



GE VERNOVA

White Paper

Power Engineering HUB &
Power Conversion & Storage LATAM

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THE ROLE OF ENERGY STORAGE IN HYBRID SYNCHRONOUS CONDENSER SOLUTIONS

POWER SYSTEM STABILITY

The future of grid stability lies in hybrid architectures that intelligently combine rotating and power-electronic technologies to restore stability, resilience, and grid performance.

PURPOSE

INTRODUCTION AND BACKGROUND

Global power systems are becoming unstable and more dynamic as the conventional synchronous generation is being replaced by inverter-based renewables (IBR) at an exponential rate.

From a demand standpoint, large and complex loads such as electric arc furnaces, electrolyzers and data centers are significantly increasing power and fast response needs.

These changes in the power landscape represent a tremendous challenge to grid stability and power quality due to the reduced inertia, lower short-circuit strength, and tighter voltage/frequency stability margins.

To address these challenges in a more system-optimized way grid operators are increasingly looking beyond standalone devices and seeking hybrid solutions that intelligently combine complementary technologies, maximize asset utilization while providing superior performance over traditional standalone solutions.

Hybrid Synchronous Condenser (HSC) solutions integrate multiple technologies, such as

synchronous condensers (SC), Battery Energy Storage Systems (BESS), and Static Synchronous Compensators (STATCOM), to address grid stability challenges. By combining the high fault current and inertia of rotating machines with the fast frequency response and advanced controllability of power electronics systems (BESS, STATCOM etc.), HSCs deliver a more robust and flexible solution.

This white paper is part of the GE Vernova Hybrids solution series and presents a HSC concept incorporating energy storage. It compares the HSC approach with standalone SC and grid-forming BESS solutions and introduces a reference architecture based on GE Vernova Rotating Stabilizers and FLEXINVERTER technology with integrated BESS energy. The proposed architecture enables a more efficient way to strengthen weak grids, increase renewable hosting capacity, and support large sensitive loads.

Source: GE Vernova assets



THE EVOLVING POWER GRID ERA

The electric power sector is undergoing a profound transformation. Rapid growth of distributed generation (DG), aging infrastructure, increasingly congested transmission and distribution networks, and the emergence of large, complex loads are reshaping how power systems are planned and operated.

At the same time, stricter environmental and sustainability targets, together with a persistent rise in global energy consumption, are accelerating the shift away from conventional synchronous machine-based power plants toward renewable, inverter-based resources.

The combination of all these factors is typically represented by the “duck curve” (figure 1) which illustrates the major challenges faced by transmission system operators (TSOs) in this dynamic generation-load environment, mainly:

- Injection of IBR generation through distribution during daytime
- Power decrease and ramp-up of dispatch from controlled sources before and after daytime

The IBRs generate significant power during a specific period in the day without inertia and control from TSO as it flows mainly in the distribution networks. It becomes harder to balance the generation and demand, which weakens the grid. Also, the load profile varies along the day which leads to power quality issues.

These changes have contributed to an increase in frequency variation and severity of system disturbances resulting in blackout events observed worldwide, particularly in networks with high renewable penetration and weak system strength.

To address these problems, utilities and grid operators are increasingly deploying solutions that can restore or emulate the essential attributes traditionally provided by synchronous machines, namely

- System Inertia (frequency response)
- Fault current contribution
- Robust voltage support

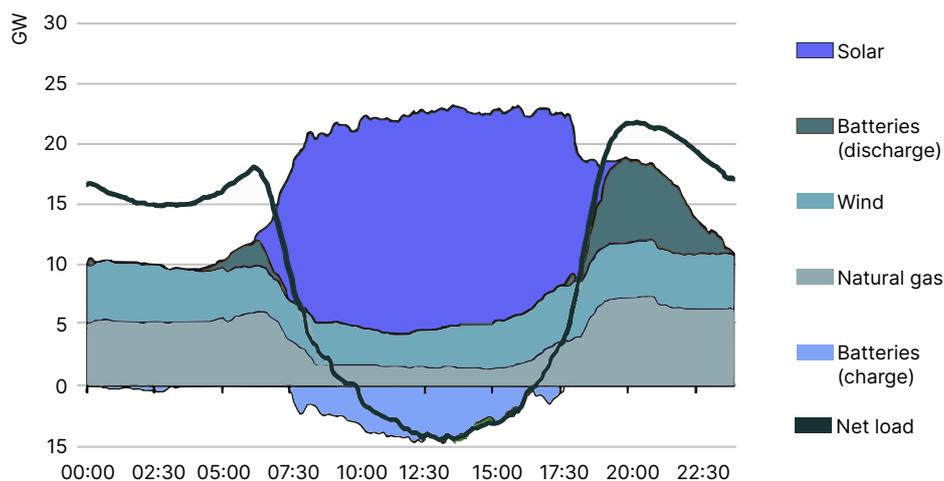


Figure 1: Duck Curve sample. Power generation in California (CAISO) April/2024.
Source: IEA based on data from Gridstatus.io

**EVOLVING LOAD PROFILES AND RENEWABLES RESOURCES ARE RESHAPING THE GRID,
DRIVING A GREENER BUT MORE CHALLENGING FUTURE**

GRID STABILITY & POWER QUALITY

TYPICAL STANDALONE SOLUTIONS

In recent years, synchronous condensers have attracted significant interest as a proven technology to mitigate the operational grid and power quality challenges arising from the decline in conventional synchronous generation and increased dynamic generation-demand behavior.

SCs deliver physical inertial response and strong voltage support, enhancing system resilience under dynamic disturbances such as voltage sags and short-circuit events. Their integration increases the system short-circuit ratio (SCR) and improves fault ride-through (FRT) performance, as reflected in higher retained voltage levels and faster post-fault voltage recovery.

In parallel, power electronics-based solutions, from conventional STATCOMs to advanced E-STATCOMs and battery energy storage systems (BESS), have seen substantial research and industrial deployment for grid stability support.

These technologies can effectively damp oscillations, strengthen weak grids, increase the hosting capacity of renewable resources in remote areas, and provide black start capabilities essential for system restoration. They also offer fast dynamic response, flexible control and advanced synchronization features, enabling operation in both grid-following (GFL) and grid-forming (GFM) modes.

However, unlike synchronous condensers, inverter-based technologies such as BESS and STATCOMs are constrained by overcurrent limits. As a result, achieving equivalent short-circuit strength in weak grids can be challenging and may require additional engineering, advanced control coordination, or usage of complementary technologies.

HYBRID SYNCHRONOUS CONDENSERS

A broad range of technologies can contribute to grid stability and combining them in a coordinated way helps achieve cost-effective and optimized solutions.

Each power system has its own constraints, performance requirements, and boundary conditions. As a result, right-sizing, strategic placement, and hybridization of different technologies are emerging as a very attractive approach.

In this context, Hybrid Synchronous Condenser solutions, composed of SC and GFM BESS, are designed to integrate and combine the benefits of synchronous condensers and power electronics-based resources.

Leveraging the physical inertia and high short-circuit capability of SCs together with the fast frequency response and advanced control capabilities of BESS enables an optimized selection of critical performance criteria for each grid location and specific project constraints.

Hybrid solutions pursue a balance between main project efficiency and viability characteristics while sustaining the necessary power stability and quality features as presented in Table 1.

Table 1: Hybrid solutions - typical targets

Technical	Project
Inertia	CAPEX
Frequency Response	OPEX
Dynamic Profile	Footprint
Short Circuit Capability	Lead Time
Response Time	Maintenance

GE VERNOVA POWER QUALITY & STABILITY

TECHNOLOGY TOPOLOGY & TECHNICAL COMPARISON

Based on each power system's requirements, GE Vernova can fine-tune the project topology using its own different technologies. Table 2 presents a comparison between the most common solutions employed in power grid stability applications in terms of technical features.

Table 2: Technologies – Technical Comparison

Technology Topology	Inertia and Frequency Response	Voltage/ Current Dynamic Profile	Short-Circuit Capability	Response Time	Black Start
SC/SC + Flywheel	Provide an inertia constant of approximately $H = 1-3$ s (SC only), which can be increased to about $H = 3-10$ s when equipped with a flywheel, significantly enhancing frequency support and overall system stability.	High overloading capability, with operational limitations when underexcited, typically restricting field current to around 0.5 pu of rated current.	3-10 pu of the rated current	Post-fault settling time and reference voltage change occur on a time scale of seconds.	No capability
GFL BESS	No intrinsic mechanical inertia; frequency support provided via droop control with the possibility of emulating synthetic inertia through advanced control strategies.	Full rated reactive current capability in both capacitive and inductive modes. There are possible instability risks due to cascaded control loops and PPL(1).	It is limited by the overcurrent limiter, with typical allowable values of 1.1-1.2 pu.	Tens of milliseconds	Black-Start Capability with change in operation mode
GFM BESS	Inertia response similar to synchronous generators, with fast frequency response comparable to synchronous machines and the possibility of providing synthetic inertia through advanced control.	Full rated reactive current in both capacitive and inductive modes, with typical overload capability of 1.1-1.2 pu.	Needs a current-limitation scheme to be activated whenever the requested current is higher than the maximum converter permissible current level.	Start within 5ms (2)	Natural Black-Start Capability
SC+ GFL BESS	Inertia constant of approximately $H = 1-3$ s from the SC, which can be increased to about $H = 3-10$ s when equipped with a flywheel, combined with instantaneous response via droop control and the possibility of providing synthetic inertia.	High overload capability, but underexcitation capability is limited to less than 1 pu due to synchronous condenser constraints. Potential instability may arise in the BESS because of cascaded control loops and the PLL.	SC can reach up to 10 pu, while BESS is typically limited to 1.1-1.2 pu; the overall achievable value is determined by the relative ratings of each unit.	Improved post-fault settling time and reference voltage response, as the BESS compensates the slower dynamic behavior of the SC.	Black-Start Capability with change in operation mode, using BESS capacity
SC+ GFM BESS	Mechanical inertia combined with instantaneous response and fast, synchronous machine-like frequency support, with the capability to provide so-called synthetic inertia.	High overload capability, but underexcitation capability is limited to less than 1 pu due to synchronous condenser constraints.	SC can reach up to 10 pu, while BESS is typically limited to 1.1-1.2 pu; the overall short-term capability is defined by the relative rating of each unit. A current-limitation scheme must be applied whenever the demanded current exceeds the converter's maximum allowable current.	Improved post-fault settling time and reference voltage response, as the BESS compensates the slower dynamic behavior of the SC.	Natural Black-Start Capability, using BESS capacity

1 Phase Locked Loop a closed-loop feedback system that generates an output signal whose is locked with the frequency and phase of the voltage at the point of common coupling (PCC) of GFL grid connected converters.

2 GFM Converter sub transient start-up response speed capability

Hybrid Synchronous Condenser solutions that combine SC and Battery Energy Storage Systems (BESS) effectively integrate the strengths of both technologies. The SC provides physical inertia and high short-circuit capability, while the BESS delivers fast frequency support, enhanced dynamic control and black-start capability.

The spider chart presented in Figure 2 illustrates the hybridization capability, showing how this combined solution expands the design space and flexibility across individual performance criteria alongside standalone SC or BESS solutions.

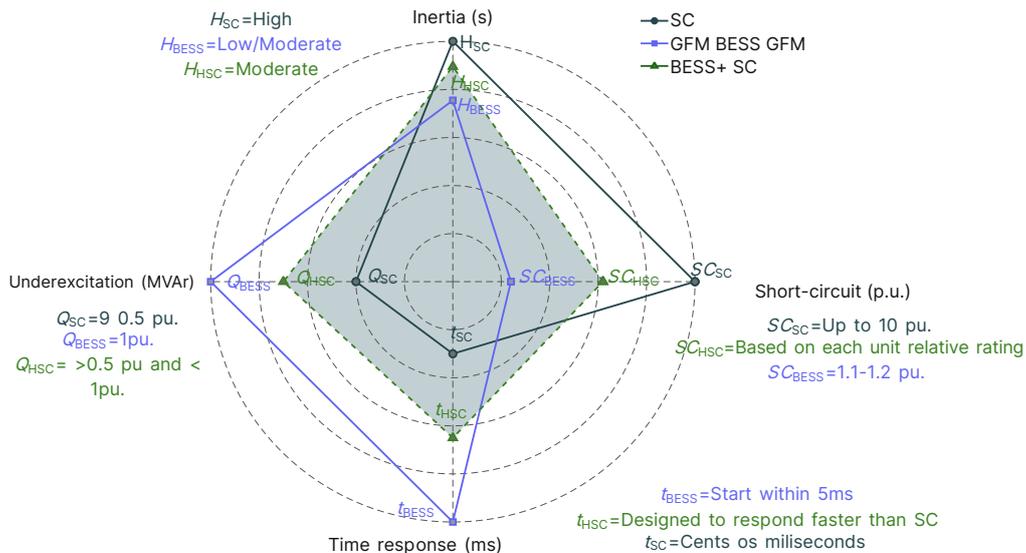


Figure 2: SC, BESS and Hybrid SC solutions Comparison

As shown in the figure above, the hybrid SC enhances underexcitation 3 capability, short-circuit contribution, inertia, and response time, resulting in a more balanced and robust solution for grid stability applications. In contrast, standalone solutions, whether based on synchronous condensers or power-electronic technologies, lack balance, as they provide either inertia and short-circuit strength or fast response time and underexcitation capability

HSC ARCHITECTURE & SIMULATIONS

One possible GE Vernova Hybrid Synchronous Condenser (HSC) solution combining an SC and a BESS is illustrated in Figure 3 and compared with a solution based on SCs only. The HSC solution uses the modular FLEXINVERTER (FI), which is widely used in solar and storage applications and is capable of operating in both grid-following and grid-forming modes in BESS applications

In order to compare the solution from a technical performance perspective, these models were modeled in PSCAD with the same MVA capacity and technical requirements (Inertia, SCC) as presented in figure 4. The simulations were performed for different scenarios: rate of change of frequency (ROCOF) of 2 Hz/s, a 30-degree phase jump, short-circuit conditions, and voltage sag and swell levels of 0.5 and 1.2 p.u. as presented in the next figures.

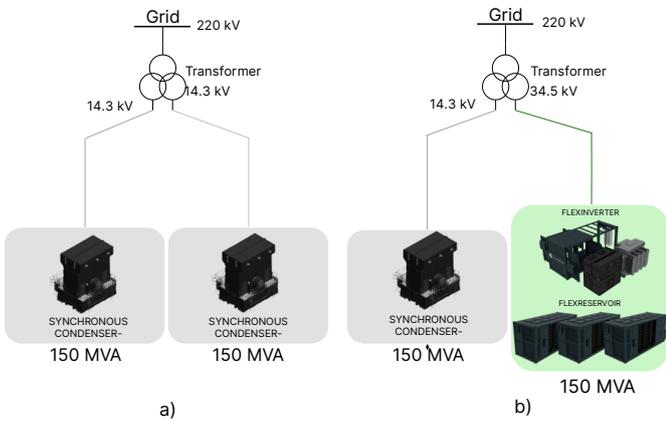


Figure 3:
a) SC Solution: Two SC, 150 MVA each
b) Hybrid-SC solution – one SC and FLEXInverter+BESS, 150 MVA each

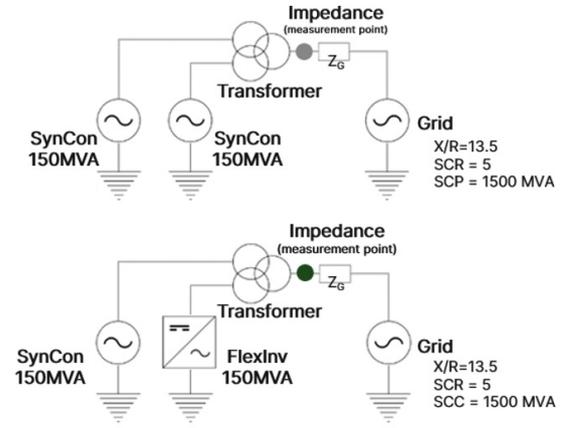


Figure 4: Simulation diagram used for technical comparison

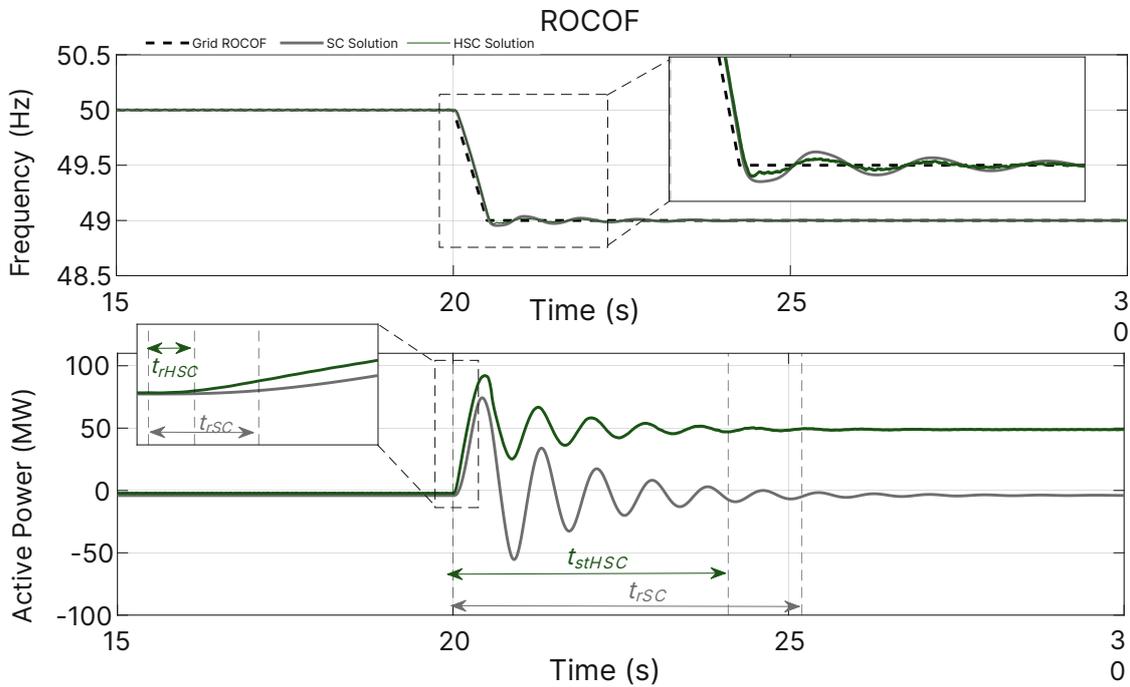


Figure 5:
Technical Comparison: Rate of Change of Frequency - 2 Hz/s at 20s (tr: response time / tst: settling time)

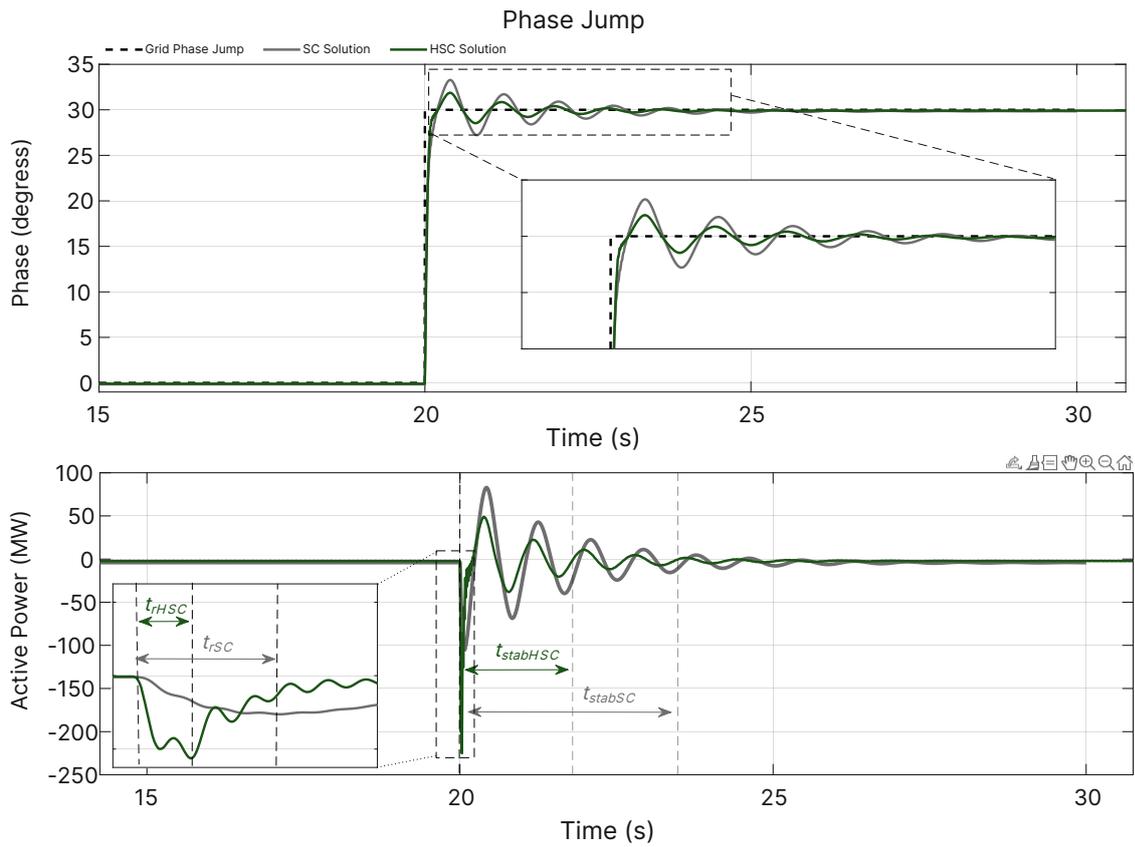


Figure 6: Technical Comparison: Phase jump of 30° applied at 20s (t_r : response time / t_{stab} : stabilization time)

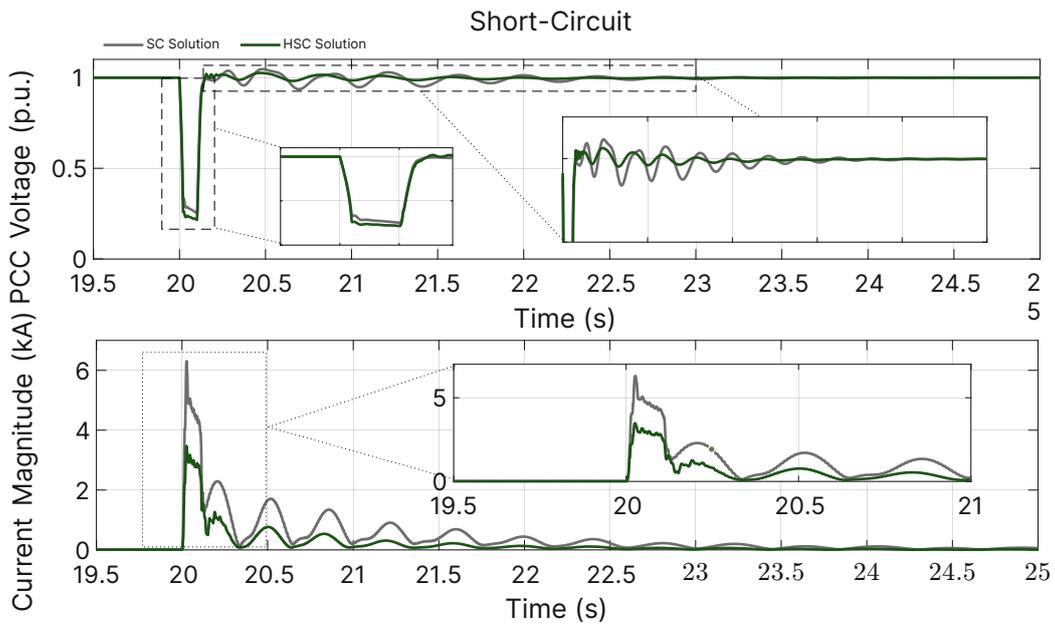


Figure 7: Technical Comparison: Short-circuit event applied at 20s

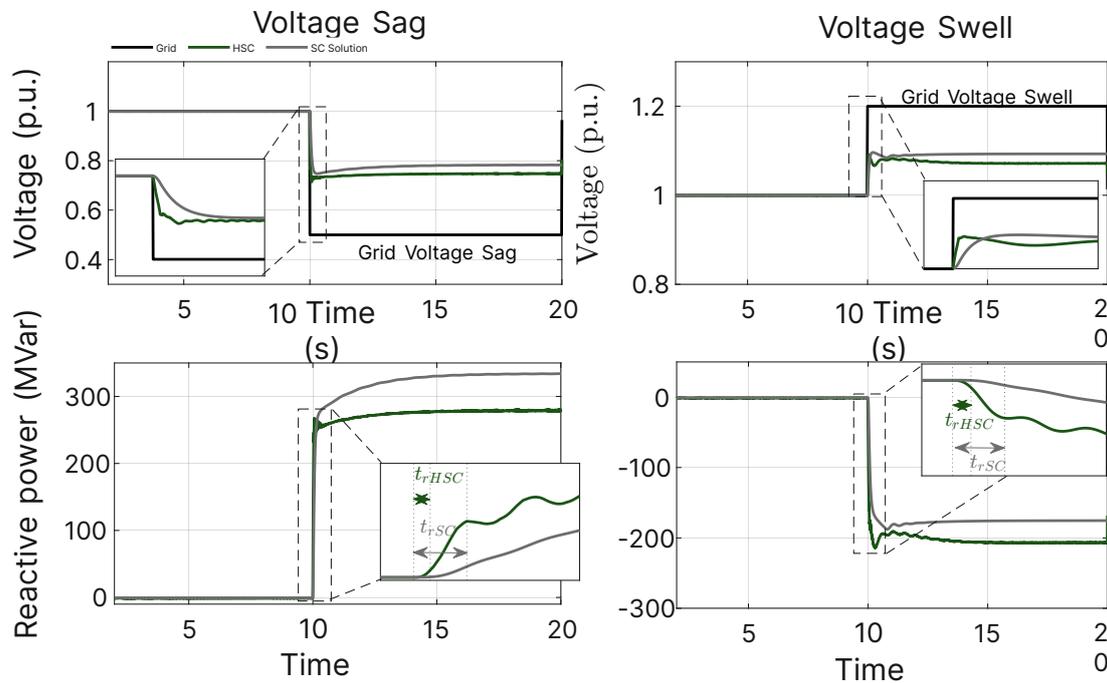


Figure 8: Technical Comparison: Voltage sag to 0.5 pu and voltage swell to 1.2 pu (t_r : response time)

Under a ROCOF (Figure 5) event, the SC-based solution provides only inertial active power support, whereas the HSC solution delivers both inertial support and primary frequency response, leading to faster response and settling times.

In the phase jump scenario (Figure 6), the solutions deliver equivalent active power contributions. However, the HSC solution exhibits a faster dynamic response and stabilization time.

During short-circuit events (Figure 7), the SC solution exhibits a higher fault current contribution than the HSC solution, due to the current limitation of the BESS. On the other hand, the HSC solution demonstrates faster post-fault recovery, while the SC solution introduces active power oscillations after fault clearance.

Finally, as illustrated in Figure 8, during voltage sags, the SC provides superior performance due to its higher overload capability.

In contrast, the HSC is more effective in

mitigating voltage swells, as it has an underexcitation limits higher than those of the SC solution. Once again, the HSC has a much faster response time during voltage disturbances.

In summary, these results clearly show that from a system perspective, the SC solution delivers stronger active and reactive power support during severe disturbances (short circuits, voltage sags, phase jumps) due to its higher inertia and transient reactive capability.

However, the HSC, despite being limited by the power electronic current rating, provides significantly faster dynamic response, resulting in improved post-fault voltage recovery and enhanced oscillation damping. It demonstrates how the HSC solution can balance between SC benefits and power-electronics dynamic response as an integrated system.

HSC PROJECT COMPARISON & KEY BENEFITS

Beyond the technical comparison, project viability is an important factor in evaluating systems solutions.

To assess the key project-related performance criteria, the standalone solution using synchronous condensers is compared with the HSC solution across the following aspects.

- **CAPEX**
Total investment required
- **Lead-Time**
Total time to produce and install the solution
- **Footprint**
Area to install the solution
- **OPEX**
Energy losses to maintain the equipment available (idle)

As solution cost, footprint, and lead time are influenced by the amount of equipment and the installed power capacity, simulations were performed under three different operating scenarios: 150 MVAR, 300 MVAR, and 600 MVAR.

For the SC solution, the number of SC has been varied from 1 to 12 units, depending on the required power rating and equipment availability. The HSC solution is always a combination of GFM BESS and SC.

In all HSC cases, the selection of synchronous condenser machine has been optimized based on the solution CAPEX for the available SC polarity and ratings, with the objective of improving the project-related criteria.

This wide range of possible configurations results in significant variation across the evaluated parameters. The estimated footprint ranges from 15,000 to 95,000 ft², CAPEX from USD 10 million to USD 100 million, energy losses from 1 to 10 MW, and lead times range from 90 to 200 weeks.

Given this level of variability, and to avoid exposure of sensitive design and competitive information, the comparison is presented as percentage variation for each simulated condition.

For each parameter and operating scenario presented, the HSC solution is used as the reference (100%), and all other results are expressed as a percentage relative to this reference.

Source: GE Vernova assets



Table 3: SC and HSC comparison for 150 MVAR scenario

MVAR total	Topology	Capex (%)	Lead Time (%)	Footprint (%)	OPEX (%)
150	1xSC	97%	126%	50%	113%
	2xSC	114%	111%	82%	115%
	3xSC	110%	105%	120%	129%
	HSC (FI + SC)	100%	100%	100%	100%

Table 4: SC and HSC comparison for 300 MVAR scenario

MVAR total	Topology	Capex (%)	Lead Time (%)	Footprint (%)	OPEX (%)
300	2xSC	104%	111%	55%	114%
	3xSC	105%	96%	81%	88%
	6xSC	120%	108%	127%	131%
	HSC (FI + SC)	100%	100%	100%	100%

Table 5: SC and HSC comparison for 600 MVAR scenario

MVAR total	Topology	Capex (%)	Lead Time (%)	Footprint (%)	OPEX (%)
600	4xSC	107%	120%	46%	115%
	6xSC	104%	109%	71%	89%
	12xSC	124%	143%	123%	132%
	HSC (FI + SC)	100%	100%	100%	100%

Tables 3, 4 and 5 present the results for the standalone SC solution with different quantities of equipment and the HSC optimized for each scenario assessed. The color coding highlights more favorable values in green, less favorable values in red, and neutral in yellow.

As demonstrated by the results, the hybrid synchronous condenser (HSC) solution provides the best overall balance across the evaluated project aspects. On average, the hybrid solution outperforms (or matches) the standalone solution in terms of CAPEX, OPEX, and lead time. In addition, the HSC typically results in a larger footprint, driven by the required sizing and layout of the BESS equipment.

SUMMARY

Hybrid Synchronous Condenser solutions that combine a Synchronous Condenser with a BESS provide a robust and flexible answer to the growing stability requirements of modern power grids. As the share of inverter-based resources increases and conventional synchronous generation retires, maintaining adequate inertia, short-circuit strength, and voltage support becomes critical for secure and reliable system operation.

By integrating the physical inertia and high short-circuit capability of the SC with the fast frequency response and advanced dynamic control of the BESS, the HSC concept overcomes what standalone technologies provide individually.

The SC contributes mechanical inertia, strong fault current, and robust reactive power support, effectively increasing system strength and improving fault ride-through (FRT) performance. The BESS complements these attributes with very fast active and reactive power response, flexible control modes (GFL and GFM), and the ability to provide synthetic inertia, fast frequency response, oscillation damping and enabling black-start functionality.

This complementary interaction provides a more balanced performance envelope in terms of inertia, underexcitation capability, short-circuit contribution, and response time than either SC or BESS alone.

As illustrated by the comparative analysis of grid stability technologies, this proposed hybrid configuration can be designed by appropriately

sizing the SC and BESS components to meet diverse grid needs ranging from strengthening very weak networks to increasing renewable hosting capacity.

This presented GE Vernova HSC solution, based on the high-power-density SC and the modular FLEXINVERTER platform, provides a practical and scalable implementation of this concept, integrating energy storage with traditional synchronous condenser solutions.

Moreover, the HSC architecture can be flexibly configured using different technologies, such as STATCOMs, to optimize the solution while meeting grid requirements and delivering a coordinated response to faults and disturbances, as well as improved transient and steady-state performance for the targeted power quality needs.

From a project perspective, the HSC demonstrates strong viability in both financial and scheduling terms. Its balanced and optimized technical architecture directly enables more efficient execution and superior overall project performance.

In summary, combining the strengths of synchronous condensers and advanced power electronics, HSCs enable technical performance while improving project viability and execution. The HSCs offers an approach to improve power system quality and stability in response to the challenges of the ongoing energy transition scenario, while balancing project needs for both early stage and lifetime requirements.

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GLOSSARY OF TERMS

AI – Artificial Intelligence

BESS – Battery Energy Storage System

FACTS – Flexible Alternating Current Transmission System

FRT – Fault Ride-Through

GFM – Grid-Forming

GFL – Grid-Following

HSC – Hybrid Synchronous Condenser

IBR – Inverter-Based Resource

MVA_r – Mega Volt-Ampere reactive

PLL- Phase Locked Loop

SCC – Short Circuit Capacity

POD – Power Oscillation Damping

PV – Photovoltaic (Solar)

ROCOF-Rate of Change of Frequency

RS2 – RS2 Synchronous Condenser (two pole)

SC – Synchronous Condenser

SCR – Short-Circuit Ratio

STATCOM – Static Synchronous Compensator

E-STATCOM – STATCOM with Energy Storage System

TSO – Transmission System Operator

DG – Distributed Generation

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