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unifi consortium
universal interoperability for grid-forming inverters

Model Specifications of Grid-Forming Hybrid Control and Plant Control—REGFM_C1 and REPCGFM_C1

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Jan. 30th, 2025

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WECC Standard Library GFM Models

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- In recent years, WECC MVS has approved two standard library grid-forming inverter (GFM) models—***REGFM_A1*** and ***REGFM_B1***
- Those two models represent 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 several OEMs, including **SMA** 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 is collaborating 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

WECC Standard Library GFM Models

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Key Features of 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

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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)

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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

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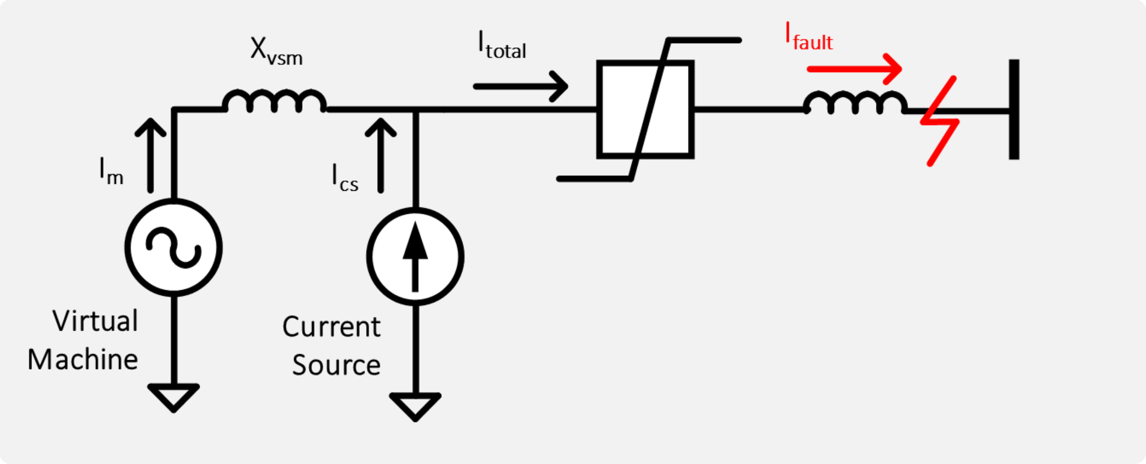
- The GFM hybrid control implements both the GFM control and GFL control simultaneously inside one inverter. Both controls work in parallel, and they do not switch between the GFM and GFL controls
- The steady state P and Q of the GFM branch is regulated to be 0, and the GFL branch provides the steady 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

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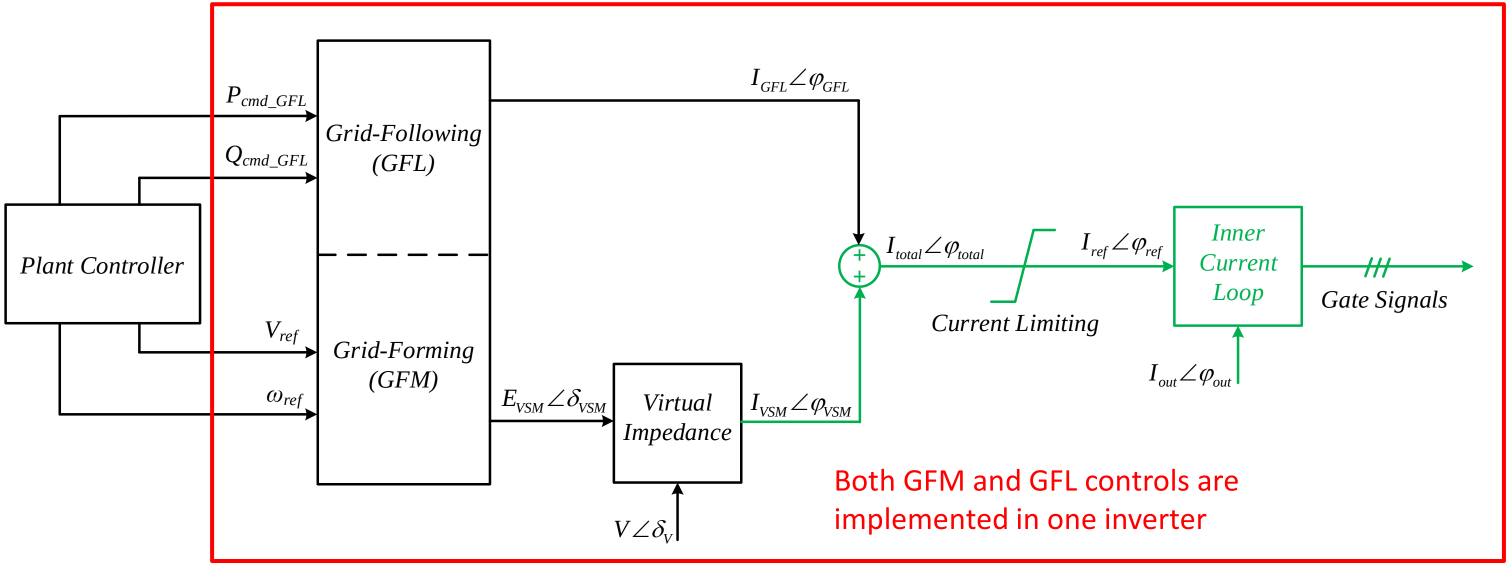
- The plant controller sends P_{cmd_GFL} and Q_{cmd_GFL} to the GFL branch, and sends V_{ref} and ω_{ref} to the GFM branch
- The steady state P and Q of the GFM branch is dispatched to be 0
- The green lines represent the virtual impedance control and the fast inner current control loop, which will 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

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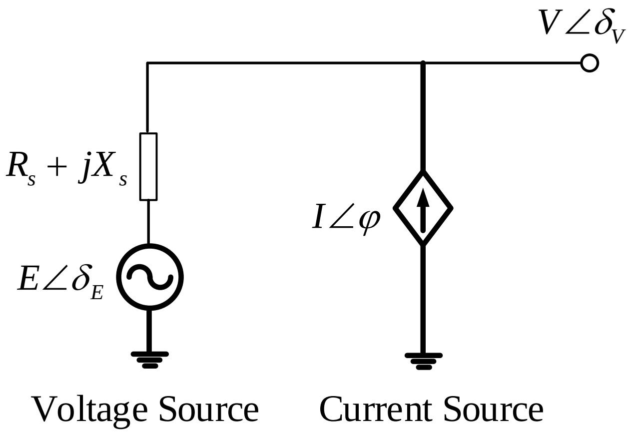
- In phasor domain, the GFM hybrid model is interfaced with the network solution through a voltage phasor behind impedance in parallel with a current phasor
- $R_s + jX_s$ represents the virtual impedance



Model Network Interface

Positive-Sequence GFM Hybrid Control Model
GFM Branch

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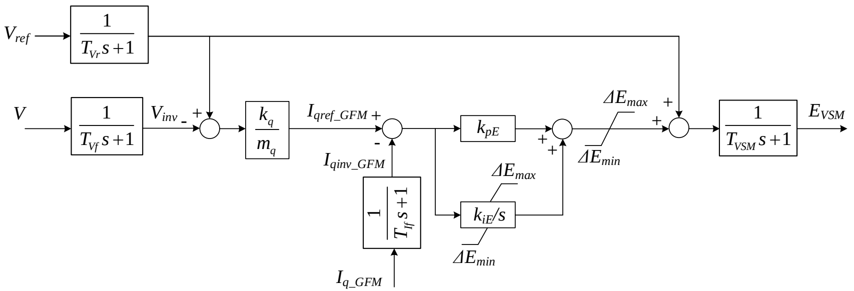
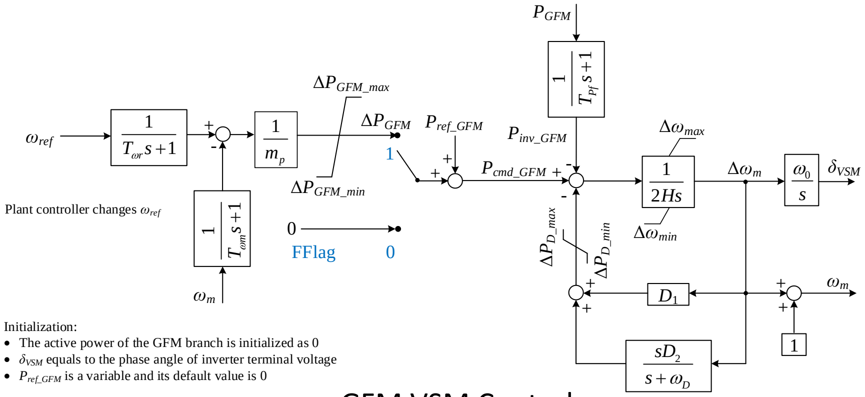
- **The GFM branch is a virtual synchronous machine (VSM) model**
- The voltage control block controls the internal voltage magnitude E_{vsm}
- The VSM control block controls the internal phase angle δ_{VSM}



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

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

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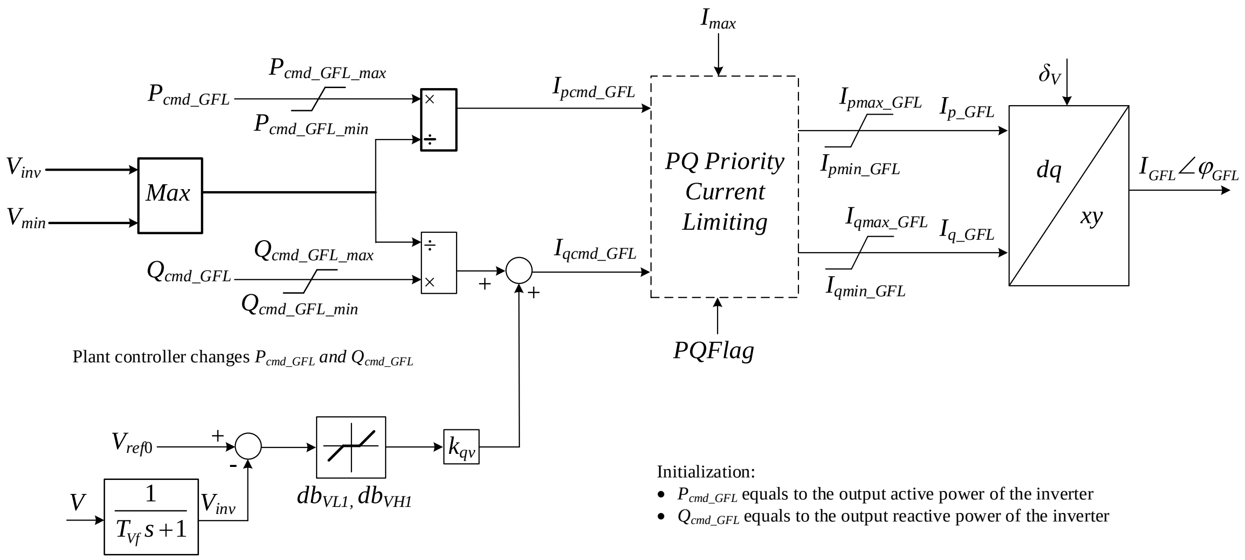
- **The GFL branch represents a typical GFL control**



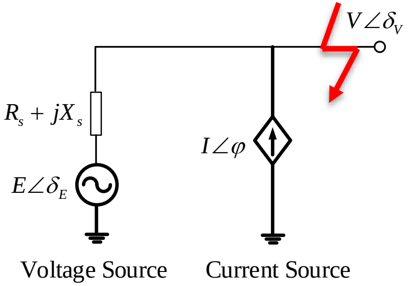
Initialization:
- P_{cmd_GFL} equals to the output active power of the inverter
- Q_{cmd_GFL} equals to the output reactive power of the inverter

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

Plant Controller Model—REPCGFM_C1

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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 GFM Branch Voltage and Frequency Reference Generator

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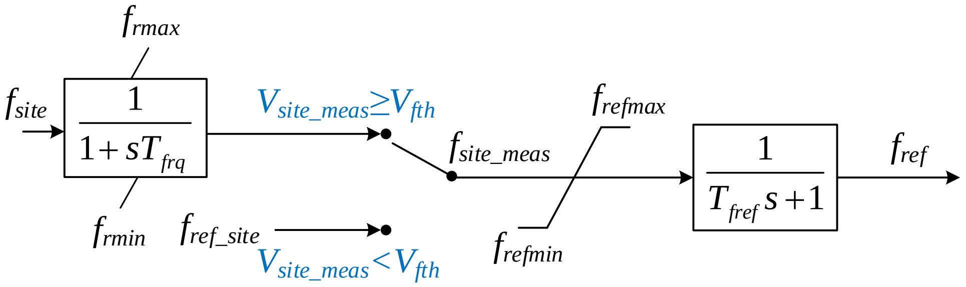
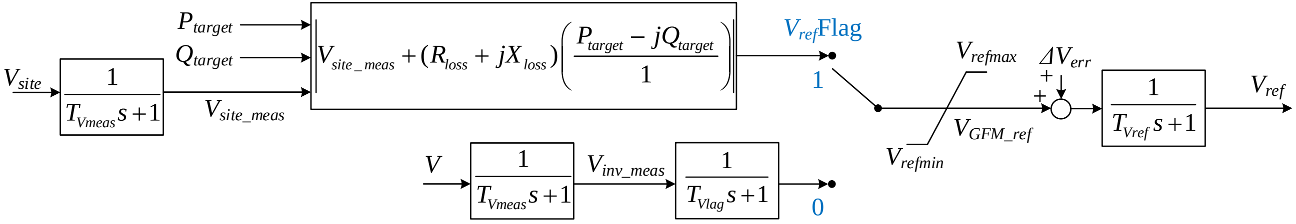
The plant controller sends the measured site frequency to the GFM branch to ensure the steady state *P* of the GFM branch is 0.



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
- $\Delta V_{err}=V-V_{GFM\_ref}$. V is the inverter terminal voltage

Voltage reference generator for the GFM branch

Plant Controller GFL Branch
Voltage Control and Reactive Power Path

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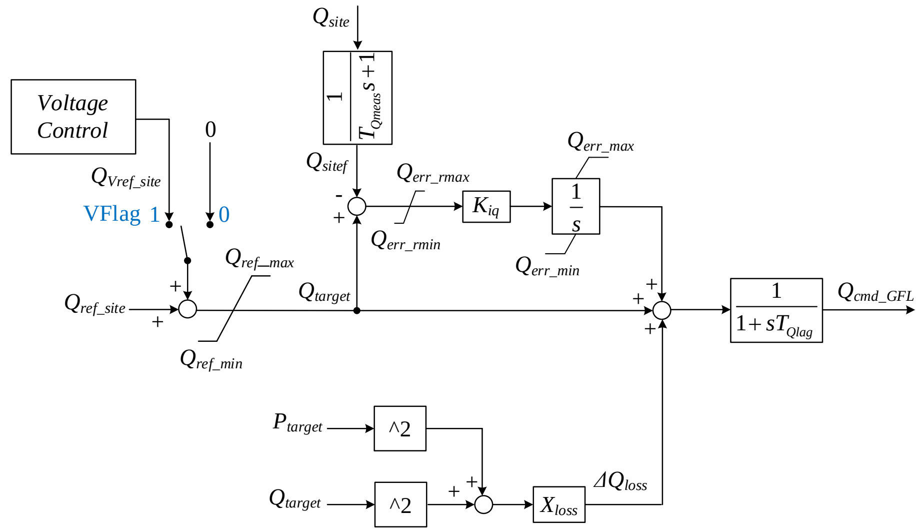
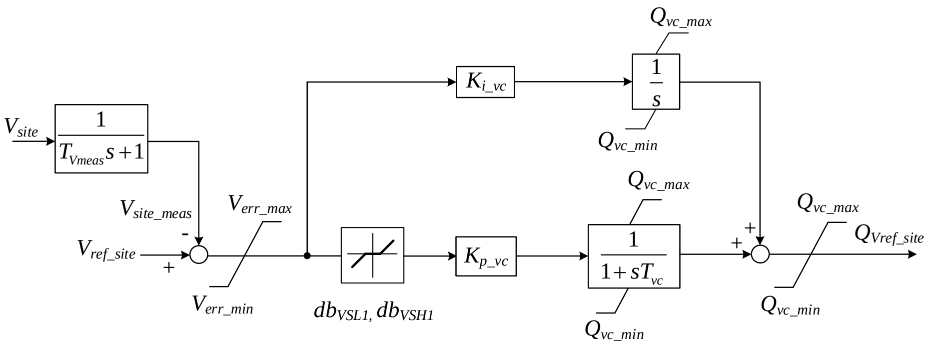
The plant controller sends the Qcmd_GFL to the GFL branch of the inverter model REGFM_C1



Initialization:

- When VFlag=0, $Q_{ref\_site}=Q_{target}=Q_{site}$
- When VFlag=1, $Q_{Vref\_site}=Q_{target}=Q_{site}$, and $Q_{ref\_site}=0$

Reactive Power Path



Voltage Control

Plant Controller GFL Branch Active Power Path

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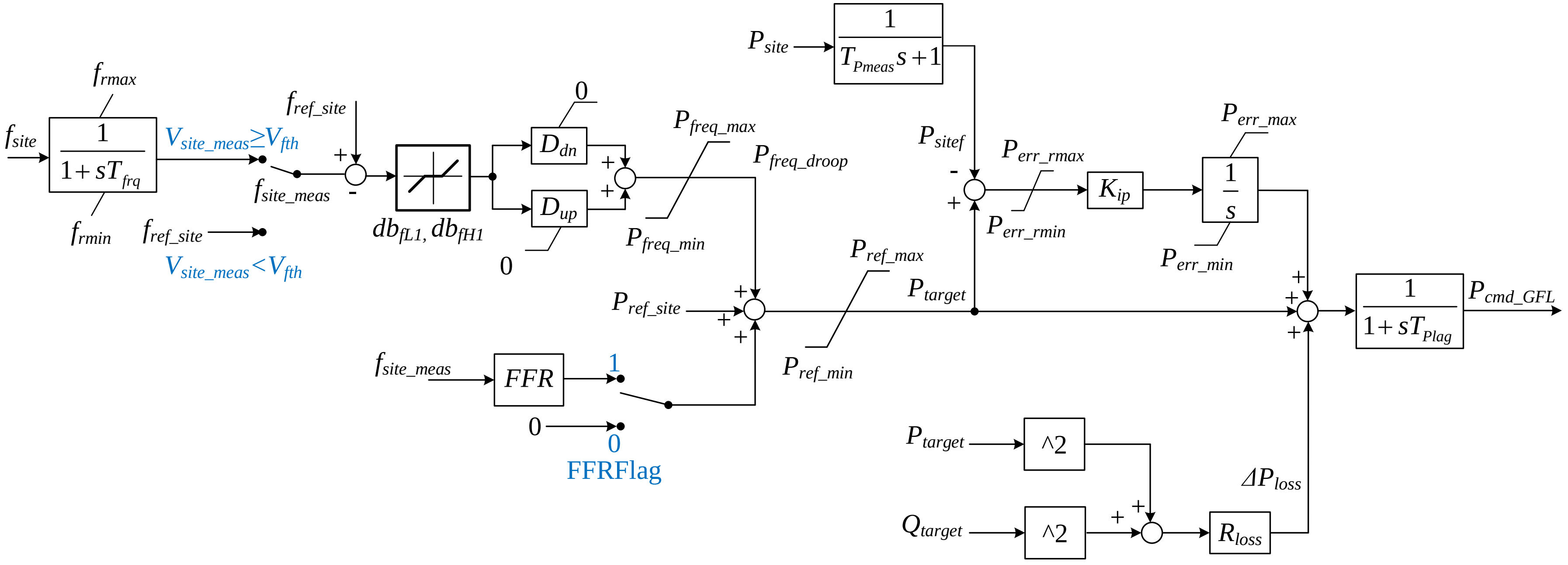
The plant controller sends the Pcmd_ GFL to the GFL branch of the inverter model REGFM_C1



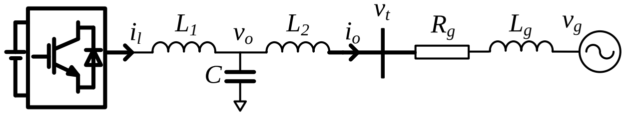
Active Power Path

Comparison between PSS/E Model and PSCAD Model

Both PSS/E model and PSCAD model have been 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

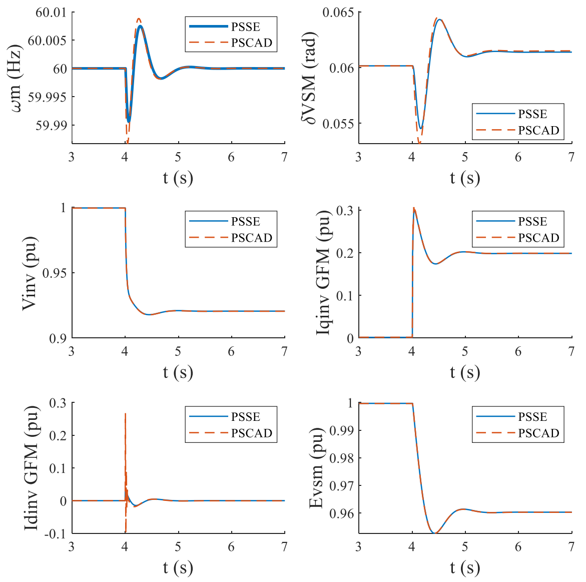
- The GFM branch responds to the voltage change by increasing Q
- The GFL branch remains constant PQ control
- All the GFM and GFL Variables achieve a good match between PSS/E and PSCAD



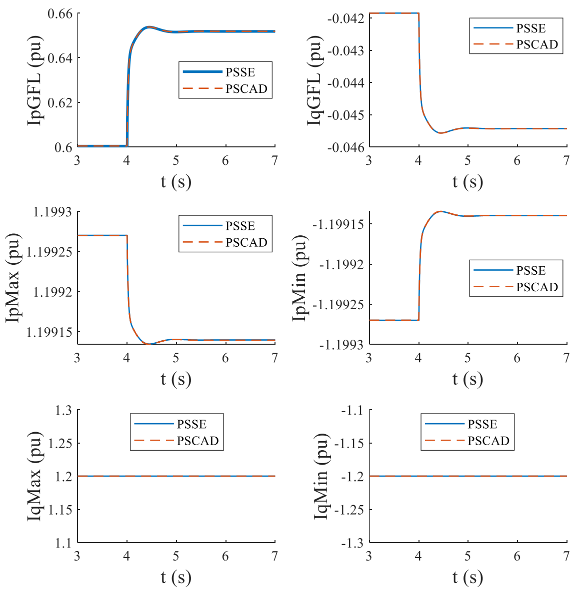
A Single-GFM Infinite-Bus System

Grid Voltage Drop by 0.1 pu (SCR=10)

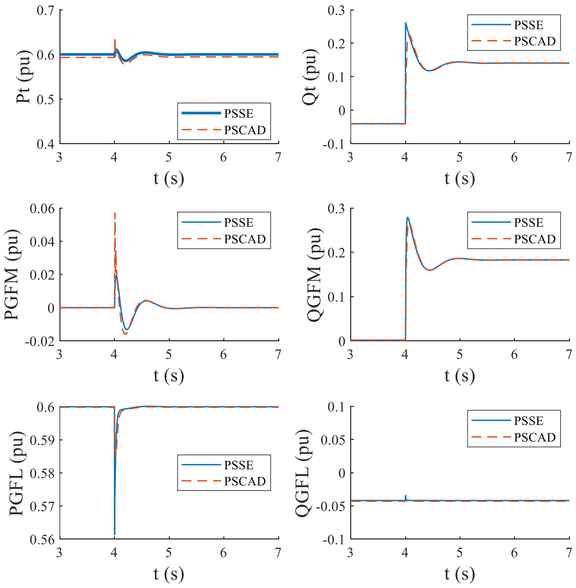
GFM Variables



GFL Variables



Output P and Q



PSCAD and PSS/E Comparison for REGFM_C1

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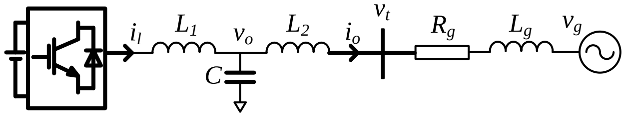
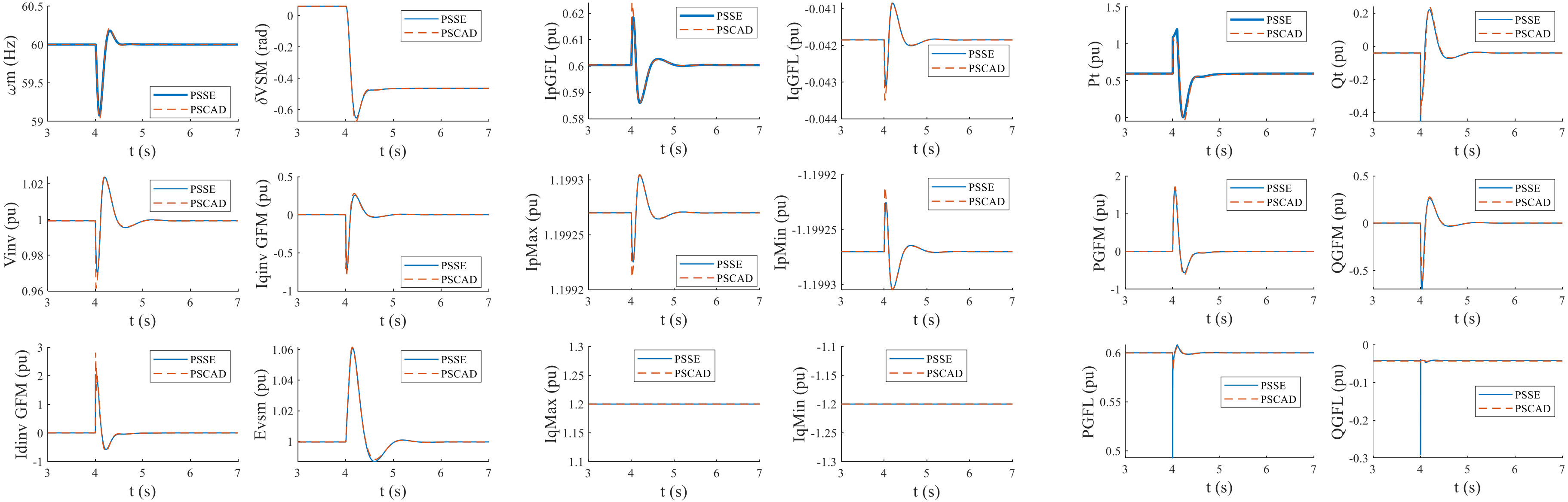
- The GFM branch responds to the phase angle jump
- The GFL branch has a very limited response to the phase angle jump
- All the GFM and GFL Variables achieve a good match between PSS/E and PSCAD



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

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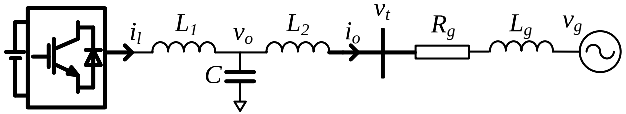
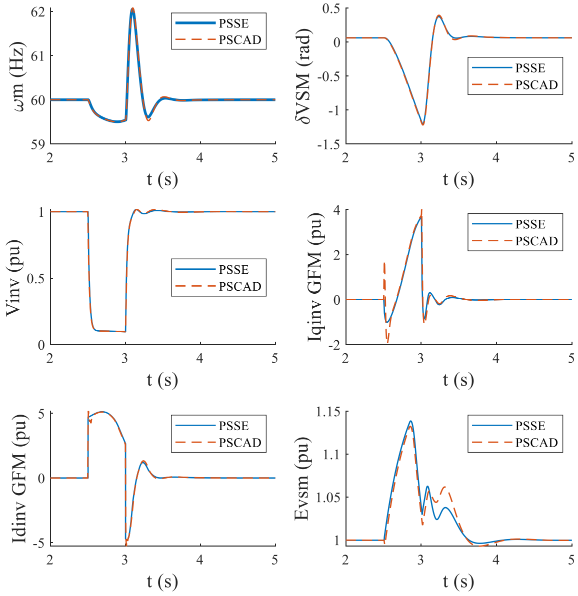
- The REGFM_C1 can ride-through a long-term fault
- The GFM branch is dispatched at zero output P
- The GFL branch uses the Q priority



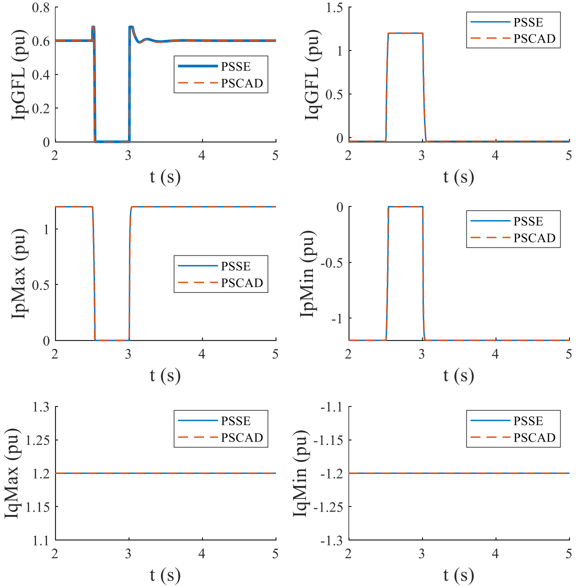
A Single-GFM Infinite-Bus System

0.5 s Short-Circuit Fault (SCR=10)

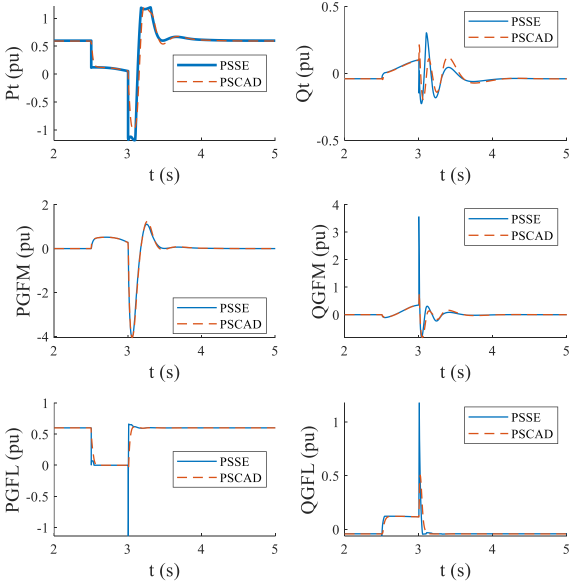
GFM Variables



GFL Variables



Output P and Q



PSCAD and PSS/E Comparison for REGFM_C1

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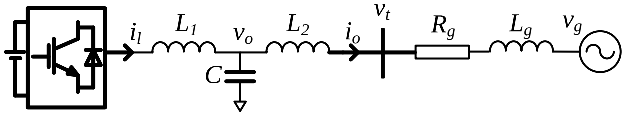
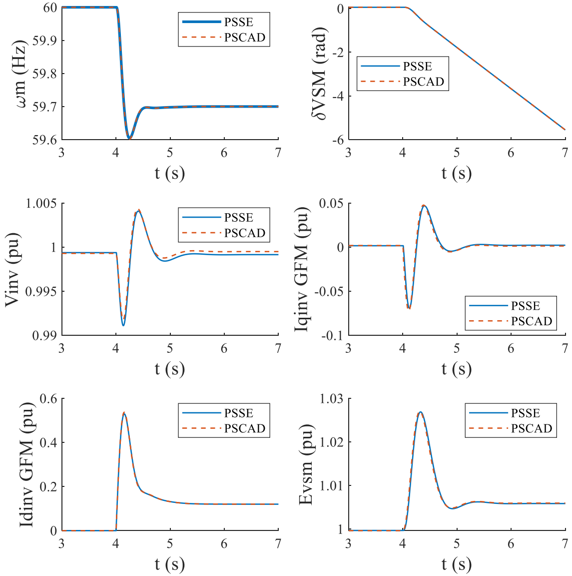
- The GFM branch responds to the frequency change because of the frequency droop
- The GFL branch is constant PQ control



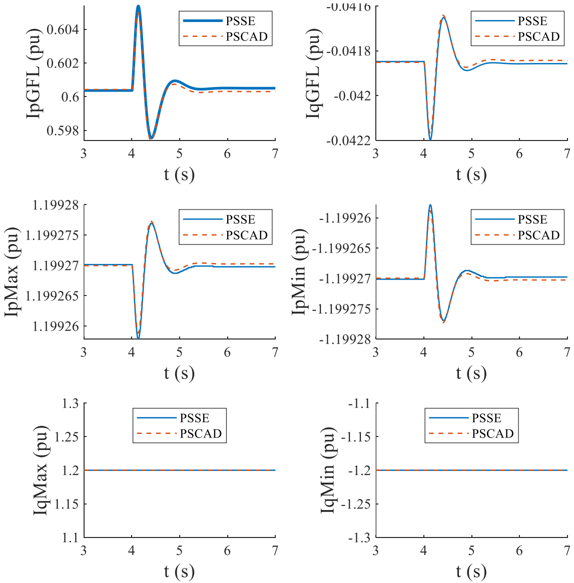
A Single-GFM Infinite-Bus System

Frequency Step down (SCR=10)

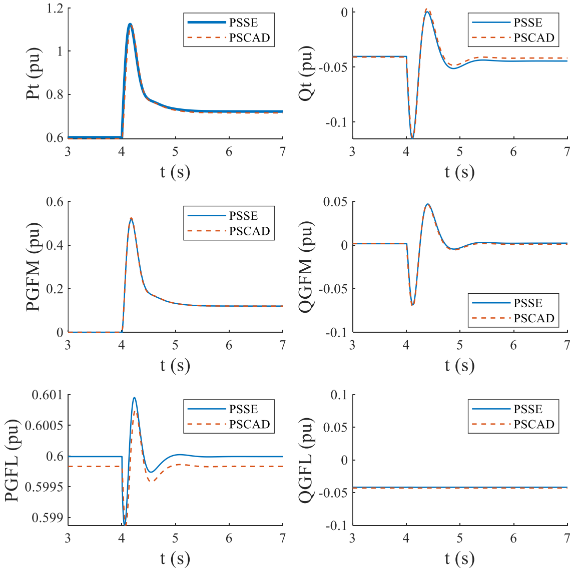
GFM Variables



GFL Variables

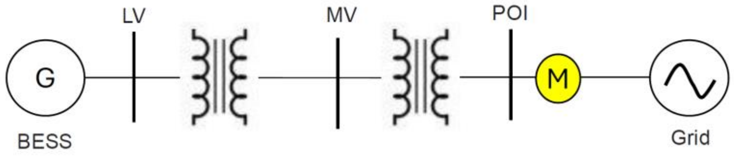


Output P and Q



Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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



Strong Grid

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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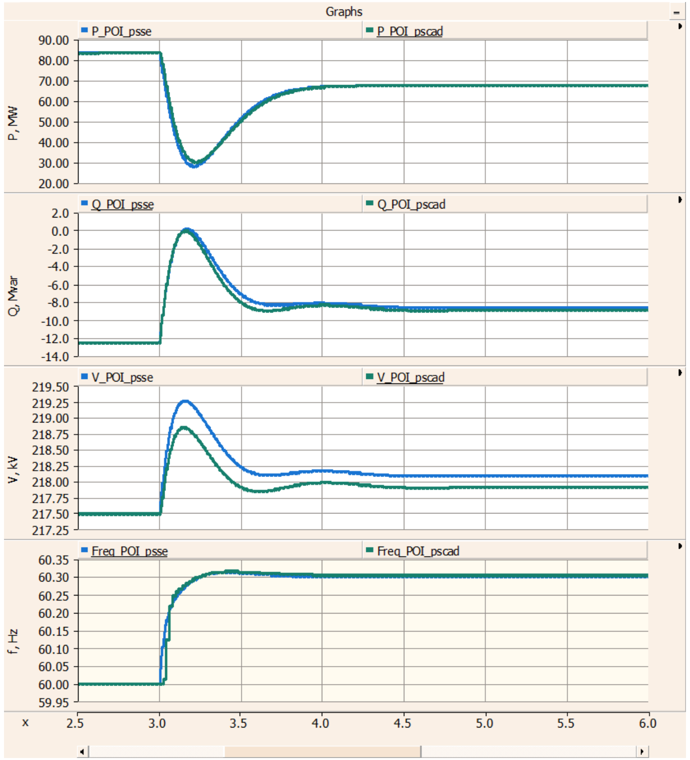
Frequency Step up

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



Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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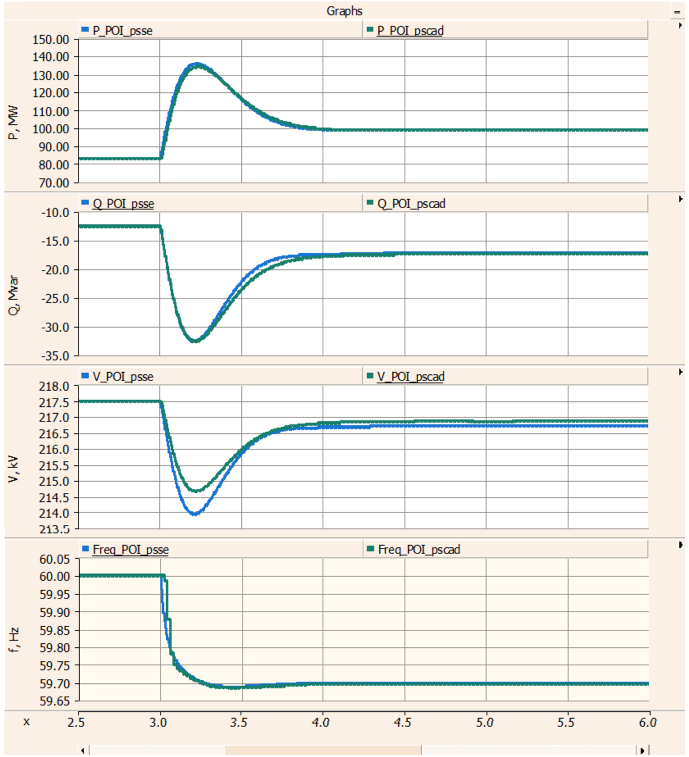
Frequency Step down

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



Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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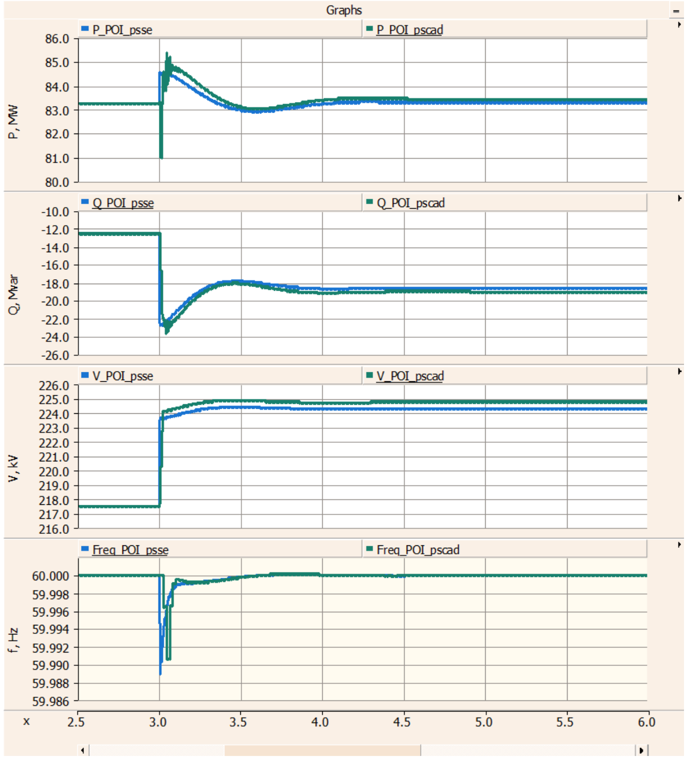
Voltage Step up

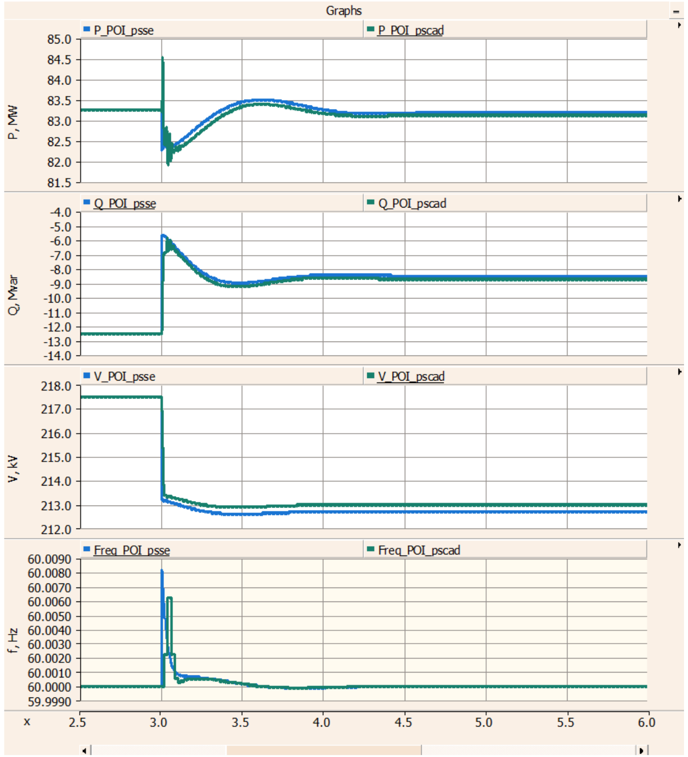
Blue Line: REGFM_C1 PSS/E Model
Green Line: Tesla's black-box PSCAD Model



Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

Voltage Step down

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



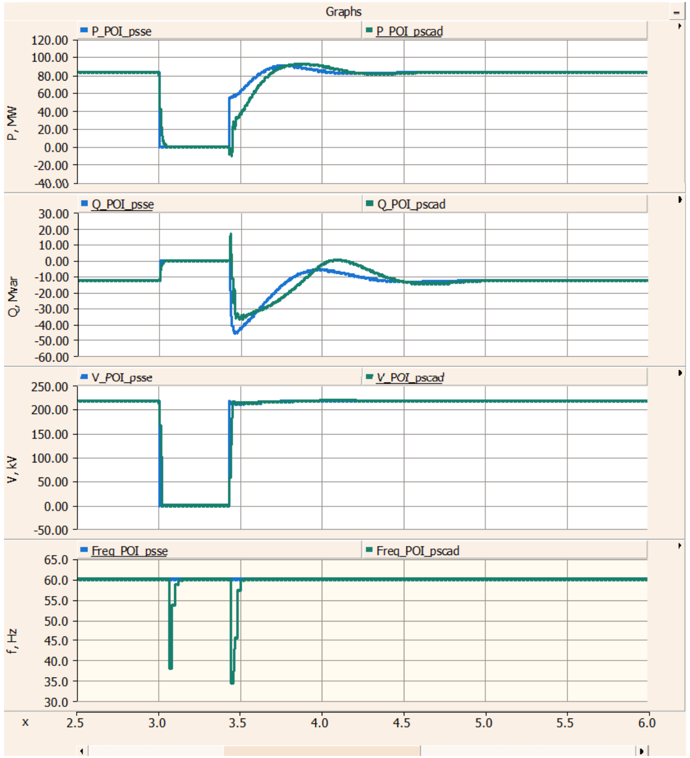
Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

Funded by:

Bolted Fault

Blue Line: REGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

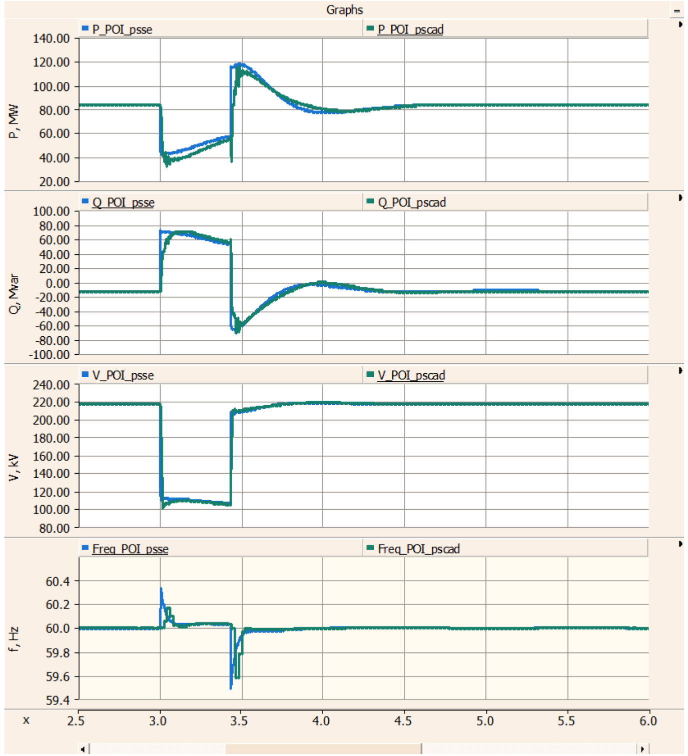


Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

Funded by:

High Impedance Fault

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



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Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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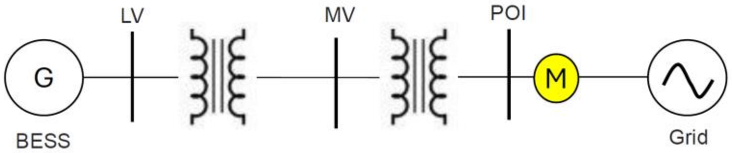

Weak Grid

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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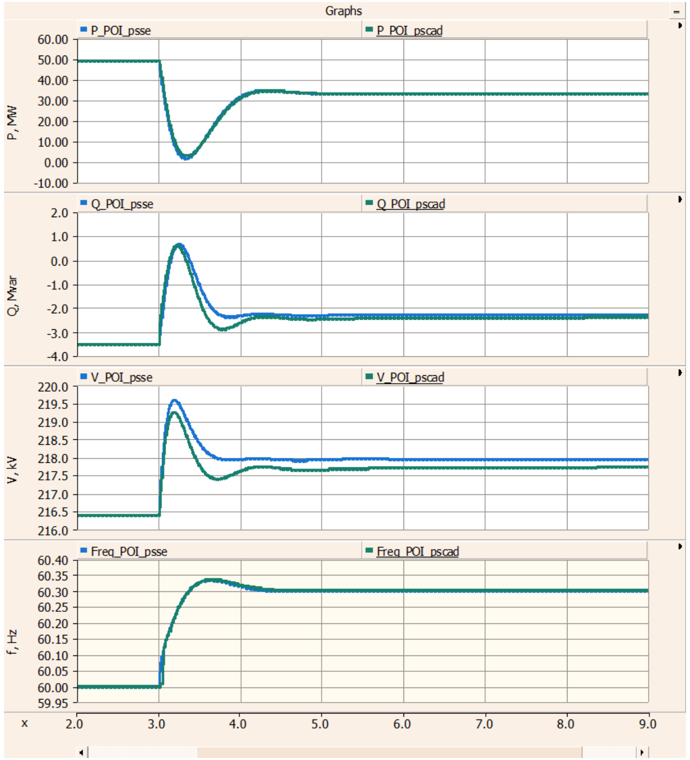
Frequency step up

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

SCR = 3, X/R = 10



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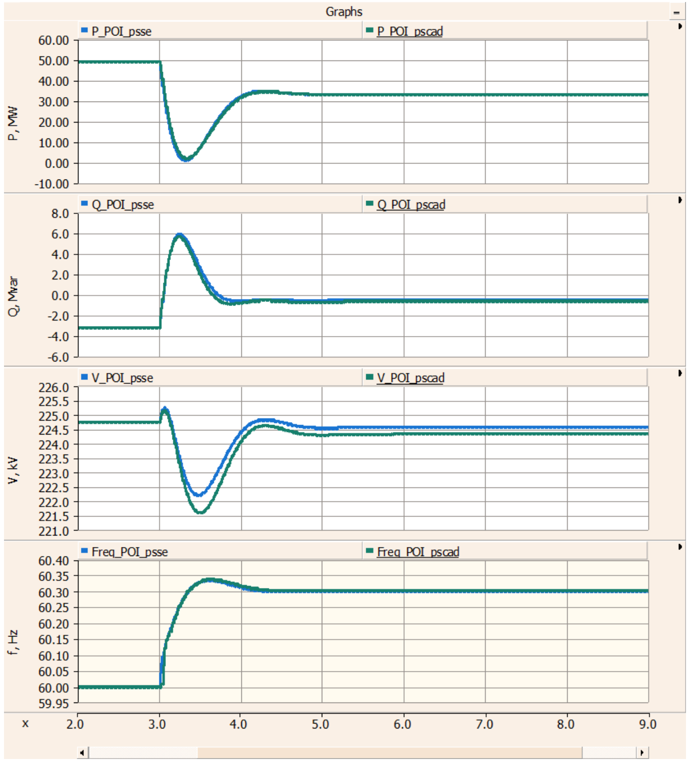

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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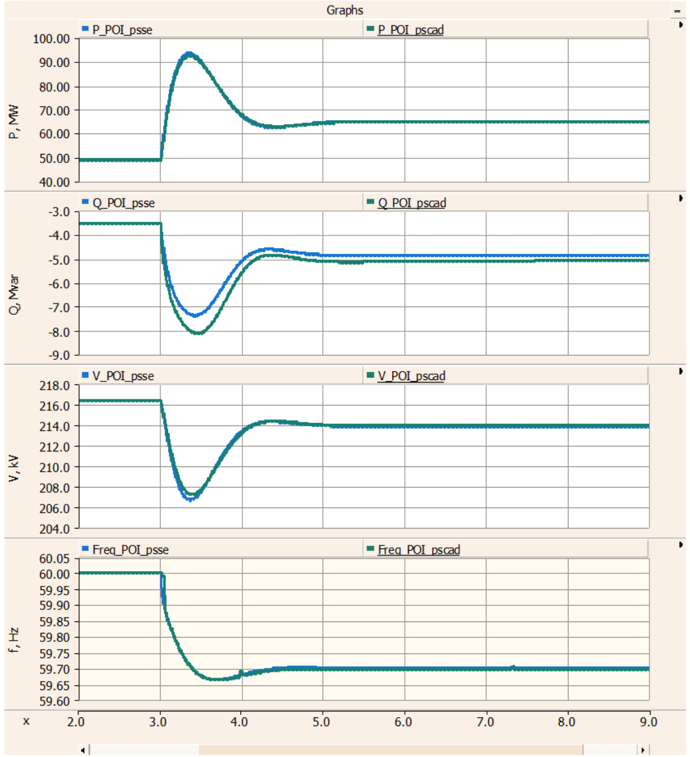
Frequency step down

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

SCR = 3, X/R = 10



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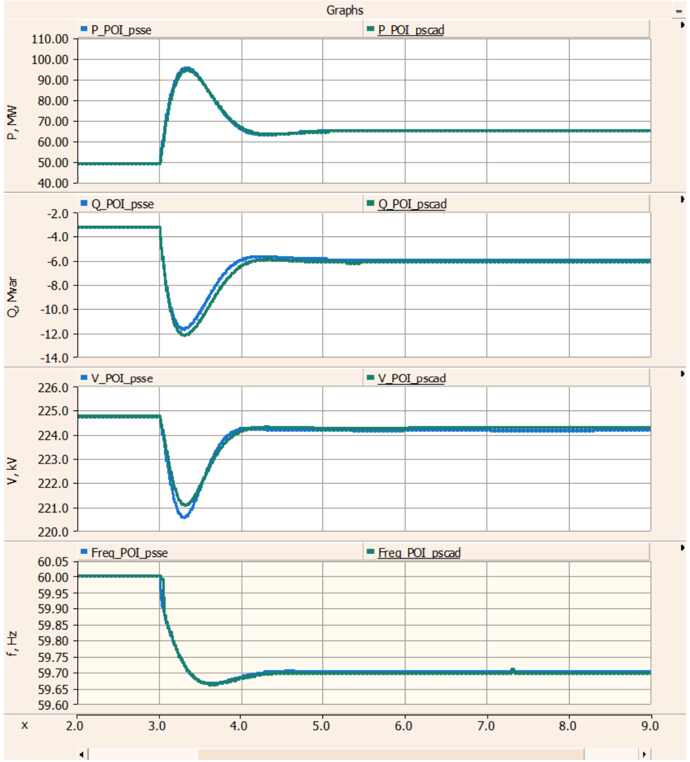

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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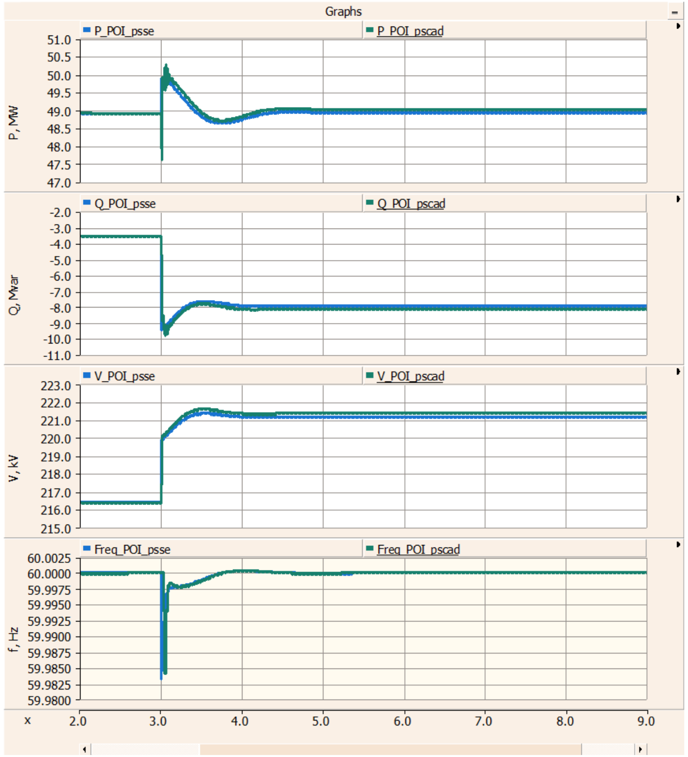
Voltage Step up

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

SCR = 3, X/R = 10



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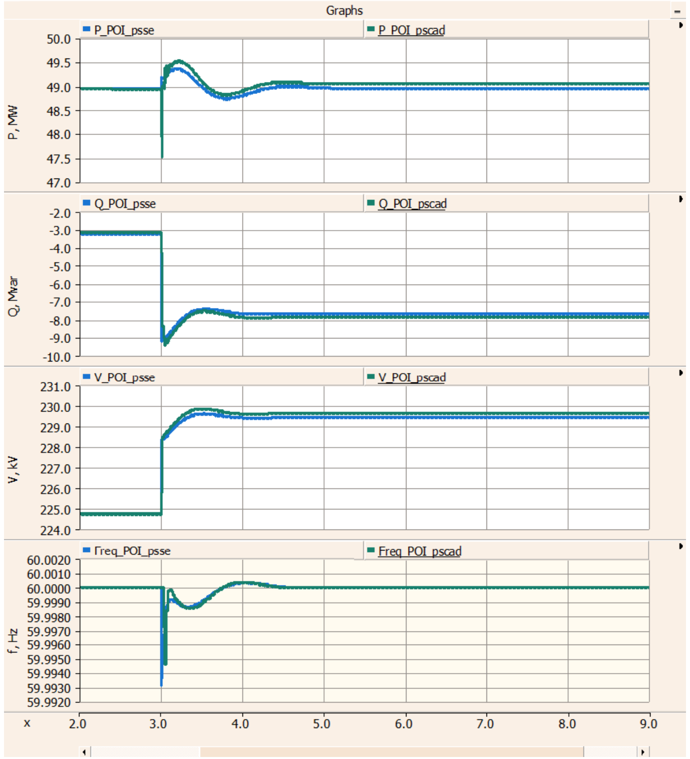

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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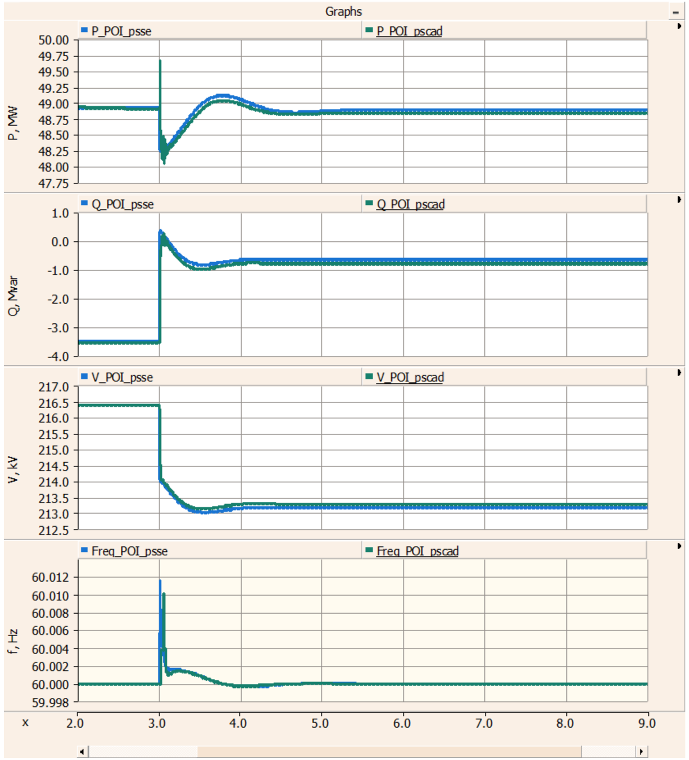
Voltage Step down

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

SCR = 3, X/R = 10



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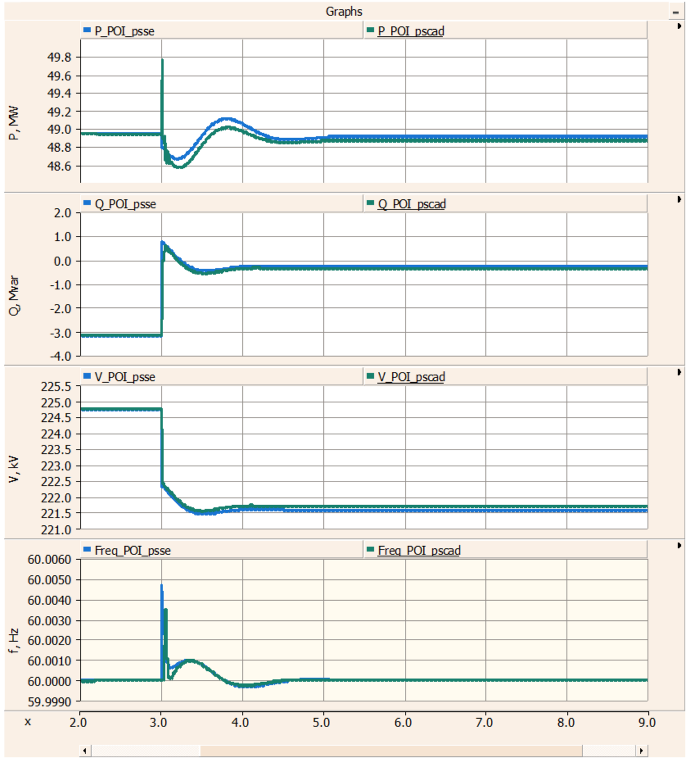

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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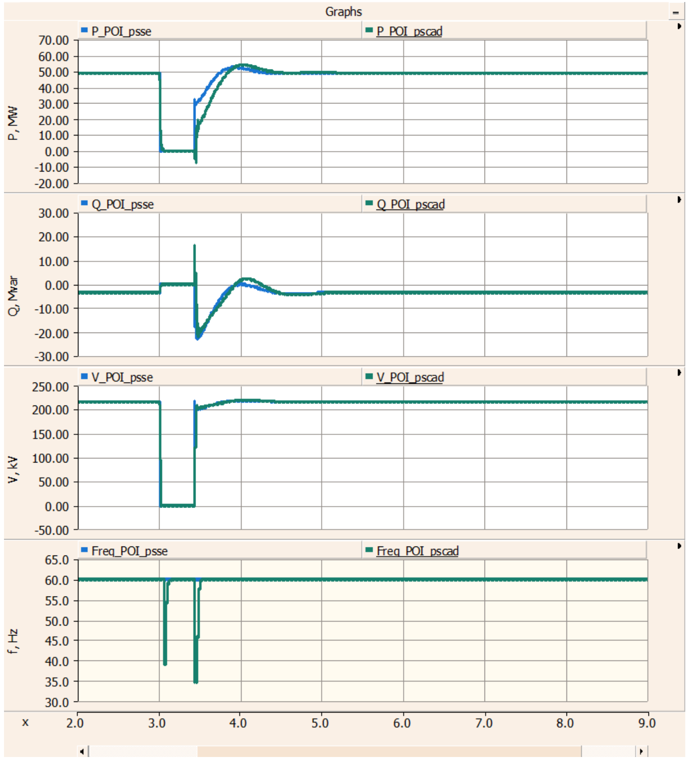
Bolted Fault

Blue Line: REGFM_C1 PSS/E Model

Green Line: Tesla's black-box PSCAD Model

SCR = 3, X/R = 10



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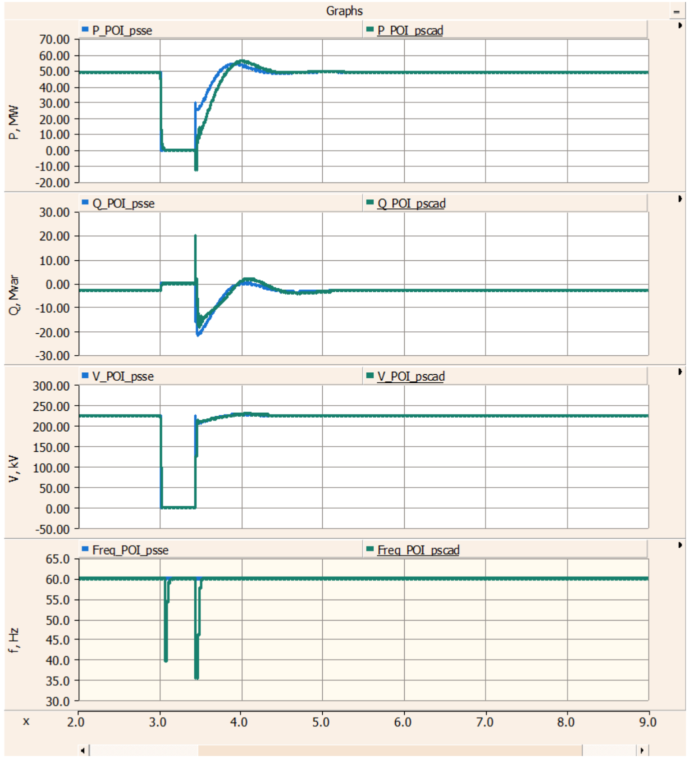

Validation of REGFM_C1 against Tesla's Black-Box PSCAD Model

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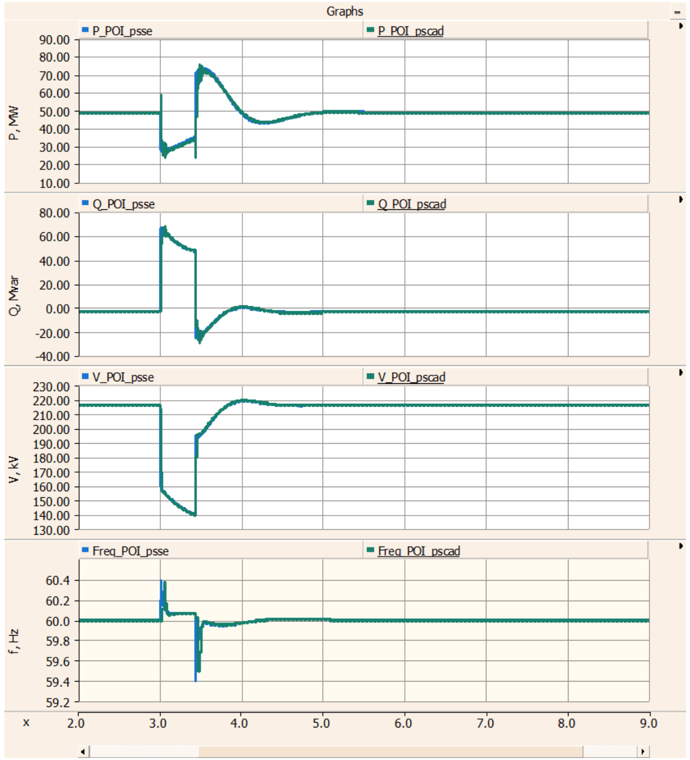
High impedance fault

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

SCR = 3, X/R = 10



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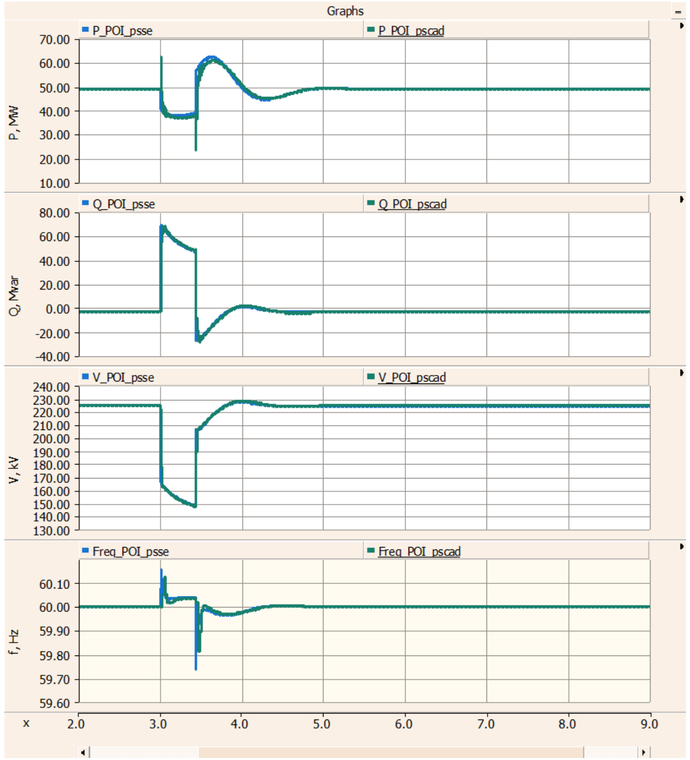

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Summary

- The GFM hybrid model, REGFM_C1, and its plant controller model, REPCGFM_C1 model have been presented
- Both PSS/E model and PSCAD model have been developed based on the specifications, and the PSS/E and PSCAD results match very well
- Furthermore, the REGFM_C1 model has been validated against Tesla Energy’s black-box PSCAD model

We’d like to make a motion to approve the REGFM_C1 and REPCGFM_C1 model specifications

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unifi consortium

universal interoperability for grid-forming inverters

THANK YOU