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FEATURE

UPGRADED CONTROL STRATEGIES TO SAFEGUARD RESILIENCY IN HYBRID AC-DC NETWORKS

A Focused Overview of the State of the Art

Monika Sharma, Jose Luis Rueda-Torres, Juan-Carlos Gonzalez, Ying Pang, Sophie Coffey, and Antoine Knockaert



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THE GLOBAL TRANSITION TO RENEW- able energy is transforming power systems, necessitating advanced transmission solutions to ensure reliability and resilience. High-voltage direct current (HVdc) systems, particularly multiterminal dc (MTdc) networks, are pivotal in integrating diverse renewable energy sources into hybrid ac/dc networks. These systems facilitate efficient power transfer over long distances and enable dynamic energy sharing across regions. However, the increasing penetration of inverter-based resources introduces complex control challenges that must be addressed to maintain grid stability and resilience.

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Introduction: Powering Resilience With Control

According to IEC TS 63291-1:2023, resilience in power systems is the ability to anticipate, withstand, and recover from disturbances through proactive and reactive measures. Control strategies

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for MTdc networks are categorized into core functions, which operate locally within converters using real-time data, and supplementary functions, which coordinate across the grid to enhance system-wide performance. This article offers a focused overview of state-of-the-art MTdc control strategies, highlights operational projects, discusses station coordination, and presents practical challenges with industry-vetted solutions, delivering actionable insights for engineers navigating renewable-rich power systems. The core contribution is to synthesize MTdc control strategies with real-world applications to guide engineers in enhancing hybrid ac/dc network resilience.

Hybrid ac/dc Network and MTdc Control

Hybrid ac/dc networks integrate ac and dc transmission to support the proliferation of renewable energy sources, such as wind and solar. MTdc networks, integral to hybrid ac/dc networks, enable flexible power flow and resilience by leveraging advanced control mechanisms. Key synchronization and control mechanisms include the following:

- ✔ *DC voltage droop (DVD) control*: DVD control regulates power sharing in MTdc networks by adjusting converter outputs based on dc voltage deviations, governed by a droop gain (K_p). Higher (K_p) values enhance responsiveness but may compromise stability in large networks.
- ✔ *Grid-following (GFL) control*: GFL converters use phase-locked loops to synchronize with ac grid voltage, delivering precise current control for wind, solar, and HVdc networks.
- ✔ *Grid-forming (GFM) control*: GFM converters emulate synchronous generators, acting as voltage sources to provide virtual inertia and stabilize frequency, using techniques like virtual synchronous machines (VSMs).

These control strategies form the backbone of MTdc networks, but their integration requires careful coordination to balance stability, power sharing, and inertia provision.

The increasing penetration of inverter-based resources introduces complex control challenges that must be addressed to maintain grid stability and resilience.

Real-World MTdc Projects and Industry Engagement

MTDC networks are deployed globally to support renewable integration and cross-regional power exchange. Key projects include the following:

- ✔ *INELFE (France-Spain)*: This HVdc link uses ac line emulation to mitigate ac grid congestion, demonstrating coordinated control across two terminals.
- ✔ *North Sea Wind Power Hub (Europe)*: This is a proposed MTdc network integrating offshore wind farms across multiple countries, relying on advanced control for stability and power sharing.
- ✔ *Zhangbei MTDC (China)*: This is a four-terminal MTdc network integrating wind and solar, utilizing DVD control and frequency support to enhance grid reliability.

Industry leaders such as Siemens, ABB, and GE are actively involved in such projects, developing and deploying MTdc control solutions. These firms collaborate with standards bodies (e.g., ENTSO-E) and research organizations (e.g., EPRI) to address challenges in stability, inertia, and power quality issues, ensuring alignment with industry needs.

State-of-the-Art MTdc Control Strategies

Advanced control strategies empower MTdc networks to ensure resilience and stability in hybrid ac/dc networks. Core control mechanisms include the following:

- ✔ *DVD with GFM integration*: Combining DVD with GFM control enables power sharing and virtual inertia provision, as shown in Figure 1. For example, GFM converters

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The core contribution is to synthesize MTdc control strategies with real-world applications to guide engineers in enhancing hybrid ac/dc network resilience.

paired with dc energy storage can emulate synchronous generator behavior, enhancing ac grid stability.

- ✔ *Phase compensator (PCom)*: PCom mitigates phase lag in GFM active power control at 1–5 Hz, improving stability under steep droop gains. It ensures robust operation in weak ac grids with low short circuit ratios (SCRs).
- ✔ *Virtual power system stabilizer (VPSS)*: VPSS counteracts negative resistance effects introduced by PCom at 10–100 Hz, preventing resonances in dc networks and stabilizing ac voltage and power flow.

Supplementary control functions, as defined in IEC TS 63291-1:2023, enhance MTdc performance as follows:

- ✔ *Low-frequency power oscillation damping (POD)*: POD controllers modulate active (POD-P) or reactive (POD-Q) power to dampen oscillations (0.1–1 Hz). Coordinated POD across MTdc converters minimizes oscillation propagation.
- ✔ *ac line emulation*: Using angle difference control, MTdc systems mimic ac network behavior, adjusting power set points based on voltage angle differences to prevent ac line overloading.
- ✔ *Frequency control*: Fast frequency response and frequency containment reserve adjust active power references via droop-based methods, stabilizing interconnected ac networks.

These strategies are implemented using hierarchical control structures, with local converters executing core functions and supervisory systems coordinating supplementary functions via communication channels.

Coordination of MTdc Stations

Effective coordination of MTdc stations is critical for system-wide stability. The "*channel-based control*" approach, as illustrated in Figure 2, ensures balanced power modulation.

- ✔ *Channel concept*: For $\mathbf{m}$ dispatchable stations, $\mathbf{m}(\mathbf{m}-\mathbf{1})/2$ channels enable pairwise power modulation. For example, if station $\boldsymbol{i}$ modulates power by $\triangle \boldsymbol{P_{ij}}$, station $\boldsymbol{j}$ counter-modulates by $(-\triangle \boldsymbol{P_{ij}})$, maintaining net-zero active power impact on dc voltage.
- ✔ *Communication*: Real-time data exchange of voltage angles and frequencies enables precise coordination, ensuring stability during disturbances. Moreover, communication delays exceeding 100 ms can degrade performance, causing phase misalignment in POD and oscillation amplification, mitigated by local fallback modes to GFL or constant power control.
- ✔ *Control layer*: A supervisory control layer in Figure 3 illustrates the possible communication channels. In a four-station network, six channels (denoted as Ch_{ij}) link dispatchable units. Each station feeds voltage angles and frequencies to the control

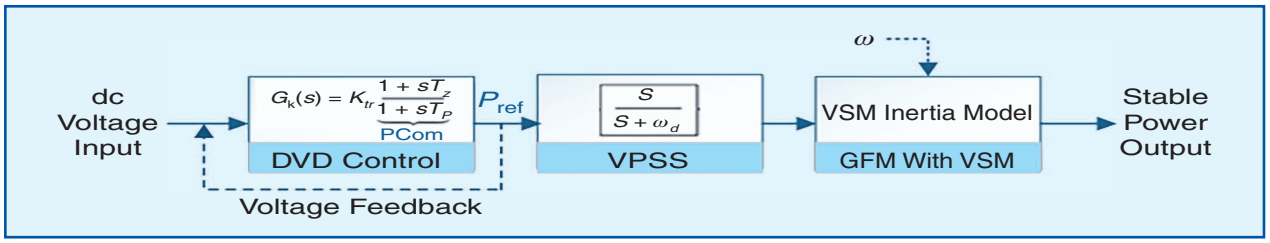


Figure 1. The control architecture for enhanced stability.

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layer, which fires back tailored active power modulations.

This coordination strategy, including POD, is exemplified in projects like INELFE, ensuring stable power exchange between France and Spain.

Practical Challenges in MTdc Control

MTDC networks face several real-world technical challenges.

1) *Low-frequency harmonic instability*: Integrating GFM with aggressive DVD gains can trigger instability at 1–5 Hz due to phase shifts in VSM low-pass filters and interactions with dc voltage regulation, as shown in Figure 4. These instabilities, including harmonic and small-signal stability issues, are pronounced in weak ac grids with low SCRs. Solutions like PCom and VPSS are discussed in the "Industry-Vetted Solutions" section.
2) *Inertia provision limitations*: Combining dc voltage control (DVC) with GFM undermines virtual inertia as DVC dynamics reduce the inertia constant, leading to oscillatory responses during frequency disturbances. For example, in a test setup, Station 2 uses a PI controller to manage dc voltage, while Stations 1 and 3 operate in constant vpower mode. Engineers tested Grid 2's frequency with two signals: a steady frequency change (rate of change of frequency) of 0.5 or 1 Hz/s and a sinusoidal variation, $\Delta f(t) = \sin(0.2\pi t)$. Figure 5 shows that with a steady rate of change of frequency, Station 2's power response (DVC PI) drops to zero after some initial swings, unlike the steady response from a dc battery, meaning that it provides no lasting inertia.
3) *Unbalanced bipole configurations*: Pole outages in bipole MTdc networks require rapid

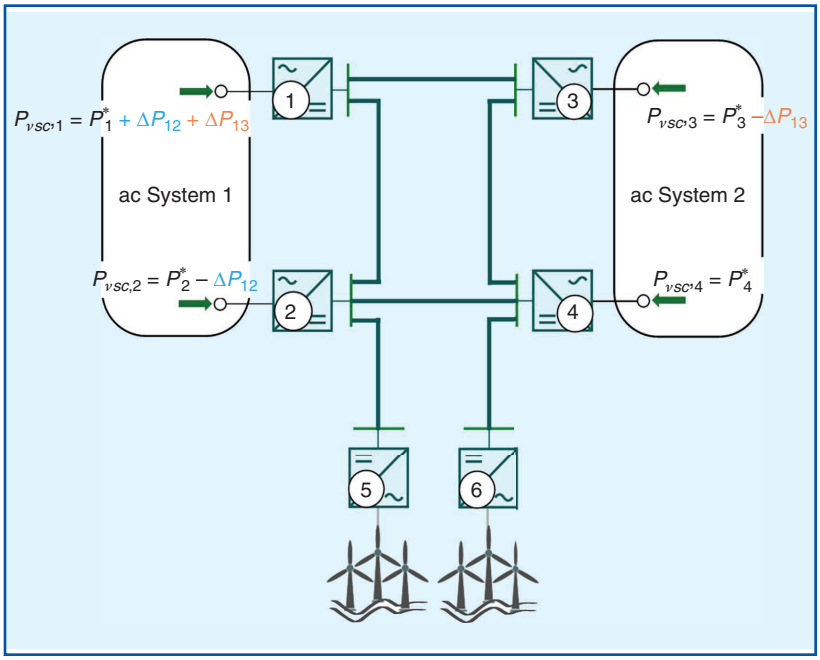


Figure 2. The channel concept.

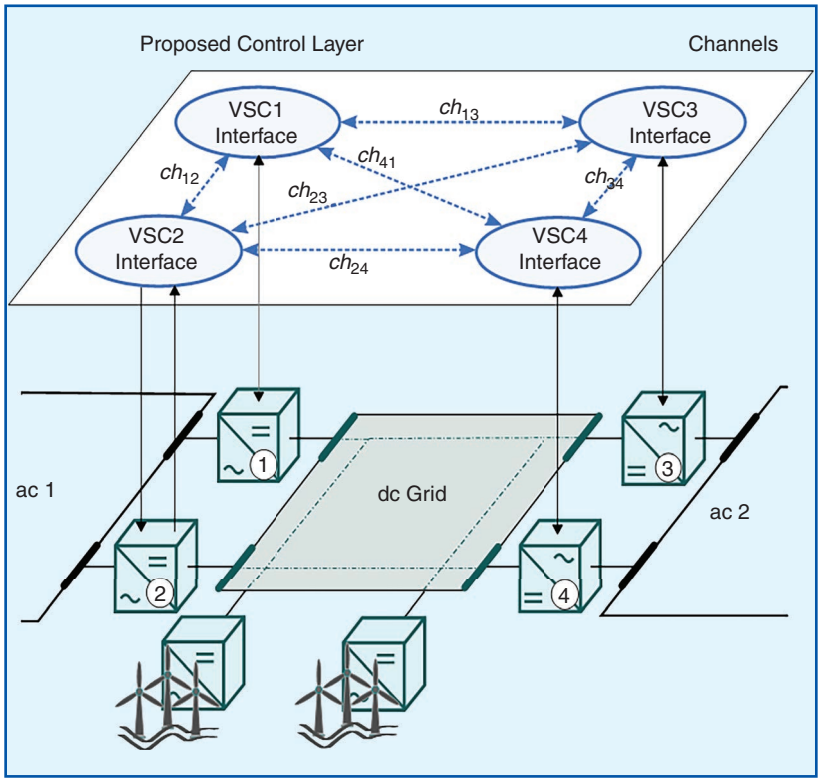


Figure 3. The supervisory control layer.

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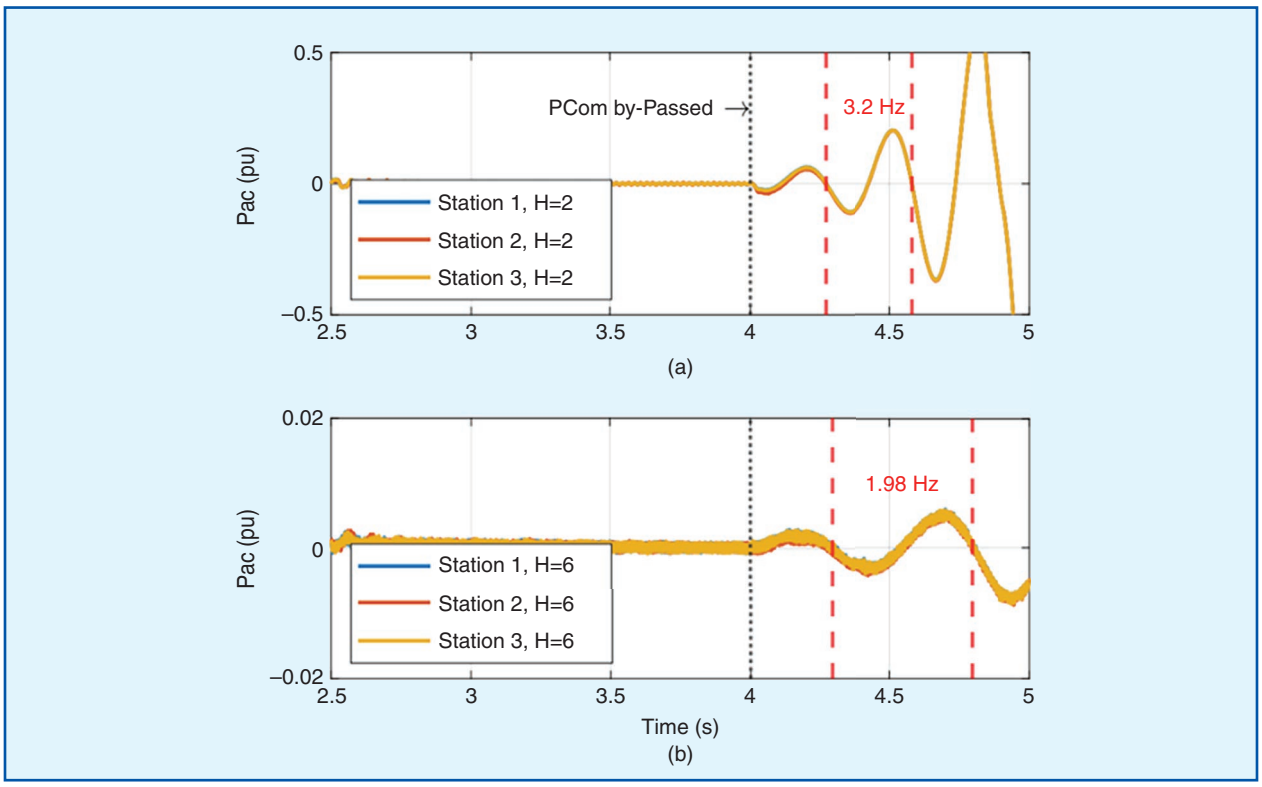


Figure 4. (a) and (b) The effectiveness of the PCom in suppressing the harmonic instability due to DVD/GFM.

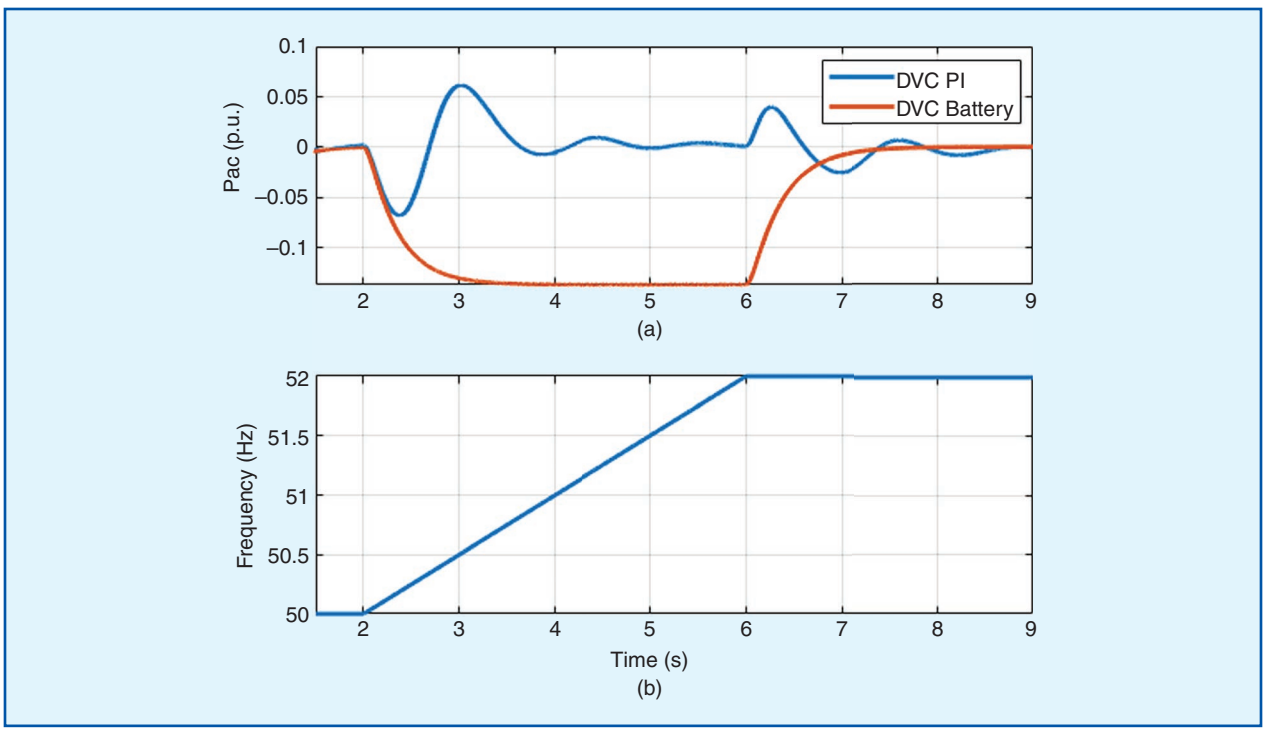


Figure 5. (a) and (b) The active power response of master station to test signal 1.

power redistribution and neutral current regulation, which standard control strategies struggle to address.

These challenges are particularly pronounced in projects like Zhangbei, where high renewable penetration amplifies stability concerns.

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Industry-Vetted Solutions

To address these challenges, the following industry-vetted solutions are being implemented:

- ✔ *PCom and VPSS*: PCom cascaded with DVD control and a VPSS have been integrated into commercial voltage source converter (VSC)-HVdc networks to stabilize low-frequency dynamics and prevent dc-side resonances. PCom mitigates phase lag in GFM control at 1–5 Hz, while VPSS counters negative resistance effects at 10–100 Hz, enhancing small-signal stability in weak ac grids with low SCRs. Figure 6 demonstrates the PCom, cascaded with DVD control and VPSS, effectively regulating power, dc voltages, and modular multilevel converter arm capacitor voltages during an N-1 contingency at t =8 s, ensuring stability as Station 1's 1-GW rectifying mode shifts with Stations 2 and 3 adapting from 0.5-GW inverting mode.
- ✔ *Coordinated control channels and grid code compliance*: Channel-based control ensures balanced power modulation in VSC-HVdc networks, mitigating oscillation bleed and enhancing frequency stability in multiterminal setups, while ENTSO-E grid codes mandate POD, fast frequency response, and ac line emulation, driving manufacturers to develop interoperable control solutions.

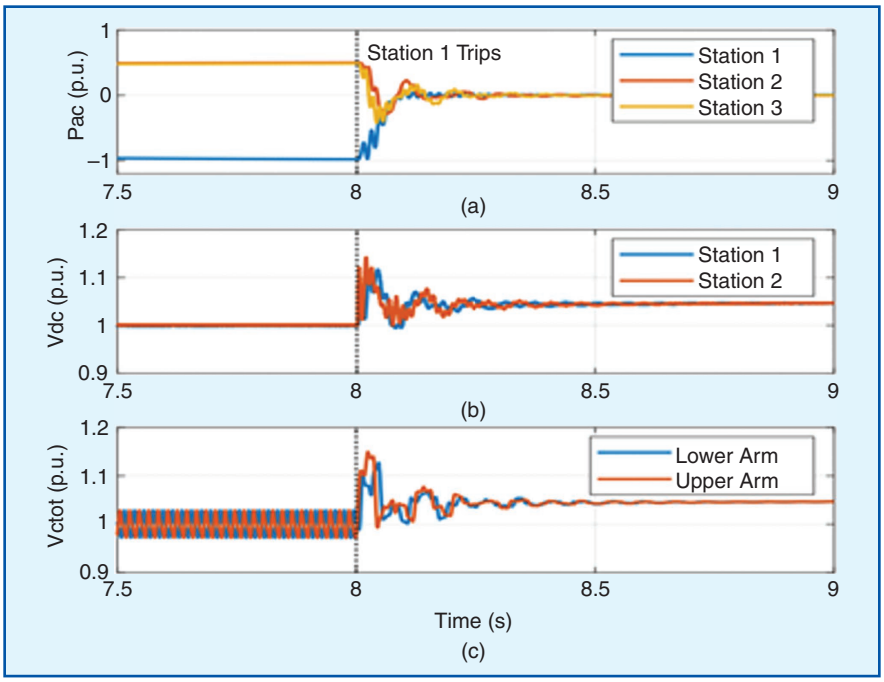


Figure 6. (a)–(c) The performance of the control during N-1 contingency ride through.

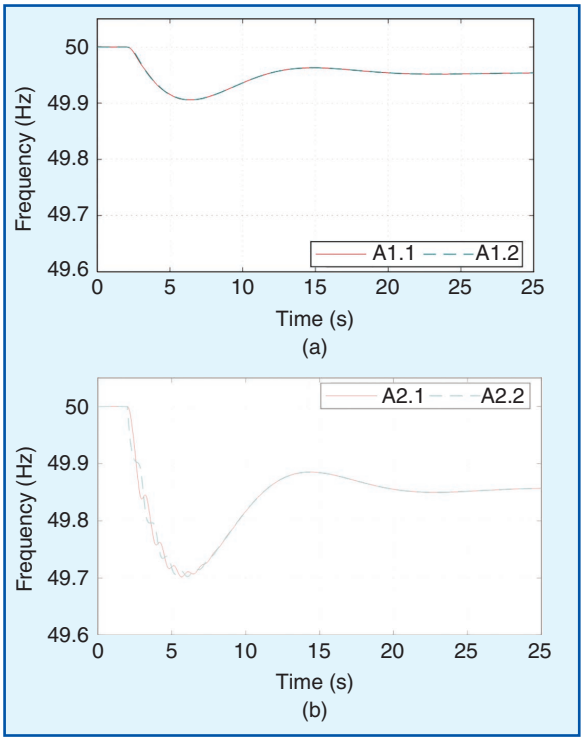


Figure 7. The frequency of (a) system A1 and (b) system A2.

Case Study: Six-Terminal MTdc Network

A six-terminal MTdc network links two asynchronous systems (A1 and A2) and offshore generation across four synchronous areas via ac corridors, analyzing rotor-angle stability, frequency dynamics, and dc voltage behavior. A coordinated control strategy—using POD, ac line emulation, and frequency control—manages six HVdc channels. Synchronous channels dampen inter-area oscillations and mimic ac flows, while asynchronous channels stabilize frequency via power exchanges. After a 200-MW load increase in A2, the approach boosts

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VPSS counteracts negative resistance effects introduced by PCom at 10–100 Hz, preventing resonances in dc networks and stabilizing ac voltage and power flow.

the frequency nadir to 49.7 Hz, curbs oscillations, and reallocates power to ease ac corridor overloading (Figure 7). Active power shifts smoothly across stations, minimizing transients and balancing frequency (Figure 8), enhancing resilience and preventing overloads.

- ✔ *Model predictive control (MPC):* Engineers deploy MPC-based supervisory control to optimize power flow and voltage regulation in bipole MTdc networks, tested in a five-terminal network study. MPC uses robust optimization to handle renewable fluctuations and disturbances, enforcing voltage and current limits. It coordinates converters, adjusts to outages, and regulates neutral voltage in dedicated metallic return setups using real-time pole data, enhancing stability across ac-dc networks.

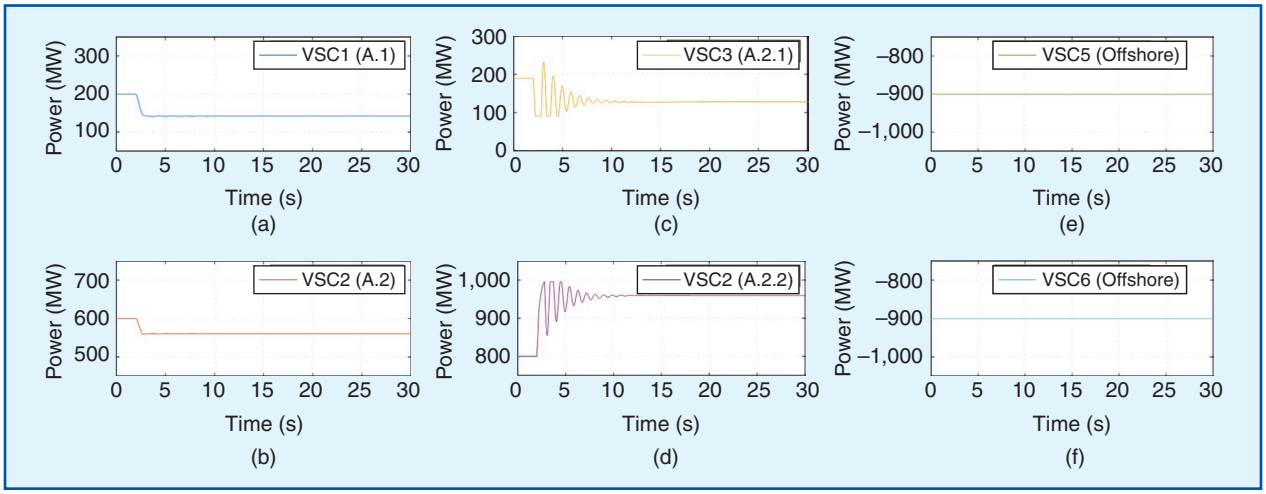


Figure 8. The active power of stations.

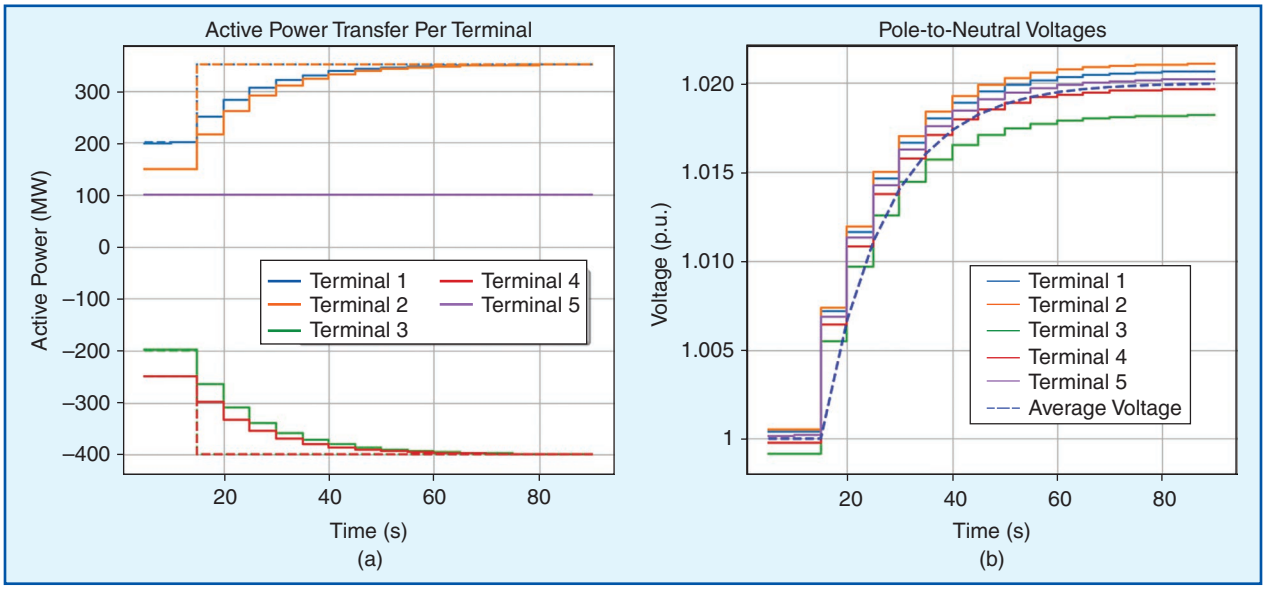


Figure 9. Active power transfer per terminal and pole-to-neutral voltages when the MPC receives new power and average voltage set points. (a) Active power transfer per terminal. (b) Pole-to-neutral voltages.

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In the study, a network with four 1,000-MW VSCs and one 350-MW VSC links two asynchronous ac systems and an offshore wind farm. DC cables feature dedicated metallic return resistances 20% higher than pole resistances, reflecting real-world conditions. MPC enforces limits on active power, dc voltage, and branch current, using a 5-s sampling rate and a three-step control horizon, optimized via Power Factory and Python. Figure 9 demonstrates the MPC controller achieving precise power and voltage targets at $t = 15$ s with a 40-s settling time in balanced mode while swiftly stabilizing dc voltages to 1 p.u. during a VSC outage or pole trip at terminal 3, optimizing power flow.

After a 200-MW load increase in A2, the approach boosts the frequency nadir to 49.7 Hz, curbs oscillations, and reallocates power to ease ac corridor overloading.

Conclusion

The future of ac-dc networks relies on advanced control strategies to address challenges arising from the proliferation of power electronic converters and renewable energy integration. Upgrading these functionalities is essential for ensuring reliable, resilient, and stable operating conditions, enabling dynamic energy sharing and efficient reserve allocation. For example, on the ac side, enhanced capability for balancing by deploying virtual inertia with DVC attached to GFM converters entails a higher level of stability performance. Moreover, scaling MTdc networks to multicountry systems like the North Sea Wind Power Hub poses challenges like communication overhead and stability risks, driving research into distributed MPC and adaptive droop gains for robust scalability. As hybrid ac-dc networks continue to evolve, these innovations will play a pivotal role in achieving reliable and resilient operations in future HVac-HVdc networks.

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For Further Readings

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