Applications of synchronous condensers in modern power systems

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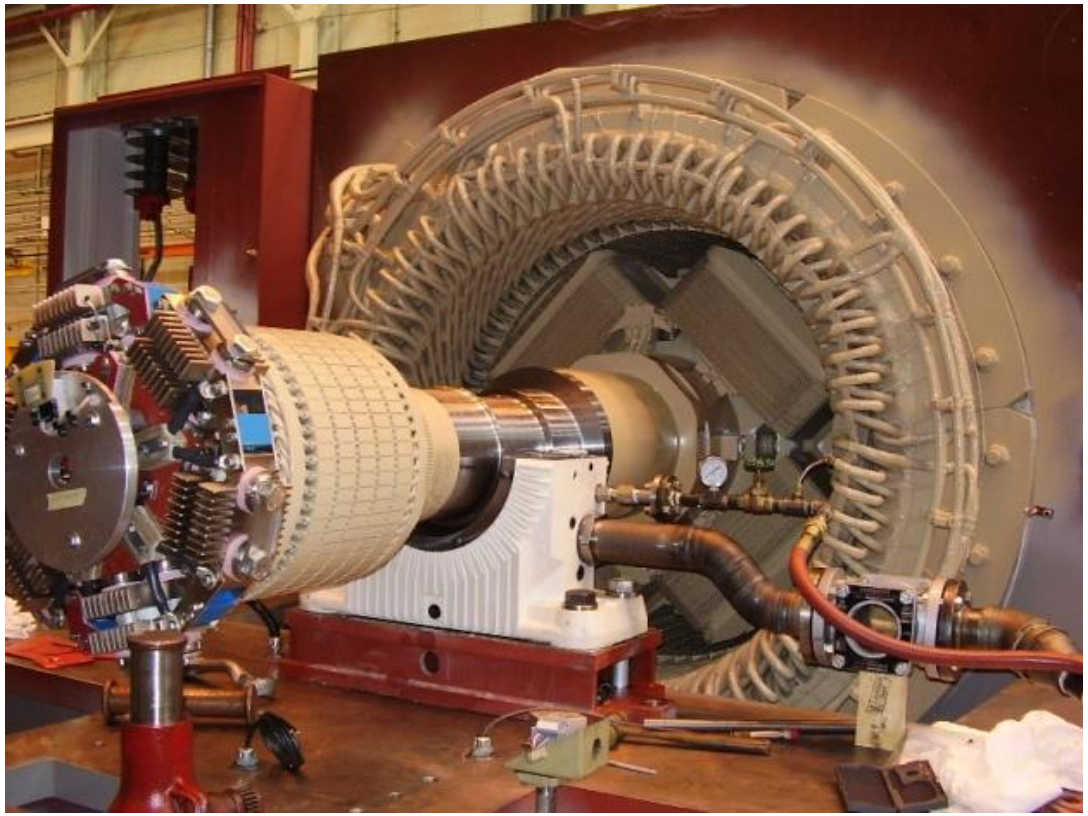
CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:
This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:
In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

Overview: Applications of synchronous condensers in modern power systems

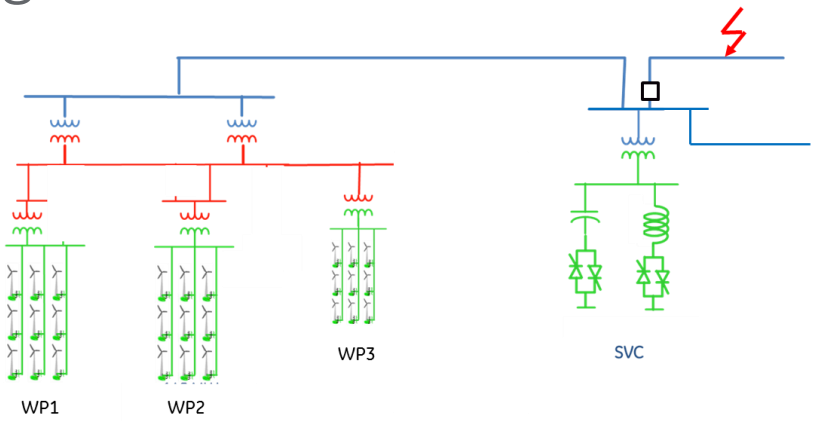
- Variable Steady-State vars
- Short-Circuit Contribution
- Dynamic Voltage Recovery
- Inertial Support
- Damping



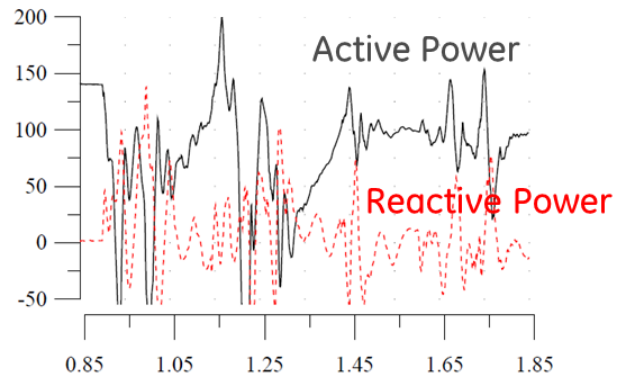
Short-Circuit Contribution

- **Current-controlled Power-Electronic (PE) sources** require grid strength to operate reliably and stably. IBRs typically include **fast** active and reactive **current controls** and require **synchronization** with the grid voltages
- In some interconnections, transmission owners need to maintain a minimum SC level under all circumstances.
- Synchronous machines contribute significant short-circuit strength to the grid.
- Properly configured power electronics can work in very demanding conditions but need extensive studies requiring significant time. Condensers are easy to apply and model.

1. Can be used to increase SC level at POI of a new renewable plant connected by long lines.
2. Can be used to increase SC level at transmission level to improve SCR for previously connected IBRs as more and more IBRs come online.

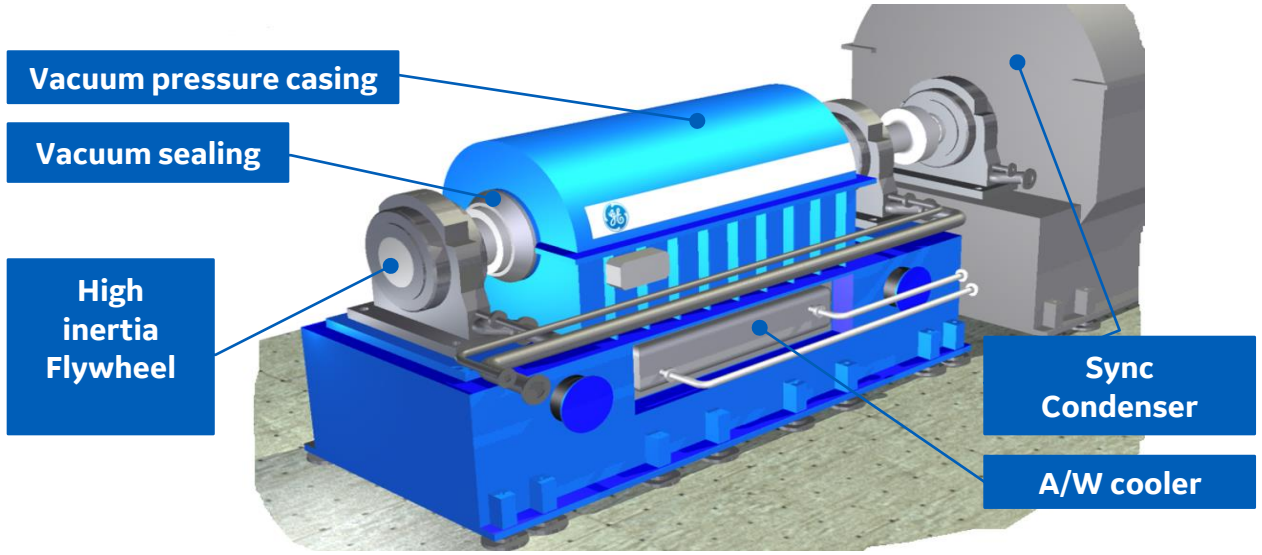


Extremely weak system after fault clearing
Same equipment stable in stronger operating condition



Reactive power oscillation (~25Hz)
SVC-WTG preventing fault recovery

Flywheel* for increased inertia



Benefits

High Inertia

- Applications for system inertia increase for enhanced grid stabilization. H increase from 1-2s to 4-8.5s.
- Higher Inertia helps to not only limit the RoCoF, but also limit the rate of change of voltage angles due to increased stiffness which is helpful for the operation of IBRs.

Low Losses

- Low friction and heat losses in vacuum

Impact on Stored Kinetic Energy

GE TOPAIR based **Synch. Condenser**	**Kinetic Energy** (3000 rpm)
• stand alone	460 MW-s
• with flywheel	1,750 MW-s

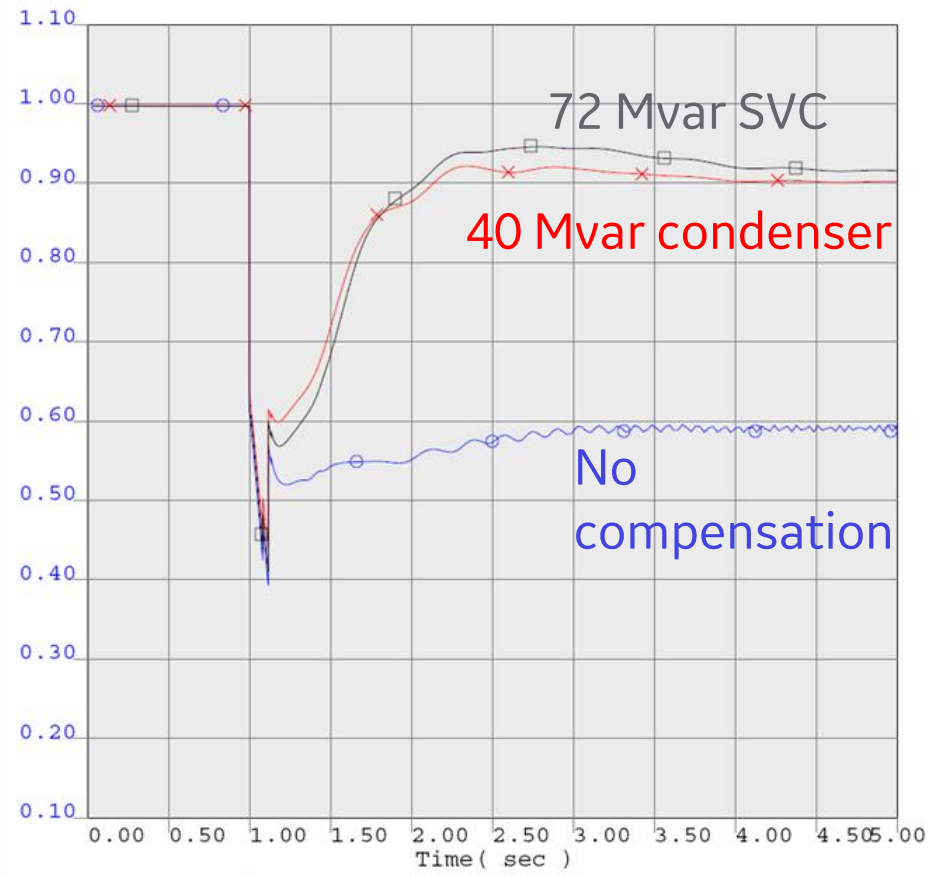
Comparison with existing steam turbine plant

• Coal fired plant 400 MVA	1,650 MW-s

Dynamic Voltage Recovery

- After clearing a fault, the transmission system needs a large var contribution to support voltage recovery.

SVC-----Output declines with square of voltage
STATCOM------Some “overload” output for fractions to a couple of seconds
Shunt Capacitors----Output declines with square of voltage
Synchronous Condensers---- More than nameplate output post-fault



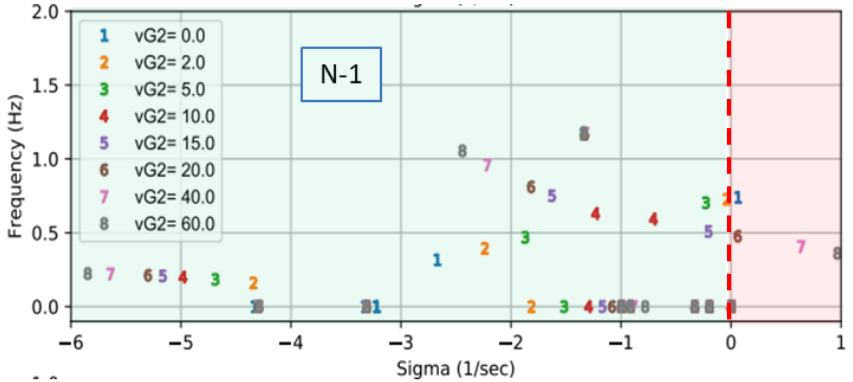
Improved Short-circuit strength from condensers assists with post-fault voltage recovery.
Synchronous condensers remain synchronized for close-in faults and extended clearing.

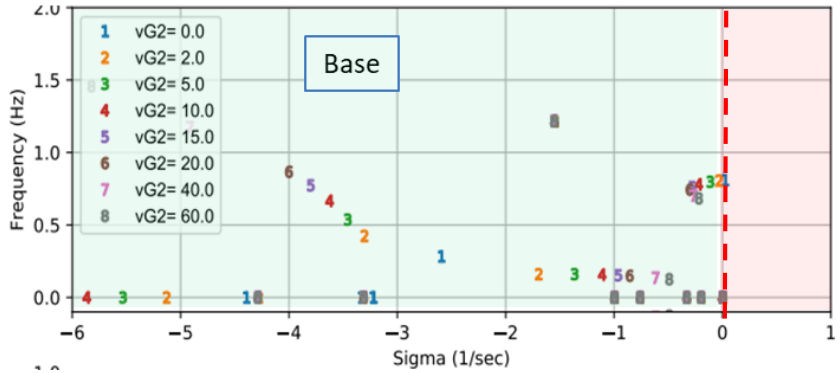
Speed of response of SVC and condenser are comparable.

Damping

- Synchronous condensers → Stiffer system → Reduced oscillations between different power electronic equipment.

- Additionally, synchronous condensers can be equipped with PSS to damp out inter-area electromechanical oscillations.



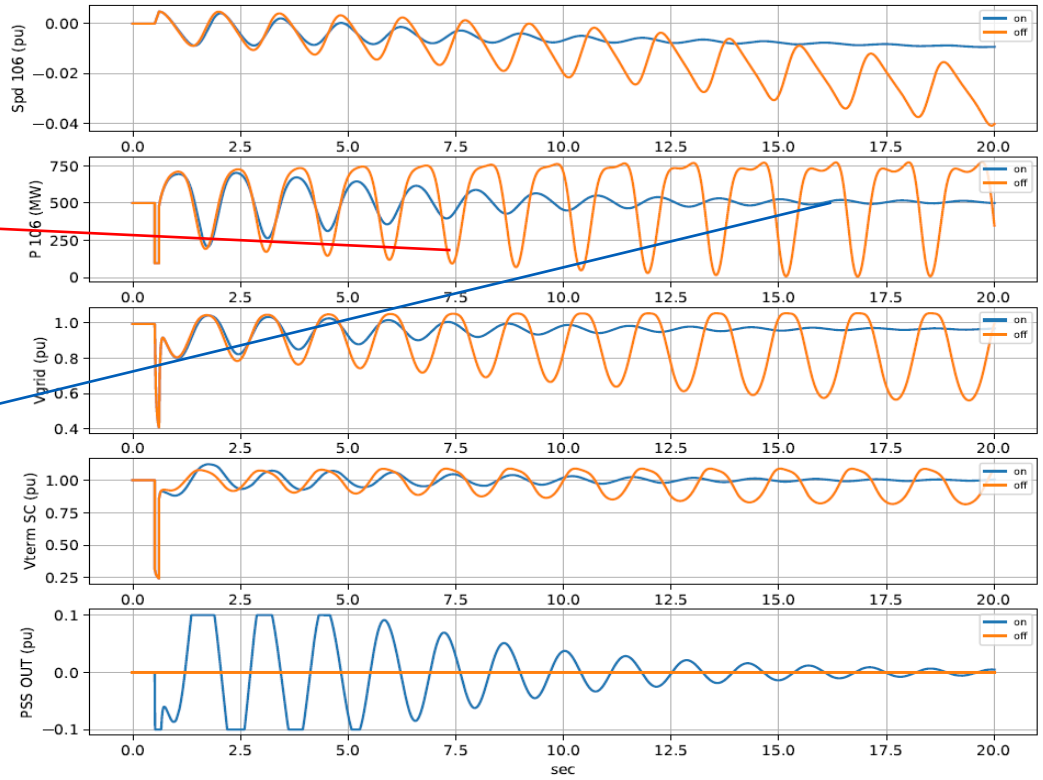


Root locus for PSS gain selection

Properly Tuned PSS

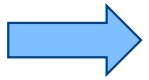
Negatively damped

Well damped



Fault and clear line: with PSS, without PSS

Selecting Synchronous Condenser Ratings

- Increased short circuit contribution requirement from the synchronous condenser does not always require a larger nameplate rating.
- A different design for a condenser of the same nameplate but lower reactances and/or increased excitation performance can provide increased short circuit contribution and improved dynamic voltage recovery after a system fault.
- Smaller machine  Lower capital cost and lower losses.
- However, there may not be sufficient time to optimize the design of condensers for every project.

Synchronous Condensers – Key Benefits to the Grid

Variable Steady-State vars: Like an SVC or STATCOM, the Synchronous Condenser continuously varies var output to regulate the grid voltage.

Short-Circuit Contribution: Increases the grid "strength." Both instantaneous and short-time fault current increased which may be required for proper IBR function, for proper protective relaying, and to reduce transient magnitudes during faults and switching events, on fault clearing etc.

Dynamic Voltage Recovery: The ability to provide more than nameplate vars for up to several seconds under depressed voltage conditions to assist with post-fault voltage recovery and prevent voltage collapse. Overload capability is higher for a longer time compared to SVC or STATCOM of equal nameplate

Inertia: Retirement of conventional generation is reducing inertia and will reduce frequency stability. Synchronous condensers provide inertia.

Damping: Stiffer system leads to reduced oscillation between power electronics equipment. Can also be equipped with PSS to help damp inter-area modes of electromechanical oscillation.

Some other differentiators between synchronous condensers and other technologies.

- Component Availability – Every SC component has availability from more than one manufacturer.
- Retired conventional power plant can be retro-fit to synchronous condensers by removing the turbine.
- Familiar Technology – Well understood and multiple organizations who can provide service.
- Life Cycle Costs – The SC has a very long expected service life versus other technologies and has a lower overall cost when maintenance, spare parts, and future upgrades are considered.
- Harmonics – SC is a natural sink. Other technologies may increase harmonics or need additional filters.