

GE
Grid Solutions

Series Compensation Systems



imagination at work

Today's Environment

Today's transmission system is becoming increasingly complex and is expected to carry bulk power in ways it was never designed for. The expectation is that transmission requirements will only increase, as power generation sources continue to evolve. Utilities around the globe are facing grid challenges such as:

- Reducing cost of new infrastructure projects and addressing changes in regulatory environments
- Meeting the rise in demand for efficient and reliable power
- Increasing electrification of rural areas and population growth of large cities
- Rapidly changing mix and location of various power generation types such as nuclear, hydro, wind and solar

Transmission utilities need to invest in new equipment, but also face increasing pressure to optimize the use of existing transmission assets to accommodate increased power transfer over longer distances.

The high voltage transmission lines are rarely limited by their thermal capacity (line sag). The transfer capabilities are more often set by voltage and stability limits, which are affected by circuit properties of the transmission systems that connect them.

To maximize the utilization of transmission assets it is necessary to adjust the circuit properties of the transmission system. The most cost-effective way to achieve this is by installing a comprehensive series compensation solution.

Strategically-placed series capacitors can often increase transmission transfer limits by a factor of two or three at a fraction of the cost of new transmission lines and can be deployed in 12 to 18 months.

Did you know?



Since 2010 GE has installed more series compensation systems than any other solution provider.



GE built the 1st ever series capacitor system in 1928 at Ballston Spa, NY.



GE has provided more than 200 systems globally.

GE's Solution

GE's Series Compensation System allows utilities to cost effectively increase power transfer capabilities of their existing infrastructure and new transmission lines.

GE offers an extensive portfolio of project management skills, engineering capabilities, equipment, and installation services, delivering an integrated and robust system.

GE's scope of work can be tailored to match the project requirements and may vary from a simple Engineered Equipment Package (EEP) through an extensive Engineer, Procure, and Construct (EPC) project, often including work beyond the series compensation system.

Extensive Global and Unmatched Technical Experience

A worldwide leader in executing and delivering series compensation projects, in a broad range of utility environments resulting in reduced implementation risk.

- More than a century of experience designing transmission networks, including the first series compensation project in 1928
- Leading the industry by delivering over 30,000 Mvars of series compensation systems in the last three years
- Globally recognized as the foremost technical experts for power system projects since 1928

Industry Leading Patented Technology

Providing superior systems enabled by GE's innovate products resulting in project cost savings and increased quality and reliability.

- Fastest Triggered Air Gap (TAG) available in the industry
- Newly patented TAG and Platform Damping Technologies
- Pioneered the use of SSR filter technology in a series capacitor system

Best-in-class Quality and Process Standards

Industry leading and well-established set of project management processes and procedures, certified to ISO® 9001 standards, resulting in on-time and on-budget execution.

- 99% record of on-time project completion
- Greater than 98% on-budget execution
- Over 3.6 million hours of project execution without an OSHA® recordable incident



Series Compensation System Overview

GE's Series Compensation solution is installed in series with the High Voltage (HV) transmission line, and consists of an integrated, custom-designed system including many power capacitors arranged in series and parallel. The most critical equipment is the parallel protective system that prevents damage to the capacitors during power system faults. The protective system design requires the careful selection and coordination of several components including the Fast By-Pass Switch, the Metal Oxide Varistor (MOV), the Triggered Air Gap (TAG), if used, and the Digital Protection System. GE optimizes the protection system design to cost effectively meet customer and system requirements. The decision to utilize the TAG or not is typically dependent upon available fault energy at the series capacitor bank location.

GE installs Series Compensation Systems in existing and new substations. They may be installed where transmission lines end or at mid-line locations within the established right-of-way boundaries. Included in GE's Series Compensation System are the following components:

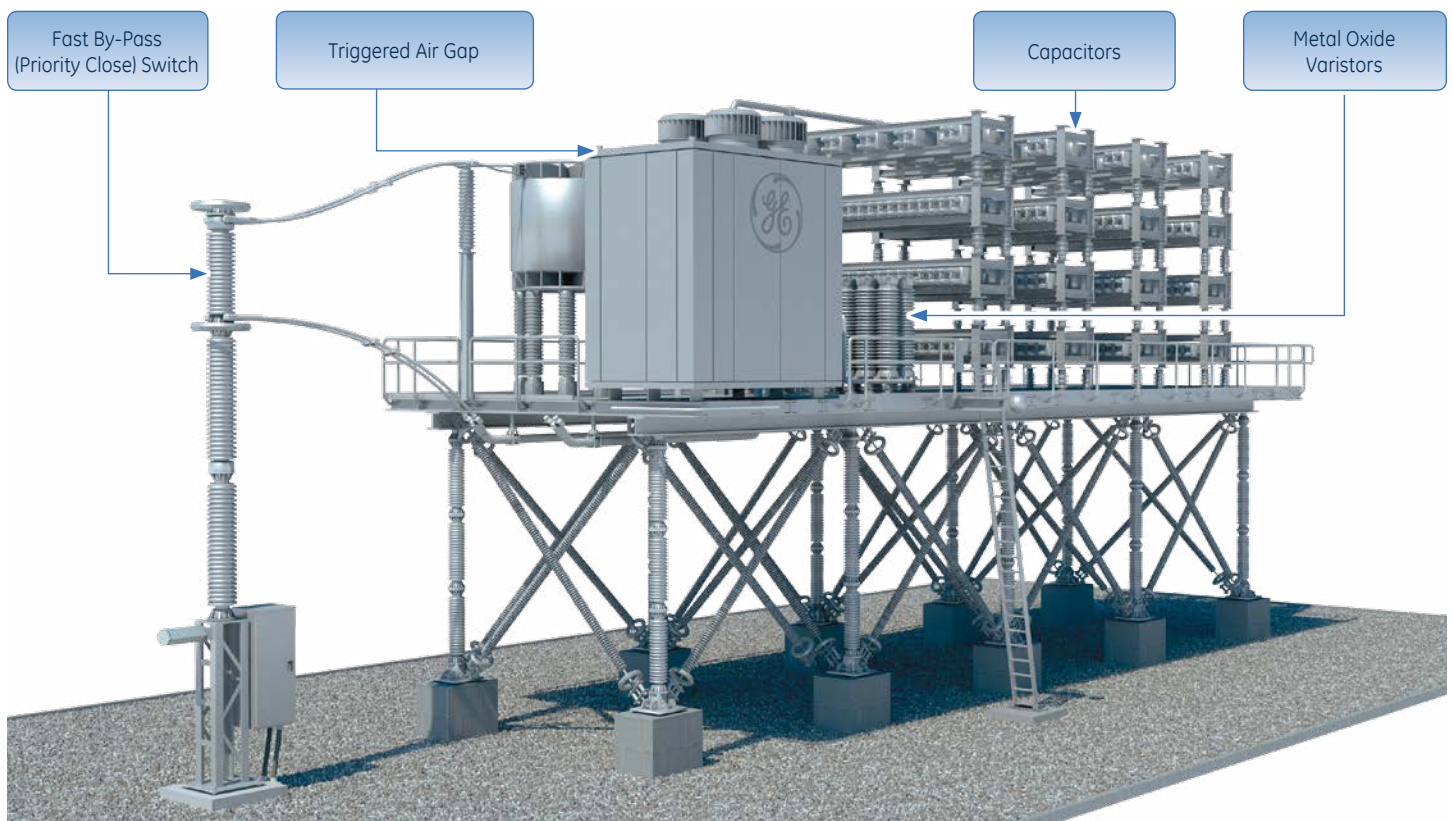
- **Capacitors:** May be fuseless, internally fused or externally fused.
- **Metal Oxide Varistor (MOV):** The MOV is connected in parallel with the capacitors and are used to limit capacitor voltage (the Protective Level Voltage) to protect the capacitors from overvoltage during system faults.
- **Triggered Air Gap (TAG):** If used, the TAG conducts to limit the energy absorbed by the MOV.
- **Discharge Damping Circuit:** Most commonly consists of a reactor only, but may also include non-linear resistors, and is used to limit capacitor discharge current.

- **Fast By-Pass Switch:** This switch closes rapidly to limit both MOV and TAG energy, removing the series capacitors from service. This switch is also used for normal switching to insert the series capacitors or bypass them. External motor operated switches are used to isolate the series capacitor bank.
- **Digital Protection and Control System:** Each three-phase bank is equipped with a fully redundant protection and control system with Human Machine Interface (HMI) and Digital Fault Recorder (DFR) capabilities per project requirements. The protection & control system is a critical component of the fast protective system and also monitors the health of all components.

Key Benefits

- Improves voltage profile and provides voltage support for long HVAC transmission lines by introducing capacitance in the line
- Reduces transmission bottlenecks, increases power flow and improves power system stability by reducing the line impedance
- As power system stability is improved, additional power transfer capability is available during a transient event, when needed the most
- Minimizes land requirements needed for system installation resulting in a lower cost solution
- Lowers environmental impact by eliminating the need for new infrastructure
- Increases short-circuit strength on the receiving end

Components of a Series Capacitor Bank



Series Compensation System Components

GE's Series Compensation System is comprised of industry leading and patented technology, helping customers achieve high reliability and lowest possible losses on their transmission lines. The major components of the Series Compensation System include Capacitors, Metal Oxide Varistors, Triggered Air Gap, and Fast By-Pass Switches.

Capacitors

The capacitors are placed in series on a transmission circuit intended to reduce the overall line impedance and offers improved load division on parallel circuits, system transient and steady state stability and allows for increased power transfer capability.



Metal Oxide Varistor

MOV is the primary device that protects the capacitors from overvoltage by diverting fault current. The MOV are semiconductors that conduct above a specific voltage, known as the Protective Level Voltage. The MOV limits the voltage across the capacitor bank to a safe value for the capacitors. They can handle very high current for short periods of time and protect the capacitors until another bypass path is established.



Modular Arc Commutating Triggered Air Gap

A Modular Arc Commutating Triggered Air Gap (MACTAG) is often used as an intermediate bypass device and is faster than the bypass switch, but not instantaneous like the Metal Oxide Varistor (MOV). GE's patented design uses plasma injection to establish an arc which bypasses the capacitors and MOV until the bypass switch can close. GE's MACTAG is the fastest in the industry (< 0.3 ms) as it does not rely on ground-based controls to initiate a bypass. A MACTAG lowers MOV cost by reducing the required MOV energy absorption.

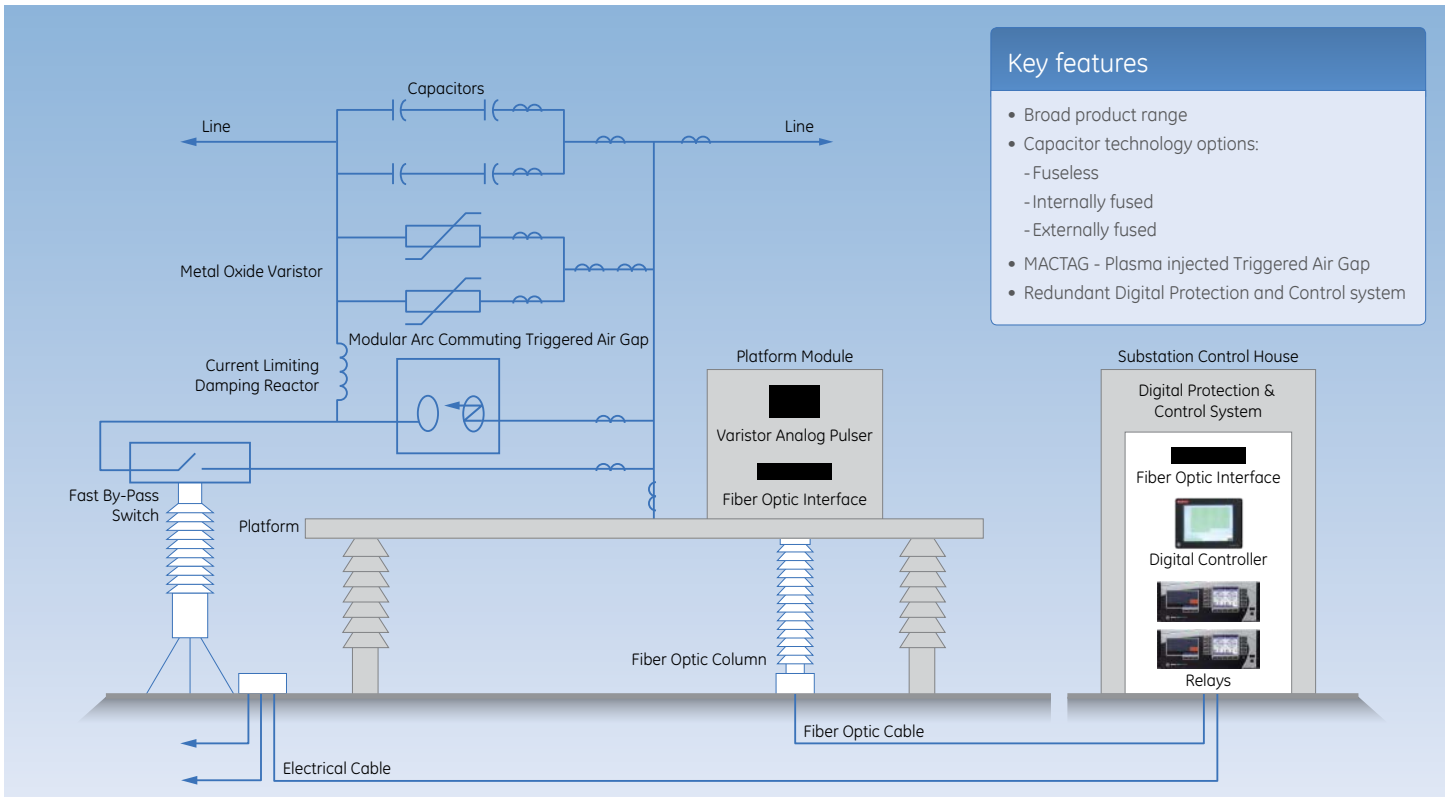


Fast By-Pass (Priority Close) Switch

The Fast By-Pass Switch closes rapidly to limit both MOV and TAG energy, removing the series capacitors from service. This switch is also used for normal switching to insert the series capacitors or bypass them.

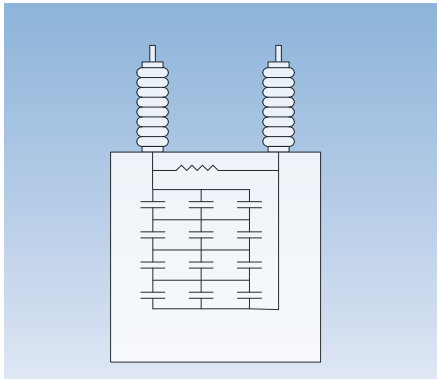


Series Capacitor Bank - One Line Diagram



Series Compensation System Capacitor Options

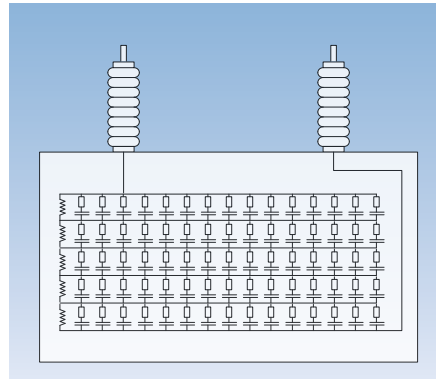
GE's Series Compensation offerings include three capacitor options: fuseless, internally fused or externally fused. GE works with customers to evaluate their requirements and determine the best technical solution to meet the customers needs to ensure a reliable and cost effective system.



Fuseless Design

GE's fuseless design option provides:

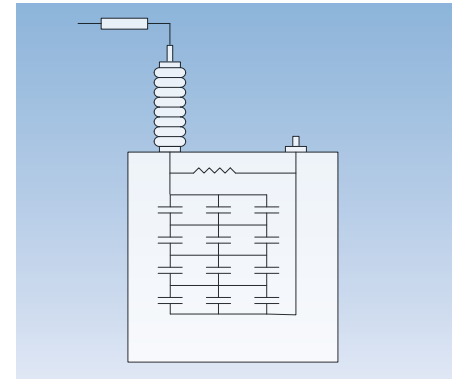
- Lowest losses, typically < 0.12 watts/kvar
- Highest reliability: A lower internal element voltage stress rise for the same number of internal failures in comparison to an internally fused option.
- A higher unbalanced current for the same internal element voltage stress.
- Fault tolerance with continued operation even with failed rolls.



Internally Fused Design

GE's internally fused design provides:

- Losses typically > 0.15 watts/kvar
- One fuse per internal roll. Each roll is protected by an internal fuse element.
- The fuse allows a roll to fail as an open circuit.
- There are multiple rolls in parallel. This places a very small incremental stress on adjacent rolls when a fuse operates. This helps prevent a cascading failure within an individual can.



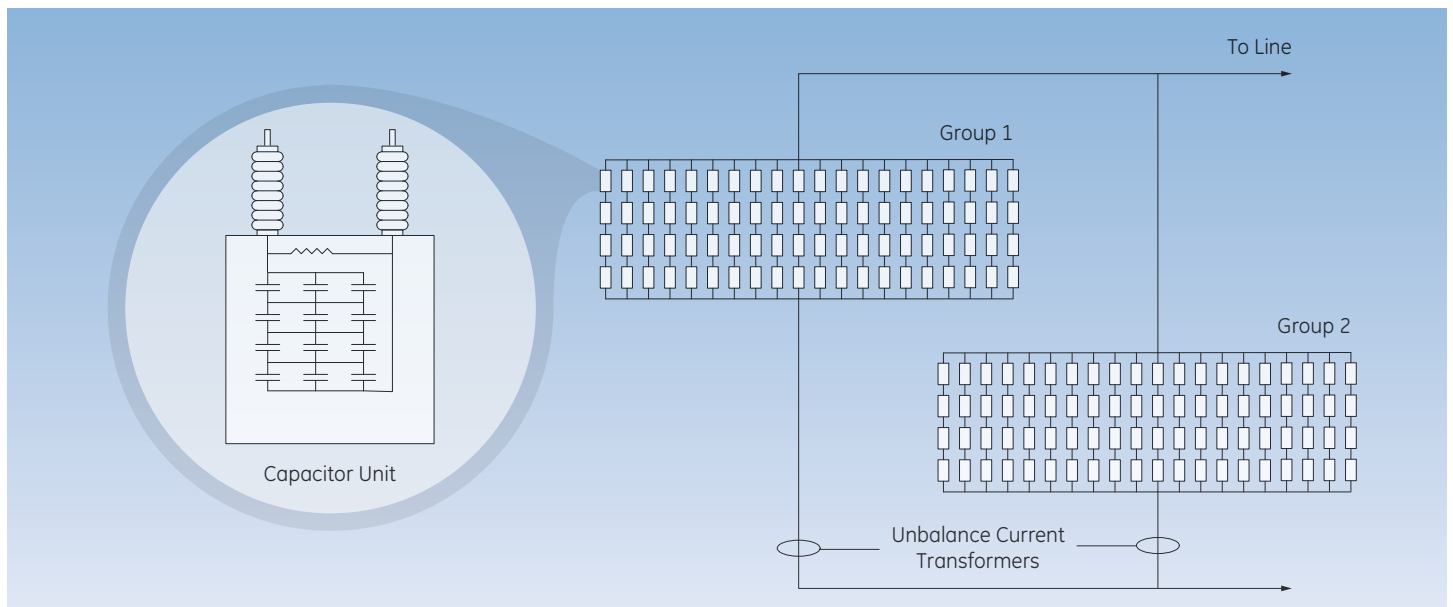
Externally Fused Design

GE 's externally fused design provides:

- One fuse per capacitor unit. Fewer connections mean fewer points of failure.
- Facilitates easy identification of a failed unit as the blown fuse is obvious.
- Once the standard, now limited to specialty applications.

GE's Fuseless Design

GE recommends the fuseless option, which has been the dominant technology since the late 1990's and is proven with a long term field failure rate of less than 0.03% per year. The film foil capacitor is a proven GE design that has been in use since the 1970s. The fuseless design produces the highest unbalance current (easy to detect a failed roll) with the lowest voltage stress on the remaining units (lower chance for a cascading failure). The diagram below depicts the two capacitor groups.



GE's Series Compensation Application Examples

GE's Series Compensation Systems brings together an extensive portfolio of products, services and engineering excellence to deliver the next generation systems for customers based on specific requirements to address both technical and business objectives as well as support several applications. GE provides highly reliable and efficient designs that have low overall maintenance and cost of ownership. Below are just a few of GE's selection of customer applications.

Cross Texas Transmission

- Three Phase Bank Rating: 2 x 716 Mvar
- Substations: Turkey, Texas – Cross Station 1 & 2

Customer Challenge

Maintain voltage stability and efficient operations of the Texas transmission system under minimum and maximum export of wind power.

Customer Application

50% compensation on two transmission lines from Tule Canyon to Tesla required series compensation to reduce the inductive line impedance compiled due to long line length.

Customer Benefit

Ability to maximize amount of wind power to be transferred across the new 345 kV transmission lines.



Electric Transmission Texas, LLC

- Joint venture between subsidiaries of American Electric Power and Berkshire Hathaway Energy
- Edison, Gauss, Kirschhoff, and Orsted Substations

Customer Challenge

Need to provide reliable and efficient power across the new 345kV transmission lines required to maximize the transfer of renewable generation

Must not negatively interact with the existing generation or system – Sub Synchronous Resonance concerns

Customer application

Eight series compensation banks located at four different sites to enable the maximum amount of power transfer capability on new 345kV transmission lines in the CREZ regions throughout Texas

Customer Benefit

Reliable and efficient means to transfer power from renewable generation on the new 345kV transmission lines in the CREZ areas



Electricity of Vietnam

- 18 banks from 2012 - 2016
- 6,588 total Mvar in operation and awarded

Customer Challenge

Improve capacity of the 500kV Vietnam transmission system with a compressed amount of time of less than 12 months to install systems.

Customer Application

Increase in the power transfer capability of existing transmission lines.

Customer Benefits

Increased reliability of existing transmission systems, improved voltage support and power transfer capability and timely delivery of equipment meeting compact schedule requirements.



Bonneville Power Administration (BPA)

- Three Phase Bank Rating: 2 X 675 Mvar
- Substations: Bakeoven 1 & 2

Customer Challenge

Need to provide reliable and efficient power across the 500 kV California-Oregon Intertie. Required to increase the overall power transfer capability across the tie to facilitate the increase in capacity requirements from renewable generation projects being added to the regional system.

Customer Application

To enable the maximum amount of power transfer capability on the California-Oregon 500 kV transmission intertie.

Customer Benefit

Reliable and efficient means to transfer power from renewable generation on the new 500 kV transmission California-Oregon Intertie. GE supported a staged fault test performed by BPA, which demonstrated the capability of the GE Series Capacitor banks to withstand a close-in fault with no damage.



Project Management and Execution

The GE project team represents unsurpassed worldwide power system engineering capabilities, comprehensive system design expertise, and unequalled project management experience. Our strength in each of these areas enables us to deliver a highly reliable solution that will fully meet your power system requirements. With each reactive compensation project GE undertakes, this team is committed to delivering 100% satisfaction.

Expertise

GE's Series Compensation project managers have an average of 24 years experience and access to industry leading project tools and processes to execute projects on-time and on budget. GE's engineering teams have advanced internal design tools that provide customers with the most robust and proven designs to ensure a fully executed system with the highest level of quality and reliability.

GE's Energy Consulting works with customers to understand the overall system and project objectives. Through comprehensive analysis and studies the team develops the optimal, most cost effective technology solution based on customers requirements.

Global Capabilities

GE provides engineering excellence to design and deliver complete Series Compensation projects tailored to each customer's requirements and needs.

Providing dedicated engineering teams that are located in regions around the world, GE's subject matter experts bring a wealth of international experience to every project. Customers benefit from GE's local systems subject matter experts who are able to drive and comply with regional/local requirements ensuring the customers business and technical objectives are met.

Post Installation Service

GE's commitment to customer satisfaction is a primary goal – just because the project is complete, our job is not done. A primary responsibility is continued support of the implemented system throughout its lifecycle.

Offering an extensive network of field engineering locations and service centers around the world, GE is uniquely capable of responding immediately to urgent situations that may arise once the equipment is placed in service. Customers are provided with 24/7 field and application call center support.

Project Process and Key Activities

GE's project management approach follows a well-established set of processes and procedures that have resulted in the highest on-time delivery in the industry.

GE has the people, process and rigor that customers require for the planning and execution of complex projects, including defined processes for the definition, analysis, design, implementation and post service support that is required for successful projects.



Energy Consulting

GE has a dedicated staff of consultants that provide engineering, technical support and expertise to the electrical power industry to support Flexible AC Transmission Systems (FACTS) projects worldwide. Below are details of the support and services GE provides its customers.

Electric Power Industry Support Activities

GE's technical subject matter experts, contribute towards advancements in the electric power industry through supporting the following activities:

- Provide seminars on a wide range of technologies and industry trends via industry forums
- Specialized instruction through its Power Systems & Energy Course (PSEC)
- Participation in standards committees such as IEEE® and IEC®
- Authoring of technical papers that are published and presented at numerous industry conferences
- Innovative technology and product development



Preliminary System Analysis and Solution Definition (Pre-RFP Support)

GE works with customers to understand the overall system and project objectives through comprehensive analysis and studies developing the optimal, most cost effective technology solution. Examples of the types of studies include:

- Load Flow Study
- Transient Stability Study
- Voltage Profile
- Sub Synchronous Resonance (SSR) and Sub Synchronous Control Interaction (SSCI) Screening and Mitigation
- Auto-Reclosing Requirements
- Overload Requirements
- Swing Current Analysis
- Transient Recovery Voltage (TRV) Analysis
- Metal Oxide Varistor (MOV) Sizing Study
- Equipment Sizing (Amps, Ohms, MJ, Mvar)
- Interaction Between Series Capacitors and Line Protection Relays
- Development of Project Specification Document



Final System Design (Post Award)

GE's subject matter experts work seamlessly with customers to finalize the system and equipment design to meet the customer's system requirements. In this stage we:

- Finalize system studies
- Develop protective relays settings,
- Specify control and operation coordination for integration into existing systems
- Finalize equipment design and sizing studies
- Generate equipment specifications



Implementation and Testing

During the project implementation phase, GE is focused on executing on the agreed design with the customer to meet the project requirements. Activities include:

- Integration of new equipment with existing equipment
- Definition of, and participation in, type testing, factory acceptance testing and field testing
- Commissioning support including highly trained field engineer and site technical advisory support.
- On-site and off-site specialized system training



Project Support

GE's commitment to customer satisfaction is a primary goal – just because the project is complete, the job is not. A primary responsibility is continued support of the implemented system throughout its lifecycle. GE provides:

- Incident analysis and troubleshooting support
- System recovery services
- Equipment upgrades and retrofits to meet changing system needs



GE's Series Compensation References

With more than 100 years of experience in delivering innovative solutions for transmission grids, GE has designed, delivered and supports more than 200 Series Compensation systems globally and an impressive 3.6 + million hours without an OSHA recordable incident. In the last three years, GE has provided more than 30,000 Mvar's, leading the industry with several global deployments across multiple applications. Some examples of our global customer experience and installed base is below.

Global Customer Experience



- | | | | |
|---|--|--|--|
| <p>1. San Diego, California, USA
Application: Gapless
Circuit kv: 500
Three-Phase Mvar: 449</p> | <p>6. Various Locations, Turkey
Application: MOV and TAG
Circuit kv: 400
Three-Phase Mvar: 4 x 346 and 1 x 196</p> | <p>11. Melbourne, Victoria, Australia
Application: MOV and TAG
Circuit kv: 330
Three-Phase Mvar: 2 x 186</p> | <p>16. Islamorada, Florida, USA
Application: Gapless
Circuit kv: 138
Three-Phase Mvar: 56</p> |
| <p>2. Bergeronne, Québec, Canada
Application: MOV and TAG
Circuit kv: 735
Three-Phase Mvar: 3 x 303</p> | <p>7. Various Locations, Sweden
Application: MOV and TAG
Circuit kv: 400
Three-Phase Mvar: 421, 1106, 330 and 778</p> | <p>12. Various Locations, Vietnam
Application: MOV and TAG
Circuit kv: 400
Three-Phase Mvar: 10 x 366, 400 and 346</p> | <p>17. Alto Jahuel, Chile
Application: MOV and TAG
Circuit kv: 500
Three-Phase Mvar: 241</p> |
| <p>3. Various Locations, Arizona, USA
Application: MOV and TAG
Circuit kv: 500
Three-Phase Mvar: 835, 2 x 372, 236, 152, 246, 489, 395, 652, 376</p> | <p>8. Luckoff, South Africa
Application: Gapless
Circuit kv: 400
Three-Phase Mvar: 2 x 570 and 1 x 524</p> | <p>13. Various Locations, Northwest, USA
Application : MOV and TAG
Circuit kv: 500
Three-Phase Mvar: 2 x 675, 2 x 474, 2 x 346, 365</p> | <p>18. Samambaia and Itaberá, Brazil
Application: MOV and TAG
Circuit kv: 765 and 500
Three-Phase Mvar: 1242, 272</p> |
| <p>4. Sandskeið, Iceland
Application: Gapless
Circuit kv: 242
Three-Phase Mvar: 29</p> | <p>9. Guangxi, China
Application: MOV and TAG
Circuit kv: 500
Three-Phase Mvar: 1 x 669 and 1 x 542</p> | <p>14. Central Utah, USA
Application: MOV and TAG
Circuit kv: 345
Three-Phase Mvar: 437, 2 x 378, 236</p> | <p>19. Donato Guerra, Mexico
Application: MOV and TAG
Circuit kv: 400
Three-Phase Mvar: 2 x 97 and 1 x 235</p> |
| <p>5. Scotland, UK
Application: MOV and TAG
Circuit kv: 400
Three-Phase Mvar: 2 x 442 and 2 x 560</p> | <p>10. Hezhou, China
Application: MOV and TAG
Circuit kv: 500
Three-Phase Mvar: 390</p> | <p>15. Beaverhead, Montana, USA
Application: Gapless
Circuit kv: 230
Three-Phase Mvar: 117</p> | <p>20. Various Locations, Texas, USA
Application: Gapless
Circuit kv: 345
Three-Phase Mvar: 8 x 933</p> |



For more information about
GE's Series Compensation Systems visit
GEGridSolutions.com/SeriesCompensation



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