MITSUBISHI ELECTRIC
Changes for the Better

WHITE PAPER

GRID FORMING STATCOM

Technology, Validation, and Applications for Next Generation Grid Support

OCTOBER 2026



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1. INTRODUCTION

This white paper presents Mitsubishi Electric's solutions to the evolving application of Grid Forming (GFM) Static Synchronous Compensator (STATCOM) technologies, with Enhanced STATCOM (E-STATCOM) introduced as an evolutionary extension that integrates energy storage to further enhance system support capabilities. The paper discusses the fundamental concepts of GFM control, representative approaches to performance validation, and practical applications of GFM STATCOM and E-STATCOM technologies. It also presents Mitsubishi Electric's implementation philosophy and representative simulation studies demonstrating the performance and capabilities of these technologies.

The electric power system is undergoing one of the most significant transformations in its history. The rapid integration of inverter-based resources (IBRs), increasing electrification, expanding renewable energy deployment, and the emergence of large dynamic loads such as AI data centers are fundamentally changing the way modern power systems are planned and operated. At the same time, the retirement of conventional synchronous generators can reduce system strength, inertia, and other characteristics that have traditionally supported stable grid operation. As a result, power electronic technologies are expected to assume a broader role in maintaining reliable, resilient, and flexible power systems.

Among these technologies, the STATCOM has become one of the most widely deployed Flexible AC Transmission System (FACTS) devices for dynamic voltage regulation and reactive power compensation. Over the past three decades, STATCOM technology has continuously evolved to address increasingly demanding system requirements, including renewable energy integration, transmission capacity enhancement, oscillation damping, power quality improvement, and weak grid support. As the role of power electronics continues to expand, GFM control is an important next step in the evolution of STATCOM technology.

STATCOM

Dynamic Reactive Power
+
Voltage Support

GFM STATCOM

All STATCOM Features
+
Voltage Source Behind Impedance Behavior
+
Enables Renewable Integration in Weak Grids

E-STATCOM

All GFM STATCOM Features
+
Energy Storage
+
Active Power
+
Enhanced Grid Resilience
+
Dynamic Active Power Response

Compared with conventional Grid Following (GFL) control, GFM control enables the STATCOM to enable voltage source behavior and contribute more actively to system stability, addressing changing grid conditions. E-STATCOM technology further extends these capabilities through the integration of energy storage, enabling active power exchange in addition to the dynamic reactive power capability of the conventional STATCOM. This expanded capability creates opportunities for additional grid support functions, including frequency stabilization, transient active power support, synthetic inertia, and mitigation of rapid load fluctuations associated with emerging applications such as AI data centers and future electrified power systems.

GFM technology has attracted significant attention across the power industry, with considerable work underway by utilities, manufacturers, standards organizations, and industry working groups to advance its application and understanding. Existing publications have explored various control implementations, application scenarios, and validation approaches.

2. GFM CONTROL

2.1 What is GFM Control?

The rapid evolution of power electronic technologies has resulted in a wide variety of GFM control implementations being proposed for applications including renewable generation, battery energy storage systems, HVDC transmission, and FACTS devices. While these implementations differ in their internal control structures and operating philosophies, they generally share the objective of enabling power electronic converters to actively contribute to the establishment and support of the AC power system.

From a technology perspective, and the purpose of this white paper, GFM is considered as a control philosophy rather than a specific control algorithm. It describes how a power electronic converter interacts with the surrounding power system, independent of the specific control algorithm implementation used to realize that behavior. Consequently, GFM can be characterized by the electrical behavior observed at the converter terminals rather than by a single control methodology.

A fundamental performance characteristic of GFM control is controllable voltage source behavior behind an impedance. Rather than relying on an externally established voltage and frequency reference for synchronization, the controller maintains an internal voltage reference and interacts with the grid through its terminal impedance. This voltage source behavior enables the converter to naturally exchange active and reactive power in response to changes in network conditions while supporting stable operation of the interconnected power system.

Unlike conventional GFL control, which primarily regulates converter current by tracking an externally measured voltage reference, GFM control establishes its own voltage reference and continuously adjusts its output in response to system conditions. This allows the converter to actively participate in voltage regulation, frequency support, and overall system stability while maintaining coordinated operation with other grid-connected equipment.

From this perspective, GFM control is not defined by a specific grid service or the implementation specified by a manufacturer, but by the voltage source behavior presented at the converter terminals and its interaction with the interconnected power system.

2.2 Fundamental Characteristics of GFM Control

Having established that GFM is a control philosophy defined by its terminal electrical behavior, the next step is to identify the fundamental performance considered in this paper. These characteristics describe how the converter behaves from the perspective of the power system, independent of the internal control architecture or specific application.

Unlike functional capabilities, which may vary depending on converter type and system requirements, the following characteristics represent the essential electrical behavior expected of any GFM controller.

Voltage Source Behavior

A fundamental characteristic of GFM control is its ability to behave as a controllable voltage source behind an impedance. Rather than operating as a controlled current source synchronized to an existing grid voltage, the converter actively establishes and regulates its terminal voltage while exchanging power with the surrounding network through its terminal impedance.

Autonomous Voltage Establishment

A GFM controller maintains an internal voltage reference and continuously regulates its terminal voltage without relying on an externally established voltage source. This enables the converter to actively contribute to voltage regulation and system strength under a wide range of operating conditions.

Inherent System Response

Because the converter behaves as a voltage source, changes in system voltage, phase angle, and network impedance naturally result in corresponding active and reactive power exchange. This inherent electrical response allows the converter to participate in maintaining system stability without relying solely on measurement-based current regulations.

Stable Network Interaction

A GFM controller should maintain stable operation while interacting with synchronous generators, GFL converters, other GFM devices, and varying network conditions. Stable operation should be maintained across a broad range of system strengths and operating scenarios while avoiding adverse control interactions.

Controlled Current Limitation

Although a GFM converter behaves as a voltage source, practical converter equipment remains subject to power electronics and equipment current limitations. Therefore, current limiting should be achieved in a controlled manner such that the GFM functionalities are resumed as soon as the disturbance is cleared.

2.3 GFM STATCOM and E-STATCOM

GFM control is a technology neutral control philosophy that can be applied to a wide range of power electronic converters. While the GFM control philosophy remains common across different applications, the converter topology, energy capability, and system integration determine the specific functions that can be delivered. Within the FACTS family, this philosophy gives rise to two complementary technologies: the **GFM STATCOM** and the **E-STATCOM**.

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GFM STATCOM

A GFM STATCOM applies GFM control to a conventional STATCOM platform, enabling the converter to behave as a controllable voltage source while maintaining the primary function of dynamic reactive power compensation. By actively establishing and regulating terminal voltage, the GFM STATCOM can enhance voltage stability and support system strength across a broad range of operating conditions, including IBRs dominated networks.

Although its primary energy exchange remains reactive power, the GFM operating philosophy fundamentally changes how the STATCOM interacts with the surrounding power system. Rather than following an existing grid voltage, the GFM STATCOM actively participates in voltage establishment and contributes to overall system stability through its voltage source behavior. These functionalities allow the stable operation of STATCOM in extremely weak grid conditions.

The GFM STATCOM considered in this paper is implemented using a conventional Delta-connected Modular Multilevel Converter (MMC) topology.

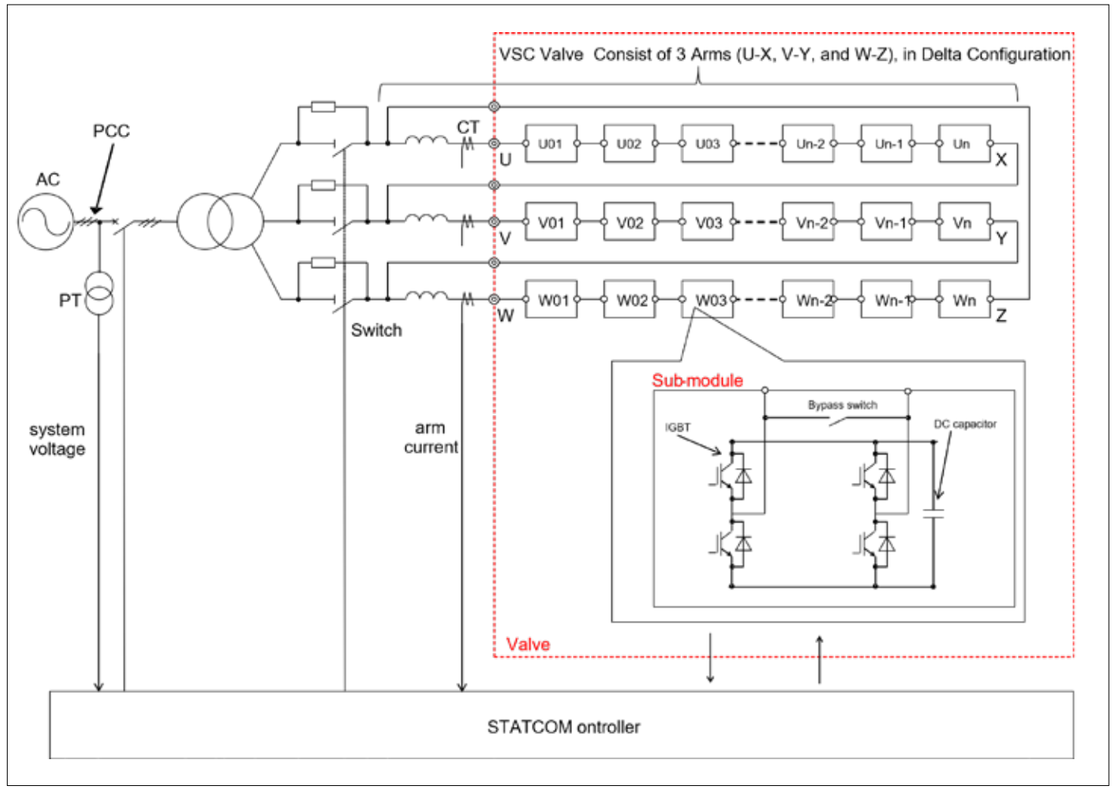


Figure 1: Schematic Diagram of GFM STATCOM

E-STATCOM

The E-STATCOM builds upon the same GFM control philosophy by integrating an energy storage system with the STATCOM platform. This additional energy capability enables controlled active power exchange with the grid while maintaining the fast dynamic reactive power performance of a conventional STATCOM.

By combining reactive and active power support within a single system, the E-STATCOM expands the range of grid support services that can be provided. E-STATCOM can support transient active power injection or absorption, frequency stabilization, synthetic inertia, and mitigation of rapid load fluctuations associated with emerging applications such as AI data centers and future electrified power systems.

To accommodate bidirectional active power exchange, the E-STATCOM considered in this paper is implemented using a Double-Y MMC topology derived from HVDC converter technology.

Although GFM STATCOM and E-STATCOM share the same GFM control philosophy, they differ in converter topology, energy capability, and the range of grid support functions they can provide. **Table 1** summarizes the principal characteristics of the two technologies.

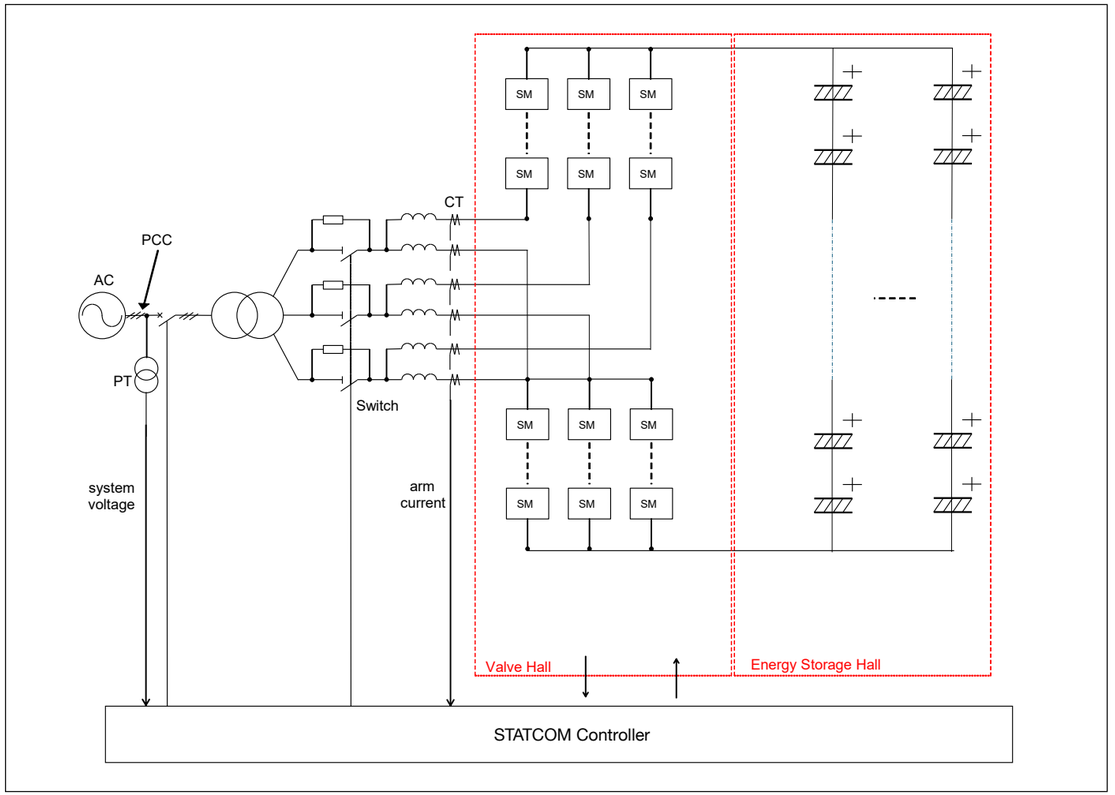


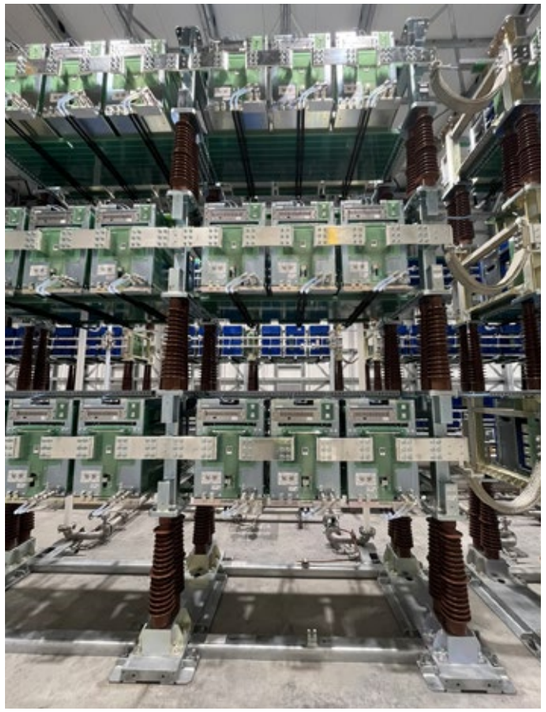
Figure 2: Schematic Diagram of E-STATCOM

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Table 1: COMPARISON OF GFM STATCOM AND E-STATCOM

ASPECT	GRID FORMING STATCOM (GFM STATCOM)	ENHANCED STATCOM (E-STATCOM)
Primary function	Dynamic voltage regulation and reactive power compensation	Dynamic voltage regulation with coordinated reactive and active power support
Reactive power capability	Dynamic reactive power injection and absorption	Dynamic reactive power injection and absorption
Active power capability	Limited by available energy stored in the submodule	Continuous and transient active power exchange through integrated energy storage
Energy storage	Not required	Integrated battery, supercapacitor, or other energy storage technology
Voltage support	Yes	Yes
System strength contribution	Yes	Yes
Frequency stabilization	Not available or limited	Limited frequency support and stabilization
Synthetic inertia	Not available or limited	Supported through active power control
Fast load fluctuation compensation	Reactive power compensation only	Coordinated active and reactive power compensation, achieved with special control
Typical applications	Renewable integration, transmission support, weak or strong grids, voltage stability	AI data centers, renewable integration, industrial electrification, grid resilience, inertia support
Technology evolution	Evolution of conventional STATCOM	Evolution of GFM STATCOM with integrated energy storage





3. VALIDATING GFM PERFORMANCE

As GFM technologies continue to evolve, industry groups are developing technical specifications and validation approaches to characterize expected GFM performance. Publications and specifications from organizations such as EPRI, NREL, UNIFI, and NERC provide important references for GFM functional requirements, while utility and system-operator documents, including the FNN Guideline and TenneT requirements, provide representative test methods and evaluation criteria.

The validation approach considered in this white paper draws upon these emerging industry references while focusing on the functions most relevant to GFM STATCOM applications and Mitsubishi Electric's control implementation. Representative validation scenarios are used to evaluate voltage source behavior, dynamic response during grid disturbances, current limiting performance, operation under varying system strength, and frequency domain characteristics.

The validation matrix below summarizes the principal scenarios considered in this paper. The matrix is intended to provide a structured basis for the performance studies presented in **Chapter 5** rather than to define an exhaustive qualification or compliance test procedure.

Table 2: VALIDATION OF GFM CAPABILITY

VALIDATION SCENARIO	OBJECTIVE	GFM CAPABILITY DEMONSTRATED
Voltage reference step response	Evaluate dynamic voltage regulation and transient performance under different system strengths	Voltage regulation and dynamic stability
System voltage step response	Evaluate reactive power response to changes in system voltage	Dynamic VAR support
Current limiting	Evaluate converter behavior when the current limit is reached during large disturbances	Controlled current limitation and stable GFM operation
Three-phase fault ride-through	Evaluate converter operation and post fault recovery during severe balanced faults	Fault ride-through and dynamic voltage recovery
Unbalanced fault performance	Evaluate positive- and negative-sequence responses during unbalanced faults	Unbalanced fault response and negative-sequence control
Phase-angle jump response	Evaluate transient response to sudden changes in grid phase angle	Inherent active power response and synchronization stability
Frequency disturbance response	Evaluate converter response to system frequency deviations	Grid interaction and frequency support characteristics
Weak grid operation (SCR sweep)	Evaluate stability over a range of system strengths	Stable operation under weak grid conditions
Parallel operation with GFL resources	Evaluate interaction between GFM and conventional GFL resources	GFM/GFL interoperability
Large disturbance recovery	Evaluate post-fault voltage recovery and system stabilization	Dynamic system recovery
Oscillation damping	Evaluate the dynamic response of GFM control to system oscillations	System damping capability
Frequency-domain impedance characterization	Characterize converter impedance	Frequency-domain characteristics and small-signal stability

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4. MITSUBISHI ELECTRIC GFM CONTROL FOR STATCOM

The GFM control for Delta-connected STATCOM is implemented by integrating GFM functionality with the established voltage and current control functions. The control consists of four main components: a Virtual Imepdance Control (VIC), an AC voltage control (AC-AVR), a current reference limiter (Limiter), and an AC output current regulator (AC-ACR) as illustrated in **Figure 3** and **Figure 4**.

The VIC employs a virtual impedance method that emulates, through control, the voltage source behavior behind an internal impedance described in **Chapter 2**. Based on an internal voltage reference and specified virtual impedance, the VIC determines the corresponding active and reactive current components in response to power system conditions.

The AC-AVR retains the established voltage regulation function of the conventional GFL-STATCOMs. It calculates the reactive current reference required to regulate the voltage at the point of connection. In this implementation, the AC-AVR operates in parallel with the VIC, allowing conventional voltage regulation functionality and GFM voltage source behavior to operate within a coordinated control structure.

The combined current reference generated by the VIC and AC-AVR is passed through the current reference limiter to maintain operation within the converter's allowable current capability. The AC-ACR then regulates the converter output current according to the resulting current reference. This architecture allows the GFM functionality to be incorporated while maintaining controlled converter current during both normal operation and system disturbances.

From a control perspective, the parallel VIC and AC-AVR structure can be regarded as two complementary control functions operating within the same converter. From the perspective of the AC-AVR, the equivalent system therefore consists of the external power system in parallel with the equivalent voltage source converter established by the VIC. As the SCR of the external power system decreases, the VIC provides an additional stabilizing contribution, such that the AC-AVR effectively operates against a stronger equivalent system than would be provided by the external power system alone. This can be interpreted as an increase in the effective system strength, or effective SCR, seen by the AC-AVR, thereby improving its stability under weak grid conditions. Furthermore, the current reference limiter and the AC-ACR constrain the converter current during AC system faults, allowing the converter to remain within its allowable operating range and avoid unnecessary converter protection operation during recoverable system disturbances.

In summary, the two key aspects of the proposed control architecture, the parallel configuration of the VIC and the AC-AVR, and the current control structure incorporating the limiter and the AC-ACR enable the GFM STATCOM to maintain stable operation under both steady-state conditions and transient conditions, including grid faults.

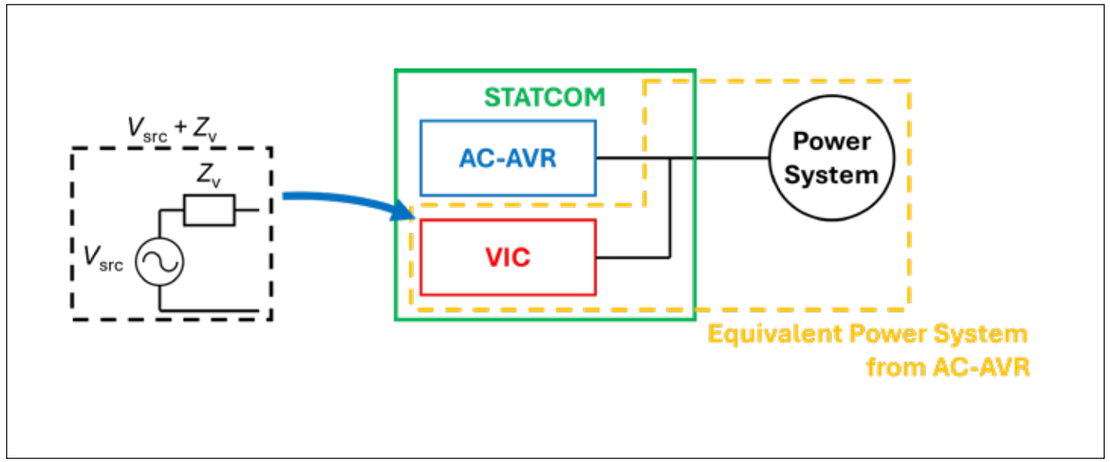


Figure 3: Conceptual Diagram of GFM Control

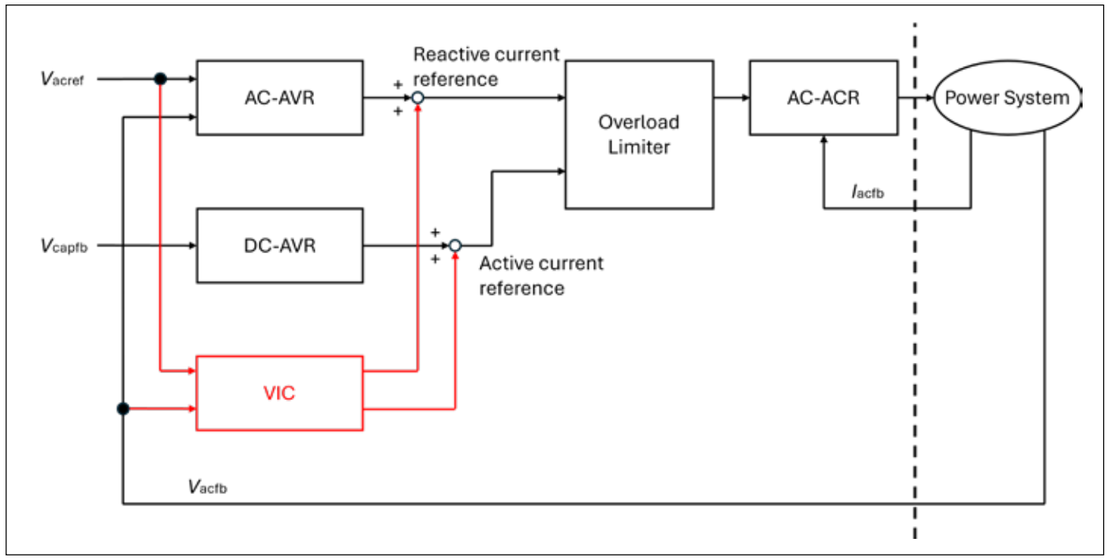


Figure 4: Block Diagram of GFM Control

5. PERFORMANCE VALIDATION

The performance of Mitsubishi Electric's GFM STATCOM control was evaluated through representative simulation studies based on the validation scenarios introduced in **Chapter 3**. The studies compare GFM and conventional GFL operation under a range of system conditions, including strong- and weak-grid conditions, balanced and unbalanced faults, phase-angle and frequency disturbances, and frequency-domain characteristics. The results presented in **Appendix A** demonstrate the principal dynamic characteristics of the proposed GFM control and its interaction with the surrounding power system.

6. SUMMARY AND CONCLUSIONS

The continued growth of inverter-based resources and changing power system characteristics are increasing the need for power electronic equipment to provide enhanced dynamic grid support. GFM control represents an important evolution of STATCOM technology to address these emerging requirements.

Mitsubishi Electric has developed a GFM control approach that combines GFM voltage source behavior with established STATCOM voltage and current control functions. Representative simulation studies demonstrate improved dynamic performance and stable operation across the evaluated conditions, including weak grid operation and major system disturbances.

The implementation and validation results presented in this paper demonstrate the potential of the proposed GFM STATCOM control for future power system applications. Further simulation, hardware-in-the-loop validation, and system-level interaction studies will continue to support the development and practical application of the technology.

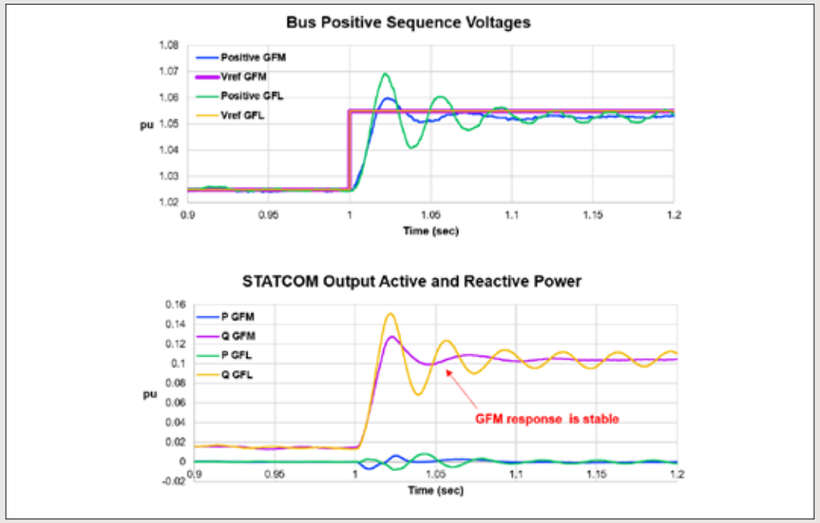


APPENDIX: PERFORMANCE VALIDATION AND STUDY RESULTS

A.1 Voltage Reference Step Response

The voltage reference step response demonstrates the dynamic voltage-regulation performance of the proposed GFM control under different system strengths. Under SCR = 20, the GFM STATCOM exhibits a faster voltage response than the conventional GFL STATCOM. When the system strength is reduced to SCR = 3, stable voltage regulation is maintained, demonstrating the ability of the proposed control architecture to maintain satisfactory dynamic performance under weak grid conditions.

Vref Step = +3% (SCR = 3)



Vref Step = +3% (SCR = 20)

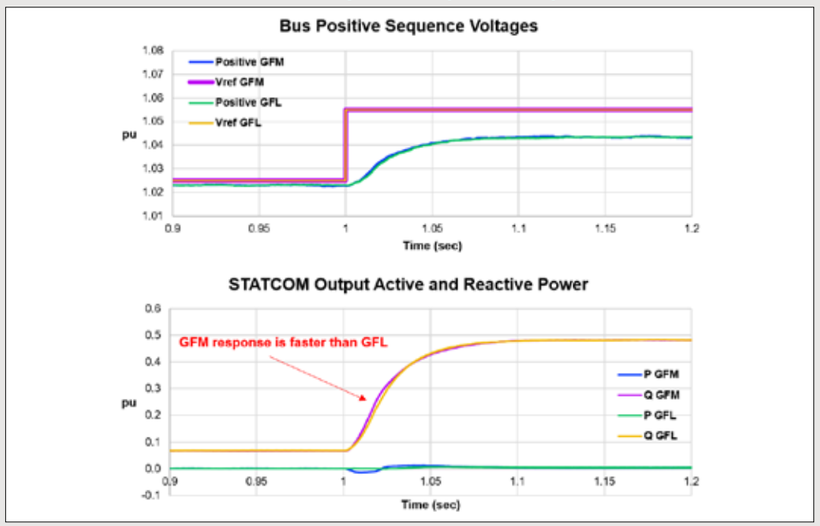
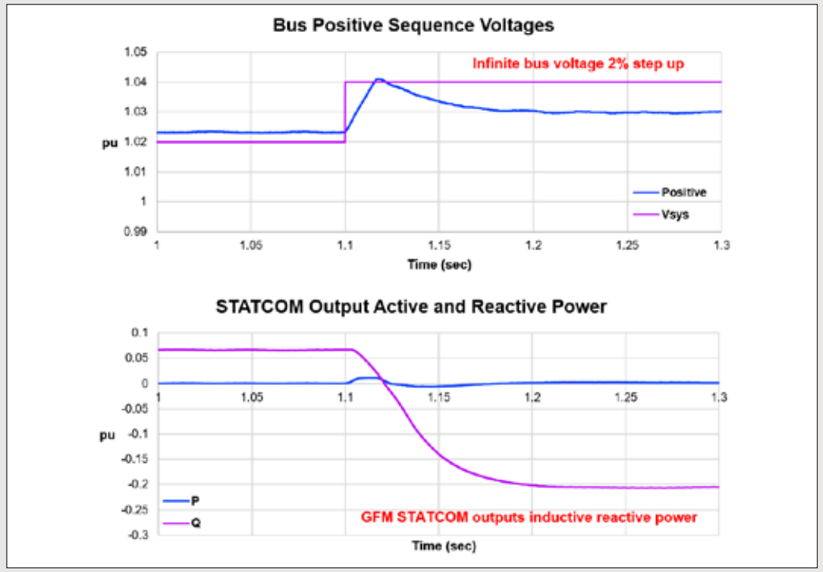


Figure 5: Validation Result of Voltage Reference Step Response

A.2 System Voltage Step Response

Following an increase in system voltage, the GFM STATCOM responds with inductive reactive power, while a decrease in system voltage results in capacitive reactive power output. This response is maintained under both SCR = 20 and SCR = 3 conditions, demonstrating the inherent relationship between terminal voltage and reactive power associated with the GFM voltage source behavior.

Vsys Step = +2% (SCR = 20)



Vsys Step = -2% (SCR = 20)

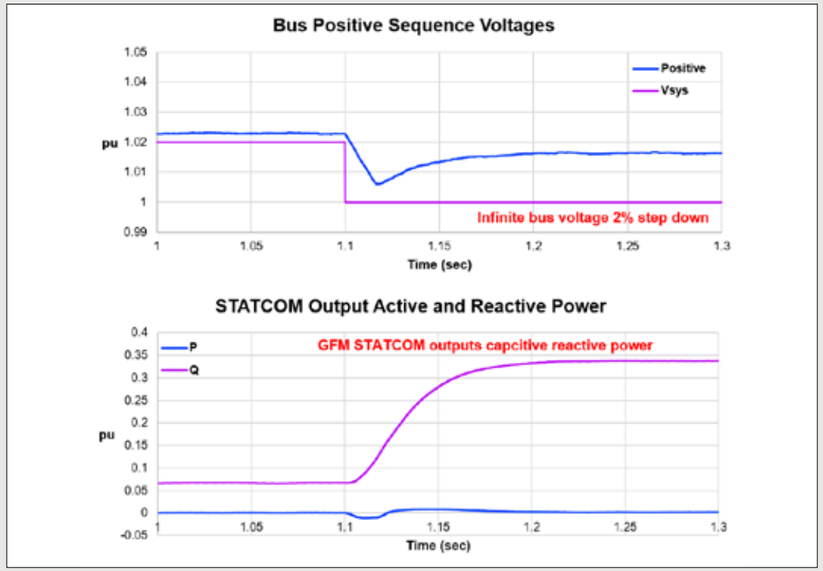
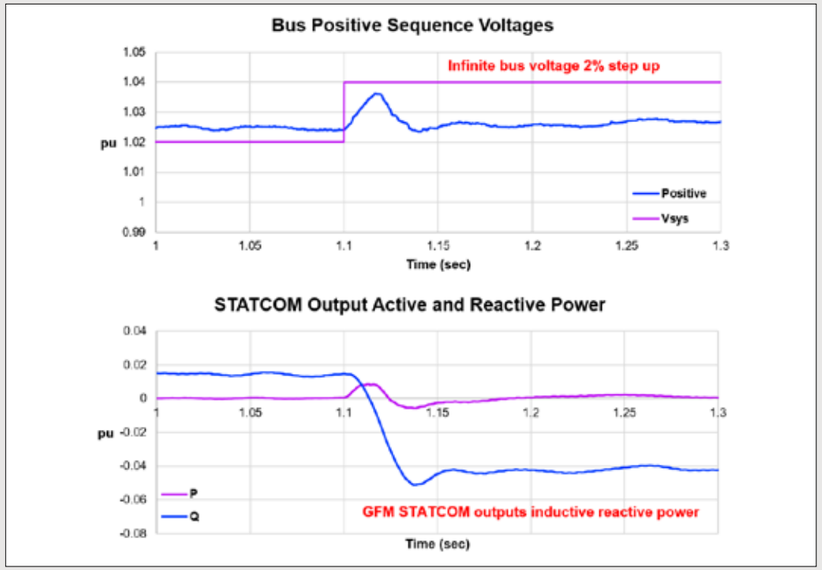


Figure 6: Validation Result of System Voltage Step Response (SCR = 20)

Vsys Step = +2% (SCR = 3)



Vsys Step = -2% (SCR = 3)

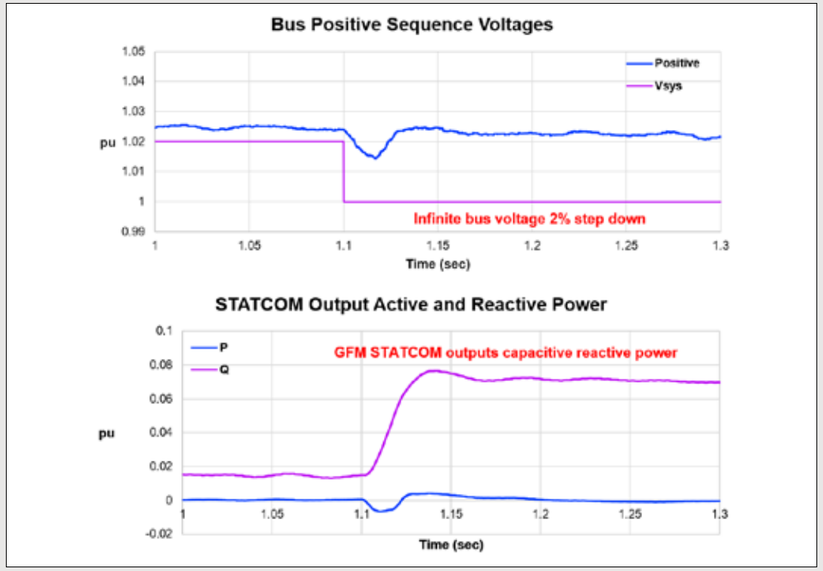


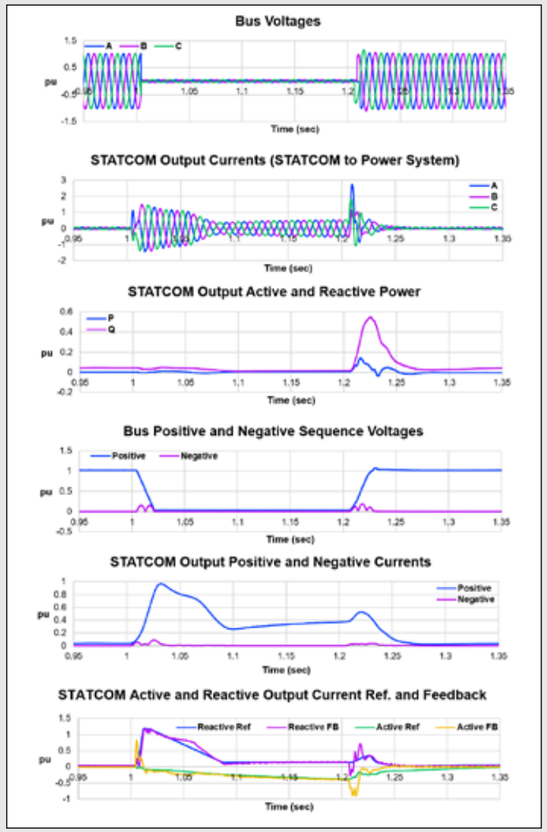
Figure 7: Validation Result of System Voltage Step Response (SCR = 3)

A.3 Three-Phase Fault Ride-Through

Both GFL STATCOM and GFM STATCOM remain in operation during the three-phase fault through the action of the V-I characteristic limiter. However, the GFM STATCOM provides improved post-fault dynamic performance, with reduced system voltage fluctuation following fault clearing. The improvement is observed under both SCR = 10 and SCR = 3 conditions, demonstrating the contribution of the GFM control to system recovery following severe disturbances.

System Fault Type: 3LG, Remaining Voltage = 0.04pu

GFL STATCOM (SCR = 10)



GFM STATCOM (SCR = 10)

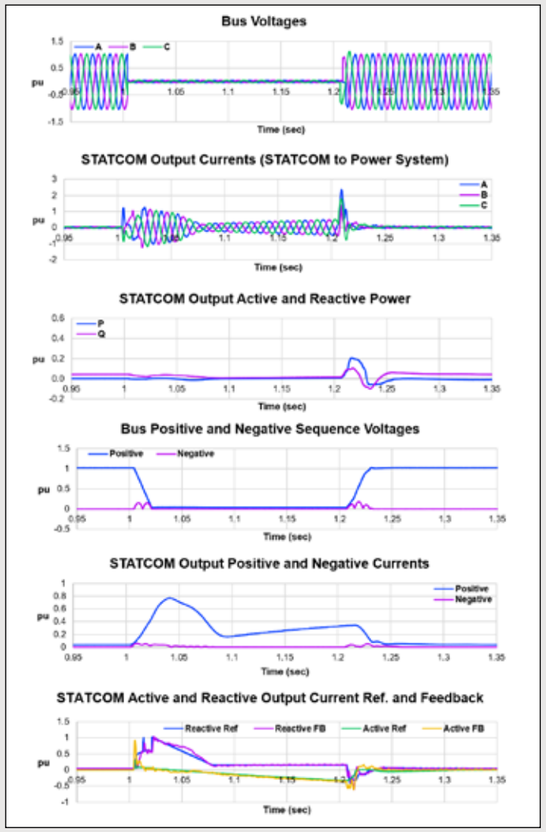
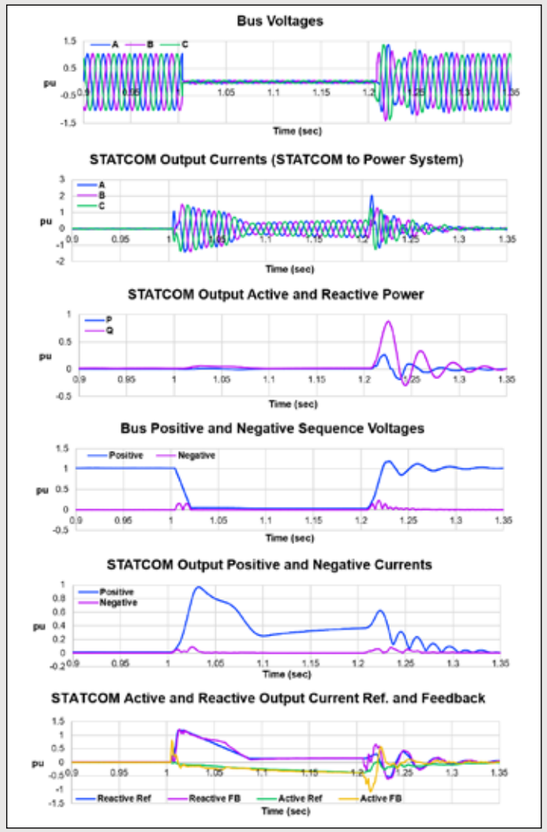


Figure 8: Validation Result of Three-Phase Fault Ride-Through (SCR = 10)

GFL STATCOM (SCR = 3)



GFM STATCOM (SCR = 3)

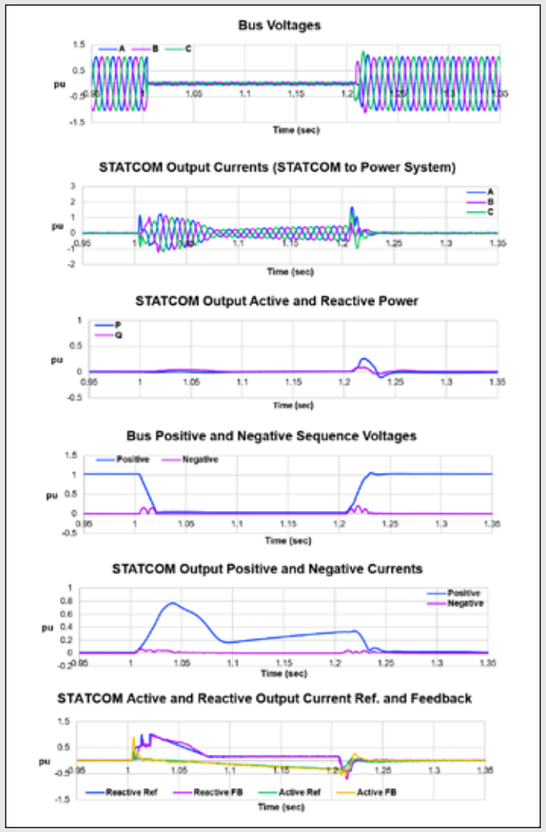


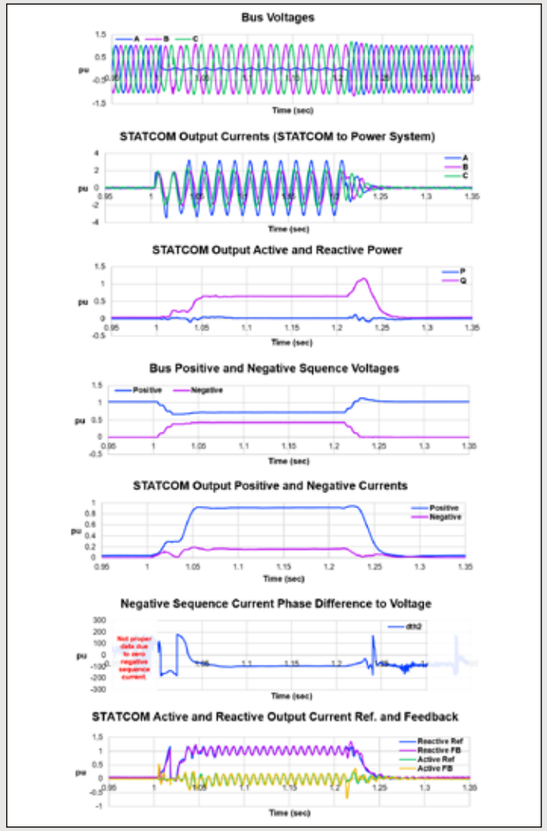
Figure 9: Validation Result of Three-Phase Fault Ride-Through (SCR = 3)

A.4 Unbalanced Fault Performance

During the single-line-to-ground fault (1LG), both control modes maintain converter operation through the positive sequence current-limiting function. The GFM STATCOM additionally produces a controlled leading negative sequence current response, while suppressing post-fault voltage fluctuations compared with conventional GFL operation. The negative sequence response provides an additional degree of control during unbalanced conditions and may support system protection functions that depend on negative sequence quantities.

System Fault Type: 1LG, Remaining Voltage = 0.04pu

GFL STATCOM (SCR = 10)



GFM STATCOM (SCR = 10)

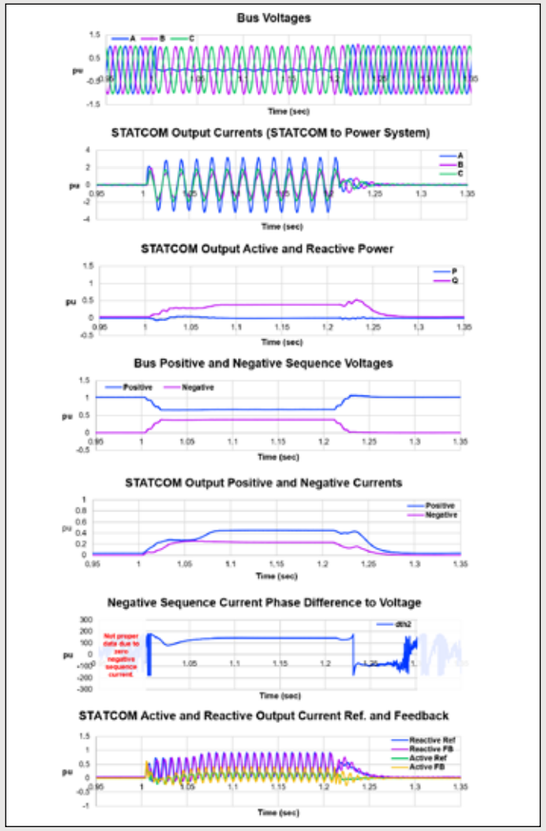
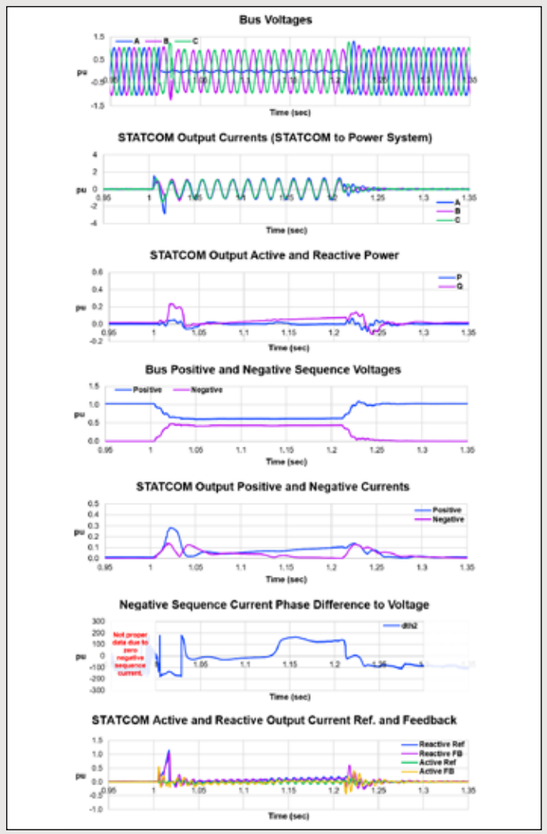


Figure 10: Validation Result of Unbalanced Fault Performance (SCR = 10)

GFL STATCOM (SCR = 3)



GFM STATCOM (SCR = 3)

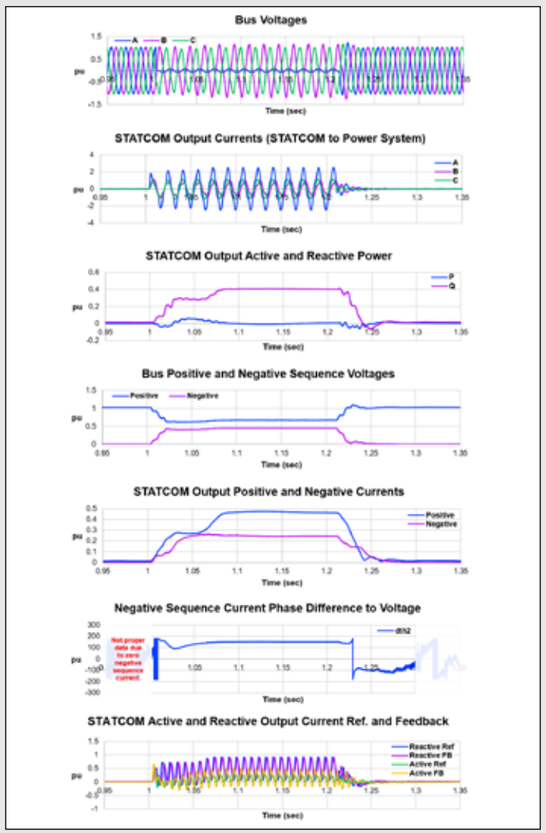
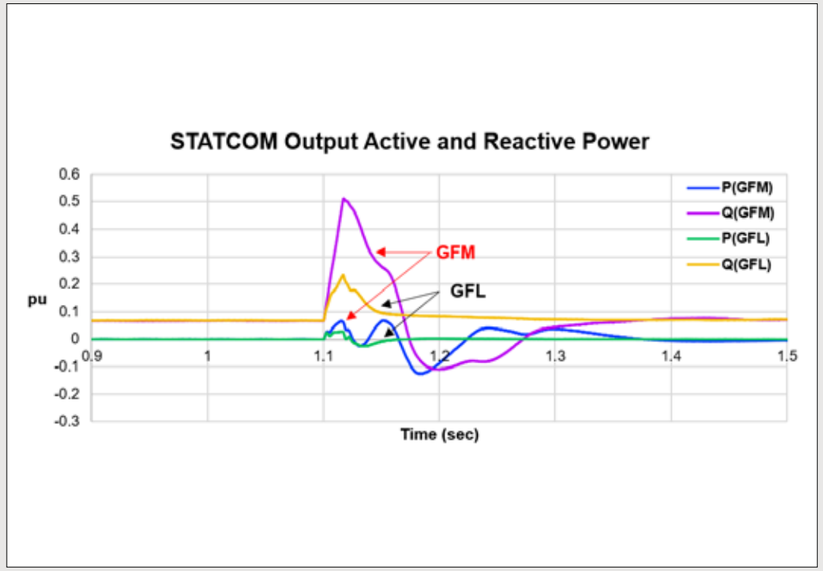


Figure 11: Validation Result of Unbalanced Fault Performance (SCR = 3)

A.5 Phase-Angle Jump Response

The phase-angle jump produces an immediate active power response from the GFM STATCOM demonstrating its voltage source behavior. Depending on the direction of the phase-angle change, the converter transiently absorbs or supplies active power using energy available within the converter. Compared with conventional GFL operation, the GFM control produces a stronger transient active power response under the evaluated conditions

Jump Angle = +30deg (SCR = 20)



Jump Angle = –30deg (SCR = 20)

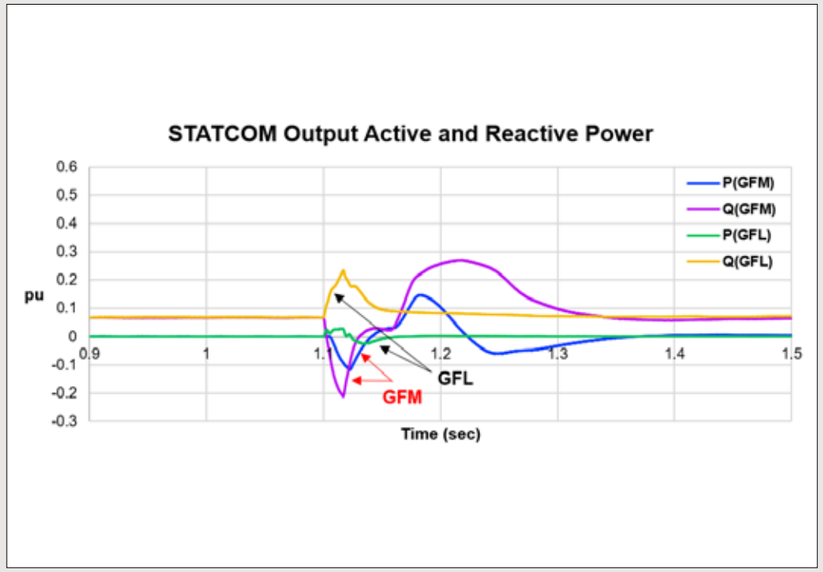
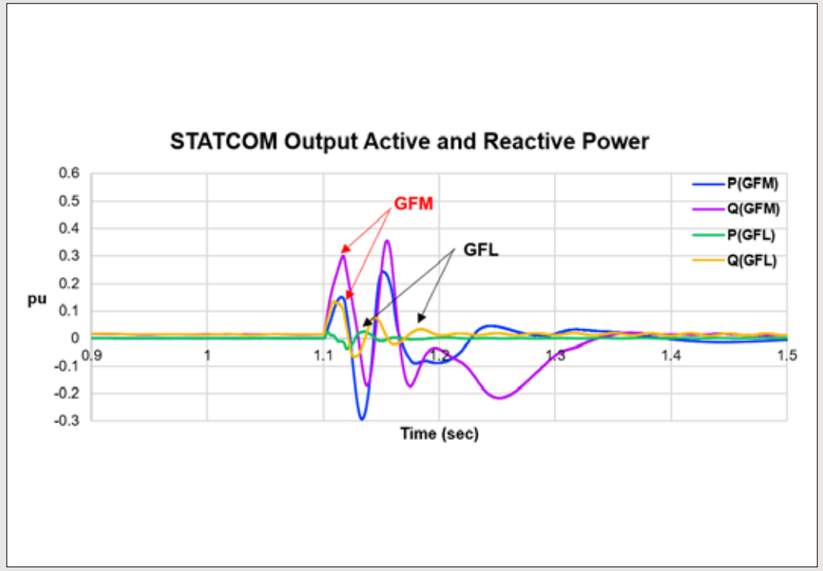


Figure 12: Validation Result of Phase-Angle Jump Response (SCR = 20)

Jump Angle = +30deg (SCR = 3))



Jump Angle = –30deg (SCR = 3)

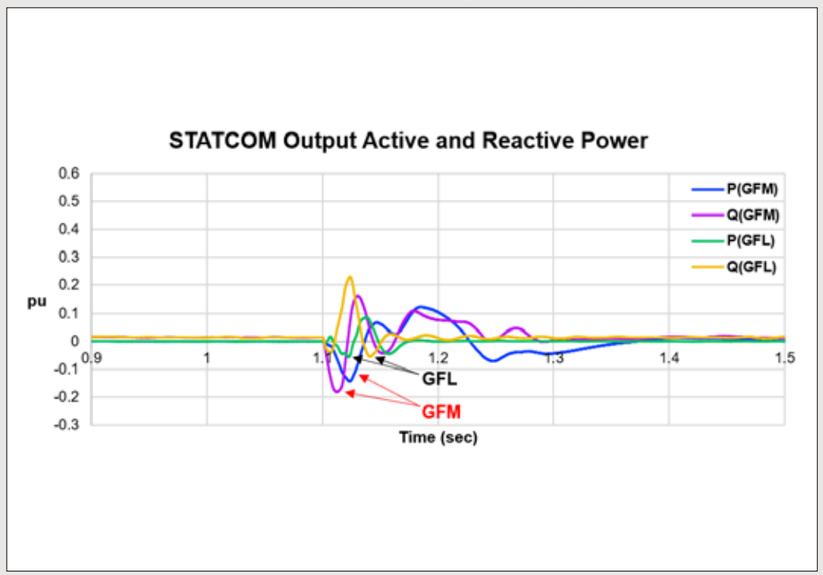
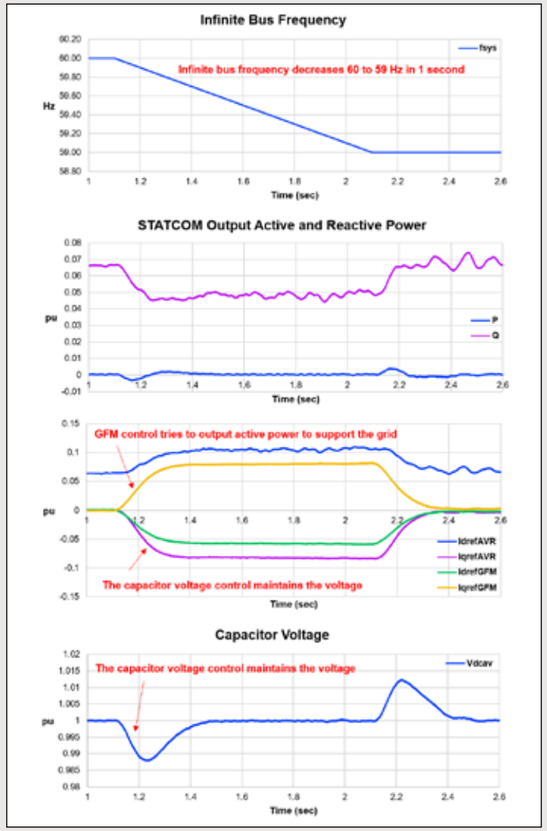


Figure 13: Validation Result of Phase-Angle Jump Response (SCR = 3)

A.6 Frequency Disturbance Response

During a system frequency decrease of 1 Hz/s, the GFM STATCOM exhibits a transient active power response in the direction of supporting the system frequency. This behavior is observed under both SCR = 20 and SCR = 3 conditions and reflects the inherent dynamic response associated with the GFM voltage source characteristic.

Infinite bus frequency decreases 1 Hz/s (SCR = 20)



Infinite bus frequency decreases 1 Hz/s (SCR = 3)

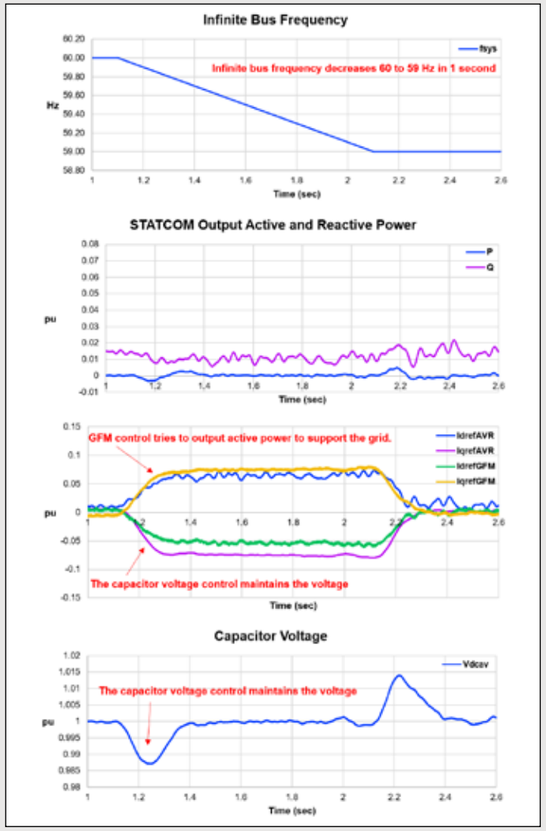


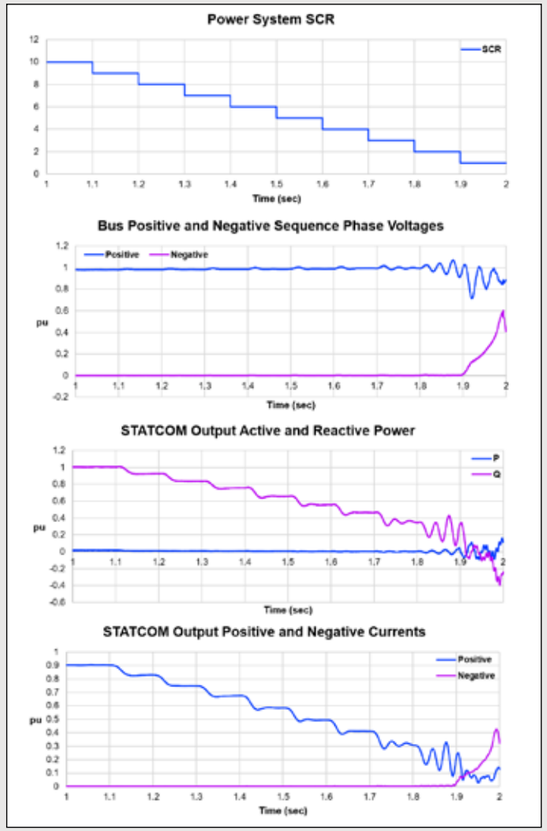
Figure 14: Validation Result of Frequency Disturbance Response

A.7 Weak Grid Operation

The system SCR was progressively reduced from 10 to 1 to evaluate control stability as system strength decreased. Under the evaluated conditions, the conventional GFL control becomes unstable as the SCR is reduced <3, whereas the proposed GFM control maintains stable operation throughout the evaluated SCR range. This result supports the stabilizing effect of the parallel VIC and AC-AVR architecture described in **Chapter 4**.

Validation Conditions: SCR = 10 ⟶ 1 (Step range = 1)

GFL STATCOM



GFM STATCOM

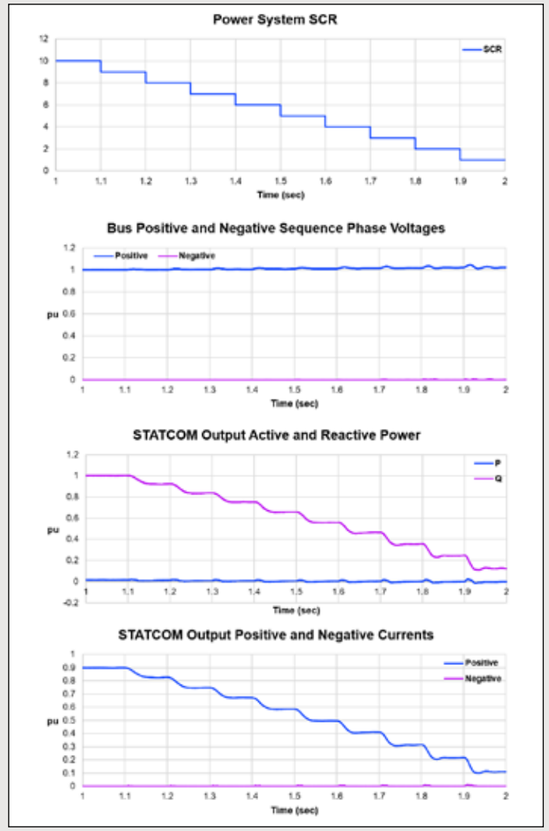


Figure 15: Validation Result of Weak Grid Operation

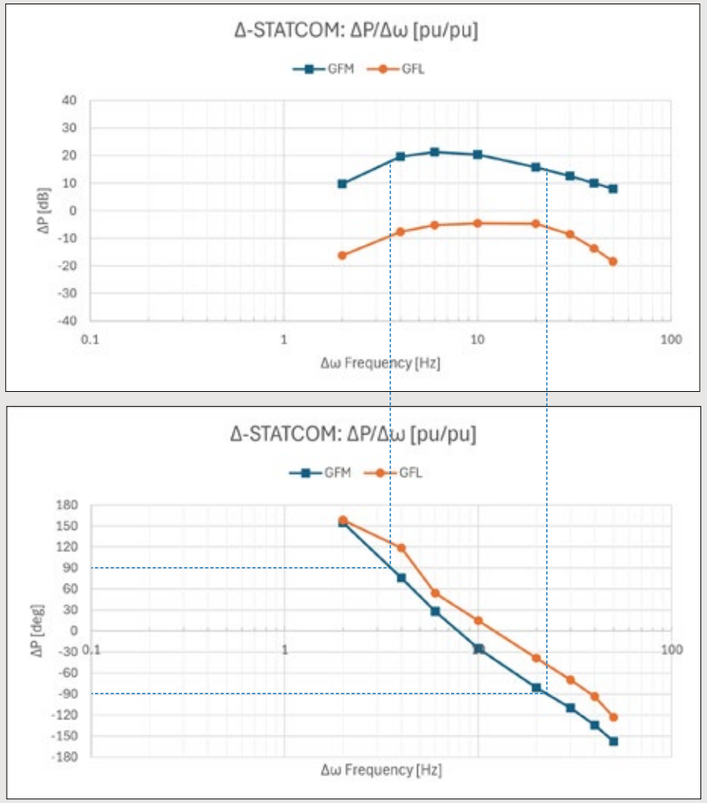
A.8 Oscillation Damping and Frequency-Domain Impedance Characterization

For power oscillation damping analysis, the transfer function from frequency deviation to active power deviation, ΔP/Δf, can be used to evaluate the damping characteristics of the STATCOM and support the design of subsynchronous damping control (SSDC). A positive real component of the transfer function indicates that the STATCOM can provide a damping contribution to the corresponding power oscillation.

Figure 16 (bottom graph) compares the frequency characteristics of the GFM and GFL controls. Within the frequency range where the phase remains between –90° and +90°, corresponding to a positive real component, the gain of the GFM control is approximately 20 dB higher than that of the GFL control. The results therefore indicate a stronger potential damping contribution from the GFM STATCOM over the evaluated frequency range.

GFM has a higher ΔP/Δω gain than GFL, resulting in greater damping.

Amplitude Frequency Characteristic



Phase Frequency Characteristic

Figure 16: Validation Result of Oscillation Damping and Frequency-Domain Impedance Characterization

A.9 Frequency Characteristics of ΔP/ΔΘ

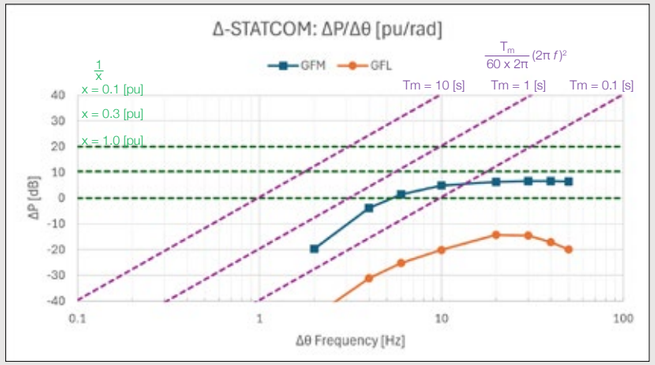
The transfer function from voltage phase angle deviation to active power deviation, ΔP/Δθ, provides additional insight into the dynamic characteristics of GFM control. In the subsynchronous frequency range, an ideal voltage source behind a reactance exhibits an approximately flat gain characteristic determined by the equivalent reactance. For a synchronous generator, the influence of the inertia time constant can also be represented in the low-frequency characteristics of this transfer function, providing a useful reference for comparison with converter-based GFM control.

Furthermore, the inertia characteristics of synchronous generators can be evaluated from the low-frequency response by considering the corresponding 40 dB/dec asymptotic characteristics, where a higher inertia time constant results in the characteristic extending over a wider frequency range. From this perspective, a higher gain maintained over a wider frequency range indicates a stronger inertia like response and provides a useful measure for comparing GFM control performance.

As shown in **Figure 17**, the GFM STATCOM exhibits a broader high-gain characteristic and approximately 20 dB higher gain than the GFL STATCOM over the evaluated frequency range. The GFM response therefore more closely approaches the characteristics associated with a voltage source and synchronous generation than the conventional GFL response. Although the STATCOM has only limited internally stored energy, the evaluated frequency characteristics correspond to an equivalent inertia time constant greater than 0.1 s under the studied conditions.

GFM has higher gain than GFL across the entire frequency range.

Amplitude Frequency Characteristic



Phase Frequency Characteristic

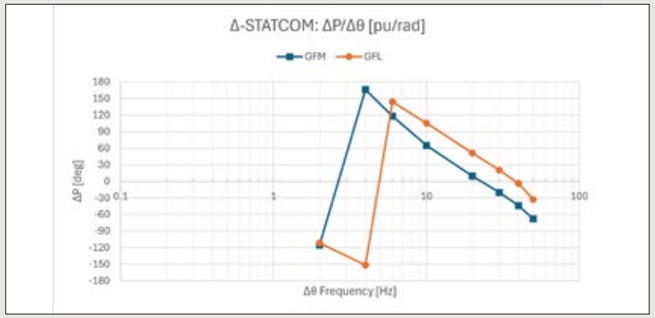


Figure 17: Validation Result of Frequency Characteristics of ΔP/ΔΘ

Authors:
Zhibo Wang, Tomonari Tsurumi, Alyssa Jenkins,
Kaho Nada, Jun Asai, Shinnosuke Yoneda,
Andrew Bailey, Adam Sapracino, and Samantha Deeney



Mitsubishi Electric Corporation
Tokyo Building, 2-7-3, Marunouchi, Chiyoda-ku,
Tokyo 100-8310, Japan

Mitsubishi Electric Power Products, Inc.
Corporate Headquarters, Thorn Hill Industrial Park, 530 Keystone Drive
Warrendale, PA 15086

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Publication No. SSD-WP-0001
October 2026