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Sequence Impedance Modeling of Grid-Forming Inverters

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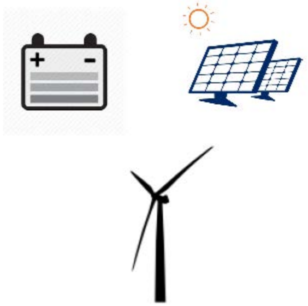
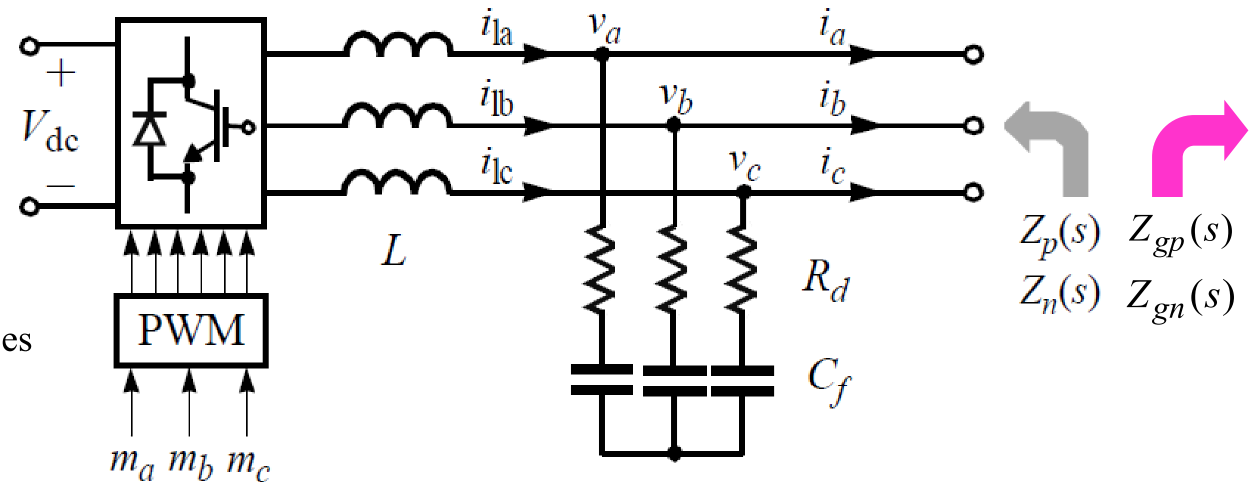
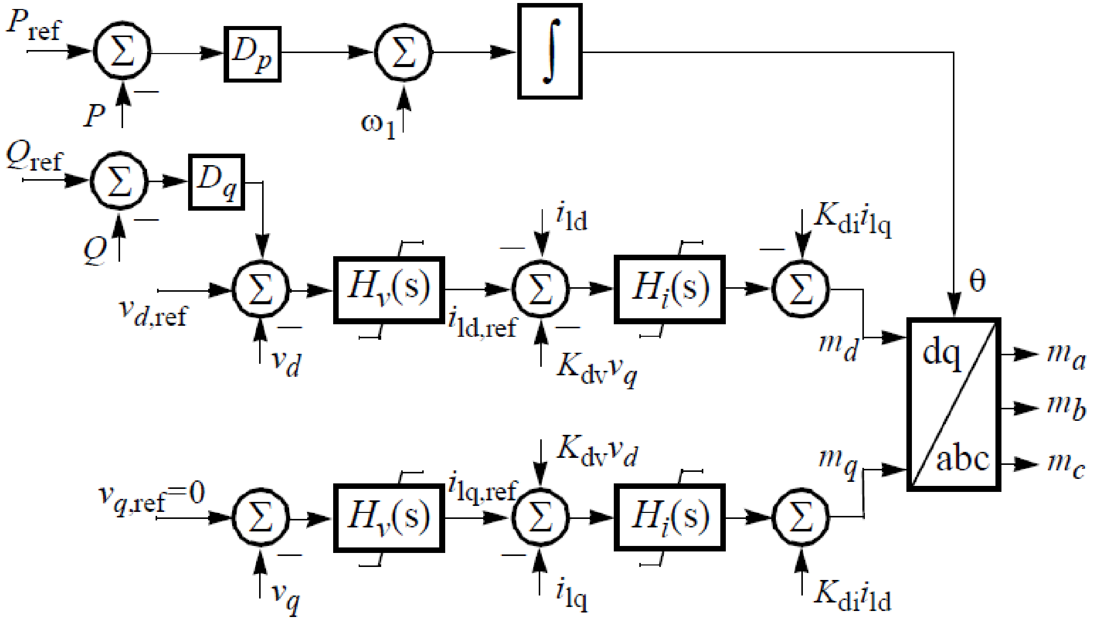


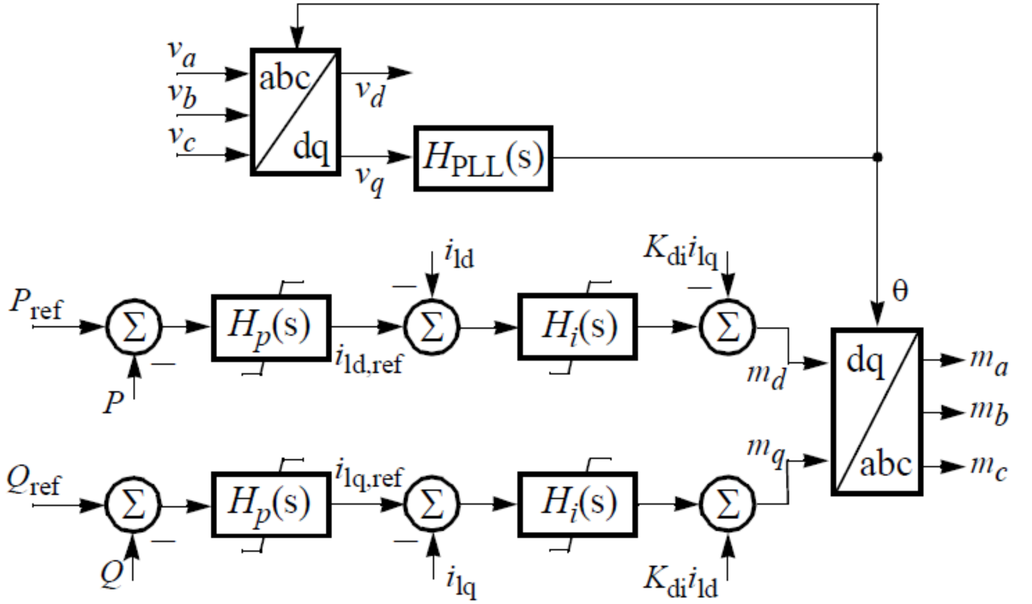
Inverter-based resources



Power network



- Control diagram of droop-controlled GFM inverter



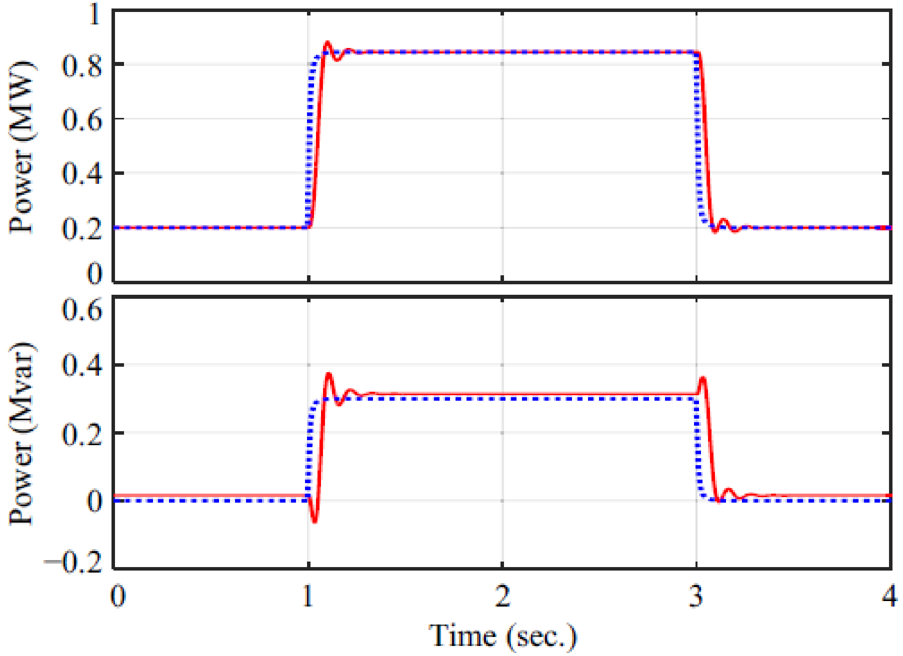
- Control diagram of PI power-controlled GFL inverter

Parameters of inverter controllers for GFL and GFM

Control & System Parameter	Value
Current inner loop crossover frequency	1200rad/s
Current inner loop phase margin/damping	45deg/≈45%
Outer loop crossover frequency	120 rad/s
Outer loop crossover phase margin/damping	90deg/>100%
PLL crossover frequency	2*pi*30 rad/s
PLL crossover phase margin/damping	45deg/≈45%
Droop coefficients	0.05pu P-ω 0.05pu Q-V
System operation condition	P=0.85MW; Q=0.32MVar;

Assumptions:
1. Frequency couplings are ignored;
2. Voltage of DC link is well controlled and considered as constant.

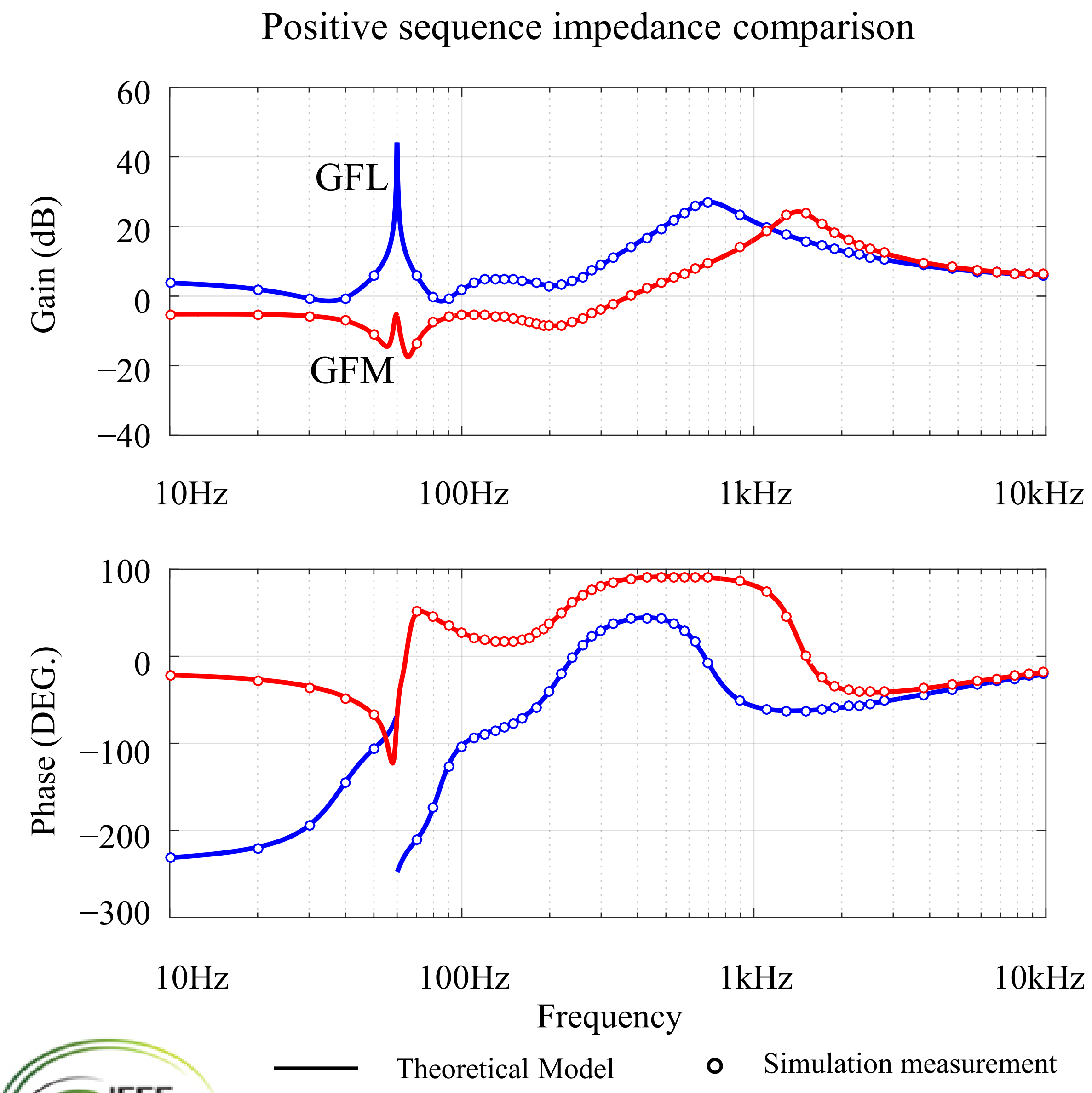
Time-domain simulation comparison



Power step change responses of GFL and GFM inverters.
Blue dashed lines: GFL inverter, red solid lines: GFM inverter.

Circuit parameters for simulations

Parameter	Value
Inverter rated power	1MVA
PCC voltage (peak), V_1	0.563kV
PCC current (peak), I_{o1}	1.082kA
Inductor current (peak), I_{l1}	1.084kA
Filter, L, C_f, R_d	3mH, 22uF, 1.87Ω
DC bus voltage, V_{dc}	2kV



- GFM inverter

$$Z_p(s)=\frac{sL+k_mV_{\text{dc}}[H_i(s-j\omega_1)-jK_{\text{di}}]+\frac{1}{2}k_mV_{\text{dc}}V_1[K_p(s-j\omega_1)-K_q(s-j\omega_1)]}{1+\frac{1}{2}k_mV_{\text{dc}}\mathbf{I}_{o1}^*[K_p(s-j\omega_1)+K_q(s-j\omega_1)]+k_mV_{\text{dc}}[H_v(s-j\omega_1)-jK_{\text{dv}}]H_i(s-j\omega_1)}$$

- GFL inverter

$$Z_p(s)=\frac{sL+k_mV_{\text{dc}}[H_i(s-j\omega_1)-jK_{\text{di}}]+\frac{3}{2}k_mV_{\text{dc}}V_1G_p(s-j\omega_1)H_p(s-j\omega_1)H_i(s-j\omega_1)}{1-\frac{1}{2}k_mV_{\text{dc}}\{\mathbf{I}_{l1}[H_i(s-j\omega_1)-jK_{\text{di}}]+\mathbf{D}_1\}\frac{T_{\text{PLL}}(s-j\omega_1)}{V_1}}$$

$$\left.\begin{aligned}K_p(s)&=j\frac{3}{2}\{V_1[H_v(s)-jK_{\text{dv}}]H_i(s)+\mathbf{I}_{l1}[H_i(s)-jK_{\text{di}}]+\mathbf{M}_1\}G_p(s)\frac{1}{s}D_p\omega_1\\K_q(s)&=j\frac{3}{2}nV_1H_vG_p(s_1)(s)H_i(s)\end{aligned}\right\}\text{ Associate with droop control}$$

- PLL is replaced with droop related terms. GFM avoids introducing negative resistance, and less likely to experience harmonic instability.
- Negative sequence impedance can be derived: $Z_n(s)=Z_p(-s)^*$

Conclusion

Impedance model of GFM inverter	• This paper presents the sequence impedance modeling of a grid-forming inverter to evaluate its small-signal stability properties.
Droop control structure is implemented and studied	• Droop control structure is implemented to control the inverter in grid-forming mode, and the impact of individual controller on the inverter impedance characteristics is discussed.
Comparison between GFM and GFL inverters	• GFM and GFL have different grid-synchronization mechanisms, which lead to the differences of impedance models. GFM inverters is less likely to experience harmonic stability problems.

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