IMPERIAL

LEVERHULME TRUST

Equivalent Circuit Modeling of GFM Inverters in (Sub)-Transient Time

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I. GFM Definition & Compliance

- **Definition:** A GFM should maintain a nearly constant internal voltage source (IVS) behind an effective impedance (Z_{Eff}), a.k.a. a Thevenin Source in (sub)-transient time.
- **Location of IVS? → ST / VCP / None?**

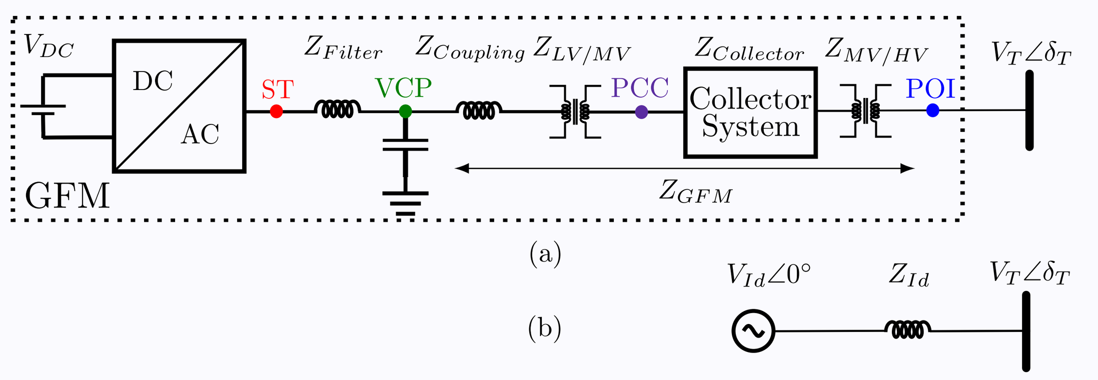

Figure 1: (a) A generic GFM plant connected to POI, (b) Ideal voltage source behind a series impedance (Z_{Id}) at POI.

- IVS location: at VCP (filter capacitor), not ST.
- IVS behind Z_{Eff} = Z_{GFM}+$Z_{Control}$.

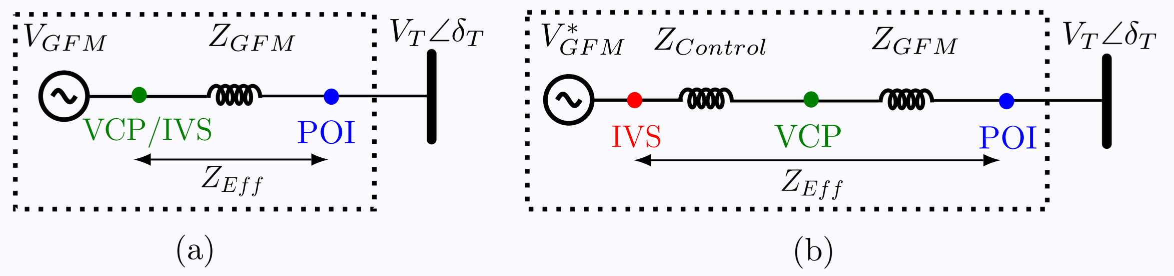

Figure 2: Equivalent GFM plant (a) without virtual impedance, (b) with virtual $Z_{Control}$.

- ENTSO-E recommends a permissible range for values of X_{Eff}; $R_{Eff}/X_{Eff} = 0.1$.

Table 1: ENTSO-E's proposed range of values of X_{Eff} (at 50 Hz) for different definitions of the POI.

Location of POI	Min (p.u.)	Default (p.u.)	Max (p.u.)
LV terminals	0.17	0.25	0.27
MV terminals	0.25	0.33	0.35
HV terminals	0.40	0.48	0.50

- **Open question:** How to quantify Z_{Eff} for a black-box GFM?

II. Admittance Spectra

- Y_{qd}/Y_{dq} → Reactive/Active power response to a voltage magnitude/phase perturbation.

$$-\begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix} = \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix} \begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix}$$

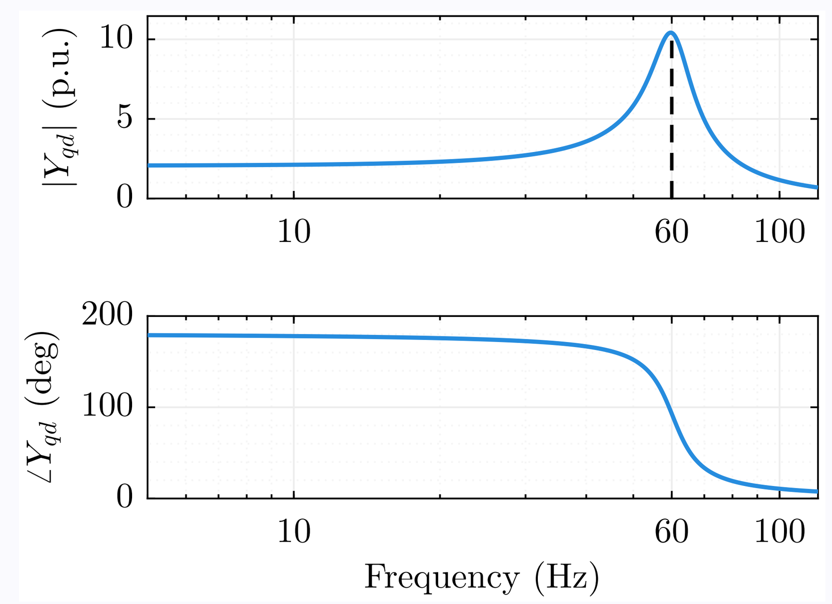

Figure 3: Y_{qd} for an ideal voltage source (HV defaults: $X_{Eff} = 0.48$ p.u., $X_{Eff}/R_{Eff} = 10$)

III. Equivalent Model

- Objective:

$$\min_{R_{th},\,L_{th}} \mathcal{J}(R_{th}, L_{th}) = \sqrt{\sum_{f_{\min}}^{f_{\max}} \frac{1}{2\pi f_k} \left(\frac{|Y^{th}_{qd}(f_k; R_{th}, L_{th})| - |Y^{full}_{qd}(f_k)|}{|Y^{full}_{qd}(f_k)|} \right)^2}$$

- f_{min} = 5 Hz → end of the transient time.
- f_{max} = 100 Hz → ignoring faster dynamics.
- More emphasis on lower frequencies.
- $|Y_{qd}|$ (p.u.) rather than Bode gain $\log_{10}^{|Y_{qd}|}$ (dB).

$$(R_{Eff}, L_{Eff}) = \arg \min_{R_{th},\,L_{th}} \mathcal{J}(R_{th}, L_{th})$$

- Compliance → (R_{Eff}, L_{Eff}) within limits?

IV. Case Studies & Application

- Ideal Voltage Source → RMS error = 0.00%.
- SM → RMS error = 0.27%, accurately captures $x_d'' =$. 0.26 p.u & $r_a = 0.0025$ p.u..

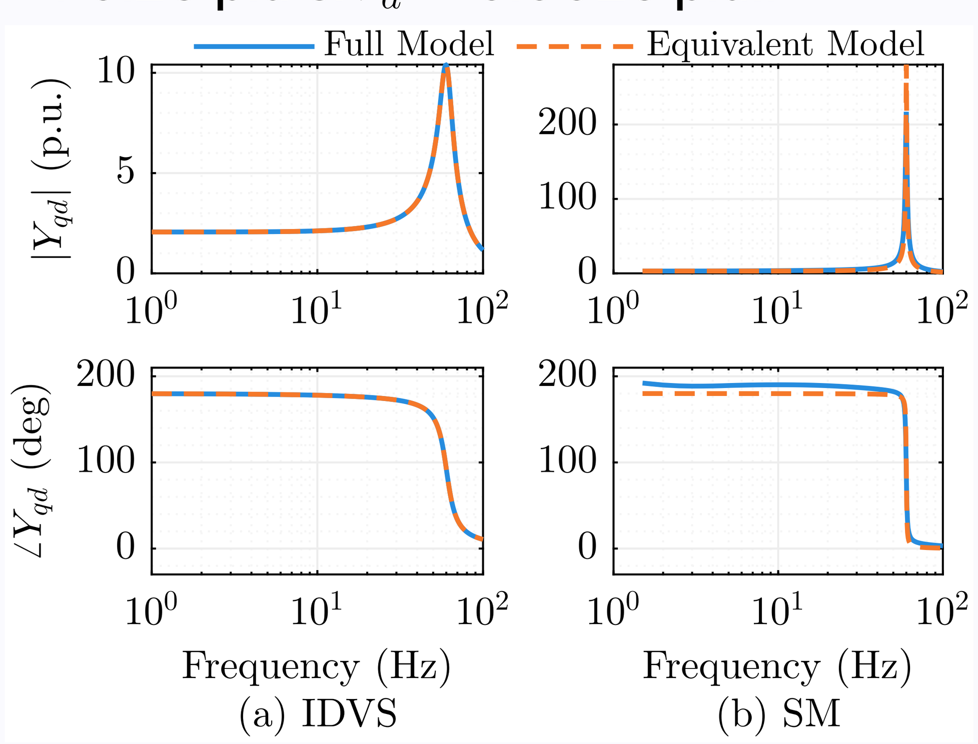

Figure 4: Y_{qd} admittance spectra for full vs equivalent models of (a). an IDVS and (b) a SM

- **NREL GFM→ RMS error = 0.037%**, Fig. 5(b).
- $(\omega^{GFM}_{res} = 58.01$ Hz$) \leq (\omega_1 = 60$ Hz$)$.
- $X^{GFM}_{Eff} = 0.447 \therefore$ Compliant at HV terminals.

- **Lower VCBW** $\rightarrow \omega_{res} \downarrow$, $R_{Eff} \uparrow$, **RMS error** $\uparrow$, $\rightarrow$ **weaker voltage-source behavior.**

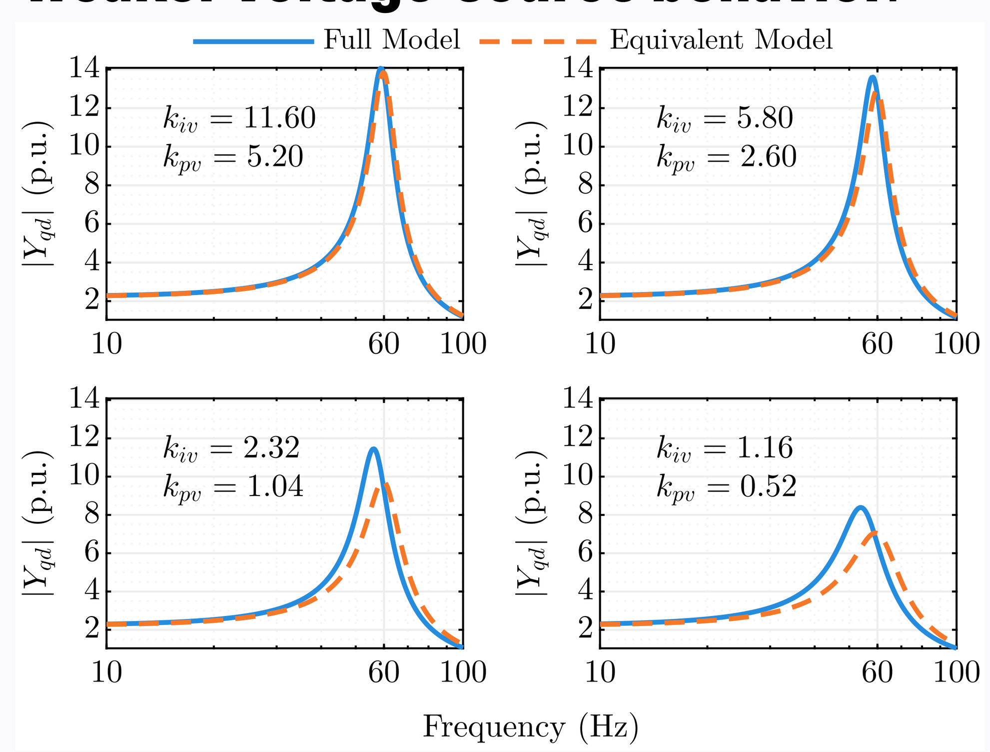

Figure 5: Y_{qd} admittance spectra for full vs equivalent models of GFM with changing voltage control gains

Table 2: Effect of changing voltage control loop gains on effective impedance (in p.u.) of the GFM

$\{k_{iv},\, k_{pv}\}$(p.u.)	ω_{res} (Hz)	X_{Eff}	R_{Eff}	RMS Error
$\{11.60,\, 5.20\}$	59.06	0.44	0.03	0.03%
$\{5.80,\, 2.60\}$	58.01	0.44	0.03	0.03%
$\{2.32,\, 1.04\}$	56.06	0.44	0.05	0.06%
$\{1.16,\, 0.52\}$	54.02	0.43	0.07	0.08%

- **The equivalent model exhibits a similar reactive power response to voltage change.**
- Q^{GFM}_{Eq} vs Q^{GFM}_{Full}: RMS error (200 ms) = 2.76%.

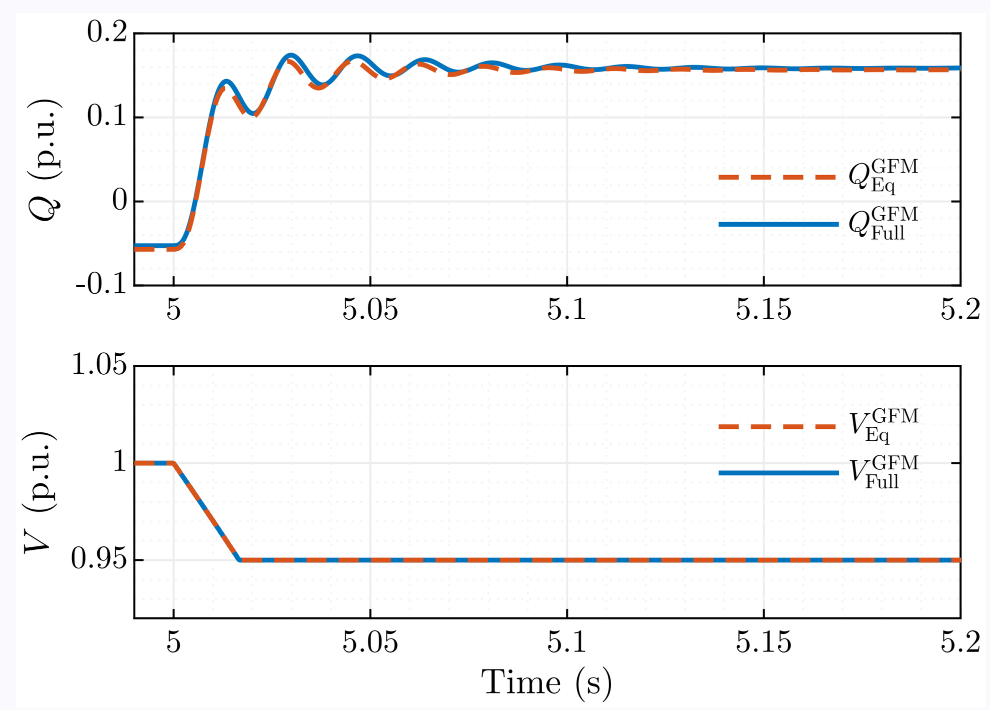

Figure 6: Reactive power response of full GFM model vs Thevenin equivalent to a 5% voltage change at its POI

- Likewise, fitting Y_{dq} would yield a similar active power response to voltage phase change.

- **The equivalent model accurately captures the static voltage stability limit.**
- Avoids the need for EMT simulations.

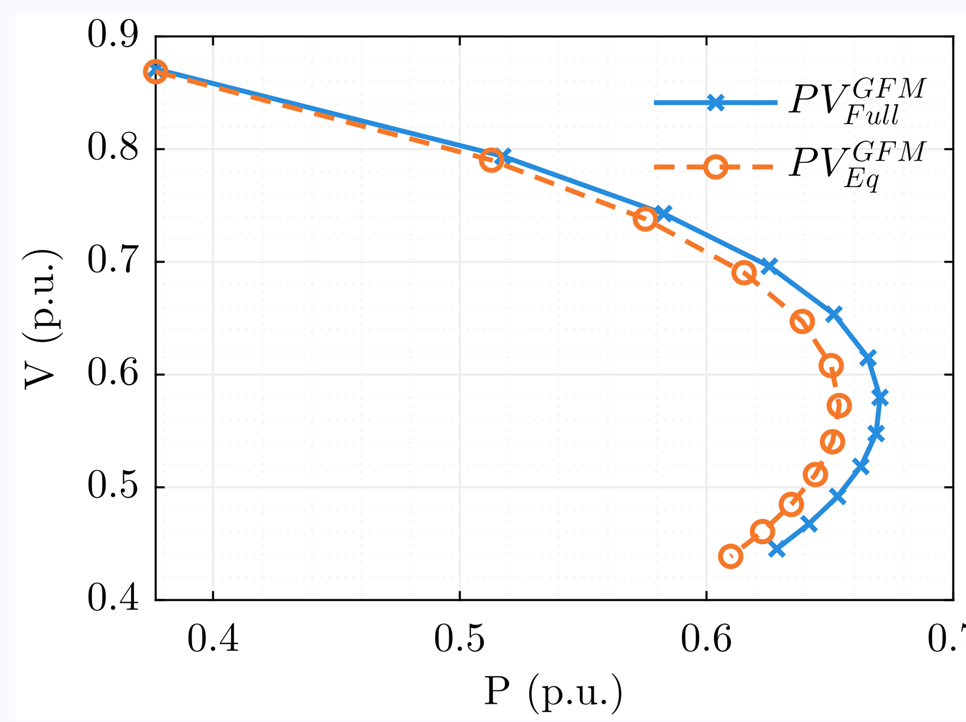

Figure 7: PV curve for full GFM model vs Thevenin equivalent

- P^{Max}_{Full} = 0.67 p.u. at $V^{PMax}_{Full} = 0.58$ p.u..
- $P^{Max}_{Eq} = 0.65$ p.u. at $V^{P_{Max}}_{Eq} = 0.57$ p.u..
- Error in P^{Max} capability = 2.46%.