



Role of STATCOM in Enhancing Voltage Stability Across the Indian Power Transmission Grid Under High Solar Photovoltaic Penetration

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Abstract : The rapid expansion of utility-scale solar photovoltaic (PV) generation across India—driven by the national target of 500 GW non-fossil capacity by 2030—presents unprecedented dynamic stability challenges for the Inter-State Transmission System (ISTS). High integration of Inverter-Based Resources (IBRs) at centralized pooling stations (e.g., Fatehgarh, Bhadla, and Bikaner) reduces synchronous system inertia and weakens short-circuit ratios, making high-voltage corridors susceptible to voltage sags, reverse power flow fluctuations, and transient voltage instability. This paper examines the critical role of Static Synchronous Compensators (STATCOMs) in mitigating voltage instability caused by high solar PV penetration. Using Voltage Source Converter (VSC) technology, STATCOMs deliver fast, bidirectional reactive power support within 30 ms. We detail the operational dynamics, dynamic response at reduced grid voltages, control dead-band optimization, and integration strategies alongside Mechanically Switched Capacitors/Reactors (MSC/MSR). Mathematical models for Q-V sensitivity and modal analysis demonstrate how dynamic STATCOM allocation stabilizes weak buses during peak irradiance shifts and grid contingencies.

Key Words: STATCOM, Solar PV Penetration, Voltage Stability, Reactive Power Compensation, Indian Transmission System, Inverter-Based Resources (IBRs), FACTS.

1. INTRODUCTION

India's energy transition has accelerated the deployment of large-scale renewable energy (RE) parks, primarily concentrated in high-irradiance regions such as Rajasthan, Gujarat, and Andhra Pradesh. Large pooling substations at 400 kV and 765 kV levels collect gigawatt-scale solar power and transport it over long transmission distances to distant urban and industrial load centers.

Unlike traditional thermal generators, which supply natural mechanical inertia and continuous overload reactive capabilities, solar PV plants interact with the grid via power electronic converters. The replacement of synchronous machines with Inverter-Based Resources (IBRs) leads to several structural changes in grid dynamics:

- **Reduced System Inertia:** Lower fault ride-through tolerance and steeper rate-of-change-of-frequency ("RoCoF").
- **Low Short-Circuit Ratio (SCR):** Weakening of grid stiffness at remote pooling nodes.
- **Severe Voltage Fluctuations:** Driven by rapid cloud transients, sudden solar ramp-downs, and reactive power deficits during grid faults.

To prevent voltage collapse and ensure grid code compliance (such as Central Electricity Authority Technical Standards for Connectivity), dynamic reactive power compensation devices are required. Static Synchronous Compensators (STATCOMs) have emerged as the primary dynamic solution deployed by Power Grid Corporation of India Limited (POWERGRID) and state transmission utilities.

2. CHALLENGES OF HIGH SOLAR PENETRATION ON GRID VOLTAGE

2.1 Voltage Ramping and Cloud Transients

Solar PV generation exhibits steep power ramps due to passing cloud cover. When active power output P_{pv} drops rapidly, the voltage profile at the Point of Common Coupling (PCC) drops, disturbing the active-reactive power balance:

$$\Delta V \approx \frac{R \cdot \Delta P + X \cdot \Delta Q}{V_n}$$

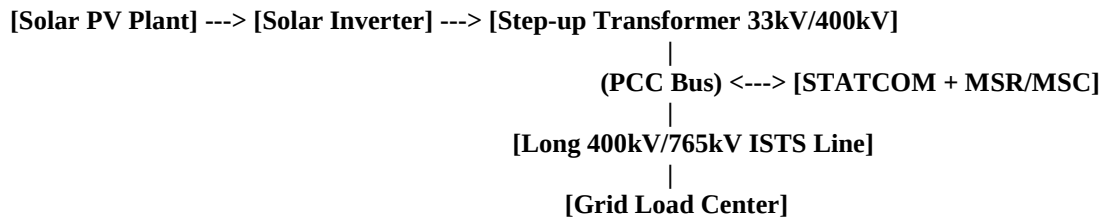
Where R and X are the line resistance and reactance, and V_n is the nominal bus voltage. In high-voltage transmission lines where $X \gg R$, active power variations cause severe phase angle shifts, while reactive power deficiencies directly drive voltage sags.

2.2 Low Short-Circuit Ratio in Remote Pooling Substations

Solar parks are often located in remote regions characterized by long 400 kV and 765 kV lines. The effective Short-Circuit Ratio (SCR_{eff}) at these buses drops below 2.0:

$$SCR_{eff} = \frac{S_{sc}}{P_{rated}}$$

Where S_{sc} is the short-circuit capacity at the PCC and P_{rated} is the total injected solar capacity. Under low SCR_{eff} conditions, standard grid-following inverter controllers experience control interaction loops, high harmonic distortion, and voltage unbalance.



3. STATCOM OPERATING PRINCIPLE AND DYNAMICS

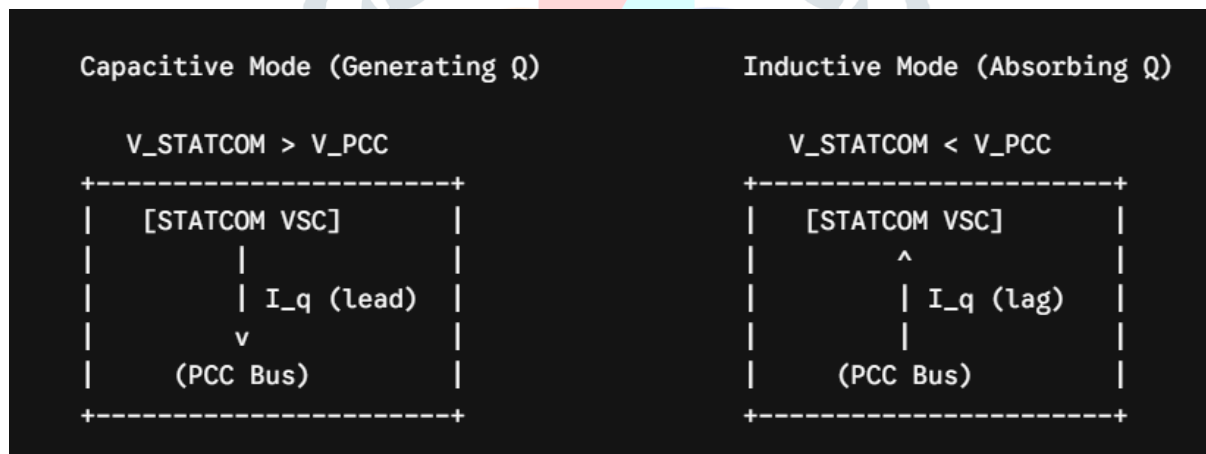
3.1 Voltage Source Converter Architecture

A STATCOM is a shunt-connected Flexible AC Transmission System (FACTS) device based on a multi-level Voltage Source Converter (VSC) using Insulated Gate Bipolar Transistors (IGBTs). Connected through a coupling transformer to the high-voltage grid, it acts as an adjustable AC voltage source behind a coupling reactance X_t .

The fundamental reactive power exchange between the STATCOM ($V_{STATCOM}$) and the grid bus (V_{PCC}) is expressed by:

$$Q_{STATCOM} = \frac{V_{PCC}}{X_t} (V_{STATCOM} - V_{PCC})$$

- **Capacitive Mode** ($V_{STATCOM} > V_{PCC}$): Injects reactive power ($+Q$) into the grid during voltage sags or high induction motor load periods.
- **Inductive Mode** ($V_{STATCOM} < V_{PCC}$): Absorbs reactive power ($-Q$) during light load conditions or high solar generation periods to suppress Ferranti effect overvoltages.



3.2 Dynamic Performance Comparison

Table - 1: Core Performance Matrix: STATCOM vs. Conventional SVC

Performance Feature	STATCOM (VSC-Based Architecture)	SVC (TCR/TSC-Based Architecture)
Current Output at Low Voltage	Maintains full rated reactive current I_{max} down to low AC levels ($V < 0.2$ p.u.)	Decreases linearly with voltage ($I \propto V$); output drops quadratically ($Q \propto V^2$)
Response Time	Ultra-fast (8 ms – 30 ms)	Moderate (20 ms – 50 ms)
Footprint Requirements	Up to 60–70% smaller area (no large air-core reactors)	Larger footprint due to harmonic filters and reactor banks

Performance Feature	STATCOM (VSC-Based Architecture)	SVC (TCR/TSC-Based Architecture)
Harmonic Emissions	Negligible (modular multi-level converter switching)	High 5th, 7th, 11th, and 13th harmonics requiring passive filters

4. MATHEMATICAL MODELING AND SENSITIVITY ANALYSIS

4.1 Static Voltage Stability and Q-V Sensitivity

To analyze the impact of dynamic reactive power compensation, the static voltage stability of the network is modeled using Q-V sensitivity and modal analysis based on the reduced system Jacobian matrix J_R :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

Assuming $\Delta P = 0$ for incremental reactive voltage stability assessment:

$$\Delta Q = (J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}) \Delta V = J_R \cdot \Delta V$$

$$\Delta V = J_R^{-1} \cdot \Delta Q$$

4.2 Q-V Modal Analysis

The reduced Jacobian matrix J_R is decomposed into its diagonal eigenvalue matrix Λ , right eigenvector matrix ξ , and left eigenvector matrix η :

$$J_R = \xi \cdot \Lambda \cdot \eta$$

$$\Delta V = \xi \cdot \Lambda^{-1} \cdot \eta \cdot \Delta Q$$

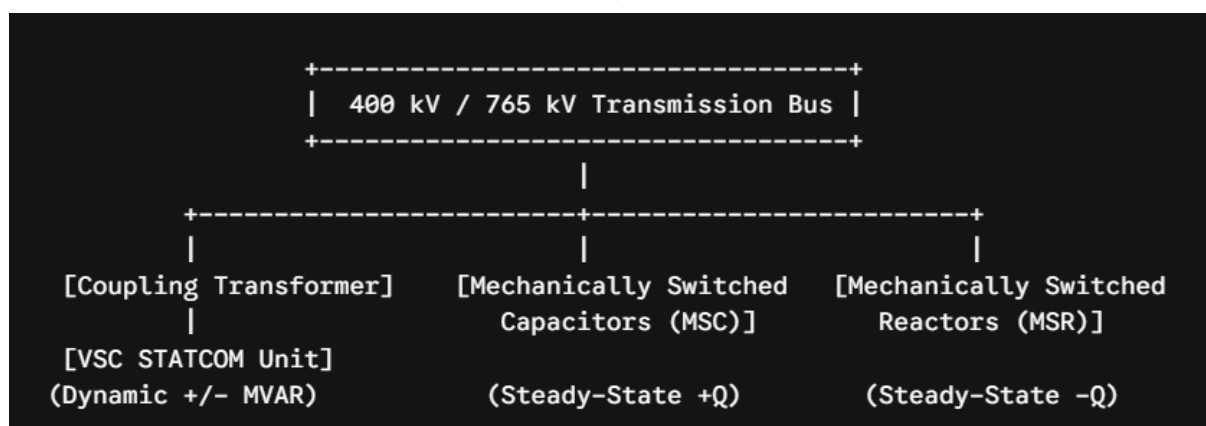
- A **positive eigenvalue** ($\lambda_i > 0$) confirms stable operation at mode i .
- As $\lambda_i \rightarrow 0$, the system approaches its voltage stability boundary.
- By placing a STATCOM at the bus with the highest **Bus Participation Factor** ($P_{ki} = \xi_{ki} \cdot \eta_{ik}$), the system eigenvalue λ_i is raised, preventing voltage collapse during sudden solar power variations.

5. APPLICATION STRATEGY IN THE INDIAN TRANSMISSION GRID

5.1 Hybrid STATCOM Architecture (STATCOM + MSR/MSC)

In high-voltage corridors such as the Rajasthan ISTS RE Complex (pooling stations at Fatehgarh, Bhadla, and Bikaner), POWERGRID utilizes a hybrid topology combining:

- Dynamic VSC Unit:** ± 100 MVAR to ± 300 MVAR for rapid transient response.
- Mechanically Switched Reactors (MSR):** Coordinated switching (e.g., 2×125 MVAR) for steady-state high-voltage suppression during off-peak hours.
- Mechanically Switched Capacitors (MSC):** For steady-state base load reactive support, preserving the STATCOM's dynamic headroom for contingent events.



5.2 Control Dead-Band Optimization

To avoid constantly depleting the STATCOM's dynamic reserve during minor continuous voltage noise, the controller employs a configurable voltage dead-band (typically ± 0.02 p.u. to ± 0.05 p.u.):

- **Within Dead-band:** The STATCOM operates in fixed reactive power mode or low-gain standby mode.
- **Outside Dead-band:** The controller switches to high-gain fast voltage regulation mode, injecting full capacitive/inductive current to return the bus voltage within operational bounds.

6. RECOMMENDATIONS AND GRID INTEGRATION ROADMAP

1. **Wide-Area Monitoring Integration:** Link STATCOM controllers with Synchronous Measurement Units (PMUs) / Wide Area Measurement Systems (WAMS) to provide coordinated dynamic voltage control across interconnected regional grids.
2. **Co-located Energy Storage (Grid-Forming STATCOM):** Incorporate Battery Energy Storage Systems (BESS) on the DC link of VSC STATCOMs to yield grid-forming capability, providing active synthetic inertia alongside dynamic VAR compensation.
3. **Optimized Tuning of Droop Settings:** Conduct regular Electromagnetic Transient (EMT) co-simulations to tune controller gains, preventing low-frequency control oscillations between neighboring inverter sources and STATCOMs.

7. CONCLUSION

As the Indian power grid accommodates higher shares of solar PV generation, STATCOM technology plays a central role in maintaining voltage stability. By providing rapid, continuous, and flexible reactive power compensation regardless of AC bus voltage degradation, STATCOMs stabilize weak pooling buses, improve short-circuit strength, and mitigate the impact of solar intermittency. Adopting hybrid STATCOM configurations with optimized dead-band controls ensures both steady-state voltage compliance and transient dynamic resilience across India's high-voltage transmission networks.

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