NREL
Transforming ENERGY

SIMULATION AND MODELING OF INVERTER BASED RESOURCES INTEGRATION IN POWER SYSTEMS

José Daniel Lara PhD

WHAT IS AN OSCILLATION?

1. Is it an underdamped dynamic state? I.e, the condition in which a state tends towards equilibrium with the amplitude gradually decreasing to zero but overshooting and crossing the equilibrium position one or more times.

2. Is it a bifurcation in an unstable system? I.e, the system is trending towards collapse while oscillating.

3. Is it a phase-lock in a controller over a limiter? I.e, is the inverter "bouncing" against the ceiling.

THE SYSTEM DYNAMICS THEORY HAS BEEN KNOWN FOR MANY DECADES NOW


Generalized Averaging Method for Power Conversion Circuits

Seth R. Sanders, J. Mark Noworolski, Xiaojun Z. Liu, and George C. Verghese, *Member, IEEE*

IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 6, NO. 2, APRIL 1991


Fast Time-Varying Phasor Analysis in the Balanced Three-Phase Large Electric Power System

Vaithianathan Venkatasubramanian, Heinz Schättler, and John Zaborszky

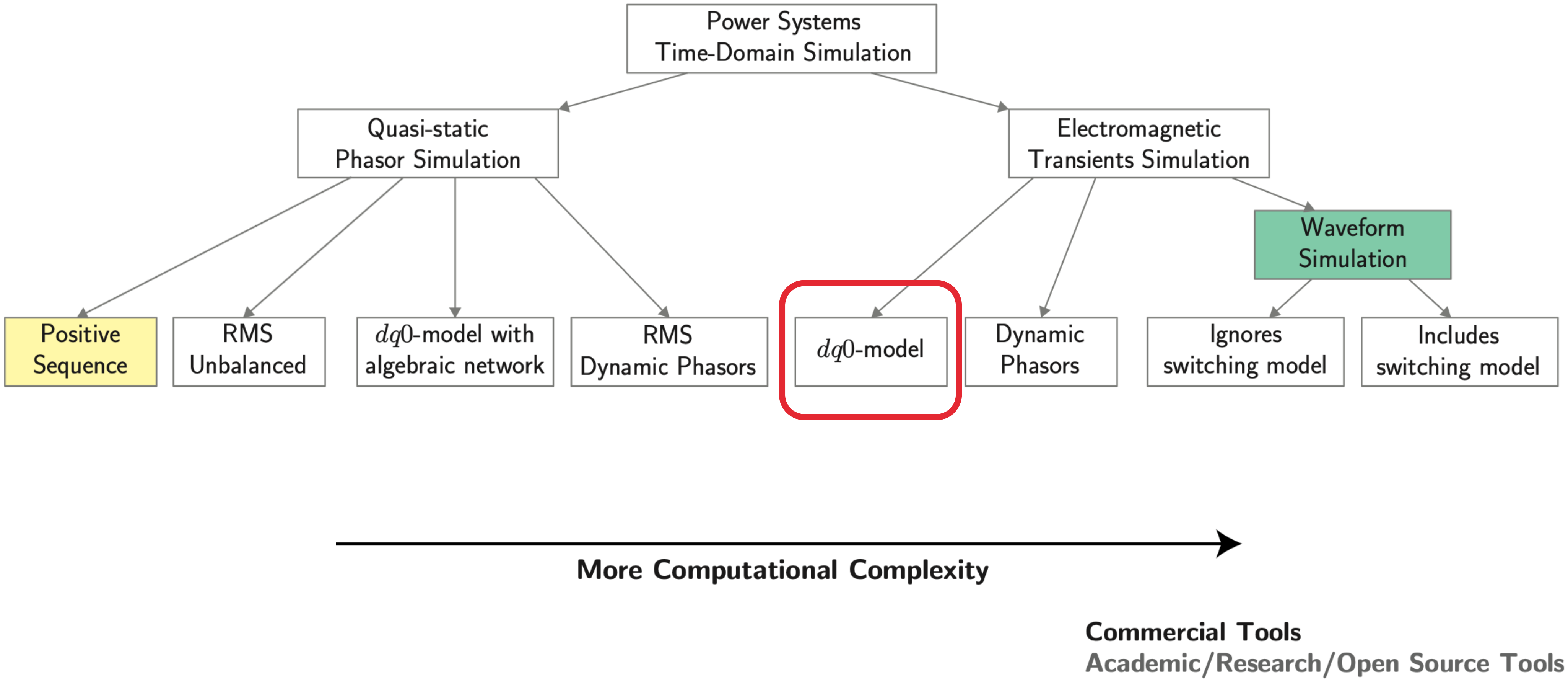
IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 40, NO. 11, NOVEMBER 1995

Shifted-Frequency Analysis for EMTP Simulation of Power-System Dynamics

Peng Zhang, *Senior Member, IEEE*, José R. Martí, *Fellow, IEEE*, and Hermann W. Dommel, *Life Fellow, IEEE*

IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 57, NO. 9, SEPTEMBER 2010

DYNAMIC SIMULATION



J. D. Lara, R. Henriquez-Auba, D. Ramasubramanian, S. Dhople, D. S. Callaway and S. Sanders, "Revisiting Power Systems Time-domain Simulation Methods and Models," in *IEEE Transactions on Power Systems*

A TIME DOMAIN DYNAMIC MODEL

$$\frac{d\boldsymbol{x}(t)}{dt} = F(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{\eta}, t), \quad \boldsymbol{x}(t_0) = \boldsymbol{x}^0$$
$$\frac{d\boldsymbol{y}(t)}{dt} = G(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{\psi}, t), \quad \boldsymbol{y}(t_0) = \boldsymbol{y}^0$$

- $\boldsymbol{x}(t)$ and $\boldsymbol{y}(t)$ are generally complex valued vectors of variables. Certain formulations/implementations use real values.
- $\boldsymbol{x}(t)$ represents the variables for devices connected to grid.
- $\boldsymbol{y}(t)$ are the network variables, usually voltages and currents. In some formulations active/reactive power can be used but it is less common.

Model choices inform the algorithm requirements

Given the system model, a time domain simulation can be set up as follows:

Given an initial condition $\overline{\boldsymbol{x}}(t_0), \overline{\boldsymbol{y}}(t_0)$ advance the solution in time t from one point to the next considering a discrete timeline. It requires a stepping algorithm that finds the solution in time t_{n+1} provided the values of the involved variables at $\{t_0, t_1, \ldots, t_n\}$.

TRANSFORMATIONS

- Models employ reference frame transformations to achieve the necessary representation of time variant signals using only their envelope.
- Commonly used transformations convert the time-variant model into a time-invariant ones or at minimum increase the required time-step to achieve a reliable result.
- The resulting transformed model is usually ”stiff” due to the multi-rate properties of power systems. The model can still be difficult to analyze but the transformation opens up possibilities.

WHY USE TRANSFORMATIONS AND SIMPLIFICATIONS?

- Transformations and simplifications are used to increase the minimum Δt required in the simulation.
- Commonly used transformations convert the time-variant model into a stiff time-invariant model that requires usage of implicit integration methods.
- The "best" possible outcome is to further reduce the model and enable use adaptive time stepping and explicit solution methods.

Implicit Scheme

$$S_F(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{x}(t+\Delta t), \boldsymbol{y}(t+\Delta t), \boldsymbol{\eta}) = 0$$

$$S_G(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{x}(t+\Delta t), \boldsymbol{y}(t+\Delta t), \boldsymbol{\psi}) = 0$$

Explicit Scheme

$$\boldsymbol{x}(t+\Delta t) = E_F(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{\eta}, \Delta t)$$

$$\boldsymbol{y}(t+\Delta t) = E_G(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{\psi}, \Delta t)$$

- Dynamic phasors in polyphase systems are not implemented uniquely as a result the limitations described previously apply depending on how the technique is used.
- When implemented phase-by-phase the limitations presented in the previous slide apply, i.e., bounded integral and bandwidth limitation

Note:

An alternative approach useful in simulations is to obtain the dynamic phasors for the 3-phase signal. This can be accomplished employing "space vectors"

$$\bar{s}(t) = c\left(\bar{s}_{+}(t)e^{\jmath\omega_s t} + \bar{s}_{-}(t)e^{-\jmath\omega_s t}\right)$$

It is not possible to model directly an arbitrary three-phase signal with one phasor quantity i.e., $\langle s(t)\rangle \neq \langle s(t)\rangle_+ + \langle s(t)\rangle_-$.

If the signal is balanced, i.e., $s_a(t) = s_b(t) = s_c(t)$ and $\theta_b(t) = \theta_a(t) - \frac{2\pi}{3}$ $\theta_c(t) = \theta_a(t) + \frac{2\pi}{3}$ the components $\overline{s}_+(t)$ and $\overline{s}_-(t)$ reduce to the following expressions.

$$\overline{s}_+(t) = 3s(t)e^{\jmath\theta(t)}, \quad \overline{s}_-(t) = 0.$$

implies that $\langle s(t)\rangle = \langle s(t)\rangle_+$.

The unreasonable effectiveness of balanced three-phase signals

This result showcases the effectiveness of averaging techniques in balanced systems: The envelope of a balanced three-phase signal is completely determined by the positive-frequency phasor.

The original Park Transform is defined as:

$$\boldsymbol{s}_{dq0}(t) = C\boldsymbol{T}_p(\theta(t))\boldsymbol{s}_{abc}(t)$$

where $\theta(t)$ is the angle between the reference axes and the axes of rotation. Park's transform is valid and reversible for any three-phase signal.

The transform is useful for the purposes of simulation complexity reduction only with careful selection of $\theta(t)$.

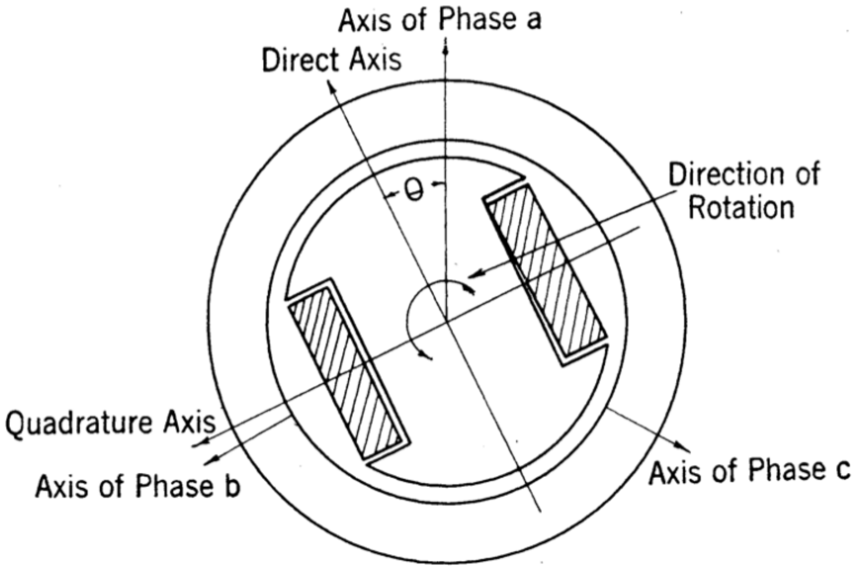


FIG. 1

$$i_d = \frac{2}{3}\{i_a \cos\theta + i_b \cos(\theta - 120) + i_c \cos(\theta + 120)\}$$

$$i_q = -\frac{2}{3}\{i_a \sin\theta + i_b \sin(\theta - 120) + i_c \sin(\theta + 120)\}$$

Figure from R. H. Park, *Two Reaction Theory of Synchronous Machines. Generalized Method of Analysis - Part I*, 1929.

In simulation models, the calculation of the angle $\theta(t)$ is usually done by integrating over frequency as follows:

$$\theta(t) = \int_{t_o}^{t} (\omega + \Delta\omega(\tau))\,\mathrm{d}\tau + \theta^0 \tag{1}$$

In a balanced system, the effectiveness of the transformation relies on choosing a reference frame with a "system frequency" $\omega = \omega_s$ and $\Delta\omega_s(t) = 0$.

$$\boldsymbol{s}_{dq0}(t) = C\boldsymbol{T}_p(\theta(t))\boldsymbol{s}_{abc}(t) = \overline{s}_+(t) \tag{2}$$

Remark:

The definition of the Park's Transform for balanced signals as a phasor transformation is used by several authors to develop time-invariant simulation models capable of representing fast dynamics without a bandwidth limitation

WHAT IS "SYSTEM FREQUENCY"?

- It is possible define the reference frame to reference transformation:

$$\boldsymbol{T}_p(\theta_1(t))\boldsymbol{T}_p(\theta_2(t))^{-1}$$

where $\Delta\theta(t) = \theta_1(t) - \theta_2(t) = \int_{t_o}^{t} (\Delta\omega_1(\tau) - \Delta\omega_2(\tau))\, d\tau + \Delta\theta^0$.

- In case of machine models $\Delta\omega(t) = \Delta\omega_r(t)$ and there are no assumptions required about ω_s.
- In fact the "system frequency" is not a modeled quantity in a simulation
- In IBR simulation the relationship with ω_s is dictated by the model's controls.
- Frequency measurement employs an idealized approach:

$$\Delta\omega_{bus}(t) = \frac{d}{dt}\tan^{-1}\frac{V_{q,bus}(t)}{V_{d,bus}(t)}$$

- The implication is that with IBRs simplifications in the network dynamics can mischaracterize the effects of frequency deviations on the controls.

The transients associated with the network decay very rapidly and there is little justification for modelling their effects in stability studies. The network transients cannot be neglected unless machine stator transients are also neglected; otherwise we would have an inconsistent set of equations representing the various elements of the power system. Inclusion of the network transients increases the order of the overall system model considerably, and hence limits the size of the system that can be simulated. In addition, a system representation with machine stator and network transients contains high frequency transients. This requires small time steps for numerical integration, resulting in an enormous increase in computational costs. Also,

Kundur, Power System Stability and Control page 170

What are the implications of network dynamics elimination in models with IBRs?

SYSTEMATIC CHOICE OF SIMPLIFICATIONS

Singular Perturbation Theory (SPT) provides the formal underpinnings for model order reduction and dynamic representation simplifications

Simplifications are commonly based on practical knowledge, but these have been formalized in terms of time-scale separation arguments derived from SPT:

$$\begin{aligned} \dot{\boldsymbol{x}}_s &= F_s(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\eta}), & \dot{\boldsymbol{y}}_s &= G_s(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\psi}) \\ \varepsilon\dot{\boldsymbol{x}}_f &= F_f(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\eta}, \varepsilon), & \varepsilon\dot{\boldsymbol{y}}_f &= G_f(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\psi}, \varepsilon) \end{aligned}$$

By setting $\varepsilon = 0$, we can reduce the system by eliminating the fast dynamics. SPT is used to guarantee that fast dynamics converge to a root of $F_f(\cdot)$ and $G_f(\cdot)$.

In practice, the theoretical underpinnings of SPT provide the justifications for neglecting line dynamics and is used to show that modeling current flows over the network via the admittance matrix $\boldsymbol{Y}$ is a reasonable approximation of the manifold.

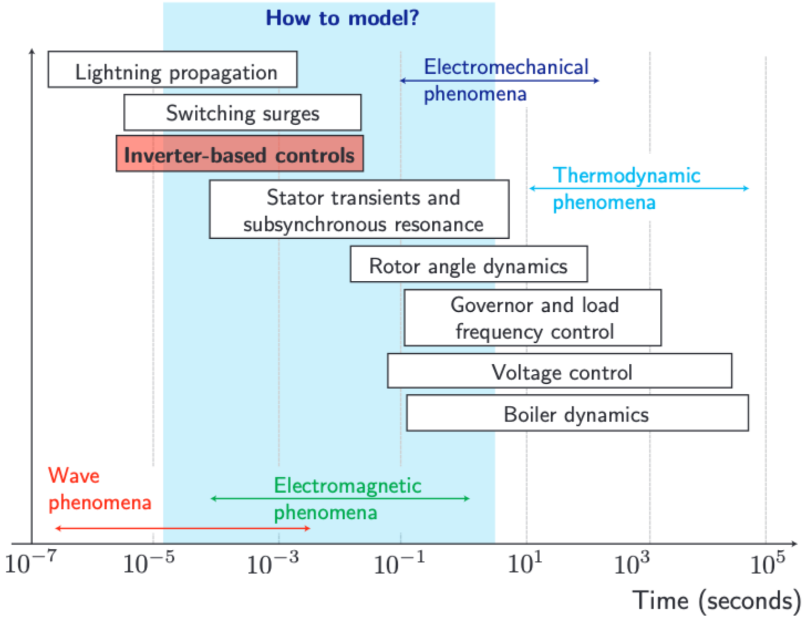
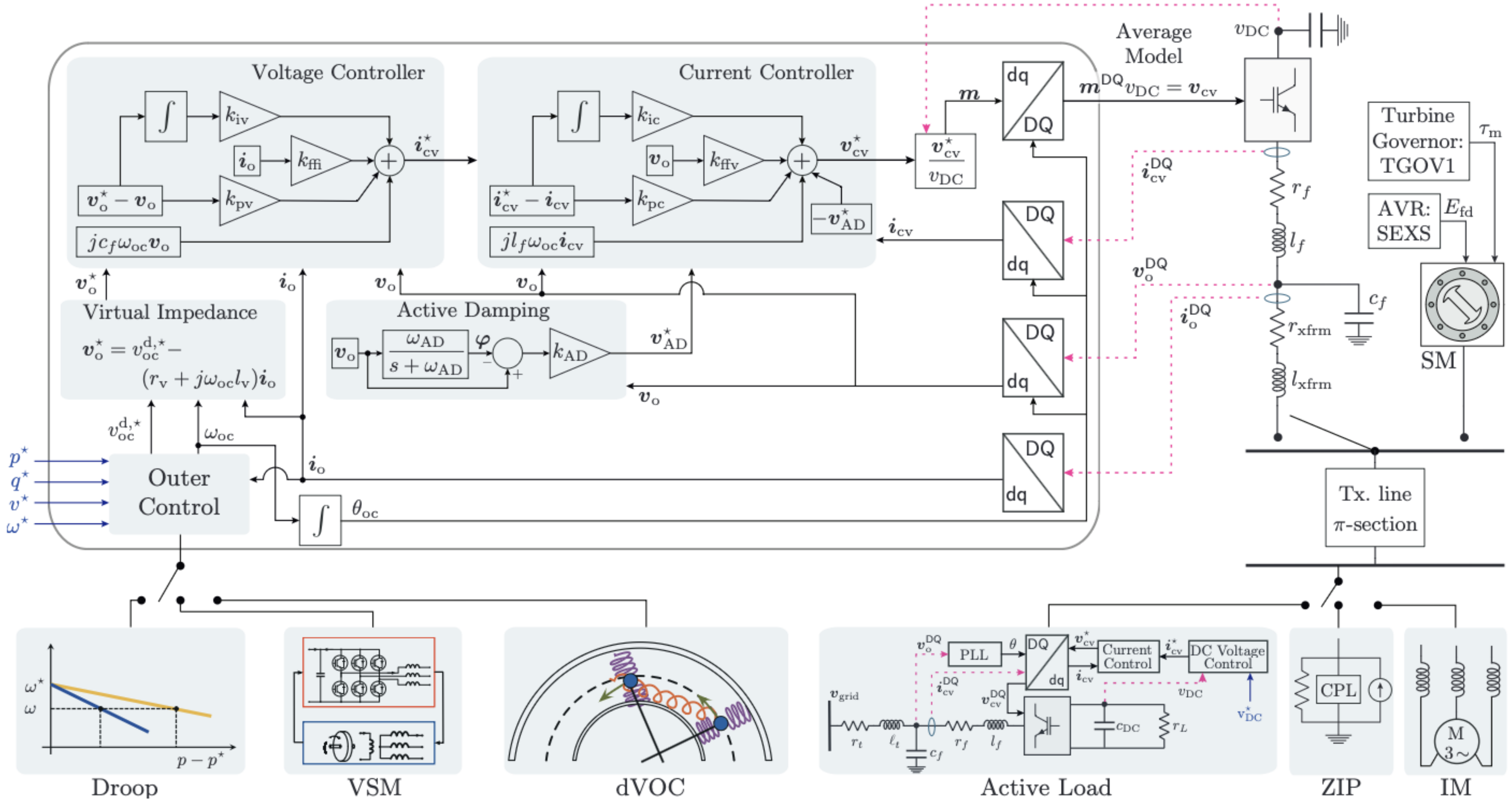
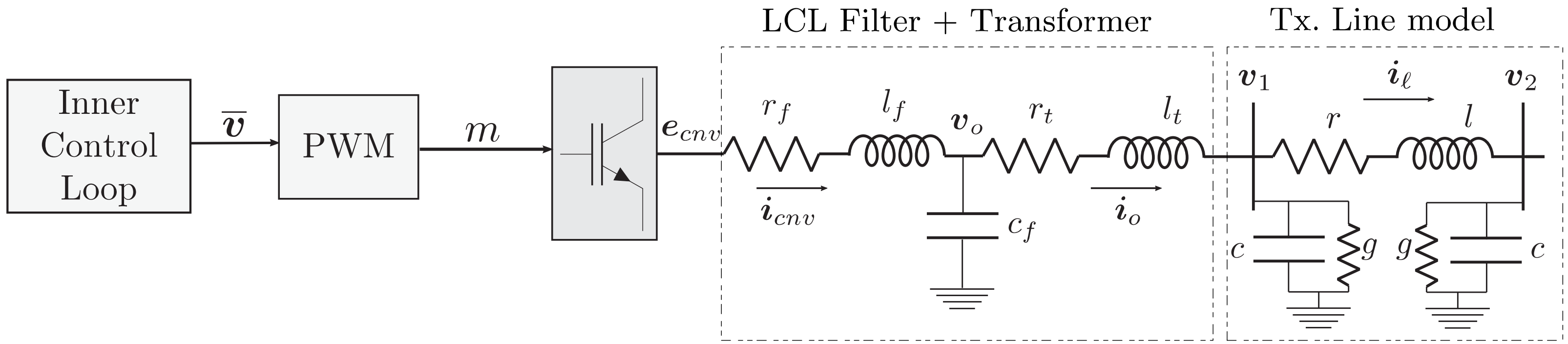


Figure adapted from N. Hatziargyriou *et al.*, *Task force on stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies*, 2020.

A GENERIC GRID FORMING INVERTER CONTROL ST



DEEPER DIVE INTO GFM CONTROLS



$$k_{pv}k_{iv}^{-1}\frac{d}{dt}\boldsymbol{\phi} = -\boldsymbol{\phi} + k_{iv}^{-1}\left(\boldsymbol{i}_{\mathrm{cv}}^{\mathrm{ref}} - \jmath c_f \boldsymbol{v}_o\right)$$

$$k_{pc}k_{ic}^{-1}\frac{d}{dt}\boldsymbol{\gamma} = -\boldsymbol{\phi} + k_{ic}^{-1}\left(\boldsymbol{v}_{\mathrm{cv}}^{\mathrm{ref}} - \jmath l_f \boldsymbol{i}_{\mathrm{cv}}\right)$$

$$\frac{l_f}{\Omega_b}\frac{d}{dt}\boldsymbol{i}_{cnv} = \left[(\boldsymbol{e}_{cnv} - \boldsymbol{v}_o) - (r_f + j l_f \omega_s)\, \boldsymbol{i}_{cnv}\right]$$

$$\frac{l_t}{\Omega_b}\frac{d}{dt}\boldsymbol{i}_o = \left[(\boldsymbol{v}_o - \boldsymbol{v}_1^{dq}) - (r_t + j\omega_s l_t)\, \boldsymbol{i}_o\right]$$

$$\frac{c_f}{\Omega_b}\frac{d}{dt}\boldsymbol{v}_o = \left[(\boldsymbol{i}_{cnv} - \boldsymbol{i}_o) - j\omega_s c_f \boldsymbol{v}_o\right]$$

$$\frac{l}{\Omega_b}\frac{d}{dt}\boldsymbol{i}_\ell = [\boldsymbol{v}_1 - \boldsymbol{v}_2] - (r + \jmath\omega_s l)\boldsymbol{i}_\ell$$

$$\frac{c}{\Omega_b}\frac{d}{dt}\boldsymbol{v}_1 = [\boldsymbol{i}_1 - \boldsymbol{i}_\ell] - (g + \jmath\omega_s c)\boldsymbol{v}_1$$

$$\frac{c}{\Omega_b}\frac{d}{dt}\boldsymbol{v}_2 = [\boldsymbol{i}_\ell - \boldsymbol{i}_2] - (g + \jmath\omega_s c)\boldsymbol{v}_2$$

Employing Modulus Optimum Criteria (i.e., pole cancelation in the open-loop transfer function

$$H_c(S) = \left(k_{pc} + \frac{k_{ic}}{s}\right)\left(\frac{1}{1 + \frac{1}{2f_{sw}}s}\right)\left(\frac{1}{r_f\left(1 + \frac{l_f}{r_f\Omega_b}s\right)}\right)$$

$$\Longrightarrow k_{pv}k_{ic}^{-1} \approx \frac{1}{r_f f_{sw}}\frac{l_f f_{sw}}{\Omega_b} \approx \frac{l_f}{r_f\Omega_b} \approx 1\text{x}10^{-3}$$

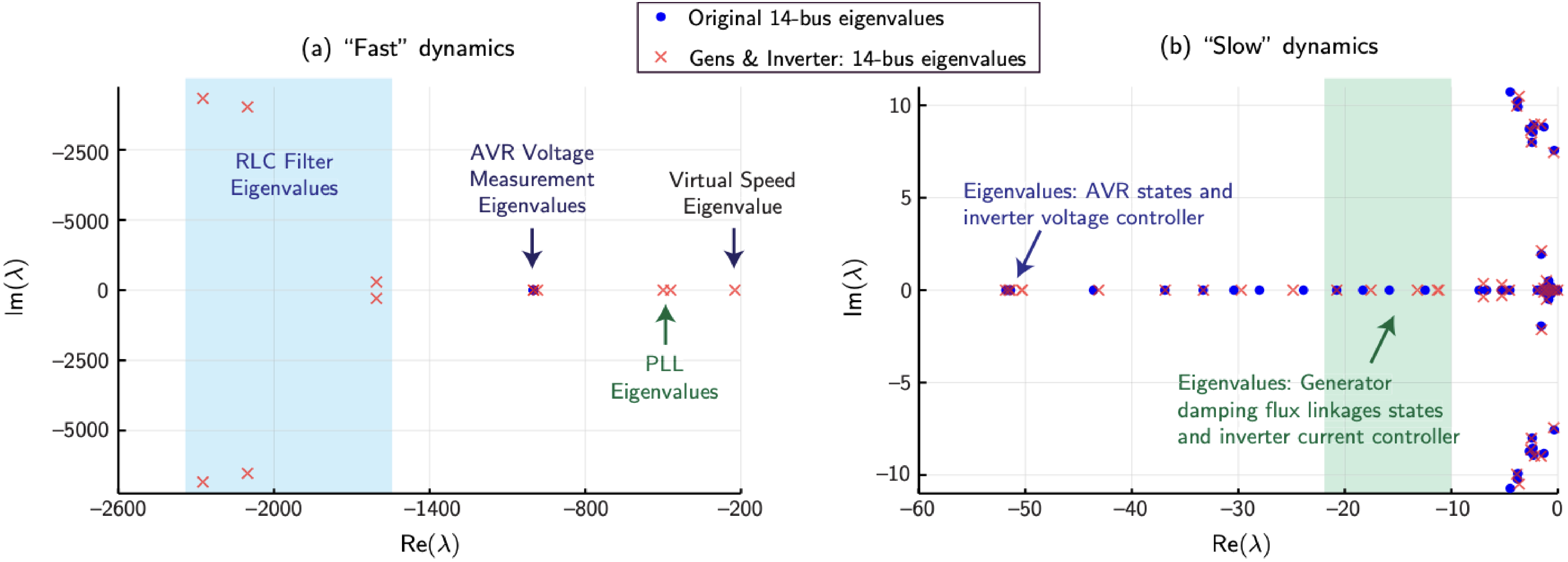
Employing symmetrical optimum (SO) criterion (i.e. maximum phase margin at the crossover frequency

$$H_v(S) = \left(k_{pv} + \frac{k_{iv}}{s}\right)\left(\frac{1}{1 + \frac{1}{f_{sw}}s}\right)\left(\frac{1}{\frac{c_f}{\Omega_b}s}\right)$$

$$\Longrightarrow k_{pv}k_{iv}^{-1} \approx \frac{\Omega_b\,(2\chi+1)^3}{c_f f_{sw}^2}\frac{c_f f_{sw}}{\Omega_b\,(2\chi+1)} \approx \frac{(2\chi+1)^2}{f_{sw}} \approx 1\text{x}10^{-4}$$

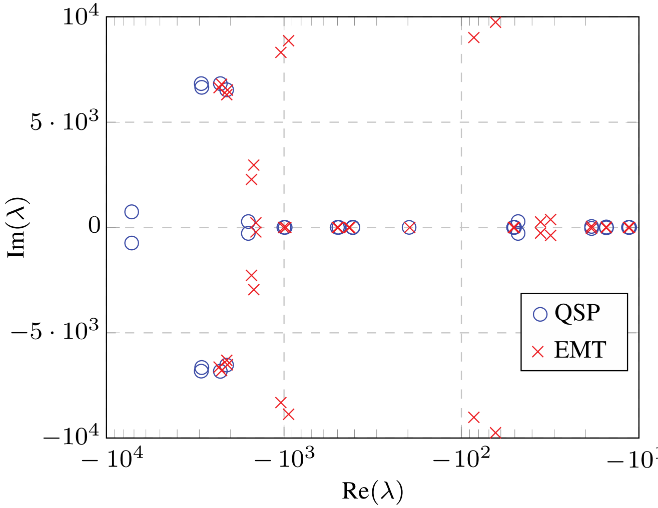
S. D'Arco, J. A. Suul and O. B. Fosso, "Automatic Tuning of Cascaded Controllers for Power Converters Using Eigenvalue Parametric Sensitivities," in *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1743-1753, March-April 2015,

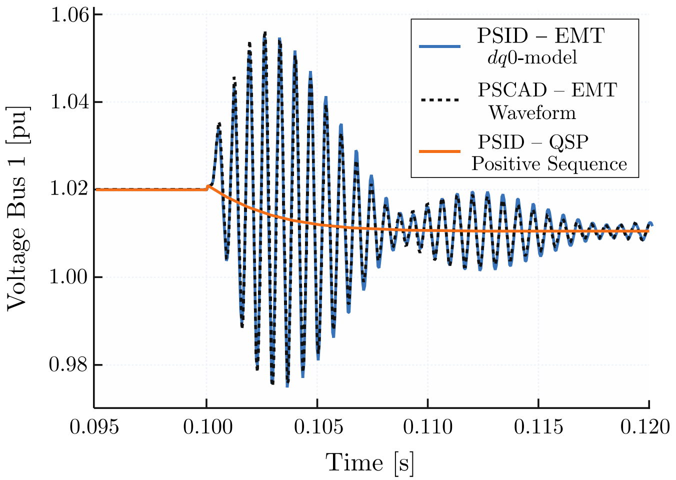
NEW DYNAMICS WITH THE ADDITION OF GFM INVERTERS

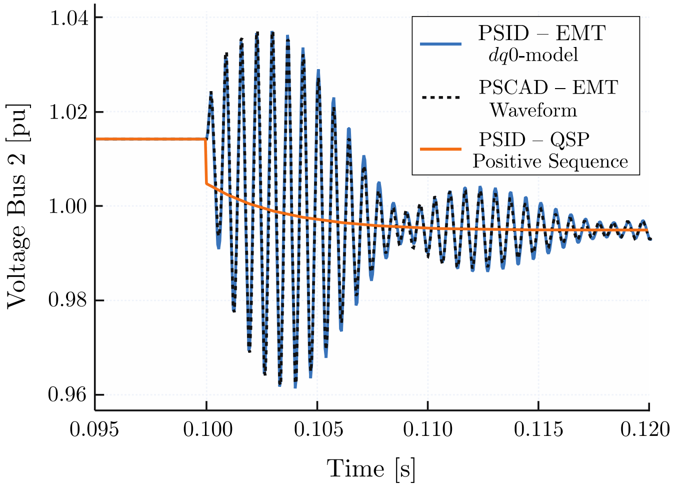


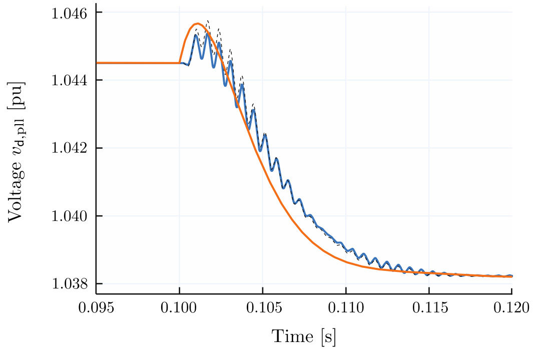
R. Henriquez-Auba, J. D. Lara, D. S. Callaway and C. Barrows, "Transient Simulations With a Large Penetration of Converter-Interfaced Generation: Scientific Computing Challenges And Opportunities," in IEEE Electrification Magazine, vol. 9, no. 2, pp. 72-82, June 2021, doi: 10.1109/MELE.2021.3070939.

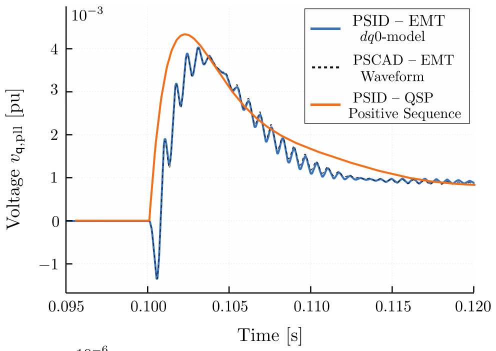
THE EFFECTS OF ADDING ELECTROMAGNETICS INTO THE MODEL

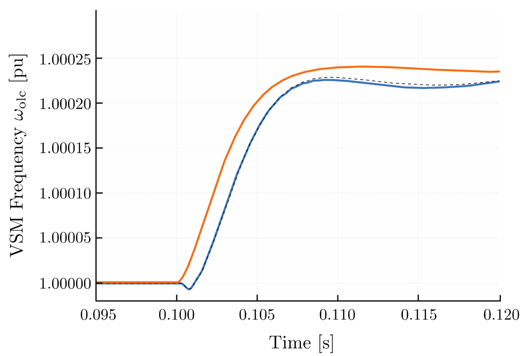


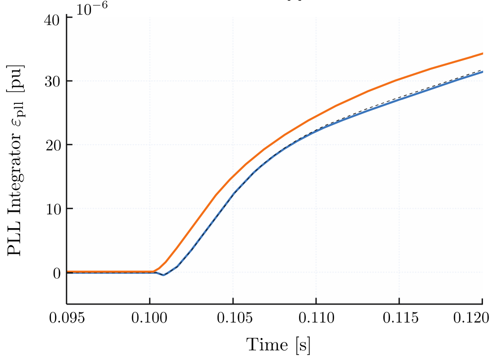






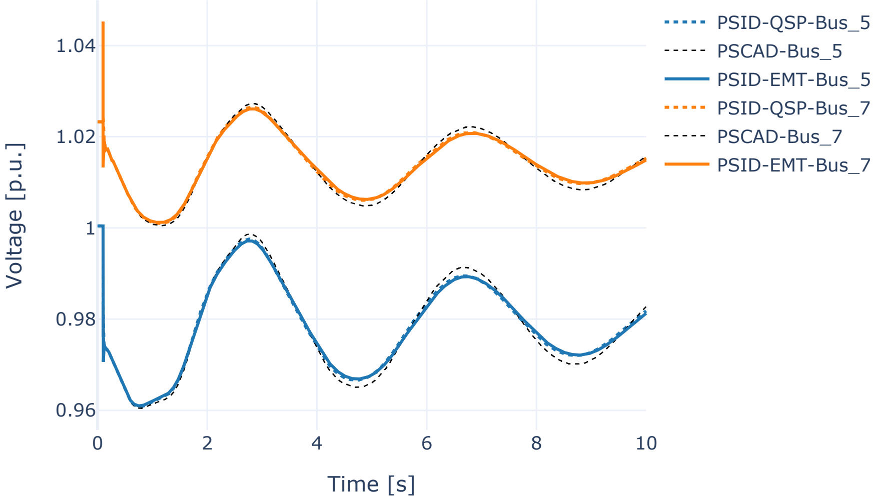


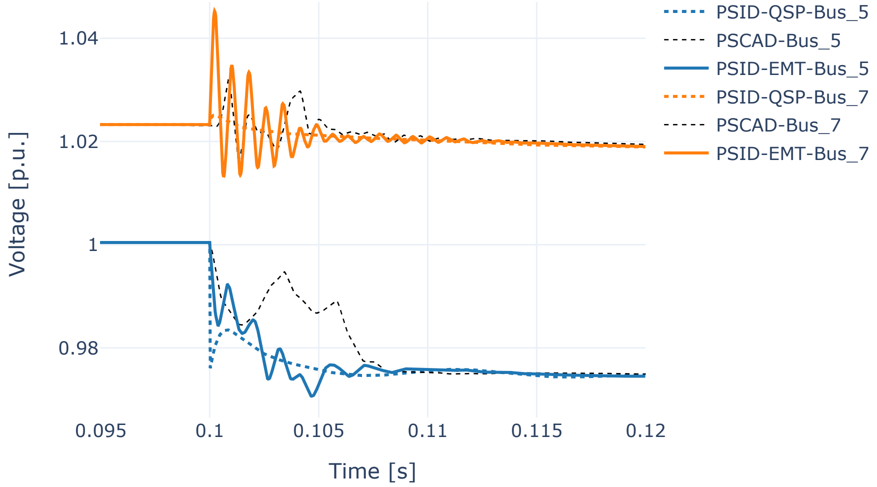




J. D. Lara, R. Henriquez-Auba, D. Ramasubramanian, S. Dhople, D. S. Callaway and S. Sanders, "Revisiting Power Systems Time-domain Simulation Methods and Models," in *IEEE Transactions on Power Systems*, doi: 10.1109/TPWRS.2023.3303291.

SPEEDING UP ANALYSIS ON BALANCED SYSTEMS





MODELS USED IN 144-BUS EMT VALIDATION

Gens	Machine	Excitation	Governor	PSS	
20	SauerPaiMachine	SEXS	TGOV	None	
IBR	**Outer**	**Inner**	**Converter**	**Filter**	**Freq. Est.**
10	Active Droop Reactive Droop	Voltage Control	Average Converter	LCL Filter	None
14	Active PI Reactive PI	Current Control	Average Converter	LCL Filter	Kaura PLL

1176 states

TABLE IV
EMT SIMULATION ERROR ANALYSIS

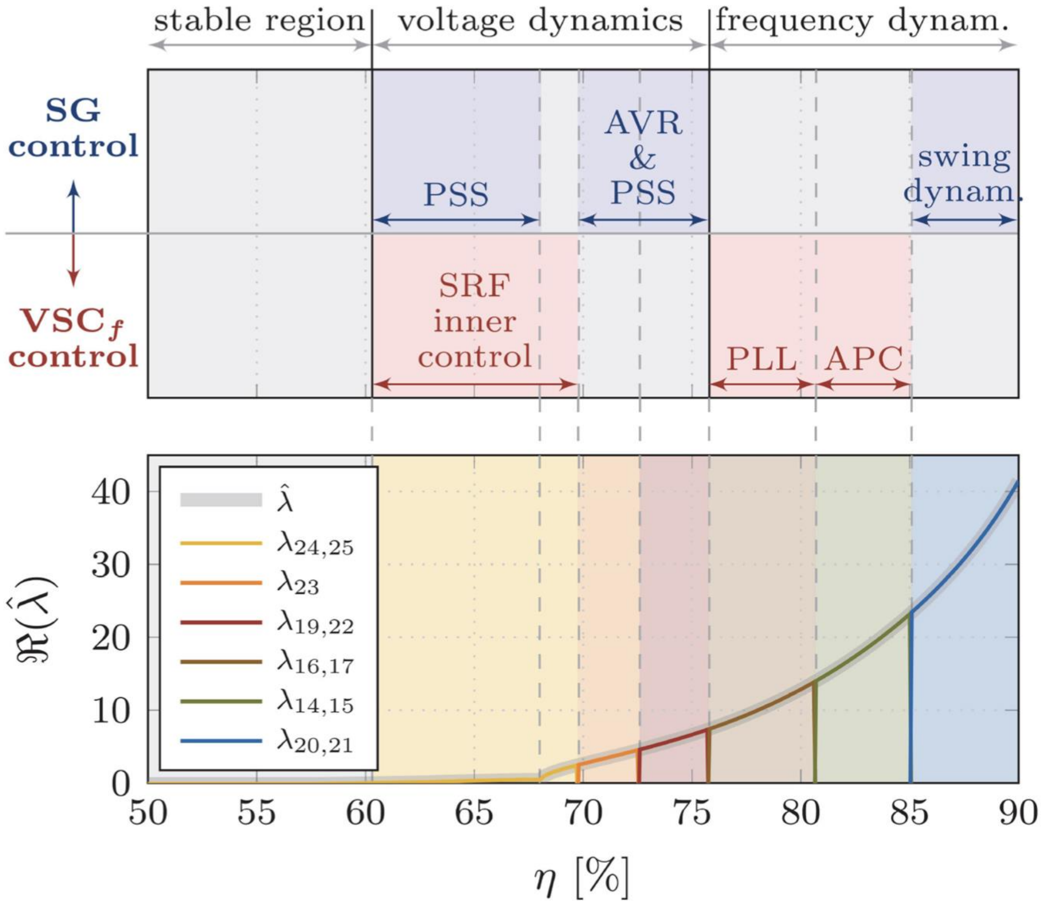
	Line Trip
Maximum Active Power RMSE [pu]	4.45×10^{-6}
Maximum Reactive Power RMSE [pu]	6.85×10^{-6}
Maximum Voltage RMSE [pu]	3.03×10^{-6}
Maximum Bus Frequency RMSE [pu]	1.35×10^{-7}
Average Active Power RMSE [pu]	1.89×10^{-6}
Average Reactive Power RMSE [pu]	2.24×10^{-6}
Average Voltage RMSE [pu]	1.03×10^{-6}
Average Bus Frequency RMSE [pu]	1.16×10^{-7}

Dq0-EMT models can obtain exact same results as a waveform EMT with significantly slower compute times. In a single core same hardware, a waveform simulation takes ~24 hrs while a dq0 can find equivalent solutions in ~100 seconds.

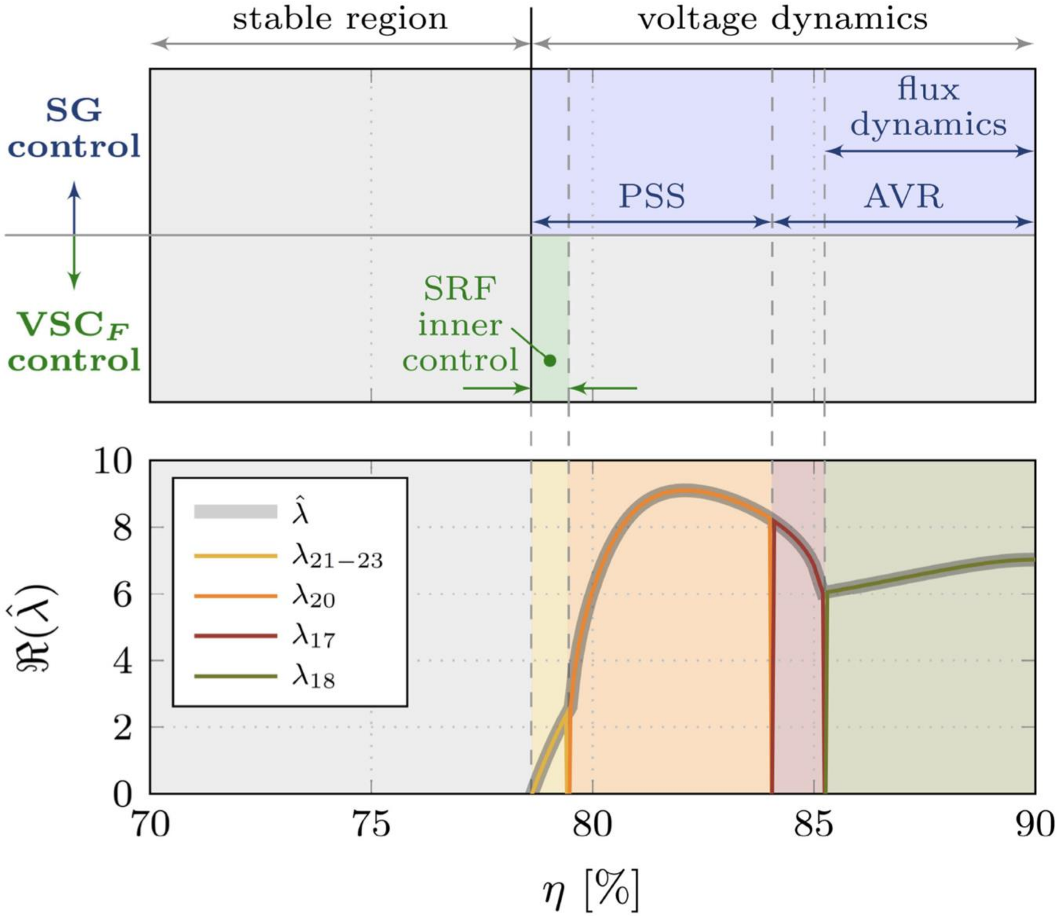
Lara, J. D., Henriquez-Auba, R., Bossart, M., Callaway, D. S., & Barrows, C. (2023). PowerSimulationsDynamics. jl--An Open Source Modeling Package for Modern Power Systems with Inverter-Based Resources. *arXiv preprint arXiv:2308.02921*.

UNSTABLE CONDITIONS CAN APPEAR AT ANY OPERATING POINT

Grid following participation



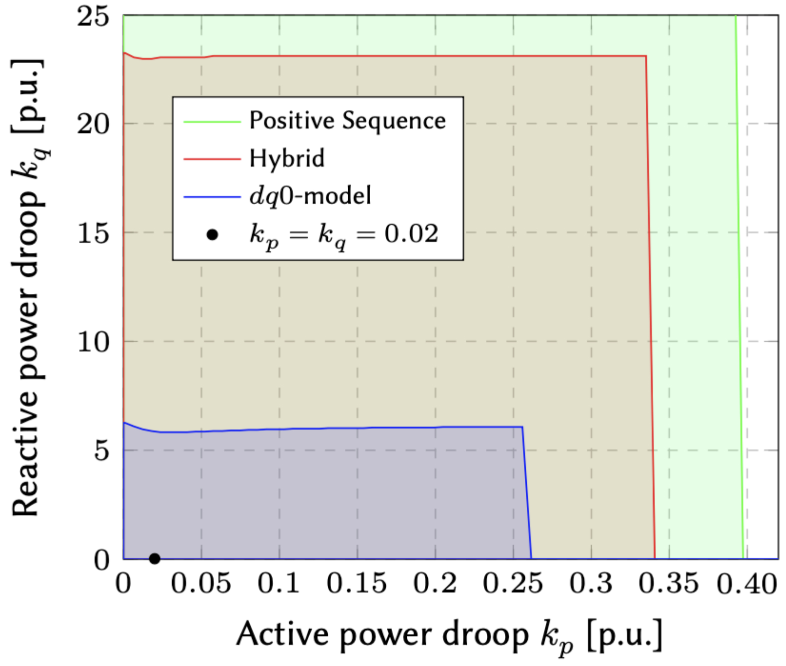
Grid forming participation



U. Markovic, O. Stanojev, P. Aristidou, E. Vrettos, D. Callaway and G. Hug, "Understanding Small-Signal Stability of Low-Inertia Systems," in *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 3997-4017, Sept. 2021, doi: 10.1109/TPWRS.2021.3061434.

ASSESSING THE EFFECTS OF LINE EMT DYNAMICS IN SYSTEM STABILITY AND SOLUTION

- The effects of network dynamics cannot be determined beforehand.
- Quasi-steady analysis is insufficient under weak-grid conditions (e.g., in a post-event configuration).
- Line dynamics can significantly reduce the expected system stability region.
- The fundamentals of the Jacobian will determine how small the timesteps need to be for accurate representation of the dynamics.

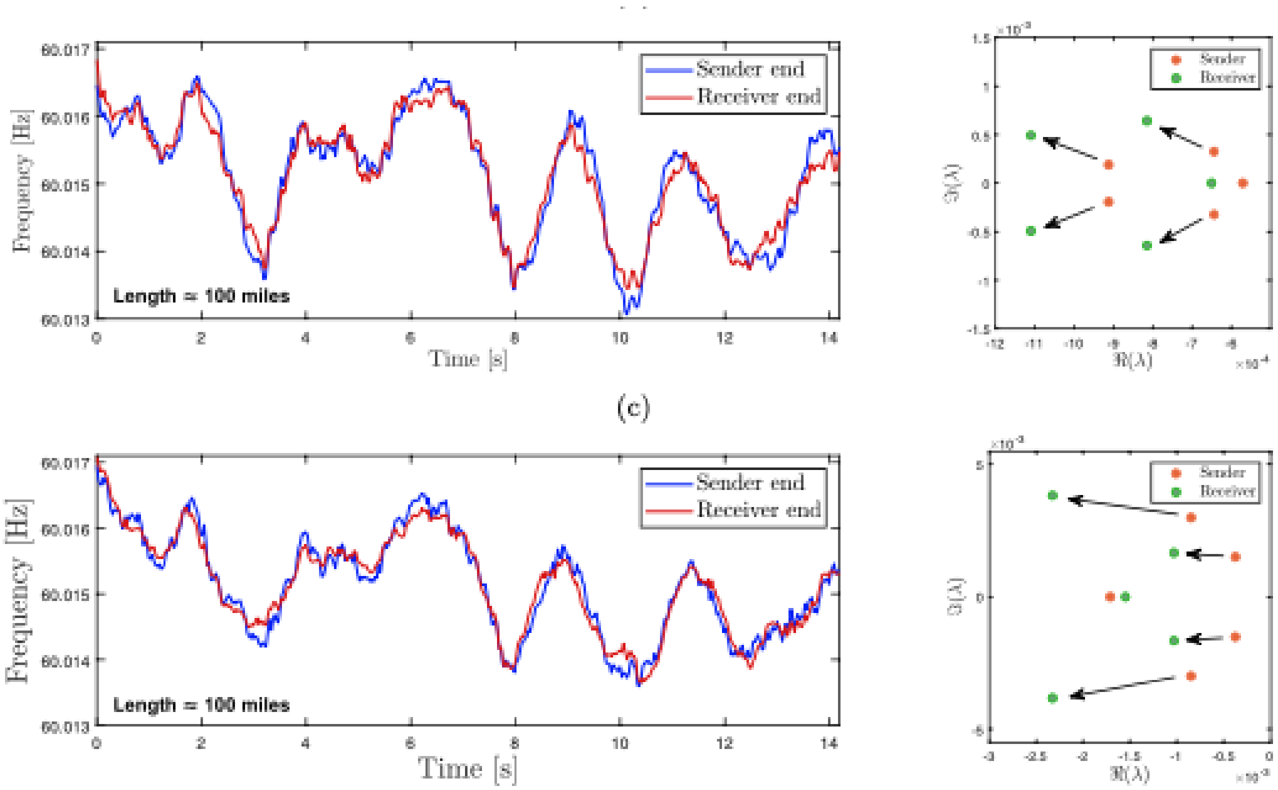


Small signal stability regions for active/reactive droop on GFM.

Henriquez-Auba, R., Lara, J. D., Roberts, C., & Callaway, D. S. (2020, October). Grid forming inverter small signal stability: Examining role of line and voltage dynamics. In *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society* (pp. 4063-4068). IEEE.

WHERE ARE ALL THESE INTERACTIONS COMING FROM?

- There is no clear-cut explanation yet of where these interactions come from.
- Intuitively it is possible to explain the changes in system dynamics by the fact that inverters “break” the chain of energy conversion and their controls essentially manipulate electromagnetics directly.
- Recent results based on “electromagnetic momentum” provide a reasonable explanation for this phenomena.



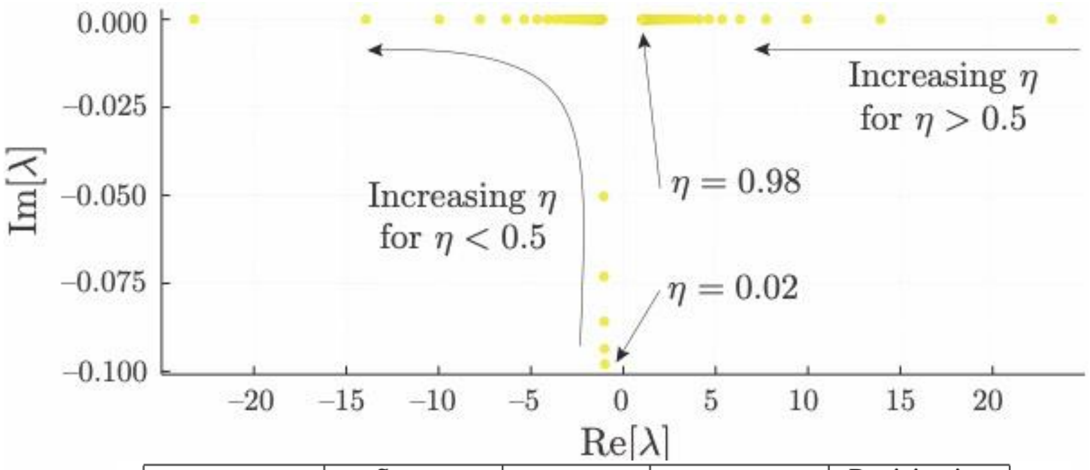
Sajadi, Amirhossein, and Bri-Mathias Hodge. "Plane Wave Dynamic Model of Electric Power Networks with High Shares of Inverter-Based Resources." arXiv preprint arXiv:2401.16703(2024).

CONSTANT POWER LOADS IN A SYSTEM WITH GFM INVERTERS

- Load composition plays a significant role in dynamic stability.
- A ZIP load can capture the static and dynamic behavior of many aggregated composite loads in power systems with the appropriate proportion assignment to each sub-model.
- Changing the power proportion of a ZIP Load (using EMT network) can "move the eigenvalues" via a transcritical bifurcation, becoming small-signal unstable.
- This example showcases how modifying the load composition can have significant effects on system stability study outcomes.

$$P_{\text{zip}} = \eta P_{\text{cpl}} + P_{r_L} = 1 \;\rightarrow\; P_{r_L} = 1 - \eta P_{\text{cpl}}$$

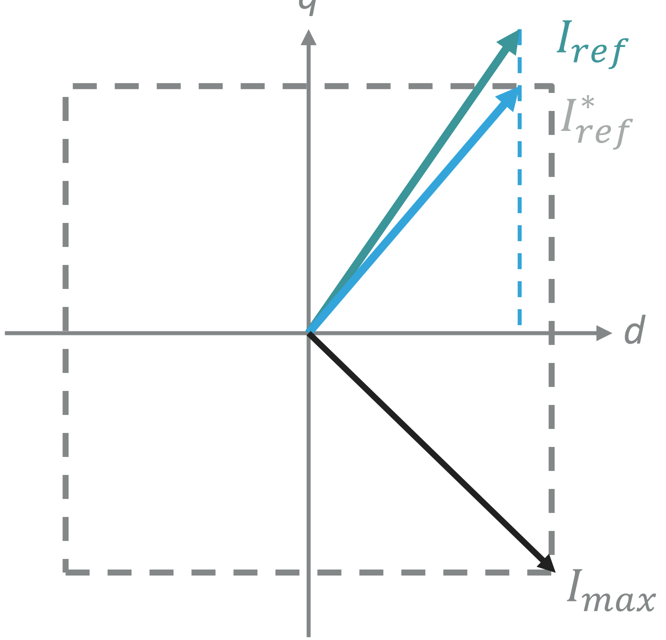
$$P_{r_L} = \frac{|\boldsymbol{v}_L|^2}{r_L} = 1 - \eta P_{\text{cpl}} \;\rightarrow\; r_L = \frac{|\boldsymbol{v}_L|^2}{1 - \eta P_{\text{cpl}}}$$

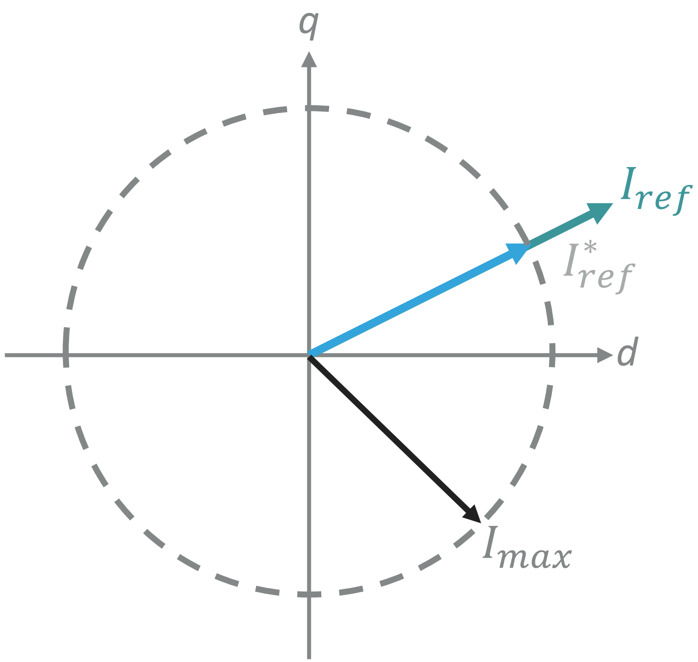


Case	Source Model	$P^\star$ [p.u.]	Bifurcation	Participating States
QSP CPL	GENROU	1.169	Hopf	e_q, E_{fd}
	Droop/VSM	1.242	Singularity-Induced	$\boldsymbol{\xi}_{dq}$
	dVOC	1.241	Singularity-Induced	$\boldsymbol{\xi}_{dq}$
EMT CPL	All	0.0	Unstable	See Sec. II
QSP/EMT CIL or CCL	All	4.5	Stable	
EMT Single -Cage IM	Marconato	0.688	Hopf	e_q, E_{fd}
	Droop/VSM	1.015	Transcritical	$\boldsymbol{\psi}_{dq}$
	dVOC	1.049	Transcritical	$\boldsymbol{\psi}_{dq}$
EMT Active Load	Marconato	1.075	Hopf	e_q, E_{fd}
	Droop/VSM	1.458	Hopf	ζ, v_{DC}
	dVOC	1.430	Hopf	ζ, v_{DC}

Henriquez-Auba, R., Lara, J. D. & Callaway, D. S. (2024, February). Small-Signal Stability Impacts of Load and Network Dynamics on Grid-Forming Inverters. In IEEE Innovative Smart Grid Technologies North America 2024

CURRENT CONTROL LIMITS DESIGN





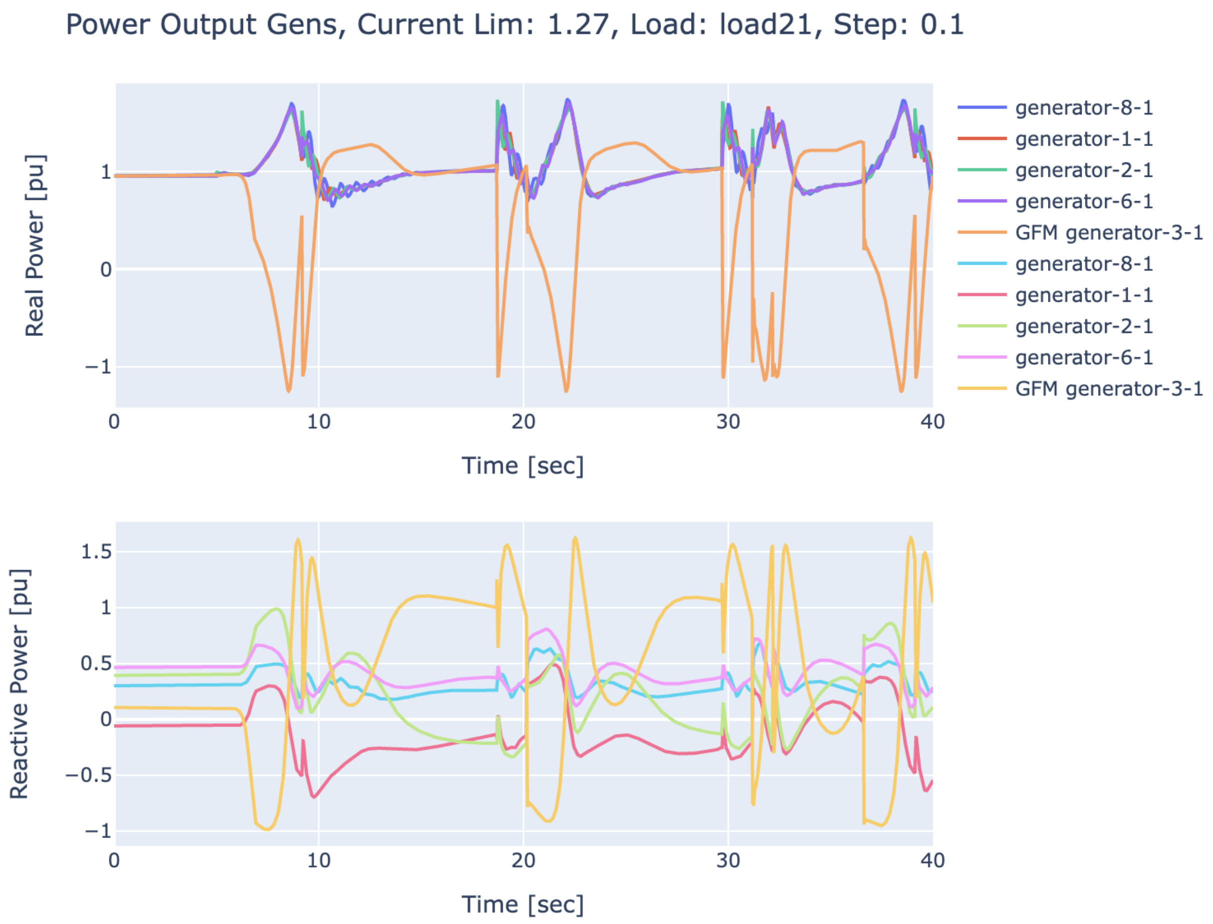
$$I^*_{ref,x} = \begin{cases} \pm I_{lim,x}, & |I_{ref,x}| > I_{lim,x} \\ I_{ref,x}, & |I_{ref,x}| \leq I_{lim,x} \end{cases}$$

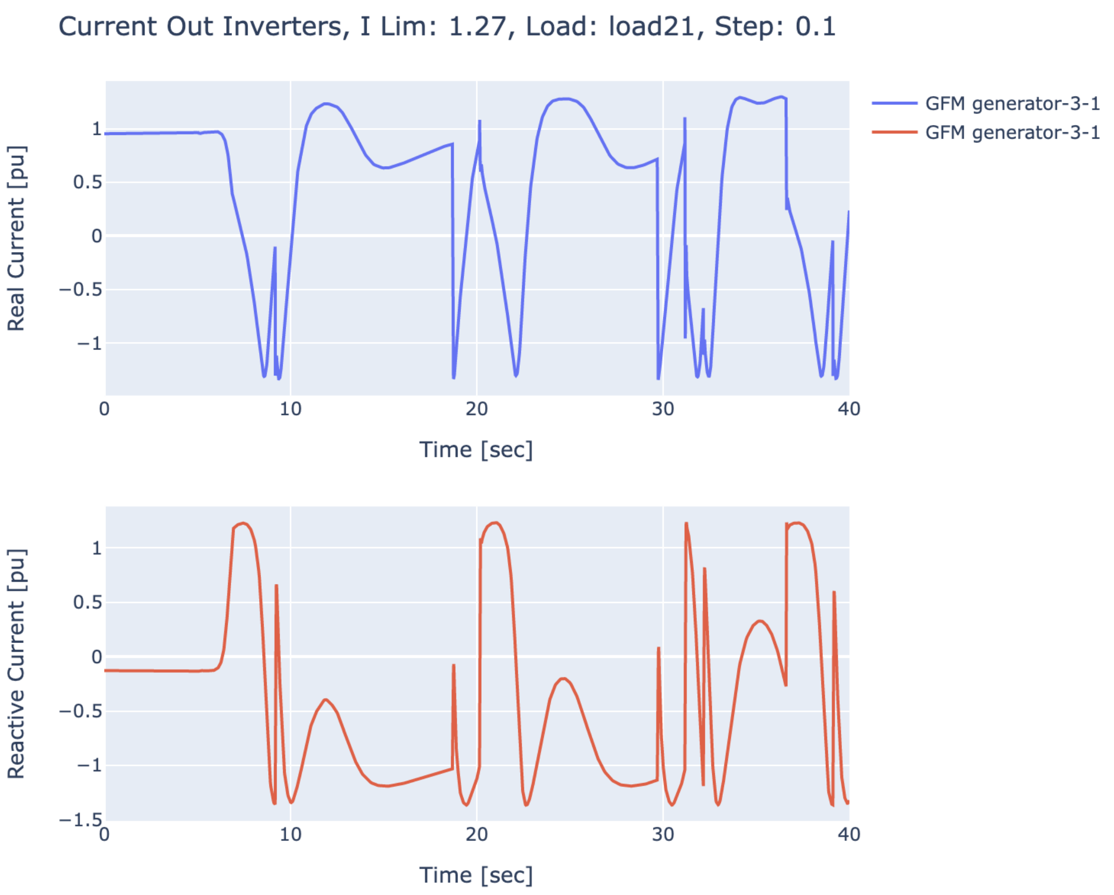
where, $I_{lim,x} = I_{max}/\sqrt{2}$

$$I^*_{ref} = \begin{cases} \frac{I_{max}}{|I_{ref}|} I_{ref}, & |I_{ref}| > I_{max} \\ I_{ref}, & |I_{ref}| \leq I_{max} \end{cases}$$

- Key difference: instantaneous changes phase angle, magnitude does not!

PERFORMANCE GFM CONTROL WITH LIMITS





Ross, H., Inverter Current Limiting Impacts on Power System Stability

CONCLUSIONS

- There is a large gap in the understanding of the underlying dynamics of interconnected power systems with large shares of inverter models. ”Probably” some of the commonly used practices in the industry are not the best examination tools.
- The interactions between EMT dynamics, constant power loads and current limiters needs more study and relying on waveform EMT to perform these studies at scale is impractical.
- Analysis practices need to evolve to provide engineers with understanding about the nature of the oscillation.