Grid-Forming Hybrid Control Inverter model and Plant Controller Model—REGFM_C1 and REPCGFM_C1

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History of WECC Standard Library GFM Models

- In recent years, WECC MVS has approved two standard library grid-forming inverter (GFM) models—***REGFM_A1*** and ***REGFM_B1***, representing two major GFM controls used in industry—***Droop Control*** and ***Virtual Synchronous Machine (VSM) Control***
- The development of those two models received a significant support from **SMA Solar Technology** and **GE Vernova**
- After the REGFM_A1 and REGFM_B1 models have been approved by WECC MVS, the team reached out to more OEMs with the goal of further improving/updating those models, including reaching out to ***Tesla Energy***
- After multiple in-depth discussions with Tesla, the team realized that there is another type of GFM control used in industry. Therefore, the team collaborates with Tesla Energy on developing a new standard library GFM model specification, aiming to better represent another important representative GFM technology used in industry
- The initial model specifications were co-developed by PNNL, Tesla Energy, and EPRI. Tesla Energy provided main control blocks to support the model development
- The model specifications have been revised multiple times to incorporate suggestions from WECC MVS members
- **The model specifications were approved on Jan. 30th, 2025**
- Recently, the model benchmarking has been completed

WECC Standard Library GFM Models

REGFM_A1	REGFM_B1	REGFM_C1 and REPCGFM_C1 (*seek for approval*)
GFM Droop Control	GFM Virtual Synchronous Machine	GFM Hybrid Control

REGFM_C1 and REPCGFM_C1 Contributors

Standard Library Grid-Forming Hybrid Control Inverter-based Resource Model Specification (REGFM_C1)

Wei Du[1], Sai Gopal Vennelaganti[2], Deepak Ramasubramanian[3], Jinho Kim[1], Udoka Nwaneto[1], Quan Nguyen[1], Ali Mohammadpour[2], Sarah Walinga[2], Lilan Karunaratne[2], Mostafa Mahfouz[2], Mohammed Nassar[2], Sushrut Thakar[3], Chengwen Zhang[3], Sheik Mohammad Mohiuddin[1], James Weber[4], Mengxi Chen[5], Jayapalan Senthil[6], James Feltes[6], Pouyan Pourbeik[7], Fred Howell[8], Jeff Bloemink[8], Song Wang[9], Doug Tucker[10], Songzhe Zhu[11], Juan Sanchez[12]

1 Pacific Northwest National Laboratory
2 Tesla Energy
3 Electric Power Research Institute
4 PowerWorld
5 GE Vernova
6 Siemens
7 Power and Energy, Analysis, Consulting and Education (PEACE®) PLLC
8 PowerTech Labs
9 Portland General Electric
10 Western Electricity Coordinating Council
11 GridBright, a Qualus Company
12 GE Vernova (retired)

Standard Library Plant Controller Model Specification for a Grid-Forming Hybrid Control Inverter-based Resource (REPCGFM_C1)

Wei Du[1], Sai Gopal Vennelaganti[2], Deepak Ramasubramanian[3], Jinho Kim[1], Udoka Nwaneto[1], Quan Nguyen[1], Ali Mohammadpour[2], Sarah Walinga[2], Lilan Karunaratne[2], Mostafa Mahfouz[2], Mohammed Nassar[2], Sushrut Thakar[3], Chengwen Zhang[3], Sheik Mohammad Mohiuddin[1], James Weber[4], Mengxi Chen[5], Jayapalan Senthil[6], James Feltes[6], Pouyan Pourbeik[7], Fred Howell[8], Jeff Bloemink[8], Song Wang[9], Doug Tucker[10], Songzhe Zhu[11], Juan Sanchez[12]

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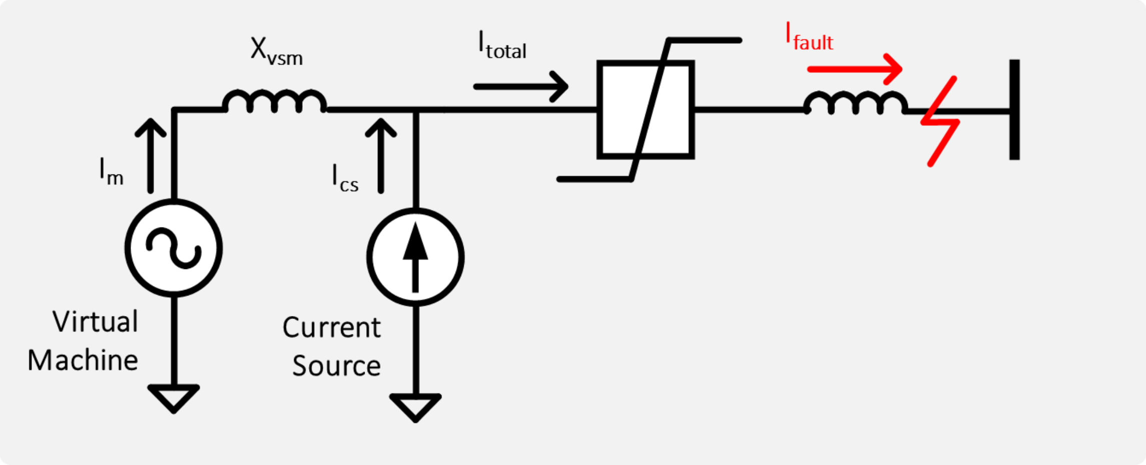
Inverter Model—REGFM_C1

The GFM Hybrid Control Approach

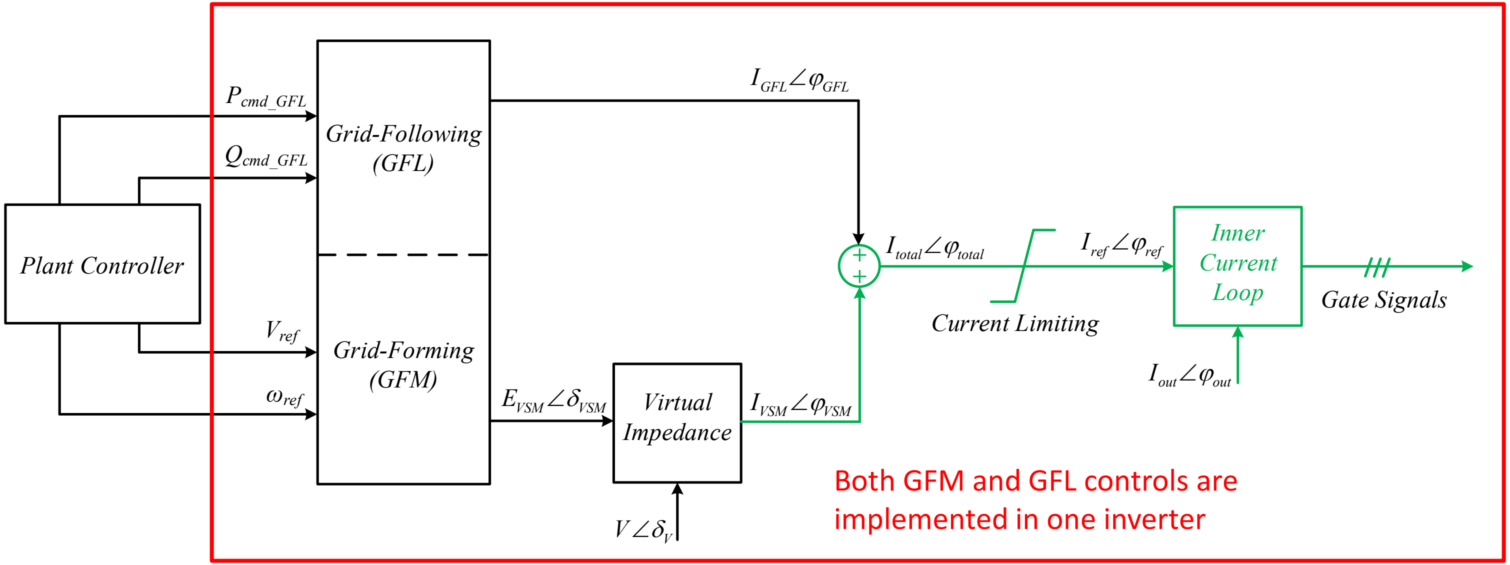
- The GFM hybrid control implements both the GFM control and GFL control simultaneously inside one inverter. Both controls work in parallel, and they do not switch between the GFM and GFL controls
- The steady state P and Q of the GFM branch is regulated to be 0, and the GFL branch provides the steady state response
- The actual control implementation has a fast inner current loop, and the current reference is the summation of the current reference from the GFM branch and the GFL branch
- The current limiting is implemented to limit the total current reference of both branches



Source: Tesla PESGM 2024 Presentation

Overall GFM Hybrid Control Structure

- The plant controller sends P_{cmd_GFL} and Q_{cmd_GFL} to the GFL branch, and sends V_{ref} and ω_{ref} to the GFM branch
- The steady state P and Q of the GFM branch is dispatched to be 0
- The green lines represent the virtual impedance control and the fast inner current control loop, which will be modeled algebraically in the phasor domain
- The current limit logic limits the current magnitude, but the current phase angle remains unchanged

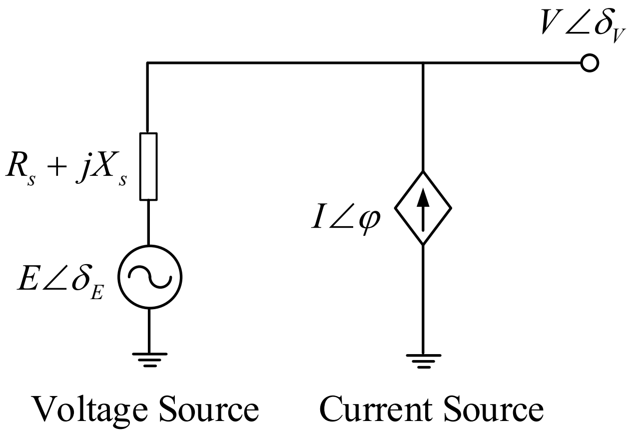


Overall Control Structure

Source: Tesla Inverter Controls Block Diagrams

Positive-Sequence GFM Hybrid Control Model Network Interface

- In phasor domain, the GFM hybrid model is interfaced with the network solution through a voltage phasor behind impedance in parallel with a current phasor
- $R_s + jX_s$ represents the virtual impedance
- $V\angle\delta_V$ represents the terminal voltage

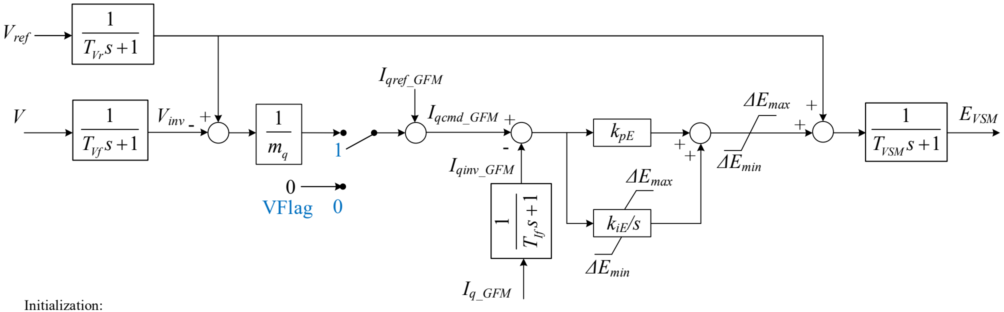


Model Network Interface

Positive-Sequence GFM Hybrid Control Model
GFM Branch

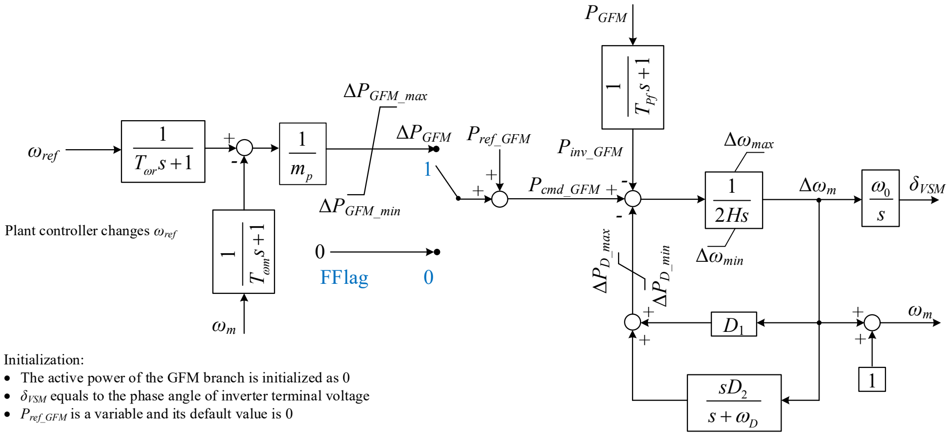
unifi consortium

- **The GFM branch is a virtual synchronous machine (VSM) model**
- The voltage control block controls the internal voltage magnitude E_{vsm}
- The VSM control block controls the internal phase angle δ_{VSM}



Initialization:
- The reactive power of the GFM branch is initialized as 0
- E_{VSM} equals to the inverter terminal voltage V
- V_{ref} equals to the terminal voltage V
- I_{qref_GFM} is a variable and its default value is 0

GFM Voltage Control

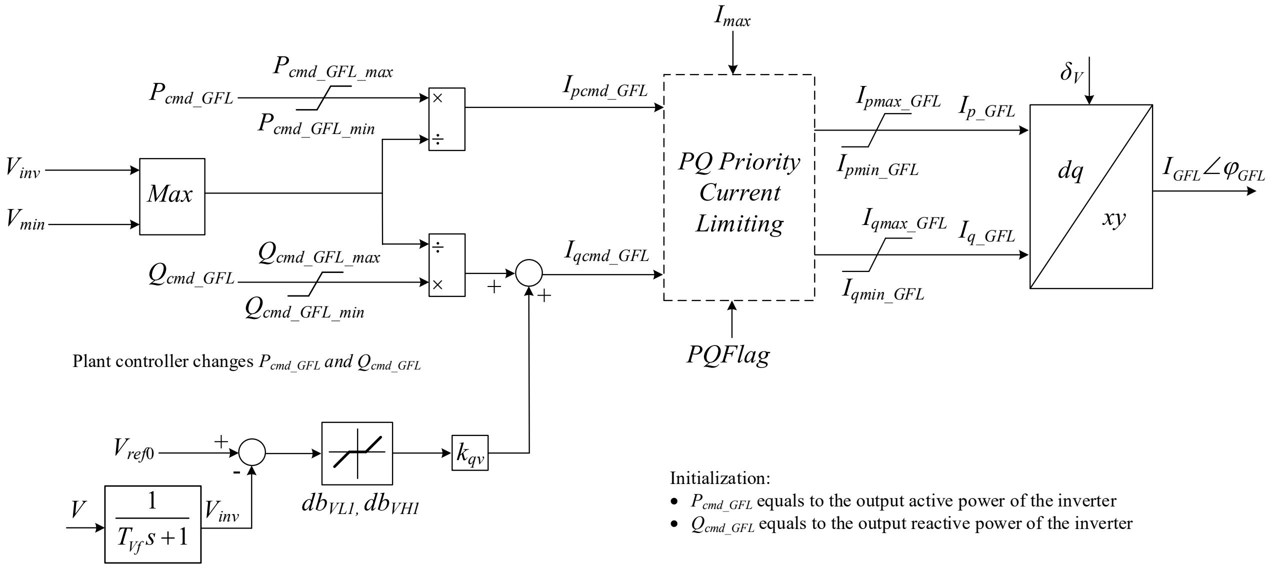


Initialization:
- The active power of the GFM branch is initialized as 0
- δ_{VSM} equals to the phase angle of inverter terminal voltage
- P_{ref_GFM} is a variable and its default value is 0

GFM VSM Control

Positive-Sequence GFM Hybrid Control Model
GFL Branch

- **The GFL branch represents a typical GFL control**



Initialization:

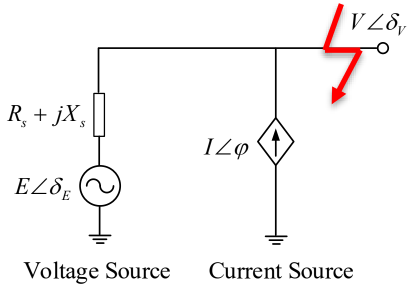
- P_{cmd_GFL} equals to the output active power of the inverter
- Q_{cmd_GFL} equals to the output reactive power of the inverter

GFL Branch Control Blocks

Positive-Sequence GFM Hybrid Control Model Current Limiter

- The current limiting is implemented algebraically The current reference from the GFM branch can be calculated using (1)

$$I_{VSM}\angle\varphi_{VSM} = \frac{E_{VSM}\angle\delta_{VSM} - V\angle\delta_V}{R_s + jX_s} \quad (1)$$



- The total current reference from both branches can be calculated using (2)

$$I_{total}\angle\varphi_{total} = I_{VSM}\angle\varphi_{VSM} + I_{GFL}\angle\varphi_{GFL} \quad (2)$$

- Define the k factor (3)

$$k = \frac{I_{total}}{I_{max}} \quad (3)$$

- The total output current can be limited by reducing the current of both branches

$$E\angle\delta_E = \begin{cases} E_{VSM}\angle\delta_{VSM}, & I_{total} < I_{max} \\ \frac{I_{VSM}\angle\varphi_{VSM}}{k}(R_s + jX_s) + V\angle\delta_V, & I_{total} \geq I_{max} \end{cases}$$

$$I\angle\varphi = \begin{cases} I_{GFL}\angle\varphi_{GFL}, & I_{total} < I_{max} \\ \frac{I_{GFL}\angle\varphi_{GFL}}{k}, & I_{total} \geq I_{max} \end{cases}$$

The goal is to ensure the magnitude of the total output current is limited at I_{max}, and its phase angle remains unchanged.

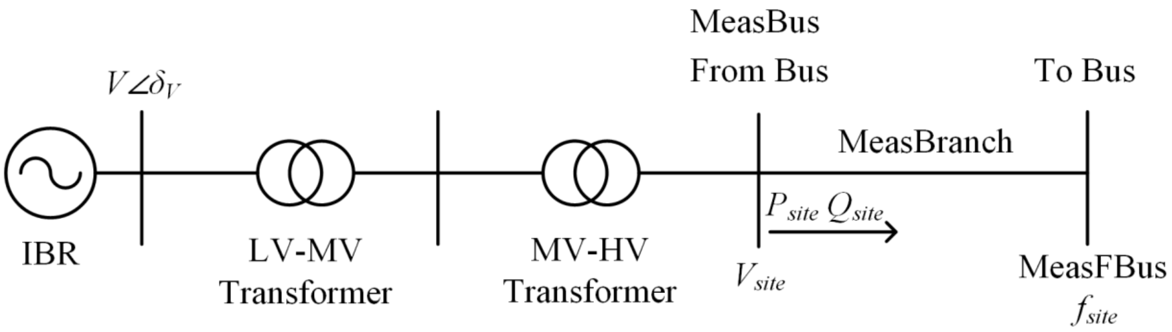
Plant Model—REPCGFM_C1

Main Functions of the Plant Controller

		Outputs
GFM Branch	• GFM voltage reference generator • GFM frequency reference generator	V_{ref} ω_{ref}
GFL Branch	• Real power path • Reactive power path • Voltage controller • Loss compensation	P_{cmd_GFL} Q_{cmd_GFL}

Plant Controller Model—REPCGFM_C1

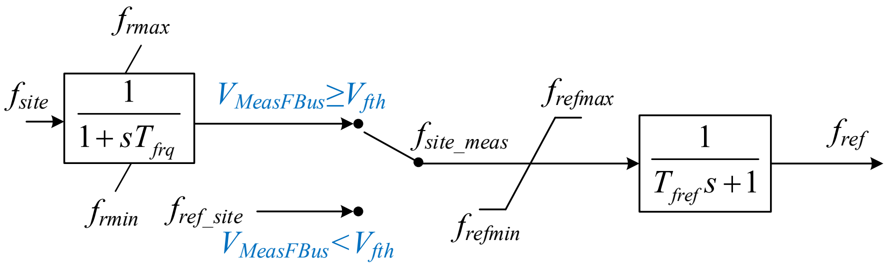
One-line diagram of a typical IBR plant and model setting



- MeasBus is used for V_{site}, P_{site}, Q_{site} measurement. By default it is the same with From Bus
- MeasFBus is used for frequency measurement
- If a branch is specified, but a MeasBus is not specified, then From Bus will be used
- If a branch is not specified, then P_{site} and Q_{site} will be the output of the generator, V_{site}=V, and R_{loss}=X_{loss}=0
- If MeasFBus is not specified, then frequency will be measured at the same location as the P_{site}, Q_{site}, and V_{site} measurements

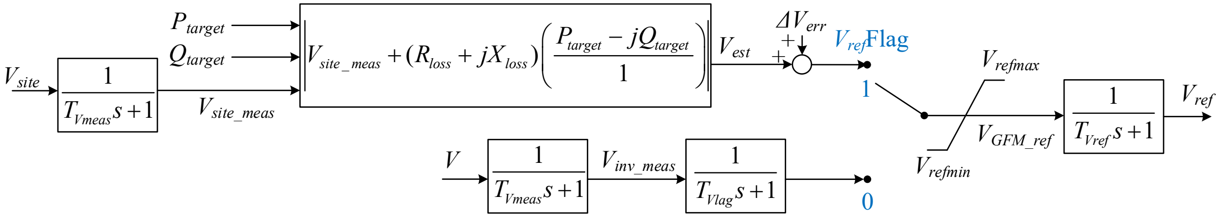
Plant Controller GFM Branch
Voltage and Frequency Reference Generator

The plant controller sends the measured site frequency to the GFM branch to ensure the steady state *P* of the GFM branch is 0.



Frequency reference generator for the GFM branch

The plant controller sends the measured voltage to the GFM branch to ensure the steady state *Q* of the GFM branch is 0.



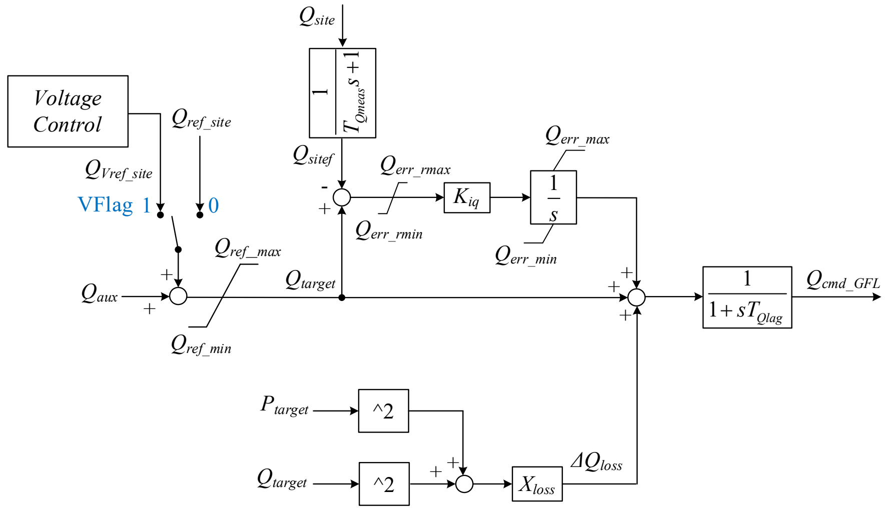
Initialization:

- ΔV_{err} is used for the initialization purpose
- $V_{GFM\_ref}=V_{ref}=V$, and V is the inverter terminal voltage
- $\Delta V_{err}=V-V_{est}$

Voltage reference generator for the GFM branch

Plant Controller GFL Branch
Voltage Control and Reactive Power Path

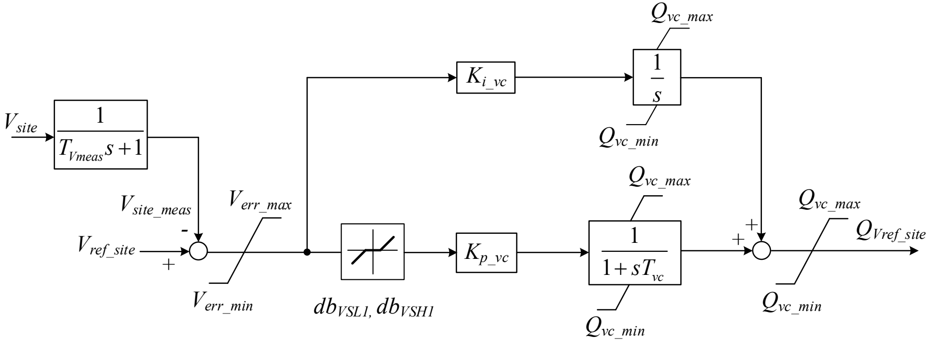
The plant controller sends the Qcmd_ GFL to the GFL branch of the inverter model REGFM_C1



Initialization:

- When VFlag=0, $Q_{ref\ site}=Q_{target}=Q_{site}$
- When VFlag=1, $Q_{Vref\ site}=Q_{target}=Q_{site}$
- Q_{aux} is a variable and its default value is 0

Reactive Power Path



Initialization:

- If K_{i_vc} is not 0, output of the integrator in the K_{i_vc} branch equals to $Q_{Vref\_site}=Q_{site}$, and $V_{ref\_site}=V_{site}$
- If K_{i_Vc} is 0, output of the lag block in the K_{P_VC} branch equals to $Q_{Vref\_site}=Q_{site}$

  If $Q_{site}=0$, $V_{ref\_site}=V_{site}$

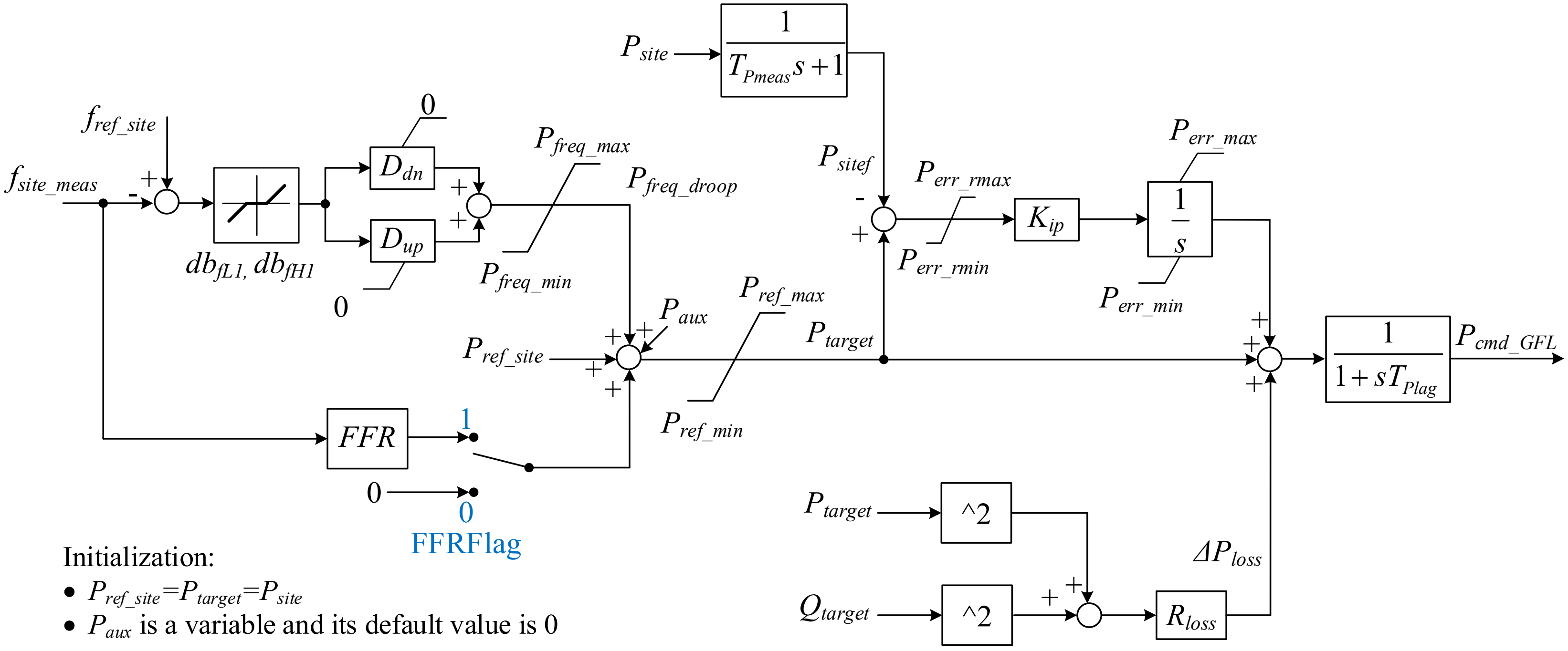
  If $Q_{site}>0$, $V_{ref\_site}=V_{site}+db_{VSH1}+Q_{site}/K_{p\_vc}$

  If $Q_{site}<0$, $V_{ref\_site}=V_{site}+db_{VSL1}+Q_{site}/K_{p\_vc}$

Voltage Control

Plant Controller GFL Branch
Active Power Path

The plant controller sends the Pcmd_ GFL to the GFL branch of the inverter model REGFM_C1



Initialization:

- $P_{ref\_site}=P_{target}=P_{site}$
- P_{aux} is a variable and its default value is 0

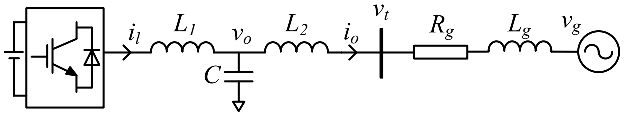
Active Power Path

Comparison between PSS/E Model and PSCAD Model

Both PSS/E model and PSCAD model were developed by the PNNL team based on the model specifications, and simulation results were compared in a single-GFM, infinite-bus system

PSCAD and PSS/E Comparison for REGFM_C1

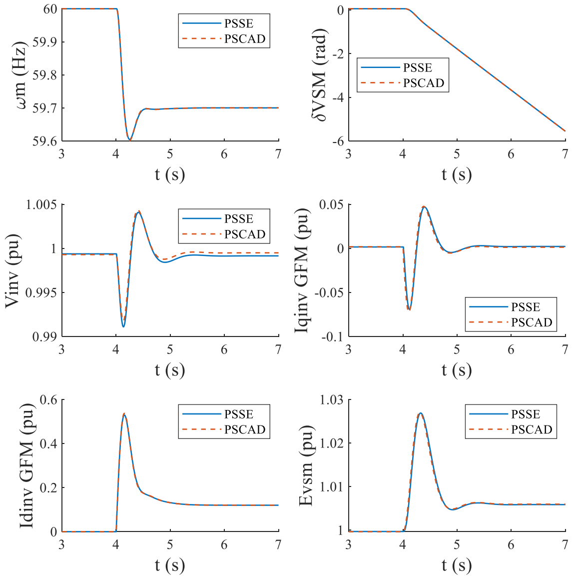
- The GFM branch responds to the frequency change because of the frequency droop
- The GFL branch is constant PQ control



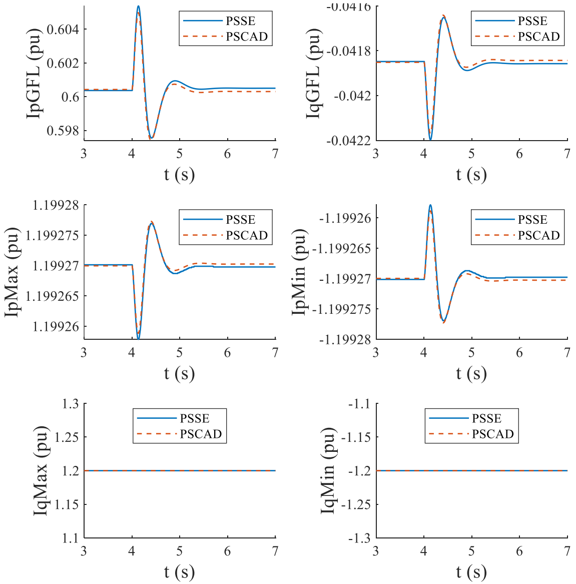
A Single-GFM Infinite-Bus System

Frequency Step down (SCR=10)

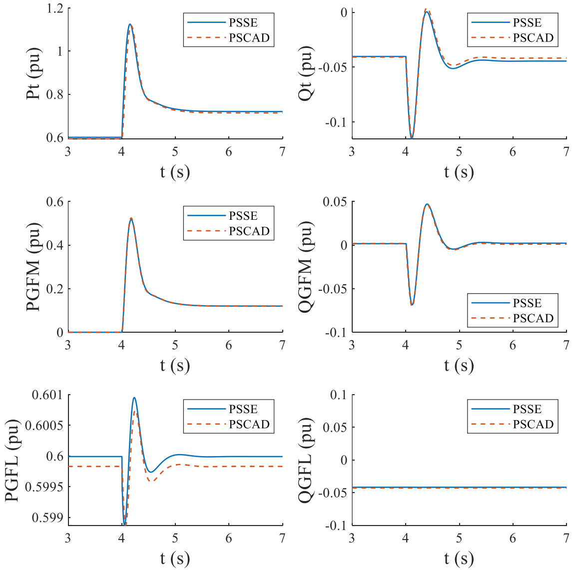
GFM Variables



GFL Variables

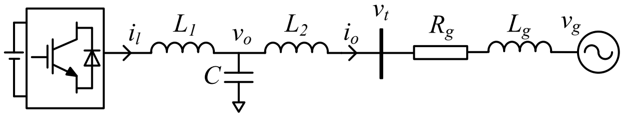


Output P and Q



PSCAD and PSS/E Comparison for REGFM_C1

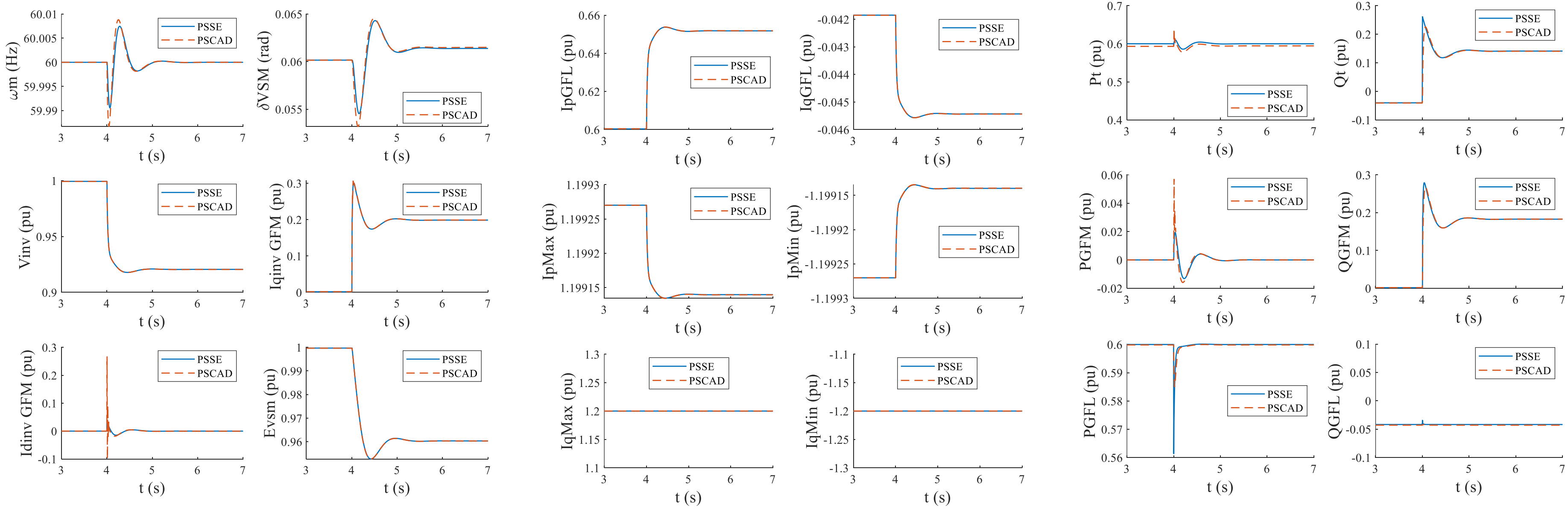
- The GFM branch responds to the voltage change by increasing *Q*
- The GFL branch remains constant PQ control
- All the GFM and GFL Variables achieve a good match between PSS/E and PSCAD



A Single-GFM Infinite-Bus System

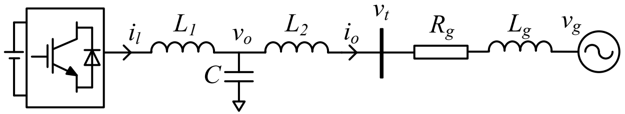
Grid Voltage Drop by 0.1 pu (SCR=10)

GFM Variables | GFL Variables | Output P and Q



PSCAD and PSS/E Comparison for REGFM_C1

- The GFM branch responds to the phase angle jump
- The GFL branch has a very limited response to the phase angle jump
- All the GFM and GFL Variables achieve a good match between PSS/E and PSCAD



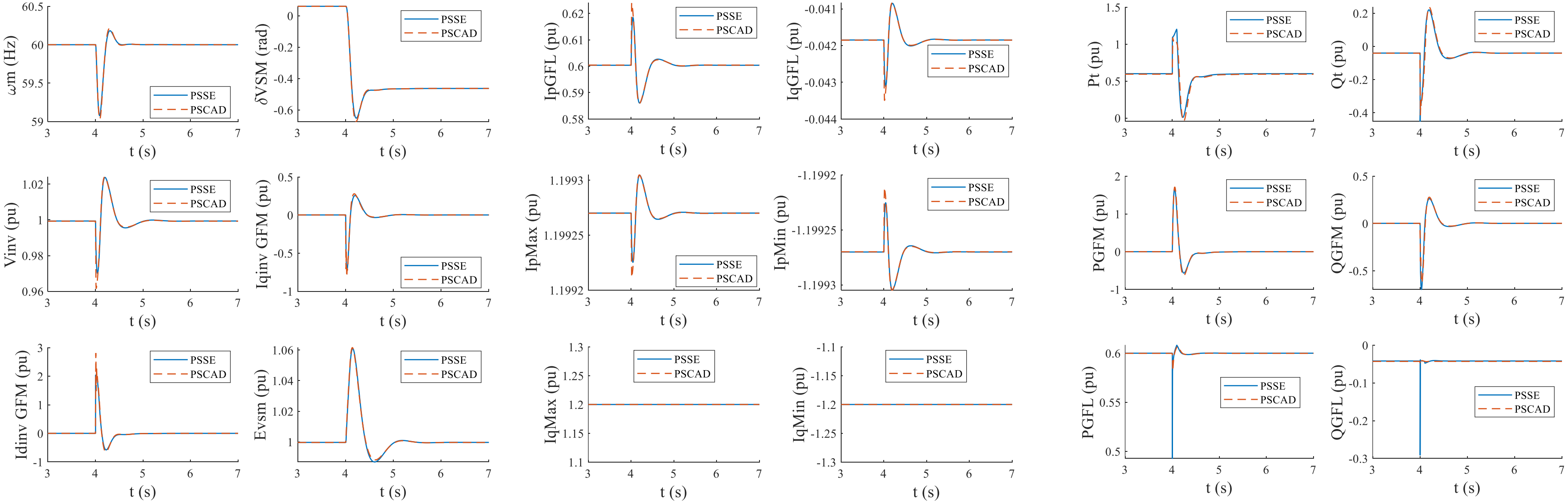
A Single-GFM Infinite-Bus System

-30° Phase Angle Jump (SCR=10)

GFM Variables

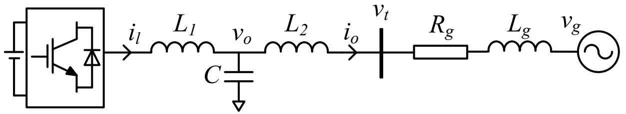
GFL Variables

Output P and Q



PSCAD and PSS/E Comparison for REGFM_C1

- The REGFM_C1 can ride-through a long-term fault
- The GFM branch is dispatched at zero output P
- The GFL branch uses the Q priority



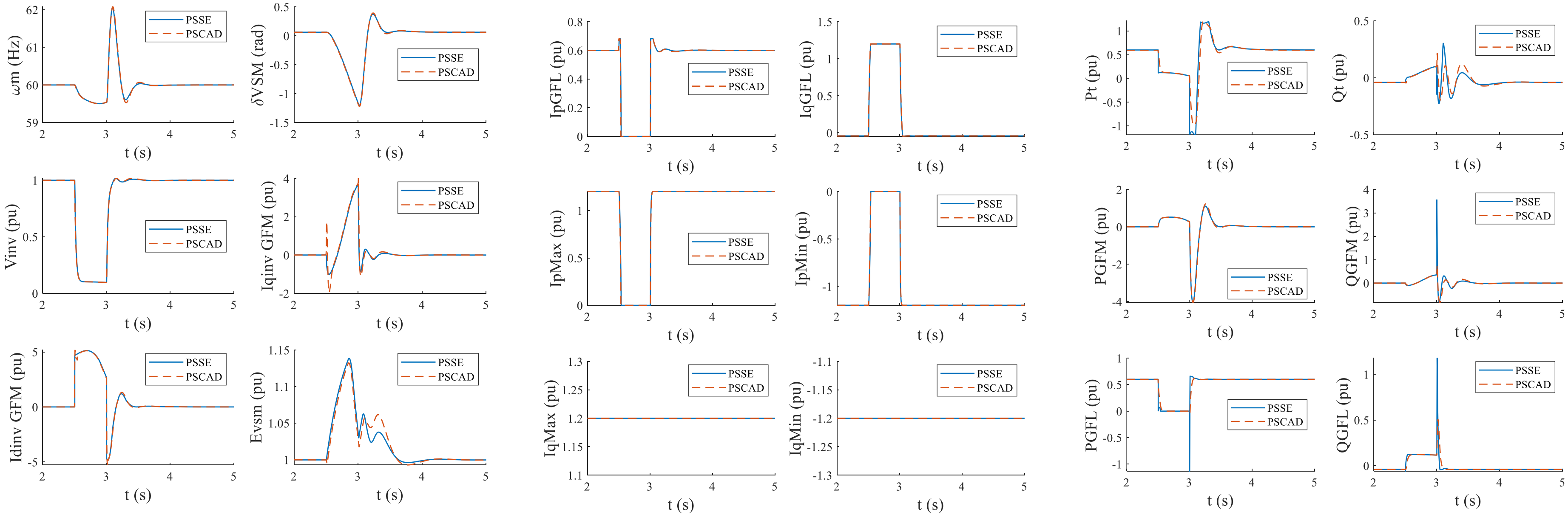
A Single-GFM Infinite-Bus System

0.5 s Short-Circuit Fault (SCR=10)

GFM Variables

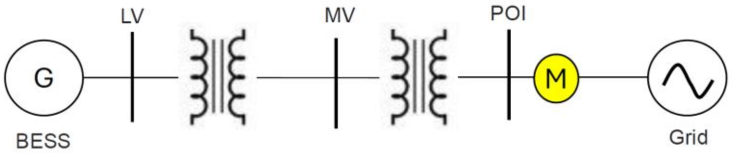
GFL Variables

Output P and Q



Validation against Tesla's Black-Box PSCAD Model

Tesla team has validated the REGFM_C1 + REPCGFM_C1 model against their black-box PSCAD model

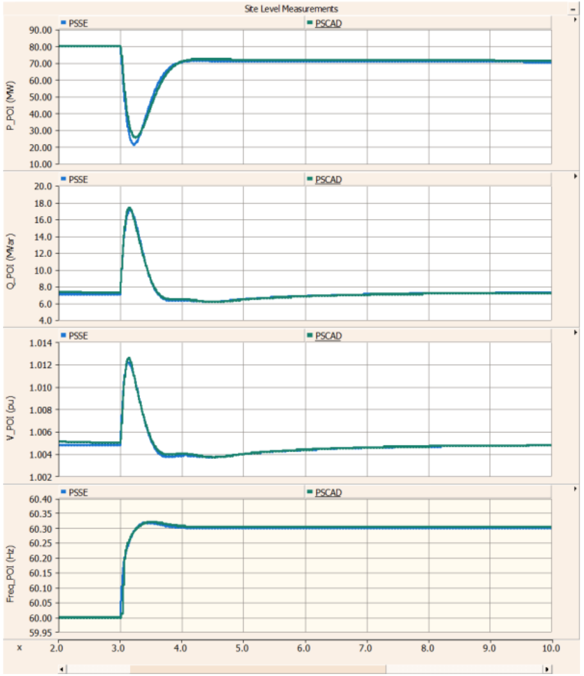


REGFM_C1 and REPCGFM_C1 Model Validation

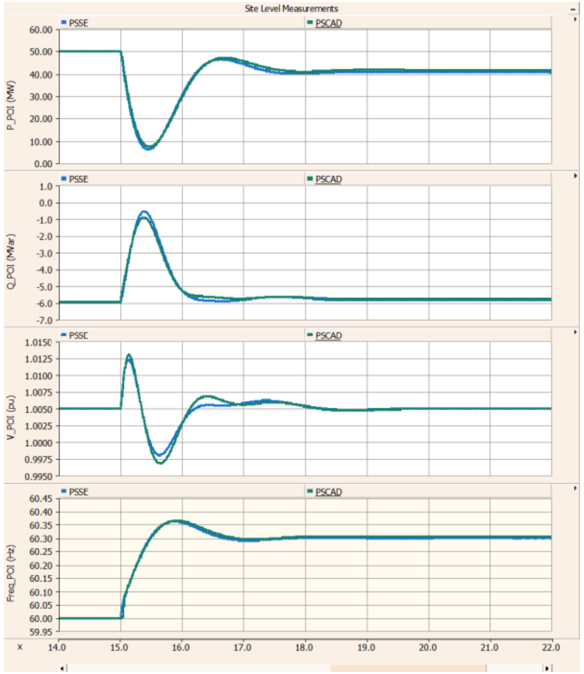
- Grid frequence step up

Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model
Green Line: Tesla's black-box PSCAD Model

High SCR and X/R
SCR = 10, X/R = 10



Low SCR and X/R
SCR = 1.5, X/R = 3



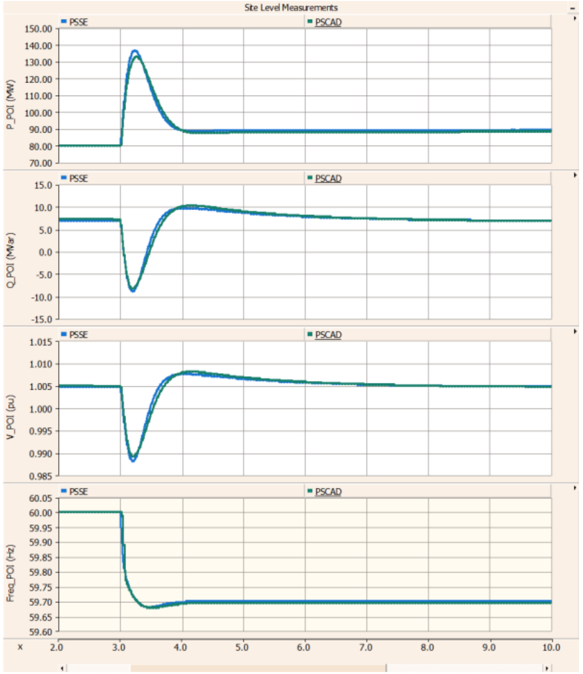
REGFM_C1 and REPCGFM_C1 Model Validation

- Grid frequence step down

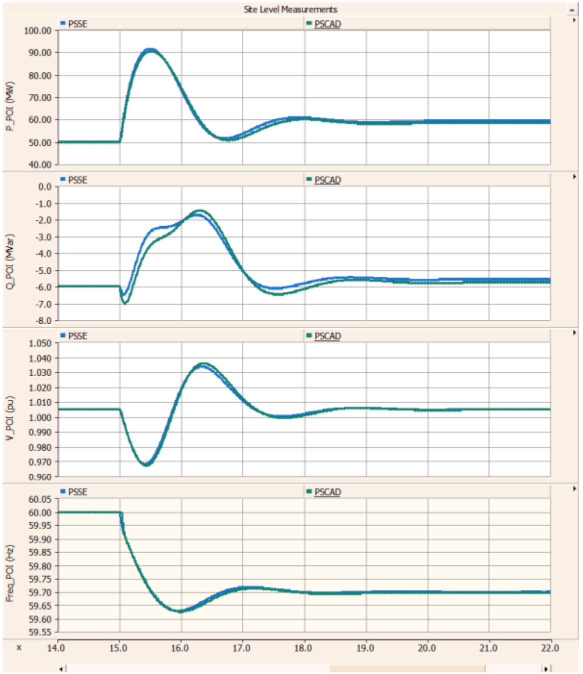
Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

High SCR and X/R
SCR = 10, X/R = 10



Low SCR and X/R
SCR = 1.5, X/R = 3



REGFM_C1 and REPCGFM_C1 Model Validation

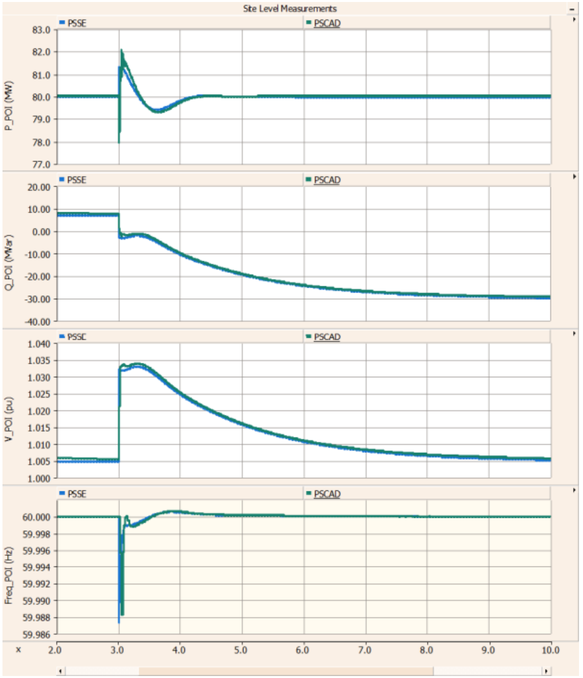
- Grid voltage step up

Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

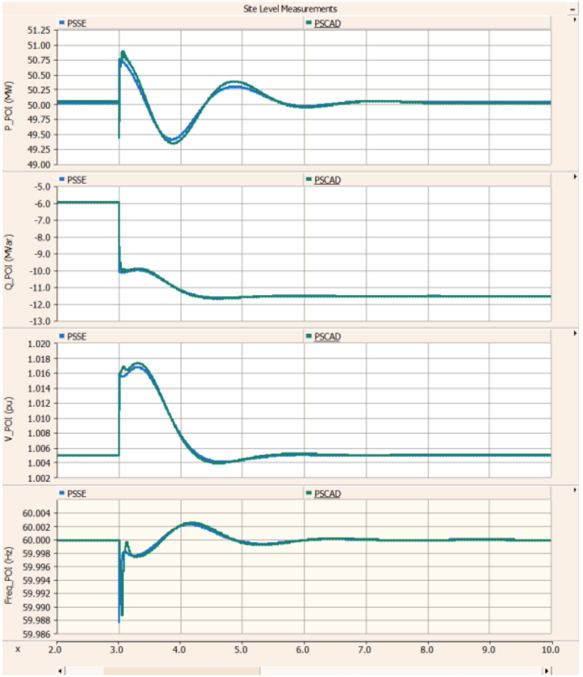
High SCR and X/R

SCR = 10, X/R = 10



Low SCR and X/R

SCR = 1.5, X/R = 3



REGFM_C1 and REPCGFM_C1 Model Validation

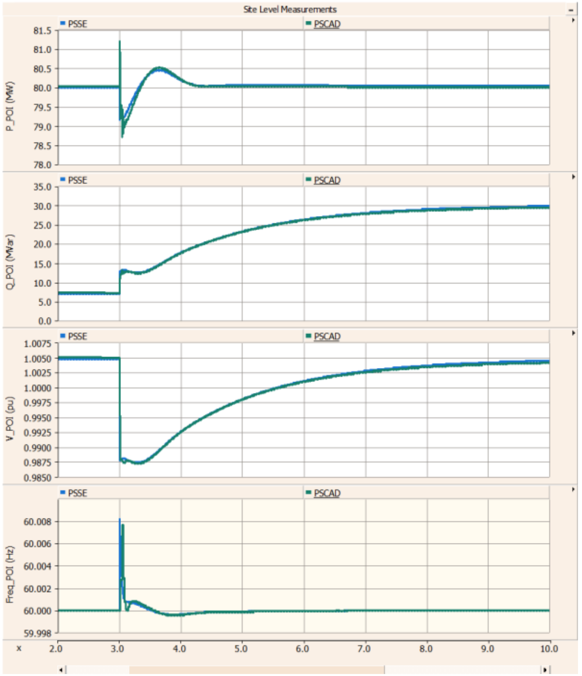
- Grid voltage step down

Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

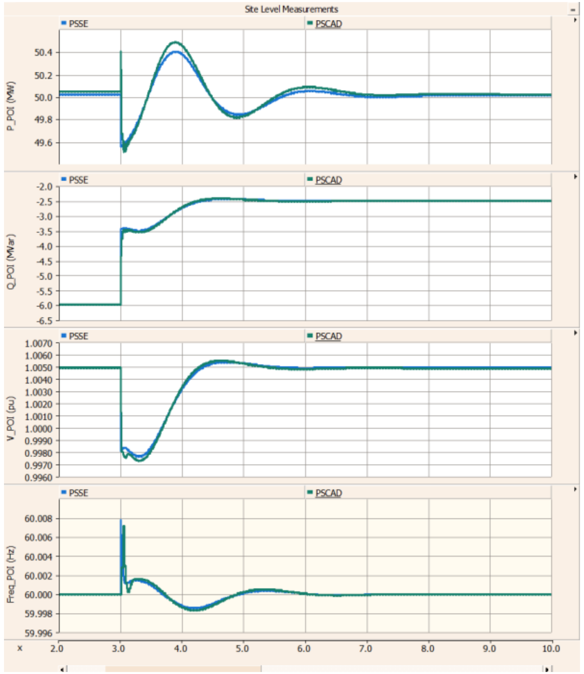
High SCR and X/R

SCR = 10, X/R = 10



Low SCR and X/R

SCR = 1.5, X/R = 3



REGFM_C1 and REPCGFM_C1 Model Validation

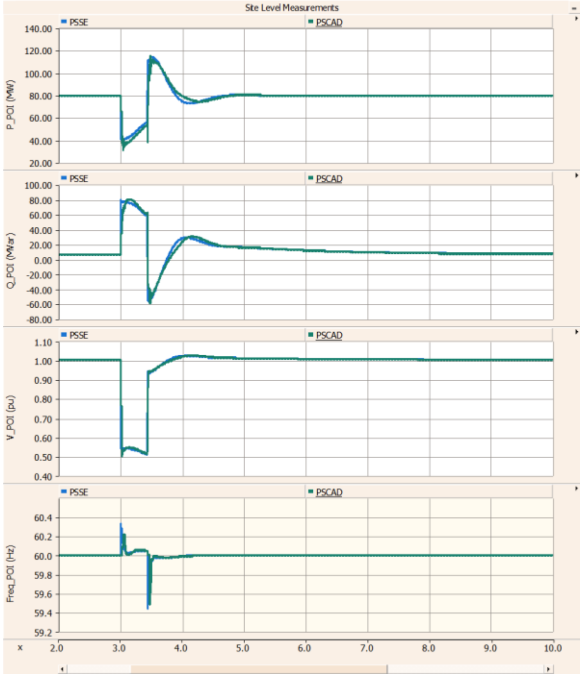
- High impedance fault at POI

Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

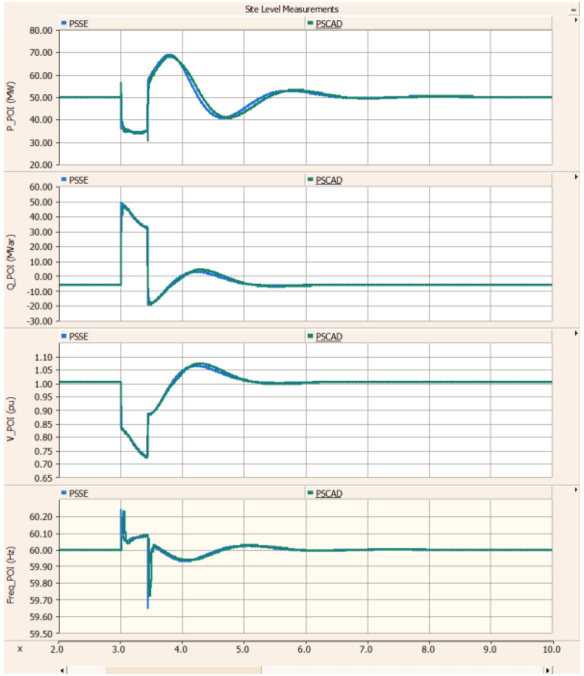
High SCR and X/R

SCR = 10, X/R = 10



Low SCR and X/R

SCR = 1.5, X/R = 3



REGFM_C1 and REPCGFM_C1 Model Validation

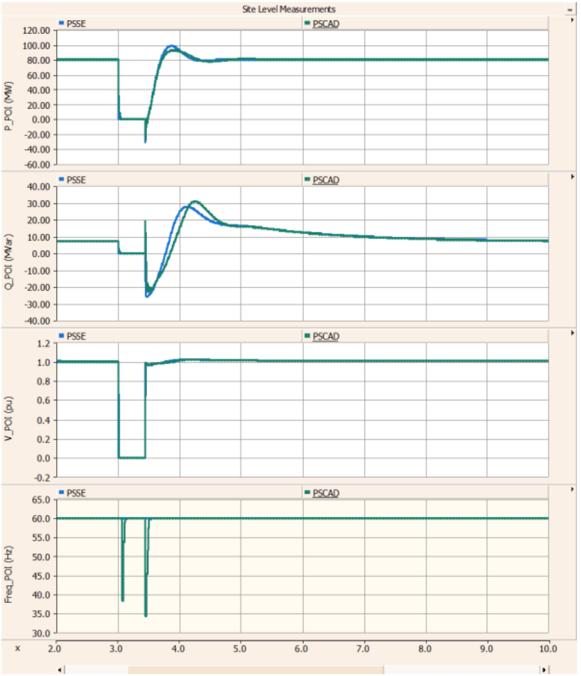
- Bolted Fault at POI

Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model
Green Line: Tesla's black-box PSCAD Model

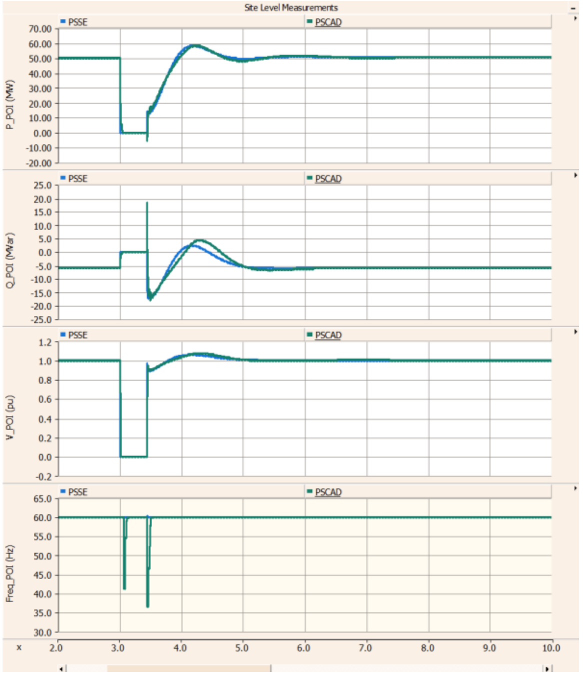
GFMs works in both strong and weak grids without the need to tune parameters

For GFMs, positive-sequence phasor models can accurately capture their dynamics

High SCR and X/R
SCR = 10, X/R = 10



Low SCR and X/R
SCR = 1.5, X/R = 3

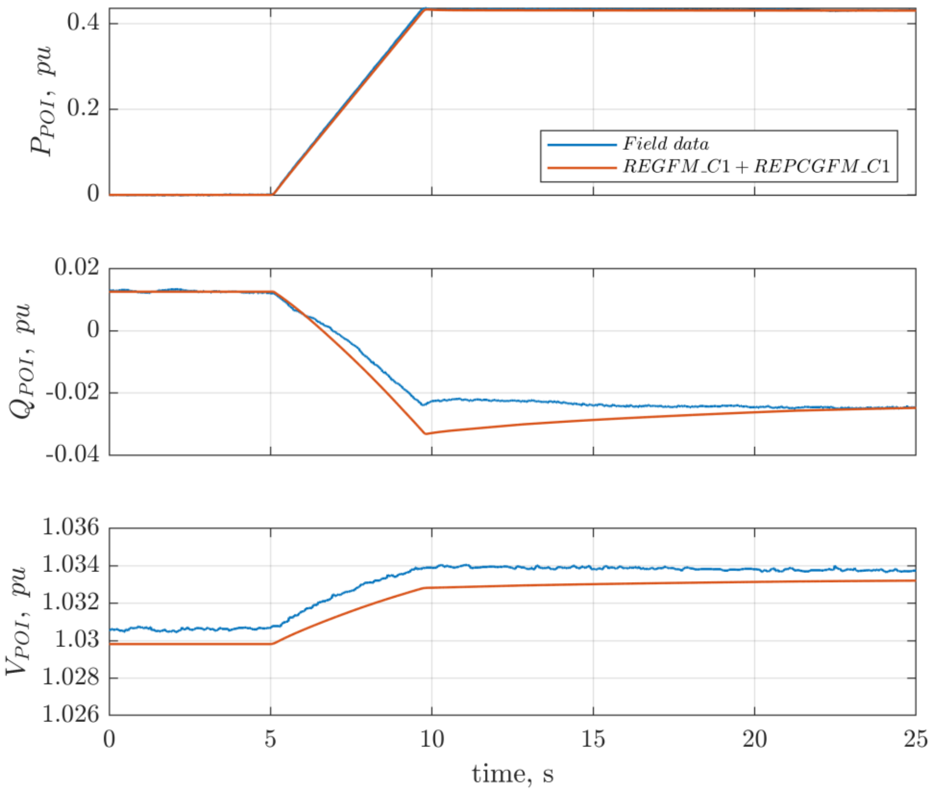


Validation against Field Test Results

Tesla team has validated the REGFM_C1 + REPCGFM_C1 model against on-site commissioning results

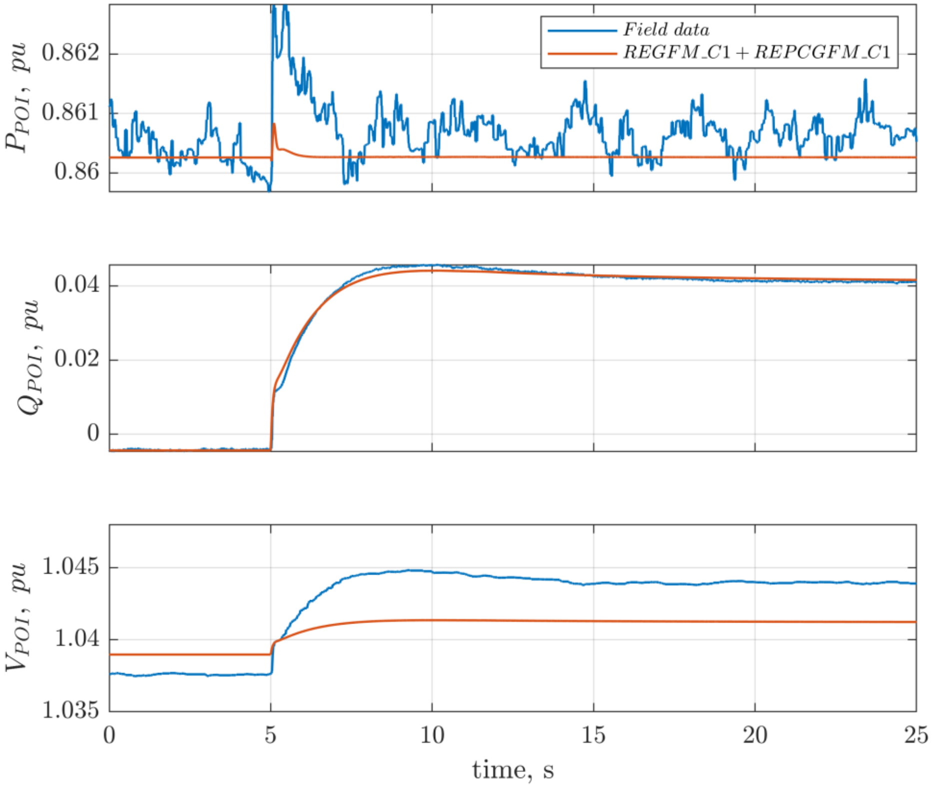
Model Validation against Field Test Results

- P reference change



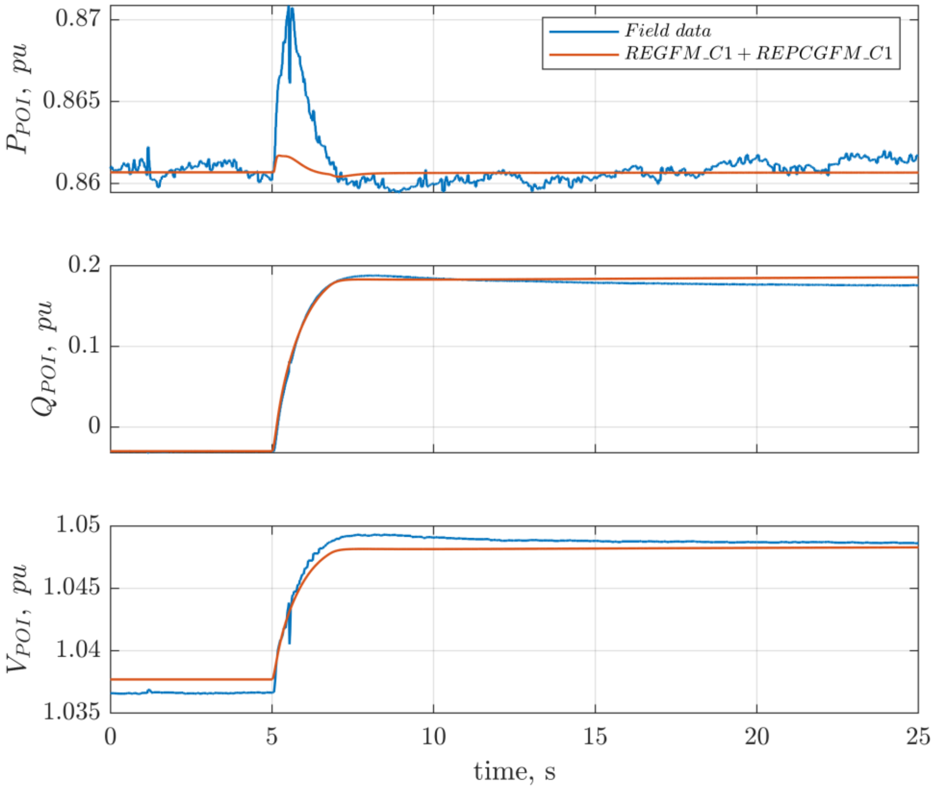
Model Validation against Field Test Results

- Q reference change



Model Validation against Field Test Results

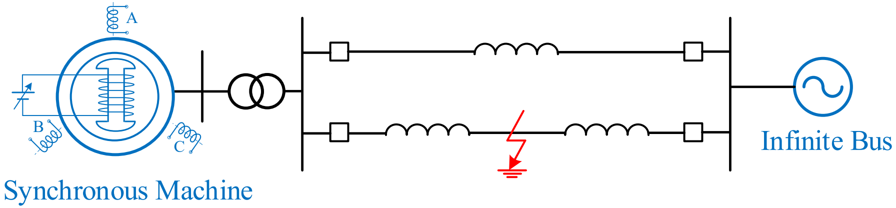
- V reference change

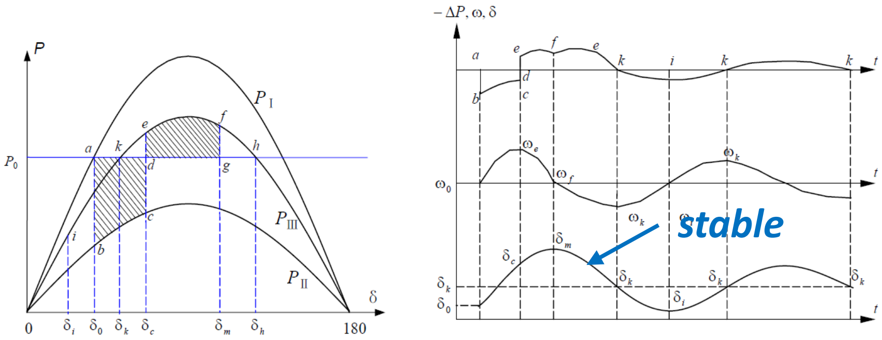


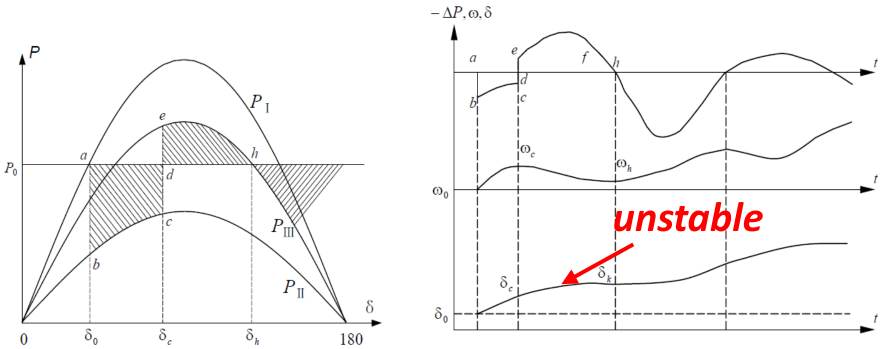
Fault Ride-through Concept of REGFM_C1 + REPCGFM_C1

Critical Clearing Time for a Synchronous Machine

- Synchronous machine cannot ride-through long-term faults because there is a critical clearing time, which can be explained using the “Equal-Area Criterion”





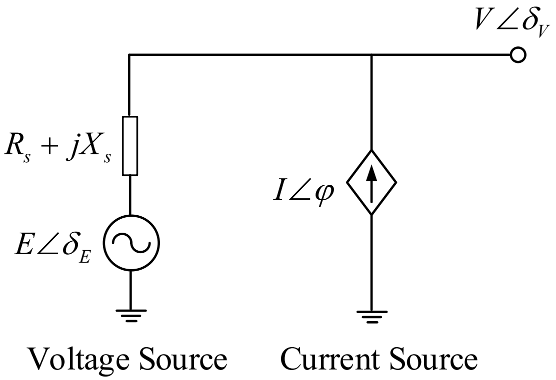


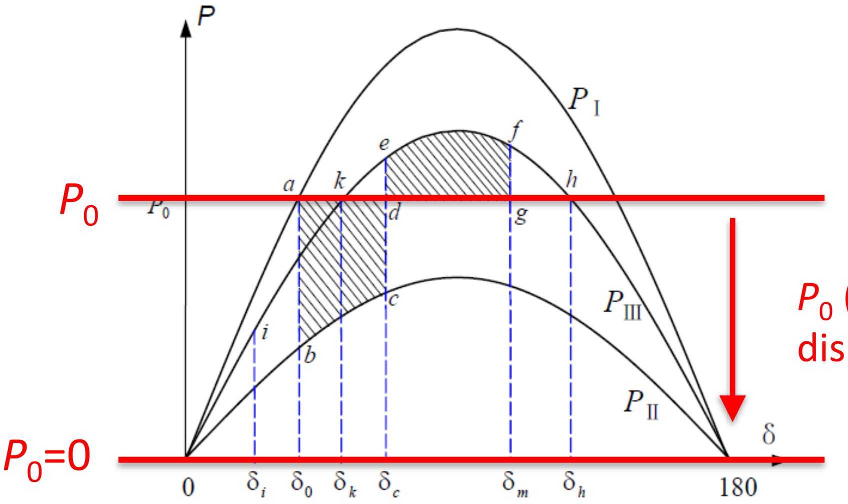
$$\int_{\delta_0}^{\delta_c} (P_0 - P_{II}) d\delta > \int_{\delta_c}^{\delta_h} (P_{III} - P_0) d\delta$$: stable

$$\int_{\delta_0}^{\delta_c} (P_0 - P_{II}) d\delta < \int_{\delta_c}^{\delta_h} (P_{III} - P_0) d\delta$$: unstable

Critical Clearing Time for a Synchronous Machine

- For the REGFM_C1 + REPCGFM_C1 model, because the P_0 (P_{cmd_GFM}) is dispatched at 0, the angle will not move too much during faults and hence significantly improves the transient stability. This mechanism is very similar to a synchronous condenser
- Although the GFM branch is dispatched at 0, the GFL branch can still provide steady state output power





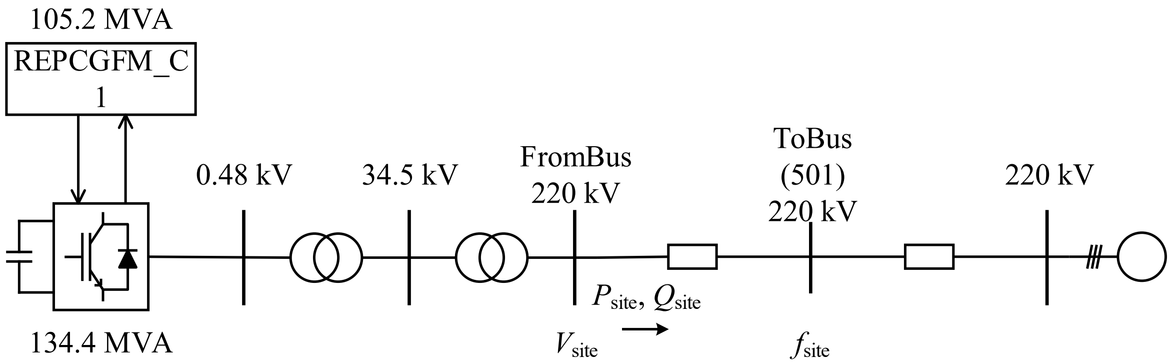
P_0 (P_{cmd_GFM}) is dispatched at 0

Model Benchmarking

All software vendors have implemented the REGFM_C1 and REPCGFM_C1, and all results match very well.

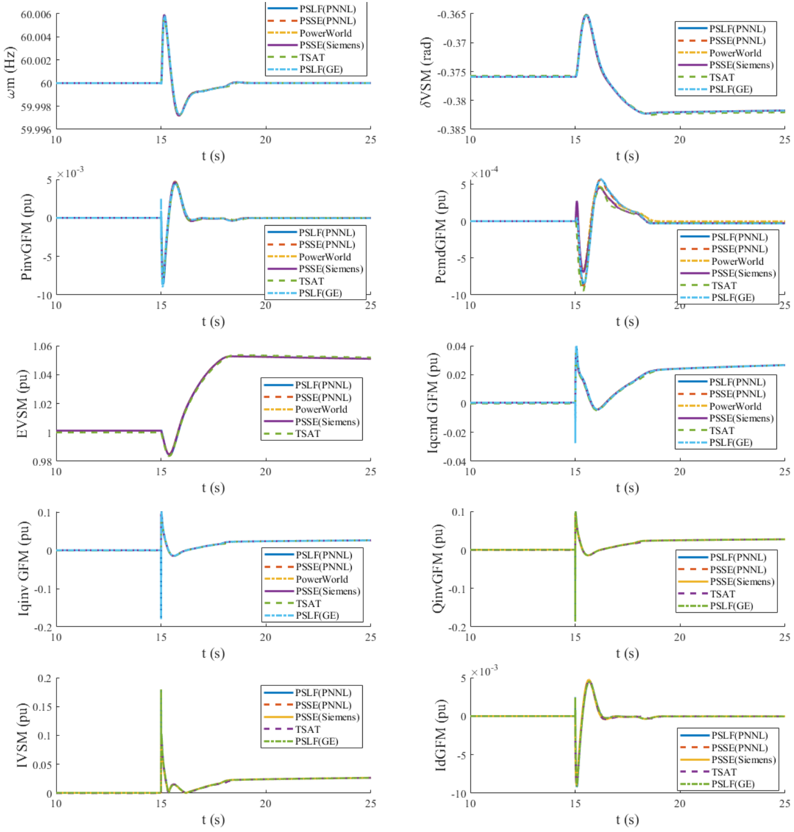
Model Benchmarking

- Summary
  - 29 cases have been compared by the PNNL team, including different test scenarios like voltage step up/down, frequency step up/down, high impedance and bolted faults, with different flag combinations
  - All the benchmarking results match well

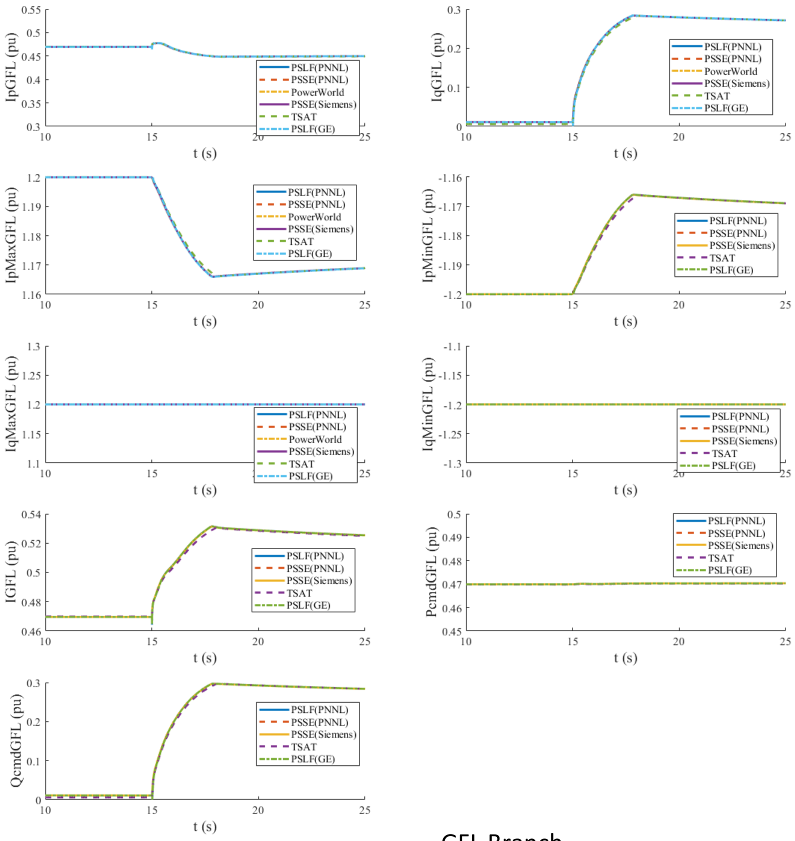


Model Benchmarking

- Voltage Step down from 1.0 p.u. to 0.95 p.u.



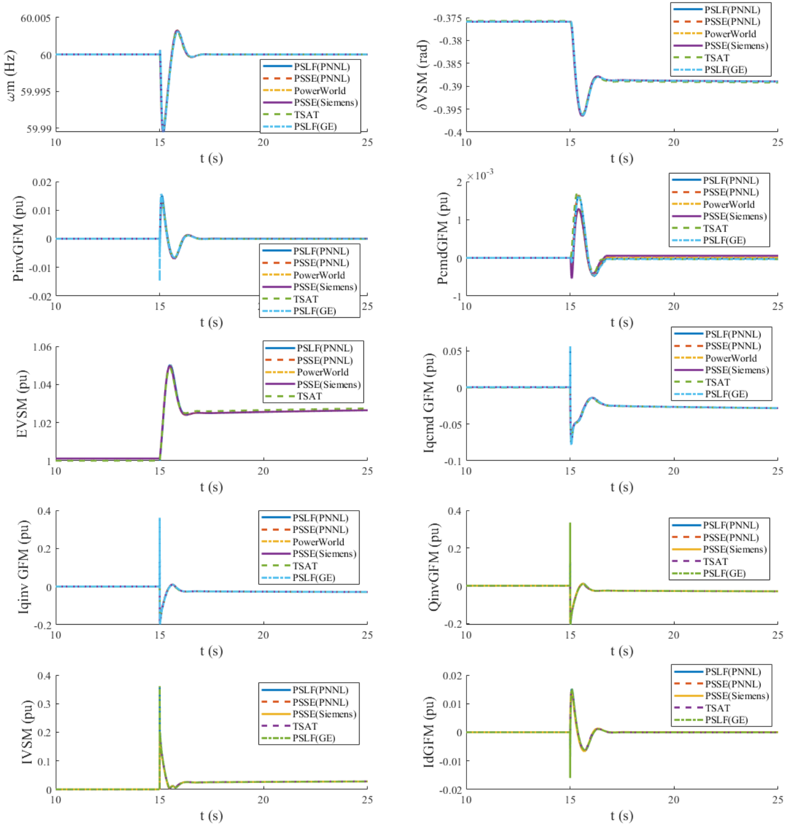
GFM Branch



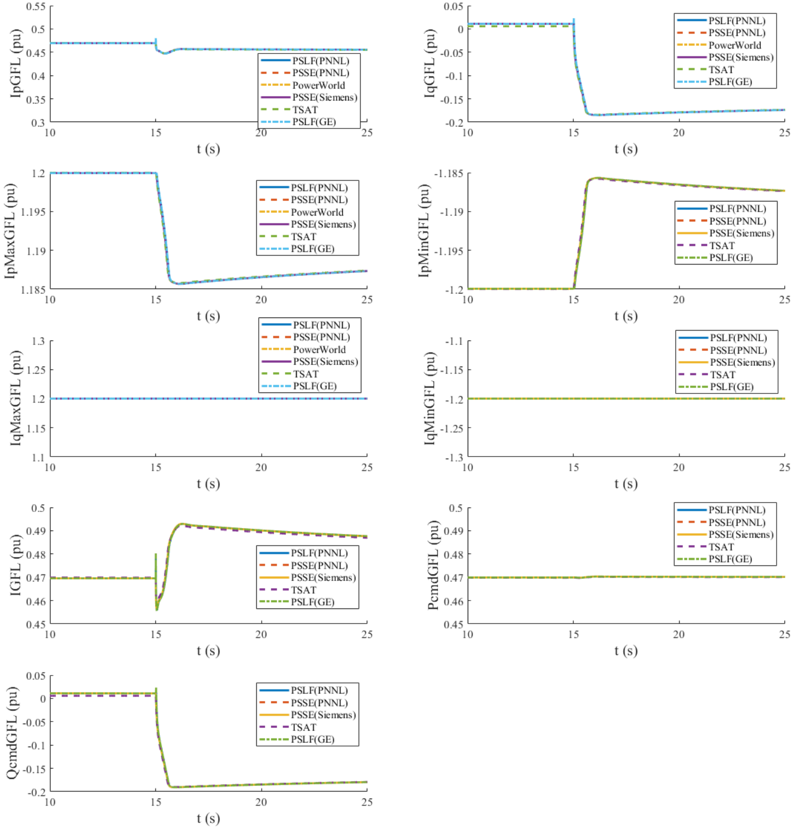
GFL Branch

Model Benchmarking

- Voltage Step up from 1.0 p.u. to 1.10 p.u.



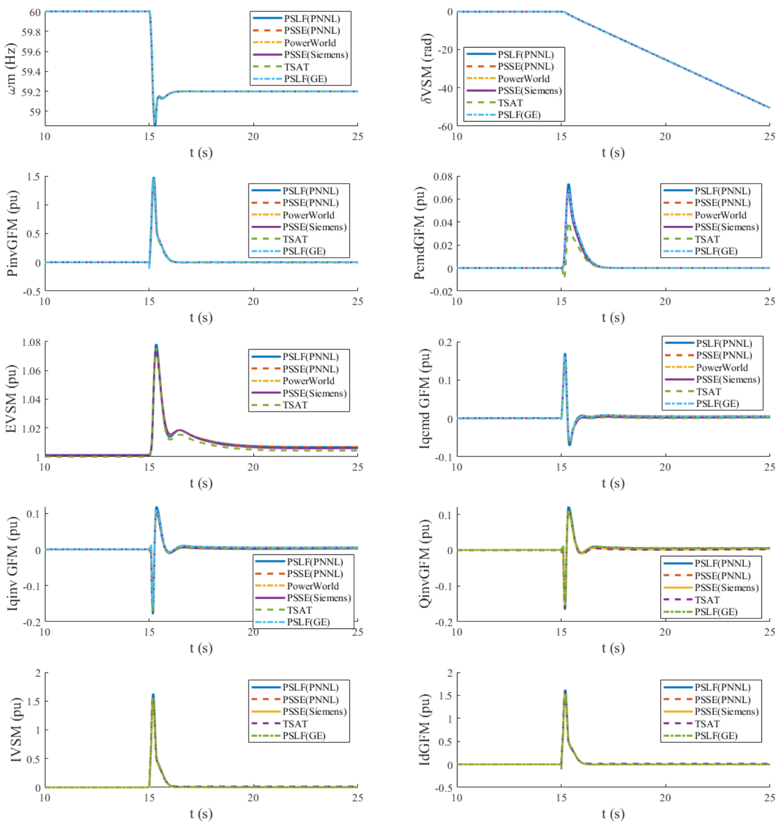
GFM Branch



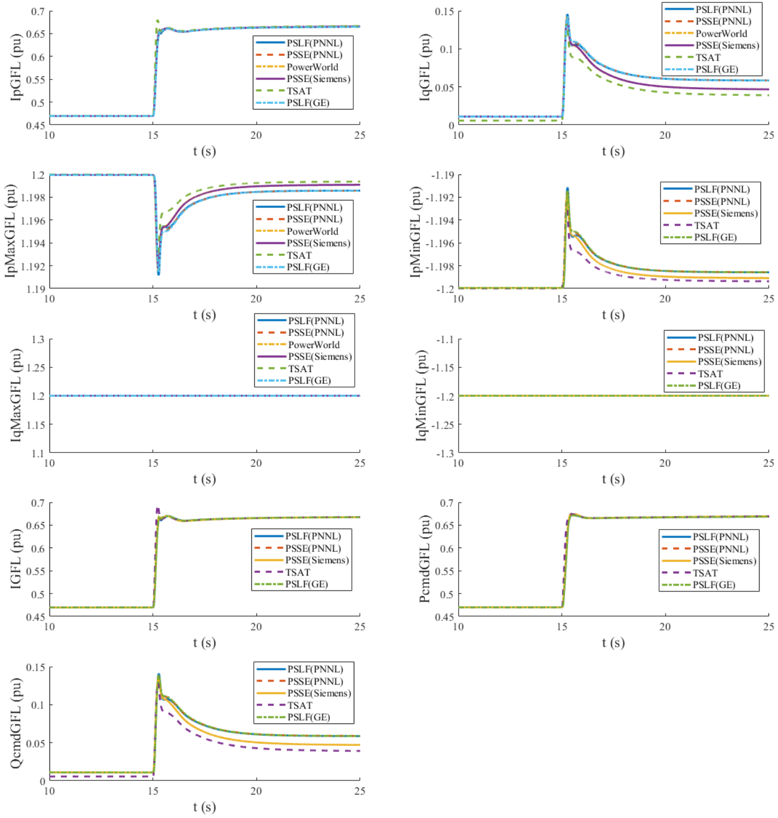
GFL Branch

Model Benchmarking

- Frequency Step Down from 60 Hz to 59.2 Hz



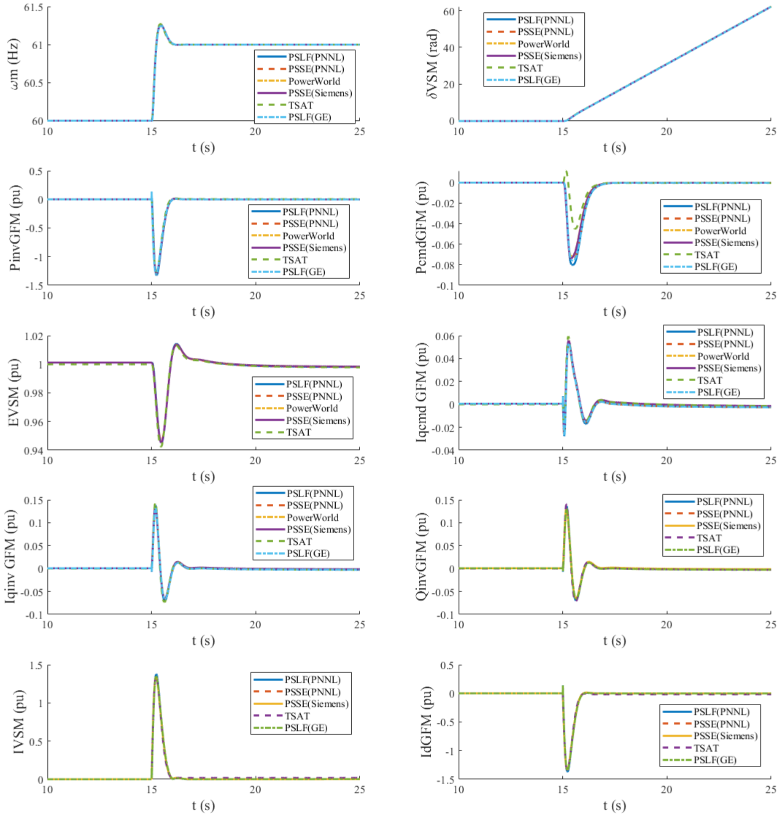
GFM Branch



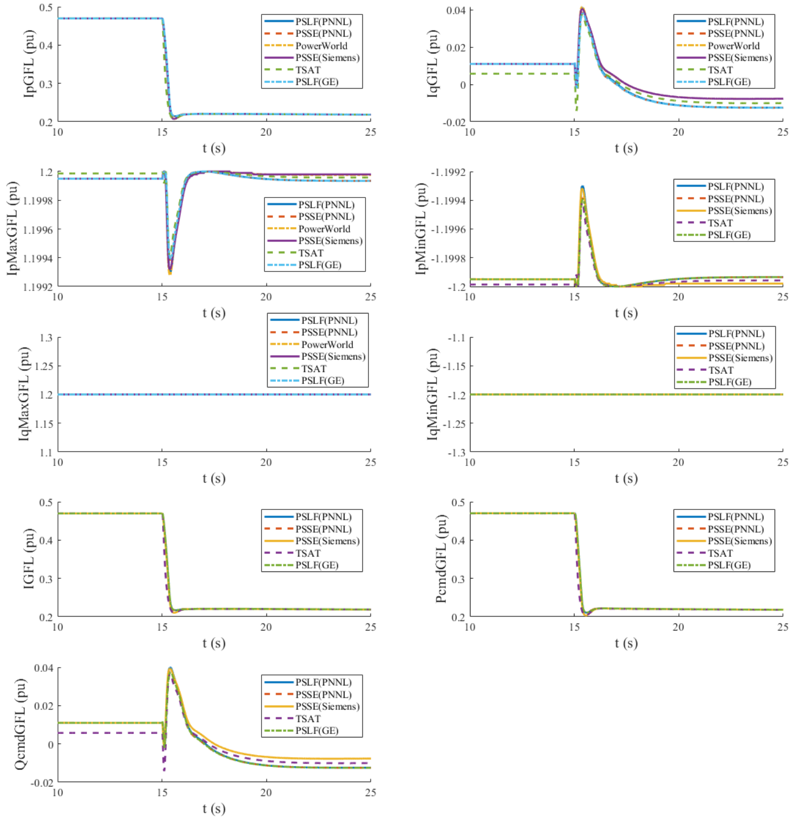
GFL Branch

Model Benchmarking

- Frequency Step Up from 60 Hz to 61 Hz



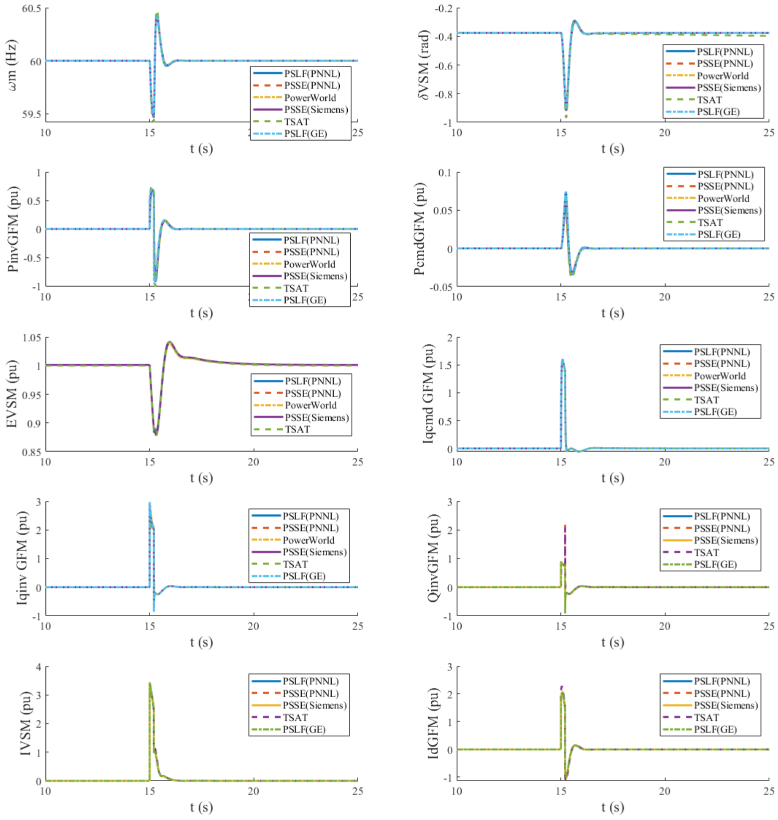
GFM Branch



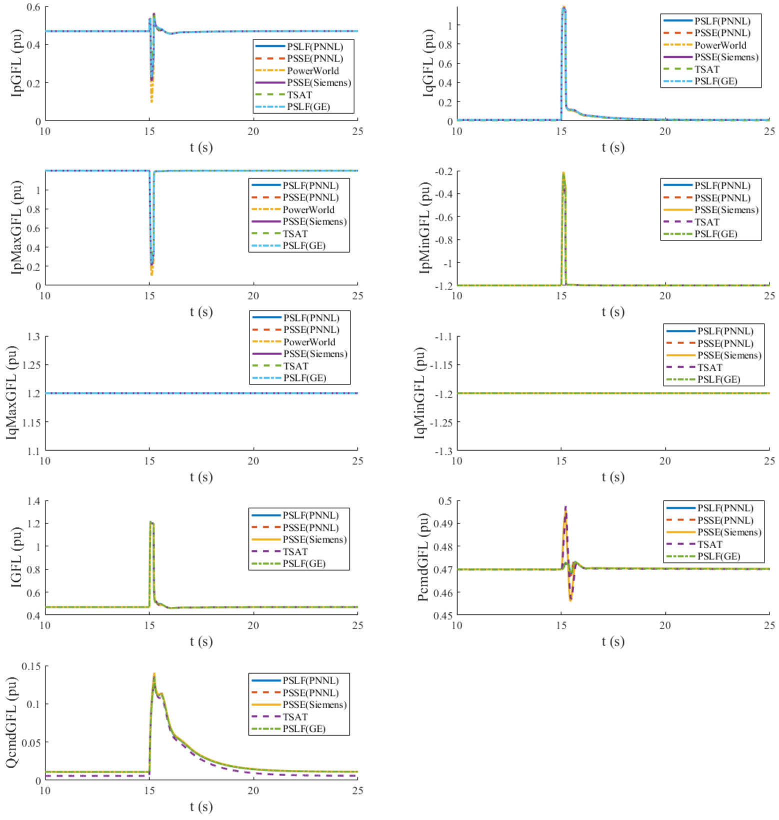
GFL Branch

Model Benchmarking

- 4.84 Ohm 3-phase-to-ground fault at Bus 501 lasting for 0.2 sec (Bolted fault)



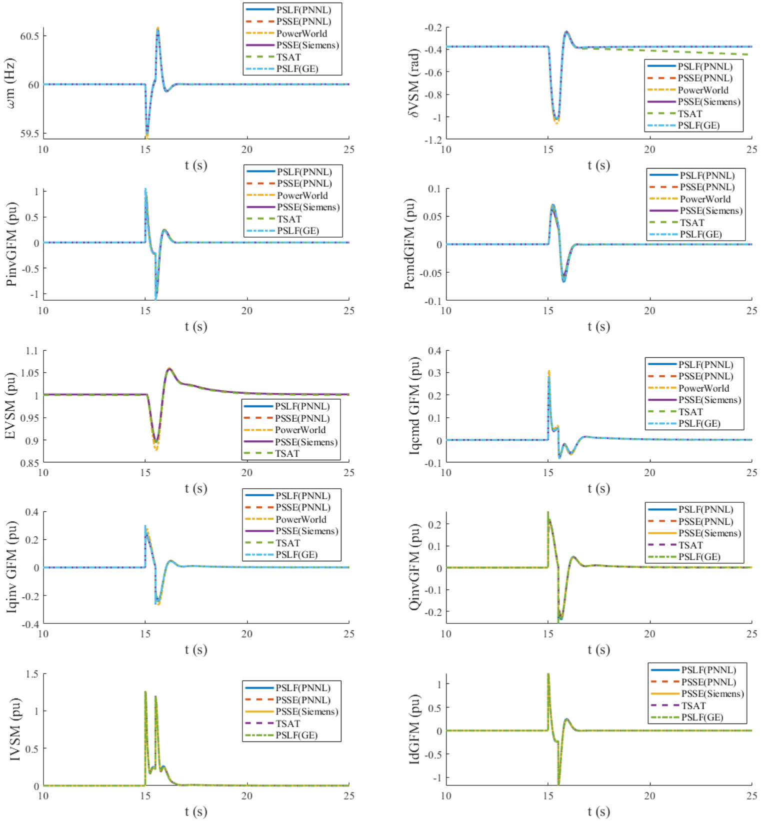
GFM Branch



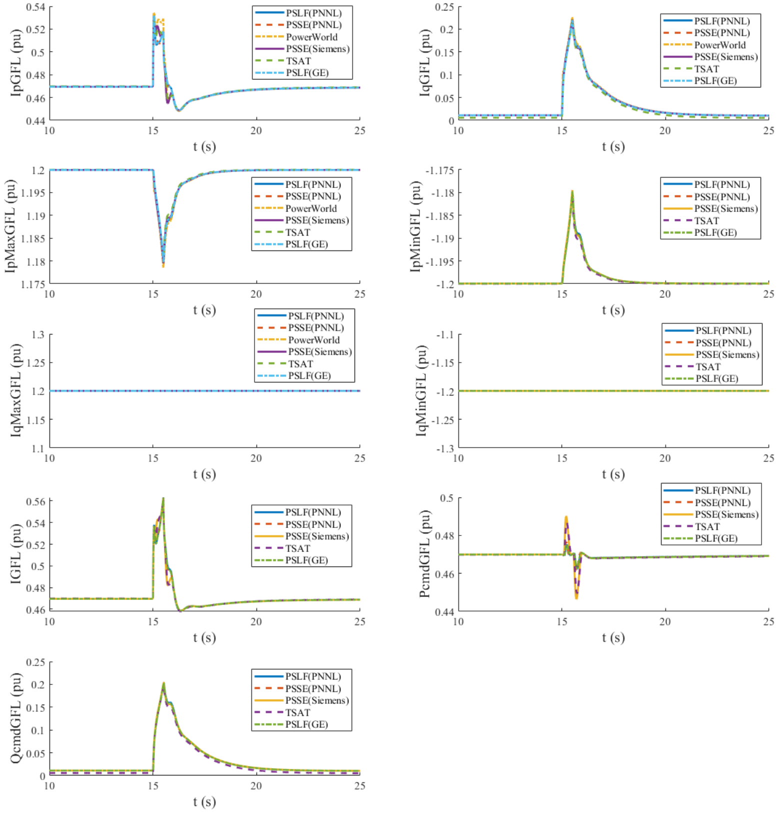
GFL Branch

Model Benchmarking

- 48.4 Ohm 3-phase-to-ground fault at Bus 501 lasting for 0.5 sec (High impedance fault)



GFM Branch



GFL Branch

Conclusion

- The model specifications of REGFM_C1 and REPCGFM_C1 were approved on Jan. 30th, 2025
- The models have been validated against Tesla Energy's black-box PSCAD model and field test results
- GFMs works in both strong and weak grids without the need to tune parameters
- For GFMs, positive-sequence phasor models can accurately capture their dynamics
- All software vendors have implemented these models, and the model benchmarking has been completed

We'd like to make a motion to approve the REGFM_C1 and REPCGFM_C1 models

U.S. DEPARTMENT of ENERGY

unifi consortium

universal interoperability for grid-forming inverters

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THANK YOU