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Design of Multifunctional Electromagnetic Transient Model for Grid-Forming Inverters

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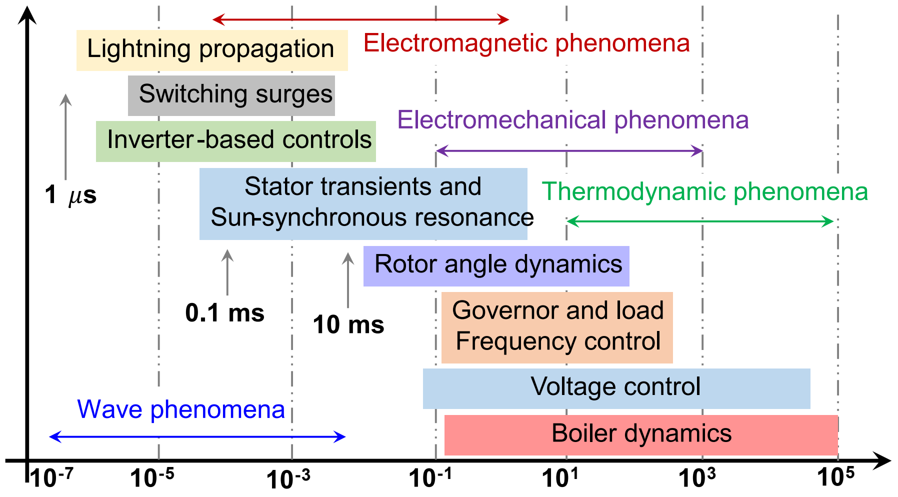
IMPORTANCE OF EMT MODEL

- Grid-forming (GFM) inverters have been a critical technology to enhance grid stability under high renewable penetration levels.
- The figure shows the timescale of inverter-based resource (IBR) control:
  - Between multiple μs and multiple ms
  - It is much smaller than that of the SGs.
- The electromagnetic transient (EMT) phenomena are of particular interest for an IBR-dominant system, particularly with GFM inverters.
- Modeling GFM IBRs provides a fundamental understanding of GFM IBR-related dynamics.
  - Developing high-fidelity GFM IBR models has been an urgent and mandatory task for academia and industry.
  - Developing a GFM EMT model is a high priority because the EMT model provides the necessary and accurate transients for stability analysis and fault studies.



[1] N. Hatziargyriou et al., "Definition and Classification of Power System Stability—Revised & Extended," *IEEE Tran. Power Systems*, vol. 36, no. 4, pp. 3271-3281, 2021.

Bird's-Eye View of GFM Inverter Model

- It is a single black box with flexibility in selecting the MVA rating.
- It is suitable for transmission systems, complies with IEEE Std. 2800[2].
- It is suitable for interfacing various types and combinations of DC sources:
  - PV module, battery module, ideal DC voltage source
  - Any combination of these DC types.
- IBR model covers:
  - Switching models
  - Averaged models.
- It includes large sets of control logic that covers:
  - Dominant GFM control: droop and virtual synchronous machine (VSM)
  - An exhaustive list of inner current control.
- It includes large sets of current-limiting protection logic that covers:
  - Instantaneous current saturation limiter
  - Current latching limiter
  - Anti-windup protections
  - Active and reactive current priorities.

DC Source [$\mathcal{S}$]	Inverter Model [$\mathcal{M}$]
$\mathcal{S}1$: PV module	$\mathcal{M}1$: switching model
$\mathcal{S}2$: Battery module	
$\mathcal{S}3$: Ideal voltage source	$\mathcal{M}2$: Averaged model
$\mathcal{S}4$: Any combination	

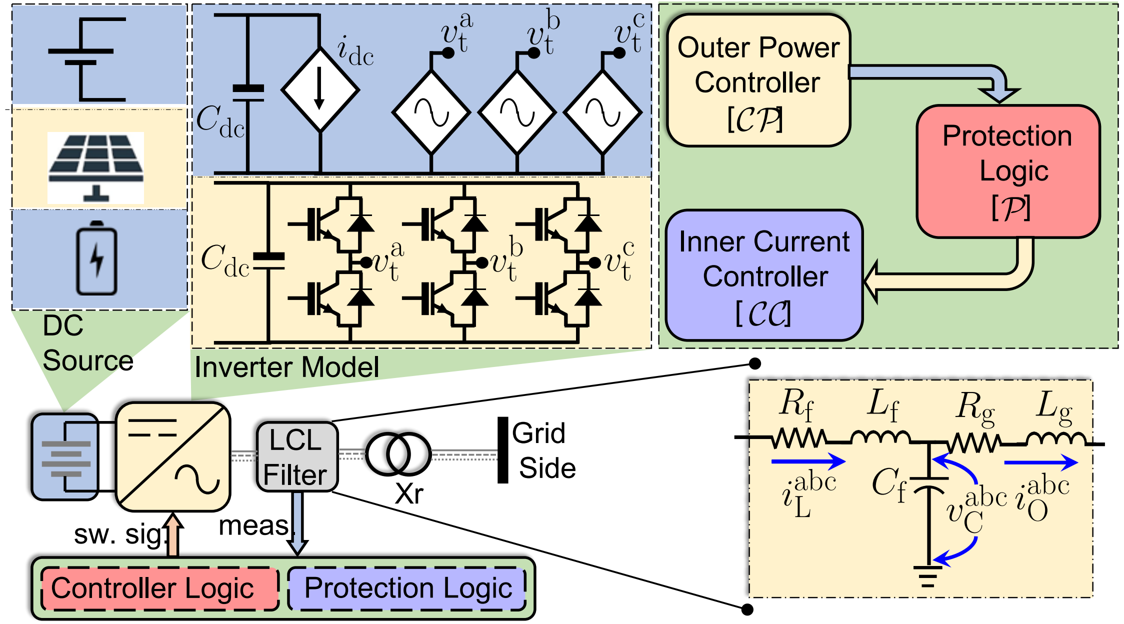
Controller Logic [$\mathcal{C}$]		
Primary Control [$\mathcal{PC}$]	Outer Voltage [$\mathcal{VC}$]	Inner Current [$\mathcal{CC}$]
$\mathcal{PC}1$: Pf-QV droop	$\mathcal{VC}1$: dq domain	$\mathcal{CC}1$: dq domain
$\mathcal{PC}2$: Virtual synchronous machine	$\mathcal{VC}2$: $\alpha\beta$ domain	$\mathcal{CC}2$: $\alpha\beta$ domain
	$\mathcal{VC}3$: Sequence domain	$\mathcal{CC}3$: Sequence domain

Limiter Logic [$\mathcal{L}$]		
Current Limiter [$\mathcal{LC}$]		Windup [$\mathcal{PW}$]
Saturation – based [$\mathcal{LCS}$]		$\mathcal{PW}1$: Anti-windup for PI controller
$\mathcal{LCS}1$: d-axis priority	$\mathcal{LCS}2$: q-axis priority	
Latching – based [$\mathcal{LCL}$]		$\mathcal{PW}2$: Anti-windup for PR controller
$\mathcal{LCL}1$: d-axis priority	$\mathcal{LCL}2$: q-axis priority	
Virtual impedance – based [$\mathcal{LCV}$]		-

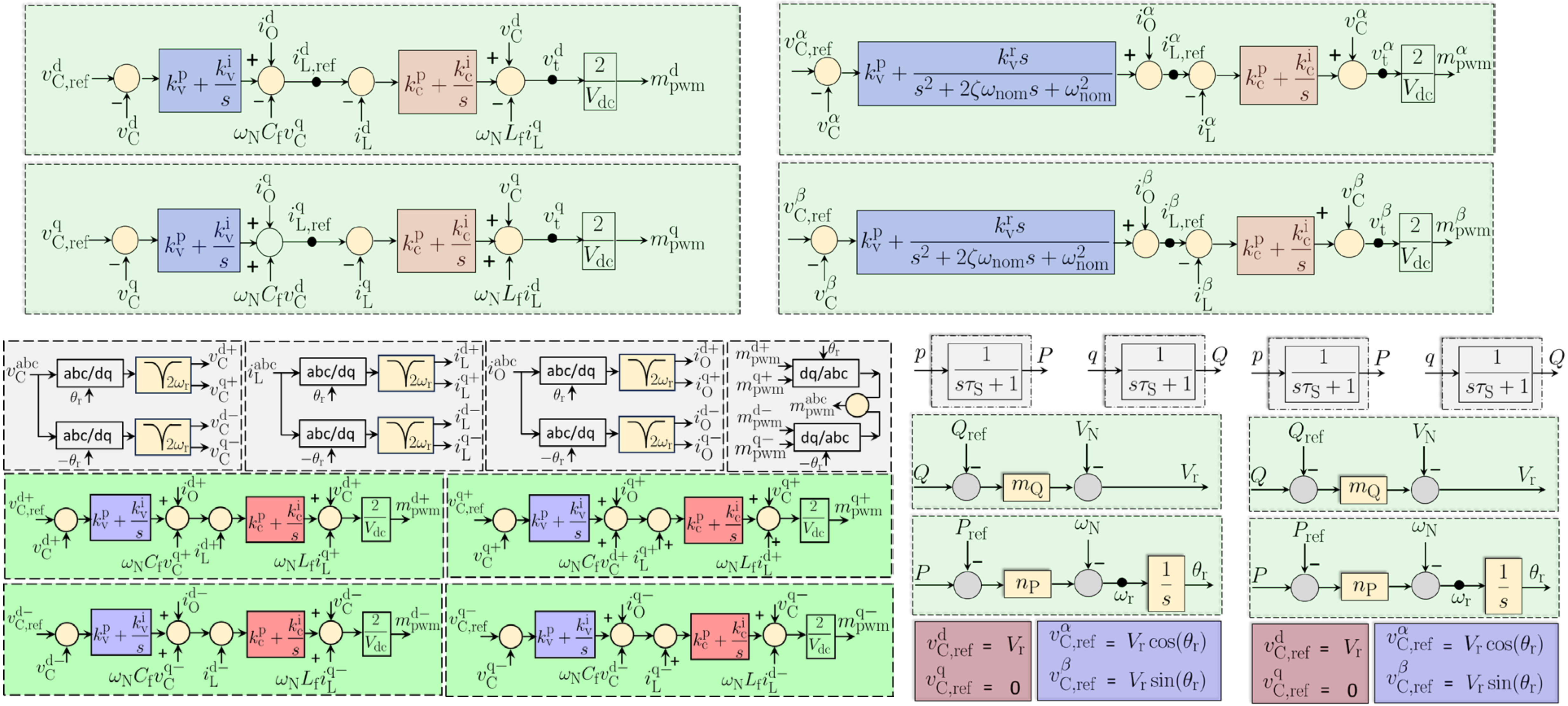
[2] IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems, in IEEE Std 2800-2022 , vol., no., pp.1-180, 22 April 2022, doi: 10.1109/IEEESTD.2022.9762253.

Bird's-Eye View of GFM Inverter Model

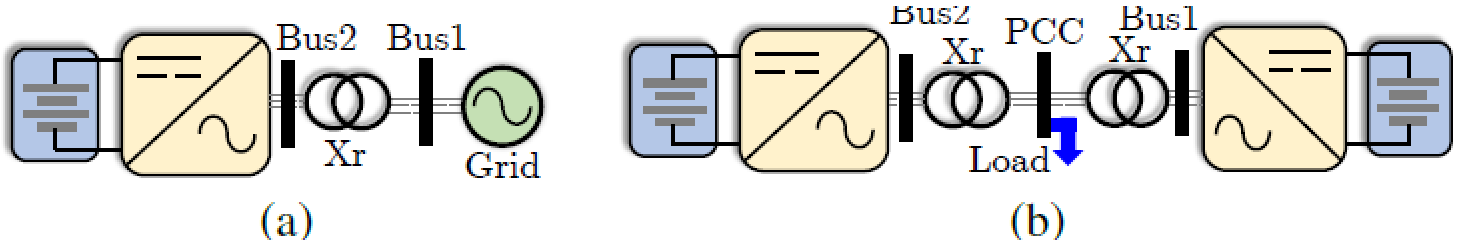
- The IBR is connected to a 34.5-kV grid via a step-up transformer of the rating of the three-phase, 0.48/34.5-kV, 1.5-MVA Yg-Δ transformer.
- The power circuit consists of the "inverter model" interfaced with the "DC source" of voltage, V_{dc}.
- At the output terminals, an LCL filter (L_f, L_g, C_f and associated equivalent series resistances, R_f, R_g, of the inductors) are connected.
- The main controller is responsible for generating the pulse width modulation (PWM) switching signals for the IBR based on processing the measurements.
- Inner inductor current measurements, i_L^{abc}.
- Output current measurements, i_O^{abc}.
- Capacitor voltage measurements, v_c^{abc}.
- The base model is of 1.25 MVA, and the factor decides the unit MVA.



Deep Dive Into the Model



Case Studies and Results



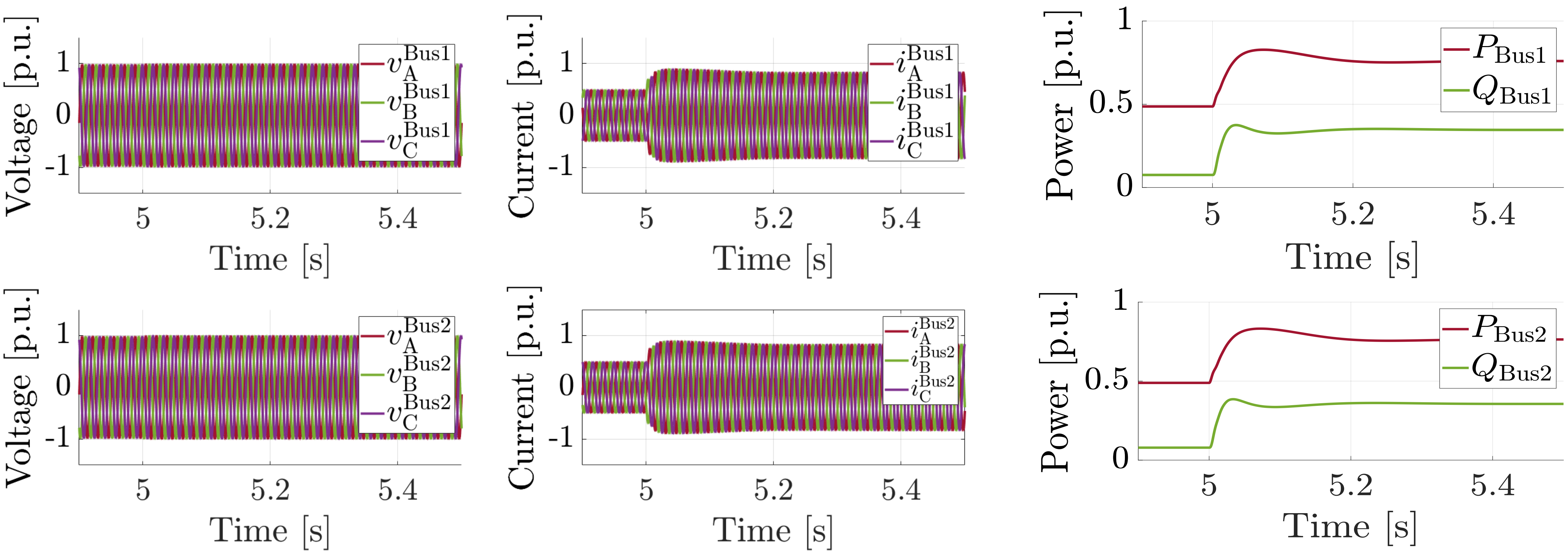
Grid-connected mode Islanded mode with another GFM in parallel

List of case studies:

- C1 (islanded mode): Switching model, DC with battery, VSM control, outer-voltage-inner-current with sequence control), saturation-based current limiter with d-priority. **Load step.**
- C2 (islanded mode): Average model, DC with battery, droop control, outer-voltage-inner-current with dq domain, virtual impedance-based current limiter. **Low-impedance fault applied.**
- C3 (grid-tied mode): Switching model, DC with battery, VSM control, outer-voltage-inner-current with αβ domain, latching-based current limiter. **Dispatchability for grid-connected mode.**
- C4 (grid-tied mode): Average model, DC with combined PV and battery, droop control, outer-voltage-inner-current in the sequence domain, saturation-based current limiter with q-priority. Unbalanced BC fault applied to the system.

Key observations:

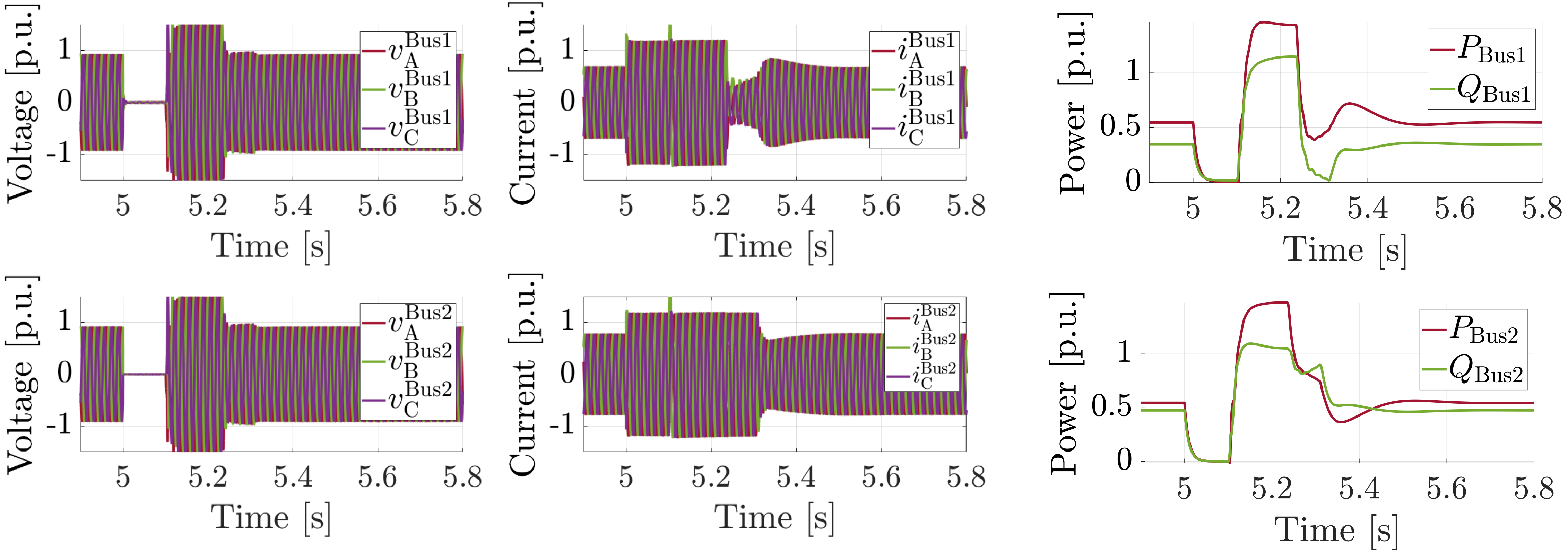
- Equal power sharing during steady state and load step change
- Smooth voltage and current waveforms
- Validated for microgrid applications.



CASE STUDIES AND RESULTS: C2

Key observations:

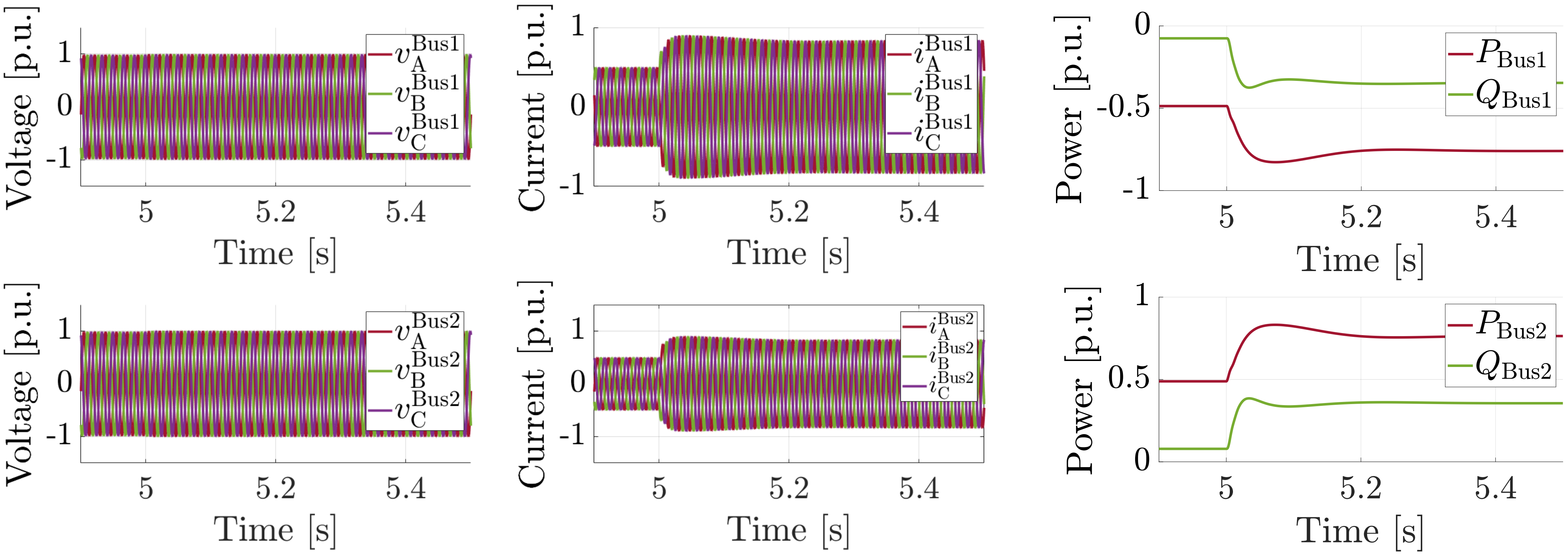
- The low-impedance fault causes a significant voltage drop, but the current limiter limits the output current to 1.2 p.u.
- Good fault recovery behavior after the fault is cleared (momentary cessation is disabled)
- Validated for fault-ride through capabilities.



CASE STUDIES AND RESULTS: C3

Key observations:

- Follows the dispatched power references during grid-connected mode
- Maintains the voltage level
- Good application for grid-connected operation.



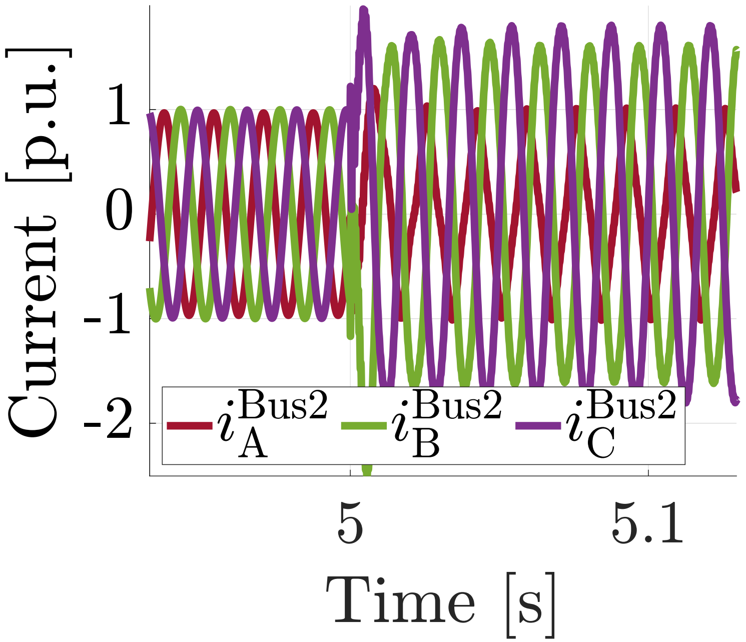
CASE STUDIES AND RESULTS: C4

Table 13 of IEEE Std. 2800

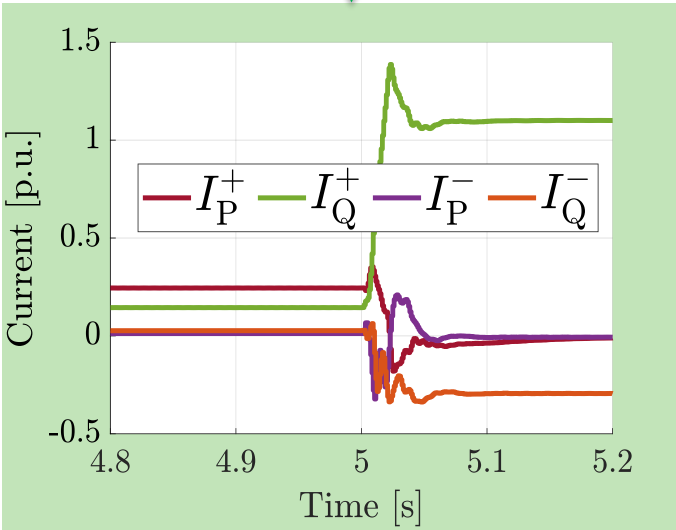
Parameter	Type III WTGs	All other IBR units
Step response time[b, c, d]	NA[a]	≤ 2.5 cycles
Settling time[b, c, d]	≤ 6 cycles	≤ 4 cycles
Settling band	−2.5%/+10% of *IBR unit maximum current*	−2.5%/+10% of *IBR unit maximum current*

$$I_{\mathrm{P}}^{+} \coloneqq |\bar{I}^{+}|\cos(\angle\bar{V}^{+} - \bar{I}^{+})$$
$$I_{\mathrm{Q}}^{+} \coloneqq |\bar{I}^{+}|\sin(\angle\bar{V}^{+} - \bar{I}^{+})$$

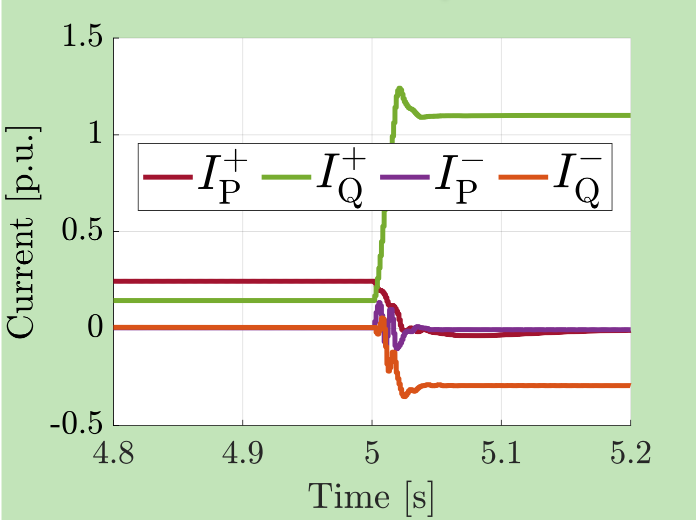
$$I_{\mathrm{P}}^{-} \coloneqq |\bar{I}^{-}|\cos(\angle\bar{V}^{-} - \bar{I}^{-})$$
$$I_{\mathrm{Q}}^{-} \coloneqq |\bar{I}^{-}|\sin(\angle\bar{V}^{-} - \bar{I}^{-})$$



Settling time is more than 6 cycles, which is not IEEE Std. 2800 compliant.



IEEE Std. 2800 compliant:
(1) settling time
(2) i2 lead v2 90°.



CONCLUSIONS

- This paper presents a generic, easy-to-scale-up MVA-rating, multifunctional, EMT dynamic model of GFL IBRs using the PSCAD software platform that complies with IEEE Std. 2800.
- The developed model includes features such as flexibility in:
  - Selecting various types and combinations of DC sources
  - Selecting either the switching or averaged model of the inverter
  - Selecting exhaustive lists of controller and protection logic.
- The generality in the power circuits and the multifunctional options in the operation and control of the developed EMT model make it suitable for both academia and industry to study various power system aspects.
- The developed model provides the user the option to study the impact of IBR power circuits and control and protection schemes on the fault behavior and will be of use to protection engineers to design protection systems.
- For transient stability analysis and for steady-state and transient operation and control of power systems interfaced with various types of GFM IBRs, this model can be used with ease and flexibility in selecting various control and protection schemes as well as types of inverter models and DC sources.

Q&A and Thank You

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