

E-STATCOM for Renewable Energy and AI Data Center Application

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Agenda

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01

Background

Modern grid challenges: wind farms and large data centers

Compensation options: E-STATCOM and synchronous condenser (SynCon)

Issues

02

Part A: Wind-farm system analysis

Frequency-domain analysis: system interactions and E-STATCOM support based on linear modeling

EMT validation: full-scale wind-farm, grid and E-STATCOM model

Part A

03

Part B: Data-center system analysis

Frequency-domain analysis: PRM-based linear-model results

EMT validation: confirmation of the frequency-domain findings

Part B

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BACKGROUND

01

Background

Modern grid challenges and compensation options
E-STATCOM and synchronous condenser (SynCon)

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Challenges with Data Center and Renewable Energy

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Key Challenges:

- IBRs introduce additional complexities and stability challenges
- Fast Frequency Response (FFR) and Primary Frequency Control
- Sub-synchronous Oscillations (SSO) due to **Area-b**
- Inter-area oscillations due to the interaction between **Area-a** and **Area-b**
- Fault Ride-Through and Dynamic Grid Support
- Additional resonance due to series-compensation
- DC (can come via phase jumps)
- TOV and Harmonics

Key Solution:

- GFM E-STATCOM can address the above issues and keep the PCC voltage and angle stable
- It can compensate for the large power fluctuations introduced by large loads

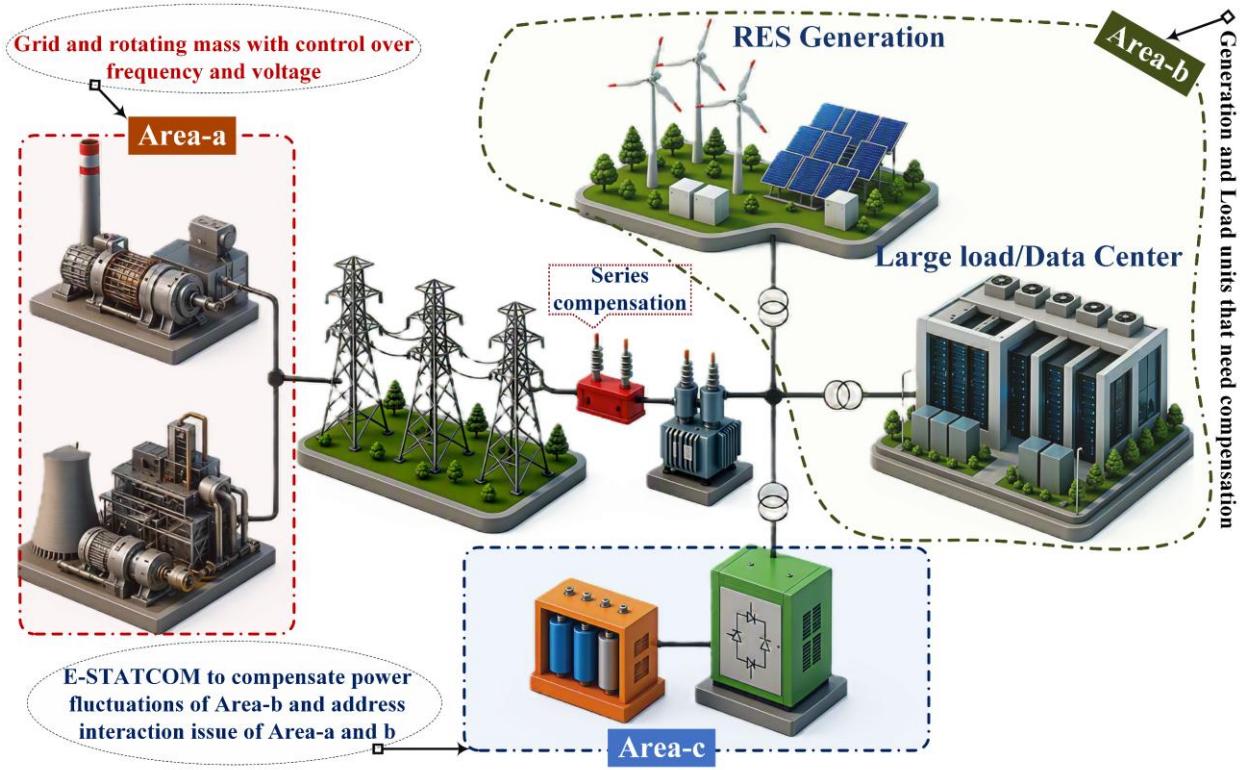


Fig. Representation of a typical power system network

How to identify the issues/Challenges?

- **NFP**: Network frequency perturbation; **PRM**: Power Response Matrix; → National Grid ESO
- Evaluates GFM converter power response to input frequency oscillations
- Helps to assess damping behavior, system stability, and potential interactions with other grid components

Ref 1: Hitachi Energy, 'High power enhanced STATCOM with Grid-Forming for transmission, renewable and industry applications', White paper
Ref 2: Great Britain Grid Forming Best Practice Guide, National Grid, ESO

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PART A

02 Wind-farm system analysis

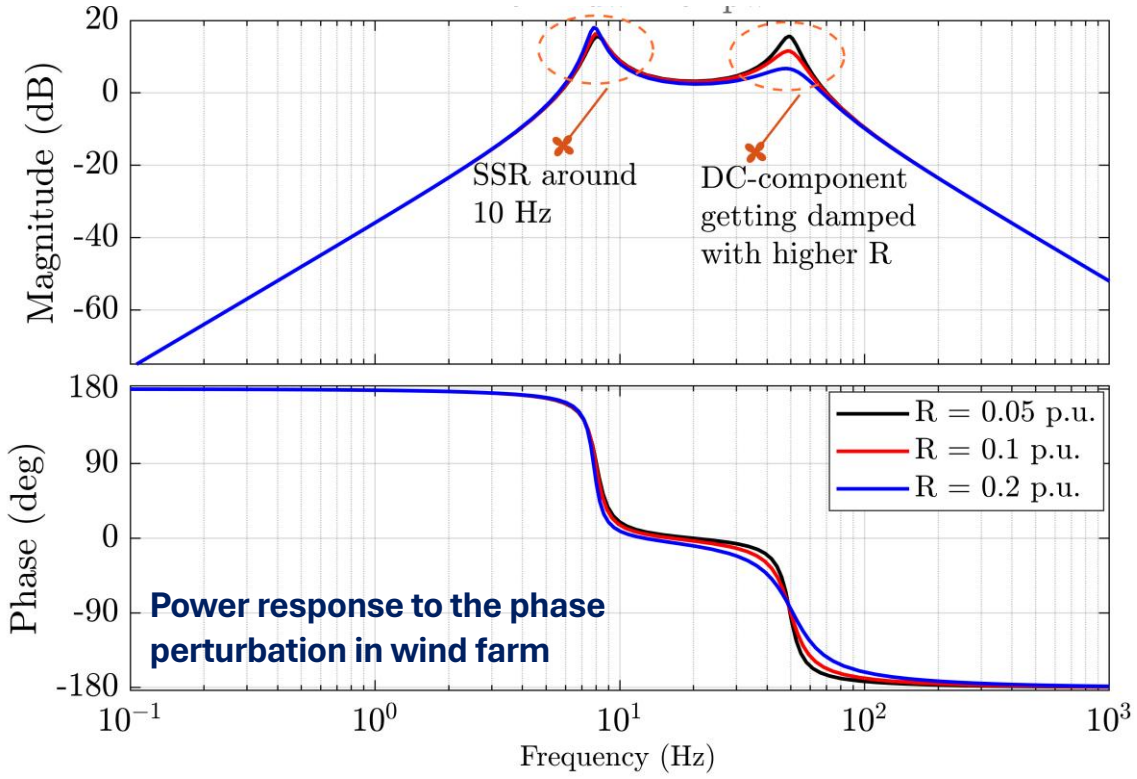
A.1 Small-signal Linear model analysis

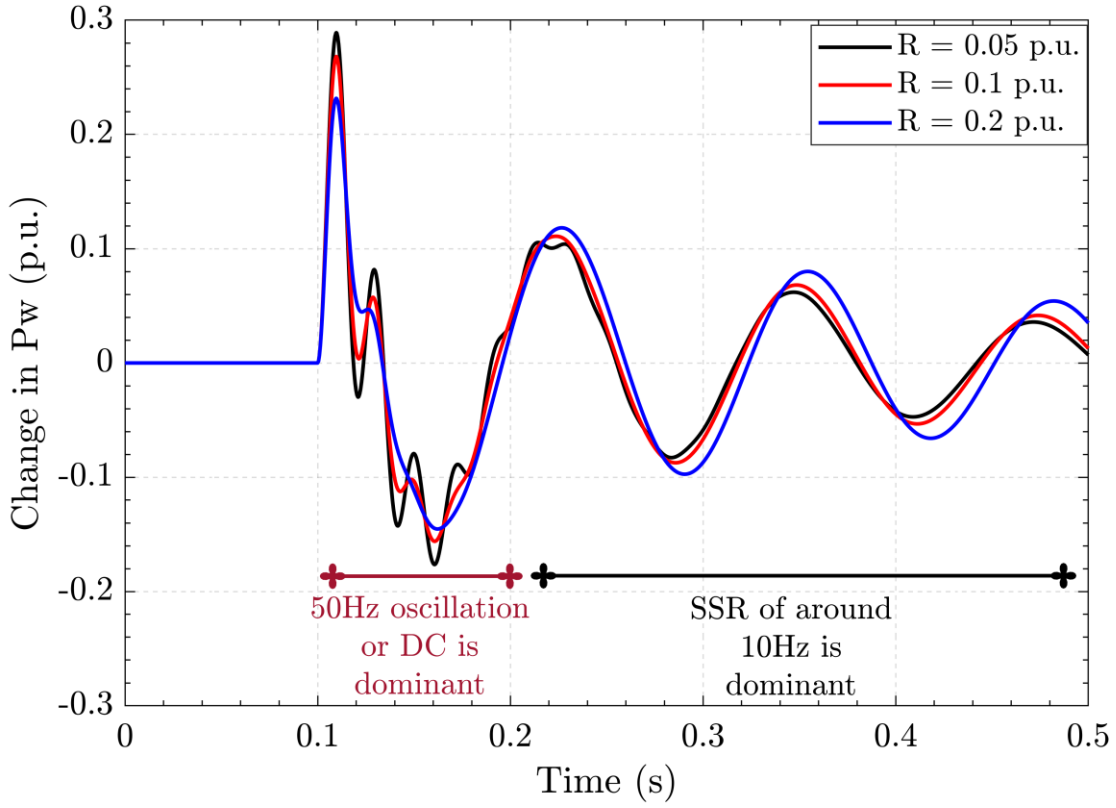
A.2 Full-scale EMT validation

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Grid-connected Wind-farm System: PRM Analysis

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$$\begin{bmatrix} dP \\ dQ \end{bmatrix} = \underbrace{\begin{bmatrix} \dfrac{1/L_w\left(s+R_w/L_w\right)}{s^2+(2R_w/L_w)s+(R_w/L_w)^2+\omega_{s0}^2} & \dfrac{\omega_{s0}/L_w}{s^2+(2R_w/L_w)s+(R_w/L_w)^2+\omega_{s0}^2} \\ \dfrac{-\omega_{s0}/L_w}{s^2+(2R_w/L_w)s+(R_w/L_w)^2+\omega_{s0}^2} & \dfrac{1/L_w\left(s+R_w/L_w\right)}{s^2+(2R_w/L_w)s+(R_w/L_w)^2+\omega_{s0}^2} \end{bmatrix}}_{\begin{bmatrix} \mathrm{Re}(Y) & -\mathrm{Im}(Y) \\ \mathrm{Im}(Y) & \mathrm{Re}(Y) \end{bmatrix};\ \omega_{s0}=\omega \text{ is the nominal source frequency}} \begin{bmatrix} \left(du_{pcc}-du_w\right) \\ \left(d\varphi_{pcc}-d\varphi_w\right) \end{bmatrix}$$

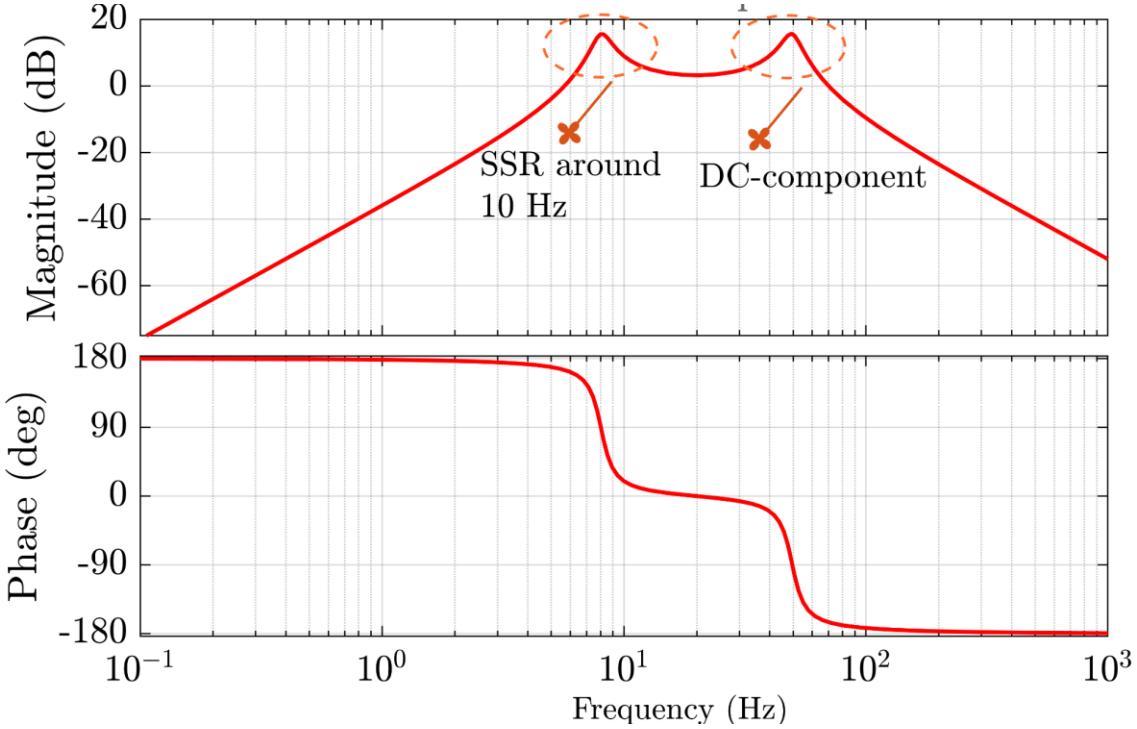
- A typical grid-connected wind-farm experiences SSR and DC
- DC can be compensated through the losses in the Grid, but not SSR
- Presence of these types of resonances can lead to TOV and other stability issues

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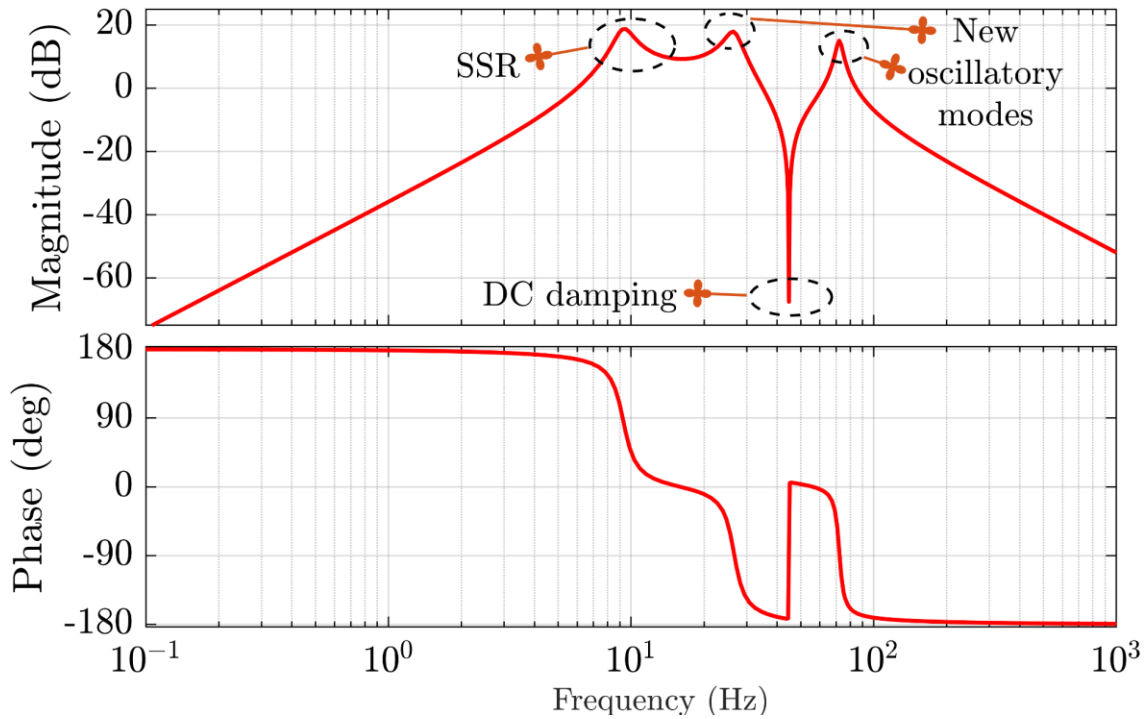
Ref: P.R. Bana, J.P. Hasler, R. Heydari, A. J. Owens & F. Chiuminatto, 'Grid-Forming Enhanced STATCOMs for Wind Power Plant Stability: Design, Modeling, and Control', CIGRE, GOTF, 2025, Denver-USA

Grid-connected Wind-farm System: Impact of Series Compensation

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(Grid-connected wind-farm)



(Grid-connected wind-farm with **series compensation**)

Takeaway:

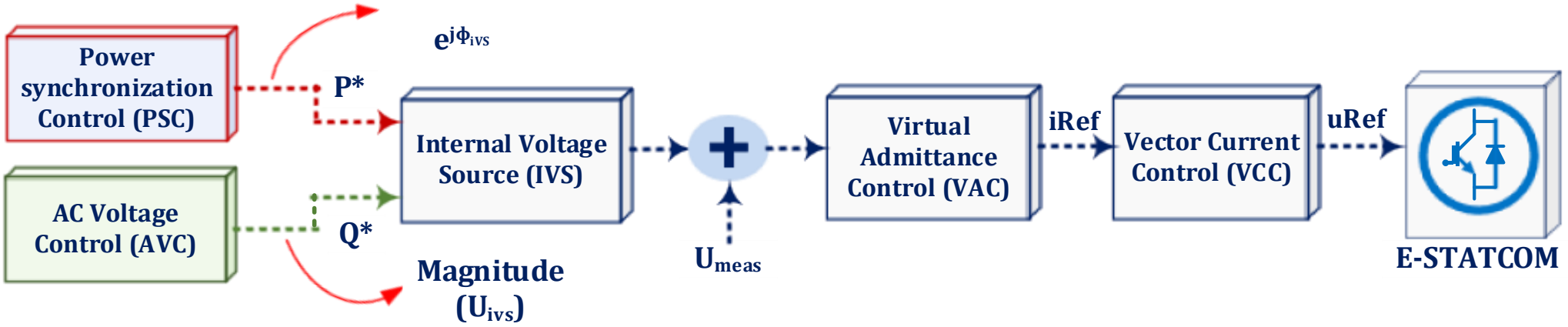
- Series compensation can improve the power flow and reduce the DC
- But, it can introduce new oscillatory modes
- The shunt compensating can damp them

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Ref: P.R. Bana, J.P. Hasler, R. Heydari, A. J. Owens & F. Chiuminatto, 'Grid-Forming Enhanced STATCOMs for Wind Power Plant Stability: Design, Modeling, and Control', CIGRE, GOTF, 2025, Denver-USA

GFM E-STATCOM: to Stabilize the Grid

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01 Key features of GFM E-STATCOM:

- Tunable control parameters
- More control functions can be added for different objectives without much complexity
- Damping functionality can be achieved in a wide frequency range

02 Working mechanism of GFM E-STATCOM:

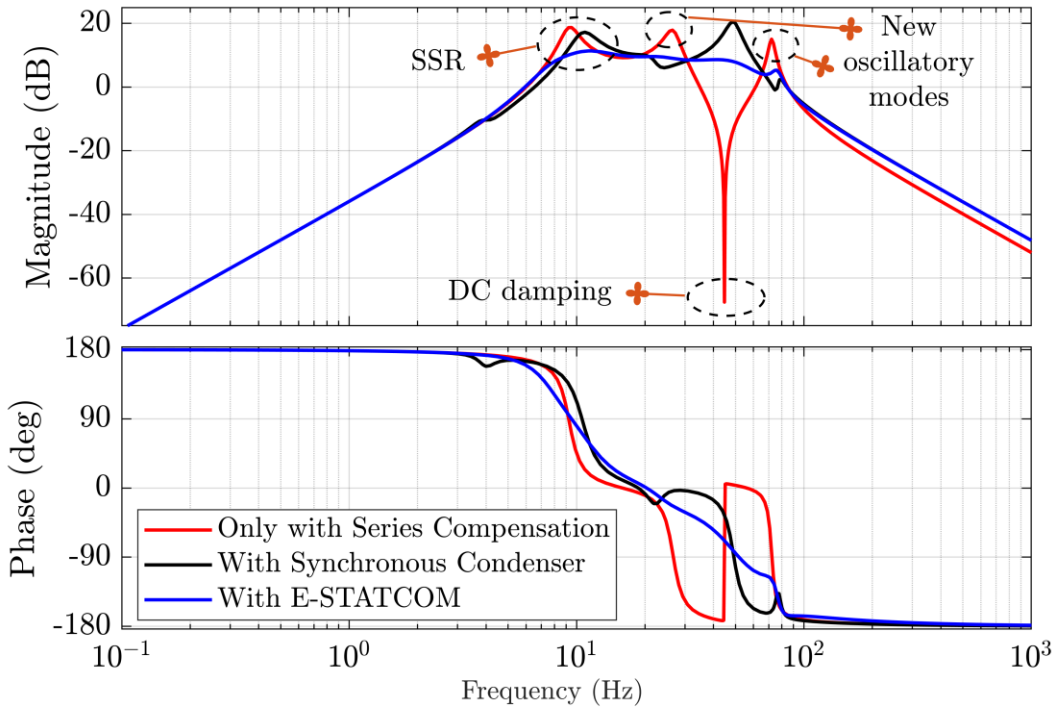
- Behaves as a voltage source (IVS) connected via an impedance (VAC)
- Magnitude and phase set points are determined from AVC and PSC
- VCC is helpful in protecting the valve

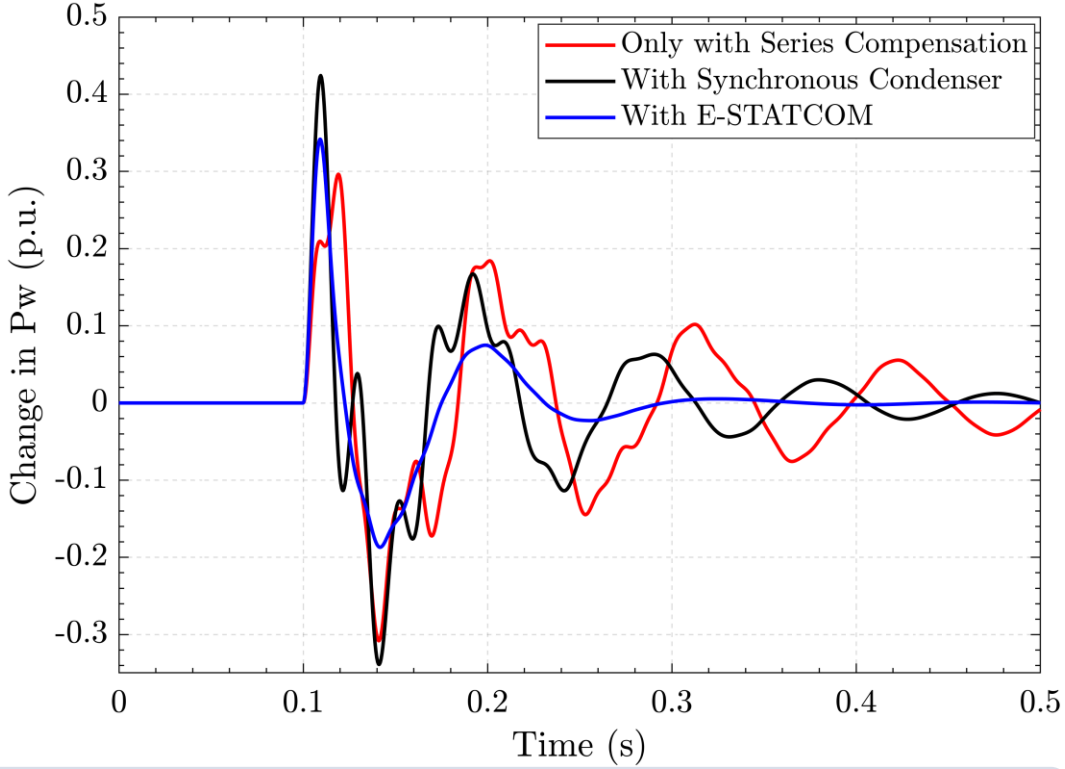
Ref 1: P.R. Bana, J.P. Hasler, R. Heydari, A. Owens & F. Chiuminatto, 'Grid-Forming Enhanced STATCOMs for Wind Power Plant Stability: Design, Modeling, and Control', CIGRE, GOTF, 2025, Denver-USA
Ref 2: R. Heydari, P.R. Bana, J.P. Hasler, A. Bostrom, & M. Halonen, 'Stability Enhancement in Weak Grids with High Renewable Penetration: Synchronous Condenser vs. Converter-based Technologies', CIGRE Symposium-2025, Montreal, Canada

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Comparative Damping Performance of GFM E-STATCOM

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Key Observations:

1. **No compensation:** Presence of DC, SSR, and other modes due to series-compensation
2. **Syncon as Shunt**: Attenuated DC, poorly damped SSR and other oscillatory modes
3. **E-STATCOM as Shunt**: Well-damped SSR and other oscillatory modes

Ref 1: P.R. Bana, J.P. Hasler, R. Heydari, A. Owens & F. Chiuminatto, 'Grid-Forming Enhanced STATCOMs for Wind Power Plant Stability: Design, Modeling, and Control', CIGRE, GOTF, 2025, Denver-USA

Ref 2: R. Heydari, P.R. Bana, J.P. Hasler, A. Bostrom, & M. Halonen, 'Stability Enhancement in Weak Grids with High Renewable Penetration: Synchronous Condenser vs. Converter-based Technologies', CIGRE Symposium-2025, Montreal, Canada

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PART B

03 Data-center system analysis

A.1 Frequency domain PRM analysis

A.2 Full-scale EMT validation

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Grid-connected Data Center System: PRM Construction

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- Consider the grid-connected Data Center system without E-STATCOM
- The active and reactive power from the grid can be given as:

$$P_g = U_g^2 g_t - U_g U_d \left(g_t \cos\delta_{gd} + b_t \sin\delta_{gd} \right), Q_g = -U_g^2 b_t - U_g U_d \left(g_t \sin\delta_{gd} - b_t \cos\delta_{gd} \right).$$

where, $$Y(s) = \frac{1}{R_t + (s + j\omega_1)L_t} = g_t(s) - jb_t(s);\ R_t = R_d + R_g \text{ and } L_t = L_d + L_g$$

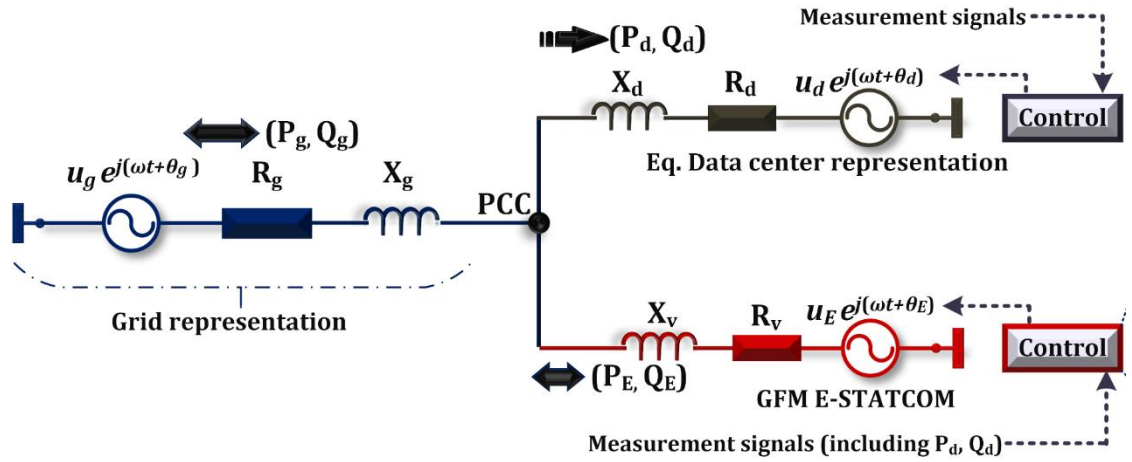


Fig. Thevenin equivalent representation of the system for Linear PRM derivation

- Linearising the above power terms by considering the $C_{p,d}$ and $C_{v,d}$ as a transformation function of the power controller and voltage controller, respectively, it becomes:

$$\begin{bmatrix} \Delta P_g \\ \Delta Q_g \end{bmatrix} = \begin{bmatrix} \frac{-U_0^2 b_t(s) C_{P,d}(s)}{1 + U_0^2 b_t(s) C_{P,d}(s)} & \frac{U_0 g_t(s) C_{V,d}(s)}{1 + U_0^2 b_t(s) C_{P,d}(s)} \\ \frac{-U_0^2 g_t(s) C_{P,d}(s)}{1 + U_0^2 b_t(s) C_{P,d}(s)} & \frac{-U_0 b_t(s) - U_0^3 \left(g_t^2(s) + b_t^2(s) \right) C_{P,d}(s)}{1 + U_0^2 b_t(s) C_{P,d}(s)} C_{V,d}(s) \end{bmatrix} \begin{bmatrix} \Delta P_{\text{ref},d} \\ \Delta U_d^\star \end{bmatrix}$$

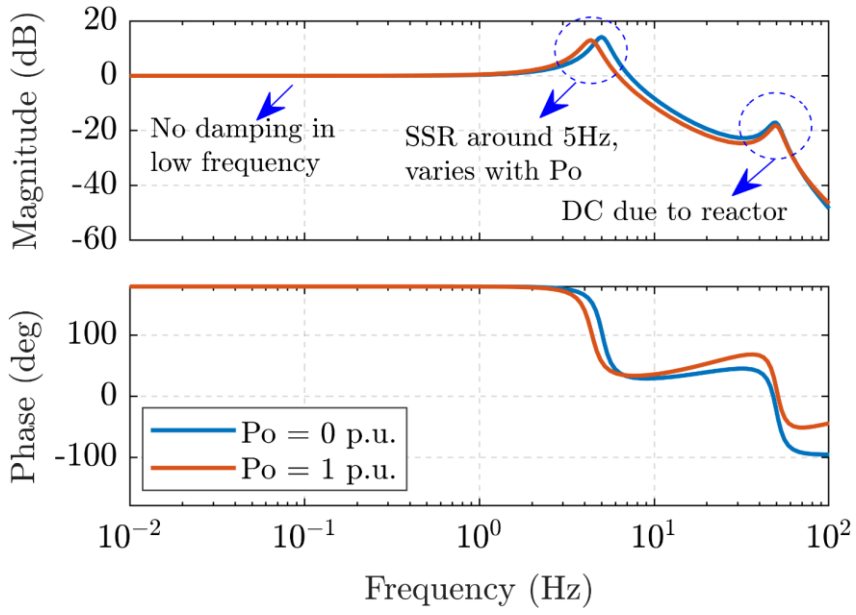
- Modified PRM (conventionally, expressed in terms of phase angle)
- Can tell the stability and resonance behavior of the system
- Only valid for a single operating point

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Ref: P.R. Bana, J.P. Hasler, N. Zakkia, C. Danielsson, ' Grid-Forming E-STATCOMs for Stable Integration of Large-Scale Data Centers: Modeling and Control', CIGRE, GOTF, 2026, USA (Upcoming)

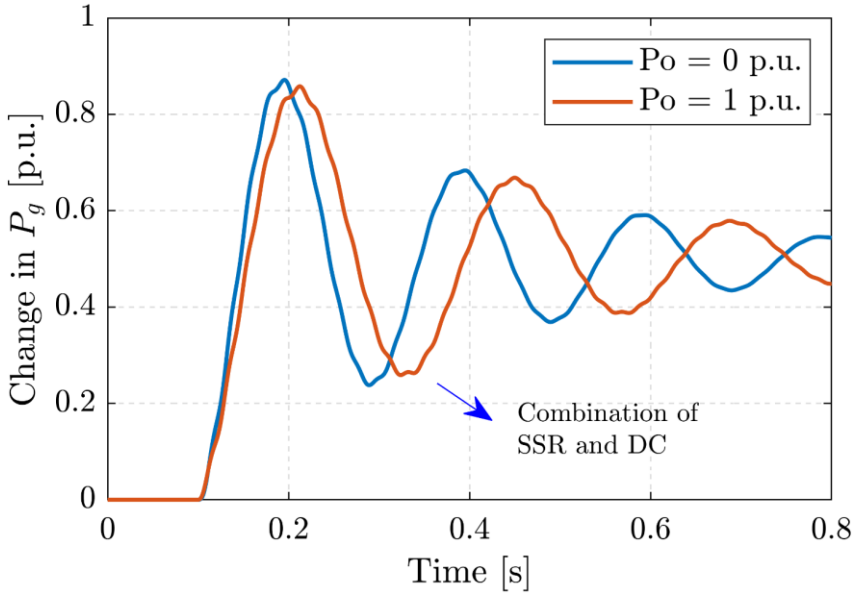
Grid-connected Data Center System: PRM Response

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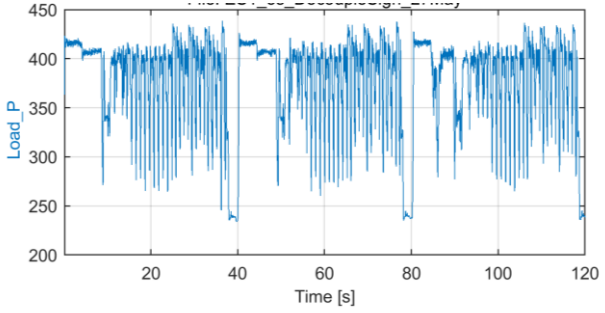
Grid power response to the perturbation in the data center power

Frequency-domain ⟷ **Time-domain**



Load-profile interaction

This type of load profile excites the low-frequency region that remains undamped in the frequency-domain plot.



Source: NERC Large Loads Task Force, "Characteristics and Risks of Emerging Large Loads," Jul. 2025. Data extracted using an AI tool.

Observations:

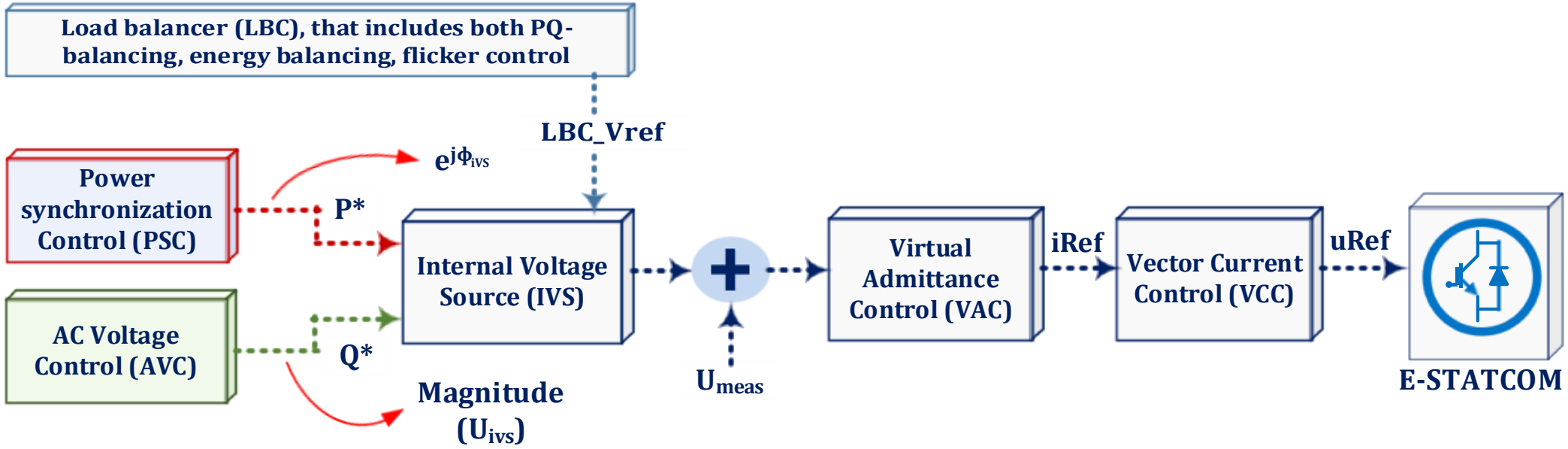
- Possible SSR due to the converters used in the data center
- DC due to the reactors
- Resonance changes with the power flow magnitude
- Undamped low-frequency region

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Ref: P.R. Bana, J.P. Hasler, N. Zakkia, C. Danielsson, ' Grid-Forming E-STATCOMs for Stable Integration of Large-Scale Data Centers: Modeling and Control', CIGRE, GOTF, 2026, USA (Upcoming)

E-STATCOM for Data Center: What has Changed?

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Key features of E-STATCOM Control for Data Center:

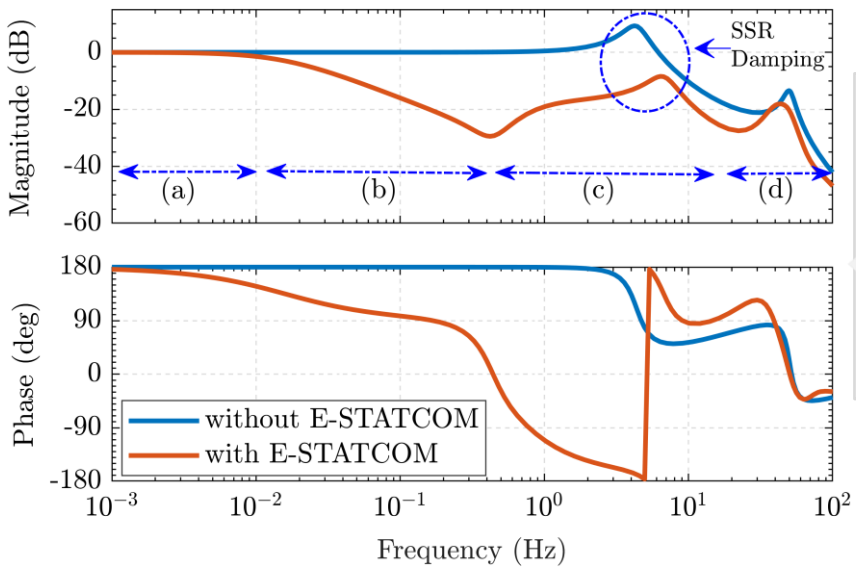
- The control system is not entirely GFM nor GFL
- The load compensation happens through the load balancer control logic, similar to the Arc furnace application (more or less the following approach)
- Meaning LBC is sitting over GFM control: This way, we perform the load compensation by retaining the advantages of GFM control (it addresses the question of what is beyond 0.1-55Hz compensation)

Ref 1: P.R. Bana, J.P. Hasler, R. Heydari, A. Owens & F. Chiuminatto, 'Grid-Forming Enhanced STATCOMs for Wind Power Plant Stability: Design, Modeling, and Control', CIGRE, GOTF, 2025, Denver-USA
Ref 2: R. Heydari, P.R. Bana, J.P. Hasler, A. Bostrom, & M. Halonen, 'Stability Enhancement in Weak Grids with High Renewable Penetration: Synchronous Condenser vs. Converter-based Technologies', CIGRE Symposium-2025, Montreal, Canada

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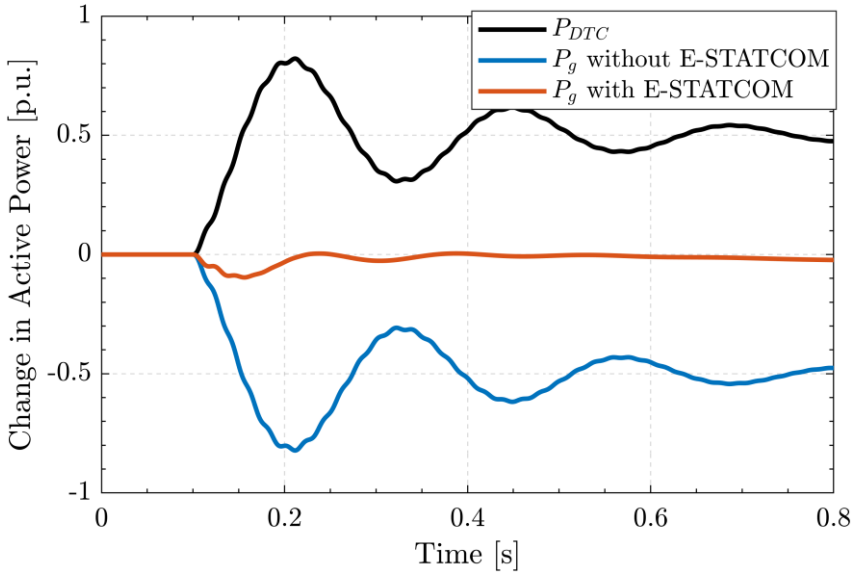
Grid-connected Data Center with E-STATCOM: PRM Response

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Grid power response to the perturbation in the data center power

Frequency-domain → **Time-domain**



Four control-response regions:

(a) Below 0.01 Hz: no active compensation

No damping from E-STATCOM (need more energy, if expected from E-STATCOM). The grid, BESS, or other asset must supply these slow variations.

(b) Load-balancing control

E-STATCOM begins compensating for load fluctuations. Its synchronizing (stiffness-type) response reduces disturbances reaching the upstream grid.

(c) Inertial response

Inertia response damps system dynamics, particularly around the SSR frequency.

(d) Virtual admittance (VAC)

VAC acts across the full frequency range. Here, its stronger influence shapes converter impedance and contributes to damping.

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Ref: P.R. Bana, J.P. Hasler, N. Zakkia, C. Danielsson, ' Grid-Forming E-STATCOMs for Stable Integration of Large-Scale Data Centers: Modeling and Control', CIGRE, GOTF, 2026, USA (Upcoming)

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PART B

03 Data-center system analysis

A.1 Frequency domain PRM analysis

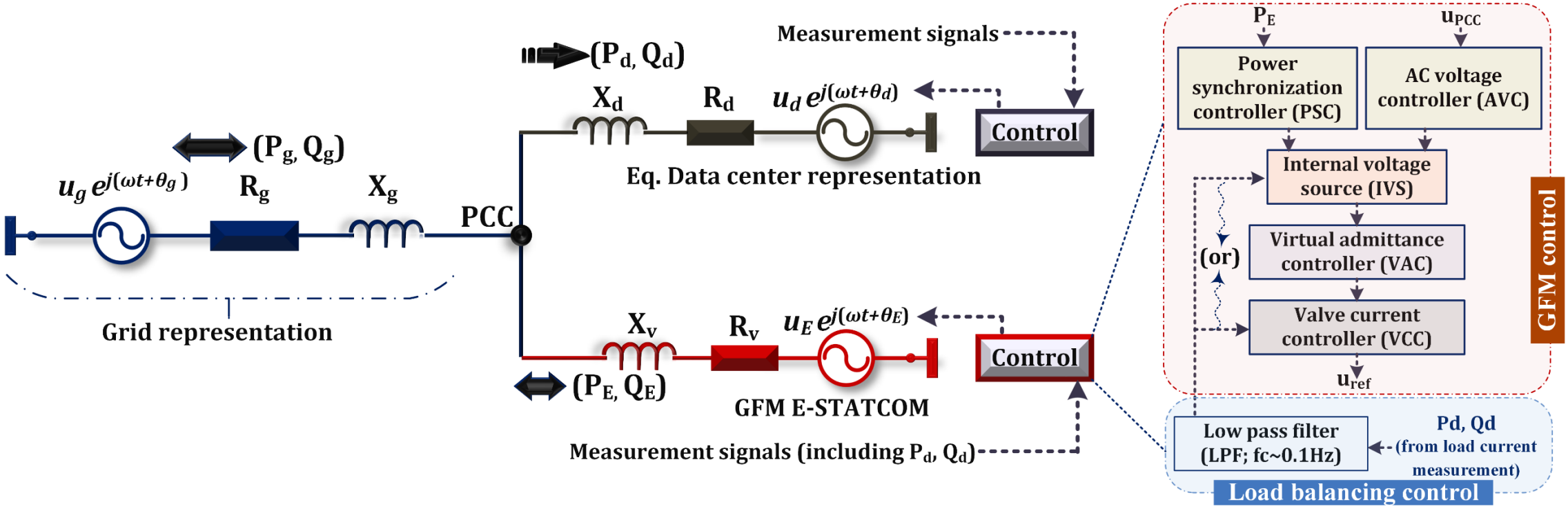
A.2 Full-scale EMT validation

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EMT System Setup

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- Grid model with rotating mass
- Detailed PNNL AI Data Center model
- Full-scale Hitachi E-STATCOM model for compensation



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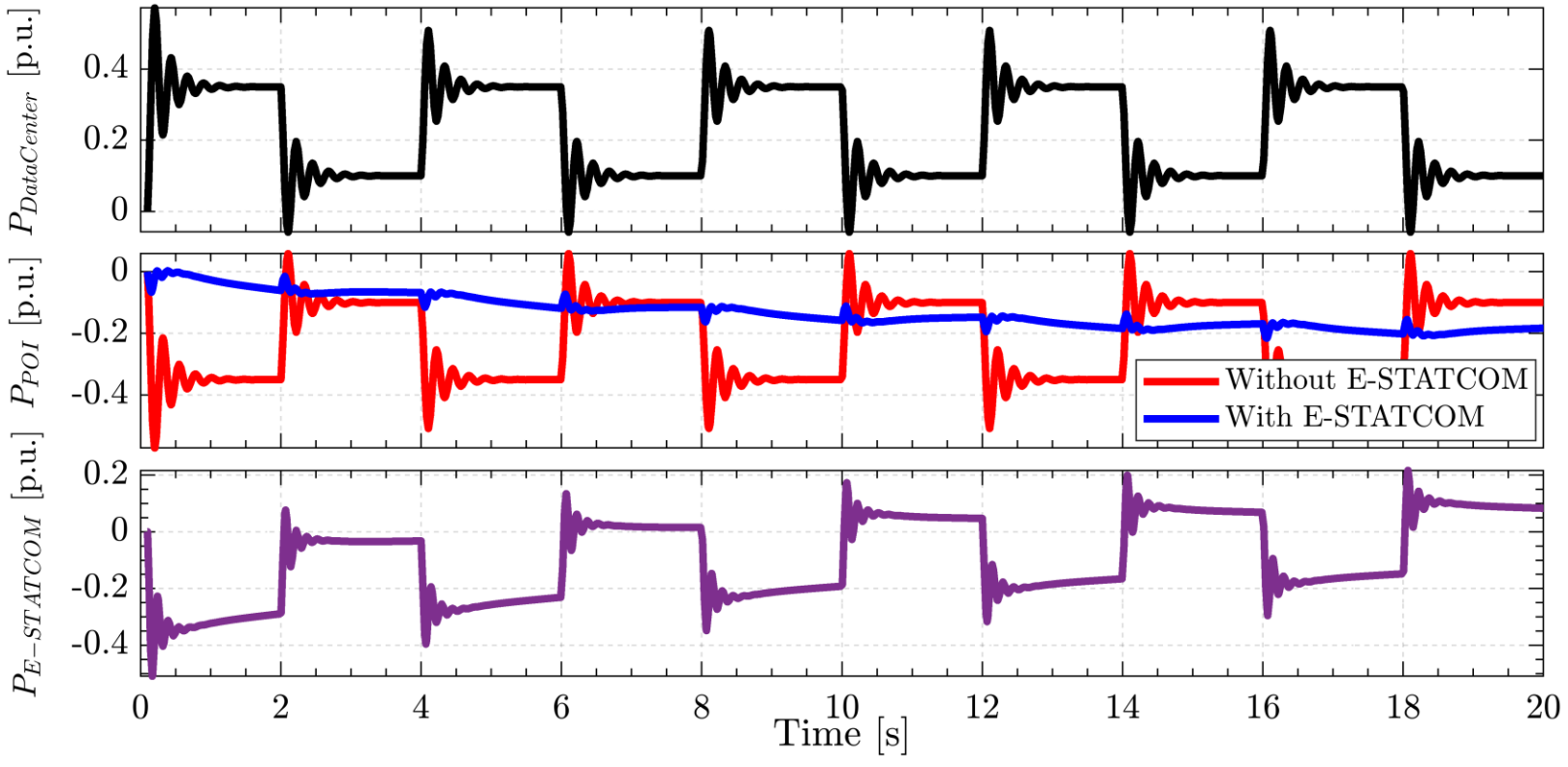
PNNL model: B. A. Ross and J. Follum, "Electromagnetic Transient Modeling of Large Data Centers for Grid-Level Studies." Pacific Northwest National Laboratory, Jan. 16, 2026

E-STATCOM Performance: SSO/Forced Oscillation Damping

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Observations

- SSO or forced oscillations can originate across a wide range of low frequencies (see reference below).
- The data-center power controller is tuned around 5 Hz.
- Changes in data-center power introduce 5 Hz SSO.
- **E-STATCOM absorbs load fluctuations and provides SSO damping.**



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Ref: C. Mishra, L. Vanfretti, J. Delaree, T. J. Purcell, and K. D. Jones, "Understanding the inception of 14.7 Hz oscillations emerging from a data center," Sustain. Energy Grids Netw., vol. 43, p. 101735, Sep. 2025

E-STATCOM Performance: Fault Ride-through Performance

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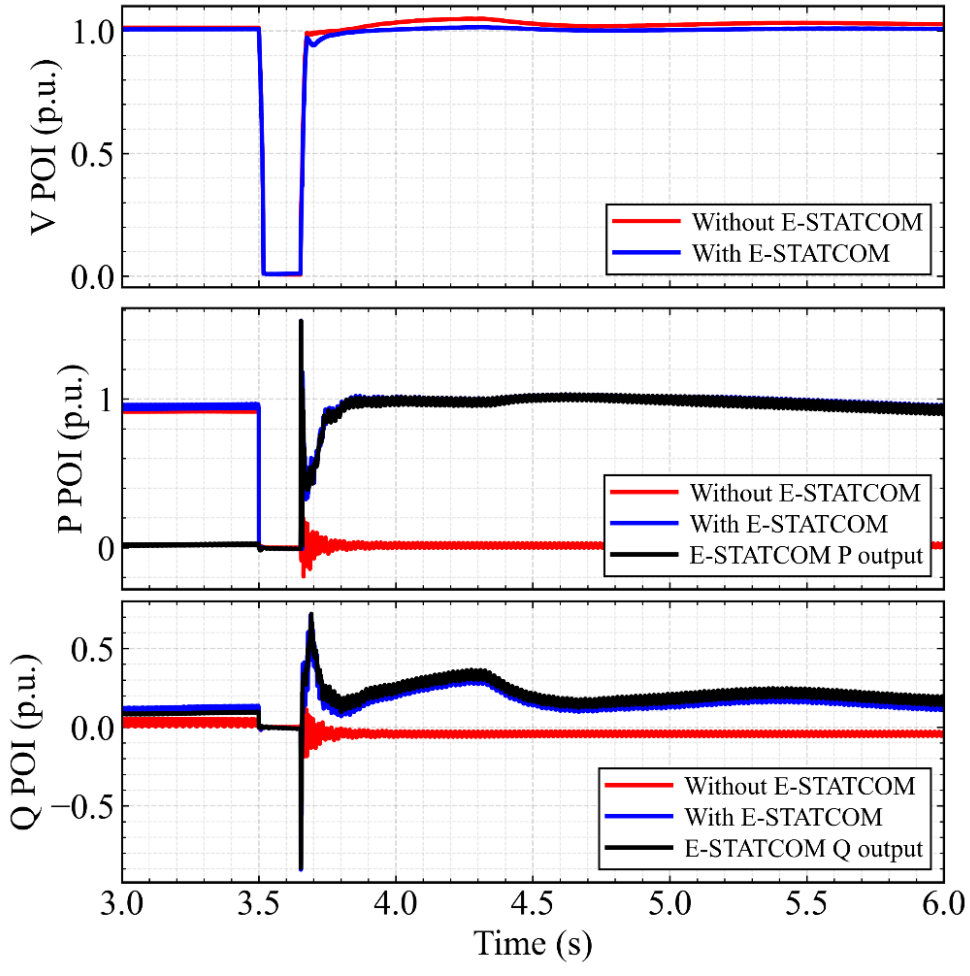
Without compensation

The data-center load trips and remains offline after the fault.

With E-STATCOM

Rapid recovery after fault clearing restores the POI load close to its pre-fault level.

Voltage and power at POI

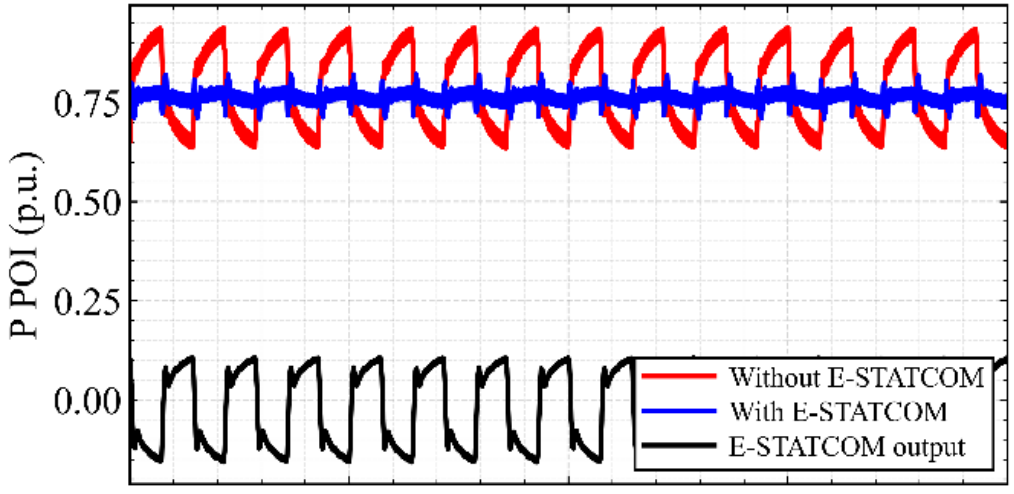


Ref 1: NERC, “Incident Review Considering Simultaneous Voltage-Sensitive Load Reductions,” Jan. 2025.
Ref 2: ATC, “American Transmission Company (ATC) Transmission System Planning Criteria,” PLG-CR-0001-V25, Aug. 2025.

E-STATCOM Performance: Flicker Analysis

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Active power response



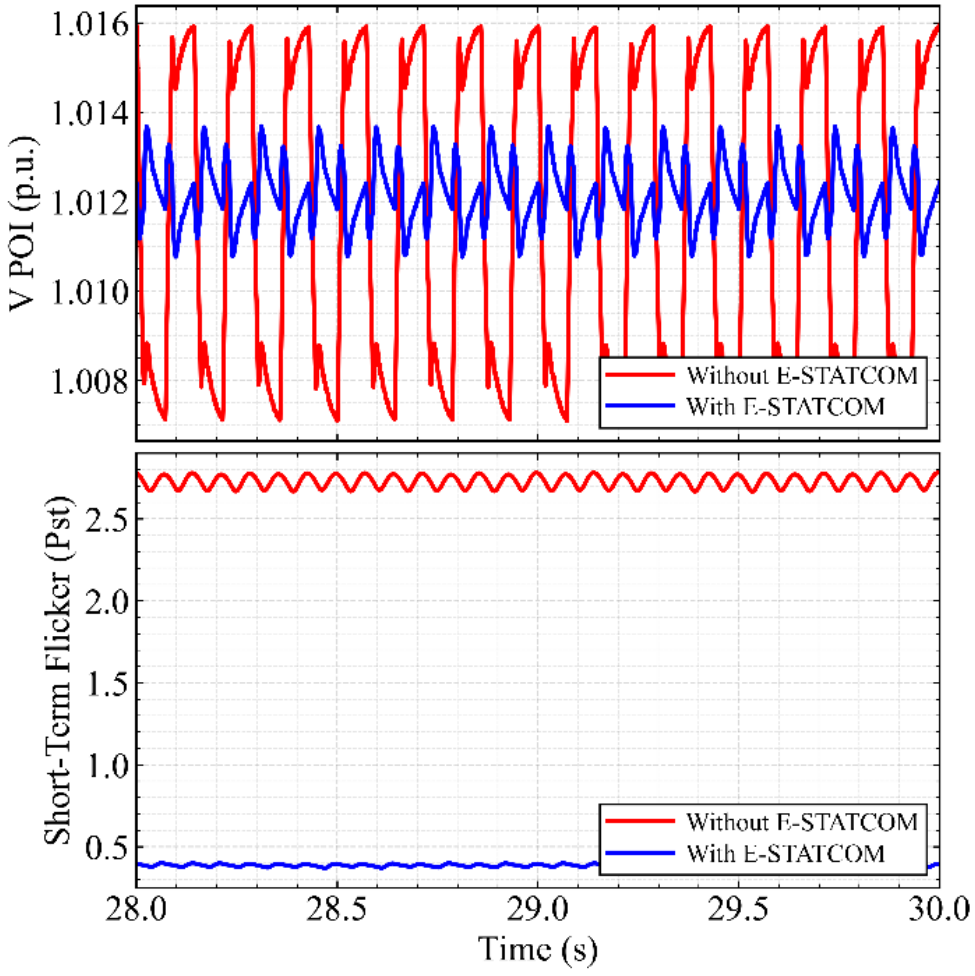
Without compensation

The short-term flicker level (Pst) is about 2.6, exceeding the IEEE 1453 planning limit of 0.8

With E-STATCOM

Fast load fluctuations are effectively suppressed, and the Pst level remains within the 0.8 limit

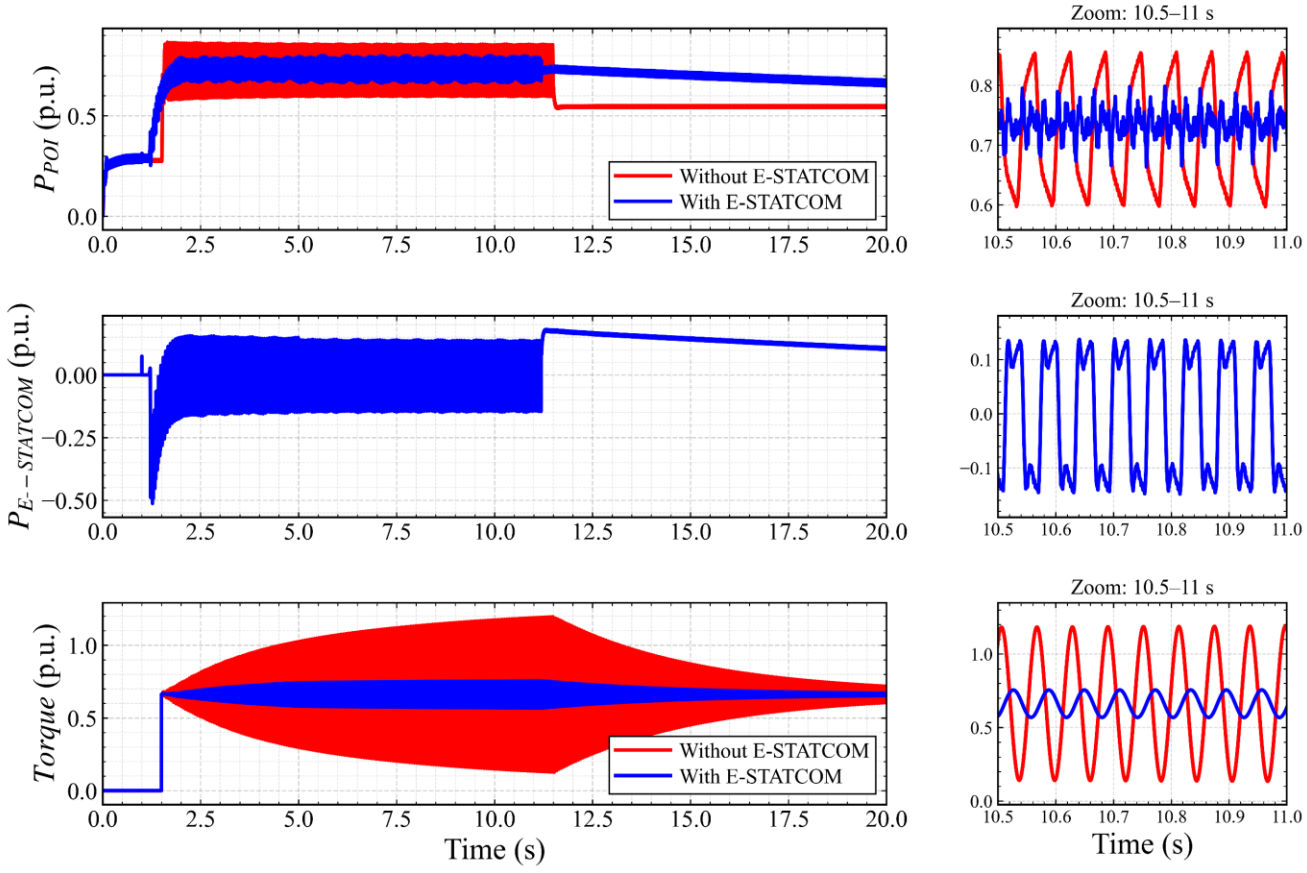
Voltage and Short-term Flicker at POI

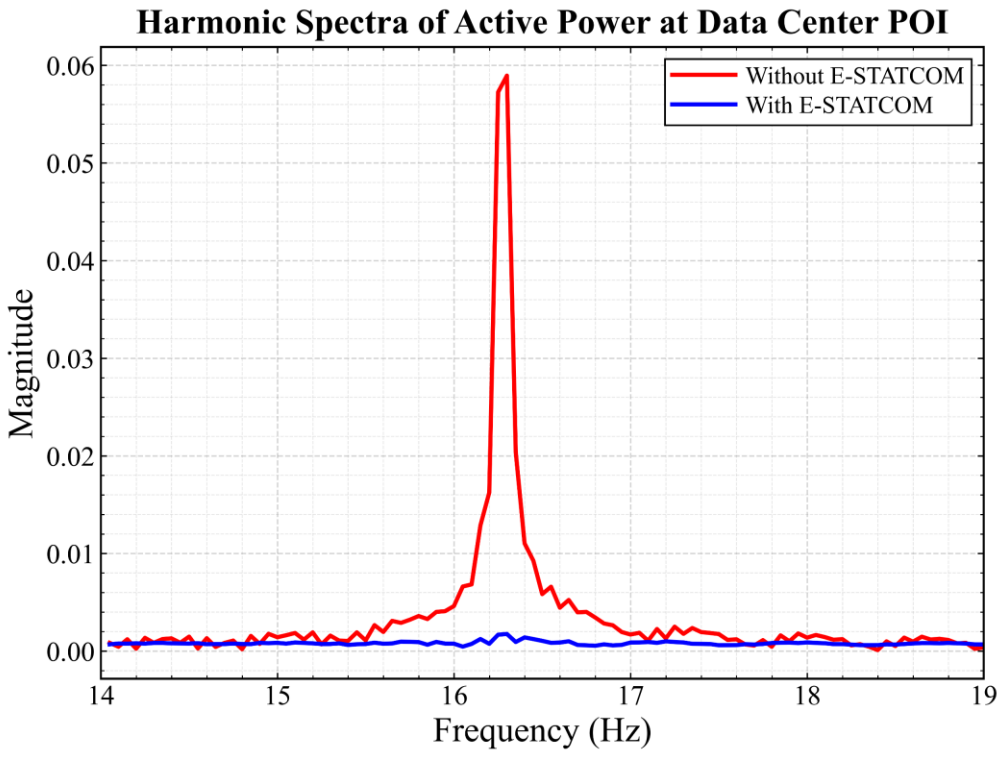


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Ref 2: ATC, “American Transmission Company (ATC) Transmission System Planning Criteria,” PLG-CR-0001-V25, Aug. 2025.

E-STATCOM Performance: SSO Impact on Nearby Generator Shaft

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Observations:

- The data center load alternates between idle and training cycles, oscillating between 0.6 p.u. and 1.0 p.u. at 16 Hz, which aligns with one of the generator's torsional modes
- The E-STATCOM effectively damps these oscillations, substantially reducing generator shaft torque oscillations

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Ref: EPRI, "Torsional Interaction Between Electrical Network Phenomena and Turbine-Generator Shafts." Accessed: Jul. 03, 2026. [Online]. Available: https://www.epri.com/research/products/1013460

Summary

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Tunable E-STATCOM control improves damping and disturbance recovery in the studied systems

PRM analysis identifies interactions and guides control design. Full-scale EMT studies assess disturbance performance.

PART A / WIND FARMS

Damping of network resonances

E-STATCOM damps SSR and series-compensation modes more effectively than SynCon in the studied cases.

Improved fault recovery

EMT results show well-damped SSO and improved control of transient overvoltage.

PART B / DATA CENTERS

Load compensation with grid support

Load-balancing control over GFM control suppresses fast power fluctuations and damps SSO.

Benefits beyond load smoothing

EMT studies show rapid post-fault recovery, lower flicker and reduced generator-shaft torque oscillations.

Design boundary: tuning must respect ESS energy and current limits. Slow load variations may need the grid or another energy source.

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Publications

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