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Sustained Oscillations of Grid-forming IBRs under Unbalanced Perturbation: Modal Analysis and EMT Studies

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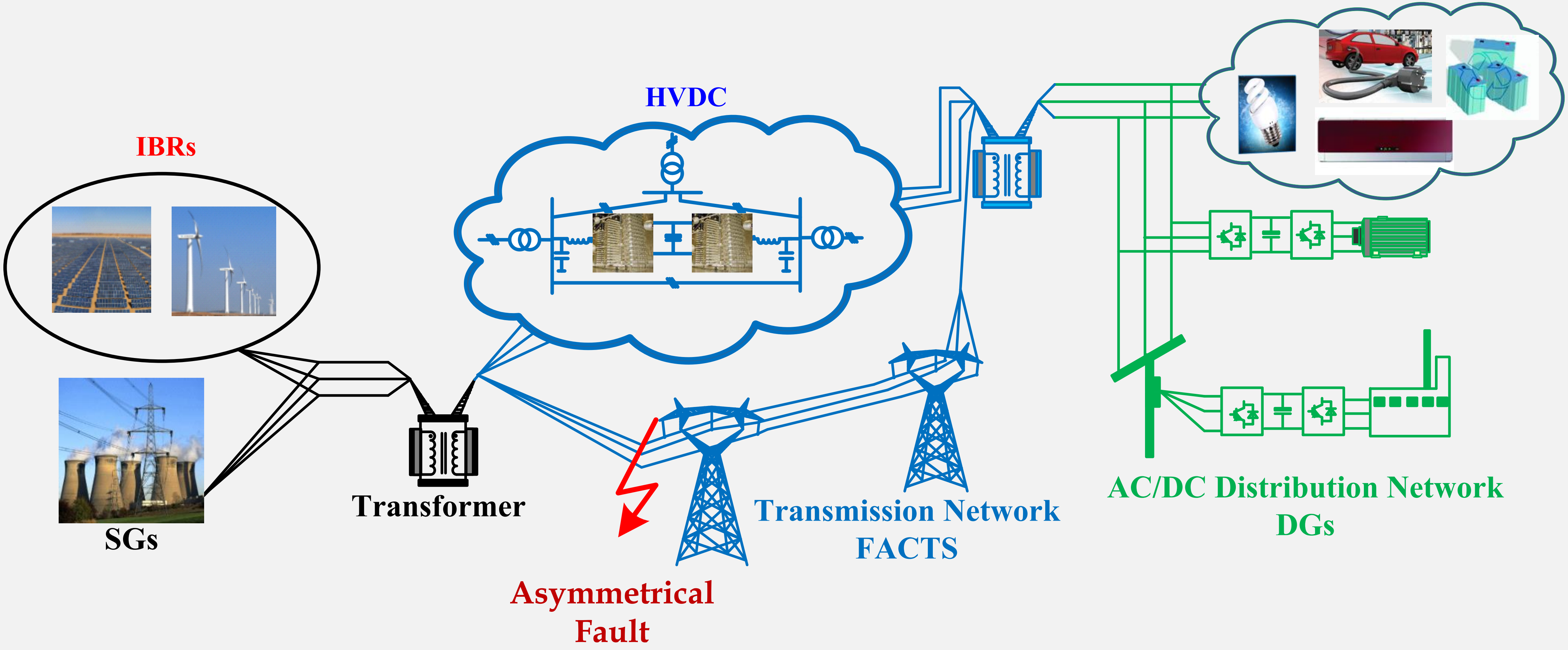
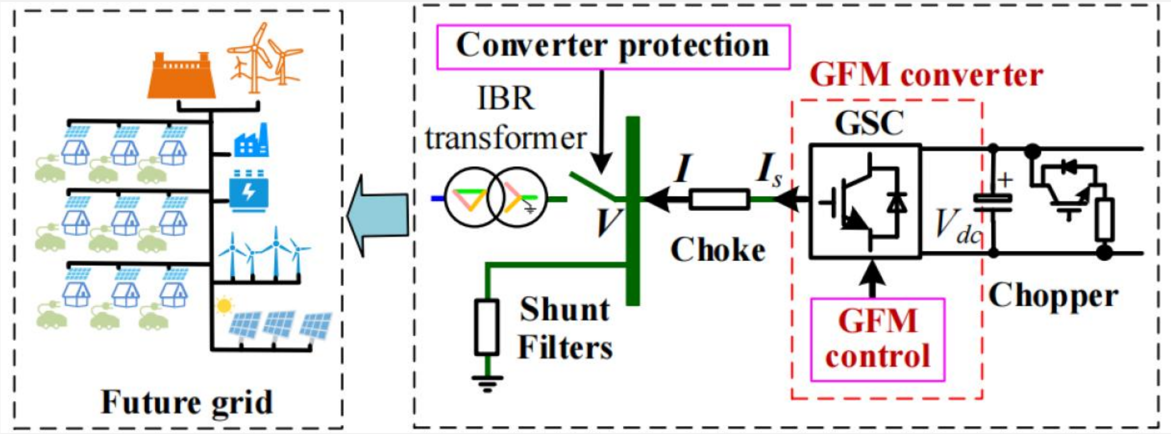
1. Introduction



1. Introduction



Grid-forming inverter-based resources (GFM-IBRs) are considered crucial for power systems with high penetration renewable energy, but their negative sequence behavior under small perturbations remains understudied.

- Develop a decoupled-sequence modeling approach for GFM-IBRs that incorporates double-fundamental-frequency (2ω) negative-sequence components.
- Analyze the oscillatory modes of GFM-IBRs in the negative-sequence system using modal analysis and EMT studies.
- Evaluate the effectiveness of additional negative sequence control strategies in improving system damping.

2. Oscillation under Unbalanced Perturbation

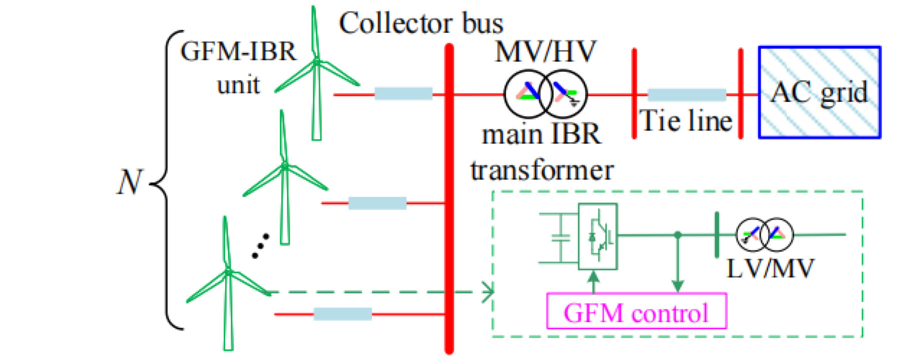


Fig. 1. GFM-IBR plant in power systems

Unbalanced AC grid conditions

$$\boldsymbol{X}_{dq} = \begin{bmatrix} X_\alpha \cos(\theta) + X_\beta \sin(\theta) \\ X_\beta \cos(\theta) - X_\alpha \sin(\theta) \end{bmatrix} = \boldsymbol{X}_{dq}^{+} + \begin{bmatrix} X_d^- \cos(2\omega t) + X_q^- \sin(2\omega t) \\ X_q^- \cos(2\omega t) - X_d^- \sin(2\omega t) \end{bmatrix} = \boldsymbol{X}_{dq}^{+} + \tilde{\boldsymbol{X}}_{dq}^{-}$$

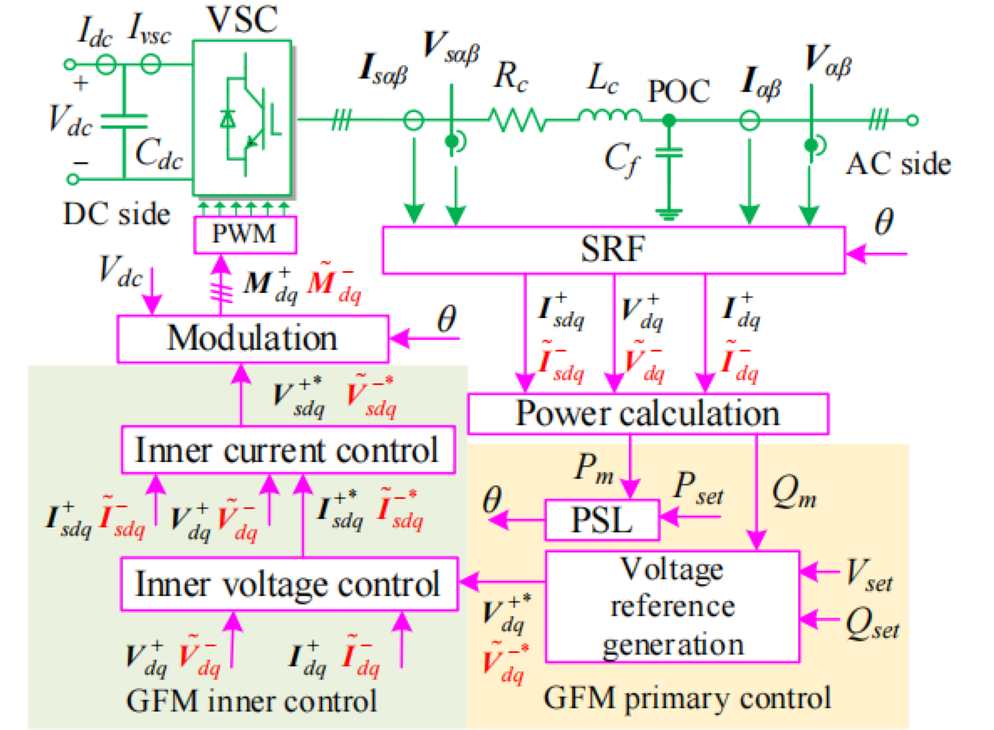


Fig. 2. Sequence components within the typical GFM BPSC system under unbalanced perturbations

- Under unbalanced perturbations, positive-, negative- and zero-sequence components of both voltages and currents are typically present in the AC grid.
- 2ω components exist in the control loop

3. Decoupled-Sequence Dynamic Modelling for GFM-IBRs

GFM primary control:

VSM control

$$\begin{cases}\dot{\omega} = \frac{(P_{set}-x_P)}{J\omega_n} + \frac{D_p(\omega_n-\omega)}{J} \\ \dot{x}_P = \omega_f(P_m - x_P)\end{cases}$$

$$V_d = V_d^+ + \tilde{V}_d^- = V_d^+ + V_d^- \cos(2\omega t) + V_q^- \sin(2\omega t)$$

$$\psi_M = \psi_M^+ + \tilde{\psi}_M^-$$

$$\begin{cases}\psi_M^+ = k_{pvac}\underbrace{(V_{set} - V_d^+)}_{\dot{x}_V^+} + k_{ivac}x_V^+ \\ \tilde{\psi}_M^- = k_{pvac}\underbrace{(0 - \tilde{V}_d^-)}_{\dot{\tilde{x}}_V^-} + k_{ivac}\tilde{x}_V^-\end{cases}$$

$$\begin{cases}\mathbf{V}_{dq}^{+*} = \mathbf{T}_{dq}(\theta)\mathbf{T}_{\alpha\beta}\omega\psi_M^+ \sin(\hat{\theta}) \\ \tilde{\mathbf{V}}_{dq}^{-*} = \mathbf{T}_{dq}(\theta)\mathbf{T}_{\alpha\beta}\omega\tilde{\psi}_M^- \sin(\hat{\theta}) \\ \sin(\hat{\theta}) = \left[\sin(\theta) \quad \sin(\theta - \frac{2\pi}{3}) \quad \sin(\theta - \frac{4\pi}{3})\right]^T\end{cases}$$

droop control

$$\omega = \omega_n - m_p(P_m - P_{set})$$

$$\begin{cases}V_d^* = V_d^{+*} + \tilde{V}_d^{-*} \\ V_q^* = 0\end{cases}$$

$$\begin{cases}V_d^{+*} = k_{pvac}\underbrace{(V_{set} - V_d^+)}_{\dot{x}_V^+} + k_{ivac}x_V^+ \\ \tilde{V}_d^{-*} = k_{pvac}\underbrace{(0 - \tilde{V}_d^-)}_{\dot{\tilde{x}}_V^-} + k_{ivac}\tilde{x}_V^-\end{cases}$$

dVOC

$$\begin{cases}\omega = \omega_n + \kappa_1\left(\frac{P_{set}}{(V_{set})^2} - \frac{x_P}{(V_d^*)^2}\right) \\ \dot{x}_P = \omega_f(P_m - x_P)\end{cases}$$

$$\begin{cases}\dot{V}_d^* = V_d^*\left(\kappa_1\left(\frac{Q_{set}}{(V_{set})^2} - \frac{x_Q}{(V_d^*)^2}\right) + \frac{\kappa_2(V_{set}^2-(V_d^*)^2)}{V_{set}^2}\right) \\ \dot{x}_Q = \omega_f(Q_m - x_Q)\end{cases}$$

3. Decoupled-Sequence Dynamic Modelling for GFM-IBRs

GFM inner control:

$$\boldsymbol{X} = \{I, V, I_s\}$$

$$\boldsymbol{X}_{dq} = \boldsymbol{X}_{dq}^{+} + \widetilde{\boldsymbol{X}}_{dq}^{-} = \begin{bmatrix} X_d^{+} + X_d^{-}\cos(2\omega t) + X_q^{-}\sin(2\omega t) \\ X_q^{+} + X_q^{-}\cos(2\omega t) - X_d^{-}\sin(2\omega t) \end{bmatrix}$$

$$\begin{cases} \boldsymbol{I}_{sdq}^{+*} = k_{iv}\boldsymbol{x}_{Vdq}^{+} + k_{pv}\underbrace{(\boldsymbol{V}_{dq}^{+*} - \boldsymbol{V}_{dq}^{+})}_{\dot{\boldsymbol{x}}_{Vdq}^{+}} + \underbrace{\boldsymbol{\gamma} C_f \boldsymbol{V}_{dq}^{+} + \boldsymbol{I}_{dq}^{+}}_{\text{feedforward}} \\ \widetilde{\boldsymbol{I}}_{sdq}^{-*} = k_{iv}\widetilde{\boldsymbol{x}}_{Vdq}^{-} + k_{pv}\underbrace{(\widetilde{\boldsymbol{V}}_{dq}^{-*} - \widetilde{\boldsymbol{V}}_{dq}^{-})}_{\dot{\widetilde{\boldsymbol{x}}}_{Vdq}^{-}} + \underbrace{\boldsymbol{\gamma} C_f \widetilde{\boldsymbol{V}}_{dq}^{-} + \widetilde{\boldsymbol{I}}_{dq}^{-}}_{\text{feedforward}} \end{cases}$$

$$\begin{cases} \boldsymbol{V}_{sdq}^{+*} = k_{pi}\underbrace{(\boldsymbol{I}_{dq}^{+*} - \boldsymbol{I}_{dq}^{+})}_{\dot{\boldsymbol{x}}_{Idq}^{+}} + k_{ii}\boldsymbol{x}_{Idq}^{+} + \underbrace{\boldsymbol{\gamma} L_c \boldsymbol{I}_{dq}^{+} + \boldsymbol{V}_{dq}^{+}}_{\text{feedforward}} \\ \widetilde{\boldsymbol{V}}_{sdq}^{-*} = k_{pi}\underbrace{(\widetilde{\boldsymbol{I}}_{dq}^{-*} - \widetilde{\boldsymbol{I}}_{dq}^{-})}_{\dot{\widetilde{\boldsymbol{x}}}_{Idq}^{-}} + k_{ii}\widetilde{\boldsymbol{x}}_{Idq}^{-} + \underbrace{\boldsymbol{\gamma} L_c \widetilde{\boldsymbol{I}}_{dq}^{-} + \widetilde{\boldsymbol{V}}_{dq}^{-}}_{\text{feedforward}} \end{cases}$$

$$\begin{cases} \boldsymbol{M}_{dq}^{+} = \frac{2}{V_{dc}}\boldsymbol{V}_{sdq}^{+*} \\ \widetilde{\boldsymbol{M}}_{dq}^{-} = \frac{2}{V_{dc}}\widetilde{\boldsymbol{V}}_{sdq}^{-*} \end{cases} \qquad \boldsymbol{M}_{dq}^{-} = \begin{bmatrix} \widetilde{M}_d^{-}\cos(2\omega t) - \widetilde{M}_q^{-}\sin(2\omega t) \\ \widetilde{M}_q^{-}\cos(2\omega t) + \widetilde{M}_d^{-}\sin(2\omega t) \end{bmatrix}$$

GFM PNSC System

Balanced voltage control strategy:

$$\begin{cases} \boldsymbol{V}_{dq}^{-*} = 0 \\ \boldsymbol{I}_{sdq}^{-*} = (k_{pv} + \frac{k_{iv}}{s})(\boldsymbol{V}_{dq}^{-*} - \boldsymbol{V}_{dq}^{-}) + \boldsymbol{\gamma} C_f \boldsymbol{V}_{dq}^{-} + \boldsymbol{I}_{dq}^{-} \\ \boldsymbol{V}_{sdq}^{-*} = (k_{pi} + \frac{k_{ii}}{s})(\boldsymbol{I}_{sdq}^{-*} - \boldsymbol{I}_{sdq}^{-}) + \boldsymbol{\gamma} L_c \boldsymbol{I}_{sdq}^{-} + \boldsymbol{V}_{dq}^{-} \\ \boldsymbol{M}_{dq}^{-} = \frac{2}{V_{dc}}\boldsymbol{V}_{sdq}^{-*} \end{cases}$$

Balanced current control strategy:

$$\begin{cases} \boldsymbol{I}_{sdq}^{-*} = 0 \\ \boldsymbol{V}_{sdq}^{-*} = (k_{pi} + \frac{k_{ii}}{s})(\boldsymbol{I}_{sdq}^{-*} - \boldsymbol{I}_{sdq}^{-}) + \boldsymbol{\gamma} L_c \boldsymbol{I}_{sdq}^{-} + \boldsymbol{V}_{dq}^{-} \\ \boldsymbol{M}_{dq}^{-} = \frac{2}{V_{dc}}\boldsymbol{V}_{sdq}^{-*} \end{cases}$$

3. Decoupled-Sequence Dynamic Modelling for GFM-IBRs

AC and DC systems

$$\begin{cases} I_{dcset} = k_{Vdc}(V_{dcset} - V_{dc}) \\ \dot{I}_{dc} = \frac{I_{dcset} - I_{dc}}{T_{dc}} \\ \dot{V}_{dc} = \frac{I_{dc} - I_{vsc}}{C_{dc}} = \frac{I_{dc} - \frac{1}{2}(\boldsymbol{M}_{\alpha\beta})^T \boldsymbol{I}_{s\alpha\beta}}{C_{dc}} \end{cases}$$

$$\begin{cases} \dot{\boldsymbol{I}}_{sdq}^{+} = \frac{\boldsymbol{V}_{sdq}^{+} - R_c \boldsymbol{I}_{sdq}^{+} - \boldsymbol{V}_{dq}^{+}}{L_c} + \boldsymbol{\gamma} \boldsymbol{I}_{sdq}^{+} \\ \dot{\boldsymbol{I}}_{sdq}^{-} = \frac{\boldsymbol{V}_{sdq}^{-} - R_c \boldsymbol{I}_{sdq}^{-} - \boldsymbol{V}_{dq}^{-}}{L_c} + \boldsymbol{\gamma} \boldsymbol{I}_{sdq}^{-} \end{cases}$$

$$\begin{cases} \dot{\boldsymbol{V}}_{dq}^{+} = \frac{\boldsymbol{I}_{sdq}^{+} - \boldsymbol{I}_{dq}^{+}}{C_f} + \boldsymbol{\gamma} \boldsymbol{V}_{dq}^{+} \\ \dot{\boldsymbol{V}}_{dq}^{-} = \frac{\boldsymbol{I}_{sdq}^{-} - \boldsymbol{I}_{dq}^{-}}{C_f} + \boldsymbol{\gamma} \boldsymbol{V}_{dq}^{-} \end{cases}$$

Linearization

$$\begin{cases} \Delta \boldsymbol{x} = \left[\Delta \boldsymbol{x}_{dq}^{+} \quad \Delta \boldsymbol{x}_{dq}^{-} \quad \Delta \boldsymbol{x}_{s} \quad \Delta \boldsymbol{x}_{dc}\right]^T \\ \Delta \dot{\boldsymbol{x}} = \boldsymbol{A} \Delta \boldsymbol{x} + \boldsymbol{B} \Delta \boldsymbol{u} \end{cases}$$

$$\Delta \boldsymbol{x}_{dq}^{+} = \left[\underbrace{\Delta \boldsymbol{I}_{sdq}^{+} \quad \Delta \boldsymbol{V}_{dq}^{+}}_{\text{AC system}} \quad \underbrace{\Delta \boldsymbol{x}_{Vdq}^{+} \quad \Delta \boldsymbol{x}_{Idq}^{+}}_{\text{Inner control}}\right]^T$$

$$\Delta \boldsymbol{x}_{dq}^{-} = \left[\underbrace{\Delta \boldsymbol{I}_{sdq}^{-} \quad \Delta \boldsymbol{V}_{dq}^{-}}_{\text{AC system}} \quad \underbrace{\Delta \boldsymbol{x}_{Vdq}^{-} \quad \Delta \boldsymbol{x}_{Idq}^{-}}_{\text{Inner control}}\right]^T$$

$$\Delta \boldsymbol{x}_{dc} = \left[\underbrace{\Delta \boldsymbol{I}_{dc} \quad \Delta \boldsymbol{V}_{dc}}_{\text{DC system}}\right]^T$$

GFM$_{\text{VSM}}$

$$\Delta \boldsymbol{x}_{s} = \left[\Delta \boldsymbol{x}_{V}^{+} \quad \Delta \boldsymbol{x}_{V}^{-} \quad \Delta\theta \quad \Delta\omega \quad \Delta x_P\right]^T$$

$$\Delta \boldsymbol{u} = \left[\Delta \boldsymbol{I}_{dq}^{+} \quad \Delta \boldsymbol{I}_{dq}^{-} \quad \underbrace{\Delta P_{set} \quad \Delta V_{set}}_{\text{VSM control input}}\right]^T$$

GFM$_{\text{droop}}$

$$\Delta \boldsymbol{x}_{s} = \left[\Delta \boldsymbol{x}_{V}^{+} \quad \Delta \boldsymbol{x}_{V}^{-} \quad \Delta\theta \quad \Delta x_P\right]^T$$

$$\Delta \boldsymbol{u} = \left[\Delta \boldsymbol{I}_{dq}^{+} \quad \Delta \boldsymbol{I}_{dq}^{-} \quad \underbrace{\Delta P_{set} \quad \Delta V_{set}}_{\text{droop control input}}\right]^T$$

GFM$_{\text{dVOC}}$

$$\Delta \boldsymbol{x}_{s} = \left[\Delta\theta \quad \Delta V_d^{*} \quad \Delta x_P \quad \Delta x_Q\right]^T$$

$$\Delta \boldsymbol{u} = \left[\Delta \boldsymbol{I}_{dq}^{+} \quad \Delta \boldsymbol{I}_{dq}^{-} \quad \underbrace{\Delta P_{set} \quad \Delta Q_{set} \quad \Delta V_{set}}_{\text{dVOC input}}\right]^T$$

4. Dynamic model vs. EMT model

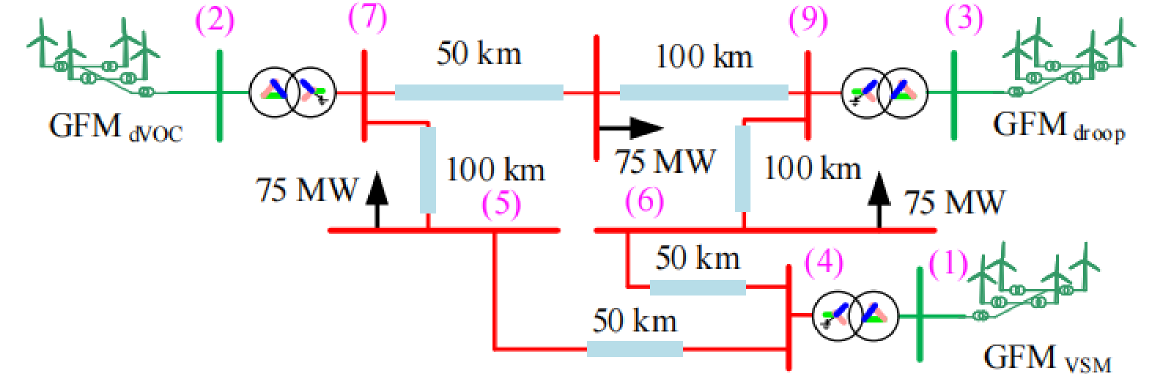


Fig. 3. Test system: 100% GFM-IBR-dominated system

TABLE AI
PARAMETER CONFIGURATION OF GFM-IBRS

Parameter	Value	Parameter	Value
N	200	(k_{pvac}, k_{ivac})	(0.001, 0.0021)
(T_{dc}, k_{Vdc})	(0.05 s, 0.83)	(k_{pv}, k_{iv})	(0.52,232.2)
ω_n	314 rad/s	(k_{pi}, k_{ii})	(0.73, 0.0059)
ω_f	31.4 rad/s	(P_{set}, Q_{set})	(1 pu, 0 pu)
(D_p, J)	(1.01e5, 2.02e3)	(V_{set}, V_{dcset})	(1 pu, 2.45 kV)
(κ_1, κ_2)	(0.0209, 1.39e3)	m_p	3.14e-8
(R_c, L_c)	(5e-6 Ω, 1e-6 H)	(C_{dc}, C_f)	(1.6 F, 0.06 F)
T_{rm}	230 kV /13.8 kV	T_{ru}	13.8 kV/1 kV

In test system, GFM-IBR operates at P_m=75 MW. For illustration, when t=15 s, a 75 MW unbalanced load is applied at Bus (6), resulting in the imbalance of grid voltages and currents.

The time step and simulation duration are set to 100 μs and 20 s, respectively.

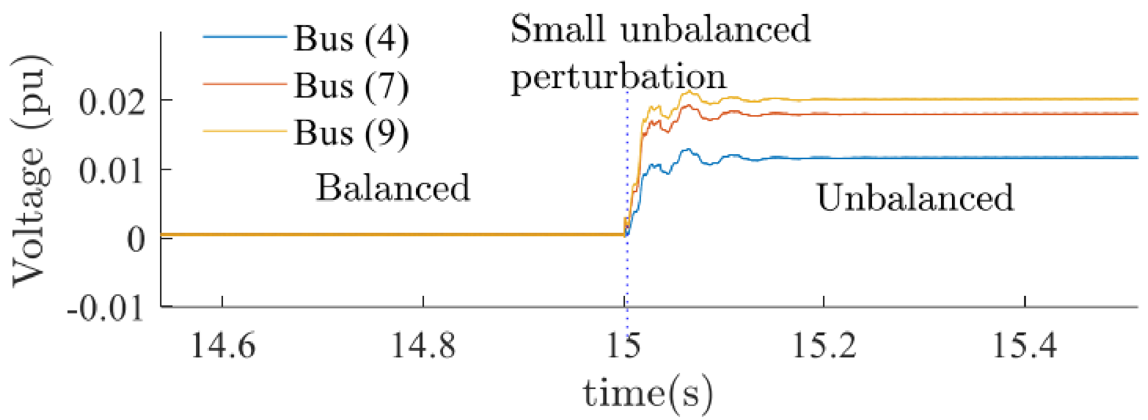


Fig. 4. Magnitude of negative-sequence grid voltages using EMT simulation

4. Dynamic model vs. EMT model

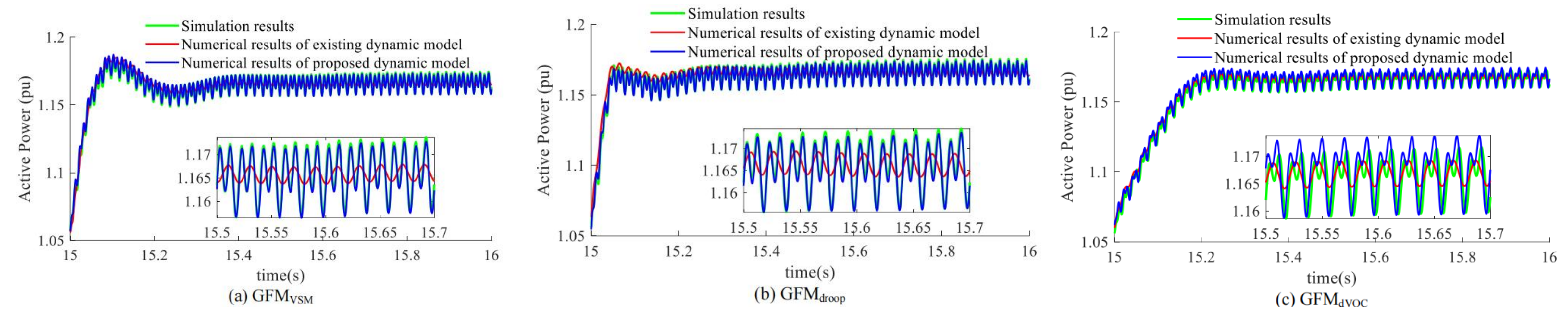


Fig. 5. Numerical results and EMT simulation results of active power responses of GFM-IBRs

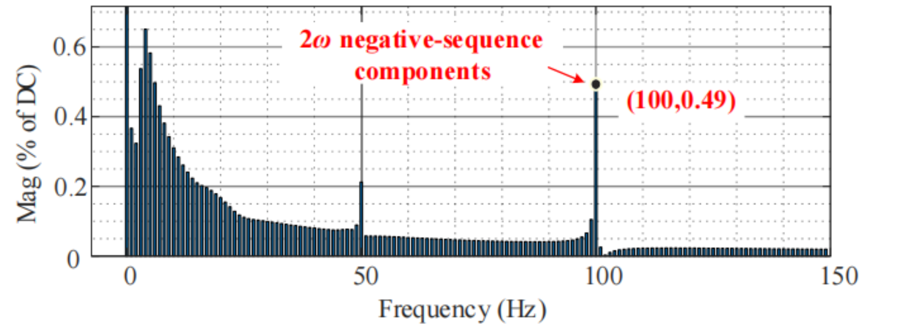


Fig. 6. FFT analysis based on EMT simulation results of active power response of GFM$_{VSM}$

During the interval t=15−15.2 s, the transient dynamics of active power differ among GFM-IBRs due to each plant's different primary control strategies. Under steady-state unbalanced grid conditions, the dynamics of the proposed model are highly consistent with the EMT simulations. In addition, Fig. 6 shows that the 100% GFM-IBR-dominated system can still provide a path for the flow of 2ω negative-sequence components.

5. Modal Analysis and EMT Studies for GFM-IBRs

A. Oscillatory Modes of GFM-IBRs under Small Unbalanced Perturbations

Based on the state-space matrix derived from the proposed dynamic model, the eigenvalue-based stability assessment (EBSA) is used to study the impacts of control settings and negative-sequence control solutions on oscillatory modes dominated by 2ω negative-sequence components.

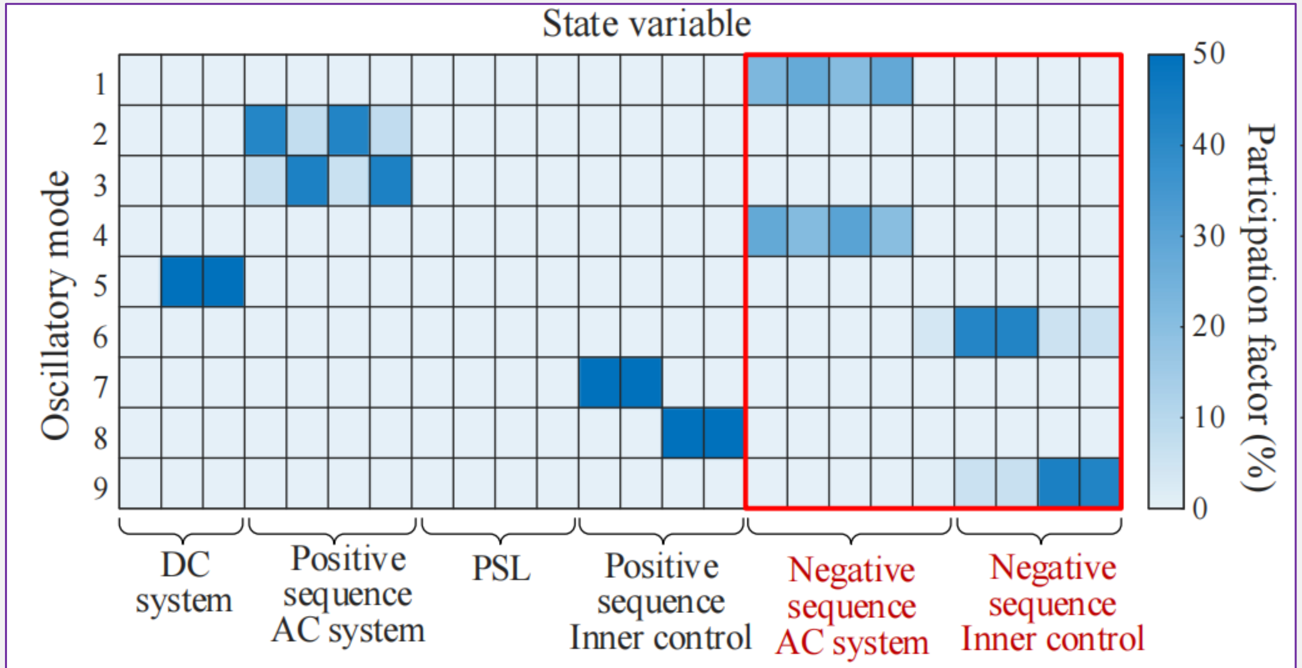


Fig. 7. Participation factors of GFM_{VSM}

5. Modal Analysis and EMT Studies for GFM-IBRs

A. Oscillatory Modes of GFM-IBRs under Small Unbalanced Perturbations

TABLE I
OSCILLATORY MODES OF GFM_{VSM}

Mode	Λ	δ	f/Hz	Dominant Variables
1	**-1719±2524i**	**0.56**	**401.82**	ΔI^-_{sdq} ΔV^-_{dq}
2	-1931±2264i	0.65	360.45	ΔI^+_{sd} ΔV^+_{d}
3	-1763±1718i	0.72	273.55	ΔI^+_{sq} ΔV^+_{q}
4	**-1976±1457i**	**0.80**	**231.89**	ΔI^-_{sdq} ΔV^-_{dq}
5	-7.20±143.7i	0.05	22.88	ΔI_{dc} ΔV_{dc}
6	**-2.17±0.73i**	**0.95**	**0.12**	Δx^-_{Vdq}
7	-2.23±0.0015i	1.00000	0.00025	Δx^+_{Vdq}
8	-1.61±0.0007i	1.00000	0.00012	Δx^+_{Idq}
9	**-1.53±0.0510i**	**0.99945**	**0.00812**	Δx^-_{Idq}

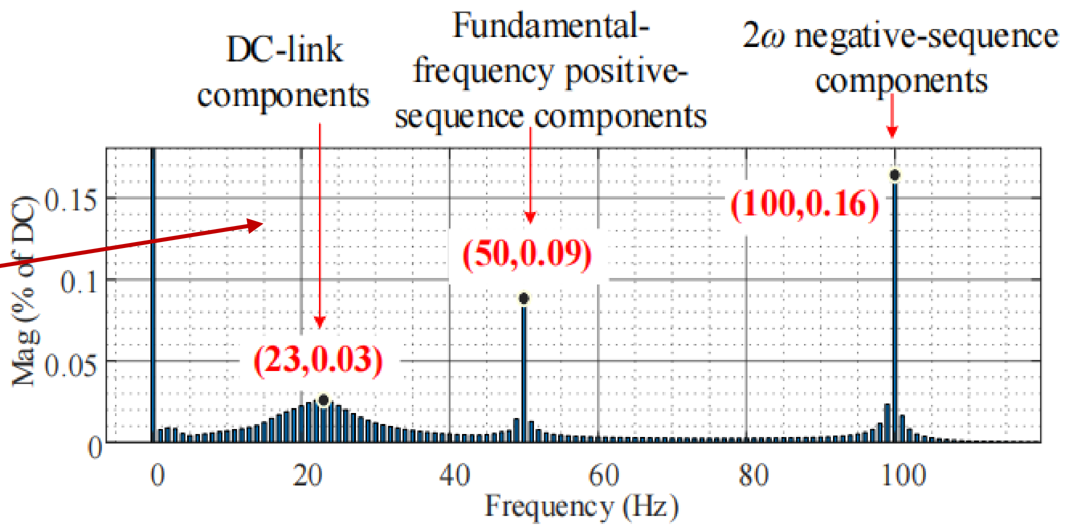


Fig. 8. FFT analysis based on EMT simulation results of the DC-link voltage under small, unbalanced perturbations

The 2ω negative-sequence components induce undesirable oscillations across various frequencies, substantially degrading system dynamic performance. This critical effect is often overlooked in conventional dynamic models that neglect negative-sequence components.

5. Modal Analysis and EMT Studies for GFM-IBRs

B. Impact of Negative-Sequence Control Solutions on Oscillatory Modes

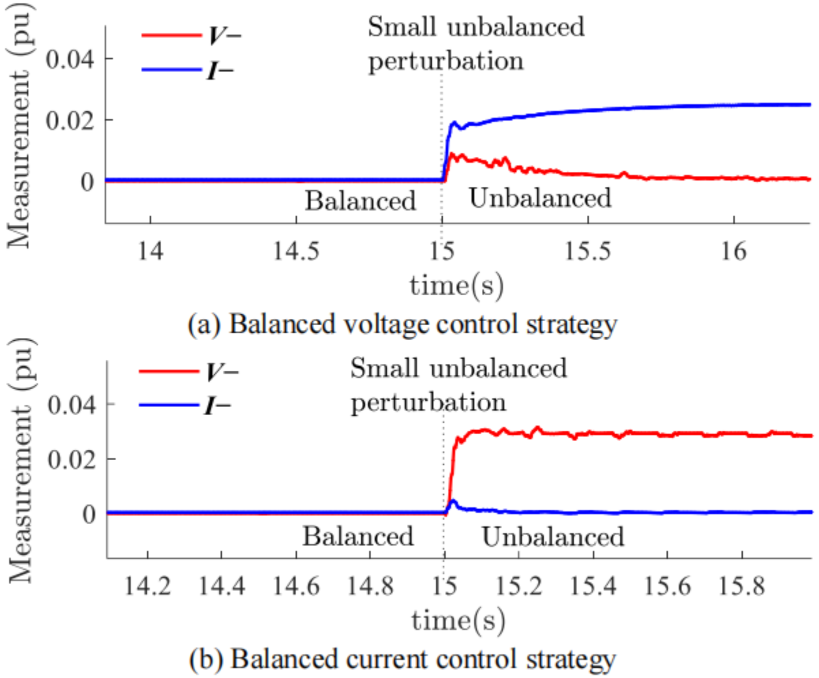


Fig. 9. EMT simulation results with negative-sequence control solutions in PNSC

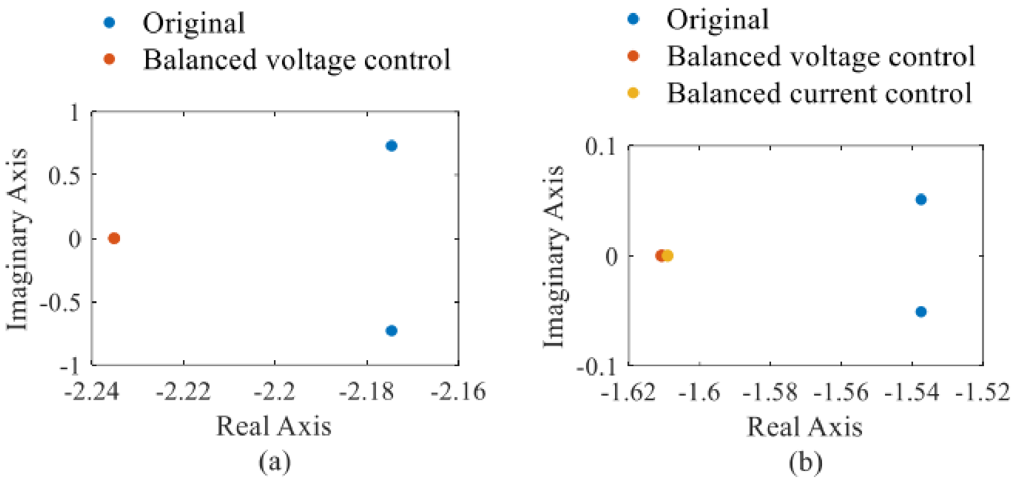


Fig. 10. Oscillatory modes dominated by negative-sequence components under BPSC and PNSC strategies: (a) Modes dominated by $\Delta \boldsymbol{x}_{Vdq}^{-}$; (b) Modes dominated by $\Delta \boldsymbol{x}_{Ida}^{-}$.

The additional negative-sequence control solution can eliminate the oscillation, thus improving the control damping of GFM-IBRs.

6. Conclusions

This paper introduces a novel generic decoupled-sequence dynamic model for GFM-IBRs, providing crucial insights into the behavior of 2ω negative-sequence components within the GFM BPSC system under small, unbalanced perturbations.

1. Impact of Negative Sequence Components: The 2ω negative-sequence components induce undesirable oscillations across various frequencies, substantially degrading system dynamic performance. This critical effect is often overlooked in conventional dynamic models that neglect negative-sequence components.

2. Effectiveness of Negative-Sequence Control: Implementing balanced current and voltage control strategies shifts oscillatory modes leftward and reduces their imaginary components to zero. This finding suggests the adoption of supplementary negative-sequence controls in GFM-IBRs to enhance control damping under small, unbalanced perturbations.

The proposed model and analysis method provide a powerful methodology for understanding and mitigating the impacts of negative-sequence behavior on system dynamics in GFM-IBR-dominated grids. While this study employs EBSA to focus on oscillatory mode analysis rather than instability mechanisms, it lays a foundation for future research.

Thank you!
Q&A

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