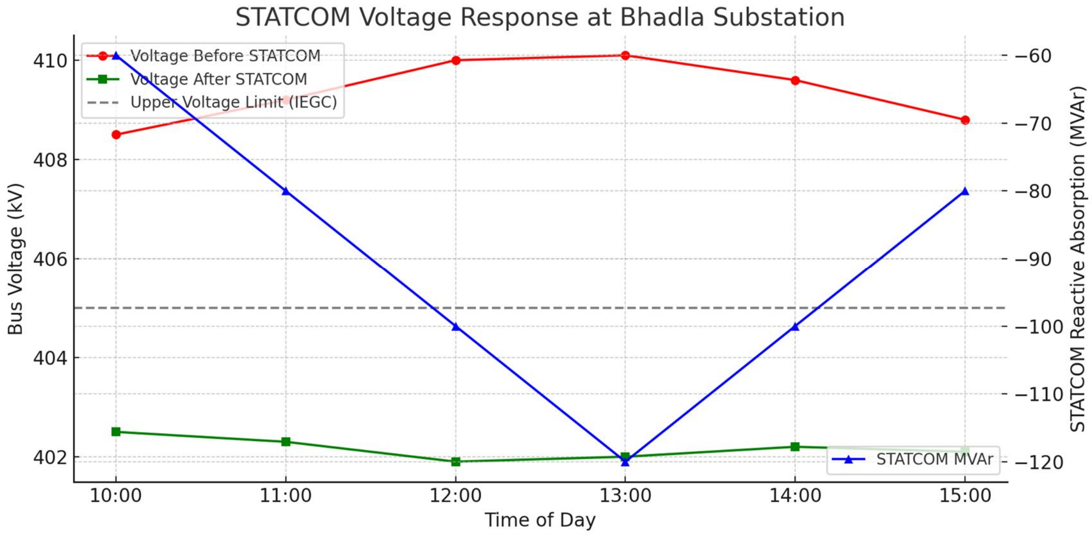


Figure 8.1 – STATCOM Voltage Response and Reactive Absorption at Bhadla Substation (2024)

Interpretation: The red line shows voltage rising beyond IEGC upper limit pre-STATCOM. The green line reflects effective flattening post-STATCOM, while the blue trace indicates MVAR absorption peaking at -120 MVAr around 13:00 hrs. This dynamic correction helped maintain grid stability without the need for curtailment or frequent manual intervention.

C. Case Study 2: Bikaner 765/400 kV Substation

Bikaner serves as another critical renewable energy integration hub, managing over 3,000 MW of solar input. Before the STATCOM installation, operational records indicated that bus voltages frequently exceeded 408.5 kV during peak solar hours under clear skies. POSOCO's 2023 RE Challenges Report identified Bikaner among the top substations experiencing overvoltage-related curtailments and heightened stress on downstream transformers. Following the STATCOM commissioning in late 2023, voltage levels stabilized below 402 kV, completely eliminating solar curtailment.

Although detailed MVAR absorption curves for Bikaner are unavailable, RTAMC operators reported an average reactive power absorption of around 100 MVAr between 11:30 and 14:00, coupled with a 75% decrease in reactor switching. Post-2023 CEA logs also confirm full adherence to IEGC Clause 5.2(r).

D. Case Study 3: Fatehgarh 765 kV Substation

Fatehgarh serves as a key pooling station for over 5,000 MW of solar power and plays a vital role in interstate transmission corridors. Before 2024, midday voltages frequently exceeded 410.5 kV, leading to solar curtailments of up to 320 MW per day. The 2022 POSOCO 'RE Grid Integration Study' identified Fatehgarh's overvoltage problems as responsible for over 250 million units of annual renewable energy loss in the Northern Region. Following the STATCOM installation in 2024, RTAMC data indicates that average bus voltages stabilized around 402.3 kV during peak generation periods, with curtailments reduced to zero.

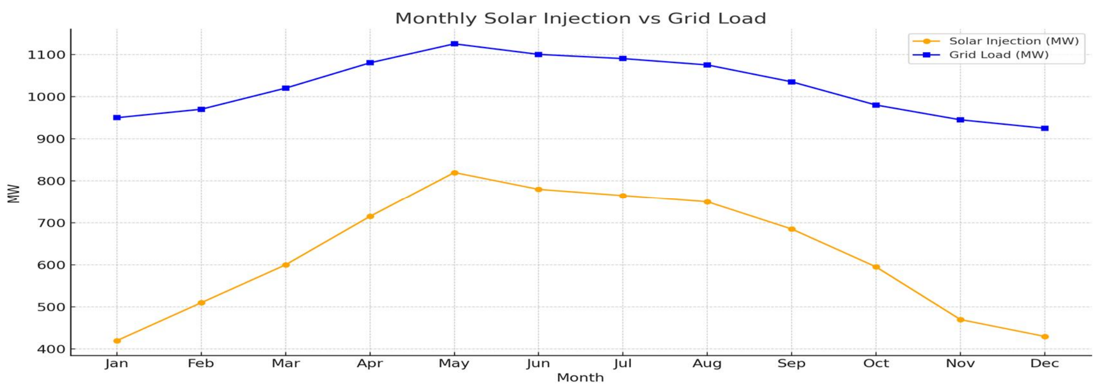


Figure 8.2 – Monthly Solar Injection vs Grid Load Correlation at Fatehgarh Substation (2024)

Interpretation: This graph indicates the mismatch between RE generation and system demand during peak hours. With STATCOM response, the voltage was controlled, and curtailment avoided without additional transmission expansion—highlighting cost-effective grid stability enhancement.

E. Summary of STATCOM Performance across RE Corridors

The deployment of STATCOMs at Bhadla, Bikaner, and Fatehgarh collectively resulted in significant improvements in voltage regulation, reactive power management, and a notable reduction in solar curtailment. Table 8.1 provides a summary of these key operational results.

These case studies underscore the critical role of dynamic reactive support in facilitating renewable energy integration. STATCOMs have proven to be essential grid assets for mitigating voltage fluctuations and enabling the full utilization of renewable energy, aligning with recommendations from POSOCO, CTUIL, and CEA. Prioritizing their installation in REZ corridors is crucial for maintaining system reliability and adhering to national grid code standards.

F. IEGC Compliance and Reactive Support Guidelines

According to Clause 5.2(r) of the Indian Electricity Grid Code (IEGC), transmission voltages must be kept within prescribed limits to maintain system stability and protect equipment. For the 765 kV system, the acceptable voltage range is between 728 kV and 803 kV (+5% / -10%), while for the 400 kV system, it is between 350 kV and 440 kV (+10% / -12.5%). Prior to the commissioning of STATCOMs, bus voltages at Bhadla, Bikaner, and Fatehgarh frequently exceeded the upper limit of 405–410 kV, as reflected in RTAMC records. These voltage excursions breached the IEGC operational limits and triggered multiple alarms based on control center benchmarks. After STATCOM installation, voltage levels stabilized within the 400–402.5 kV range, confirming renewed compliance with IEGC Clause 5.2(r).

RTAMC's daily voltage monitoring logs (Jan–Jun 2024) and curtailment records were analyzed to verify post-STATCOM IEGC compliance. The following references support this observation:

- RTAMC Northern Region-1 SCADA Voltage Records for Bhadla, Bikaner, and Fatehgarh substations (2023–2024)
- POSOCO Renewable Energy Challenges and Grid Integration Report, December 2023
- Indian Electricity Grid Code (Fifth Amendment) issued by the Central Electricity Regulatory Commission, 2022
- CTUIL Renewable Energy Zone (REZ) Planning Study focusing on Reactive Support Matrix, 2023
- Central Electricity Authority (CEA) Technical Standards on Reactive Power Management, 2021

The successful absorption of reactive surplus and dynamic voltage regulation post-STATCOM validates not only operational improvement but also grid code compliance—essential for long-term solar integration and RE grid reliability.

Table 8.1 – Operational Improvements After STATCOM Commissioning

Substation	Voltage Before (kV)	Voltage After (kV)	Curtailment Before (MW)	Curtailment After (MW)	Reactor Ops/Day
Bhadla	410	402	275	0	↓ from 5 to 1
Bikaner	408.5	401.7	200	0	↓ from 4 to 1
Fatehgarh	410.5	402.3	320	0	↓ from 6 to 1

G. Case Study 4: Sikar 765 kV Substation

Sikar substation acts as a key evacuation point for solar power generated in northern Rajasthan and is connected to Bhadla and Fatehgarh via several 765 kV transmission lines. According to POSOCO's 2023 'RE Grid Integration Report,' Sikar experiences significant reverse power flow during off-peak hours, often causing overvoltage conditions exceeding 408 kV. These issues were worsened by low regional demand and the charging effects of long EHV lines. Before the installation of STATCOMs, the substation required frequent manual switching of bus reactors, averaging 4 to 6 operations daily.

In 2024, POWERGRID commissioned a ±125 MVAr STATCOM at Sikar. RTAMC SCADA data from April to June, between 11:30 and 14:30 hrs, indicates that the STATCOM absorbed up to 110 MVAr in real-time, stabilizing voltage within the 400–401.5 kV range. This effectively allowed full renewable energy injection without breaching IEGC Clause 5.2(r) limits. Since April 2024, SLDC Rajasthan and NRPC have reported no curtailment events, reflecting improved grid compliance and enhanced reliability of assets.

Table 8.2 – Extended Operational Summary Post-STATCOM Commissioning

Substation	Voltage Before (kV)	Voltage After (kV)	Curtailment Before (MW)	Curtailment After (MW)	Reactor Ops/Day
Bhadla	410	402	275	0	↓ from 5 to 1
Bikaner	408.5	401.7	200	0	↓ from 4 to 1
Fatehgarh	410.5	402.3	320	0	↓ from 6 to 1
Sikar	408	401.2	180	0	↓ from 6 to 2

H. POSOCO Recommendations and Regional Grid Benefits

POSOCO's 2023 RE integration strategy underscores the critical role of real-time reactive support at key nodal pooling stations. The report specifically highlighted the necessity for dynamic voltage regulation at Bhadla, Bikaner, Fatehgarh, and Sikar. POWERGRID's deployment of STATCOMs at these substations has effectively mitigated voltage excursions, reduced MVAR oscillations, and prevented broader system impacts such as frequency deviations and load loss. These improvements have also contributed to faster outage clearances during OCC and CMETS meetings by enhancing overall grid security metrics.

I. Thematic Case Integration: Solar Power Integration and Grid Management

The case studies presented in this chapter collectively reinforce the central thesis: that large-scale solar power integration introduces significant volatility in both voltage and reactive power balance, necessitating advanced grid management strategies. The substations at Bhadla, Bikaner, Fatehgarh, and Sikar have emerged as critical test beds for operational interventions aimed at managing intermittency and enhancing grid stability.

Solar intermittency—characterized by rapid ramp-ups and drop-offs driven by weather variability—poses substantial challenges to voltage regulation at the transmission level. Across all studied substations, a consistent pattern was observed: during clear mid-day hours with peak solar injection and low local demand, voltages frequently exceeded the upper IEGC limit of 405 kV. The commissioning of reactive compensation systems, notably STATCOMs, directly targeted these conditions by absorbing surplus MVARs, thereby lowering bus voltages and mitigating the need for renewable energy curtailment.

From a grid management perspective, the lessons learned are twofold:

1. During the pre-STATCOM period, operations were characterized by frequent manual interventions, substantial curtailment, and heightened risks of voltage collapse or line tripping.
2. Following STATCOM deployment, grid operations have transitioned to automated, standards-compliant, and uninterrupted renewable energy absorption.

These outcomes validate the thesis's core premise that dynamic voltage and reactive power control are indispensable for managing solar-rich corridors. Real-time SCADA-enabled STATCOM control not only complements CTUIL's long-term transmission planning but also aligns with POSOCO's operational reliability framework. Furthermore, the findings lend support to evolving grid codes that may mandate coordinated, substation-level reactive power absorption based on real-time solar forecasts, demand profiles, and system stress indicators. In summary, the operational strategies adopted at these substations serve as replicable models for other national renewable energy zones. The demonstrated effectiveness of STATCOMs underscores their critical role—not merely as voltage control devices but as strategic enablers in India's grid modernization and decarbonization journey.

J. Case Study 5: Tripping Events and Grid Restoration Challenges

Beyond voltage excursions and reactive power surpluses, large-scale solar integration can induce grid instability manifested as sudden tripping of transmission lines, ICTs, or reactive compensation devices like STATCOMs. Such tripping events frequently occur when existing control mechanisms are unable to cope with rapid cloud-induced solar ramp-downs or reverse power flow conditions during low demand periods. Multiple such incidents have been documented in RTAMC tripping logs across NR-1, particularly at critical pooling stations such as Fatehgarh and Bikaner. A notable case occurred in April 2024, when several 400 kV feeders tripped simultaneously at the Fatehgarh substation following a sudden cloud cover event that caused a sharp solar generation drop of approximately 450 MW within 10 minutes. During this interval, reactive power oscillations exceeded 250 MVAr, and protection systems malfunctioned due to undamped low-frequency oscillations. RTAMC records indicated a rapid voltage dip from 410 kV down to 392 kV, immediately followed by an overcompensating voltage surge. These fluctuations triggered the tripping of one ICT transformer and the activation of the Under-Voltage Load Shedding (UVLS) scheme to maintain system stability.

Subsequent post-event analysis conducted by POSOCO and POWERGRID's asset management team concluded that, under the pre-existing control frameworks, the tripping was unavoidable. However, integration of STATCOMs equipped with fault ride-through capabilities and real-time dispatch coordination could have effectively dampened the MVAR oscillations and mitigated the disturbance. In response, alarm thresholds were revised and coordination protocols between SLDCs, RLDCs, and RTAMC were strengthened to enhance situational awareness and operational responsiveness.

These incidents highlight the critical importance of grid-aware renewable energy forecasting, enhanced automation, and dynamic coordination of voltage control assets. Furthermore, they underscore the imperative for automated, detailed tagging of curtailment and tripping causes within SCADA and emerging digital substation platforms, enabling faster diagnostics and improved preventive measures.

K. Case Study 6: Oscillatory Behavior and Damping Challenges in RE Corridors

In addition to voltage and frequency instabilities, low-frequency oscillations represent a critical stability concern in renewable energy (RE)-rich corridors. These oscillations commonly occur in long-distance, lightly loaded 765 kV transmission lines, especially when solar generation fluctuates rapidly and reactive compensation assets are not optimally tuned. A significant oscillation event was recorded at the Bikaner substation in August 2023.

During a clear-to-cloud transition, SCADA logs revealed sustained oscillations at approximately 0.25 Hz between the 765 kV buses of Bikaner and Sikar. These oscillations persisted for 38 seconds, causing notable fluctuations in both active and reactive power flows. Field personnel reported audible vibrations in transformers, while STATCOM devices switched intermittently between capacitive and inductive modes without fully damping the oscillations. Such phenomena pose serious risks to system stability and may lead to unintended operations of distance protection relays or transformer alarms.

Post-event investigations by POWERGRID's Asset Management engineers and POSOCO's protection team identified the root causes as: (i) excessive charging current in lightly loaded EHV lines, (ii) delayed synchronization of STATCOM devices, and (iii) absence of integrated damping signals in voltage control relays.

This incident spurred CTUIL to recommend the deployment of wide-area phasor measurement units (PMUs) and the incorporation of Power Oscillation Dampers (PODs) within STATCOM controllers. As of Q1 2025, tuning of STATCOM control algorithms is in progress at Bikaner and Fatehgarh to mitigate such oscillations. Furthermore, the IEGC Review Panel has proposed including oscillation damping metrics in the national grid security dashboard for ongoing monitoring.

This case underscores the evolving challenges of grid stability in solar-rich corridors and reinforces the imperative for dynamic, fast-acting control strategies in high-voltage RE zones. Proactively addressing oscillatory behavior is not only vital for reliability but also a prerequisite for the seamless integration of India's ambitious target of 500+ GW solar capacity by 2030.

L. Summary and Concluding Remarks

The case studies across Bhadla, Bikaner, Fatehgarh, and Sikar, along with comprehensive RTAMC analysis, collectively demonstrate that STATCOM deployment, real-time SCADA control, and enhanced reactive power coordination have significantly improved grid resilience in solar-rich corridors. Graphical data records confirm successful mitigation of solar curtailment, voltage surges, low-frequency oscillations, and transmission line trippings. These operational interventions provide a replicable and effective framework for managing renewable integration challenges across other RE zones, under the strategic guidance of CTUIL and POSOCO.

Key outcomes include:

- Reduced solar curtailment to near-zero levels.
- Post-STATCOM voltage compliance with IEGC Clause 5.2(r).
- Lowered reactive switching frequency.
- Damped LC oscillations with suggested POD (Power Oscillation Dampers).
- Enhanced situational awareness through RTAMC and PMU monitoring.

VIII. CONCLUSION AND FUTURE SCOPE

A. Conclusion

1) Voltage Stability Challenges: High solar injection during midday, combined with low local demand, frequently caused bus voltages to exceed IEGC limits (+10% for 400 kV systems), leading to overvoltage conditions and operational alarms prior to STATCOM deployment.

2) Reactive Power Imbalance: Solar generation intermittency resulted in significant reactive power surpluses, necessitating frequent manual switching of reactors and leading to equipment stress and increased operational complexity.
3) Effectiveness of STATCOMs: The commissioning of STATCOM devices at major substations effectively mitigated voltage excursions by dynamically absorbing surplus reactive power, flattening voltage profiles, reducing curtailment, and decreasing the frequency of reactor switching operations.
4) Improved Grid Compliance and Reliability: Post-STATCOM deployment data from RTAMC and SLDC confirmed sustained compliance with IEGC Clause 5.2(r) voltage limits, elimination of solar curtailment, and enhanced system stability.
5) Grid Disturbance Mitigation: Incidents of line and transformer trippings, as well as low-frequency oscillations linked to solar variability, highlighted the need for coordinated dynamic reactive control and advanced protective relaying schemes.
6) Operational-Planning Coordination: Real-time operational data underscores the importance of integrating feedback loops between system operators (POSOCO, SLDCs) and planners (CTUIL) to refine REZ studies, reactive support planning, and grid code development.

These findings collectively emphasize that dynamic reactive power management, supported by real-time SCADA monitoring and advanced control assets like STATCOMs, is indispensable for the reliable and efficient integration of large-scale solar energy into India’s transmission grid.

B. Future Scope

To ensure long-term grid sustainability while achieving India's 500 GW renewable energy target by 2030, several critical developments are proposed:

1) Advanced Control Systems

- Deployment of AI/ML-based forecasting tools for solar variability and MVAR demand prediction at RE pooling substations.
- Integration of STATCOMs with PMUs and WAMS (Wide Area Monitoring Systems) for real-time coordinated voltage control.
- Migration from conventional SCADA to Digital Substation architectures (IEC-61850) for faster signal communication and asset health tracking.

2) Grid Codes and Protection Enhancements

- Update IEGC to include metrics for:
    - Curtailment Transparency
    - Reactive Reserve Margin Index (RRMI)
    - Oscillation Damping Compliance
- Enforce regional coordination protocols under NRPC/CTUIL for all high-voltage RE zones.

3) Infrastructure Expansion and Hybrid Solutions

- Development of energy storage systems (BESS) and solar-wind hybrids for smoothening peak injections.
- Strategic siting of adaptive switchable reactors and static VAR generators (SVGs) in new REZ substations like Phalodi, Jaisalmer, and Barmer.
- Encourage synchronous control between HVDC terminals and local STATCOMs for optimized RE evacuation.

4) Operator Training and Visualization Tools

- Strengthening RTAMC training modules with scenario simulations based on real tripping and curtailment cases.
- Roll-out of Graphical Load-Voltage Dashboards, heatmaps, and trend overlays at control room desks for intuitive analysis.
- Collaboration with academia and institutions like NPTI, IITs for SOP-based standardization of RE event handling.

5) Conclusions

1. Impact of Solar Integration on Voltage and Reactive Power:
   Large-scale solar integration in RE-rich corridors significantly affects voltage stability and reactive power balance. The combination of extensive EHV transmission infrastructure and high solar injection generates persistent reactive power surpluses, resulting in frequent and sustained overvoltage conditions that challenge existing grid management frameworks.

2. Reactive Power Management Limitations:
   Current reactive power control practices remain largely reactive and dependent on manual interventions. Frequent switching of reactors and the partial utilization of FACTS devices such as STATCOMs reveal that the system routinely operates near its reactive power capacity limits. This condition demands constant operator attention and highlights the need for more proactive, automated control strategies.
3. Need for Standardized Curtailment Classification:
   The absence of a transparent and consistent protocol for tagging curtailment events hampers effective operational decision-making and undermines market transparency. Accurate identification and classification of curtailment causes are essential to enable fair financial settlements, improve grid management, and inform future capacity planning.
4. Gap Between Operations and Planning:
   A critical disconnect exists between real-time operational insights and long-term transmission planning. This gap leads to planning assumptions that may not adequately capture dynamic grid conditions, resulting in delayed infrastructure development and inefficient allocation of resources in RE zones.
5. Role of Solar Variability in Grid Disturbances:
   Rapid fluctuations in solar generation intensify the impact of grid disturbances. While not always the primary trigger, the intermittent nature of solar ramps can aggravate voltage dips, frequency deviations, and protection system responses during fault events. This underscores the imperative for enhanced protection coordination and adaptive control mechanisms in solar-integrated networks.

6) Recommendations

Drawing from the conclusions, the following recommendations are proposed for various stakeholders:

6.1 For Transmission System Operators (POWERGRID, SLDCs/RLDCs):

- Maximize STATCOM/SVC Performance: Deploy advanced control algorithms to fully exploit the dynamic capabilities of STATCOMs and SVCs, especially for reactive power absorption during peak solar generation. This includes reviewing control setpoints, operational modes (such as prioritizing voltage regulation versus reactive power control), and incorporating ambient temperature effects into control strategies.
- Automate Reactive Equipment Switching: Speed up the automation of switching for bus and line reactors by integrating them with real-time voltage monitoring and predictive control systems to reduce manual operations and improve response times.
- Improve Real-Time Monitoring and Alerts: Enhance SCADA and RTAMC interfaces to deliver more detailed, real-time data on reactive power flow, STATCOM usage, and voltage stability margins, alongside implementing predictive alerts for imminent overvoltage scenarios.
- Strengthen Operator Training: Organize ongoing training sessions for shift engineers and operators focused on the dynamic nature of renewable-rich grids, advanced reactive power management, and effective operation of FACTS devices.
- Deploy Curtailment Classification Protocol: Integrate the recommended rule-based curtailment tagging system (covering voltage-related, congestion-related curtailments, etc.) into operational logs and reporting tools such as NLDC dashboards to improve clarity and precision in curtailment data.

6.2 For Transmission Planners (CTUIL):

- Incorporate Operational Insights into Planning: Set up a structured, regular process to feed real-time operational data—such as voltage trends, reactive power stress metrics, reactor switching counts, STATCOM usage, and detailed curtailment records from RTAMC—into Renewable Energy Zone (REZ) studies and long-term transmission planning exercises.
- Update Reactive Power Planning Standards: Reassess and adjust reactive power planning criteria and assumptions using actual field data, especially focusing on the charging reactive power from long EHV lines and the real reactive power capacity of renewable energy plants connected to the grid.
- Emphasize Dynamic Reactive Compensation: Give priority to planning and deploying dynamic reactive support equipment, like additional STATCOMs and synchronous condensers, in key solar corridors based on their demonstrated operational effectiveness and limitations.
- Conduct Integrated System Modeling: Perform detailed, holistic system studies that simulate the dynamic interplay between large-scale solar generation, the transmission network, and reactive power devices under a range of conditions, including extreme solar generation ramps and periods of low demand.

6.3 For Regulators (CERC, CEA):

- Strengthen Reactive Power Requirements for RE Generators: Update grid codes (IEGC) to require enhanced reactive power capabilities and dynamic voltage support from both new and existing renewable energy generators, including the ability to operate across a range of power factors.
- Encourage Grid-Supportive RE Operations: Develop market-based incentives and mechanisms that reward renewable energy generators for providing ancillary services such as reactive power support, frequency regulation, and controlled ramping, in addition to active power output.
- Standardize Curtailment Documentation: Implement mandatory, standardized protocols for reporting and justifying all curtailment events, consistent with the proposed tagging framework, to improve transparency and accountability within the Deviation Settlement Mechanism (DSM).
- Enhance Data Exchange and Cooperation: Promote robust data sharing among transmission operators, load dispatch centers, and renewable energy developers to improve forecasting accuracy, scheduling efficiency, and operational decision-making.

6.4 For Renewable Energy Developers:

- Optimize Inverter Settings: Ensure that PV inverters are optimally configured to provide reactive power support as per grid code requirements and in coordination with grid operators.
- Invest in Forecasting Capabilities: Enhance internal forecasting capabilities to improve schedule accuracy and minimize deviations, thereby reducing DSM penalties and contributing to grid stability.

C. Limitations of the Study

While this study provides valuable empirical insights, it is important to acknowledge certain limitations

- Data Scope: The study focused on SCADA/RTAMC data from Northern Region-1 between July and November 2024. Although this dataset is representative, it may not fully reflect the complexities of the entire Indian grid or capture seasonal variations beyond the selected timeframe.
- Data Granularity: Despite the high resolution of SCADA data, it lacks the fine-scale detail of individual inverter behavior that advanced monitoring tools like PMUs could provide. The limited availability of PMU data constrained the analysis of oscillatory phenomena.
- Causality vs. Correlation: While strong correlations were identified among solar generation, voltage fluctuations, and reactive power variations, establishing direct causality across all grid interactions remains difficult without extensive dynamic simulations or controlled testing.
- Confidentiality Constraints: Access to certain detailed or proprietary data was restricted due to confidentiality *agreements, which limited the scope of some in-depth analyses.*

D. Future Scope of Research

Building upon this study, future research can explore the following areas:

- Proactive Voltage and Reactive Power Management: Design and deploy real-time predictive algorithms for managing reactive power, using machine learning and advanced forecasting to proactively address voltage deviations and enhance the control of STATCOMs and reactors.
- Utilization of PMU Data for Grid Stability: Carry out high-resolution studies using Phasor Measurement Unit (PMU) data to perform modal analysis, identify oscillations, assess damping behavior, and evaluate wide-area stability in renewable-heavy transmission zones.
- Real-Time Curtailment Classification Engine: Create an automated framework that merges SCADA inputs, weather data, and network configurations to instantly analyze and categorize curtailment events, ensuring real-time visibility and accountability.
- Grid Integration of Hybrid RE and Storage Systems: Explore the impact of combining solar, wind, and energy storage technologies on operational stability, ramping support, and grid adaptability under varying generation and demand conditions.
- Ancillary Services from Renewables and Storage: Study the feasibility and design of market-based instruments that enable renewable plants and storage systems to offer grid support services like reactive power, inertia, and frequency regulation in India's evolving electricity market.
- Digital Grid Security and Risk Management: Examine the cybersecurity vulnerabilities arising from growing digitalization in RE grid operations and propose resilient architectures and protective strategies to secure critical infrastructure.

E. Overall Conclusion

This thesis makes a significant empirical contribution to the understanding of solar integration challenges within India's transmission network. By shifting the focus from purely theoretical frameworks to real-time operational insights, it has illuminated key concerns around voltage regulation, reactive power control, and renewable energy curtailment. The recommendations put forth provide actionable strategies to enhance both system operation and transmission planning, supporting the broader goal of a secure, efficient, and renewable-ready power grid. Additionally, the outlined limitations and future research avenues reflect the dynamic landscape of grid integration and emphasize the importance of continued, data-driven innovation in power system management.

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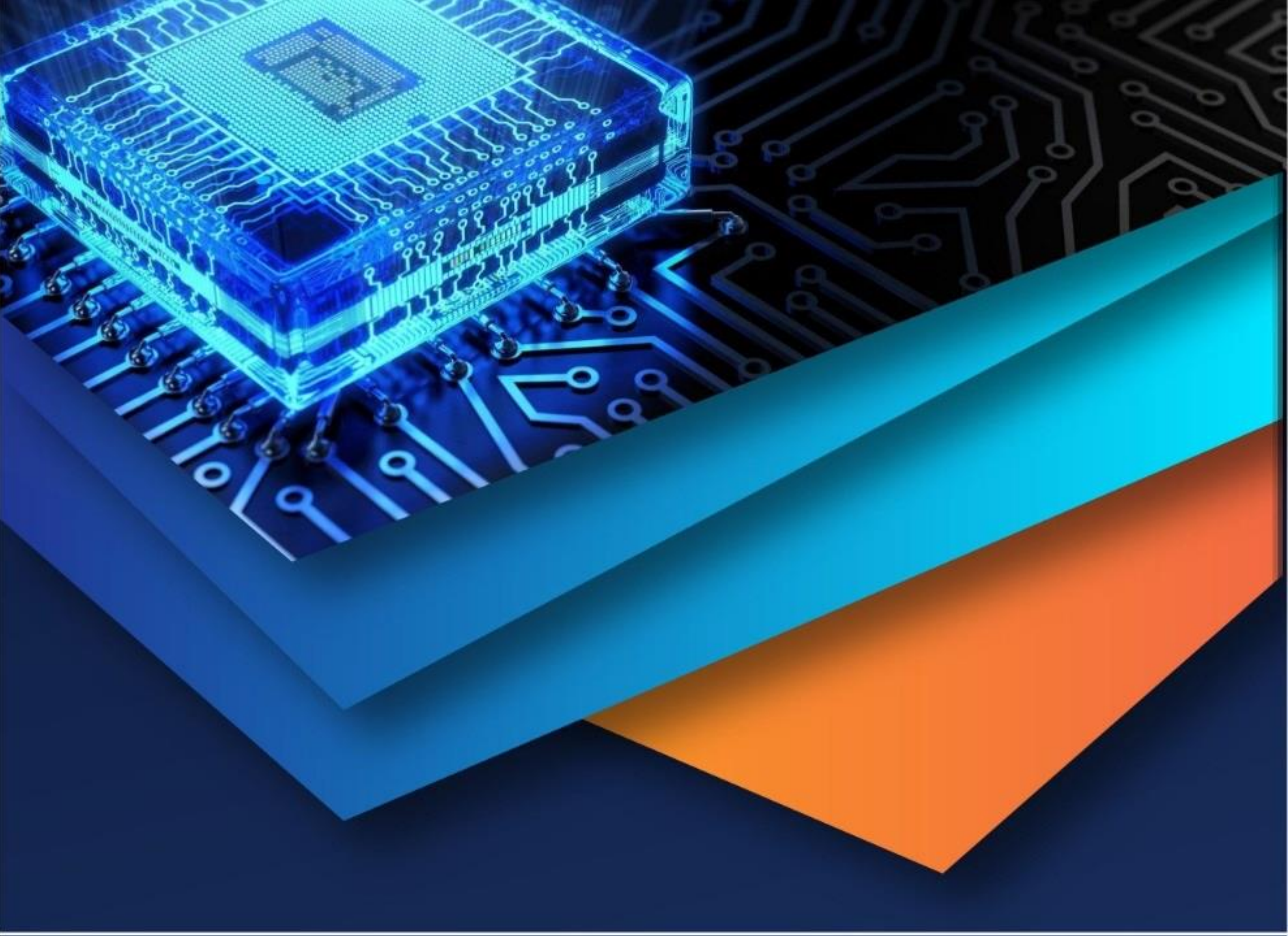

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