STABILIZING THE FUTURE

How synchronous condensers help power grids integrate more renewable energy

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EXECUTIVE SUMMARY

As global power grids transition from centralized fossil-based generation to decentralized, renewable sources, system stability has become a critical challenge. The phasing out of synchronous generators has significantly reduced spinning inertia, fault-level support, and reactive power capabilities, all functions that are essential for grid reliability.

In response, utilities and regulators are turning to advanced grid support technologies. Among these, synchronous condensers have emerged as a key solution. By restoring spinning inertia and delivering reactive power compensation, voltage stabilization and fault current support, synchronous condensers ensure resilient and secure operation of modern renewables.

This whitepaper explores:

- Market and regulatory trends driving demand for grid support technologies
- The unique technical advantages of synchronous condensers compared to alternatives like Static synchronous compensator (STATCOMs), Battery Energy Storage System (BESS), and capacitor banks
- Real-world use cases and case studies from Australia, Canada and other industrial settings
- Strategic recommendations for utilities, industrial operators, and developers navigating renewable integration and grid modernization

Through innovations in design and increasing support from grid operation policy makers, synchronous condensers are becoming indispensable assets for managing the complexities of today's evolving energy landscape.

TRANSFORMATIONS IN THE GLOBAL ENERGY LANDSCAPE

The global energy landscape is experiencing a major transformation as renewable energy sources are increasingly integrated into power grids. This shift is accompanied by the accelerated phase-out of traditional synchronous generation based on large turbines powered by coal, oil, gas and nuclear energy, leading to a reduction in grid inertia. While these changes present significant opportunities for cleaner and more sustainable energy systems, they also pose challenges to grid stability, reliability, and efficiency.

Regulatory and market trends

One of the most prominent regulatory trends is the focus on renewable energy integration and grid modernization. Governments and regulatory bodies are working to facilitate the adoption of distributed energy resources (DERs), including solar, wind, and energy storage, while maintaining grid stability. Initiatives such as the EU Green Deal and the "Clean Energy for All Europeans" package exemplify these efforts. In addition, stricter grid reliability standards are being set by entities like the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) in the U.S. These standards encourage grid operators to explore solutions for frequency regulation and reactive power compensation.

The expansion of ancillary services markets is a direct response to these demands, with similar actions being taken by The European Network of Transmission System Operators for Electricity (ENTSO-E).

Policies promoting flexibility and Distributed Energy Resources (DER) deployment are also gaining traction. Battery storage and demand response are increasingly encouraged, with market participation models evolving to include these flexible resources. Examples of such policies can be seen in California's energy initiatives and Australia's energy markets managed by the Australian Energy Market Operator (AEMO).

Governments and utilities are further incentivizing advanced grid support technologies to stabilize renewable-dominated energy mixes. Synchronous condensers and grid-forming inverters are receiving attention for their potential to enhance grid stability. Notable programs in the UK and US illustrate this trend.

Decentralization is another critical focus area. Peer-to-peer energy trading and microgrids are emerging as decentralized solutions to provide local grid services. These innovations, supported by regulations such as the EU's Clean Energy Package and platforms like Australia's Power Ledger blockchain, are gaining momentum.

Lastly, increasingly stringent environmental regulations are driving utilities to adopt renewable energy sources and efficient grid support technologies. Carbon emission reduction goals in regions like the EU, the U.S., South Korea, and China are accelerating the deployment of energy storage and advanced grid systems.

GRID SUPPORT TECHNOLOGIES FOR RENEWABLE INTEGRATION

As traditional synchronous generation declines, maintaining grid frequency stability is becoming increasingly difficult. Technologies such as synthetic inertia (inverter-based technology designed to mimic rotating mass inertia), BESS, and demand response are proving effective in stabilizing the frequency in grids with high penetration of renewable energy.

Reactive power compensation is another critical need. Renewable energy sources often fail to supply the reactive power required for voltage regulation. To address this, technologies like synchronous condensers, Static Var Compensators (SVC), and Flexible AC Transmission Systems (FACTS) are being deployed to enhance voltage stability.

Additionally, the shift from synchronous generators to inverter-based resources reduces the available short-circuit power, complicating fault detection and protection. To overcome these challenges, synchronous condensers and grid-forming inverters are being utilized to generate short-circuit power and support fault clearing, ensuring reliable grid operation.

Synchronous condenser

An effective technology for ensuring grid stability

A synchronous condenser, also known as a synchronous capacitor or synchronous compensator, is an effective method of improving grid stability and reliability. Fundamentally, it is a synchronous generator without a prime mover, meaning its shaft is not connected to any driving equipment. The term synchronous means that the frequency of the voltage produced is synchronized with the speed at which it rotates. However, instead of generating real power, the synchronous condenser provides reactive power to the grid, which is essential for maintaining voltage levels and ensuring efficient power transmission.

At its core, a synchronous condenser is a rotating electrical machine connected to the grid or network. Unlike motors that drive loads or generators powered by turbines, synchronous condensers are controlled through excitation regulation to either generate or absorb reactive power as needed. This capability allows them to perform real-time voltage regulation by injecting or withdrawing reactive power from the grid.

KEY FEATURES

- Inertia contribution
- Fault current contribution
- Reactive power compensation
- Sink for harmonics and negative sequence currents (unbalance)
- Voltage stabilization

Additionally, they contribute to frequency stability through their rotating mass, which provides extra inertia to the grid, and enhances short-circuit capacity by supplying short-term withstand current stored in the generator.

Historically, synchronous condensers were used primarily for power factor correction and deployed widely across power grids. However, in recent decades they were replaced in this role by systems based on power electronics. Synchronous condensers are now experiencing a resurgence due to evolving energy systems. The rapid growth of renewable energy sources, particularly wind and solar photovoltaic installations, has created a need for improved grid stability and resilience. The reason is that these renewable sources are typically inverter based, for example a solar plant produces direct current (DC) that must be converted to alternating current (AC) to feed into the grid. Therefore, the inherently asynchronous nature of renewables means they cannot provide grid inertia in the same way as traditional power plants. Because synchronous condensers can restore this missing inertia, they become an essential technology for modern electric power systems.

As inverter-based renewable energy sources become more prevalent, the grid can experience low short-circuit strength and/or reduced system inertia. Addressing these issues may require technologies such as synchronous condensers, or grid-forming inverters that utilize power electronics to control the output voltage waveform.

Finally, synchronous condensers can support grid constraints at specific locations.
For example, they can be used to strengthen grid weak points or renewable generation hubs to provide maximum benefits.

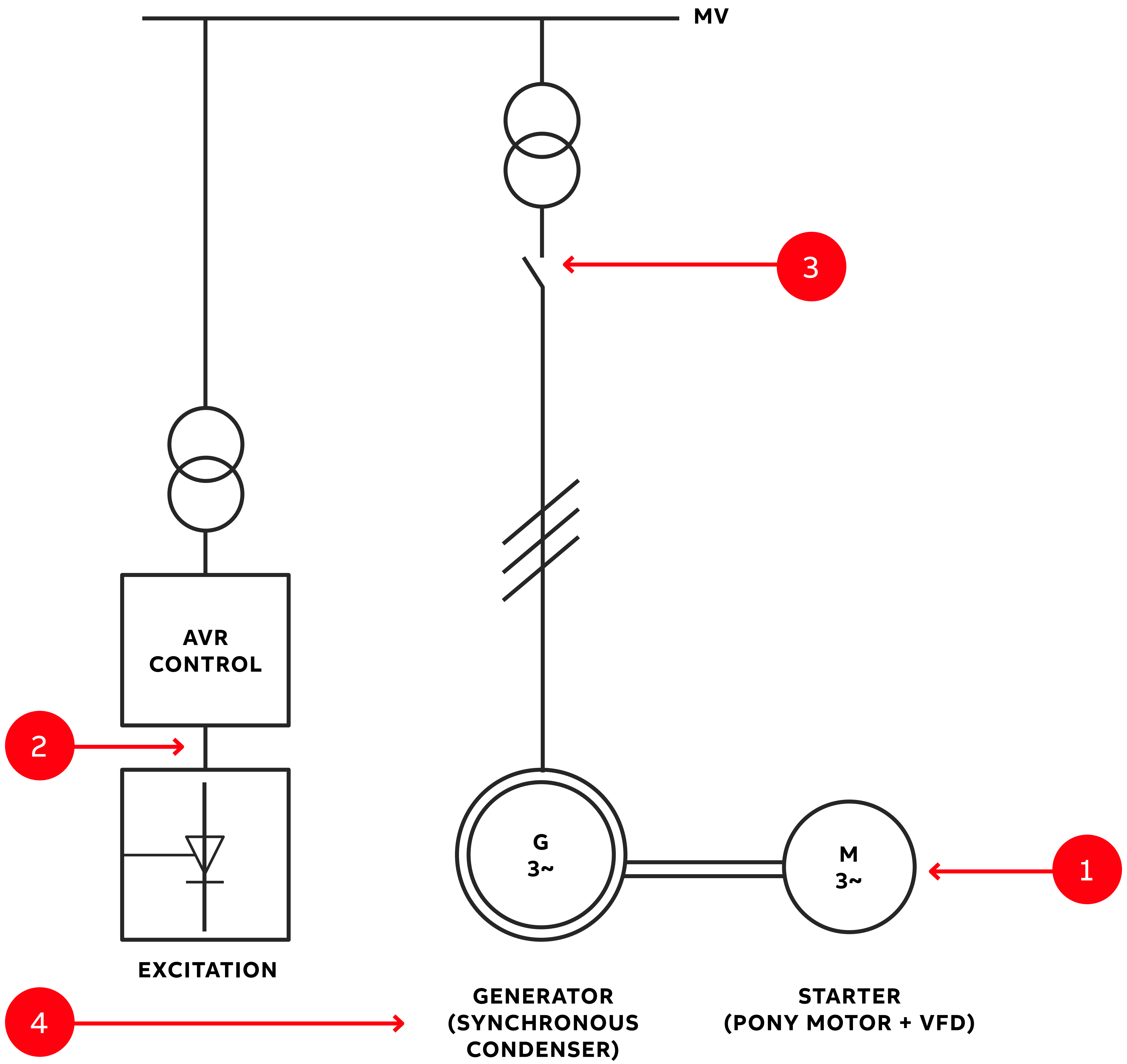
However, obtaining the necessary permissions for construction and grid connection in optimal locations can involve additional costs and could result in project delays if not considered right from the beginning of a renewable hub development.

	Utility – Grid owner	**Renewable**	**Industry**
Market trends	• Ensure grid reliability, efficiency, & security, and maintain the power quality in the grid • Increased distributed power generation • De-commissioning of large thermal power plant • Political decisions or legislation • Countries with weak networks that call for inertia and short circuit power	• Investment in grid stabilization to handle increasing grid complexity as the penetration of renewable energy such as wind and solar PV grows • Environmental and regulatory policies	• Increase power quality (to control voltage dips and/or frequency variations) in remote industries such as microgrids serving large mines and large chemical, oil and gas (COG) complexes, steel plants, green hydrogen, green ammonia
Customer	• Transmission System Operators (TSOs) • Power Generation Owner • Utilities de-commissioning thermal plant • Distributed power system operators • Microgrids and/or island operation	• EPC and developers for renewable plants, mainly wind and solar PV • Wind power OEMs • Energy storage provider	• Large industries, especially COG and mining, green hydrogen, metals, water & wastewater • Customers that previously used to rotating machines, but now are unclear on how to solve power quality (PQ) challanges

How synchronous condenser operate

Synchronous condensers are regulated in the same way as synchronous generators—through excitation control to produce or to consume reactive power (MVAr). Synchronous condensers are a re-born technology necessary to cope with the changes resulting from the energy transition.

1. A small pony motor controlled by a variable frequency drive (VFD) accelerates the synchronous condenser to match the network synchronous speed
2. Once the synchronous condenser is rotating, auxiliary power is provided to the excitation system. Now the voltage and power-factor regulator starts to operate based on the voltage and power-factor reference
3. When synchronization is reached between the network and the synchronous condenser, the breaker to the network closes. The synchronous condenser is now running on-line
4. After successful synchronization, the starter de-energizes, and runs at idling speed



Benefits of synchronous condensers

- **Increasing the short-circuit** capacity of the network, making the network more robust against faults and corrresponding voltage dips
- **Contribution of spinning inertia** to maintain frequency control
- **Voltage support** during prolonged voltage sags
- **Controlling the voltage** in the network node where they are connected
- **Reactive power produced or consumed** is less affected by the system voltage
- **Power factor correction**
- **Good fault ride-thru capability**
- **High overload capacity** to prevent voltage collapse

OTHER BENEFITS

UTILITIES AND GRID OPERATORS

Enhanced grid resilience and stability

Seamless renewable energy integration

Improved voltage control and reduced outages

Sink for unbalance and harmonics

INDUSTRIAL USERS

Support for high-demand applications

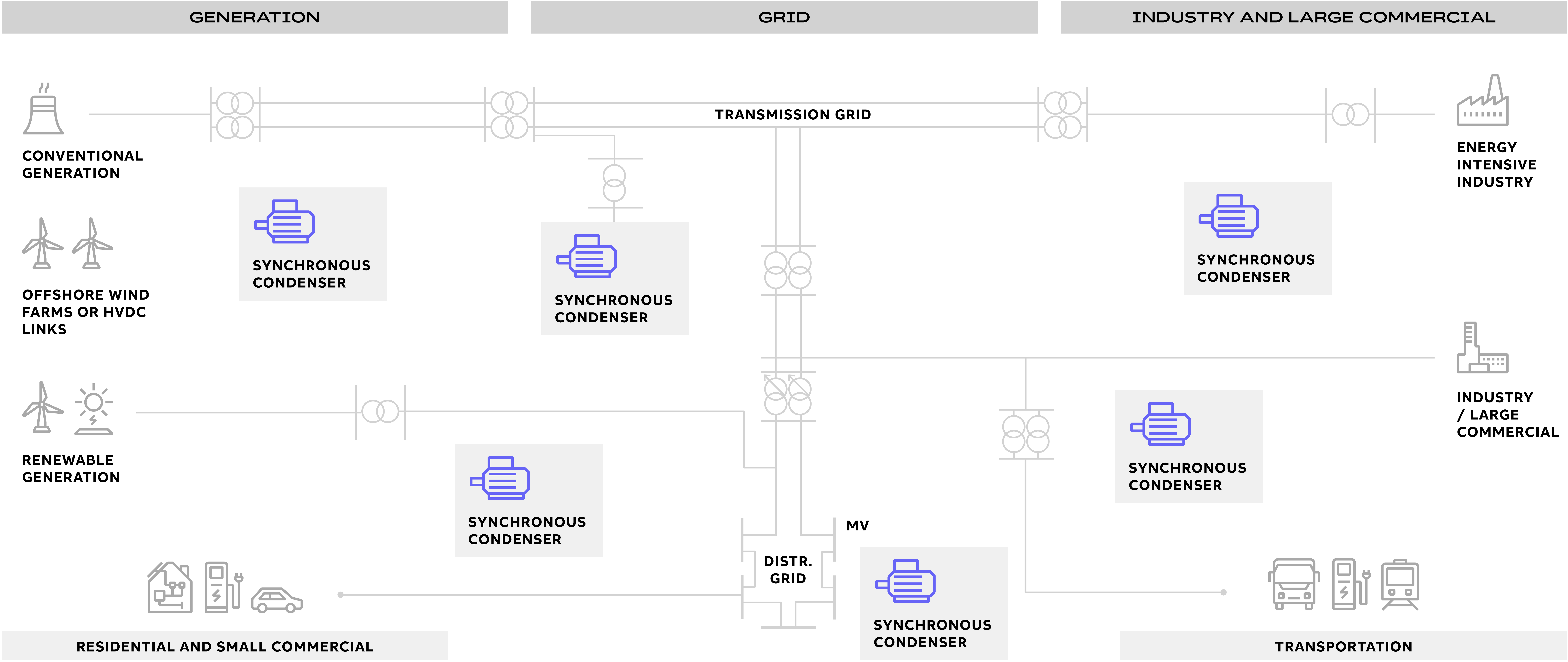
Improve operational efficiency

Support for power quality issues

Mitigate voltage stability issues

Increase fault current

Potential grid locations for synchronous condensers



Challenges for the deployment of synchronous condensers

The synchronous condenser industry faces several hurdles, beginning with high initial investment costs. Procuring, installing, and commissioning these devices require significant capital, which can deter utilities and grid operators. In comparison, alternative technologies such as STATCOMs may be seen as more cost-effective, but they do NOT provide comparable functionalities.

Synchronous condensers are rated in terms of their ability to provide reactive power as measured by megavolt-ampere reactive (MVAr). Typical sizes range from 20 to 200 MVAr. Large synchronous condensers are less flexible as their fixed capacity makes them less adaptable to evolving grid demands or large-scale renewable integration.

The alternative is to deploy smaller multiple units that provide more flexibility to address these issues, but this may increase costs and space requirements. The advantage of multiple units is the element of redundancy and the possibility to optimize systems losses in the case of less inertia or MVAr requirements that can occur during certain periods of the year.

Operational and maintenance complexity is a further obstacle. The mechanical components of synchronous condensers demand regular maintenance and skilled operators, which drive up operational costs and may result in potential downtime at single unit sites.

Other technologies that can help the grid integration of renewables

Static Var Compensator (SVC)
A Static Var Compensator is a high-voltage device that uses thyristor technology to generate reactive power, either lagging, leading, or both. Its primary function is to regulate electricity network voltage at its coupling point, ensuring it remains at a constant set reference level. In addition to voltage control, an SVC offers reactive power control, damping of power oscillations, and unbalance control, making it an effective solution for enhancing grid stability and performance. However, SVCs do require significant installation space.

Static Synchronous Compensator (STATCOM)
A static synchronous compensator is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. It is categorized under FACTS devices.

STATCOMs are widely used in modern power system to improve stability by providing fast-acting, precise and adjustable reactive power compensation. A STATCOM uses Voltage Source Converter (VSC) based on IGBT (Insulated Gate Bipolar Transistor) or GTO (Gate Turn-Off Thyristor) technology.

Battery Energy Storage System (BESS)
The essential function of a BESS is to capture excess energy from multiple sources within the grid and store it in rechargeable batteries for later use. A BESS provides various functions that enhance grid stability and flexibility such as frequency regulation and voltage support, helping to stabilize grids with high levels of intermittent renewable sources, reducing the need for traditional backup power.

Capacitor Banks
A capacitor bank is a collection of capacitors connected in series or parallel to store electrical energy that is primarily used for power-factor correction and voltage stabilization. Capacitor banks help to regulate the power factor in electrical systems. They can be installed parallel to a load to reduce the amount of reactive power flowing through lines. This improves the power factor by reducing the phase difference between voltage and current. A negative impact is the switching of capacitor banks, which creats voltage dips caused by the inrush current.

Challenges in power system networks

		Solution				
Problem	**Reason**	**SynCon solution**	**Capacitor Bank**	**SVC**	**Statcom**	**BESS**
Voltage sags	Energizing of step-up power transformer (inrush current)	Provides system strength support and MVAr's	May help, but will increase transients	☑	☑	☑
Voltage fluctuations	Active power variations caused by wind variations	Provides voltage regulation	Is not changing the fluctuations	☑	☑	☑
Over voltage	Switching of cables (collection grid)	Provides system strength support and MVAr's	☒	Yes, depends on SVC design	☑	☑
Under voltage	—	Provides voltage regulation	May help, but increase transients	☑	☑	☑
Flicker	Caused by tower shadow / older wind turbines	Increases system strength, which directly reduce flicker impact from the renewable plant	☒	☑	☑	Depends on control system
Oscillations	Control interaction between WT controller/plant controller and other renewable plants	Power Oscillation damping (POD) is part of voltage control of the SynCon	Increase risk for resonance	☒	Yes, depends on control system	Yes, depends on control system
Transients	Switching transients during cable switching or switching of filter banks	Increased fault level impact on lower transients	☒	☒	☒	☒
Harmonics	Wide spectra of voltage harmonics caused by power electronics of the wind turbine	Increased fault level impact on lower harmonics seen at POC, SynCon act as a sink	May decrease certain harmonics, but issue with resonance	Yes, depends on filter design	Yes, depends on filter design control system (for active filtering)	Yes, depends on filter design control system (for active filtering)
Fault ride thru	Change of active power output during LVRT events of the wind turbine	Reduces system dip (easier for wing turbines to handle LVRT)	☒	☒	☒	☒
Low inertia	Frequency variations in the grid	Provides inertia support	☒	☒	☒	Eventually, depends on control system
Short circuit contribution	Low system strength at the connecting grid	Provides system strength	☒	☒	☒	☒

USE CASES AND APPLICATIONS

Use case 1: Integrating renewable energy

Power grids are changing in nature from the topology designed historically to serve large centralized power generation plants in which the electricity only had to flow in one direction to the grid edge. The reason is that wind and solar farms are largely decentralized and often located in remote areas where the grid was designed only to deliver electricity to consumers, but now also has to receive it from producers. The result is that grids now need the flexibility to handle complex, multi-directional flows.

In addition, the remote points where renewable energy feeds into the grid are where it is often "weak" - meaning it has low short circuit level (SCL). When the SCL is low, sudden changes in voltage can result in disturbances that propagate through the system. The transmission network must be strengthened to accommodate these changes in the generation mix. Political decisions and legislation in different countries often shape how this support is implemented, leading to varied market environments. Players in the renewable energy segment must adapt to these local market requirements to remain competitive and compliant.

To address these challenges, ABB focuses on supporting renewable energy players in meeting specific local market demands. Depending on the region, markets can be driven by different regulatory and operational models. In market-driven systems, regulators or transmission system operators (TSOs) purchase support services through competitive markets, as seen in countries like the UK, Ireland, and the US. Centralized systems, such as those in Germany, France, and Russia, place responsibility for investment directly with TSOs. Some countries, like Sweden, Canada, and Australia, adopt a hybrid approach, using both TSOs and competitive markets to achieve grid support objectives.

Customer types

The market for grid support solutions comprises a diverse range of players, each with unique purchasing preferences and operational roles. TSOs, for example, typically procure turnkey solutions from large Engineering, Procurement, and Construction (EPC) companies or from specialized consortiums that combine expertise from multiple entities.

Their primary role is to deliver critical services to TSOs, such as providing inertia, short circuit contributions, reactive power (MVAr), and frequency regulation. Similarly, developers of renewable plants often act as system service providers. These developers either buy turnkey solutions from renewable OEMs or manage the integration process internally.

Power generation owners tend to focus on retrofit solutions or engineered packages tailored to their existing infrastructure. Distribution System Operators (DSOs), on the other hand, usually procure turnkey solutions from smaller EPCs or opt for engineered packages that meet their specific requirements.

Other key players include energy storage and inertia providers, who predominantly purchase engineered packages designed for their unique needs. Similarly, suppliers of High Voltage Direct Current (HVDC) systems and STATCOM solutions generally favor engineered packages to integrate with their offerings. This varied landscape underscores the need for tailored approaches to serve the distinct requirements of each customer group.

Supporting wind and solar farms in areas with weak grids requires strengthening the transmission network to adapt to changes in the generation mix. Political decisions or legislation in the country often define how this support should be handled, leading to different market environments that players in the renewable segment must follow. ABB's approach is to support these players in fulfilling local market requirements.

Main market environments:

1. Market-driven: Regulators or TSOs purchase support services on the competitive market (e.g., UK, IE, US)
2. Centrally-driven: Governments give the responsibility to TSOs, who handle the investment (e.g., DE, FR, RU)
3. Mixture: Regulators use both TSOs and the market to achieve results (e.g., SE, CA, AU).

Use case 2: Grid expansion or upgrades

As power systems evolve and grids come under increasings stress, strengthening the transmission network is critical. The traditional route is to install new power lines and transmissions. However, there are now viable, cost-effective and faster-to-implement alternatives. The approach to implementing these alternatives is often shaped by political decisions and legislation, which define how grid support should be managed. These frameworks create different market environments and pathways, requiring tailored strategies for success.

ABB recognizes the importance of adapting to this diverse business environment to meet market-specific demands. Depending on the region, the structure of grid support systems varies as we have seen on the previous page. In market-driven models, such as those in the UK, Ireland, and the US, regulators or transmission system operators (TSOs) procure support services through competitive markets. Centralized systems, seen in countries like Germany, France, and Russia, assign responsibility for investments directly to TSOs. Hybrid models, as adopted in Sweden, Canada, and Australia, combine the use of TSOs and competitive markets to achieve results.

This dynamic landscape means that a variety of players may emerge as potential customers. ABB's strategy is to align its approach with these varying business environments, providing flexible and region-specific solutions that address the unique needs of each market.

To address the challenges caused by changes in the power system, the transmission network must be strengthened. Political decisions or local legislation often define how this support should be handled, leading to different market environments and ways to the market. This can result in various players appearing as potential customers. ABB's approach is to follow this business environment.

Main market environments

1. Centrally-driven: Governments give the responsibility to TSOs who handle the investment (e.g., DE, FR, RU)
2. Mixture: Regulators use both TSOs and the market to achieve results (e.g., SE, CA, AU).

Customer types

- TSOs: Buy turn-key solutions from large EPCs or consortiums
- System services provider (i.e., in UK): Buy turn-key solutions or could integrate themselves to provide services such as inertia, short circuit contribution, MVAr, and frequency regulation to the TSO
- Developers for renewable plants (act as system service providers): Buy turn-key solutions from renewable OEMs or integrate themselves
- Power generation owners: Buy retrofit solutions or engineered packages
- DSOs: Buy turn-key from minor EPCs or engineered packages

Use case 3: Industrial applications

Sectors such as mining and manufacturing that are high power consumers with a major reliance on consistency and reliability are leading the investment in grid support and power factor correction (PFC) solutions. Within these industries, three primary factors encourage the adoption of these technologies.

First, industries in remote locations such as mining operations and offshore oil and gas plants, face unique challenges. These facilities are often located a long distance from the main power grid, where the grid is weak, with a low fault level. Or they may have to operate in "island mode" with no grid supply. This setup leads to power quality issues and an increased risk of interruptions, making grid support solutions essential for maintaining reliable operations.

Second, power quality concerns are a critical issue for industries located on weak grids or those with sensitive processes. These customers often encounter issues, such as voltage sags. Addressing these challenges is vital to ensure stable and efficient production.

Lastly, many industries prioritize dynamic power factor correction for both commercial and technical reasons. Companies seek to reduce costs associated with reactive power charges on their electricity bills or mitigate voltage variations caused by fluctuating loads and frequent starts of equipment with high inrush currents. These issues make dynamic solutions an attractive investment for enhancing power efficiency and system stability.

Customer types

- **Remotely-located industries:** mining companies, offshore wind or O&G companies at remote sites: Buy turn-key solutions or engineered packages
- **Power quality customers:** Buy engineered packages
- **Power factor correction:** Buy engineered packages or turn-key solutions for larger investments

Solution providers to the above

- **Developers for renewable plants:** Buy engineered packages or integrate themselves
- **Power generation OEM´s:** Buy engineered packages
- **STATCOM / BESS suppliers:** Buy engineered packages
- **Microgrids or island operation:** Most likely buy engineered packages

Sectors with high-demands on power quantity and quality like mining or manufacturing, offshore wind or oil & gas have three main drivers for investing in grid support or power factor correction:

1. **Remote industries:** These are industries that establish their plants at remote sites or operate in "island mode," which implies low fault levels and power quality problems, leading to risks of interruptions. Typically, these are mining companies or remote oil and gas plants, including offshore facilities.
2. **Power quality customers:** These industries are located at weak grids or have sensitive processes. They experience power quality problems.
3. **Power factor correction:** Industries looking for dynamic power factor correction due to commercial or technical reasons, such as bills for reactive power or voltage variations caused by varying loads and frequent starting loads with high inrush currents.

Solution providers for the above:

- **Developers for renewable plants:** They buy engineered packages or integrate them themselves
- **Power generation OEMs:** Buy engineered packages
- **STATCOM/BESS suppliers:** They buy engineered packages
- **Microgrids or island operations:** These customers most likely buy engineered packages

THE COST OF UNSTABLE GRID

The cost of operating an unstable power grid is generally linked to the risk of a black out (for utilities) or interruption of the power supply (for industry).

A black out can have severe consequences for society since electrical power is crucial for communications, water supply, heating/cooling, payment transfer, and all types of commerce. While mission critical operations such as hospitals have their own backup generation, the impact on society at large can be enormous. The actual cost of a black out depends on the timing, size of network and the number of people affected. Conservatively, the cost will be several $USD millions for each minute. In fact, the one-day outage that affected the Iberian peninsular in April 2025 left millions of people without electricity, caused several Spanish regions to declare a state of emergency and is estimated to have caused economic losses of between $USD 2.5 to 5 billion.

For industrial plants an interruption of the plant can be calculated based on the type of production and the time of the interruption. For some industrial plants a power black out can cause damage to equipment or impact on security and safety (i.e. pump stop or ventilation stop in a mine). ABB’s Value of Reliability global report that surveyed industrial businesses in 2023 put the cost of unplanned outages at $USD 125,000 per hour.

Clearly, the costs of power black outs can be very high. But, obtaining a clear view of the contribution that a synchronous condenser can make to reducing these costs requires detailed simulations related to the impacts of the fault to the power grid. Some results of this type of simulation are shown in the tables on the right.

Table 1. Interruption cost in 1996 for the Industrial sector (US$/kW)

	Duration of Interruption		
Industry	**20 Minutes**	**1.0 Hour**	**4.0 Hours**
Agriculture — crops	0.02	0.12	1.28
Coal Mining	1.34	2.11	4.66
Oil and Gas Extraction	81.47	193.88	205.85
Food and Kindred Products	4.74	15.10	50.52
Primary Metals Industry	1.55	2.49	5.26
Industrial Machinery and Equipment	3.02	5.40	18.45
Electrical and Electronic Equipment	3.48	6.60	19.89

Table 2. Interruption cost for selected sensitive electricity cosumers in the Commercial sector (US$/hr)

Industry	Average Cost
Cellular Communications	41,000
Telephone Ticket Sales	72,000
Airline Reservations	90,000
Credit Card Operations	2,580,000
Brokerage Operations	6,480,000

Source: United States Department of Energy, Strategic Plan for Distributed Energy Resources, 2000.

CASE STUDIES AND REAL-WORLD APPLICATIONS


Case study 1: Darlington Point, Australia

This project was carried out during 2019/2020 at Darlington Point, Australia's largest solar plant, rated at 333 megawatt (MW) and connected to the Australian Transmission Grid. AEMO, the Australian Regulator, requested fault current contribution and inertia as a "no harm" requirement. This meant the solar plant needed to provide the same inertia and fault-level contribution that would be available from conventional power plant.

Because the plant is in New South Wales (NSW), the Grid operator, Transgrid, required this contribution of inertia and fault current at the 220kV Burunga substation. ABB´s solution, provided with a local EPC contractor, was based on the installation of two synchronous condensers.

In the early stage, these synchronous condensers were switched on/off daily in line with the output of the solar plant. Later, inertia and fault current became increasingly important in the Australian Grid, so an additional agreement between the owner of the synchronous condensers (Solar Plant), Transgrid and AEMO called for additional compensation, so that the SCs would also run through the night. With this change, the synchronous condensers became essential for the operation of the transmission grid in the region.

Case study 2: Coté Gold Mining Project, Canada

The Coté Gold Mining project in 2021 saw the development of a new gold mine in Ontario, Canada.

This region has a very weak power network. Therefore, the mine owner needed to secure a stable power system for its operation. Synchronous condensers were introduced early into the industrial power system to provide power stability and to act as a voltage-dip mitigator. This was because voltage dips were expected both from the power system side caused by lightning strikes and the high inrush current from the large industrial loads. In both cases, the synchronous condenser was able to support the network. One critical consideration was the low ambient temperatures during the winter that fell well below zero.

ABB met this challenge with a special water-cooling system with glycol mix.

Reported quantifiable improvements from the Coté Gold Mining project include reduced outages, increased efficiency, and better integration of renewable energy.

FUTURE TRENDS

Evolution of grid needs with increasing renewable penetration

The transition to renewable energy is driving significant changes in power grids worldwide, necessitating modernization to ensure stability and reliability. To manage these challenges, grid operators are increasingly turning to advanced technologies such as synchronous condensers and BESS, which provide the flexibility and stability required for modern grids (European Commission, 2020; U.S. Department of Energy, 2021).

Grid flexibility is another critical focus, with the growing share of variable renewable energy (VRE) pushing for innovative solutions. Technologies like demand response and energy storage are crucial to balancing fluctuating supply and demand, enabling the grid to operate efficiently even under variable conditions (IRENA, 2020).

Decentralization is also transforming energy management. The rise of DERs is fostering decentralized models that allow for seamless integration of renewable energy. This shift is evident in regions like USA, Europe and Australia, where DERs actively contribute to grid services such as frequency regulation (AEMO, 2021; CPUC, 2020).

Finally, enhanced grid support is becoming increasingly important as traditional synchronous generators are phased out. Synchronous condensers are stepping in to provide critical inertia and voltage support, especially in areas with high renewable penetration such as Texas (in the US) and Germany, ensuring that the grid remains stable and resilient despite the changes in energy generation (ERCOT, 2023; Fraunhofer UMSICHT, 2021).

Innovations in synchronous condenser design

The evolving energy landscape is driving innovations in synchronous condenser technology, enabling it to address modern grid challenges more effectively. One key development is a hybrid solutions that integrate synchronous condensers with capacitors, energy storage, and battery systems. These hybrid configurations provide enhanced reactive power compensation while minimizing the operational complexity and installation footprint of traditional systems.

Another important trend is the integration of synchronous condensers with advanced power electronics, such as inverters and FACTS devices. This combination enhances performance, improves response times, and boosts efficiency, allowing synchronous condensers to adapt more quickly to the fast-changing demands of grids increasingly powered by renewable energy.

The development of modular and scalable synchronous condensers is also gaining momentum. These designs offer grid operators the flexibility to tailor installations to specific grid requirements. By scaling the units up or down as needed, operators can achieve cost-effective solutions that provide the necessary support for varying grid demands. These advance position synchronous condensers as a critical component in modern, resilient, and sustainable power systems.

Potential policy, regulations and market drivers favoring synchronous condensers

The growing emphasis on grid stability and reliability is driving new policies, incentives, and market opportunities that position synchronous condensers as a critical technology for modern power systems. Governments worldwide are introducing financial incentives and policy frameworks to promote grid stability technologies. Initiatives like the European Union's Green Deal and the U.S. Department of Energy's Clean Energy Standard actively support the adoption of solutions such as synchronous condensers to enhance grid performance and resilience (European Commission, 2020; U.S. Department of Energy, 2021).

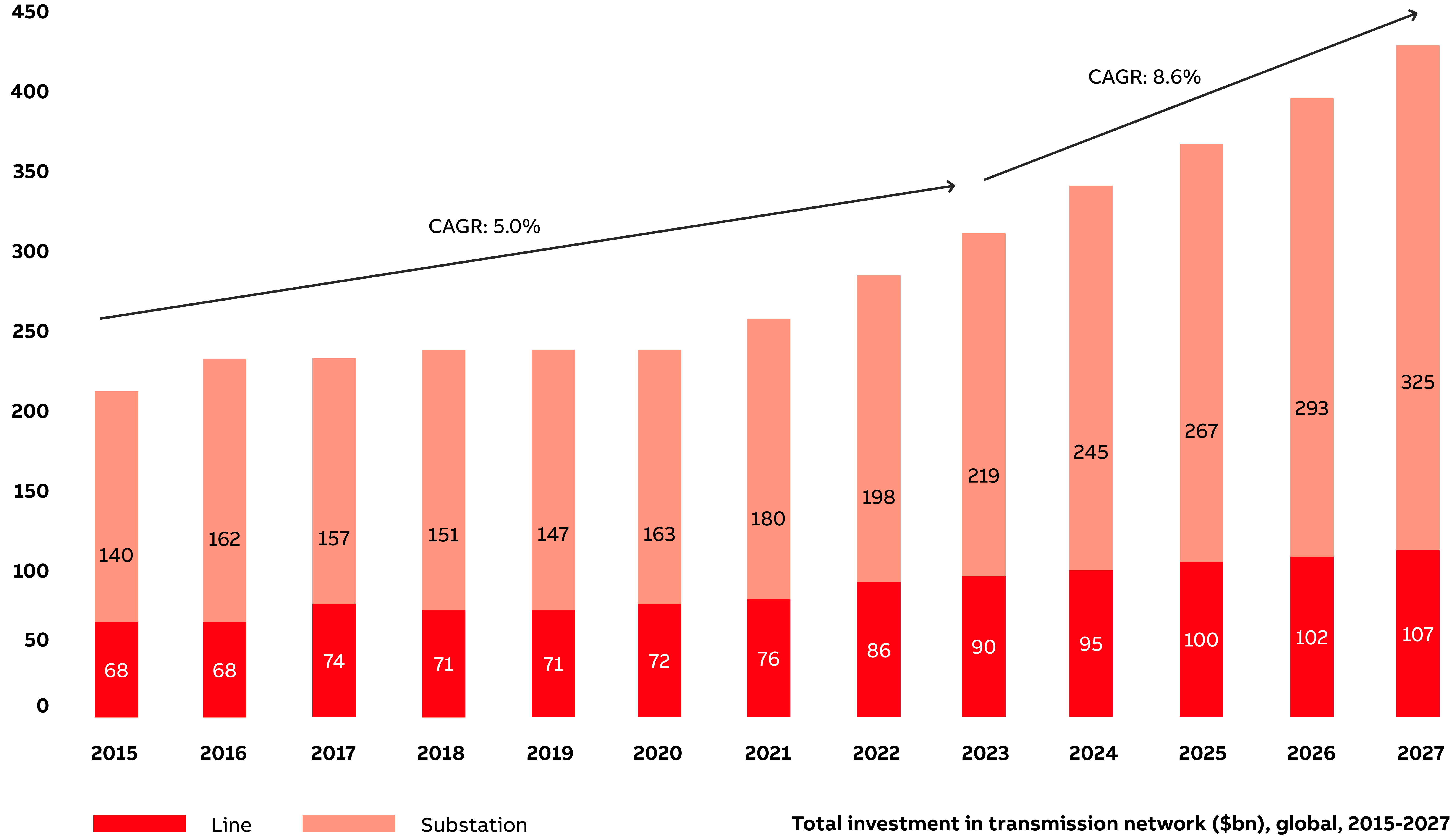
In parallel, regulatory bodies are enforcing stronger grid reliability standards to address the challenges of increasing renewable energy penetration. These standards call for advanced technologies like synchronous condensers to provide essential services, including frequency regulation, reactive power, and fault protection, ensuring the grid remains robust and reliable (NERC, 2021; FERC, 2020).

Renewable integration policies are also fueling demand for grid support technologies. Policies incentivizing renewable energy generation necessitate investments in solutions that can manage the variable nature of renewable sources like wind and solar. Synchronous condensers play a vital role in maintaining grid stability amidst these fluctuations, making them a cornerstone of renewable energy integration (IRENA, 2020; U.S. Clean Power Plan, 2020).

Additionally, the expansion of ancillary services markets creates new opportunities for synchronous condensers. These markets provide compensation for operators that deliver critical services such as frequency regulation and voltage support. Utilities and independent system operators (ISOs) are increasingly turning to synchronous condensers to provide reliable and cost-effective grid services, further driving their adoption (California ISO, 2020; National Grid ESO, 2021).

Growth in transmission investment

- Transmission investment in 2023 is estimated at $310 bn, growing at 9% over 2022
- Around 71% of the investment was in substations, while the remaining was in transmission lines
- The investment is expected to increase to $431 bn by 2027
- Renewable energy integration with the grid has been a major driver of transmission investment
- Utilities are also investing to make the T&D grid more resilient in wake of extreme climate events
- Digtalisation of the grid is also among the key growth drivers for transmission investment
- Over the next five years, the investment in transmission is expected to grow at a CAGR of 8.6%



Total investment in transmission network ($bn), global, 2015-2027

Source: GlobalData

Conclusion — The time has come again for synchronous condensers

As the energy transition accelerates, grid operators and industrial users face mounting pressure to maintain system reliability as the level of synchronous generation that provides useful grid services to support stability declines. Synchronous condensers offer a proven, flexible solution, enhancing grid stability, enabling renewable integration, and mitigating risks such as voltage collapse and blackouts.

Whether deployed to support weak grids, integrate renewable generation, or improve industrial power quality, synchronous condensers provide unmatched benefits in inertia, voltage regulation, and fault ride-through. Innovations in hybrid configurations and scalable designs make them even more relevant as power networks evolve.

Now is the time for energy stakeholders—utilities, developers, system operators, and policymakers—to recognize the strategic role of synchronous condensers in building secure, efficient, and future-ready power systems. Investing in this technology today is an investment in tomorrow's resilient energy infrastructure.

Key Glossary

AC	Alternating Current
AEMO	Australian Energy Market Operator
BESS	Battery Energy Storage System
COG	Oil and Gas Industry
DC	Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operators
EPC	Engineering, Procurement, Construction
ENTSO-E	The European Network of Transmission System Operators for Electricity
FACTS	Flexible AC Transmission System
FERC	Federal Energy Regulatory Commission
GTO	Gate Turn-off Thyristor
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
ISO	Independent System Operator
LVRT	Low Voltage Ride Through
MVAr	Megavolt-Ampere Reactive
NERC	North American Electric Reliability Corporation
NSW	New South Wales
OEM	Original Equipment Manufactured
PFC	Power Factor Correction
POC	Point of Connection
POD	Power Oscillation Damping
PQ	Power Quality
SCL	Short Circuit Level
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensators
TSO	Transmission System Operator
VFD	Variable Frequency Drive
VRE	Variable Renewable Energy
VSC	Voltage Source Converter

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