Modeling Grid-Forming Technologies and Standardization

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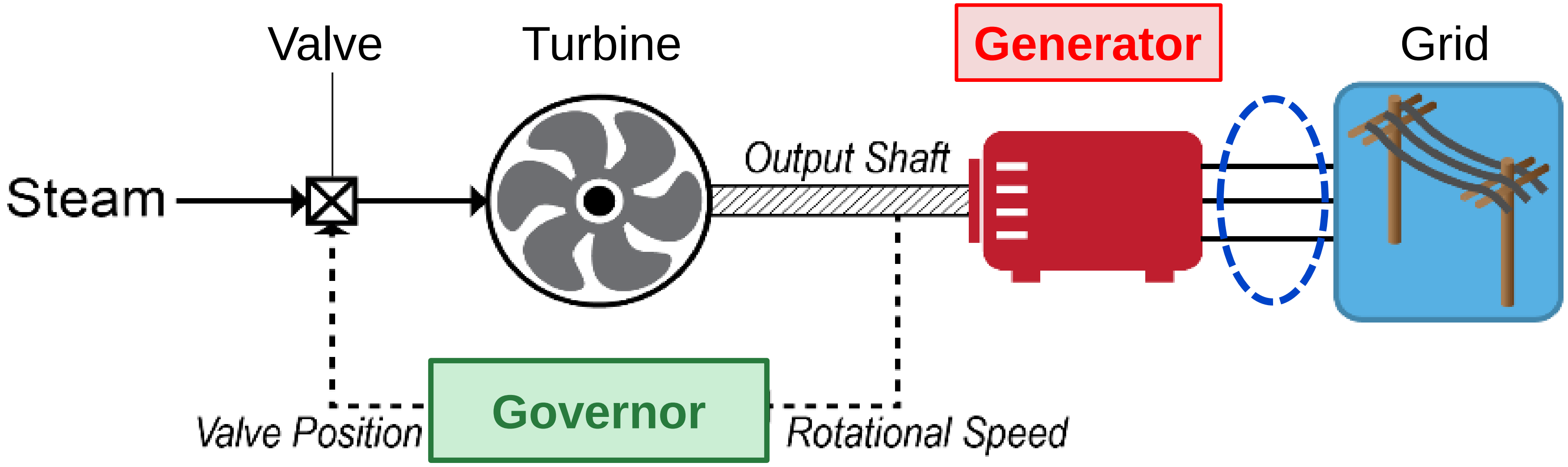
Key Features of Synchronous Generators

- **Mechanical inertia of the machine's rotor**
- **Damping torque**
  provided by internal machine construction as well as external (machine-based) loads and their resistance to increasing frequency
- **Synchronizing torque**
  resulting from the completed reluctance path between machines and their resistance to changing load angle
- **Governor response**
  that adjusts the generator prime mover to regulate grid frequency (proportionally)

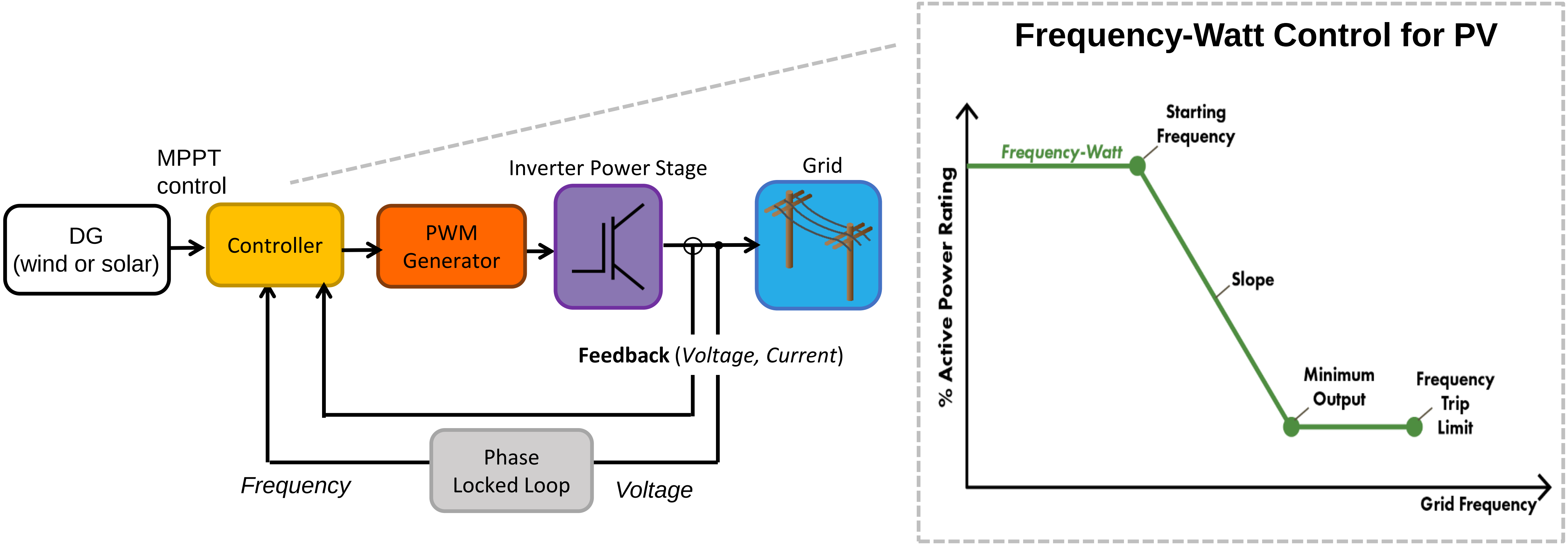


What About Inverters…

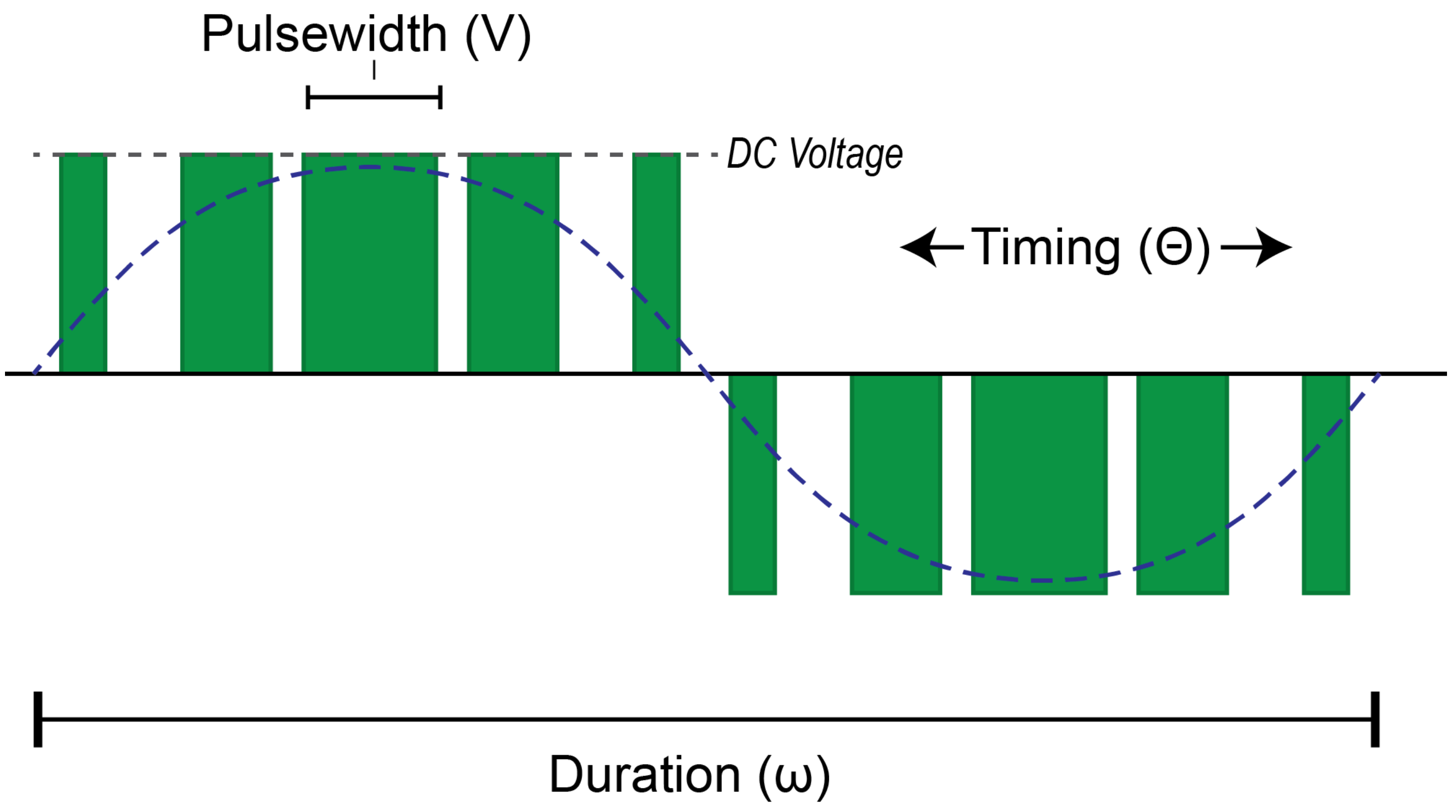
- Inverter-based generation in their standard form do not possess any of characteristics of synchronous machine

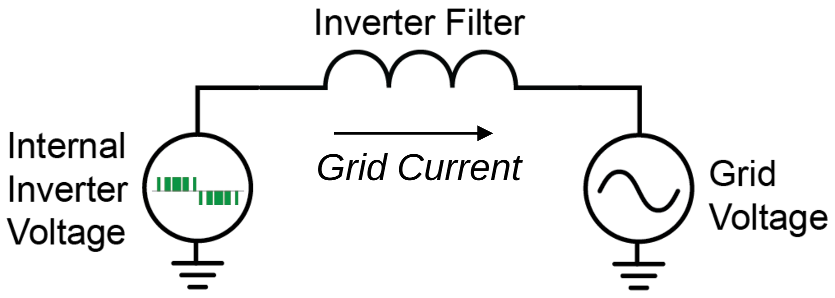
- It is possible to emulate them by adding additional (software) controls to the inverter

Emulation of Governor Response with Frequency-Watt



Controlling Voltage, Frequency, and Angle With PWM

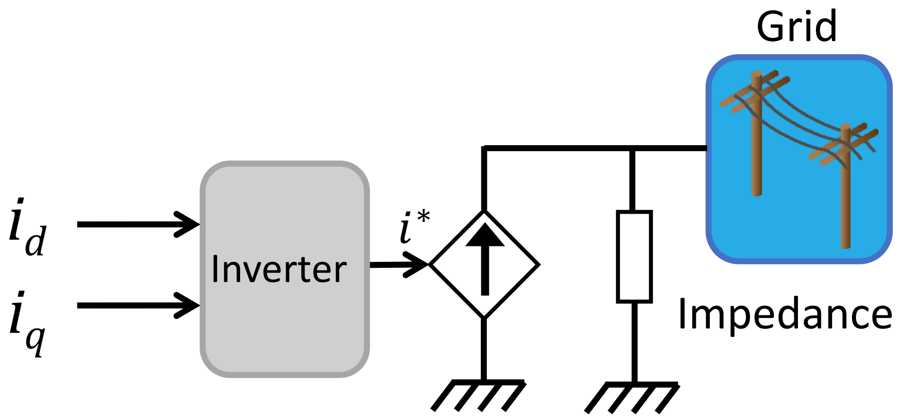




Inverter hardware always creates a voltage source behind a (filter) impedance. It is the inverter control that creates a current or voltage source

Grid-Following and Grid-Following Inverters

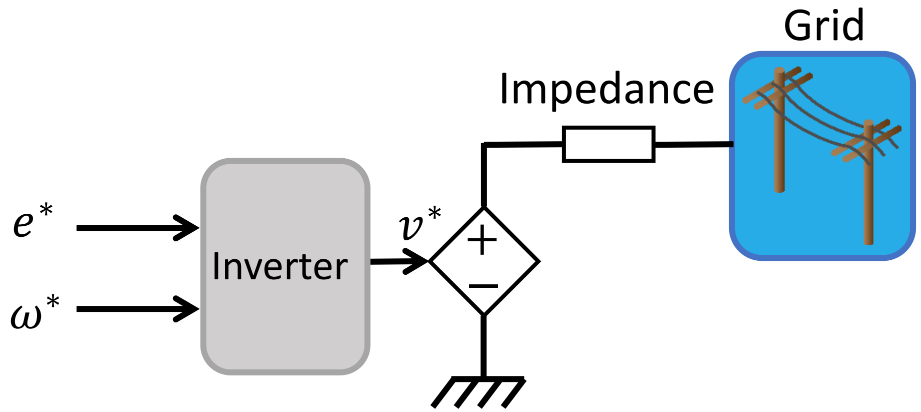
Grid-Following Inverter
(Current-Controlled Voltage Source)



Control **output current** based on desired output power (active and reactive)

Requires a grid voltage reference to follow

Grid-Forming Inverter
(Voltage-Controlled Voltage Source)

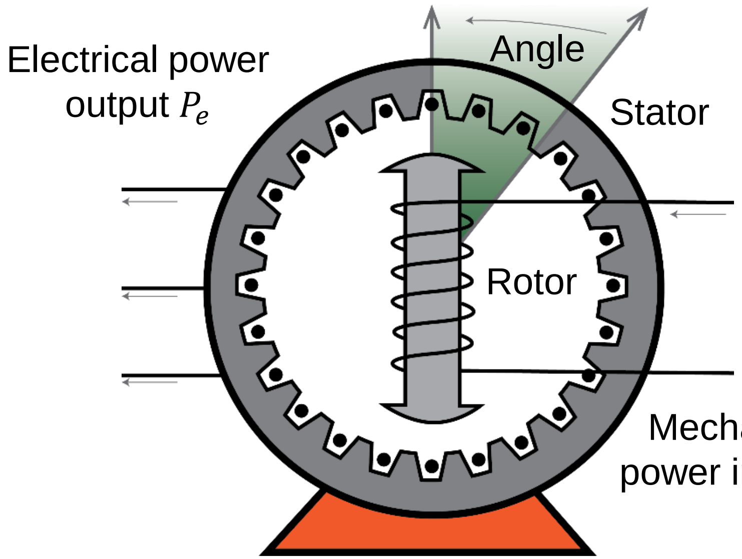


Control **PWM voltage/angle** based on desired output power (active and reactive)

Degrees of Machine Emulation with Inverters

Synchronous generator model based approach

Full representation of physical model
- Mechanical equations
- Electrical equations



Output: voltage magnitude e and angle θ

Swing equation

Simplification

Swing equation based approach

Inertia Damping

$$\begin{cases} J\omega \dfrac{d\omega}{dt} + D\omega = P_m - P_e \\ \Delta\omega = \omega - \omega_{grid} \end{cases}$$

Virtual frequency

Output: voltage angle θ

Simplification

Frequency-power based approach

Damping Inertia

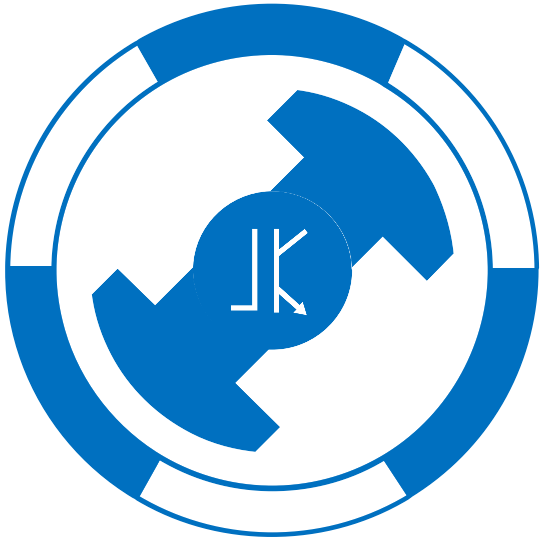
$$\begin{cases} P_{VSG} = P_0 + K_D \Delta\omega + K_I \dfrac{d\Delta\omega}{dt} \\ \Delta\omega = \omega_{grid} - \omega_0 \end{cases}$$

Reference frequency (No virtual frequency, no need to solve differential equations)

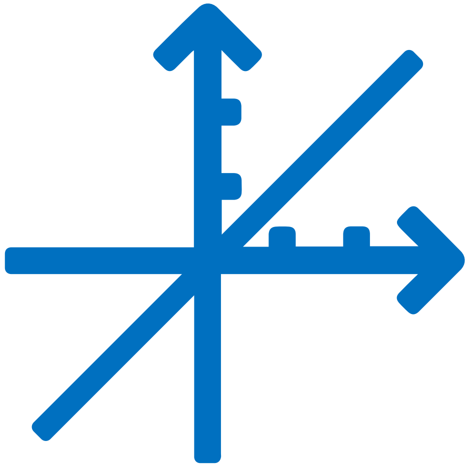
Output: active power P_{VSG}

Example Grid-Forming Control Methods

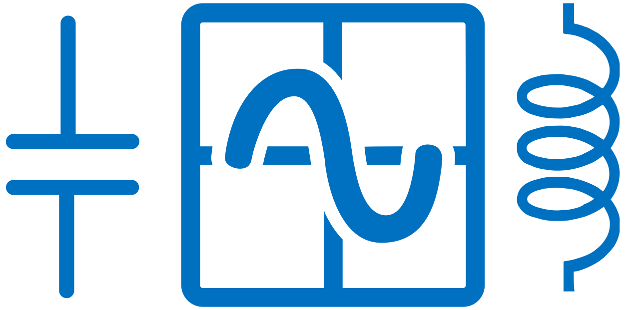
Virtual Synchronous Machine (VSM)



Droop



Dispatchable Virtual Oscillator (dVOC)



UNIFI Modeling and Simulation Deliverables

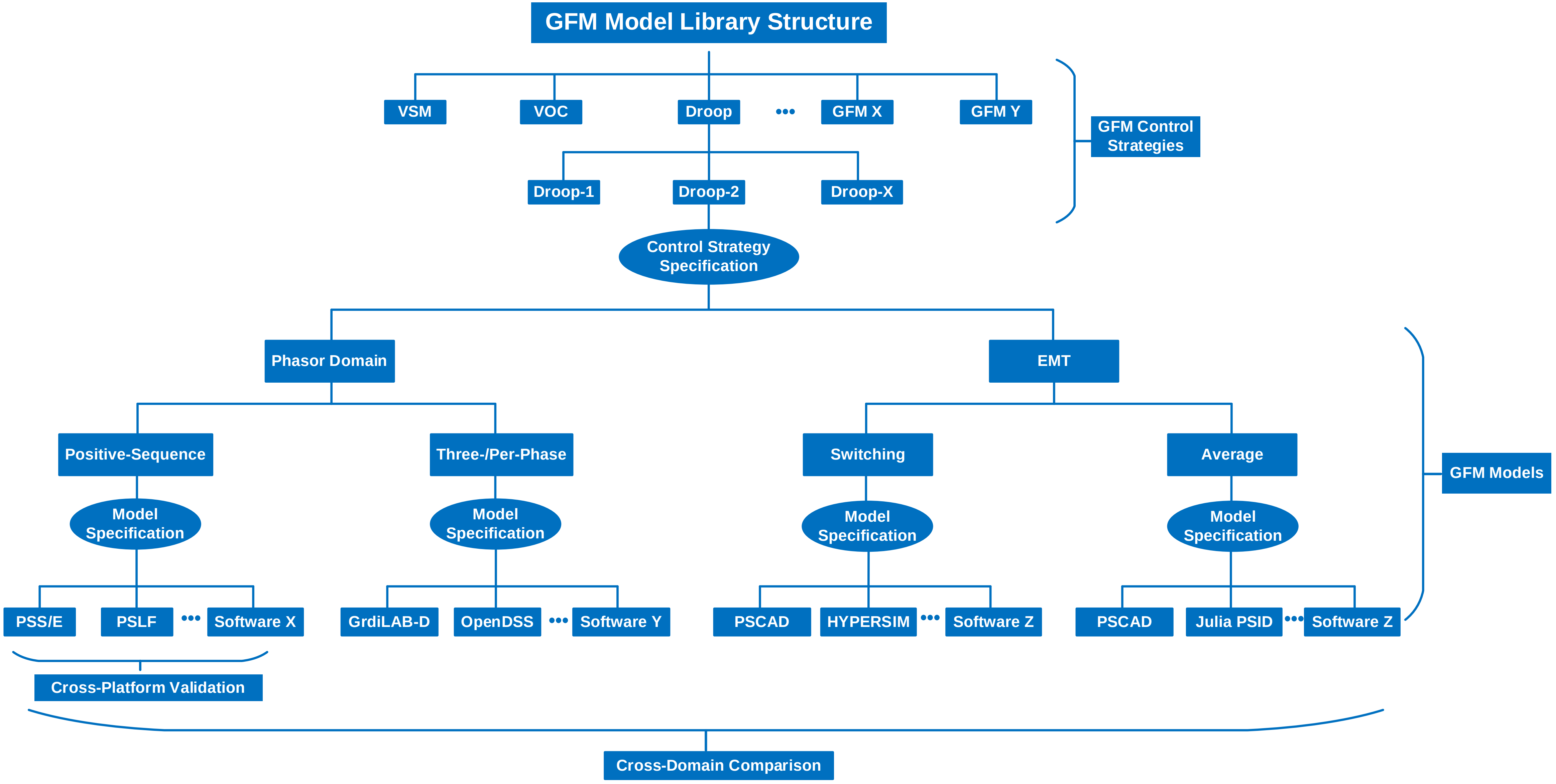
- Compile GFM Model Library
- Creqte software test-bed
- Improve model accuracy and simulation scalability
- Document analytical approaches
- Demonstrate GFM model interoperability

EPRI

Modeling and Simulation Working Groups

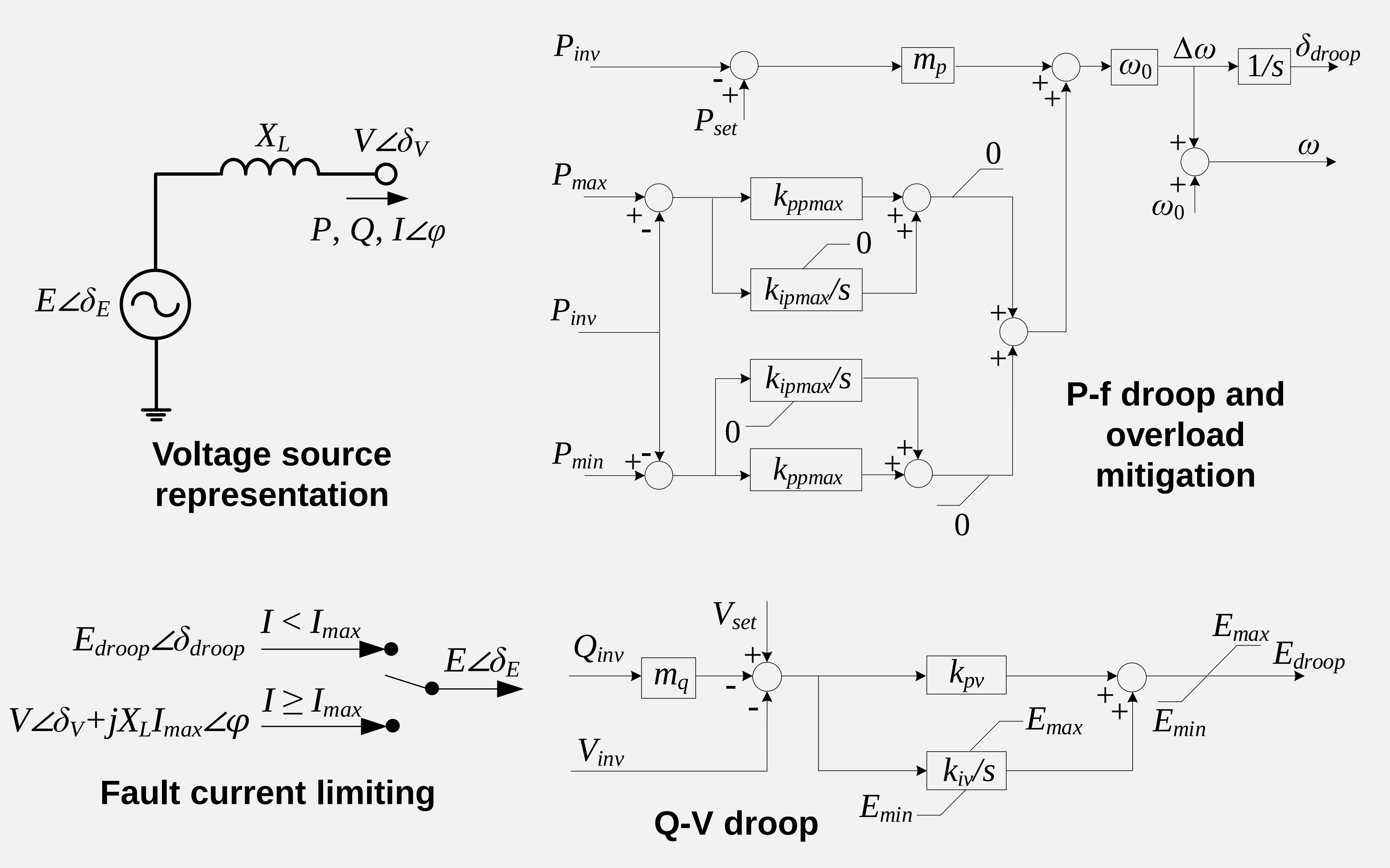
- **WG 1**: GFM Model Development and Theoretical Innovations WG
- **WG 2**: Use Case, Software Testbed, and Interoperability WG
- 15-20 members per WG from national labs, research institutes, universities, vendors, and utilities (meeting monthly)

GFM Model Library Structure



A few positive-sequence GFM models have been developed to represent popular control methods…

Positive-Sequence Model Developed by PNNL by Extending CERTS Droop

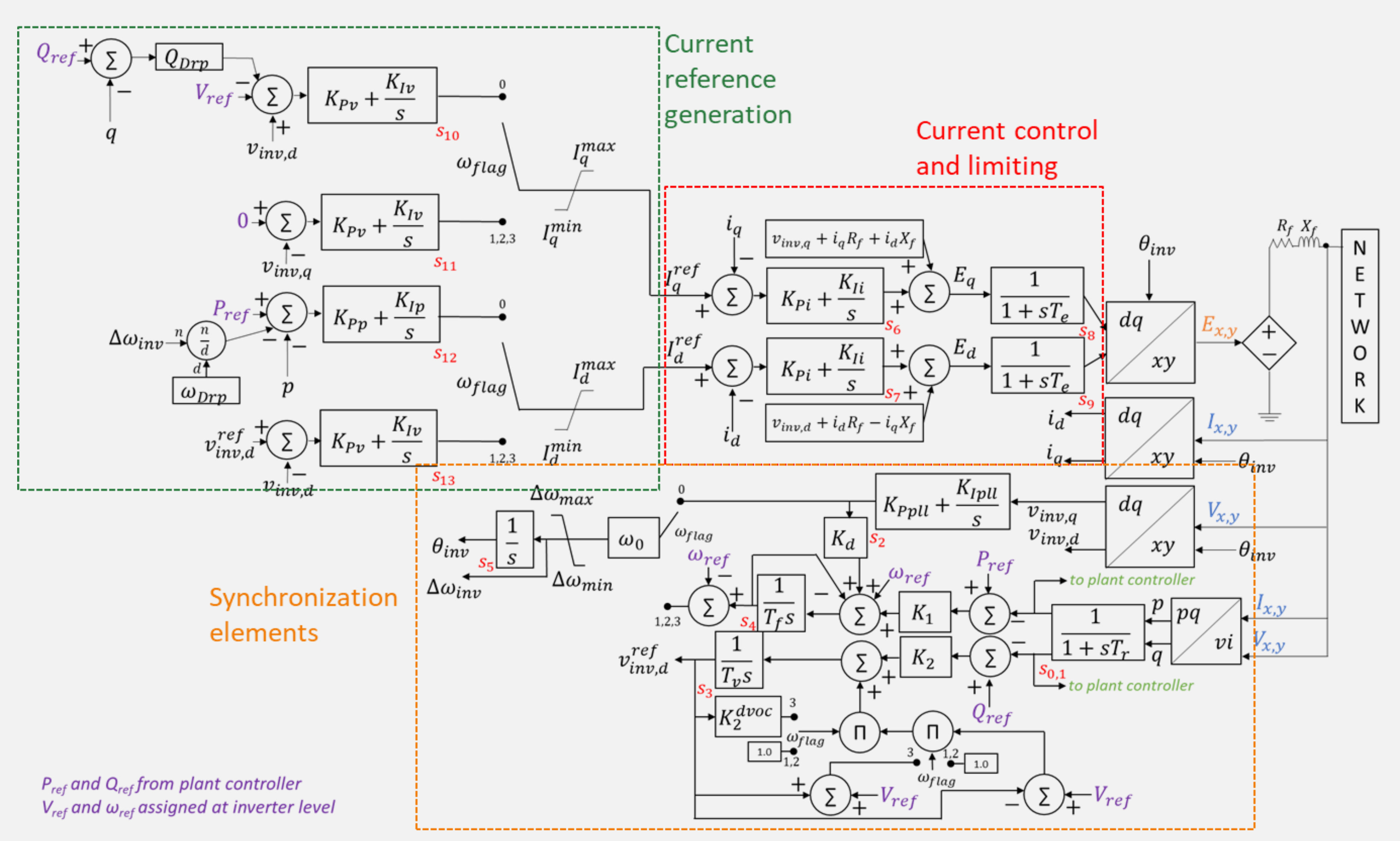


https://www.wecc.org/Reliability/Model%20Specification%20of%20Droop-Controlled,%20Grid-Forming%20Inverters_PNNL-V2-Final.pdf

Single-loop structure model

Does not use/model cascaded inner loops

Positive-Sequence Model Co-Developed by EPRI, UIUC, UW, and UMN



Multi-loop structure model

Attempts to capture "fast" transients of inverter inner loops in the phasor domain

https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Memo%20on%20Proposal%20for%20Generic%20GFM%20Model_v2.pdf&action=default&DefaultItemOpen=1

Status of generic GFM model development

Domain	Positive Sequence (Balanced RMS)			3-Phase (Unbalanced RMS)			
Software	PSS/E	PSLF	PowerFactory	OpenDSS	PowerFactory	CYME	Synergi
Available Models	Droop VSM dVOC	Droop VSM dVOC	dVOC	dVOC	dVOC		

Domain	Electromagnetic Transient (EMT)					Real-time
Software	PSCAD	EMTP	PowerFactory	SIMULINK	PLECS	RTDS/Opal-RT/RSCAD/HyperSIM
Available Models	Droop VSM dVOC	Droop VSM dVOC	Droop VSM dVOC	Droop VSM dVOC	Droop (A) VSM dVOC	dVOC

Model Validation

- ☑ Comparison of PSS/E, PSLF, and PSCAD (EMT) simulation results for the single-loop droop GFM control
- ☑ Comparison of PSLF and PSCAD simulation results for the multi-loop GFM model (PLL-based, droop, VSM, and dVOC)
- ☑ Comparison of PSLF and PSSE simulation results for the multi-loop GFM model (PLL-based, droop, VSM, and dVOC)

Upcoming Work

- Work on initial GFM model library that includes the model specifications and IBR models with basic GFM controls
- Coordinate with the Integration and Validation area on the use-case design
- Work with IBR vendors to get their inputs on the developed generic models
- Coordinate with the Control Area on the GFM control strategies
- Understand the applicability and limitations of different GFM models, and provide guidance on selecting these models for different study purposes