Transmission and Distribution Network augmentations for Solar and Wind Power Injections

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Introduction

The next phase of the energy transition is not only about building more solar and wind farms—it is about building smarter, stronger, and more flexible grids capable of integrating them reliably. The future pace of renewable growth will increasingly depend on grid readiness.

Introduction – Key Takeaways & Latest Statistics (2024–2025)

Theme	Key Takeaway	Latest Statistics (2024–2025)		Source (2024–2025)
		Global	SAARC Region*	
1. Unprecedented Renewable Growth	Renewable energy is becoming the backbone of global electricity expansion. Solar PV and wind account for the majority of new power capacity additions.	• Global renewable capacity reached **4,448 GW** in 2024 (+15.1% YoY). • Renewables are expected to add **~5,600 GW** between 2024–2030. • Solar PV is set to surpass **2 TW** of installed capacity in 2025. • Renewables are projected to supply **~46%** of global electricity by 2030.	• Total installed renewable capacity **~180 GW** in 2024. • Expected to reach **~270 GW** by 2030 (+50% over 2024). • Share of renewables in electricity mix **~23%** in 2024, projected to reach **~30%** by 2030.	• IEA – Renewables 2025 • IEA – World Energy Outlook 2025 • IRENA – Renewable Capacity Statistics 2025 • CEA India – Installed Capacity Report 2025 • SAARC Energy Centre Data 2024
2. Solar PV Leading the Transition	Global solar PV deployment has accelerated due to falling costs, technological improvements, and strong policy support.	• Global solar PV capacity reached **~2.1 TW** in 2024 (↑32% YoY). • Annual solar additions in 2024 exceeded **600 GW**. • Solar PV is expected to represent **~80%** of new renewable capacity additions through 2030.	• Solar PV capacity **~105 GW** in 2024. • Annual additions **~28 GW** in 2024 (↑131% YoY). • India installed ~24.5 GW solar in FY 2024–25.	• IEA – Renewables 2025 • SolarPower Europe – Global Market Outlook 2024–2028 • MNRE India – Annual Report 2024–25 • SAARC Energy Centre Data 2024
3. Wind Power as a Major Clean Energy Pillar	Wind energy has become the second-largest contributor to renewable expansion, with strong growth in both onshore and offshore.	• Global wind capacity reached **~1,100 GW** in 2024(↑14% YoY). • Offshore wind capacity **~75 GW** in 2024 (↑23% YoY). • Wind and solar together accounted for **91%** of new renewable capacity in 2024.	• Wind capacity **~60 GW** in 2024. • India ~46 GW, Pakistan ~1.8 GW, Sri Lanka **~0.27 GW**. • Large onshore projects continue in resource-rich regions (India, Pakistan, Nepal).	• IEA – Renewables 2025 • GWEC – Global Wind Report 2024 • CEB Sri Lanka – Annual Report 2024 • National Reports (India, Pakistan, Sri Lanka) • SAARC Energy Centre Data 2024
4. Grid Readiness is the New Bottleneck	The challenge is shifting from renewable availability to grid integration capability including networks, storage, flexibility, and digitalization.	• **~80 million km** of grids need expansion/modernization by 2040 globally (3× today's rate). • Investments in grids to reach **~USD 600 billion/year** by 2030 (>2× current level). • Global battery storage capacity **~220 GW / 880 GWh** in 2024 (↑30% YoY).	• **~200,000 km** of additional transmission lines required by 2030. • Storage capacity **~8.5 GW / 18 GWh** in 2024, expected to reach **~25 GW / 60 GWh** by 2030. • Significant investments needed in cross-border interconnections and digital infrastructure.	• IEA – World Energy Outlook 2025 • BloombergNEF – Energy Transition Outlook 2024 • IEA – Electricity Grids Report 2024 • SAARC Energy Centre Data 2024
5. Emerging Technical Challenges for Utilities	High renewable penetration introduces technical challenges that require advanced technologies and smarter operations.	Challenges include: intermittency, reduced inertia, voltage fluctuations, reverse power flows, limited fault current, and transmission congestion. **Solutions:** HVDC, FACTS, BESS, smart inverters, ADMS, digital substations, and advanced protection systems.	Utilities are adopting: HVDC links (India), FACTS (India, Bangladesh), large-scale BESS pilots, smart grids, advanced protection schemes, and regional power trade initiatives.	• IEA – Renewables 2025 • CIGRE – Technical Brochures 2024 • Utilities Annual Reports (2024–2025) • SAARC Energy Centre Outlook 2024
6. SAARC Region – Huge Potential, Major Grid Transformation Needed	SAARC countries possess vast renewable resources, but require major grid transformation to harness their potential effectively.	• Estimated renewable potential in SAARC: **~2,150 GW** (Solar ~1,050 GW, Wind ~530 GW, Hydro ~520 GW, Others ~50 GW). • Regional power trade can unlock additional **~25–30 GW** of cost-effective capacity.	• India targets 500 GW non-fossil capacity by 2030 (incl. 292 GW RE). • Nepal target ~283 GW by 2035. • Bangladesh target 40% RE by 2041. • Regional collaboration critical for integration, flexibility, and reliability.	• IEA – South Asia Energy Outlook 2024 • National Energy Plans (India, Nepal, Bangladesh, Pakistan, Sri Lanka) • SAARC Energy Centre Outlook 2024

Bottom Line: Modern protection and control techniques, along with grid modernization and coordinated operations, are essential to ensure secure, reliable, and resilient power systems in a high-renewable future.

*SAARC includes: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka.

SAARC Countries and Their Main Renewable Energy Sources

Country	Main Renewable Energy Sources	Key Regions / Notes
India	Solar, Wind, Hydropower, Biomass, Green Hydrogen	• Solar: Rajasthan, Gujarat • Wind: Tamil Nadu, Gujarat • Hydropower: Himalayan states, North-East India
Pakistan	Solar, Wind, Hydropower, Biomass	• Solar: Balochistan • Wind: Sindh • Hydropower: Northern Areas (KPK)
Bangladesh	Hydropower, Biomass, Biogas, Solar	• Biomass & Biogas widely used • Solar gaining importance in rooftop and off-grid systems
Sri Lanka	Wind, Solar, Hydropower, Waste-to-Energy, Biomass	• Wind: Mannar (NW coast) • Solar: Northern & Eastern Provinces • Hydropower from hill country rivers
Nepal	Hydropower	• Abundant hydropower potential from Himalayan rivers • Major source of renewable energy
Bhutan	Hydropower	• Hydropower is the backbone of energy sector • Large export potential
Maldives	Solar, Ocean Energy (Potential)	• High solar potential due to tropical location • Ocean energy (waves, OTEC) – future opportunity
Afghanistan	Solar, Wind, Hydropower, Biomass	• Solar & wind in high potential areas • Hydropower from rivers and streams • Biomass for rural energy needs

Challenges Faced by SAARC Countries

- **Resource–demand mismatch**: The best solar and wind resources are often located far from major load centres, requiring substantial investment in long-distance transmission corridors.
- **Insufficient transmission capacity**: Existing grids were largely designed around conventional, centrally located generation and are not always capable of accommodating large volumes of variable renewable energy (VRE).
- **Grid congestion and curtailment**: Limited evacuation capacity can result in renewable-energy curtailment, particularly during periods of high solar or wind output and low demand.
- **Weak distribution networks**: Rapid growth of rooftop solar and distributed generation can create voltage excursions, reverse power flows, protection coordination issues and transformer/feeder loading problems.

Challenges..

- **Limited grid flexibility**: Inadequate energy storage, flexible generation, demand response and ancillary-service mechanisms can constrain renewable integration.
- **Protection and operational challenges**: High penetration of inverter-based generation changes fault-current characteristics, power-flow patterns and conventional protection assumptions.
- **Planning and investment gaps**: Renewable generation, transmission, distribution and storage are not always planned as an integrated system, while financing constraints can delay critical grid upgrades.
- **Cross-border limitations**: Although regional power trading could significantly improve balancing and renewable utilisation, cross-border transmission capacity, market arrangements and regulatory coordination remain limited.

Future Actions

- **Develop renewable-energy transmission corridors** linking major solar and wind resource zones with demand centres.
- **Accelerate grid reinforcement and expansion**, including high-capacity AC/DC transmission, substations and strategically located interconnections.
- **Modernise distribution networks** to accommodate rooftop solar, distributed generation, electric vehicles and future prosumers.
- **Deploy grid-scale and distributed energy storage**, including BESS and pumped-storage hydropower, to provide balancing and flexibility.
- **Strengthen forecasting, SCADA/EMS, automation and real-time grid management** for variable renewable generation.

Future Actions..

- **Introduce dynamic network tariffs, demand response and ancillary-service markets** to improve system flexibility.
- **Upgrade protection and grid codes** to address high penetration of inverter-based resources and bidirectional power flows.
- **Adopt Dynamic Line Rating (DLR), FACTS and other advanced technologies** to increase the utilisation of existing transmission infrastructure before constructing entirely new corridors.
- **Promote coordinated regional power trading** and strengthen cross-border transmission interconnections among SAARC countries.
- **Establish integrated long-term planning mechanisms** in which generation, T&D, storage and demand growth are planned together, supported by appropriate regulatory frameworks and innovative financing.

Why Transmission Corridors?

- Renewable energy is abundant where people are not; transmission corridors connect clean energy to consumers.
- Renewable resources are geographically concentrated, while electricity demand is dispersed.
- Dedicated transmission corridors enable large-scale integration of renewable energy.
- They improve grid reliability, reduce renewable energy curtailment, and lower system costs.
- Cross-border interconnections enhance regional energy security and optimize resource utilization.

Benefits of Regional Transmission Corridors

- Facilitates large-scale renewable energy integration.
- Enables cross-border electricity trade and regional power markets.
- Reduces dependence on imported fossil fuels.
- Improves grid flexibility and resilience.
- Shares balancing reserves among neighbouring countries.
- Lowers overall electricity generation costs.
- Reduces renewable energy curtailment
- Supports national decarbonization goals

Challenges

- High capital investment
- Long approval and permitting processes
- Land acquisition and right-of-way issues
- Environmental and social impacts
- Coordination between transmission operators and renewable developers
- Maintaining reliability under variable renewable generation

Enabling Technologies

- High Voltage Direct Current (HVDC)
- Flexible AC Transmission Systems (FACTS)
- Dynamic Line Rating (DLR)
- Wide Area Monitoring Systems (WAMS)
- Battery Energy Storage Systems (BESS)
- AI-based Renewable Forecasting

Technologies to Optimize Transmission Network Utilization

Aspect	High Voltage Direct Current (HVDC)	Flexible AC Transmission Systems (FACTS)	Dynamic Line Rating (DLR)	Wide Area Monitoring Systems (WAMS)	Battery Energy Storage Systems (BESS)	AI-based Renewable Forecasting
Primary Purpose	Transmit large amounts of power over long distances with low losses and better controllability.	Increase power transfer capability and controllability of AC networks.	Increase real-time thermal capacity of existing lines safely.	Provide real-time visibility of the grid for better situational awareness and control.	Support the grid by storing energy and providing flexible power.	Improve accuracy of renewable generation forecasting to enable better grid operation.
How it Optimizes Utilization	Allows efficient bulk power transfer and relieves congestion between regions.	Controls power flow, reduces congestion, and increases stability margins.	Utilizes more of the existing line capacity based on real-time conditions.	Enables proactive decisions, congestion management, and emergency control.	Shifts energy, reduces peaks, and relieves congestion.	Reduces uncertainty, optimizes scheduling and dispatch, and minimizes curtailment.
Key Function	Point-to-point or multi-terminal DC power transmission.	Real-time control of voltage, impedance and phase angle.	Real-time monitoring of conductor temperature and environment.	Synchronized measurements and wide-area visibility (PMUs).	Charge / discharge to balance supply and demand.	Machine learning models to forecast solar, wind and load.
Response Speed	Fast (seconds to milliseconds with VSC-HVDC)	Very fast (milliseconds)	Real-time (minutes)	Very fast (30–120 samples/s)	Very fast (milliseconds to seconds)	Ahead of time (minutes to days depending on model)
Main Benefits	• High transfer capacity • Low losses • Asynchronous interconnection • Controllable flows	• Higher transfer capability • Improved voltage profile • Enhanced stability • Congestion relief	• Higher usable capacity • Better asset utilization • Cost-effective solution	• Better awareness • Proactive control • Faster fault detection • Improved reliability and security	• Peak shaving • Congestion relief • Frequency & voltage support • Renewable integration	• Higher forecast accuracy • Better planning and dispatch • Reduced reserves and curtailment
Typical Applications	Long-distance bulk transmission, cross-border links, offshore wind integration.	Congested corridors, voltage support, oscillation damping, weak grids.	Overloaded lines, seasonal rating changes, extreme weather areas.	Real-time monitoring, state estimation, oscillation detection, emergency control.	Peak demand management, renewable smoothing, black start support.	Day-ahead and real-time forecasting of solar, wind and load.
Investment Cost	High ★★★★☆ (High)	Medium to High ★★★☆☆ (Med–High)	Low to Medium ★★☆☆☆ (Low–Med)	High ★★★★☆ (High)	High ★★★★☆ (High)	Low to Medium ★★☆☆☆ (Low–Med)
Implementation Complexity	High (Planning, converters, protection)	Medium to High (Device selection, coordination)	Medium (Sensors, models, integration)	High (PMUs, communication, data management)	Medium to High (Sizing, controls, integration)	Medium (Data quality, model training, validation)
In Summary	Best for long-distance bulk transfer and controllability.	Best for increasing capacity and controlling power flow in AC grids.	Best for unlocking extra capacity of existing lines.	Best for real-time visibility and proactive network management.	Best for flexibility, stability and peak management.	Best for better decision-making through accurate forecasts.

SCADA vs WAMS – Key Differences

Feature	SCADA	WAMS
Full Form	Supervisory Control and Data Acquisition	Wide Area Monitoring System
Primary Purpose	Monitoring & control of **normal** power system **operations**	Monitoring wide-area **dynamic** behavior and system **stability**
Measurement Device	**RTUs**, PLCs, conventional meters	**Phasor Measurement Units (PMUs)**
Main Measurements	**Voltage**, current, power, energy, breaker status, alarms	**Synchronized voltages & currents (phasors), phase angle, frequency, ROCOF**
Time Synchronization	**Not precisely synchronized**	**GPS / precise time synchronized**
Data Reporting Rate	Typically **2 – 10 seconds**	Typically **30 – 120 samples per second**
Measurement Type	Primarily **magnitude & status**	**Magnitude + phase angle (phasor)**
Geographic Coverage	**Substation** / **control area** level	**Wide area – entire interconnected system**
Event Detection	**Limited** for fast / dynamic events	**Detects fast disturbances, oscillations, angle instability, frequency events**
Phase Angle Information	**Not available**	**Directly measured**
Communication Requirement	**Lower bandwidth**	**High bandwidth, low latency, highly reliable**
Data Concentration	**SCADA Master Station / EMS**	**Phasor Data Concentrator (PDC)**
Typical Applications	Breaker control, tap changing, capacitor switching, alarm handling, **routine supervision**	**Wide-area protection, oscillation damping, controlled islanding, emergency control, stability enhancement**
Stability Assessment	Mainly **steady-state** monitoring	**Real-time transient, voltage & small-signal stability assessment**
Role in Renewable Integration	Monitors renewable generation, loading, and equipment **status**	**Monitors variability impact, ensures stability, coordinates control of renewables & storage**
Cost & Complexity	**Lower**	**Higher**
Key Limitation	**Too slow** and not synchronized for fast dynamic events	**Requires PMUs, precise timing, fast communication and large data handling capability**
Relationship	**WAMS complements SCADA – not a replacement**	

Technical Challenges of Renewable Energy (RE) Integration

Challenge	Description	Impact on Power System	Why It Happens (RE Context)	Key Mitigation / Solutions
1 Variability and Intermittency	Solar and wind generation vary with weather, time of day, and seasons, making output uncertain and less predictable.	• Frequency fluctuations • Reserve requirement increases • Difficulty in supply–demand balancing	RE sources (solar, wind, small hydro) are non-dispatchable and depend on natural conditions.	✔ Forecasting & advanced scheduling ✔ Energy storage (BESS, pumped hydro) ✔ Flexible generation and demand response ✔ Hybrid systems (solar–wind–storage)
2 Reduced System Inertia	High RE penetration (through inverters) displaces synchronous generators, reducing the system's inertia.	• Higher RoCoF (rate of change of frequency) • Lower system stability margins • Risk of frequency instability	Inverter-based RE does not provide natural rotating mass and kinetic inertia.	✔ Synthetic inertia from inverters (grid-forming) ✔ Fast frequency response (BESS, HESS) ✔ Retain synchronous condensers ✔ Appropriate grid codes and standards
3 Voltage Fluctuations and Poor Voltage Regulation	Rapid changes in RE output cause voltage variations and poor voltage control, especially in weak grids.	• Voltage instability • Equipment maloperation/tripping • Reduced power quality	RE output fluctuations and reverse power flows affect voltage profiles, particularly in distribution networks.	✔ Volt/VAR control from inverters ✔ FACTS devices (STATCOM, SVC, UPFC) ✔ Smart tap changers and capacitors ✔ Strong grid and proper planning
4 Reverse Power Flows	Power flows from distribution to transmission or substation due to high local RE generation.	• Overloading of transformers/lines • Protection coordination issues • Voltage rise and instability	Distributed RE generation often exceeds local demand, pushing power back into the grid.	✔ Time-of-use control and curtailment ✔ Energy storage at distribution level ✔ Smart inverters and dynamic limits ✔ Network reinforcement
5 Limited Fault Current Contribution	Inverter-based RE provides very low short-circuit current during faults.	• Impacts protection coordination • Increases fault detection time • May lead to misoperation or protection failure	Inverters limit current to protect semiconductors; no natural fault current like synchronous machines.	✔ Inverter fault current support functions ✔ Protection system redesign ✔ Adaptive protection schemes ✔ Grid-forming inverter technologies
6 Transmission Congestion and Bottlenecks	RE is often located far from load centers, overloading existing transmission corridors.	• Curtailment of RE generation • Increased operational cost • Delayed RE evacuation	Mismatch between resource-rich areas (remote) and demand centers (urban/industrial).	✔ Grid expansion and strengthening ✔ HVDC transmission ✔ Optimal power flow and congestion management tools
7 Supply–Demand Imbalance	Mismatch between variable RE supply and demand at different time scales.	• Increased ramping of conventional units • Higher balancing cost • Risk of load shedding	Uncertain RE output vs. inflexible demand patterns.	✔ Load forecasting and scheduling ✔ Demand response programs ✔ Energy storage and flexible resources
8 Power Quality Issues	High RE integration can cause harmonics, flicker, unbalance, and DC offsets.	• Reduced equipment life • Disturbance to sensitive loads • Compliance with power quality standards	Power electronic interfaces and rapid switching in inverters.	✔ Advanced inverter controls and filters ✔ Active power quality conditioners ✔ Compliance with IEEE/IEC standards
9 System Stability Challenges	Reduced damping and weak grid conditions can lead to oscillations and instability.	• Electromechanical oscillations • Voltage collapse risk • Reduced transient stability	Low system strength, high RE penetration, and weak interconnection infrastructure.	✔ FACTS devices (PSS, STATCOM, SSSC) ✔ Grid-forming inverters ✔ Strengthen grid and interconnections

Key Takeaway Successful RE integration requires a combination of advanced forecasting, grid strengthening, storage, smart inverters, FACTS technologies, and updated codes & standards to ensure a reliable, secure, and resilient power system.

Limited inertia

Modern evacuation systems therefore include:

- ➢Synthetic inertia
- ➢Grid-forming inverters
- ➢Dynamic voltage support
- ➢Fast frequency response

Comparison of Advanced Grid Support Techniques

(Synthetic Inertia, Grid-Forming Inverters, Dynamic Voltage Support, Fast Frequency Response)

Feature	Synthetic Inertia	Grid-Forming Inverters	Dynamic Voltage Support	Fast Frequency Response (FFR)
Primary Purpose	Mimic natural inertia to slow initial rate of frequency decline.	Establish and maintain stable voltage and frequency.	Maintain and restore voltage magnitude at buses.	Stabilize frequency quickly and arrest further decline.
What it Does	Injects/absorbs active power proportional to RoCoF.	Sets voltage & frequency reference and supplies power to the grid.	Injects/absorbs reactive power (or controls voltage).	Injects/absorbs active power based on frequency deviation.
Trigger	Rate of Change of Frequency (RoCoF)	Need to form a grid or support weak grids / disturbances	Voltage deviation from set point	Frequency deviation (Δf) and/or RoCoF
Response Speed	Very fast (milliseconds) ~1–10 ms	Fast (tens of milliseconds) ~10–100 ms	Fast (tens of milliseconds) ~10–100 ms	Very fast (hundreds of milliseconds to ~1 s) ~100 ms – 1 s
Duration	Very short (sub-second) ~0.1 – 1 s	Sustained (as long as resources available)	Short to medium term (several seconds)	Short duration (typically 5 – 30 s)
Energy Source	Kinetic energy (rotating machines) or batteries	Energy from DERs, storage, or other sources	Inverter/STATCOM capability, capacitors, batteries	Battery, wind, demand response, hybrid resources
Key Capability	Inertial (active power) support based on RoCoF	Voltage & frequency control, black start, islanded operation	Voltage regulation, reactive power support	Fast active power support to restore frequency
Typical Providers	Wind turbines (with inertia emulation), batteries, VSCs	Grid-forming inverters, synchronous condensers, certain generators	Inverters/STATCOMs, SVCs, capacitors	Batteries, wind, solar (with fast controls), DR, gas/hydro
Impact on System	Reduces initial RoCoF and buys time for other actions	Strengthens system stability, creates a stable grid reference	Maintains voltage profile, prevents voltage collapse	Stops frequency decline and restores balance
Best Used For	Very first instant after a generation loss	Weak grids, microgrids, black start, high renewable penetration	Voltage sags/swells, weak buses, renewable integration	Immediately after frequency drops below threshold
Key Advantage	Extremely fast and automatic, no communication delay	Provides full grid support ("acts like a synchronous machine")	Improves voltage stability and power quality	Very fast delivery of real active power
In Summary	Acts in the **first instant** to **slow frequency fall** (RoCoF control).	Provides a stable reference and can **run the grid**, even without it.	Keeps **voltage within limits** through **fast** reactive power support.	Acts quickly after frequency drops to **arrest decline and restore balance.**

Natural vs. Synthetic Inertia

Feature	Natural Inertia (Synchronous Machines)	Synthetic Inertia (From Power Electronics)
Definition	Inertia provided by the **physical rotating mass** of synchronous generators (turbines and alternators).	Inertia-like response provided by power electronic converters (**inverters, batteries, VSCs,** etc.) through fast active power injection.
Source of Energy	Kinetic energy stored in the **rotating mass** of synchronous machines.	Stored energy in **DC links, batteries, supercapacitors**, or other energy storage devices.
Physical Nature	Physical phenomenon based on **mechanics** (mass and speed).	Control-based phenomenon implemented via **software/controls**.
Response Time	Inherent and **instantaneous** (milliseconds) on frequency deviation.	**Very fast** (milliseconds) and fully controllable.
Duration of Support	**Sustained** as long as the machine remains connected and rotating.	Limited by available stored energy. Typically **short-term** (seconds to minutes).
Dependency	Depends on the presence and speed of **synchronous machines**.	Independent of rotating machines. Can be provided by **inverter-based resources**.
Controllability	**Not directly controllable.** Depends on system frequency deviation.	**Fully controllable** (magnitude, response time, duration, droop settings, etc.).
Scalability	**Limited** by the size and number of synchronous machines.	**Highly scalable** – can be added quickly through software/firmware updates.
Location	Usually at **large power plants** connected to the grid.	Can be located **anywhere** – wind farms, solar plants, BESS, HVDC links, STATCOMs, etc.
Effect on Frequency	**Slows down** the Rate of Change of Frequency (RoCoF) naturally by releasing kinetic energy.	**Actively reduces RoCoF** by injecting/absorbing active power as per control strategy.
Reliability	**Very reliable** and proven technology with decades of operational experience.	**Reliability depends** on controls, communication, and available stored energy.
Cost	**No additional cost** (part of existing synchronous machines).	**Additional cost** for power electronics and energy storage systems.
Examples	Steam turbines, hydro turbines, gas turbines, diesel generators.	Batteries (BESS), wind/solar inverters with inertia emulation, STATCOM, VSC-HVDC, flywheels.
In Summary	Natural Inertia is **inherent, reliable and long-lasting,** but limited by the physical presence of synchronous machines.	Synthetic Inertia is **fast, controllable and scalable**, but limited by stored energy and control systems.

Grid-Forming vs. Grid-Following Inverters

Feature	Grid-Forming (GFM) Inverters	Grid-Following (GFL) Inverters
Operating Principle	**Sets** the grid voltage magnitude and frequency. Acts as a voltage source.	**Tracks** the grid voltage and frequency. Acts as a **current** source.
Role in the Grid	**Creates and sustains** the grid. Can operate without an existing grid.	**Requires an existing grid** to operate. Injects current according to grid conditions.
Dependence on Grid	**Independent.** Can operate in islanded (standalone) mode.	**Dependent.** Cannot operate in islanded mode.
Inertia & Frequency Support	**Provides synthetic inertia.** Actively controls frequency (RoCoF, nadir).	**No inherent inertia.** Limited frequency support unless programmed.
Voltage Support	**Strong voltage support.** Can regulate voltage and reactive power.	**Limited voltage support.** Reactive power is set based on PLL measurements.
Black Start Capability	**Yes.** Can energize the grid on its own.	**No.** Needs an energised grid.
Synchronization	**Not required** (it defines the reference).	**Requires PLL to synchronize with grid voltage.**
Stability Contribution	**High.** Improves small-signal & transient stability.	**Lower.** May reduce system strength if dominant.
Control Complexity	**High.** Needs advanced droop, virtual oscillator or dispatchable control.	**Lower.** Uses simpler current/Power control with PLL.
Typical Applications	**Microgrids, weak grids, black start,** system restoration, grid stability services.	**Grid-tied solar PV, wind turbines,** battery systems in strong grids.
Response to Disturbances	**Fast and proactive.** Maintains voltage and frequency.	**Reactive.** Follows grid disturbances.
Cost	**Higher** (more controls & capability).	**Lower.**
Penetration in Future Grids	**Essential as inverter-based resources** become dominant.	**Suitable for strong grids with synchronous generation.**
In Summary	Grid-Forming inverters **build and stabilize the grid,** provide inertia, voltage & frequency support, and enable operation without the grid.	Grid-Following inverters **follow the grid,** depend on it for reference, and inject current based on grid conditions.

What is PLL? PLL stands for **Phase-Locked Loop.**
It is an electronic control system used by grid-following inverters to measure the grid voltage phase angle, frequency and magnitude, and to generate a synchronized reference signal so the inverter can inject current in the correct phase with the grid.

Fast Frequency Response (FFR) vs. Synthetic Inertia

Feature	Synthetic Inertia	Fast Frequency Response (FFR)
Trigger	**Rate of Change of Frequency (RoCoF)** Detects how quickly frequency is changing	**Frequency deviation (Δf) and/or RoCoF** Responds once frequency deviates from set point
Response Action	**Emulates inertial energy release** Instantaneous injection/absorption of power proportional to RoCoF	**Controlled active power injection/absorption** To arrest frequency decline and bring frequency back to normal
Response Speed	**Very fast (milliseconds)** Almost instantaneous response	**Fast (hundreds of milliseconds to ~1 second)** Slower than synthetic inertia but still fast
Duration	**Very short duration** Typically sub-second (hundreds of milliseconds to ~1 second)	**Short duration** Typically several seconds (5–30 s)
Energy Source	**Kinetic energy from rotating machines (e.g., wind turbines) or batteries** No additional energy required (inertia response)	**Stored energy or fast-acting resources** Batteries, wind, demand response, hydro, hybrid systems, etc.
Primary Objective	**Slow down the initial rate of frequency decline** Mimics the natural inertia of synchronous machines	**Stabilize frequency and stop further decline** Restore frequency toward nominal value
Power Contribution	**Power output proportional to RoCoF** Higher RoCoF → higher inertial power	**Predefined power response** Based on droop/control settings and available capacity
Typical Providers	**Wind turbines (with inertia emulation), battery systems, VSC-based resources**	**Batteries, wind, solar (with fast controls), demand response, gas/hydro, hybrid plants**
Control Basis	**RoCoF-based control** Measures how fast frequency is changing	**Δf-based and/or RoCoF-based control** Activated when frequency crosses a threshold
Market / Application	**Inertia services market** Short-term, first line of defense	**Ancillary services (FFR)** Primary frequency control service
Key Benefit	**Provides instantaneous support** Reduces RoCoF and helps prevent deep frequency dips	**Provides sustained support** Helps recover frequency and maintain stability
In Summary	**Synthetic Inertia acts in the first instant to slow the rate of frequency decline (RoCoF).**	**Fast Frequency Response acts slightly later to stabilize and restore frequency.**

Integration of HVDC and FACTS Devices for Congestion Relief

As renewable energy generation increases, transmission corridors often become congested, limiting the transfer of electricity from renewable energy zones to demand centers. High Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) enhance the utilization of existing transmission infrastructure, improve power flow control, and relieve network congestion without extensive construction of new transmission lines.

Role of HVDC in the Integration of Renewable Energy (RE)

Role of HVDC	How HVDC Helps	Benefits for RE Integration	Typical RE Applications	Impact on Power System
1. Precise and Controllable Power Transfer Between Regions	HVDC allows accurate control of power flows through converter stations, enabling operators to manage the amount and direction of power transfer in real time.	• Balances variable RE generation across regions. • Supports dynamic scheduling and market operations. • Enhances grid flexibility and reliability.	Inter-regional transfer of solar & wind power from high-resource areas to high-demand centers.	✔ Better utilization of RE resources ✔ Improved operational efficiency ✔ Reduced imbalance and curtailment
2. Transfers Large Amounts of Power Over Long Distances with Lower Losses	HVDC transmits power at higher voltages with lower line losses compared to AC, especially over long distances (> ~600–800 km).	• Delivers bulk RE power economically from remote locations. • Reduces transmission losses (typically 30–50% less than AC over long distances). • Lowers lifecycle cost of long-distance transmission.	Offshore wind farms, desert solar parks, and remote hydro projects connected to load centers.	✔ Lower transmission losses ✔ Higher transfer capability ✔ Cost-effective delivery of clean power
3. Bypasses Congested AC Transmission Corridors	HVDC lines can create new transmission corridors over land or subsea routes, avoiding congested or unstable AC paths.	• Relieves congestion on existing AC networks. • Expands transfer capability without overloading AC lines. • Enables direct delivery of RE power to demand centers.	New HVDC corridors to bring RE from resource-rich regions while avoiding weak or congested AC networks.	✔ Reduced congestion ✔ Improved reliability ✔ Deferred investment in new AC lines
4. Enables Asynchronous Interconnection of Different Power Systems	HVDC converter stations decouple AC systems, allowing power exchange between networks with different frequencies, phases, or stability characteristics.	• Connects grids operating at different frequencies. • Prevents propagation of disturbances between systems. • Enables cross-border RE trading and energy security.	Interconnection between countries or regions with asynchronous grids (e.g., 50 Hz and 60 Hz).	✔ Enhanced grid resilience ✔ Greater interconnection capability ✔ Facilitates regional energy markets
5. Improves System Stability and Supports Integration of Remote RE Resources	HVDC provides controllable power support and enhances voltage and frequency stability in weak or remote grids.	• Provides fast active and reactive power support. • Enhances frequency and voltage stability. • Facilitates large-scale integration of variable RE (solar, wind, hydro).	Integration of large-scale offshore wind, desert solar parks, and hybrid RE projects.	✔ Improved voltage & frequency stability ✔ Better fault management ✔ Higher hosting capacity for RE

Key Takeaway HVDC is a critical enabler for the modern power system, allowing efficient, reliable, and flexible integration of large-scale renewable energy across regions and countries.

Global HVDC Capacity (2024) **~900 GW** (Installed & under construction)

New HVDC Capacity Additions (2024) **~20–25 GW** (Record High)

HVDC Projects in Pipeline (2025–2030) **> 300 GW** Globally

CO_2 Enables integration of cleaner energy at scale and supports net-zero emissions goals.

Note: Statistics are based on latest available data from IEA, CIGRE, and industry reports (2024–2025). Figures are approximate.

Role of FACTS Devices

FACTS devices use power electronics to control voltage, impedance, and power flow in AC transmission systems.

- STATCOM – Dynamic voltage support and reactive power compensation.
- SVC (Static VAR Compensator) – Voltage regulation and reactive power control.
- TCSC (Thyristor Controlled Series Capacitor) – Controls line impedance to increase power transfer capability.
- UPFC (Unified Power Flow Controller) – Simultaneously controls voltage, impedance, and power flow.

Role of FACTS Devices in the Integration of Renewable Energy (RE)

FACTS Device	Primary Function	How It Helps RE Integration	Key Benefits for RE-Rich Grids	Typical Applications	Impact on Power System
STATCOM (Static Synchronous Compensator)	Provides dynamic voltage support and reactive power compensation.	• Maintains stable voltage at PCC with variable RE output. • Supports weak grids where RE causes voltage fluctuations. • Absorbs or supplies reactive power rapidly.	Improves voltage stability Reduces voltage flicker from wind/solar Enhances power quality Increases RE hosting capacity	Wind farms (onshore/offshore) Large solar PV plants Weak or long transmission networks RE-rich distribution systems	Better voltage profile Reduced curtailment Enhanced reliability Stronger grid support during disturbances
SVC (Static VAR Compensator)	Provides voltage regulation and reactive power control using thyristor-controlled reactors and capacitors.	• Regulates voltage under varying RE generation. • Compensates for reactive power demand of RE-connected grids. • Maintains power factor and reduces line losses.	Cost-effective voltage control Improves power factor Reduces transmission losses Mitigates congestion-related voltage issues	Wind and solar integration at sub-transmission level Voltage support in radial and weak networks Utility substations and industrial loads	Stable voltage Improved system efficiency Increased RE penetration Reduced equipment stress
TCSC (Thyristor Controlled Series Capacitor)	Controls line impedance (capacitive or inductive) to increase power transfer capability.	• Increases power transfer capability from RE-rich areas to load centres. • Prevents line overloading by adjusting series compensation. • Enhances transient stability.	Increases transfer capability Prevents congestion and overloading Improves system stability Optimizes use of existing infrastructure	Bulk power transfer from RE-rich regions Congested AC corridors Renewable evacuation corridors	Higher power transfer Deferred transmission expansion Reduced congestion costs Improved grid utilization
UPFC (Unified Power Flow Controller)	Simultaneously controls voltage, impedance, and power flow in a transmission line.	• Provides independent control of real and reactive power flow. • Maintains voltage and controls line impedance dynamically. • Enables optimal routing of power from multiple RE sources.	Simultaneous control of V, Z, and power flow Maximizes grid utilization Improves stability margins Enhances operational flexibility	Multi-source RE integration Power flow management in meshed networks Inter-regional and interconnected grids	Optimal power flow control Better stability and security Higher RE hosting capacity Resilient and flexible grid operation

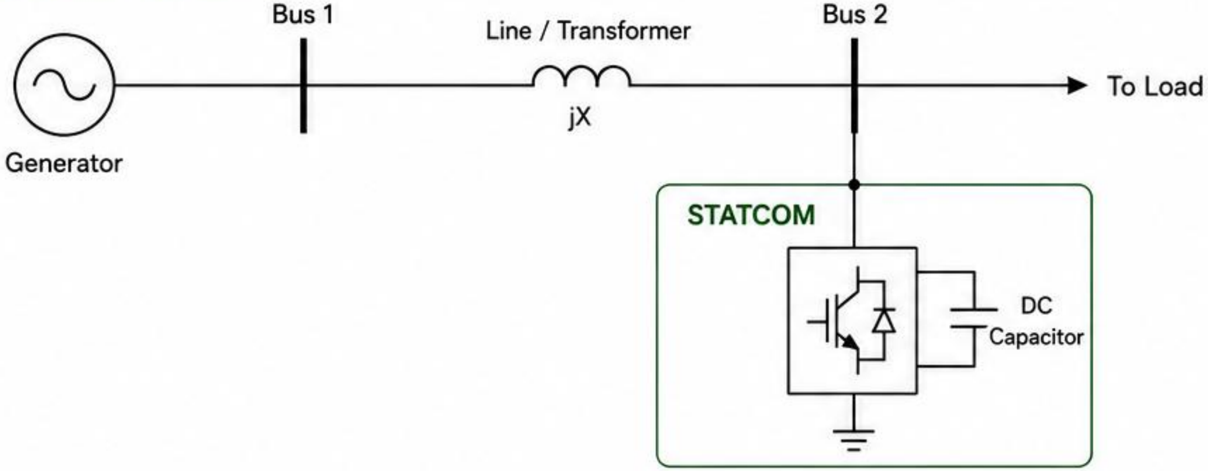
Overall Impact of FACTS Devices on RE Integration

- Enable higher penetration of variable renewables
- Improve voltage and frequency stability
- Reduce curtailment and improve reliability
- Support clean energy transition and sustainability

Note: FACTS – Flexible AC Transmission System; RE – Renewable Energy; PCC – Point of Common Coupling; VAR – Volt-Ampere Reactive.

STATCOM (Static Synchronous Compensator) in Power System

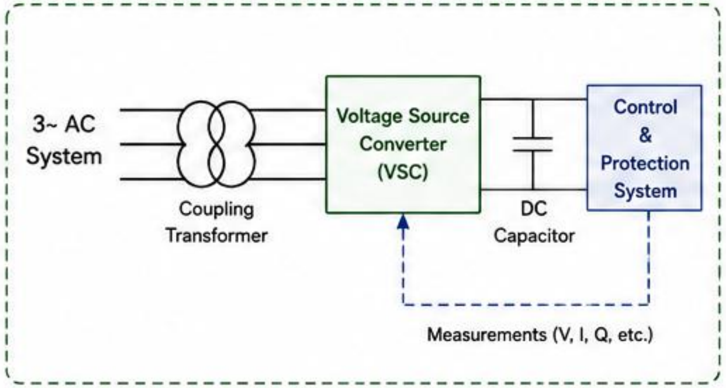
Single Line Diagram



How STATCOM Works

- STATCOM is a shunt connected, voltage sourced converter (VSC) based FACTS controller.
- It generates or absorbs reactive power by controlling the magnitude and phase angle of its AC output voltage (V_{conv}) with respect to the bus voltage (V_s).
- If $|V_{conv}| > |V_s|$ (in phase), STATCOM supplies capacitive reactive power (Q).
- If $|V_{conv}| < |V_s|$ (in phase), STATCOM absorbs inductive reactive power (Q).
- Response time is very fast (in a few milliseconds).

Internal Structure of STATCOM

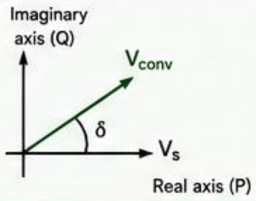


Operating Modes

1. Capacitive Mode (Generate Q)

$|V_{conv}| > |V_s|$

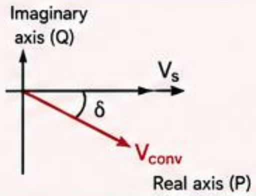
STATCOM supplies reactive power to the system.



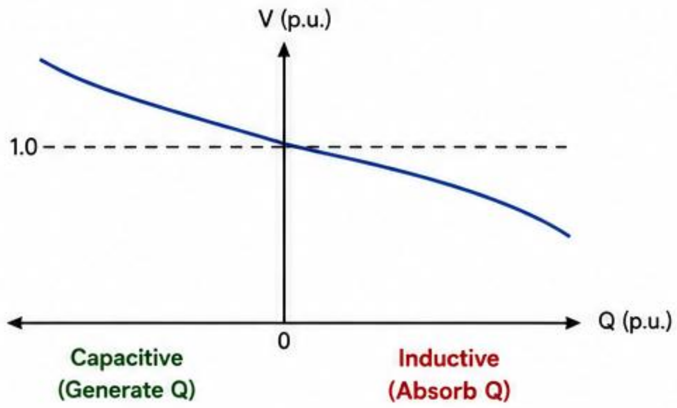
2. Inductive Mode (Absorb Q)

$|V_{conv}| < |V_s|$

STATCOM absorbs reactive power from the system.



V – Q Characteristic



Functions / Benefits

- Maintains / regulates bus voltage.
- Improves power factor.
- Enhances transient stability.
- Reduces voltage fluctuations and flicker.
- Increases system loading capability.
- Fast dynamic response (milliseconds).

Key Features

- Provides both leading and lagging reactive power continuously.
- Maintains bus voltage by fast control of reactive power.
- Improves power factor, system stability and increases transmission capacity.
- No energy storage required (only small DC capacitor for VSC).

Typical Range of STATCOM

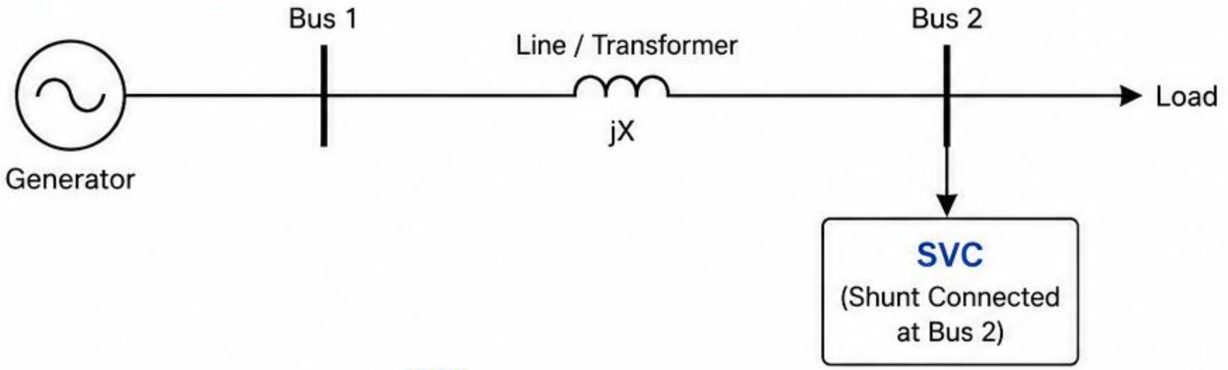
$Q_{statcom}$: from – (inductive) to + (capacitive)

(typically ±0.5 to ±1.0 p.u. of system MVA at the bus)

Response Time : < 1 to 2 cycles (≈ 5–20 ms)

SVC (Static Var Compensator) in Power System

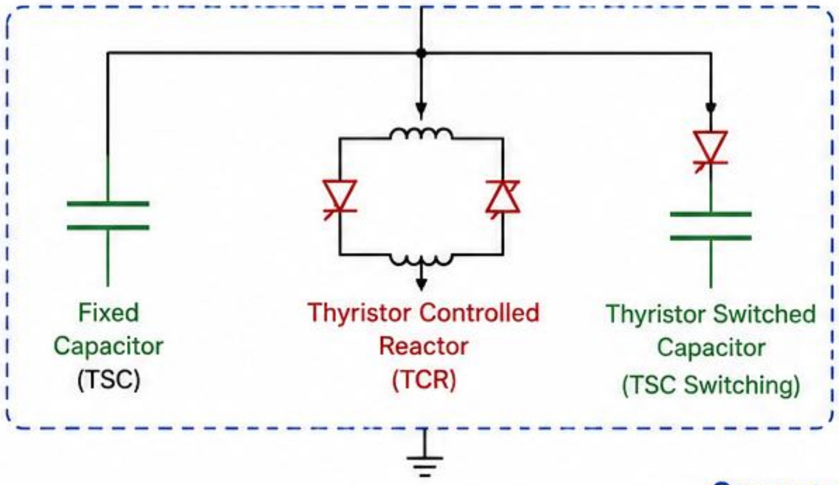
Single Line Diagram



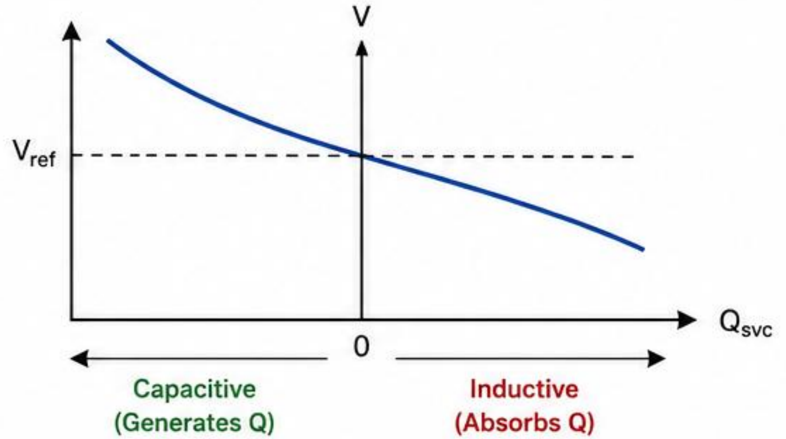
How SVC Works

- SVC is a shunt connected FACTS controller that generates or absorbs reactive power at the point of connection.
- It controls the AC bus voltage by varying its reactive power output (Q_{svc}).
- Main components: TCR, TSC (switched capacitors) and fixed capacitors.
- By adjusting the firing angle (α) of thyristors in the TCR and switching capacitors, SVC provides smooth and fast control of reactive power.

SVC



V – Q Characteristic



Functions / Benefits

- Maintains or improves bus voltage.
- Improves power factor.
- Enhances transient stability.
- Increases system loading capability.
- Fast dynamic response (in a few cycles).

Summary

Condition	SVC Action
Voltage drops	SVC generates reactive power (capacitive mode)
Voltage rises	SVC absorbs reactive power (inductive mode)
Voltage normal	SVC maintains required Q (near zero output)

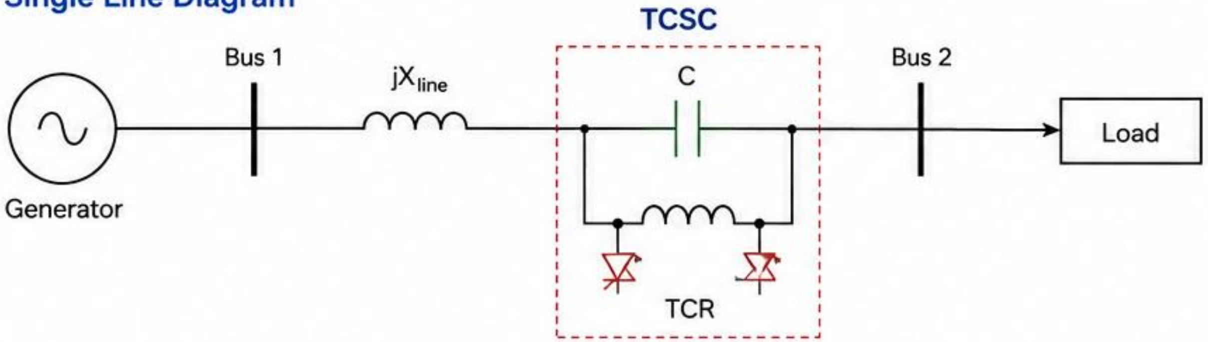
Typical Range of SVC

Q_{svc} : from – (capacitive) to + (inductive)
(typically 20% to 60% of system MVA at the bus)

Response Time : 1 – 2 cycles

TCSC (Thyristor Controlled Series Capacitor) in Power System

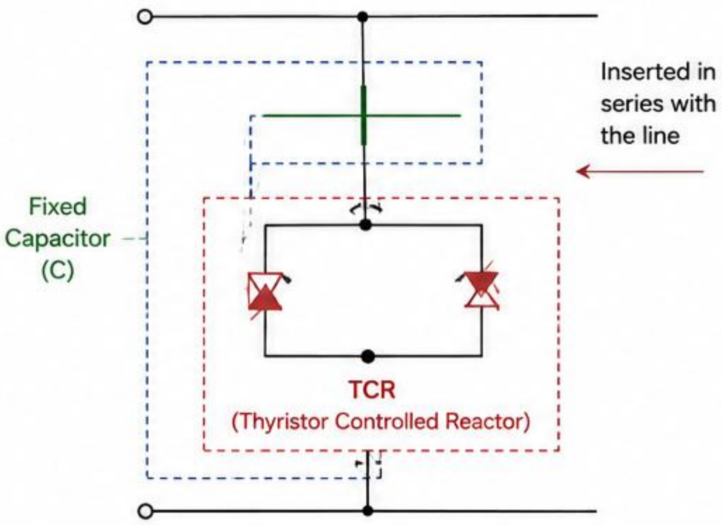
1. Single Line Diagram



2. How TCSC Works

- TCSC is a series compensated device used to control the effective reactance of a transmission line.
- It consists of a fixed capacitor (C) in parallel with a thyristor controlled reactor (TCR), and this combination is connected in series with the line.
- By controlling the firing angle (α) of thyristors in the TCR, the inductive reactance of TCR is varied.
- This changes the net series reactance inserted in the line, thus controlling power flow, line impedance, and system stability.

3. TCSC Structure



4. Operating Principle

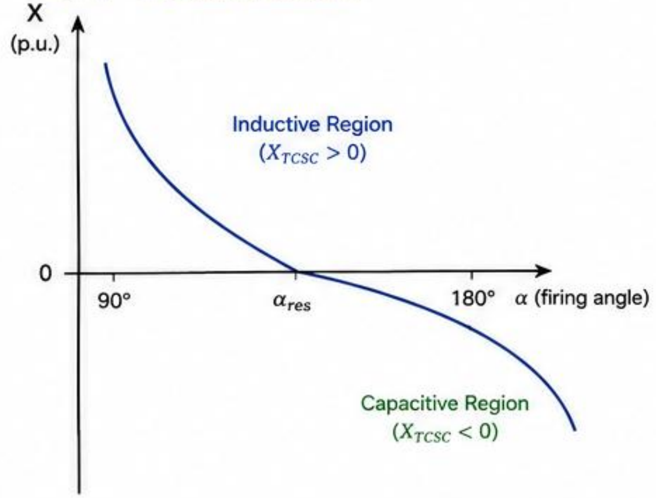
- The TCR provides variable inductive reactance.
- When thyristor firing angle (α) is small (near 90°), TCR reactance is maximum (inductive).
- When α increases toward 180°, TCR reactance decreases.
- The net reactance X_{TCSC} seen by the line is:

$$X_{TCSC} = \frac{X_C \cdot X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C}$$

where $X_C = \frac{1}{\omega C}$ and $X_{TCR}(\alpha)$ = variable reactance of TCR (inductive).

- If $X_{TCR}(\alpha) > X_C$ → Net reactance is inductive.
- If $X_{TCR}(\alpha) = X_C$ → Net reactance approaches infinity (resonance – avoided in operation).
- If $X_{TCR}(\alpha) < X_C$ → Net reactance becomes capacitive.
- By proper control of α, TCSC can provide variable capacitive or inductive series compensation.

5. V – X Characteristic



(α_{res} : Resonant point where $X_{TCR}(\alpha_{res}) = X_C$)

6. Key Features / Benefits

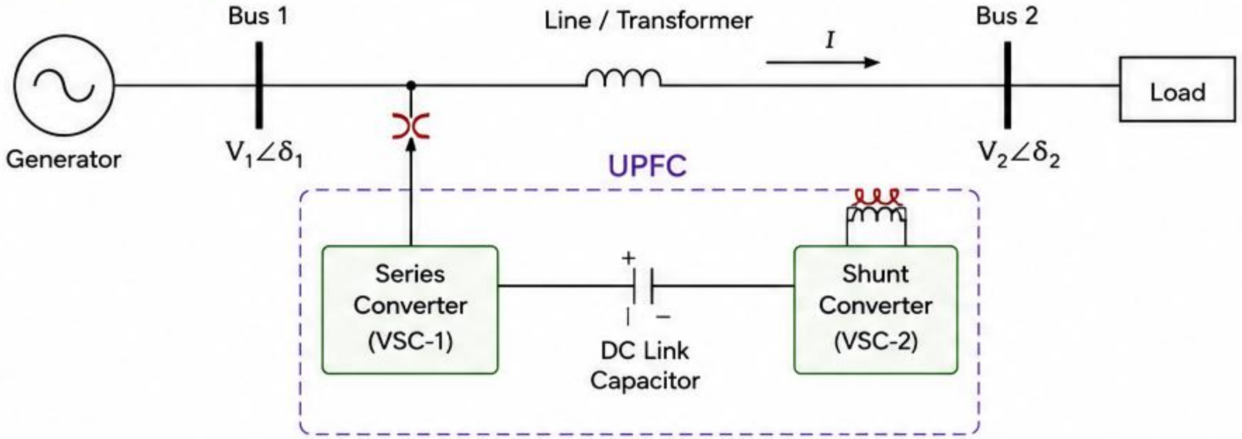
- Provides continuous control of line reactance (capacitive or inductive).
- Improves power transfer capability of transmission lines.
- Enhances transient stability and damping.
- Reduces power oscillations.
- Helps in load balancing and congestion management.
- Fast control with thyristors.

7. Typical Applications

- Increase power transfer capability of existing transmission lines.
- Power flow control and congestion relief.
- Improvement of transient stability.
- Damping of power oscillations in low-frequency oscillatory systems.
- Interconnection of asynchronous networks.

UPFC (Unified Power Flow Controller) in Power System

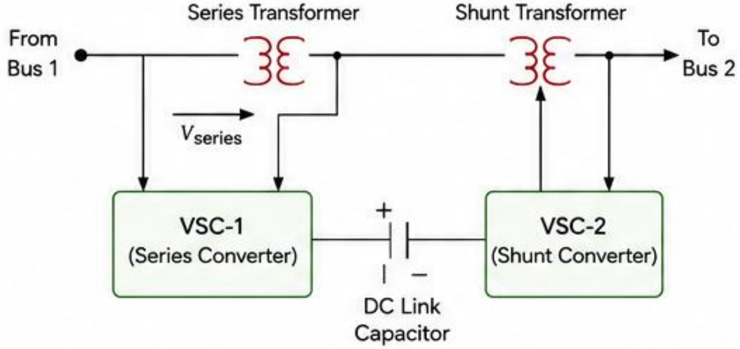
1. Single Line Diagram



2. How UPFC Works

- UPFC is the most flexible FACTS device that can control voltage, line impedance and phase angle simultaneously.
- It consists of two voltage source converters (VSCs) connected back-to-back through a common DC link.
- VSC-1 (Series Converter) injects a controllable AC voltage (V_{series}) in series with the line through a series transformer.
- VSC-2 (Shunt Converter) injects/absorbs current at the bus through a shunt transformer to maintain the DC capacitor voltage and to exchange reactive power.
- By controlling the magnitude and phase of V_{series} and the shunt current, UPFC independently controls real and reactive power flow in the line.

3. Internal Structure



4. Operating Principle

Series Converter (VSC-1)

- Injects a voltage V_{series} in series with line.
- Changes the effective line voltage seen by the system.
- By adjusting magnitude ($|V_{series}|$) and phase angle (ϕ), it controls:
  - Real power flow (P)
  - Line impedance (X)

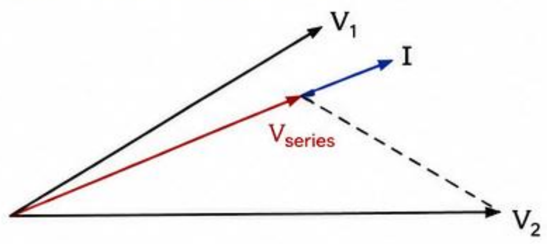
Shunt Converter (VSC-2)

- Injects/absorbs current I_{sh} at the bus.
- Provides the real power required by VSC-1 through the DC link.
- Controls:
  - Bus voltage magnitude (|V|)
  - Reactive power (Q)

Result

Independent control of real power (P), reactive power (Q) and bus voltage.

5. Phasor Diagram (Concept)



By varying V_{series} (magnitude and angle), the power flow (P and Q) in the line can be controlled.

6. Key Features / Benefits

- Simultaneous control of real power, reactive power and bus voltage.
- Independent control of P and Q.
- Improves power transfer capability and system stability.
- Reduces line losses and congestion.
- Fast dynamic response.
- Can control power flow in either direction.
- Enhances transient stability and damping.

What UPFC Can Control

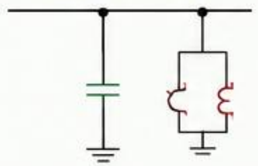
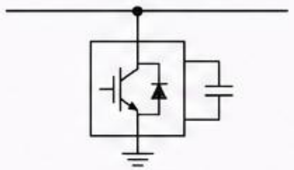
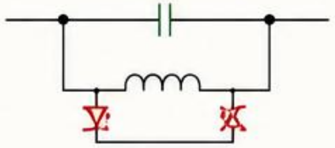
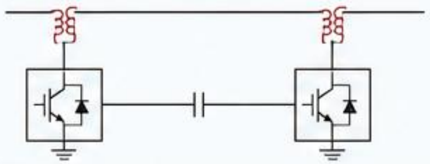
- ✓ Real Power Flow (P)
- ✓ Reactive Power Flow (Q)
- ✓ Bus Voltage Magnitude (|V|)
- ✓ Line Impedance (X)
- ✓ Phase Angle (δ)

All simultaneously and independently.

7. Typical Applications

- Power flow control in transmission corridors.
- Congestion management.
- Voltage regulation and reactive power support.
- Enhancement of transient stability.
- Interconnection of asynchronous power systems.
- Improving power transfer capability of existing lines.

Comparison among SVC, STATCOM, TCSC and UPFC

Parameter	SVC (Static Var Compensator)	STATCOM (Static Synchronous Compensator)	TCSC (Thyristor Controlled Series Capacitor)	UPFC (Unified Power Flow Controller)
Basic diagram (connection)	Shunt connected 	Shunt connected 	Series connected 	Series + Shunt connected (Back-to-back VSCs) 
Technology	Thyristor controlled reactor (TCR) + Thyristor switched capacitor (TSC)	Voltage source converter (VSC) based (IGBT / GTO / IGCT)	Thyristor controlled reactor (TCR) in series with fixed capacitor	Two voltage source converters (VSCs) back-to-back with DC link
Connection in system	Shunt (parallel)	Shunt (parallel)	Series	Series + Shunt
Primary function	Reactive power compensation (Bus voltage support)	Reactive power compensation (Bus voltage support)	Series compensation to control line reactance	Simultaneous control of real power (P), reactive power (Q) and bus voltage
Controlled variables	Reactive power (Q) Bus voltage (|V|)	Reactive power (Q) Bus voltage (|V|)	Line reactance (X_{line}) Power flow (P)	P, Q, |V|, line impedance (X) and phase angle (δ)
Type of compensation	Only shunt reactive (inductive or capacitive)	Only shunt reactive (inductive or capacitive)	Series capacitive or inductive	Series + shunt (combined)
Reactive power range	Limited (≈ −0.2 to +0.5 p.u. of system MVA)	Wide (≈ −1.0 to +1.0 p.u. of system MVA)	Not applicable (controls reactance)	Wide (both P and Q independently)
Response time	Relatively slow (1 to 2 cycles)	Very fast (< 1 to 2 cycles, few ms)	Fast (1 to 2 cycles)	Very fast (< 1 to 2 cycles, few ms)
Output at low voltage	Reduces with system voltage (variable output)	Full reactive current even at low voltage (constant current source)	Depends on line current and system voltage	Maintains capability at low voltage
Harmonics	Generates harmonics (5th, 7th, 11th ...) Filters required	Nearly harmonic free (with PWM) No or small filters	Generates harmonics due to TCR Filters required	Nearly harmonic free (with PWM) No or small filters
Power factor improvement	Improves (limited range)	Improves over wide range (leading/lagging)	Indirectly improves via power flow control	Improves (indirectly through P & Q control)
Effect on power flow	Indirect (by Q support)	Indirect (by Q support)	Direct control of line impedance ⇒ controls power flow	Direct control of real and reactive power flow
Capability	Good for voltage support	Excellent voltage support	Enhances transmission capacity (by reducing X_{line})	Maximal – controls all key power system parameters
Size & footprint	Large (reactors, capacitors, filters)	More compact than SVC	Relatively compact	Largest (two converters, transformers, DC link, filters)
Losses	Higher (reactor losses)	Lower	Low to moderate	Higher (two VSCs + transformers)
Cost	Lowest	Higher than SVC	Moderate	Highest
Control flexibility	Low to medium (step or limited continuous)	High (continuous, smooth)	Medium to high (continuous)	Very high (independent & simultaneous)
Typical applications	Voltage regulation, power factor correction, weak system support	Voltage support, flicker mitigation, wind/solar integration, weak grids	Increase line power transfer, congestion management	Power flow control, voltage regulation, congestion relief, inter-area control
Typical locations	Distribution & transmission buses, industrial loads	Transmission & distribution buses, renewable plants, utility grids	Transmission lines, corridors (long EHV lines)	Transmission corridors, interconnection points, critical system areas

Comparison of FACTS Devices

Aspect	Static Var Compensator (SVC)	STATCOM (STATCOM)	Thyristor Controlled Series Capacitor (TCSC)	Static Synchronous Series Compensator (SSSC)	Unified Power Flow Controller (UPFC)
Primary Function	Shunt reactive power compensation for voltage control	Shunt reactive power compensation with fast, continuous control	Series compensation to control line reactance and power flow	Series voltage injection to control power flow and improve stability	Simultaneous control of voltage, impedance, and phase angle
Connection	Shunt (parallel)	Shunt (parallel)	Series	Series	Series + Shunt (combination)
Voltage Control	✓ Yes (Good)	✓ Yes (Excellent)	✗ No (Indirect)	✓ Yes (Good)	✓ Yes (Excellent)
Reactive Power Control	✓ Yes (Good)	✓ Yes (Excellent)	Limited (Small range)	Limited (Through injected V)	✓ Yes (Excellent)
Active Power Flow Control	✗ No	✗ No	✓ Yes (By varying line X)	✓ Yes (By voltage injection)	✓ Yes (Excellent)
Series Compensation / Impedance Control	✗ No	✗ No	✓ Yes (Variable X)	✓ Yes (Controllable series V)	✓ Yes (Full control)
Response Speed	Medium (~50–100 ms)	Very Fast (<10 ms)	Fast (~10–20 ms)	Fast (~10–20 ms)	Very Fast (<10 ms)
Control Range	Moderate	Wide	Moderate to Wide	Wide	Very Wide
Main Advantages	• Mature technology • Cost-effective • Good for voltage support	• Fast dynamic response • Continuous control • Improves power quality	• Increases transfer capacity • Reduces line losses	• Improves stability • Controls both real & reactive power	• Most versatile • Independent control of P, Q, V and impedance
Limitations	• Slower than STATCOM • Limited dynamic performance	• Higher cost • Higher losses • (converter based)	• Limited reactive power capability • Possible sub-synchronous resonance (SSR)	• Higher cost • Requires high-rated series converter	• Highest cost • More complex • design & control
Typical Applications	Voltage regulation, power factor correction, voltage support	Voltage stability, flicker mitigation, rapid VAR support, weak grids	Power flow control, congestion management, increasing transfer limit	Power flow control, stability enhancement, damping oscillations	Comprehensive power flow control, network stability, congestion management
Overall Capability	★★★☆☆ (Good)	★★★★☆ (Very Good)	★★★☆☆ (Good)	★★★★☆ (Very Good)	★★★★★ (Excellent)

Note: *Performance depends on system conditions, design, and controller implementation.*

Legend: *✓ = Yes (Direct/Strong)   Limited = Limited Capability   ✗ = No (Not Direct)*

Voltage Control Techniques for Rooftop PV Connected Distribution Lines

Approximate voltage rise at a bus: $\Delta V \approx \dfrac{RP + XQ}{V}$ — R = line resistance, X = line reactance, P = active power, Q = reactive power, V = voltage

Technique	How It Works	Main Benefits	Typical Devices / Tools	Response Speed	Effectiveness for Voltage Control	Key Considerations
1. Smart-Inverter Reactive-Power Control (Volt–VAR Control)	Inverter absorbs or supplies reactive power based on local voltage measurement. When voltage rises, inverter absorbs reactive power to reduce the voltage.	• Fast and continuous control • Improves voltage profile • No extra hardware • Enhances PV hosting capacity	Smart PV inverters with Volt–VAR / Volt–Watt functions and local voltage sensing	Very Fast (Seconds to milliseconds)	★★★★★ High	• Limited by inverter apparent power rating • May reduce real power output at high voltage • Proper settings are critical
2. Active-Power Curtailment (Volt–Watt Control)	Inverters reduce active power output when voltage exceeds upper limit by following a Volt–Watt curve.	• Simple and effective • Prevents over-voltage • Protects equipment	Smart PV inverters with Volt–Watt function	Fast (Seconds)	★★★☆☆ Moderate	• Reduces exported energy and owner revenue • Should be used only when other options are insufficient
3. Battery Energy Storage Systems (BESS)	Excess PV generation during high-voltage periods is stored in the battery and discharged later when needed.	• Reduces reverse power flow • Improves self-consumption • Supports voltage & frequency stability • Defers network upgrades	BESS (lithium-ion batteries, PCS, energy management system)	Very Fast (Milliseconds to seconds)	★★★★★ High	• Higher initial cost • Requires space and appropriate sizing • Battery degradation management
4. On-Load Tap Changers (OLTC) & Voltage Regulators	Adjust transformer tap or regulator position to raise or lower downstream voltage levels.	• Maintains voltage within limits • Proven and reliable • Works for a wide range of operating conditions	Distribution transformers with OLTC, step voltage regulators, capacitor banks (if used in voltage mode)	Medium (Seconds to minutes)	★★★★☆ High	• Mechanical wear & maintenance • Slower response compared to electronics • Proper coordination needed
5. Network Reinforcement	Upgrade network assets to reduce impedance and voltage rise.	• Permanent solution • Increases hosting capacity • Improves reliability	Larger conductors, additional/parallel feeders, new transformers, phase balancing	N/A (Planning & construction based)	★★★★☆ High (Long-term)	• High capital cost • Requires planning, permits & outages • Long implementation time
6. Coordinated Control & Advanced Distribution Management	Coordinated operation of smart inverters, BESS, transformer taps, capacitor banks and other devices using ADMS/DERMS.	• Optimizes overall performance • Maximizes PV hosting capacity • Reduces losses & congestion • Enables real-time decisions	ADMS/DERMS platform, smart inverters, BESS, OLTC, capacitors, sensors, communications	Fast to Very Fast (Seconds to milliseconds)	★★★★★ Very High	• Requires communication infrastructure • Needs proper modeling and coordination logic • Higher implementation complexity

Overall Takeaway: A combination of local (smart inverters, BESS), operational (tap changers, regulators) and infrastructure (network reinforcement) measures, coordinated through advanced control systems, is the most effective approach for managing voltage rise in rooftop PV connected distribution networks.

Effectiveness Scale

★★★★★	★★★★☆	★★★☆☆	★★☆☆	★☆☆☆☆
Very High	High	Moderate	Low	Very Low

Hosting Capacity and Thermal Limits of Feeders

It defines how much renewable energy a distribution network can accommodate without major grid reinforcement.

Key Factors Limiting Hosting Capacity

- **Voltage Rise**
  - ➢ High solar PV generation during low-load periods can raise feeder voltage beyond allowable limits.
  - ➢ Requires voltage regulation, smart inverters, or reactive power control.
- **Thermal Loading**
  - ➢ Conductors, transformers, and switchgear have maximum current-carrying capacities.
  - ➢ Excess generation can overload distribution assets.
- **Protection Coordination**
  - ➢ Reverse power flows and increased fault currents may affect protection settings.
  - ➢ Existing relay coordination may require modification.

Key Factors Limiting Hosting Capacity

- **Power Quality Issues**
  - Voltage fluctuations and harmonics from inverter-based resources.
  - Flicker due to variable renewable generation.
- **Reverse Power Flow**
  - Distribution feeders traditionally designed for one-way power flow may experience power export toward substations.
- **System Stability**
  - High penetration of inverter-based resources may affect voltage stability and fault response.

Methods to Increase Hosting Capacity

- Upgrade conductors and transformers.
- Install voltage regulators and capacitor banks.
- Deploy smart inverter functions(Volt–Var control,Volt–Watt control, Frequency support)
- Install Battery Energy Storage Systems (BESS).
- Implement Advanced Distribution Management Systems (ADMS).
- Use demand response and flexible loads.
- Apply Dynamic Line Rating.

Why Protection Upgrades are Required

1. Reverse Power Flow

- Distributed generation can export power back toward the distribution substation.
- Conventional overcurrent relays may not detect faults correctly due to changed fault current direction.
- Protection coordination between upstream and downstream devices can be affected.

2. Changed Fault Current Levels

- Inverter-based resources provide limited and controlled fault current.
- Fault currents may be lower than expected, making traditional overcurrent protection less effective.
- Contribution from multiple sources can complicate fault analysis.

3. Protection Coordination Challenges

- Existing relay settings are based on one-way power flow assumptions.
- Direction and magnitude of fault currents can vary depending on generation availability.
- Risk of unnecessary tripping or delayed fault clearing increases.

Protections for Inverter-Based Resources

Modern renewable plants require:

- ➢Low-voltage ride-through (LVRT) protection.
- ➢Frequency ride-through capability.
- ➢Anti-islanding protection.
- ➢Coordination between grid protection and inverter controls.
- ➢Fast fault detection despite limited inverter fault current contribution.

Modern Protection Requirements for Inverter-Based Generation

(Applicable to Transmission / Distribution Lines)

Aspect	1. Low-Voltage Ride-Through (LVRT) Protection	2. Frequency Ride-Through Capability	3. Anti-Islanding Protection	4. Coordination between Grid Protection and Inverter Controls	5. Fast Fault Detection with Limited Inverter Fault Current Contribution
Purpose	Keep inverter connected and support the grid during short-term voltage dips.	Maintain stable operation during frequency deviations from nominal.	Prevent unsafe islanded operation when grid is de-energized.	Ensure proper interaction between inverter controls and system protection schemes.	Detect faults quickly and clear them safely despite limited fault current contribution.
What It Protects Against	Voltage sags/dips, short interruptions, severe voltage fluctuations.	Under-frequency (UF), over-frequency (OF) events.	Unintentional islanding causing safety hazards, equipment damage, poor power quality.	Misoperations, unwanted tripping, loss of selectivity and stability issues.	Faults that may not produce sufficient current for traditional protection to detect.
Key Requirements (for Inverters)	• Remain connected within defined voltage–time curve • Inject reactive current during voltage dips • Recover smoothly after disturbance	• Stay connected within frequency deadband • Provide active power support (if required) • Meet defined frequency ride-through curves	• Detect islanding in all operating conditions • Operate within specified detection time • Comply with non-detection zone (NDZ) limits	• Coordinate with grid relays (OC, EF, UV/OV, etc.) • Avoid nuisance tripping • Ensure ride-through and protection settings are aligned	• Fast detection of internal and external faults • Support protection with current limiting strategy and control • Enable rapid isolation
Typical Functions/ Features	Volt–VAR control, dynamic reactive injection, power reference reduction, fault ride-through logic	Frequency measurement, active power modulation, droop/response control, ride-through timers	Passive (e.g., ROCOF, vector shift, impedance, passive methods) and Active methods	Communication with relays, status exchange, logical interlocks, adaptive settings, GOOSE/IEC 61850	High-speed fault detection, traveling wave / differential techniques, inverter protection I/O
Response Time	Cycles to Seconds (typ. 20 ms – 2 s)	Seconds (typ. 0.1 – 5 s)	Fast (typ. < 2 s)	Depends on relay coordination (typ. 20 ms – 1 s)	Very Fast (typ. < 20 ms)
Benefits	• Improves grid stability • Reduces unwanted tripping • Supports voltage recovery	• Supports frequency stability • Prevents large generation loss • Meets grid code compliance	• Ensures safety of personnel and equipment • Prevents damage and poor power quality	• Improves reliability and selectivity • Prevents nuisance tripping • Ensures compliance	• Enables fast fault clearance • Protects equipment • Enhances system security
Implementation Considerations	• Need for accurate voltage measurement • Adequate reactive power capacity • Grid code settings	• Accurate frequency measurement • Communication (if required) • Tuning of response parameters	• Avoid non-detection zones • Periodic testing required • Method selection based on plant size and topology	• Clear settings and documentation • Communication infrastructure • Testing & validation	• High-sampling measurement • Coordination with line protection • Cybersecurity & reliability
Standards / Guidelines (Examples)	IEEE 1547-2018/2023, IEC 62116, EN 50549, CIGRE TB 725	IEEE 1547-2018/2023, NERC PRC-024, EN 50549, IEC 61000-4-30	IEEE 1547-2018/2023, IEC 62116, UL 1741 SA, NERC PRC-024	IEC 61850, IEEE C37.242, IEEE 1547-2018/2023, NERC PRC-024	IEEE C37.5, IEEE C37.118, IEC 60255, CIGRE TB 881, IEEE 1547-2018/2023

Note: The exact requirements vary by grid code, system strength, and equipment design. Proper testing, commissioning, and coordination are essential for reliable operation.

Why Modern Techniques Are Essential

Aspect	Traditional Approach (Synchronous Era)	Modern Approach (Inverter-Based Era)	Why It Matters
1. Integrated Operation	Protection and controls typically operate independently.	Grid protection systems and inverter controls must operate as an **integrated system.**	• Isolates only genuine faults • Inverters remain connected during temporary disturbances • Actively supports voltage and frequency recovery • Achieves secure, reliable, and resilient power systems with high renewable integration
2. Source of Fault Current	High fault currents naturally provided by synchronous generators.	Inverter-based resources intentionally **limit fault current** to protect power electronics.	• Changes fault characteristics of the system • Requires new protection principles • Ensures equipment safety and reliability
3. Protection Effectiveness	Conventional overcurrent protection is effective due to high and predictable fault current.	Limited fault current makes conventional overcurrent protection **less effective** and may cause misoperation or non-operation.	• Risk of missed faults or unnecessary tripping • Requires advanced and adaptive protection • Improves selectivity and dependability
4. Irtotection Philosophy	Relied mainly on single principle protection (e.g., overcurrent).	Combines **multiple modern techniques:** differential, distance, directional, voltage-based, and communication-assisted protection.	• Complements the limitations of individual methods • Provides fast, selective, and reliable fault detection • Maintains grid stability under all conditions
5. Speed & Selectivity	Slower clearing possible due to higher fault current and simpler coordination.	Modern techniques enable **fast and selective** fault detection with coordinated protection and inverter controls.	• Reduces fault impact and outage duration • Protects equipment and power quality • Supports dynamic and real-time grid conditions
6. Grid Stability & Resilience	Lower shares of renewables; less need for active support from resources.	Active support from inverter controls is essential for **voltage and frequency regulation and system resilience.**	• Ensures stable operation with high renewable penetration • Enhances system resilience to disturbances • Future-proofs the power system

Key Takeaway: Modern protection is not just about detecting faults — it is about coordinated, adaptive, and communication-enabled protection working hand-in-hand with inverter controls to ensure a secure, reliable, and resilient power system.

Modern Protection Solutions for Power Systems

Protection Solution	Principle	What It Does	Key Features / Advantages	Typical Applications
Differential Protection	Compares currents entering and leaving a protected zone.	Detects internal faults within the protected zone and trips only the associated equipment.	• High speed and high sensitivity • Excellent selectivity • Unaffected by external faults	Transformers, generators, busbars, motors, reactor banks
Distance Protection	Uses apparent impedance (V/I) to estimate fault location.	Determines the distance to a fault and trips if the fault is within the preset zone.	• Works for a wide range of faults • Provides backup protection • Zone-wise operation for selectivity	Transmission lines, cables, feeders
Directional Protection	Determines the direction of power flow or fault current.	Operates only for faults in the specified (forward or reverse) direction.	• Improves selectivity • Prevents misoperation • Essential in radial and meshed networks	Radial feeders, tie lines, distributed generation interfaces
Communication-Assisted Protection	Uses communication links (e.g., IEC 61850) to exchange information.	Enhances protection speed and reliability through data sharing and pilot signals.	• Faster tripping with pilot signals • Improved dependability • Supports wide-area protection	Line differential, pilot protection schemes, inter-tripping
Adaptive Protection	Changes protection settings based on real-time network conditions.	Maintains optimal coordination and sensitivity under changing system configurations.	• Improves reliability and security • Reduces nuisance tripping • Supports dynamic networks and DG integration	Smart grids, variable networks, systems with renewables
Travelling-Wave Protection	Detects high-frequency electromagnetic transients.	Identifies faults within a few microseconds and trips very fast.	• Ultra-fast fault detection • High accuracy for location • Effective for high-speed transient faults	Transmission lines, EHV/UHV systems, long lines, GIS

Benefits of Modern Protection Solutions:
- Enhanced system reliability
- Selective and secure operation
- Faster fault clearance and isolation
- Supports grid stability and resilience

Feeder automation and advanced metering

High penetration of rooftop PV, wind, batteries, and EVs makes distribution networks more variable and bidirectional. Feeder automation provides real-time control of the network, while advanced metering infrastructure (AMI) provides detailed measurements from customers and distributed-energy resources.

- Feeder automation uses remotely controlled switches, reclosers, voltage regulators, capacitor banks, sensors, and distribution-management software.
- AMI consists of smart meters, communication networks, and utility data-management systems. Unlike traditional meters, smart meters measure energy at short intervals and support two-way communication.

Feeder automation

- **Monitoring voltage and power flow:** Sensors detect voltage rise, reverse power flow, overloads, and phase imbalance caused by distributed PV.
- **Automatic voltage regulation:** Tap-changing transformers, voltage regulators, capacitor banks, and smart inverters are coordinated to keep voltage within limits.
- **Feeder reconfiguration:** Automated switches transfer loads or renewable generation between feeders, reducing congestion and improving voltage profiles.
- **Fault detection and restoration:** Faulted sections are isolated automatically and healthy sections are resupplied, reducing renewable-generator disconnection time.
- **Managing reverse power flow:** Control systems identify when power flows from customers toward the substation and adjust protection and voltage-control settings.
- **Increasing hosting capacity:** Better visibility and control allow more rooftop PV to connect without immediate conductor or transformer upgrades.

Advanced metering infrastructure

- **Measuring import and export separately:** It records electricity taken from and injected into the grid.
- **Identifying local PV surplus:** Utilities can locate feeders and phases experiencing high reverse power flow.
- **Detecting voltage violations:** Smart meters provide customer-level voltage measurements, helping identify overvoltage and undervoltage locations.
- **Supporting remote reading, disconnection and reconnection:** It saves a lot for the utility.
- **Improving forecasting:** Historical PV generation and consumption data improve load and renewable-output forecasts.
- **Enabling demand response:** Flexible loads such as water heaters, air conditioners, batteries, and EV chargers can be shifted to periods of high renewable generation.
- **Detecting phase imbalance and losses:** Meter data helps redistribute single-phase PV systems and loads across the three phases.
- **Supporting dynamic tariffs:** Electricity prices can encourage customers to consume energy when solar or wind production is high.

IoT Solutions for Real-Time Monitoring

IoT solutions are essential for managing modern electricity networks with increasing:

- Rooftop solar PV.
- Utility-scale renewable plants.
- Battery Energy Storage Systems (BESS).
- Electric vehicle charging infrastructure.

Key Applications

- Real-Time Asset Monitoring
- Distribution Network Monitoring
- Renewable Energy Monitoring
- Smart Metering and Consumer Monitoring
- Predictive Maintenance
- Grid Automation and Control

Key Technologies

- IoT sensors and smart devices.
- Wireless communication (5G, LoRaWAN, RF mesh).
- Edge computing for rapid local processing.
- Cloud-based data platforms.
- Artificial Intelligence (AI) and machine learning analytics.
- Digital twins for network simulation and optimization.

Challenges

- Cybersecurity and data privacy risks.
- Requirement for reliable communication infrastructure.
- Large volume of data management.
- Integration with legacy utility systems.
- Initial investment cost.