CIGRE-India Study Committee C2, in collaboration with GRID-INDIA and Forum of Load Despatchers (FOLD)

Grid Forming Inverters and Possible Applications for Indian Power System

Presenters: Priyam Jain and Gaurab Dash

Other Core Team Members: Prabhankar Porwal, Raj Kishan, Arpan Saha and teams across NLDC/RLDCs

GRID CONTROLLER OF INDIA LIMITED

Discussion Paper by GRID-INDIA

GRID-INDIA has published a Discussion Paper on

"Grid-Forming Technology and Possible Applications in the Indian Power System

https://webcdn.grid-india.in/files/grdw/2025/12/Discussion%20Paper_Grid-Forming%20Inverters_Final_956.pdf

Review of grid-forming (GFM) technology vis-à-vis the currently prevalent grid-following (GFL) technology

Literature review

Detailed simulation studies

International deployment experience

Suggestions for a potential roadmap for future deployment

Comments and inputs are invited from stakeholders and domain experts on the observations and analysis presented in this paper.

The comments may be shared at nldcreliability@grid-india.in

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Contents

Listener's Perspective

1. Nature of VRE Capacity Addition in India

2. Fundamentals of Inverter Control

   - Grid Following Control
   - Grid Forming Control
   - Types of Grid Forming Control

Too complex... 😥
What is the need for this??
We already know the fundamentals

3. Stability related concerns in large VRE complexes in Indian power system

4. Simulation studies – Description and Insights

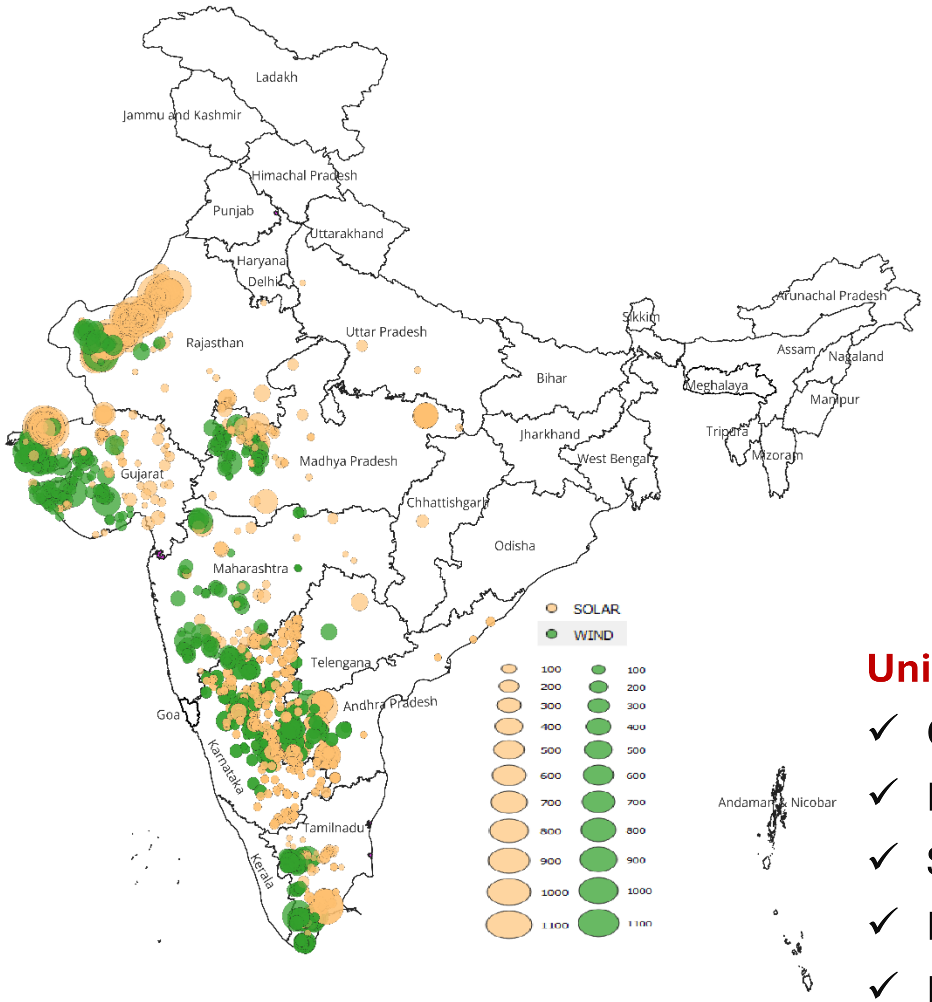
5. Global experience with Grid Forming

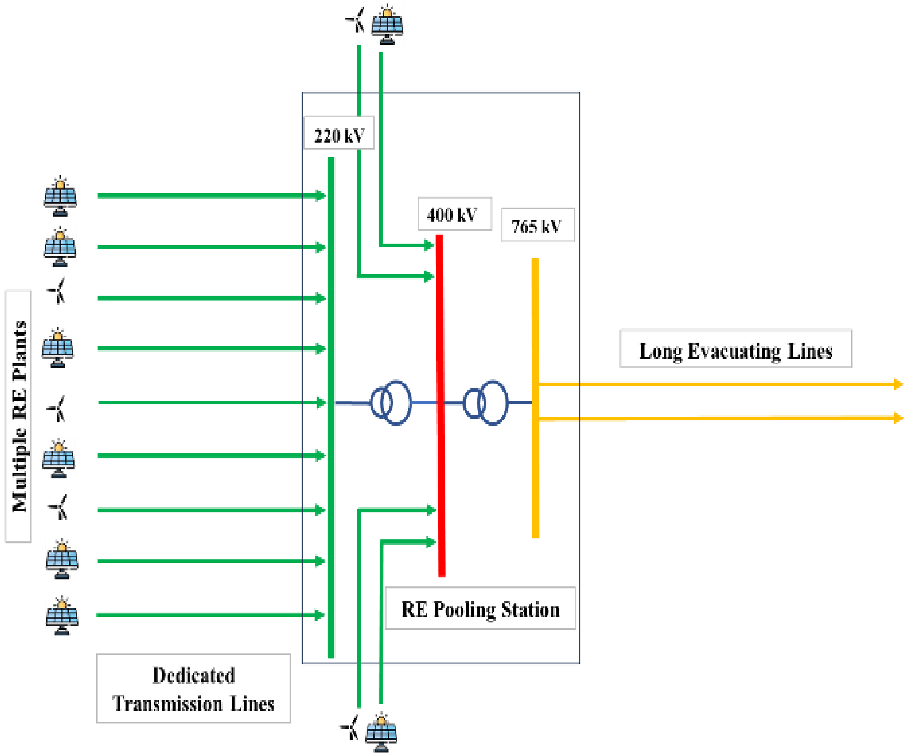
6. Specifications related to grid forming capability in Grid Codes and Standards

Thank God !!
Something exciting 🙂

7. Way Forward

RE Capacity Addition in India: Concentrated Manner





Unique VRE capacity addition in India in terms of:

- ✓ Concentrated RE zones
- ✓ Large RE pooling stations at the EHV level for power evacuation (4000 – 8000 GW)
- ✓ Substations aggregating power from multiple pooling stations
- ✓ Remotely located, far from load centres
- ✓ Long UHV/EHV lines to evacuate bulk intermittent/variable power from IBR to the grid

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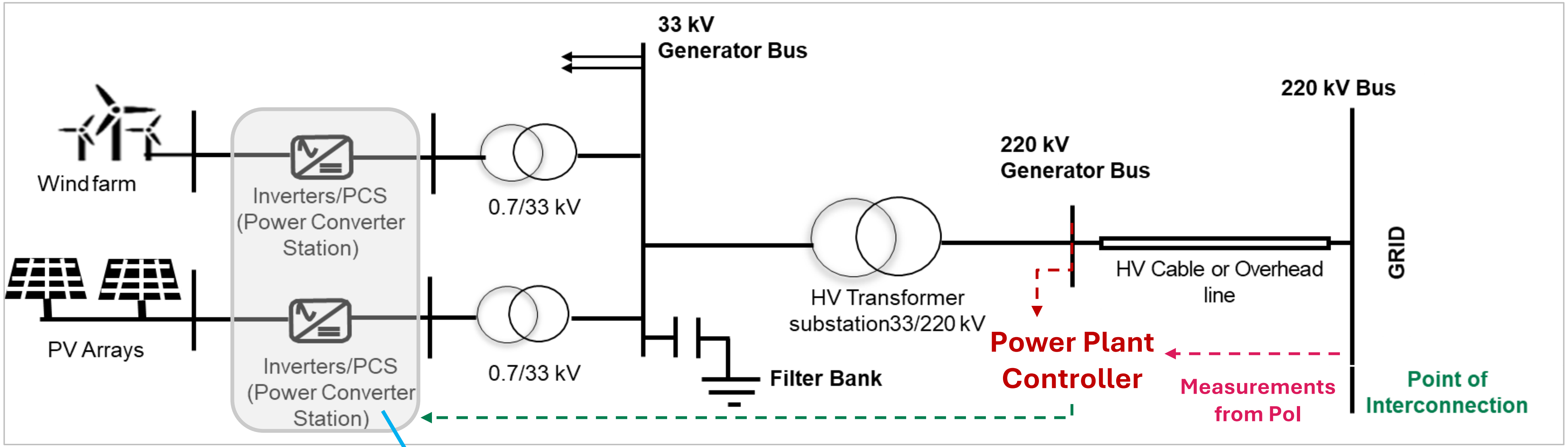
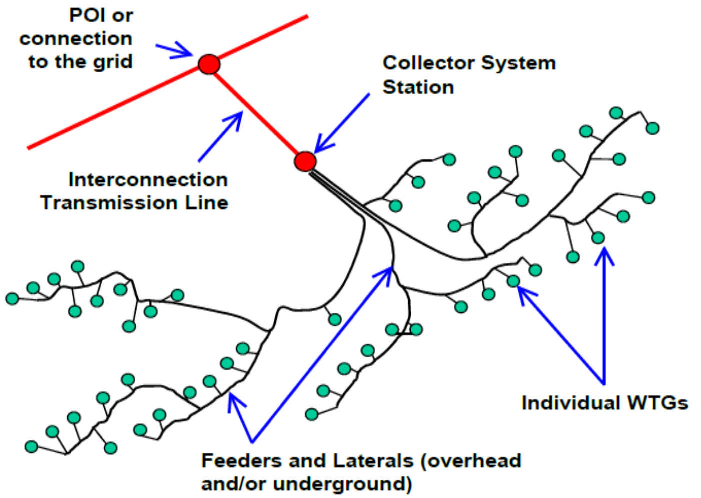
RE Capacity Addition in India: Typical Plant Layout



AREA OF
INTEREST



Understanding the fundamentals is important !!

1. GFL behaves as a current source while GFM behaves as a voltage source but both GFL and GFM use voltage source converters — so what does that really mean?

2. If GFM behaves as a voltage source, isn’t it automatically better than GFL?

3. If both GFL and GFM generate terminal voltage using PWM, why is one termed as current source and other as voltage source?

4. Can GFL operate reliably in weak grids?

5. Does removing the PLL instantly make an inverter grid-forming?

6. Can any standard GFL inverter be 'converted' to GFM via a firmware update, or is the hardware actually different?

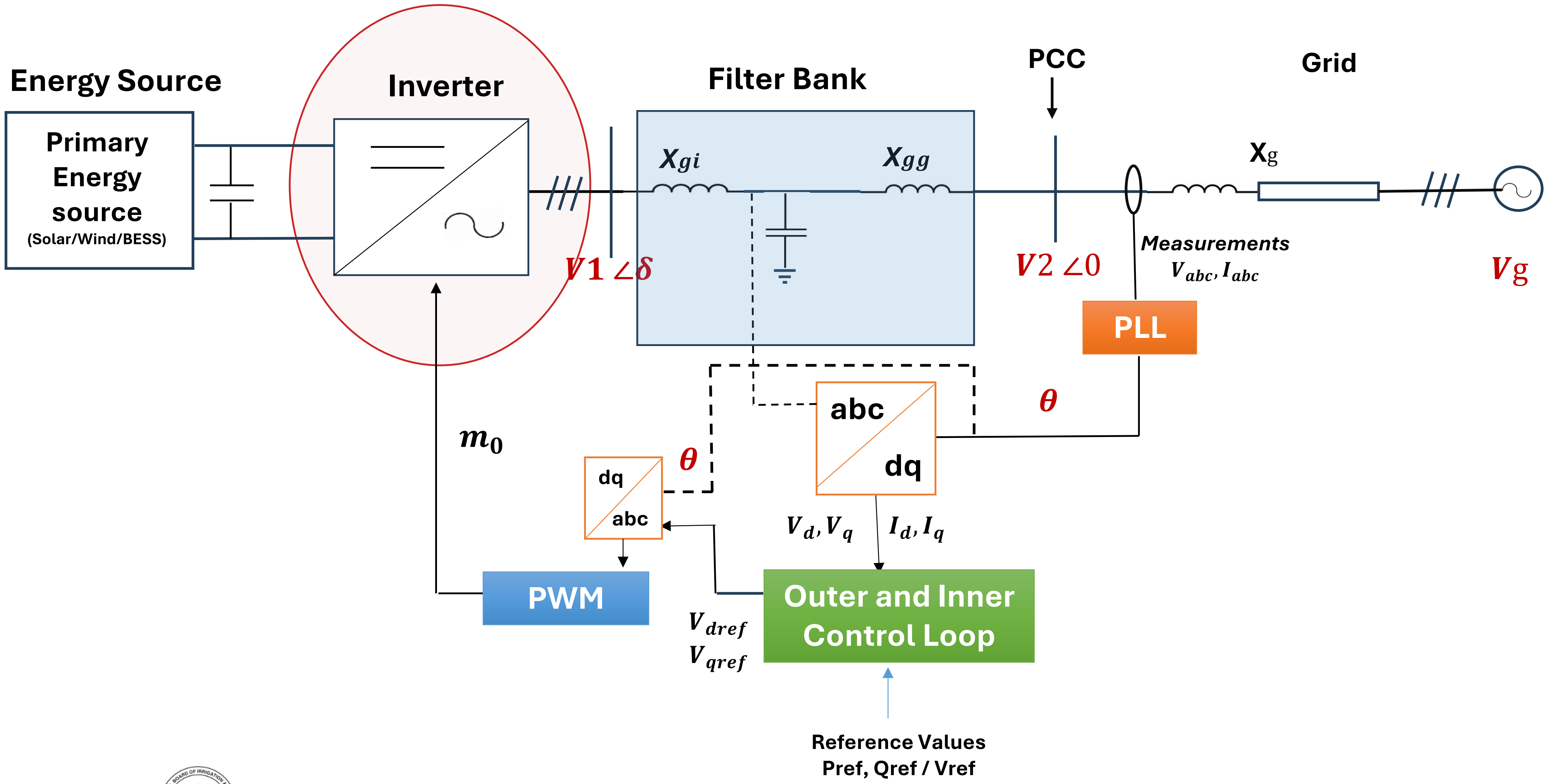
....and many more

GFL: *Grid Following Inverter*

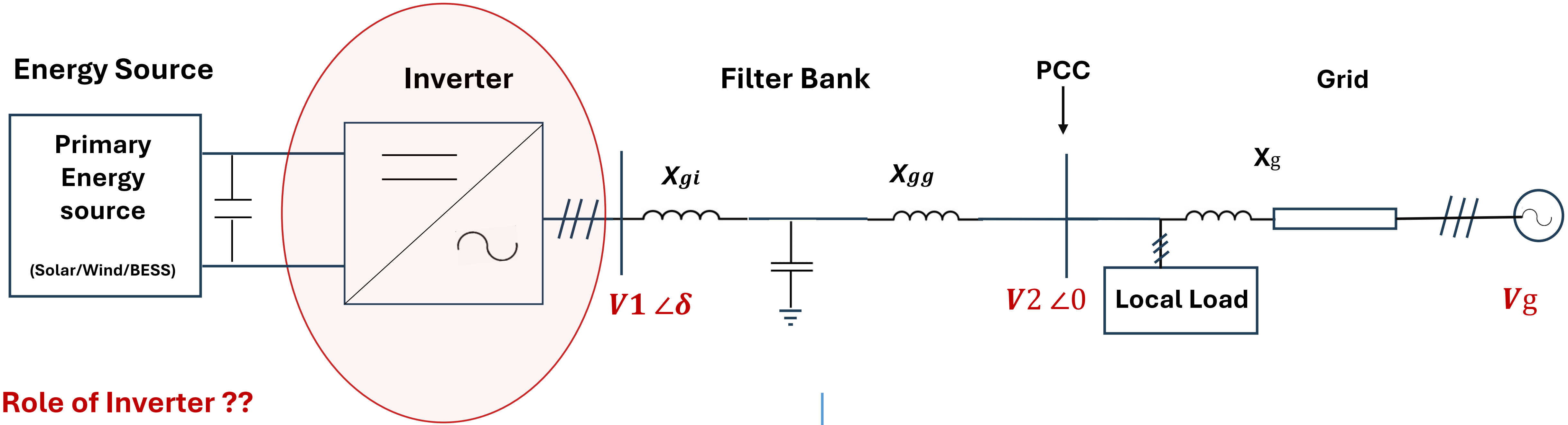
GFM: *Grid Forming Inverter*

Contents

High Level Architecture of Inverter Control



High Level Architecture of Inverter Control



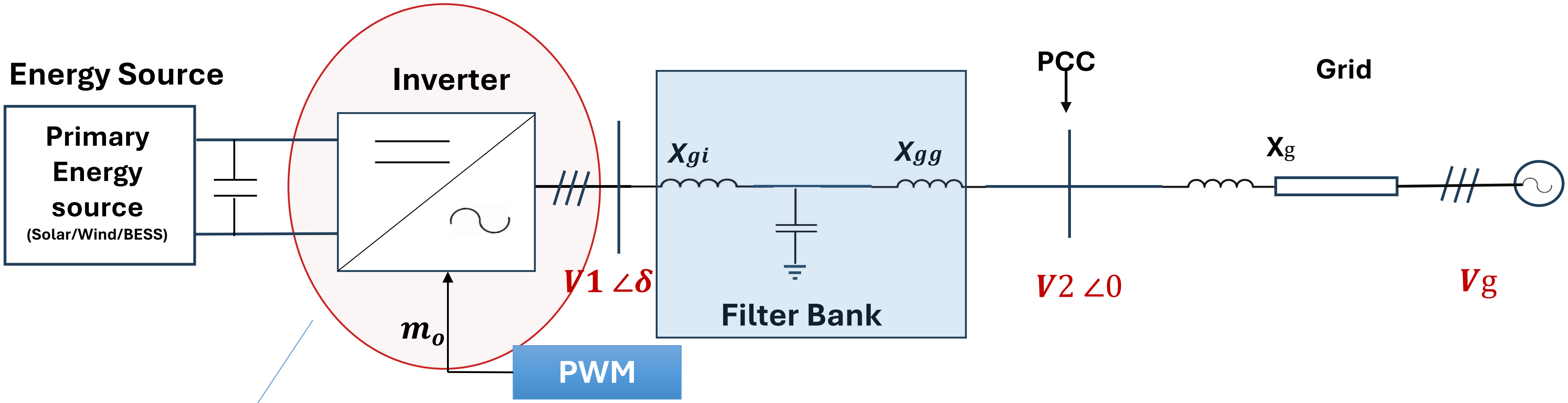
Role of Inverter ??

Active Power Flow: $\frac{V1\, V2 \sin\delta}{X_f}$

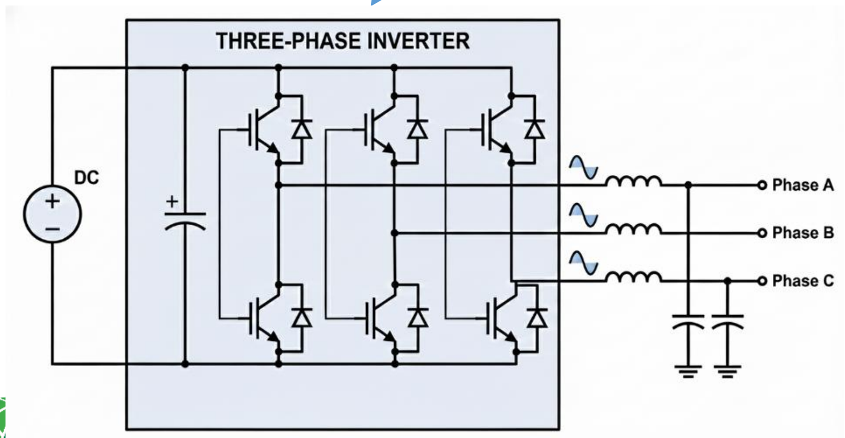
Reactive Power Flow: $\frac{V1^2 - V1\, V2 \cos\delta}{X_f} = \frac{V1\,(V1 - V2)}{X_f}$

- Control Phase Angle 'δ' → Control Active Power
- Control Voltage 'Magnitude' → Control Reactive Power

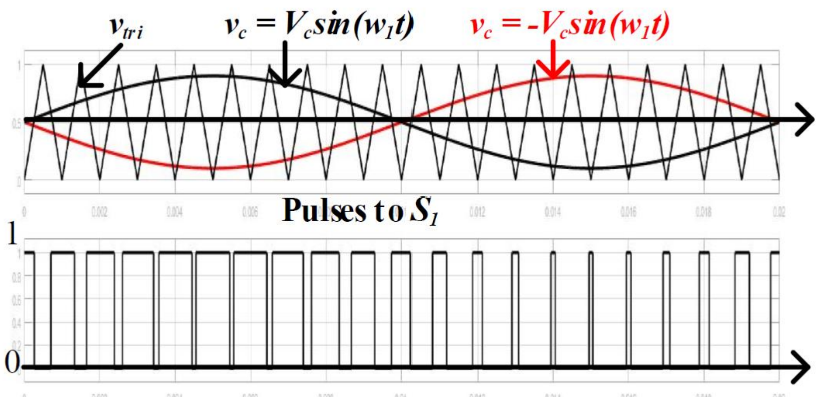
High Level Architecture of Inverter Control

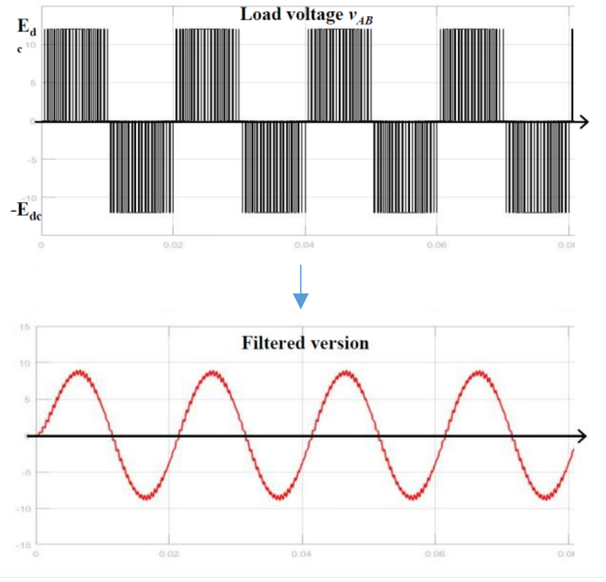


If an inverter can synthesize the desired voltage magnitude and angle at its terminal, it can provide the required active and reactive power voltage?

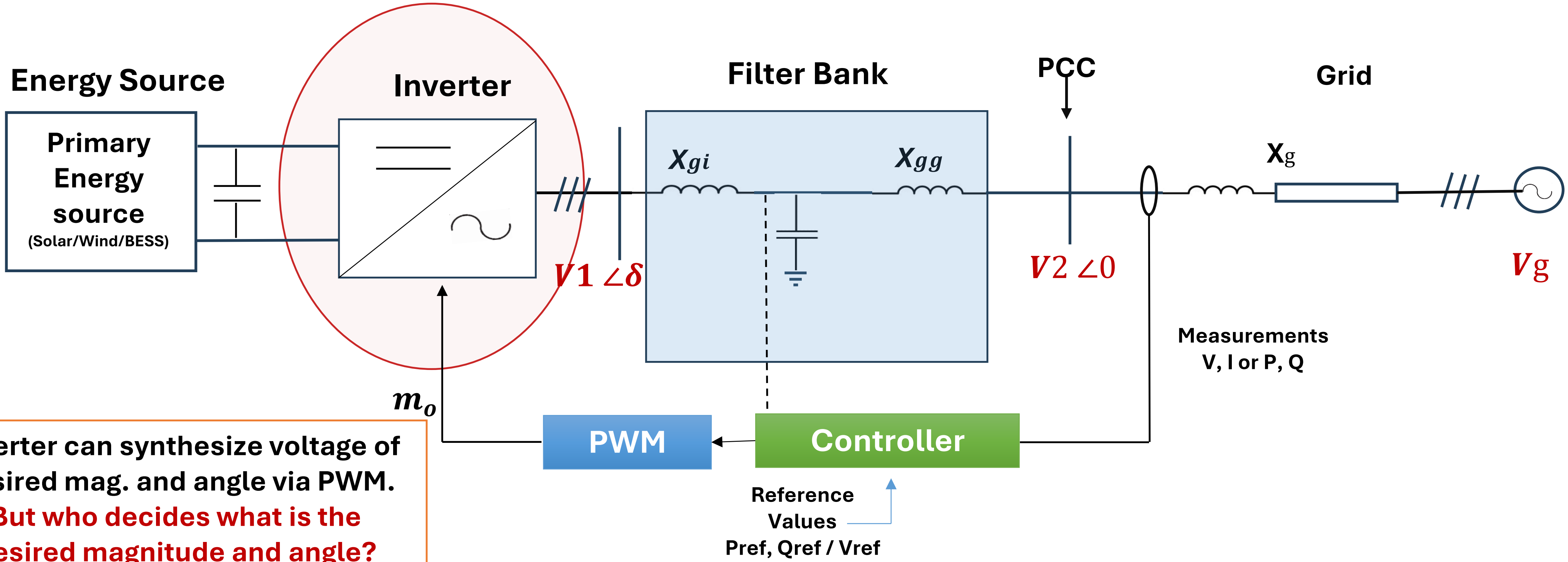


PWM – Pulse Width Modulation





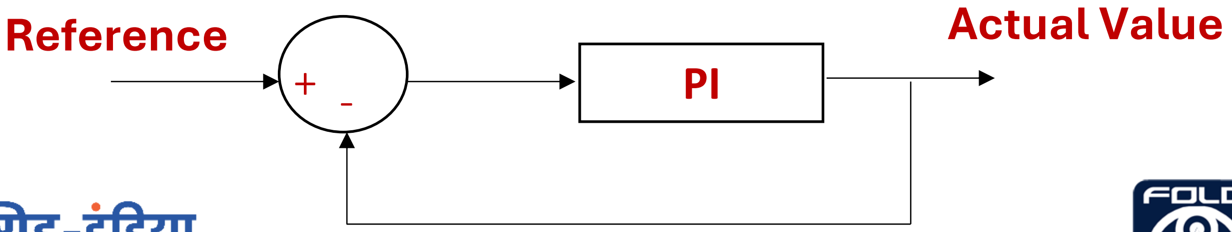
High Level Architecture of Inverter Control



Inverter can synthesize voltage of desired mag. and angle via PWM.
But who decides what is the desired magnitude and angle?

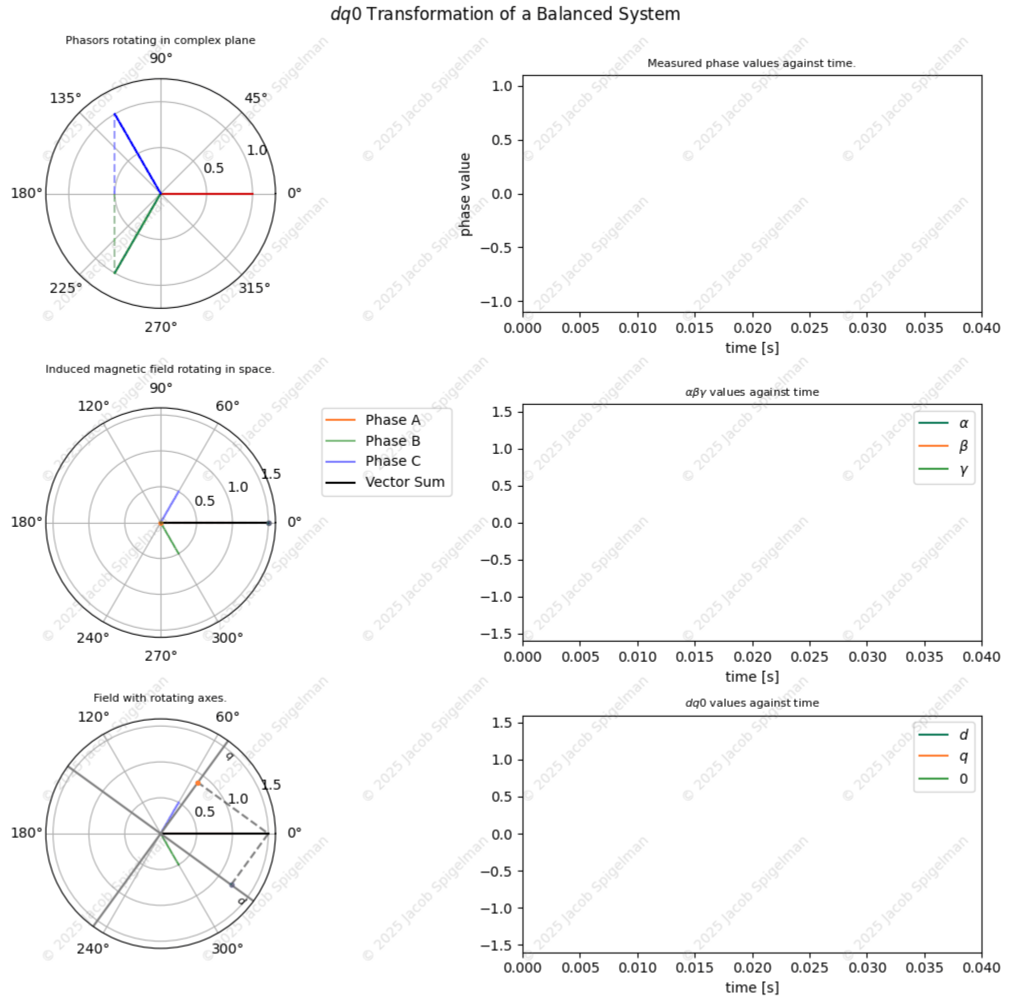
Controller Design

- Should we control 3-phase quantities (A, B, C) or it there a better approach?

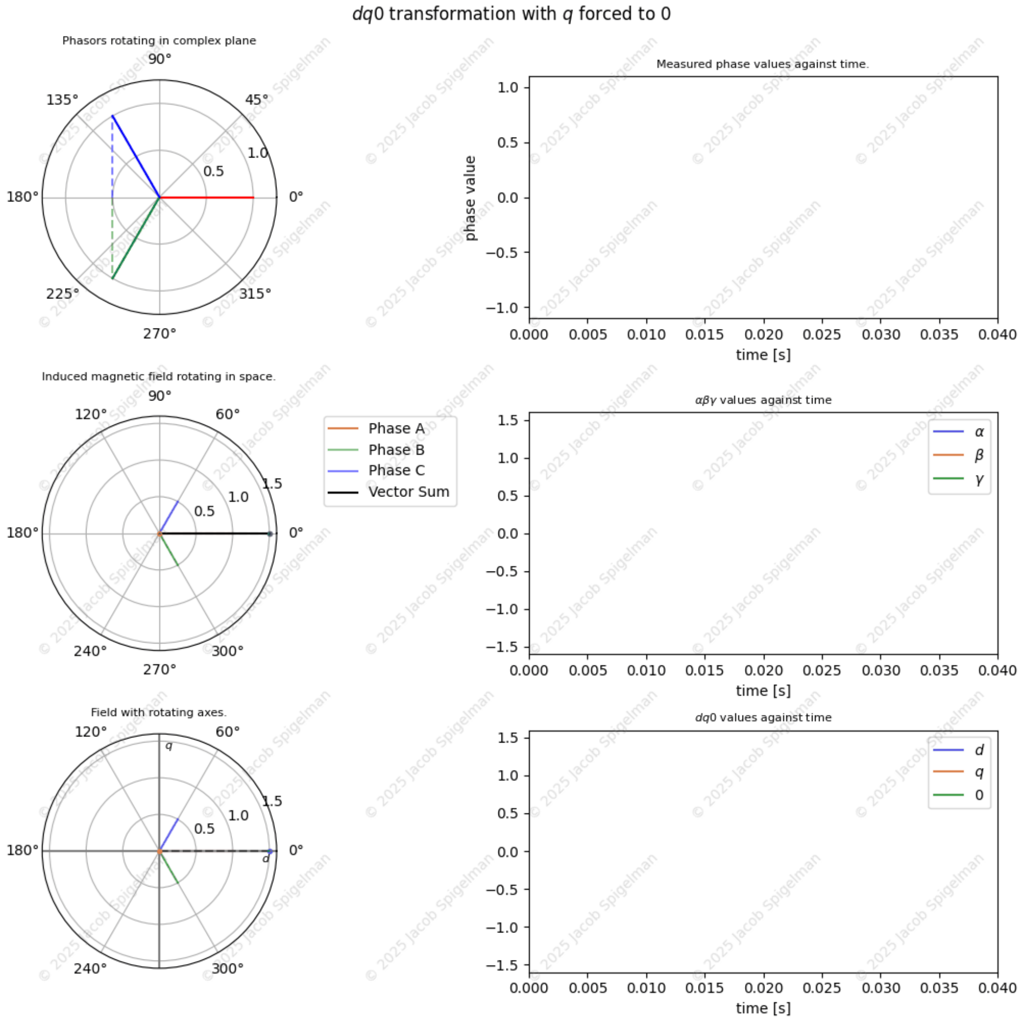


High Level Architecture of Inverter Control

abc to dq0 transformation



What happens in an inverter through PLL?



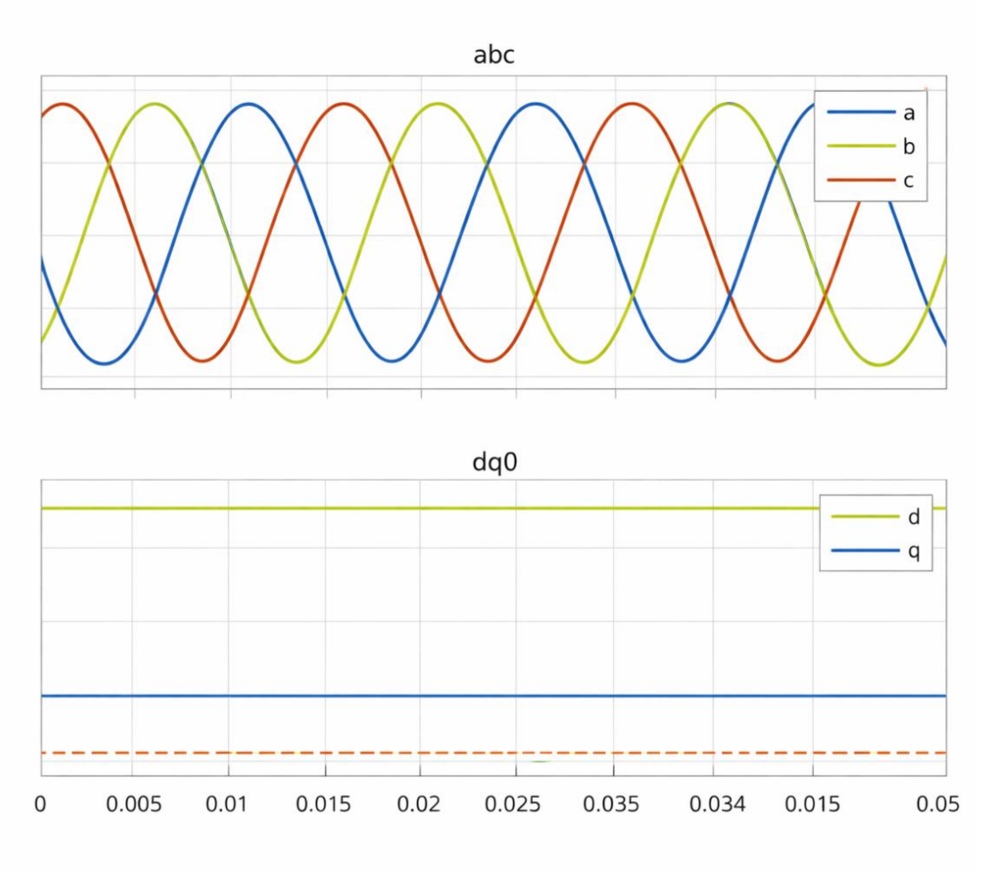
GIF Credit: https://jmspigelman.github.io/dq0_symm_comp_tutorial/ By Jacob Spigelman

High Level Architecture of Inverter Control

Controller Design

Park's Transformation

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$



- In d-q frame, apparent power (S) equation becomes:

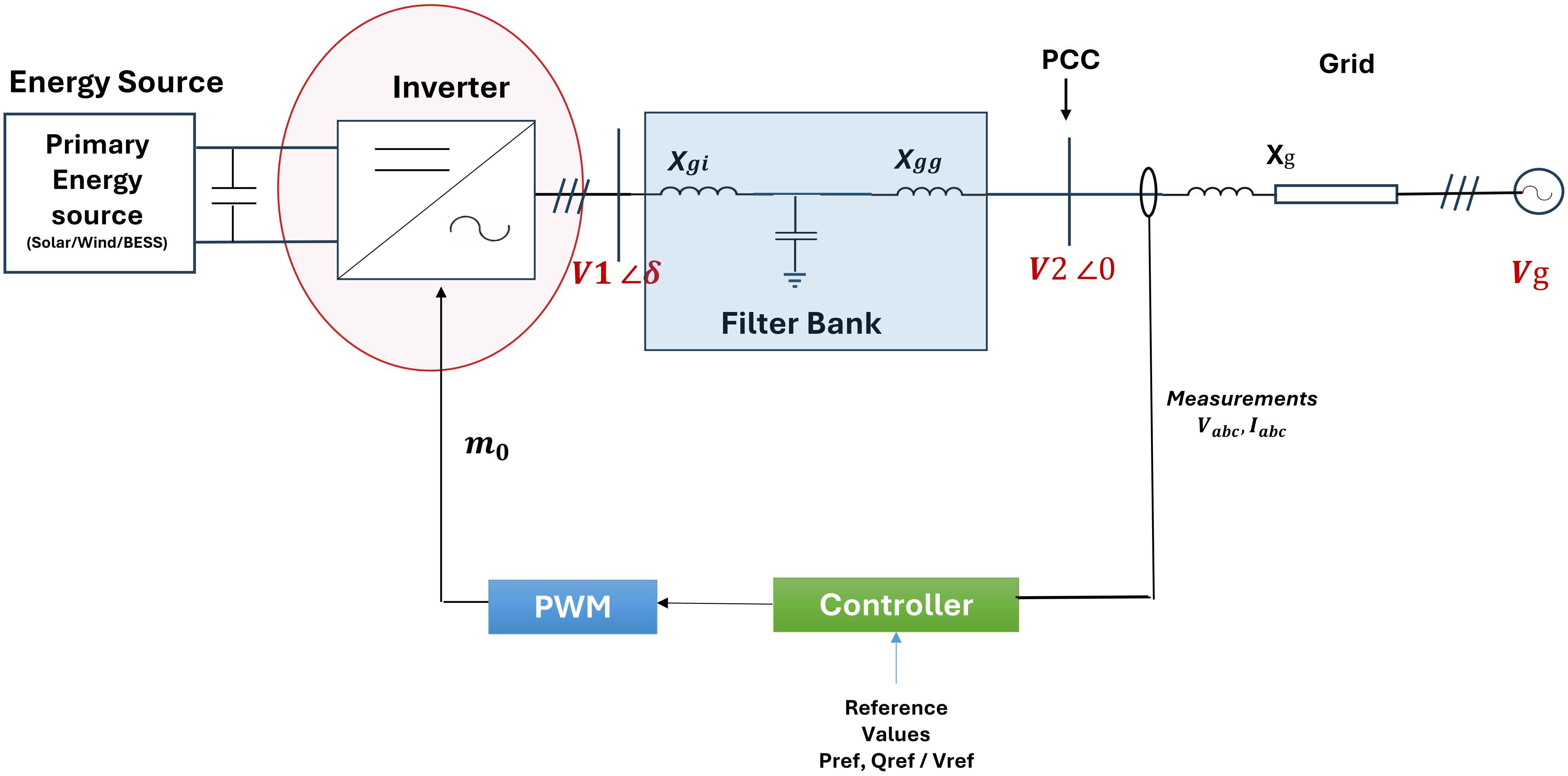
$$S = \frac{3}{2}\left[\left(V_d I_d + V_q I_q\right) + j\left(V_q I_d - V_d I_q\right)\right]$$

- For a balanced system, $V_q = 0$

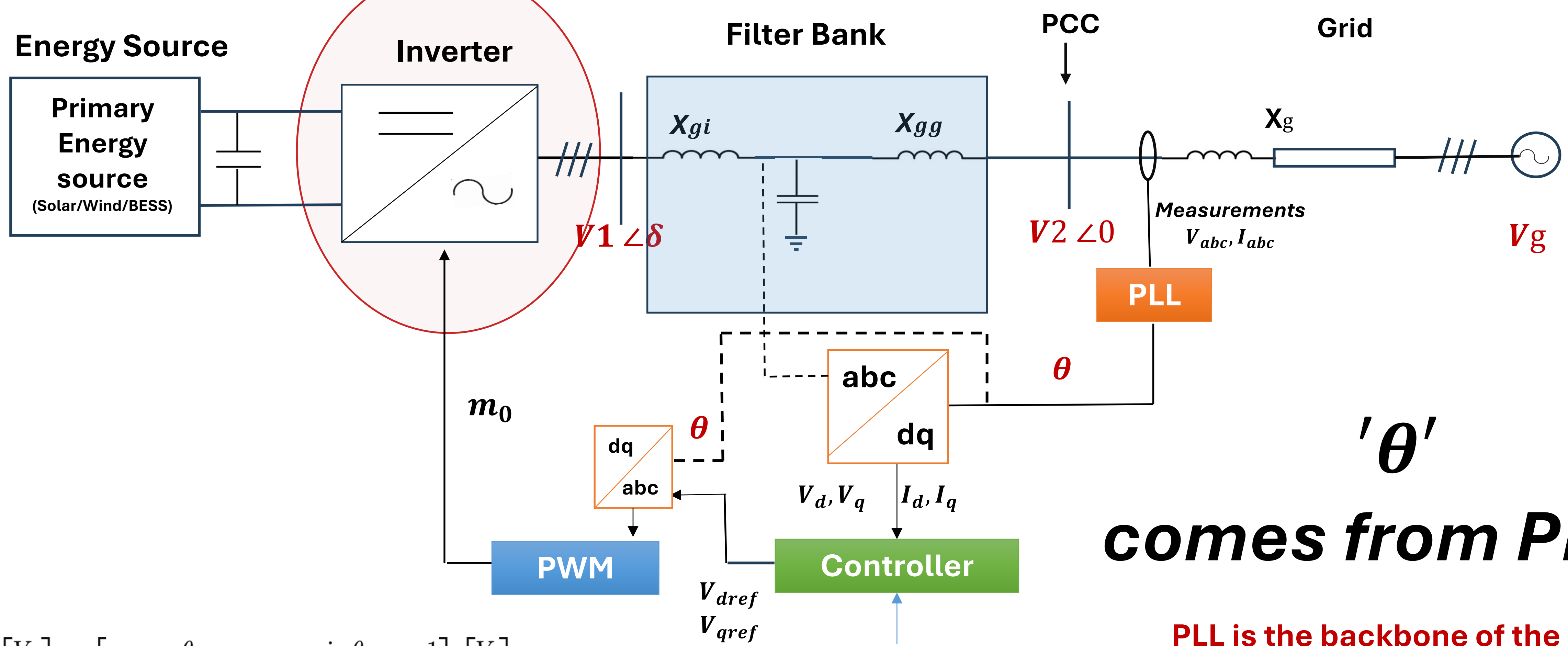
$$S = P - jQ = \frac{3}{2}\left(V_d I_d - jV_d I_q\right)$$ **Decoupled Control**

By controlling I_d and I_q, **P and Q** can be controlled independently; hence, named as decoupled control

High Level Architecture of Inverter Control



High Level Architecture of Inverter Control



$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$

$'\theta'$

comes from PLL !!

PLL is the backbone of the entire control hierarchy of grid following inverter

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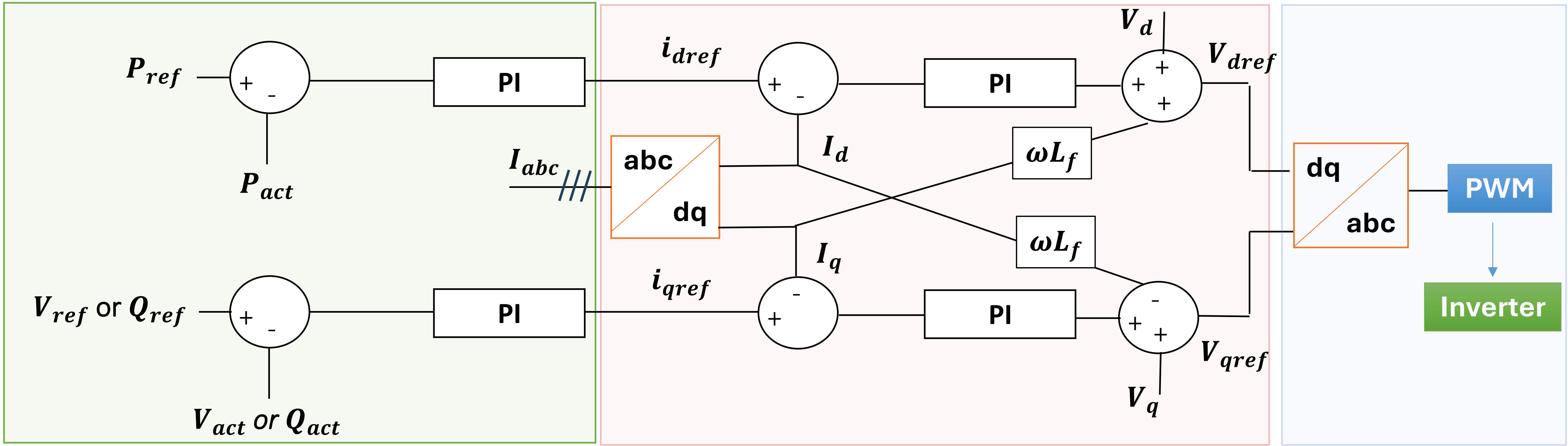
High Level Architecture of Inverter Control

Controller Design



Outer Control Loop

Slow Controller

(~1/20 of inner control loop)

Inner Control Loop

Fast Controller

(~1/10 of Switching / PWM)

PWM

Very Fast

(~5k – 40k Hz)

High Level Architecture of Inverter Control

PLL → Treadmill Analogy

- **Person walking on a treadmill**
  - **Grid voltage vector** → moving conveyor belt
  - **PLL** → speed + position sensor
  - **Inverter control** → person walking on the belt

Like the person on the belt, inverter must match the grid's speed and direction (angle / frequency) to safely inject current

Major Functions of PLL in a Grid-Following Inverter

- **Reference frame** generation (ABC to dq transformation)
- Enables **decoupled active and reactive power control**
  - **id** → P control; **iq** → Q control
- **Grid synchronization**
  - estimates grid angle and freq. and locks to the grid voltage

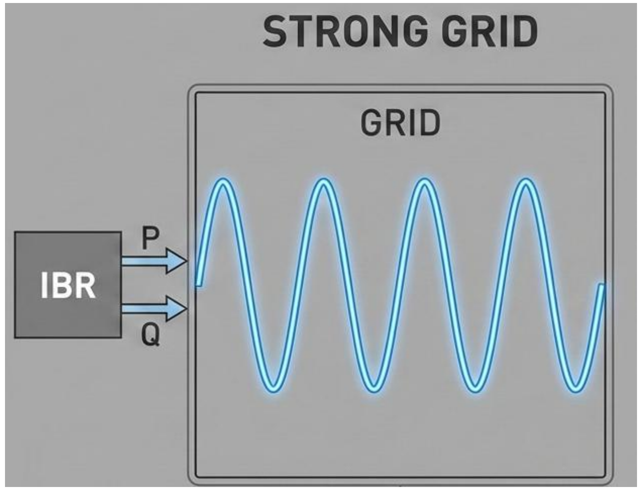
Issues with synchronization **(if frequencies are different)**

- Large circulating currents
- Oscillatory and uncontrolled power flow
- Loss of P–Q decoupling
- PLL instability or failure to lock

What happens in a Weak Grid!

Strong Grid

Power/Current injected by the IBR does not move the System



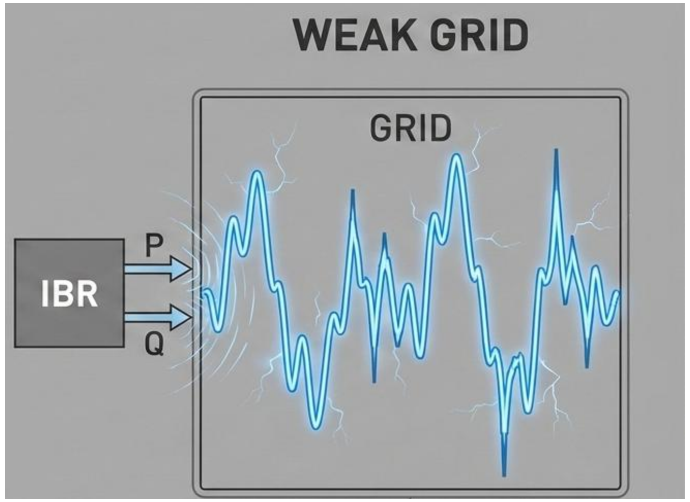
Strong Grid

PLL tracks the grid voltage and frequency

Weak Grid

Power/Current injected by the IBR can impact the system

Grid disturbances also impact the voltage waveform



PLL Instability

May lead to loss of Synchronism

Weak Grid

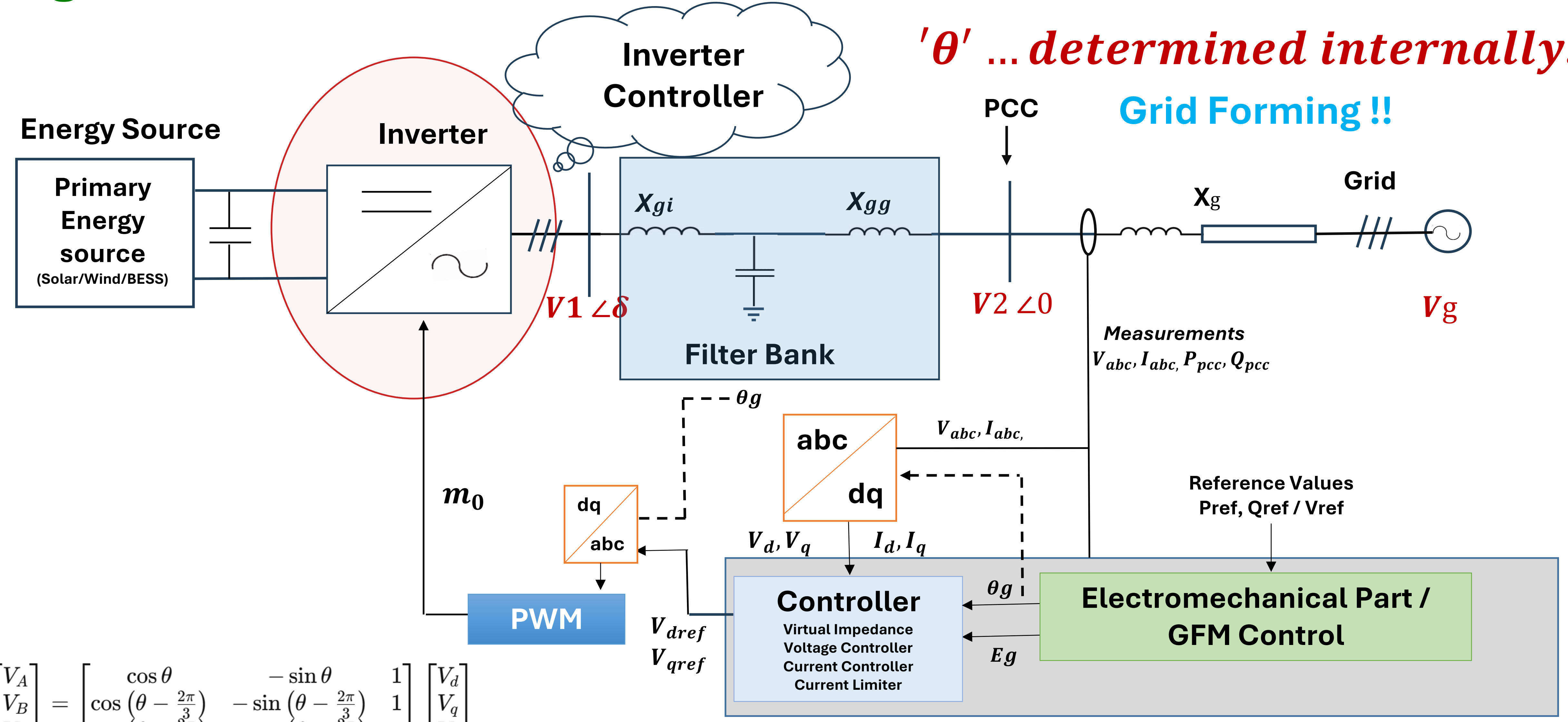
PLL fails to track the grid voltage and frequency

Contents

High Level Architecture of Inverter Control

'θ' … determined internally!!

Grid Forming !!



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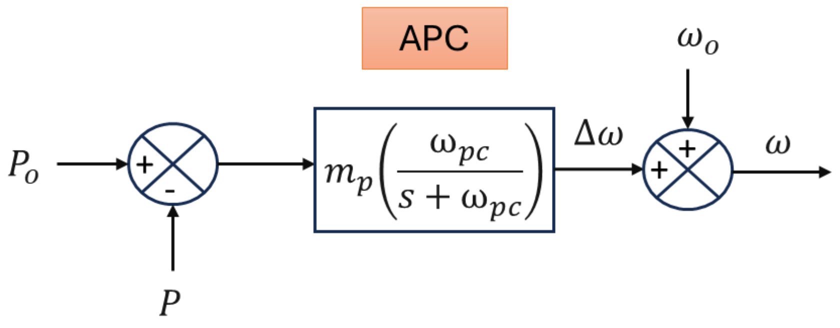
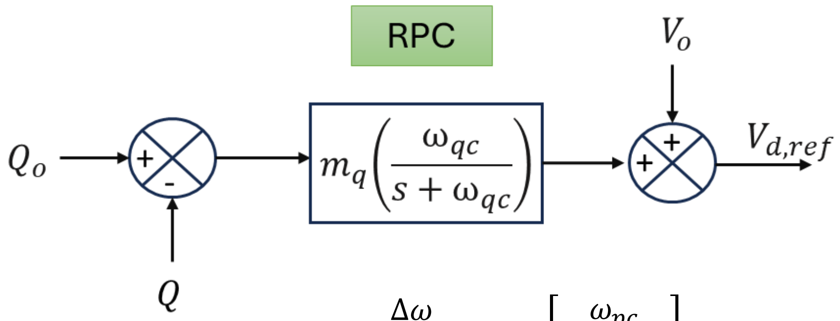
Grid Forming Inverter (GFM) Controls

Droop Control

EQUIVALENT

- P–f and Q–V droop characteristics.
- Mirrors the governor and AVR functions of synchronous generator behaviour.



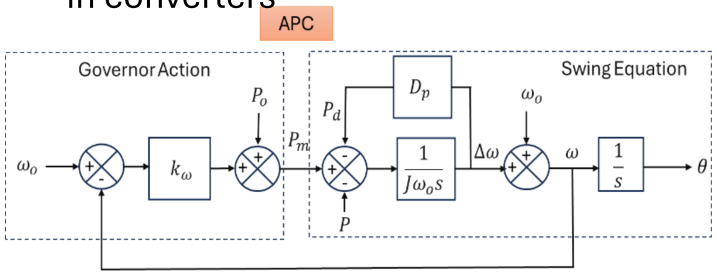


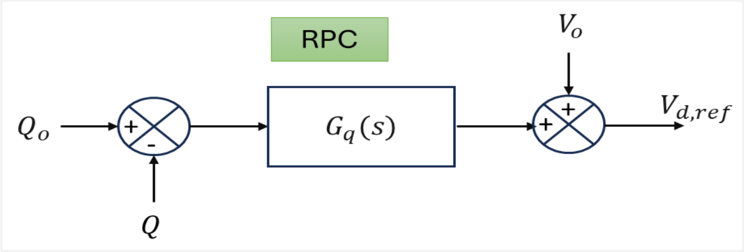
$$K_{Pfdroop} = \frac{\Delta\omega}{\Delta P} = m_p\left[\frac{\omega_{pc}}{s+\omega_{pc}}\right]$$

$$K_{Qfdroop} = \frac{\Delta V}{\Delta Q} = m_q\left[\frac{\omega_{qc}}{s+\omega_{qc}}\right]$$

Virtual Synchronous Machine (VSM) Control

- Emulates synchronous machine swing dynamics
- Compensates for reduced physical inertia in converters





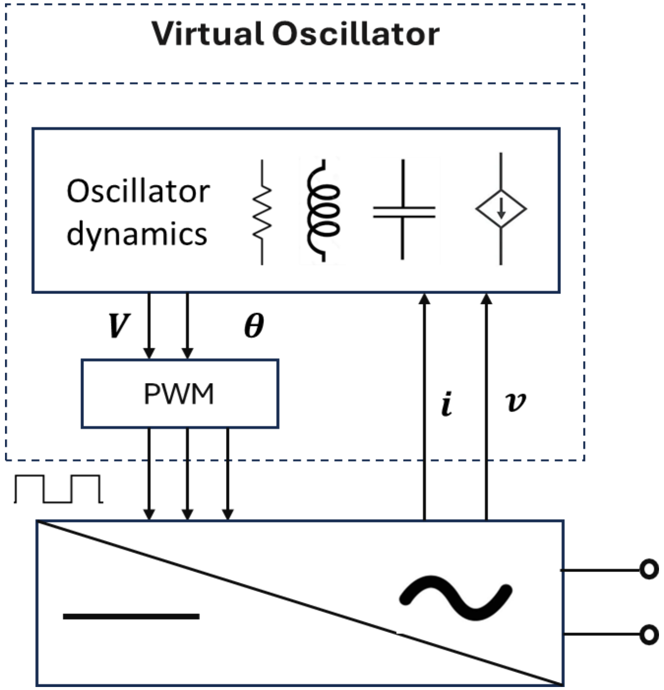
$$J\dot{\omega} = P_m - P - P_d$$

$$P_d = D_p\Delta\omega$$

$$K_{vsg} = \frac{\Delta\omega}{\Delta P} = \frac{1}{(D_p + K_m)}\,\frac{1}{\left(\frac{J\omega_o}{D_p + K_m}s + 1\right)}$$

Virtual Oscillator Control (VOC)

- Nonlinear oscillator-based control
- Natural P–f and Q–V droop,
- Fast synchronization and good stability
- Largely at the research stage



And other evolving controls.....

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Grid Forming Inverter (GFM) Controls: Types

Grid Forming Control Methodologies

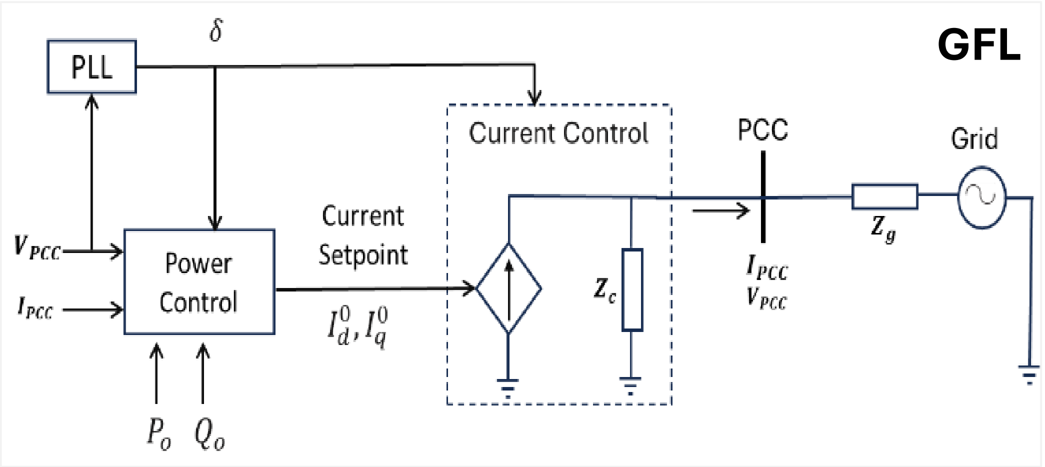
- **Droop Control**
  - Frequency-based
  - Angle-based
- **Synchronous-Machine-Based Control**
  - Virtual Synchronous Machine
  - Swing Equation Emulation
  - Augmented VSG Control
  - Synchronverter
  - Matching Control
- **Other Control Types**
  - Virtual oscillator based
  - Virtual Synchronous Control Utilizing Dc-Link Capacitor Dynamics (ViSynC)
  - Frequency Shaping-Based
  - H∞/H2-Based

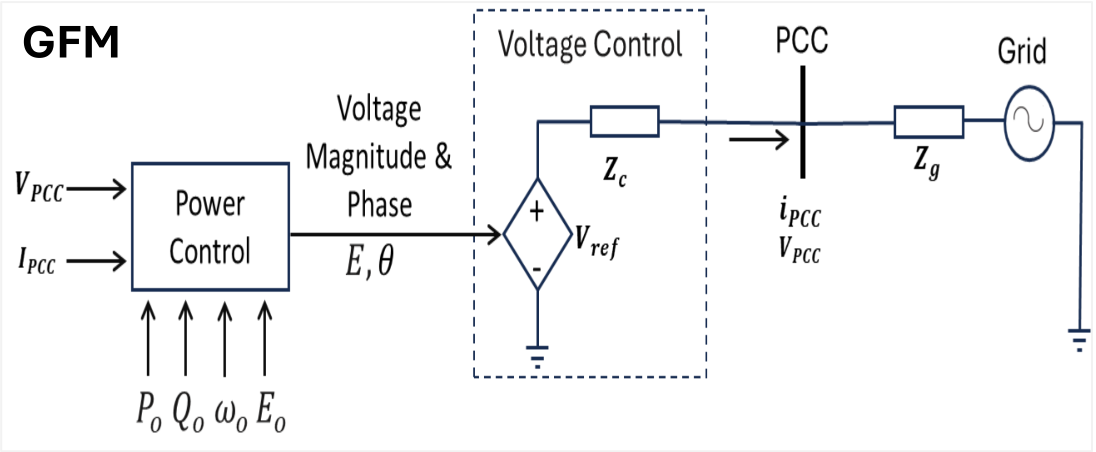
- ➢ Differences mainly in control software; all exhibit voltage-source behaviour
- ➢ Two-layer control: reference generation (slow dynamics) and tracking (fast dynamics)
- ➢ Various combinations create multiple GFM schemes, named by the generation layer

Source: D. B. Rathnayake et al.: "Grid Forming Inverter Modelling, Control, and Applications", IEEE Access, Volume 9, August 2021.

And other evolving controls.....

Grid Forming Inverter (GFM) vs Grid Following Control (GFL)





GFL		GFM
➢ Voltage Source Converter	=	➢ Voltage Source Converter
➢ Adjusts the terminal voltage through PWM	=	➢ Adjusts the terminal voltage through PWM
➢ **Control objective:** Inverter current magnitude for achieving desired "P" and "Q"	≠	➢ **Control objective:** To achieve AC voltage, phase angle and frequency
➢ **Reference for controllers:** Phase angle evaluated by PLL to remain synchronized	≠	➢ **Reference for controllers:** Internal phase angle generation
➢ Current Source Behaviour	≠	➢ Voltage Source Behaviour*

*until the current limit of the hardware devices is reached

Behaviour during fault conditions??

Challenges With High RE Penetration

Frequency Support

- Increasing Rate of Change of Frequency (RoCoF)
- Decreasing nadir frequency
- Excessive frequency deviations

Voltage Support

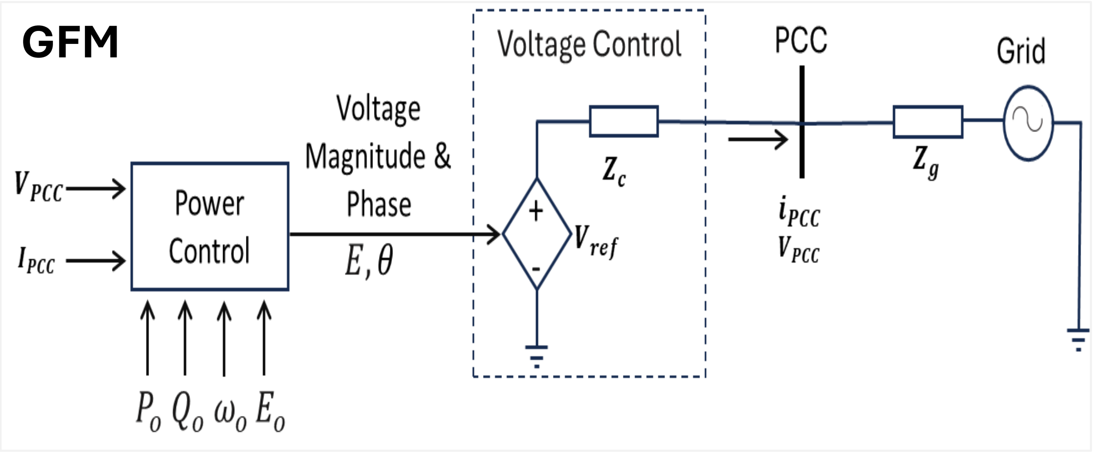
- Static reactive power balance
- Dynamic reactive power balance
- Larger voltage dips

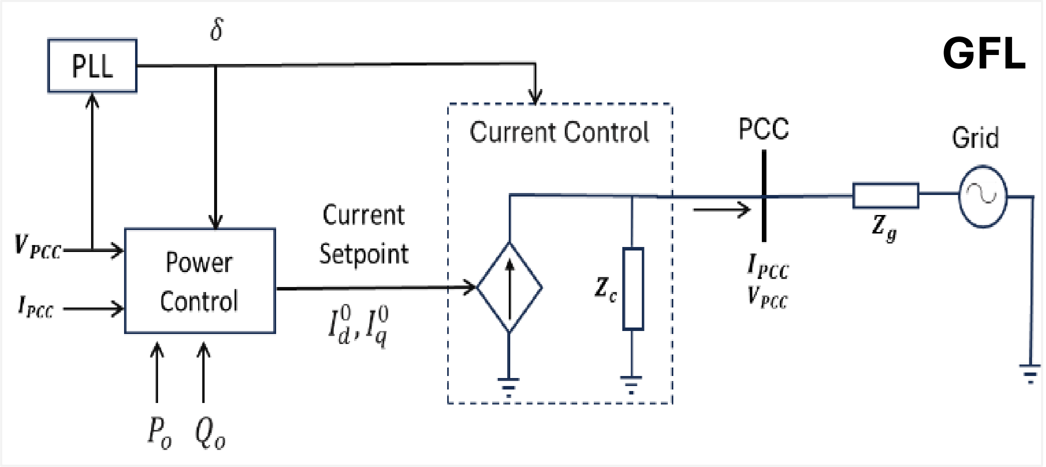
New Behavior of the Power System

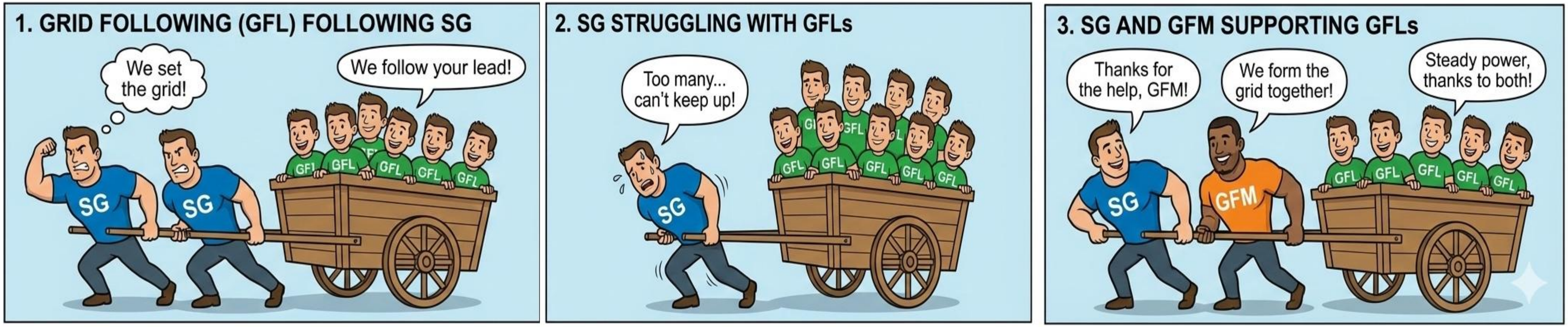
- Fault ride through failures
- Decreased damping
- Oscillations
- Control of bi-directional flows
- Lack of power system restoration sources

Bulk of essential reliability services such as inertia, frequency, and voltage control, system restoration support, power oscillation damping, short-circuit power, etc. were being provided by conventional generation sources

Grid Forming Inverter (GFM) vs Grid Following Control (GFL)







AI Generated Image: Analogy of a stable inverter-dominated grid: adding GFM inverters as new anchors restores platform stability

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Available Resources to learn more about Grid Forming Inverters

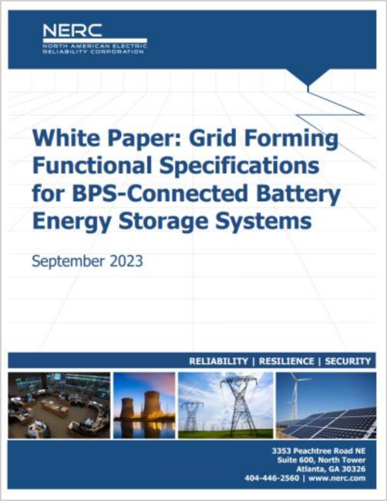

Research Roadmap on Grid-Forming Inverters

NREL

Yashen Lin, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, and Abraham Ellis

With editing and support from Hariharan Krishnaswami, Jeremiah Miller, and Guohui Yuan

Link


NERC

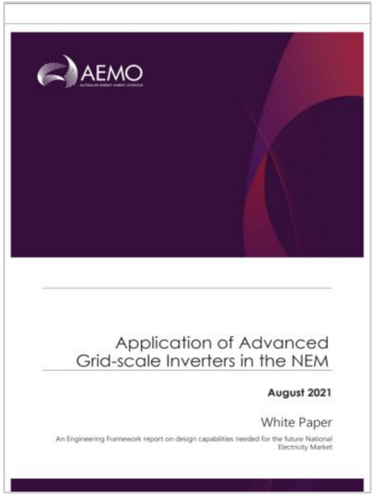
White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

September 2023

RELIABILITY | RESILIENCE | SECURITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Link


AEMO

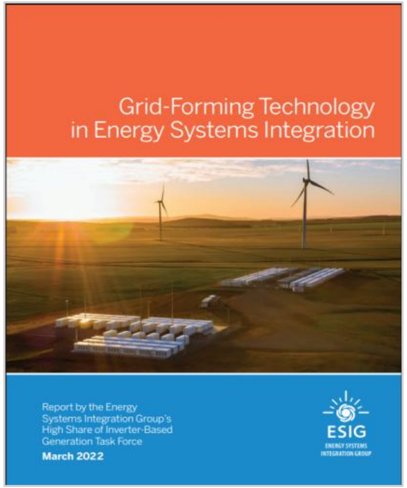
Application of Advanced Grid-scale Inverters in the NEM

August 2021

White Paper

An Engineering Framework report on design capabilities needed for the future National Electricity Market

Link

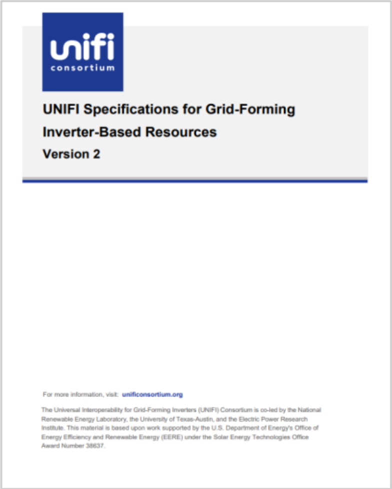

Grid-Forming Technology in Energy Systems Integration

Report by the Energy Systems Integration Group's High Share of Inverter-Based Generation Task Force

March 2022

ESIG

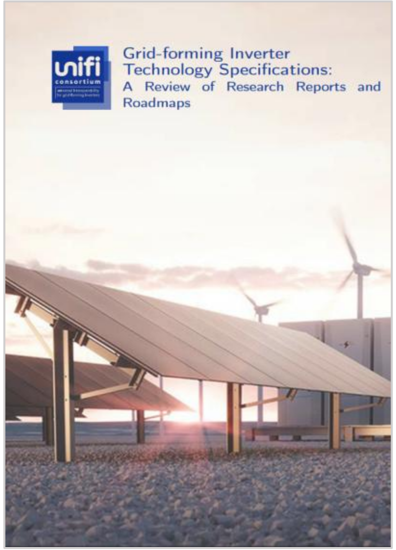
Link


unifi consortium

UNIFI Specifications for Grid-Forming Inverter-Based Resources

Version 2

Link


unifi consortium

Grid-forming Inverter Technology Specifications: A Review of Research Reports and Roadmaps

Link

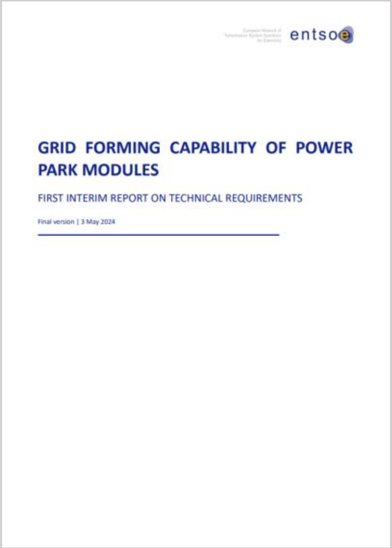

Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework

January 2024

AEMO

A set of simulation test methods to guide the assessment of a grid-forming inverter's compliance to the core capabilities in AEMO's May 2023 'Voluntary Specification for Grid-forming Inverters'

Link


entsoe

GRID FORMING CAPABILITY OF POWER PARK MODULES

FIRST INTERIM REPORT ON TECHNICAL REQUIREMENTS

Final version | 3 May 2024

Link


EPRI

TECHNICAL BRIEF

Grid-Forming Inverter Fundamentals and FAQs

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INTRODUCTION

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EPRI

Grid Forming Inverters

EPRI Tutorial (2025)

Advanced Grid Support/Grid Forming Controls

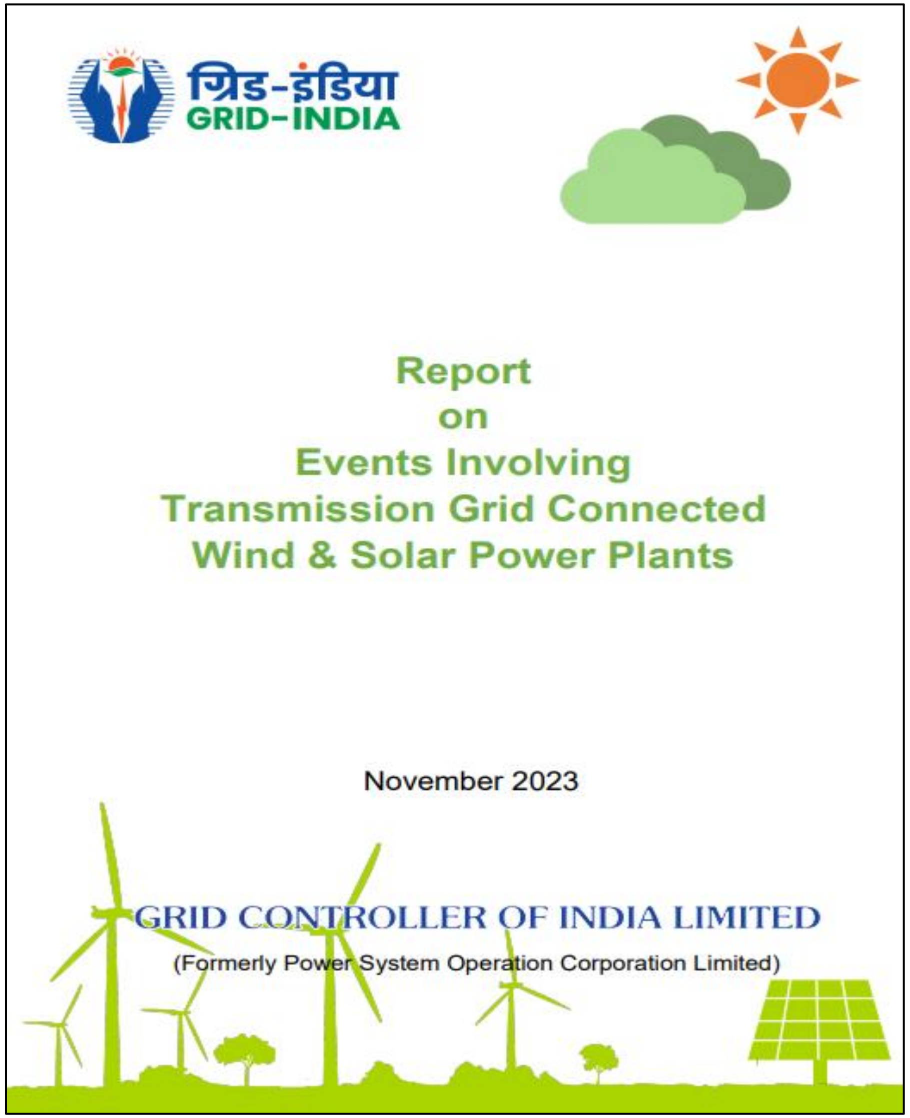
Project Managers
W. Wang and D. Ramasubramanian
3002033960
October 2025

www.epri.com

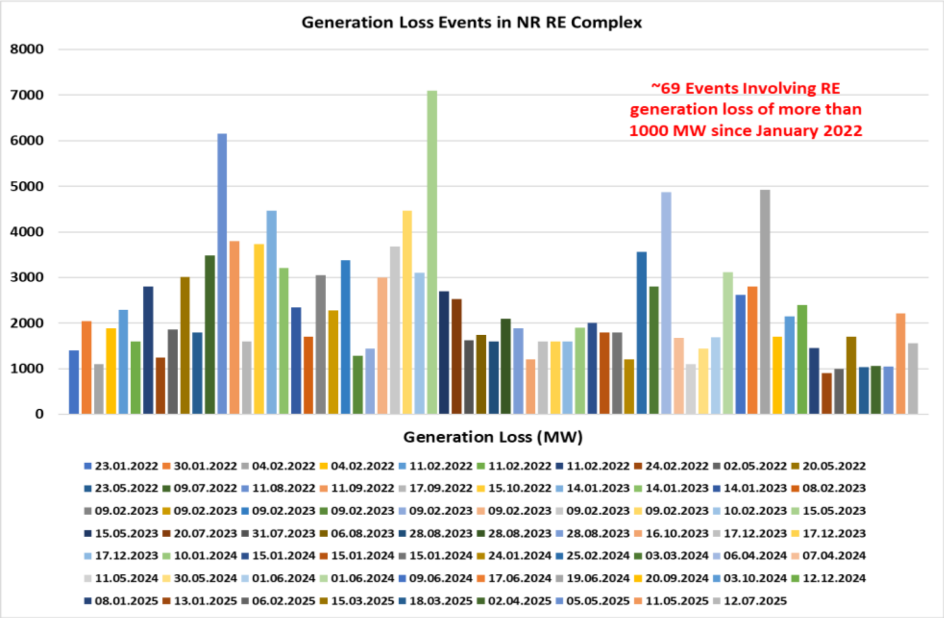
Link

Contents

Major Grid Events in RE Complexes in India



1. **~69 events involving RE generation** loss of above **1000 MW** between Jan’22 to Oct’25
   - Fault-ride through failure of the RE plants observed
2. **Forced low frequency (voltage and reactive power) oscillations** in large RE complexes
   - Low system strength in remote RE pockets; Controller tuning challenges



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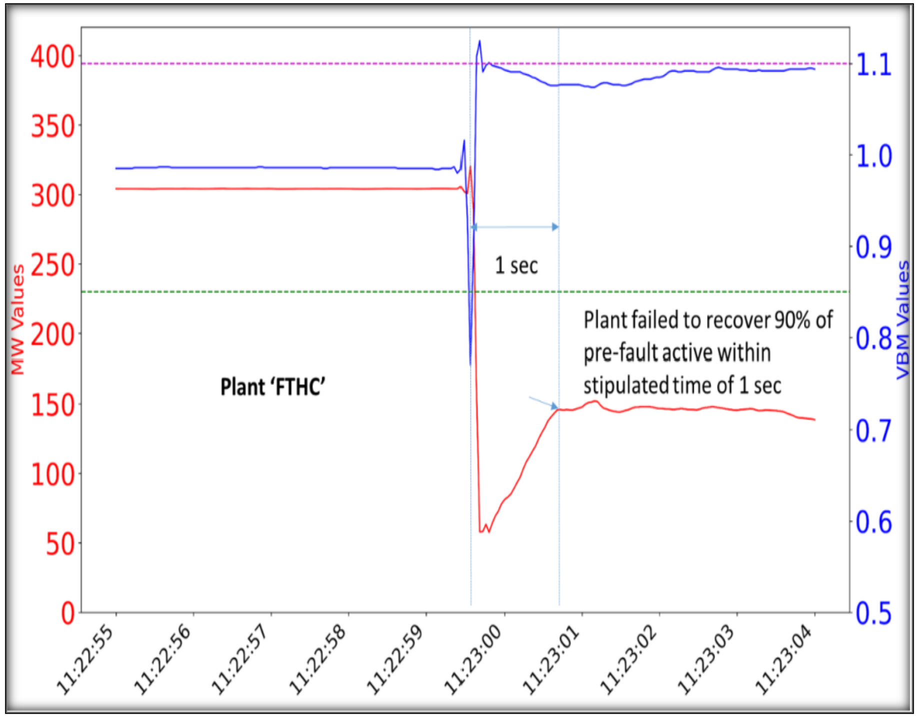
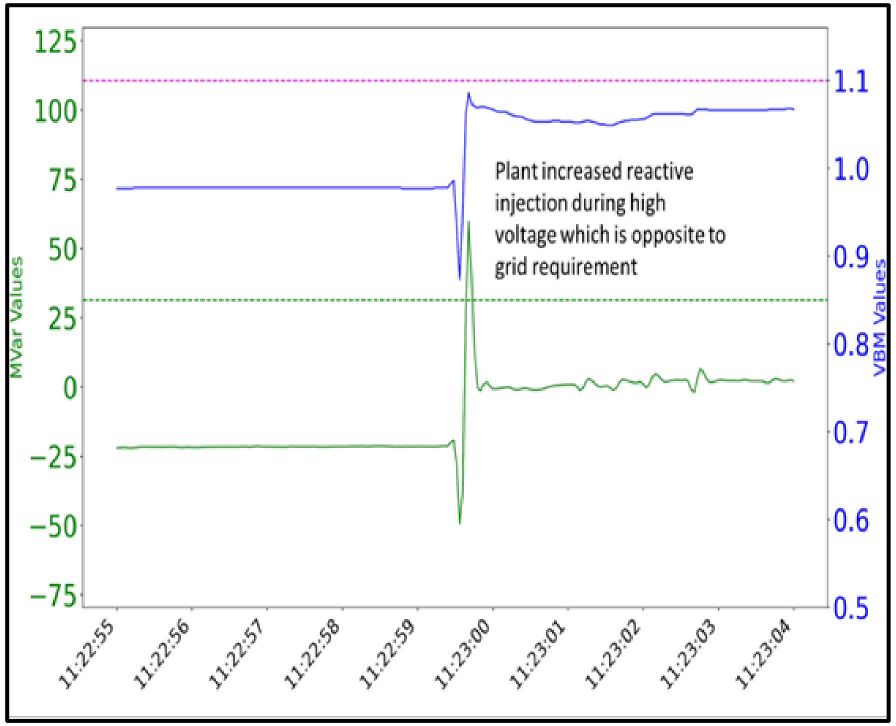
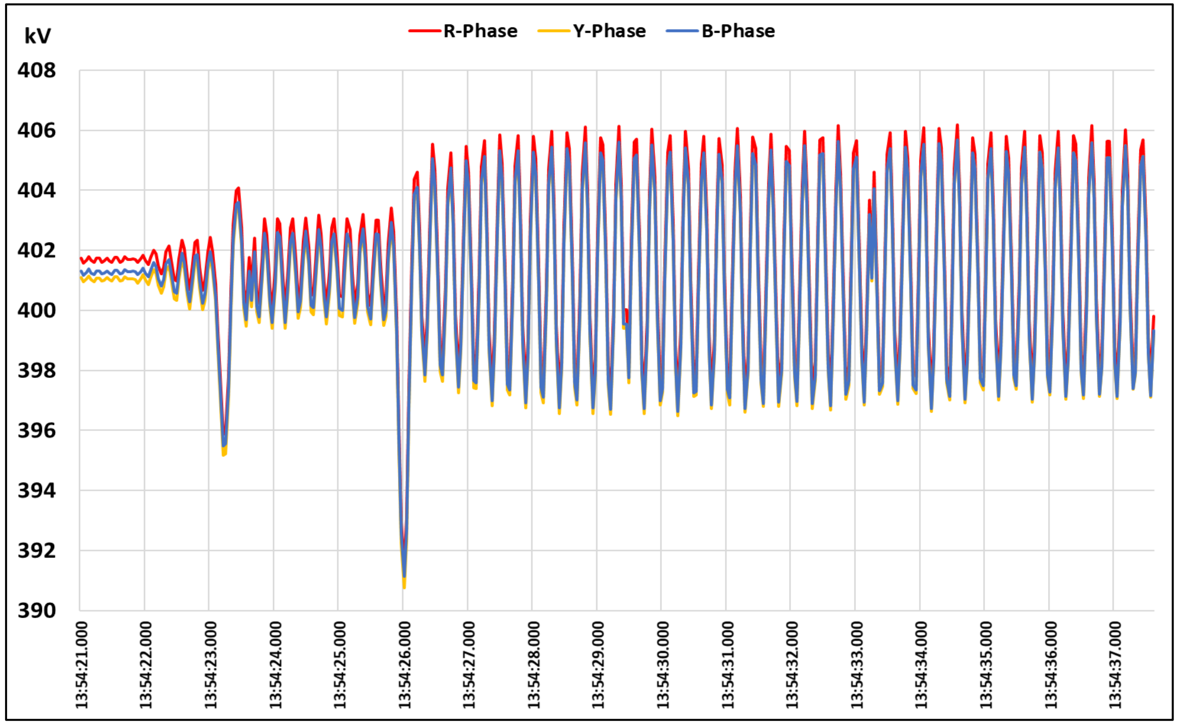
Issues Observed During Fault Ride Through

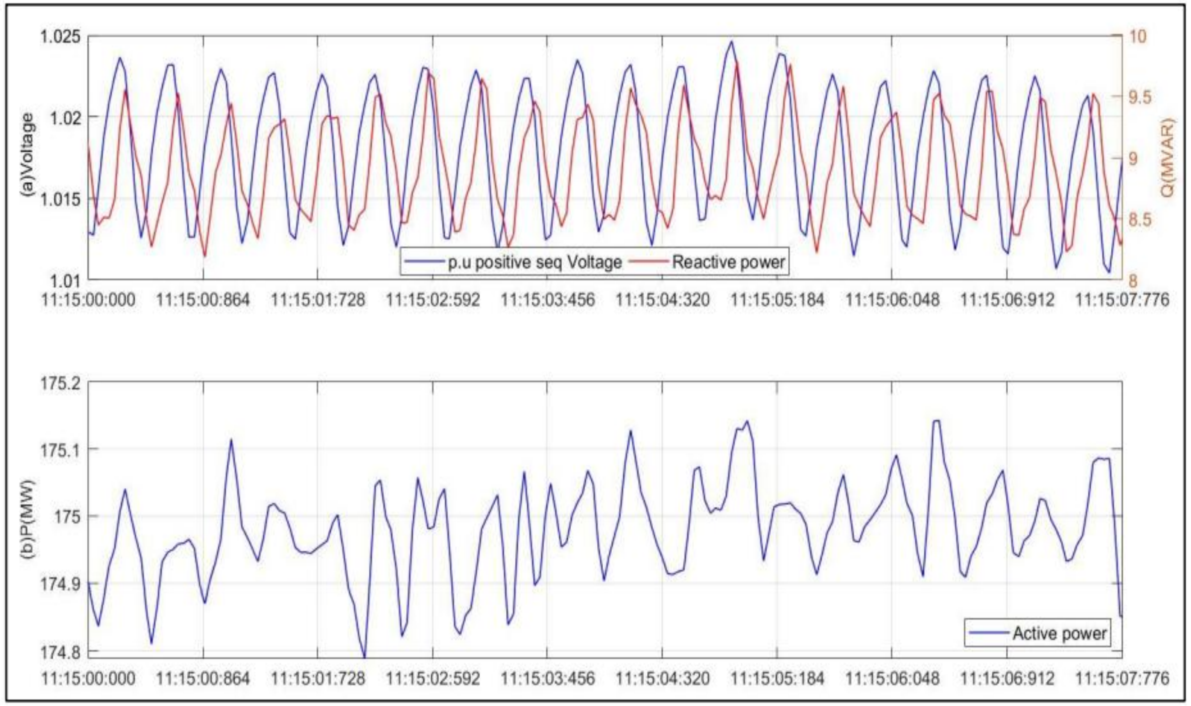




- ➢ Reduction of active power by the RE plants during fault to accommodate reactive power injection
- ➢ Inadequate and delayed reactive power support during ride through conditions
- ➢ Delayed active power recovery post-fault-clearance
- ➢ High voltage post-fault clearance leading to tripping of inverters on HVRT and transmission lines on over-voltage

Low Frequency Oscillations

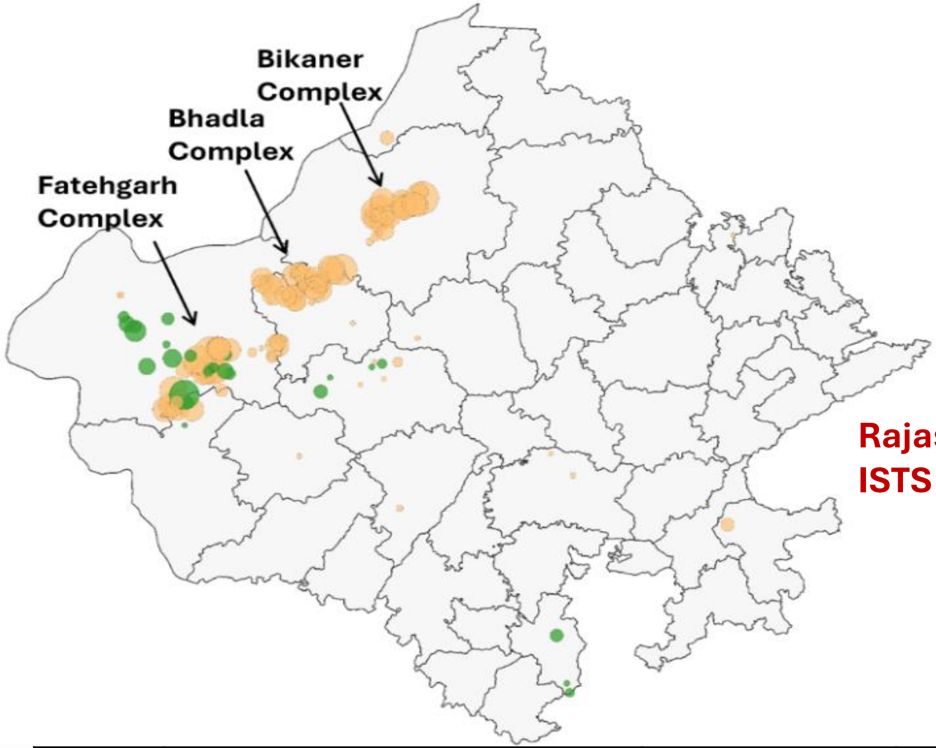




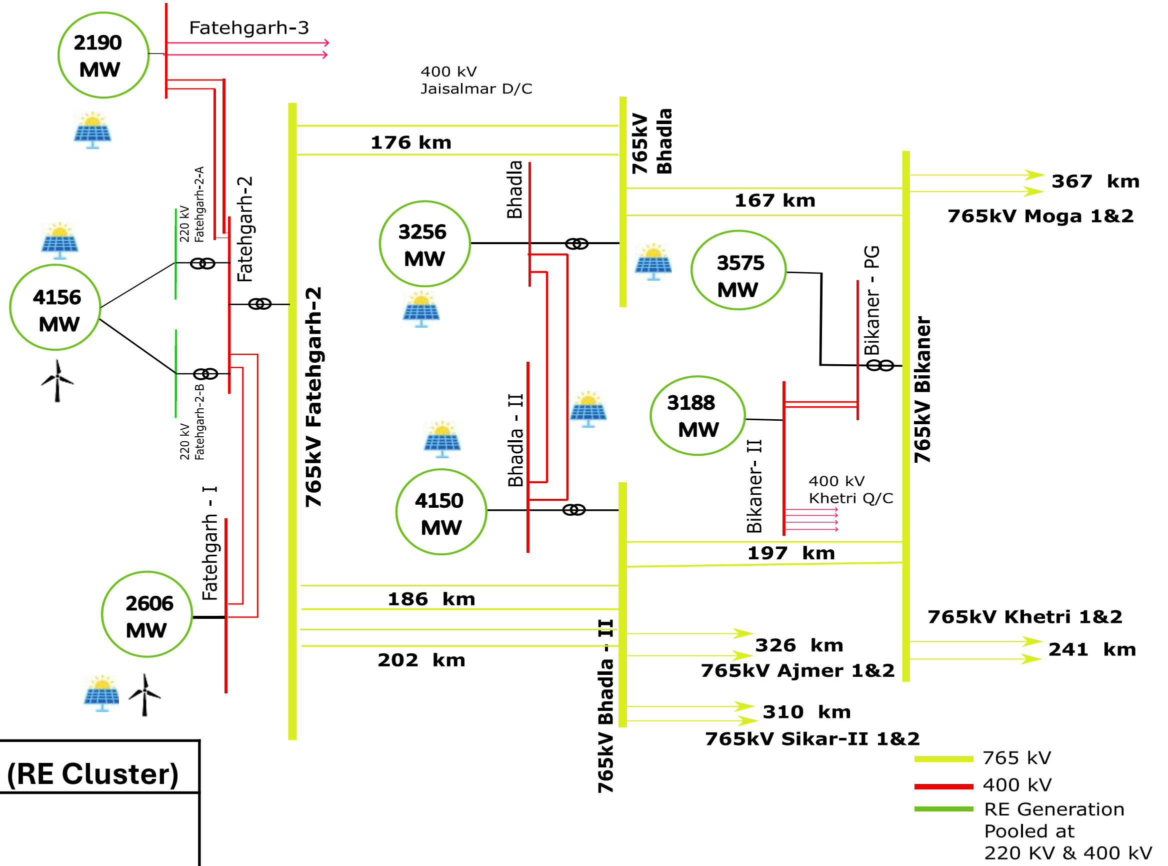
- **Oscillations appearing without any trigger event**
- **Predominantly reflected in bus voltage and reactive power**
- **Modes: Low-Frequency Oscillations:** 0.1 - 0.2 Hz
- **Modes: High-Frequency Oscillations:** 3.5 - 5 Hz - amplitude of these oscillations gets enhanced after interaction with STATCOMs in the RE complex
- **Major reasons:** Delay in communication from PPC to IBRs, Improper tuning of controllers, Low system strength

Contents

All India Simulation Study: Rajasthan ISTS RE Complex



Rajasthan: 3 Prominent ISTS RE Complexes



S. No.	Pooling Station Name	RE Complex	Installed RE Capacity in MW (RE Cluster)
1	Fatehgarh – I	Fatehgarh	8952
2	Fatehgarh – II		
3	Fatehgarh – III		
4	Bhadla – I	Bhadla	7406
5	Bhadla – II		
6	Bikaner – I	Bikaner	6763
7	Bikaner - II		

As on 31st July 2025

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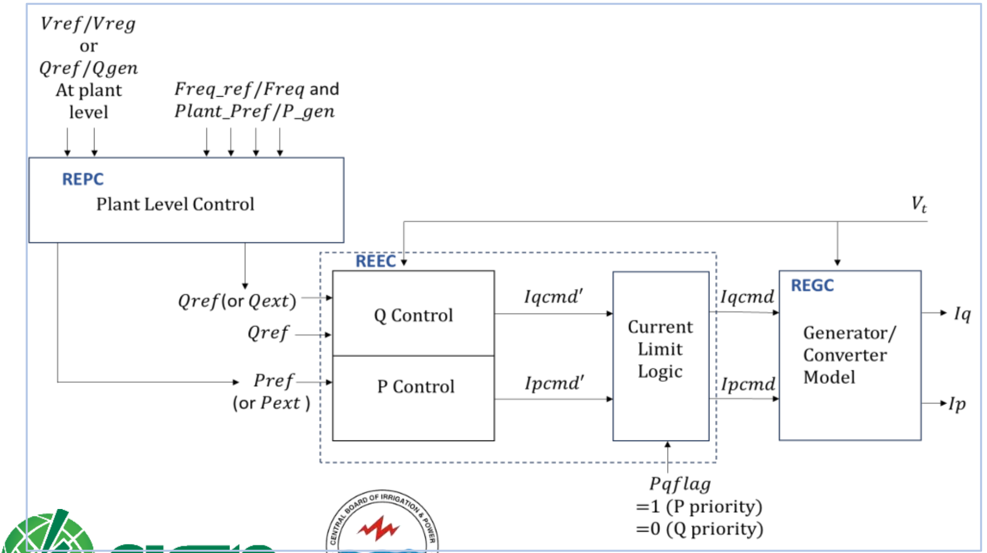
All India Simulation Study: Modelling Philosophy

a) The latest all-India simulation base case (~14500 buses) has been considered for the study.

b) Dynamic models of all the synchronous generators of the capacity of more than 100 MVA, all the HVDC links, STATCOMs and ISTS RE plants have been considered in the dynamic case.

Details of RE Models Used in Study				
S. No.	**Type**	**Generator Model**	**Electrical Control Model**	**Plant Controller**
1	**Grid Following**	REGC_A / B **REGC_C**	REEC_A	REPC_A
2	**Grid Forming**	**REGFM_A1**	Coupled with the generator model	REPC_A



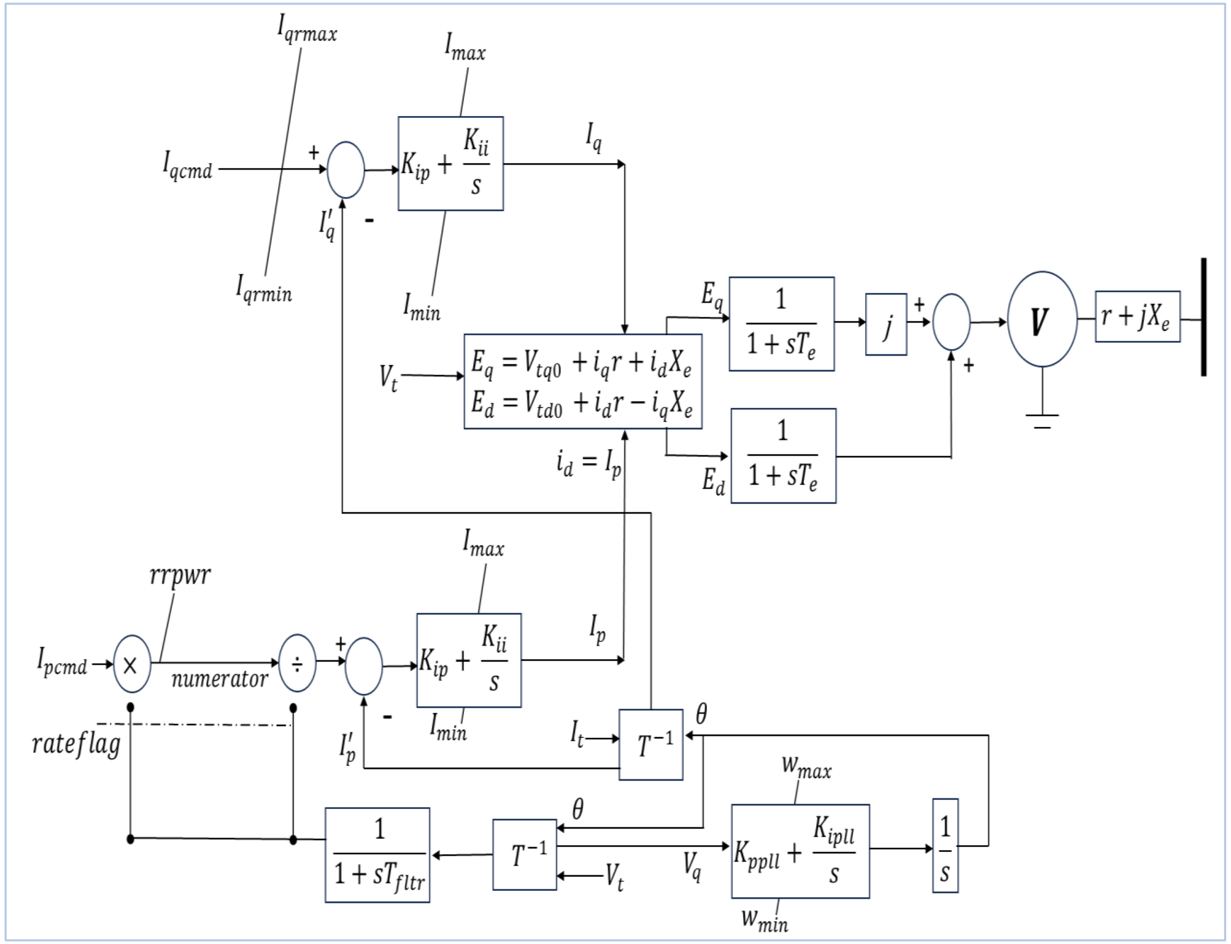
REGC_C

- Developed and released around 2019-20
- Voltage-source interface model
- **Includes a generic representation of the inner current loop and PLL phenomenon**
- Better numerical stability than REGC_A

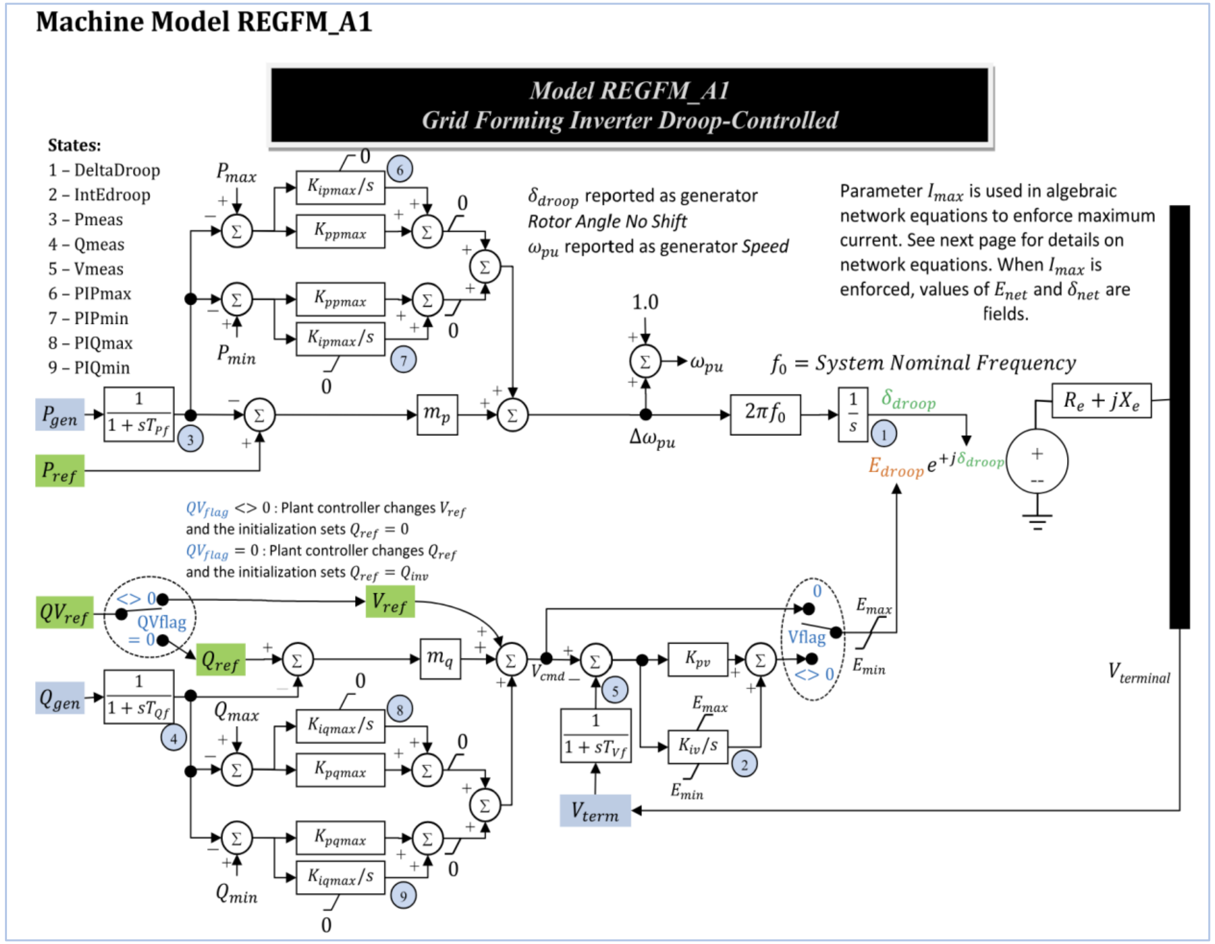
REGFM_A1 - Droop control based GFM model released in 2023-24

Models submitted by vendors have been used in the study to the extent possible. Wherever, models were not available, suitable parametrization has been carried out in standard generic models

All India Simulation Study: Modelling Philosophy



Control block diagram of GFL Generator Model – REGC_C



Control block diagram of GFM Droop-Based Model – REGFM_A1

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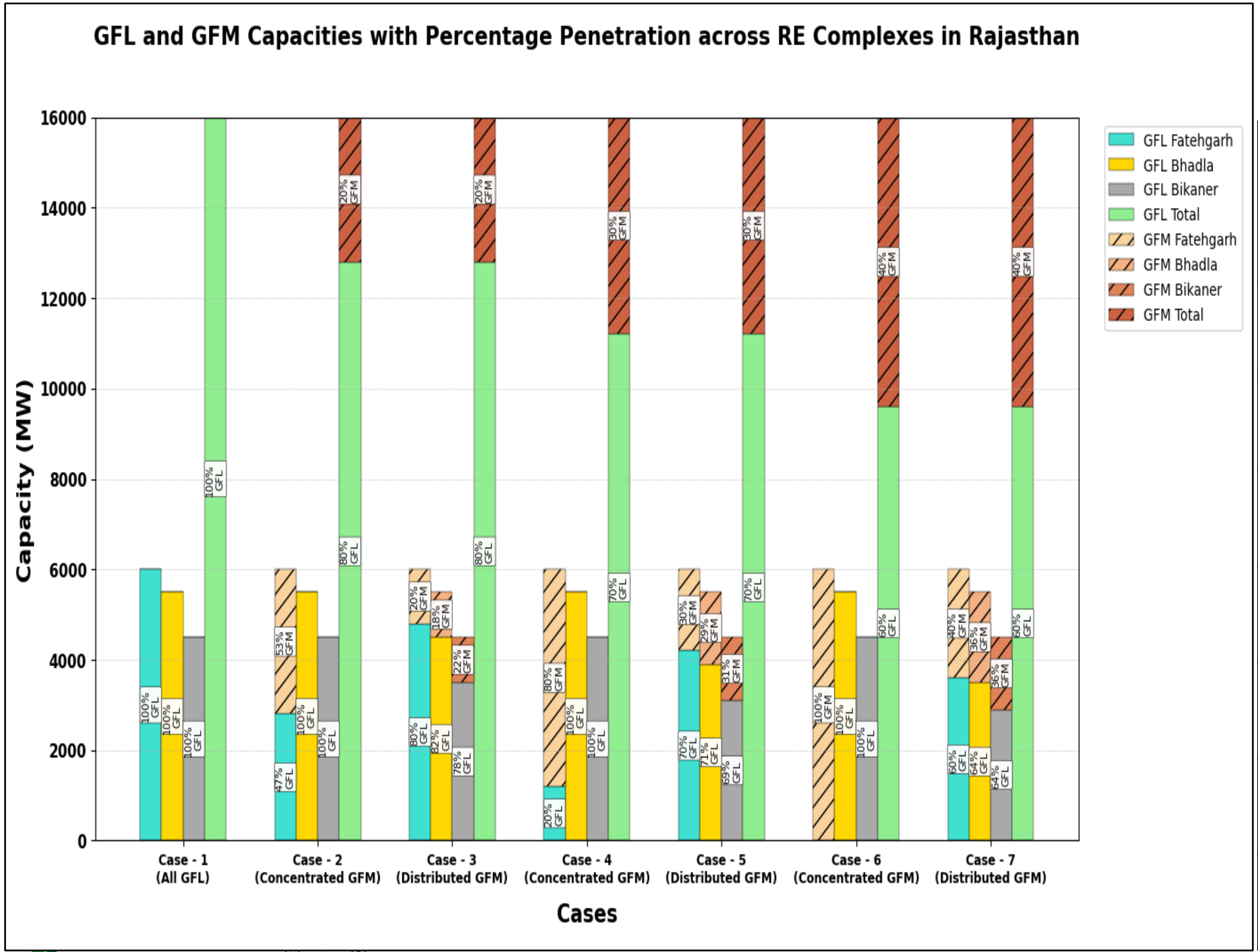
All India Simulation Study: Study Case Scenarios

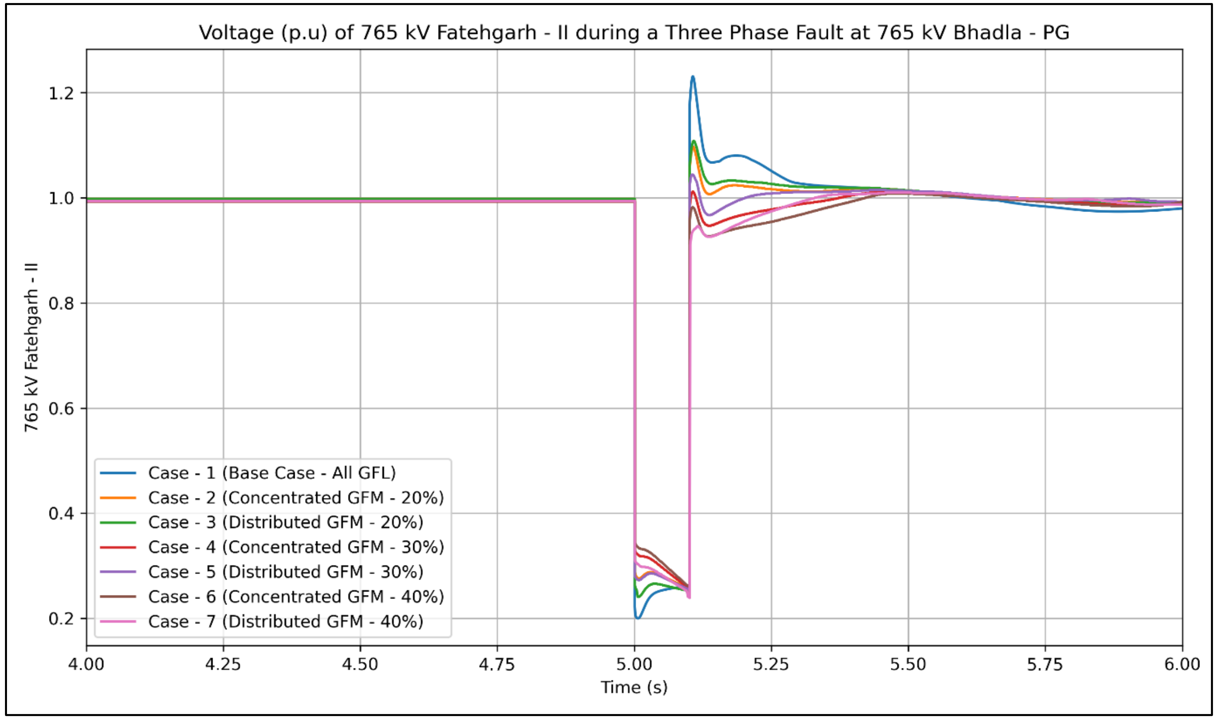


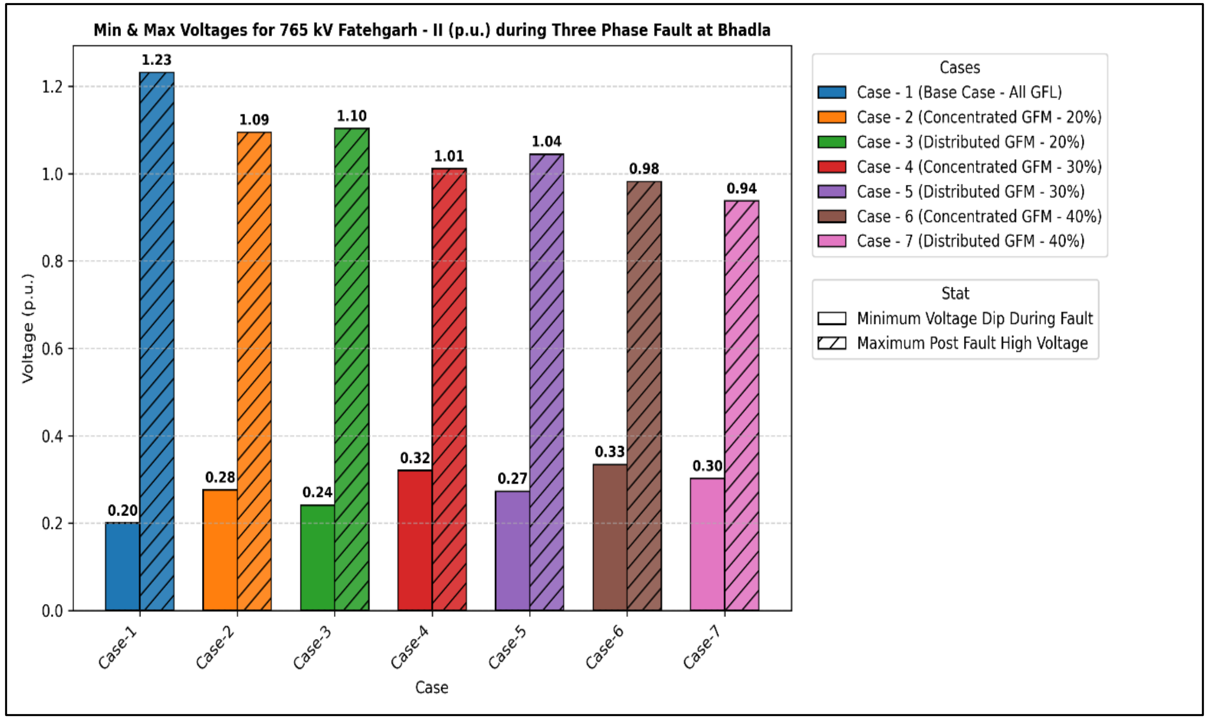
Seven GFM/GFL penetration configurations are evaluated across **three** RE complexes, comparing **two** (concentrated and distributed) GFM deployment strategies

Cases for Study	Fatehgarh Complex		Bhadla Complex		Bikaner Complex		Total Rajasthan RE Complex	
	% GFL	% GFM	% GFL	% GFM	% GFL	% GFM	% GFL	% GFM
Case - 1 (Base Scenario)	100%	0%	100%	0%	100%	0%	100%	0%
Case - 2 (Concentrated GFM)	47%	53%	100%	0%	100%	0%	80%	20%
Case - 3 (Distributed GFM)	80%	20%	82%	18%	78%	22%	80%	20%
Case - 4 (Concentrated GFM)	20%	80%	100%	0%	100%	0%	70%	30%
Case - 5 (Distributed GFM)	70%	30%	71%	29%	69%	31%	70%	30%
Case - 6 (Concentrated GFM)	0%	100 %	100%	0%	100%	0%	60%	40%
Case - 7 (Distributed GFM)	60%	40%	64%	36%	64%	36%	60%	40%

All India Simulation Study: Results

1. 3-Phase fault in Rajasthan RE Complex: 3 - phase fault at Bhadla PG at t = 5 seconds and simulation run for total 20 seconds

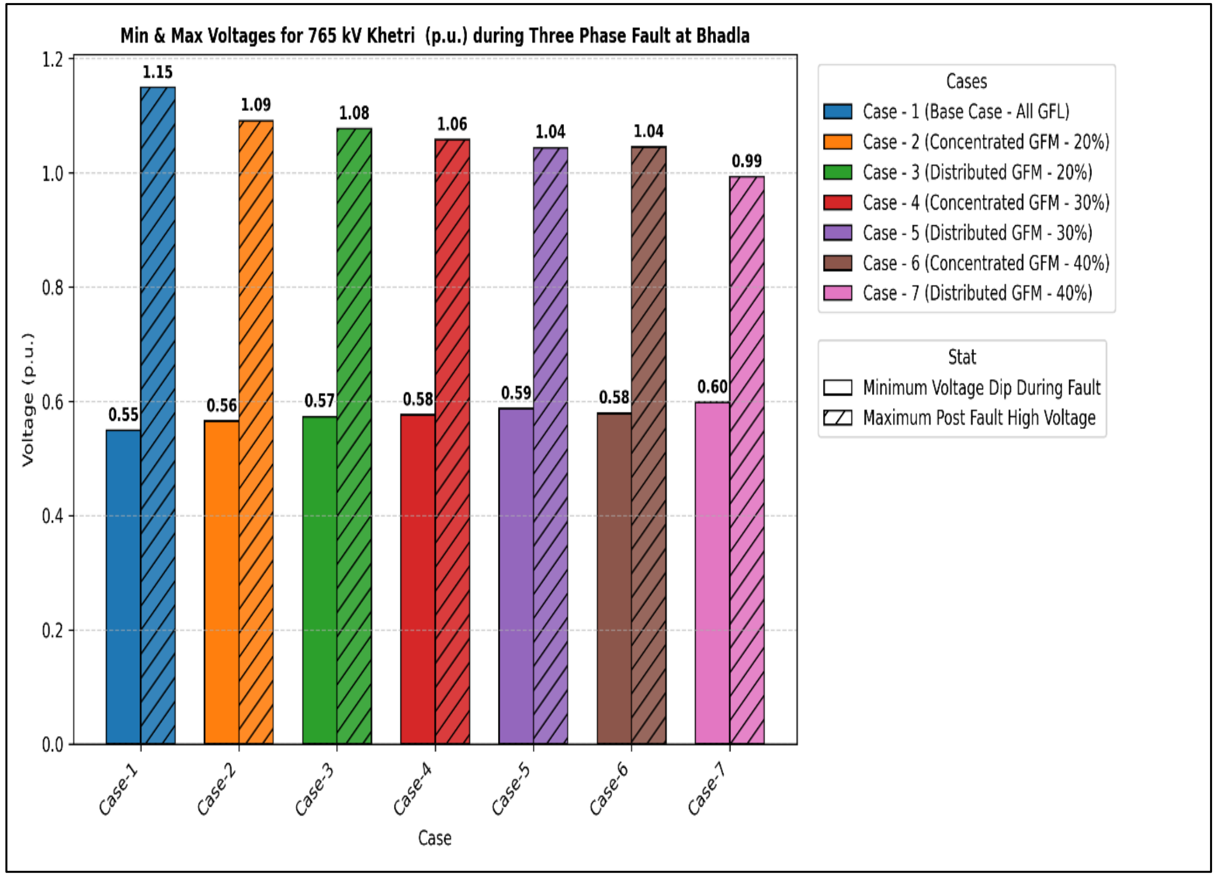


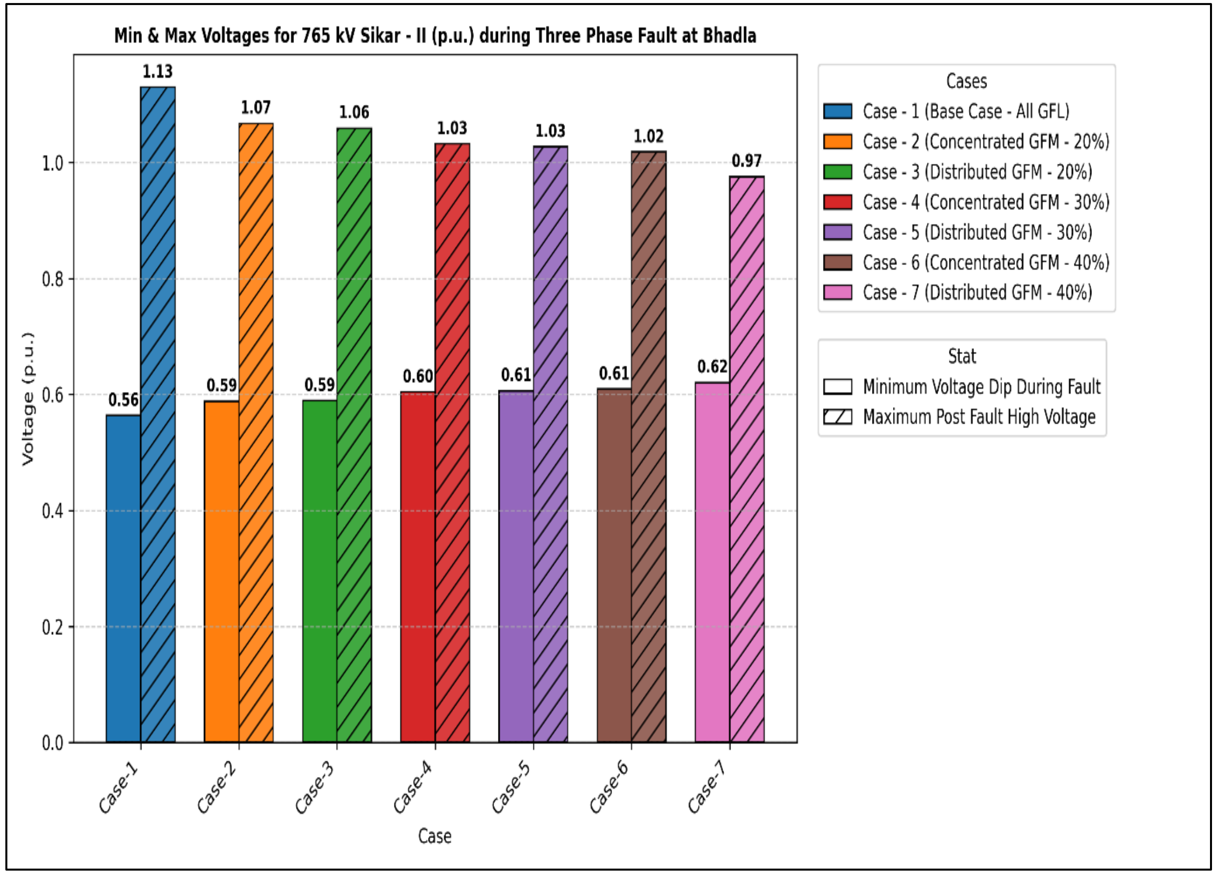


- During **LVRT**, **reactive power is injected by GFL** inverters **proportional to the voltage dip (ΔV)** and the K-factor; **weak system strength** amplifies this effect.
- With **GFM deployment**, **droop control** regulates the inverter **internal voltage** and **prevents post-fault overvoltage**.
- **Voltage dip** during a fault is **reduced where GFMs are present**.
- Best improvement at Fatehgarh-II is observed for concentrated **GFM cases (Case-2, Case-4, Case-6) due to higher local GFM share;**

All India Simulation Study: Results

1. 3-Phase fault in Rajasthan RE Complex: 3 - phase fault at Bhadla PG at t = 5 seconds and simulation run for total 20 seconds





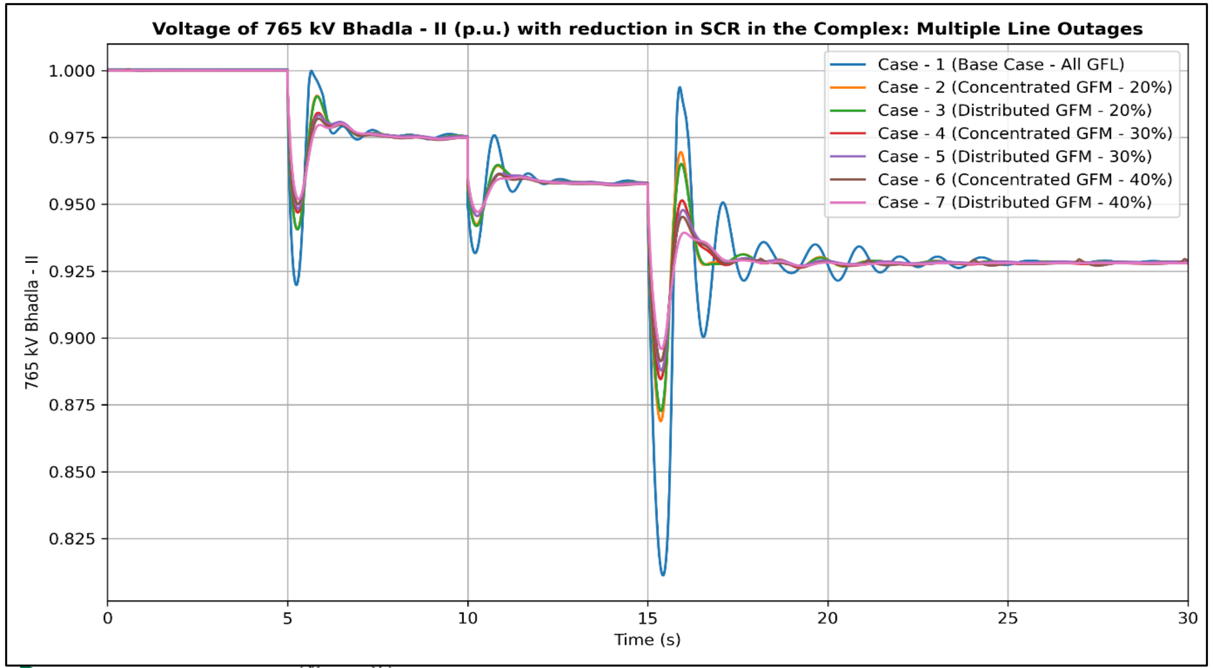
- Buses such as Sikar-II and Khetri show superior voltage profiles when **GFMs are distributed (Case-3, Case-5, Case-7) – System level benefit**

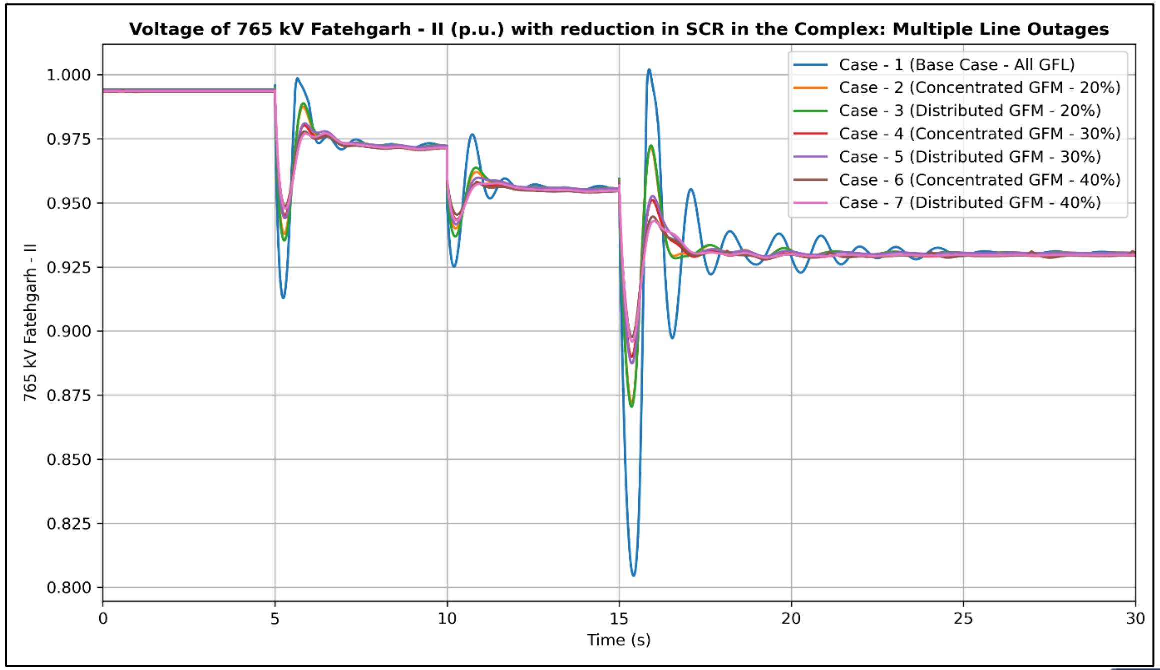
All India Simulation Study: Results

2. SCR Reduction: Multiple Outages in Rajasthan RE Complex

- Disturbance – 1: Outage of 765 kV Bhadla - II - Sikar - II - 1 at t = 5 seconds
- Disturbance – 2: Outage of 765 kV Fatehgarh - II - Bhadla - II - 1 at t = 10 seconds
- Disturbance – 3: Outage of 765 kV Bikaner - Moga - 1 & 765 kV Bikaner - Khetri – 1 at t = 15 seconds

Bus	Base Case	After Disturbance - 1	After Disturbance - 2	After Disturbance - 3
	SCR			
220 kV Fatehgarh -II -A	4.0	3.9	3.8	3.7
220 kV Fatehgarh - II - B	7.0	6.9	6.8	6.7
220 kV Bhadla - PG	4.4	4.3	4.2	4.1





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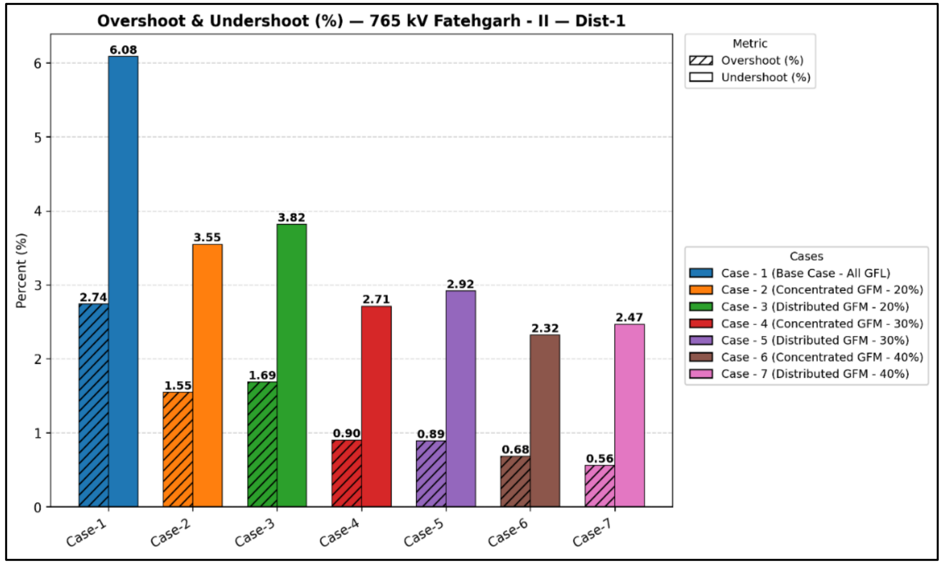
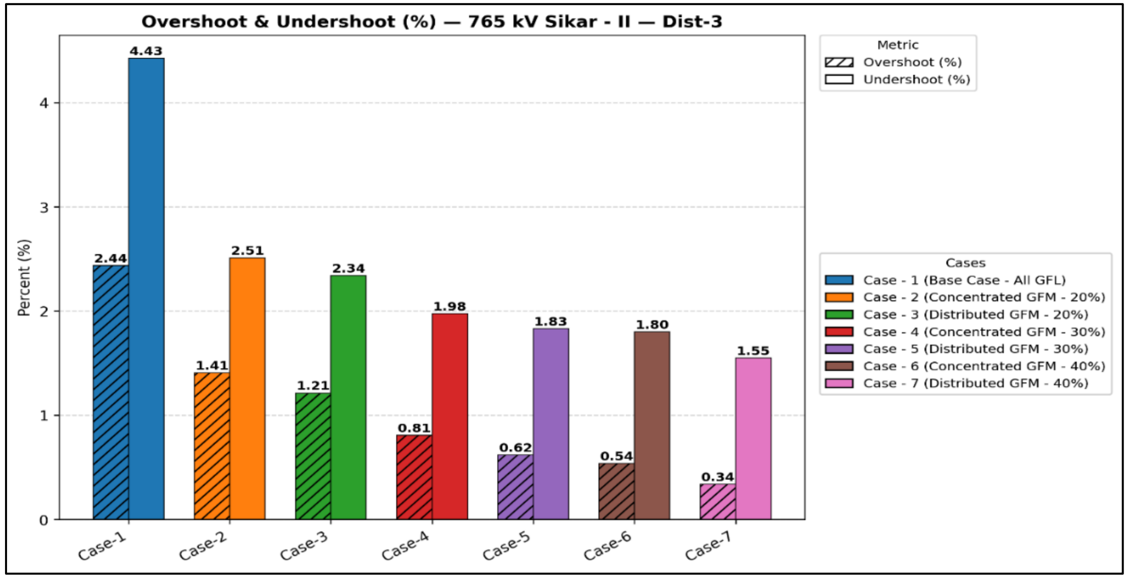
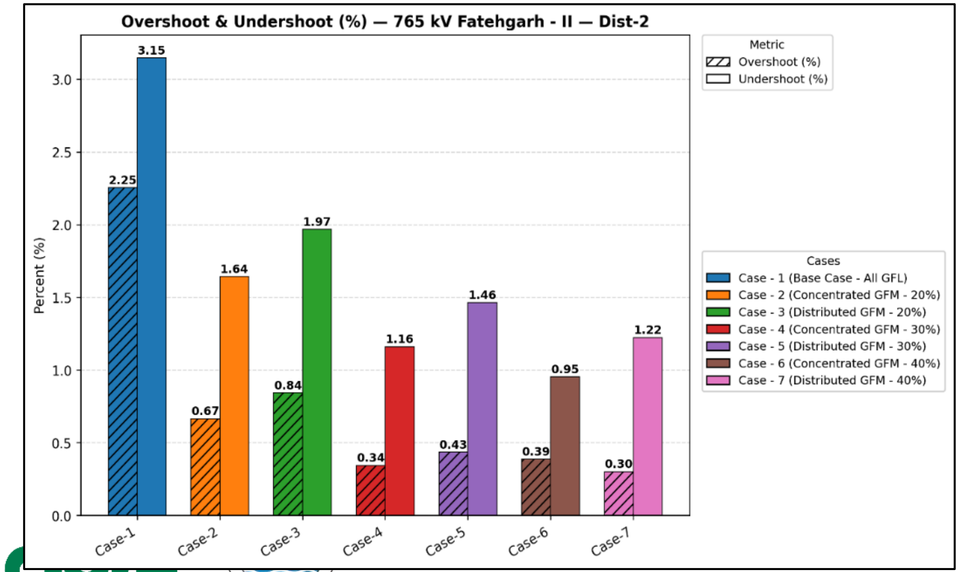
All India Simulation Study: Results

2. SCR Reduction: Multiple Outages in Rajasthan RE Complex





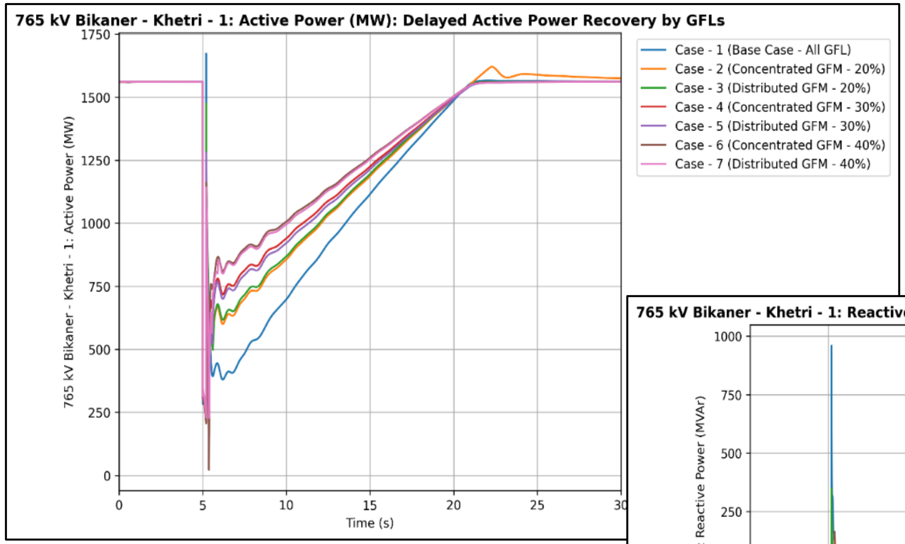


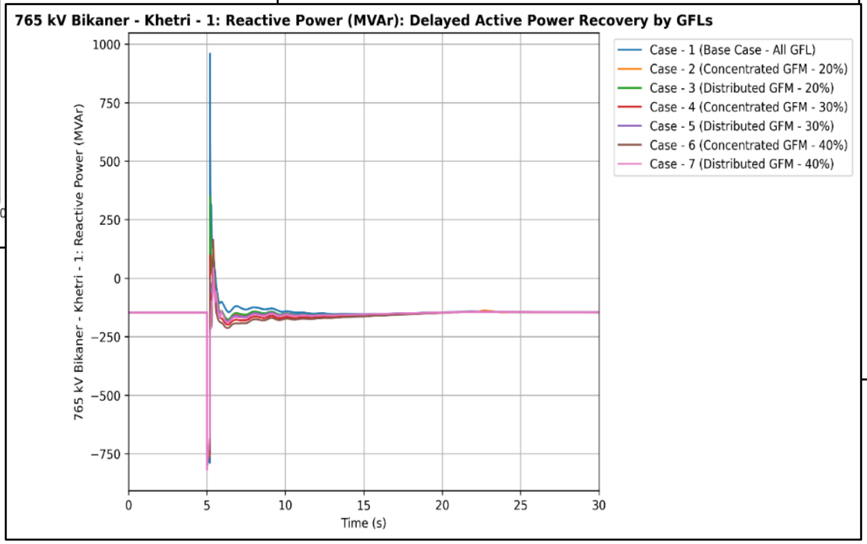
- **Maximum voltage dip** is observed **when only GFL inverters are present** (Case-1).
- **Increasing GFM penetration** has a **minimal impact on steady-state voltage, but significantly improves damping, thereby** reducing voltage oscillations, undershoot, and overshoot.
- **GFM penetration restores reactive power headroom in GFL inverters**, enabling additional reactive support for subsequent disturbances.
- **Best voltage improvement at the Fatehgarh complex is observed with concentrated GFM**, while **better performance at Sikar-II and Khetri is observed with distributed GFM**.

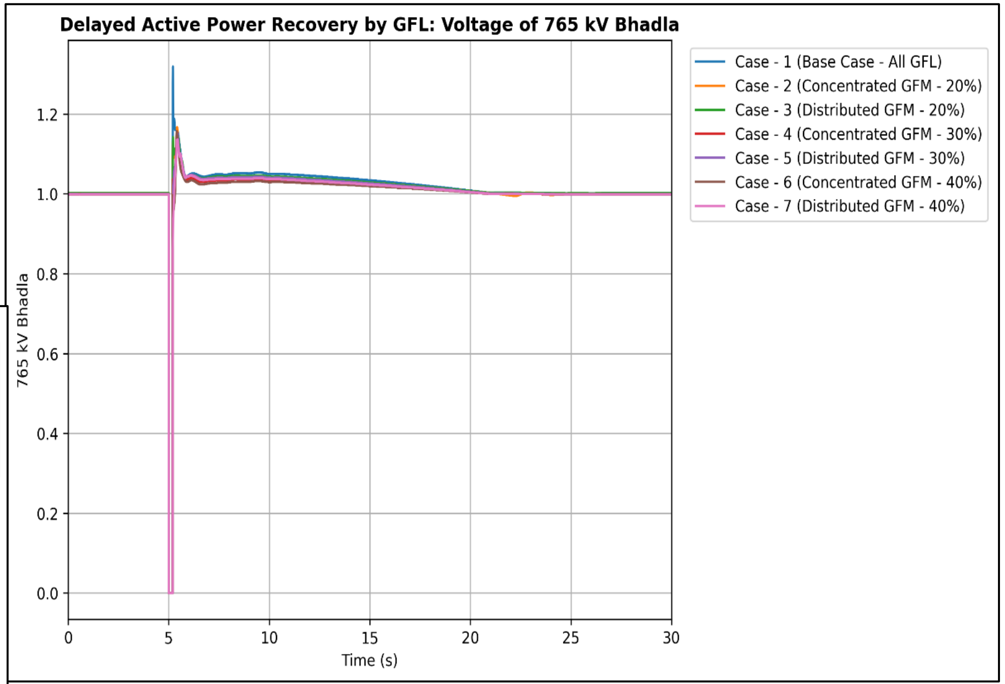
All India Simulation Study: Results

3. Impact of Delayed Active Power Recovery after a Fault

- A 3-phase fault is applied at the 765 kV Bhadla–PG bus at t = 5 s and cleared after 100 ms.
- Post-fault, delayed active power recovery of GFL RE plants is considered, consistent with real-time event observations.
- The delayed recovery is emulated in simulation by intentionally reducing the ramp-rate of GFL plants

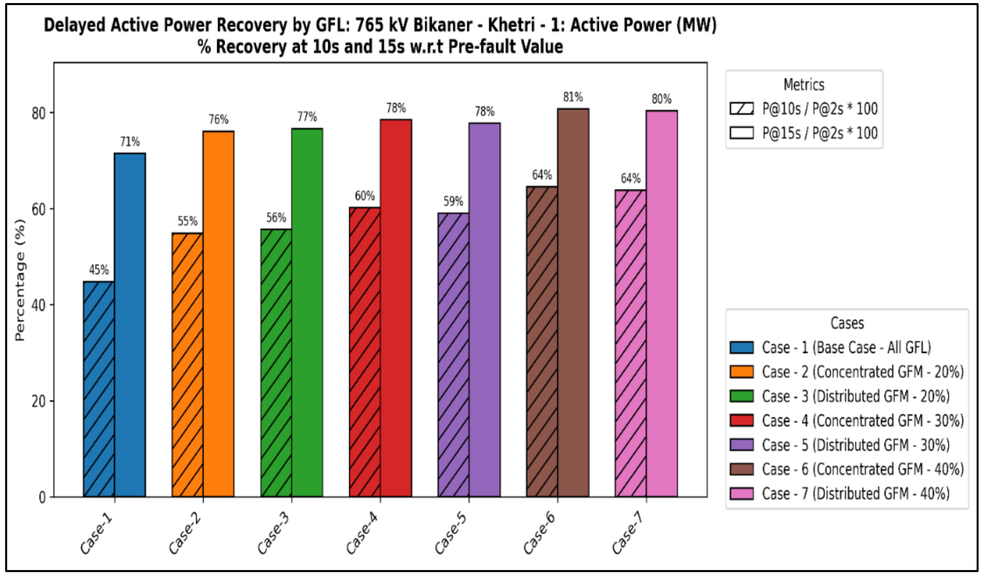


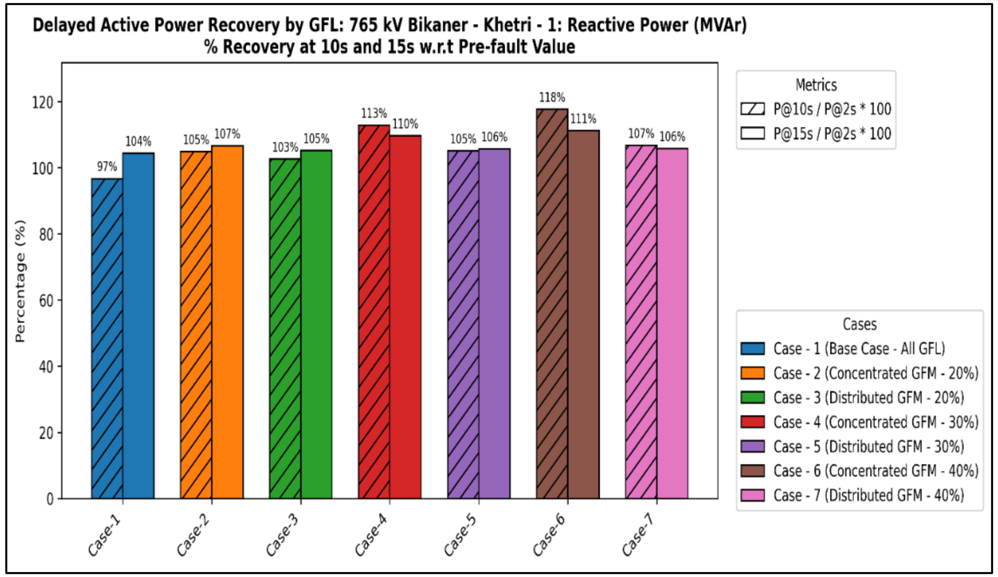


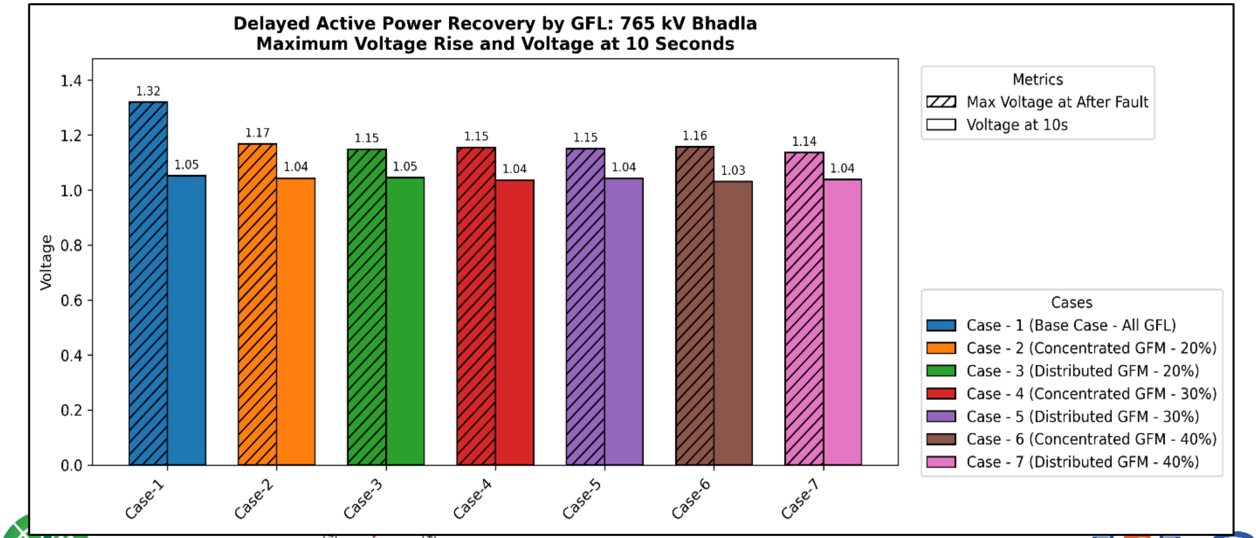


All India Simulation Study: Results

3. Impact of Delayed Active Power Recovery after a Fault





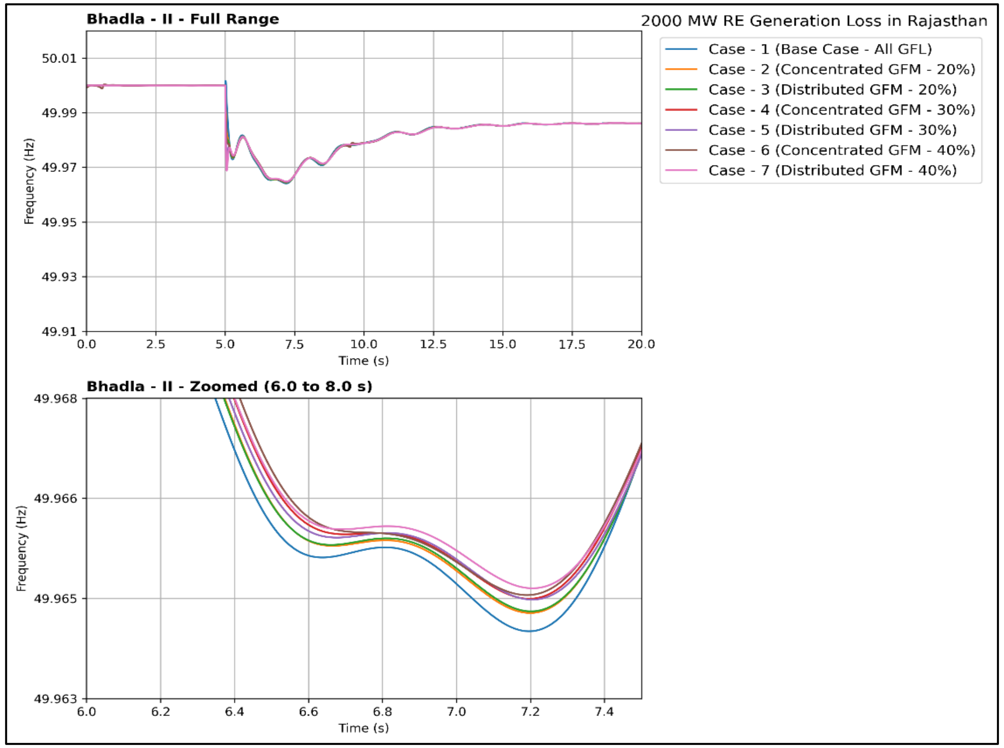


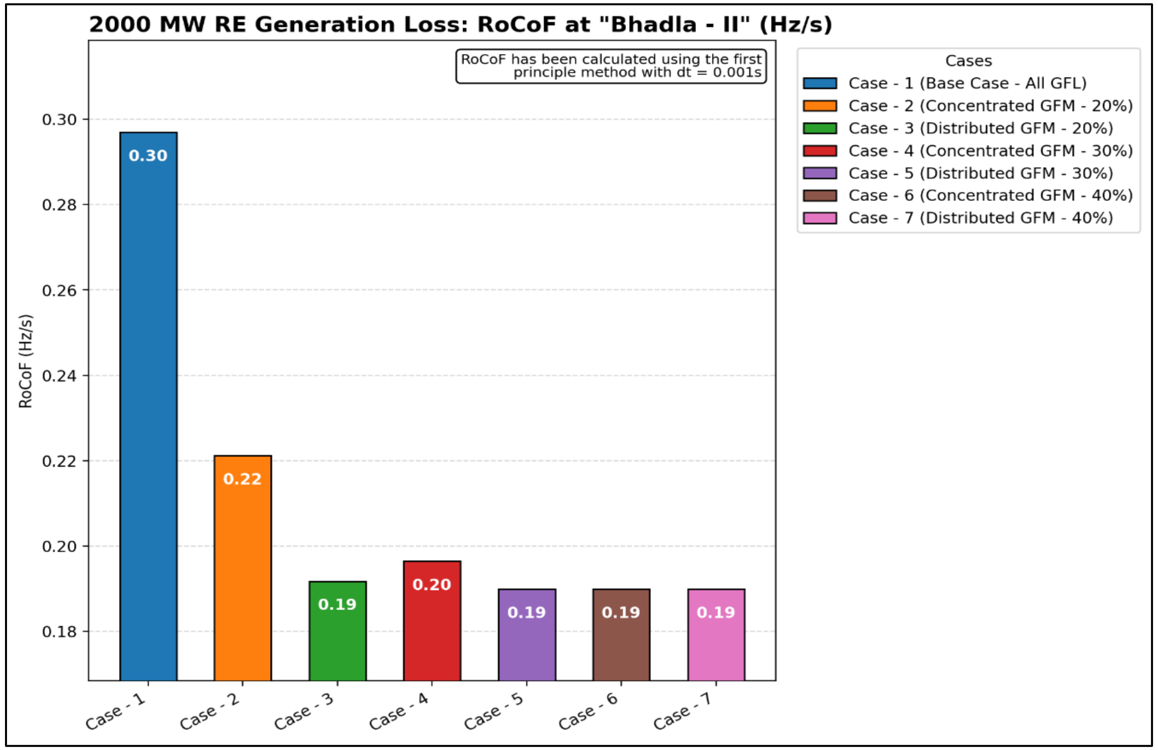
- Delayed active-power recovery leads to lightly loaded EHV lines, excess reactive power, overvoltage, and higher HVRT risk.
- GFMs recover active power instantaneously, improving overall recovery as GFM penetration increases.
- Higher GFM penetration mitigates post-fault overvoltage and accelerates power recovery.

All India Simulation Study: Results

4. Frequency Response Event: Tripping of RE Generators in Rajasthan

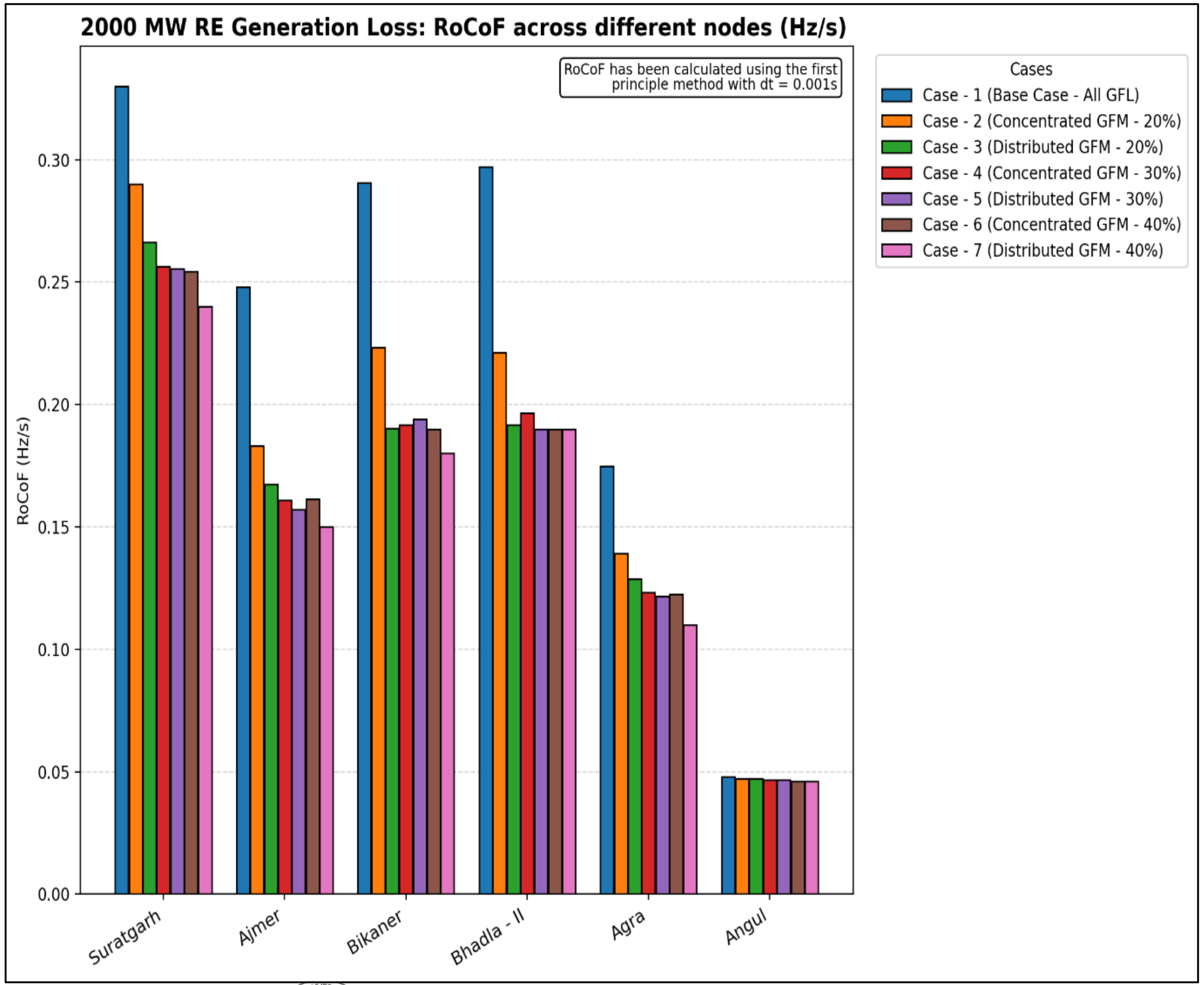
- All GFL and GFM plants are enabled for frequency response through active frequency controllers, supplying power based on available headroom.
- At t = 5 s, 2000 MW of generation is tripped in the Rajasthan RE complex.
- Frequency and RoCoF are monitored at key buses: **Bhadla-II, Bikaner, Ajmer, Suratgarh, Agra, and Angul.**
- Simulated frequency response shows an ideal, high Power Number, unlike practical values in the Indian system.
- RoCoF is computed using the derivative method and is higher near the Rajasthan RE complex than at distant regional buses.





All India Simulation Study: Results

4. Frequency Response Event: Tripping of RE Generators in Rajasthan



- Nadir frequency shows only marginal improvement across cases with higher GFM penetration, as equal active-power headroom is assumed for GFL and GFM.
- Significant improvement is observed in RoCoF, especially at buses close to the Rajasthan RE complex.
- RoCoF impact reduces with distance from the disturbance location.
- Higher GFM penetration significantly lowers the maximum RoCoF near the RE complex.
- Distributed GFM placement further reduces RoCoF at buses such as Bikaner and Ajmer compared to concentrated GFM, due to faster GFM response.

Note: The calculated RoCoF in this case may not be the same as observed by df/dt relays as there are multiple processing units, filters and robust logics for calculating the RoCoF at any point. The maximum RoCoF values plotted below are indication of the inertial strength of the concerned nodes

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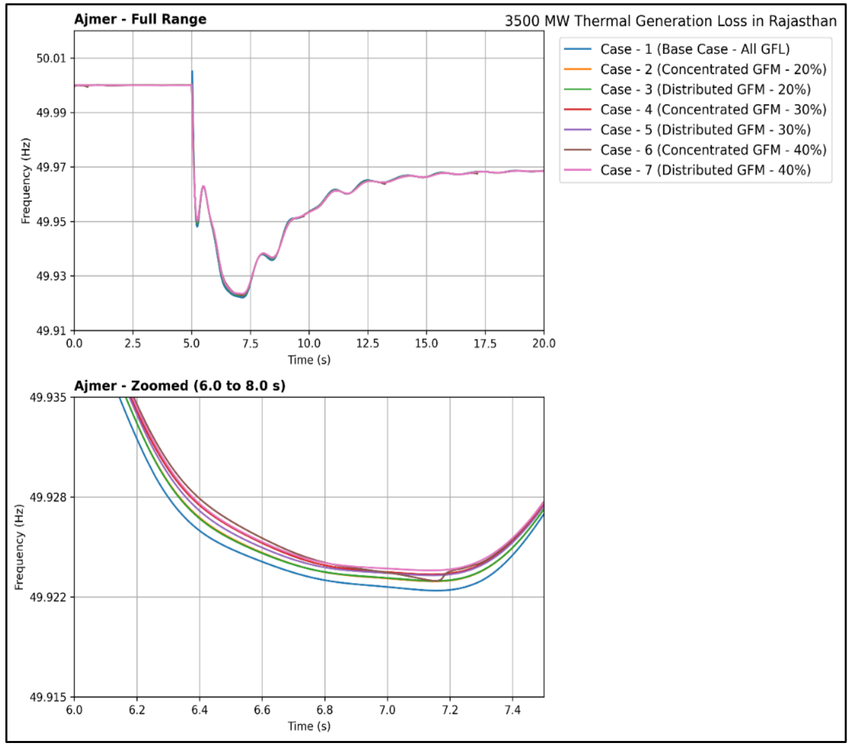
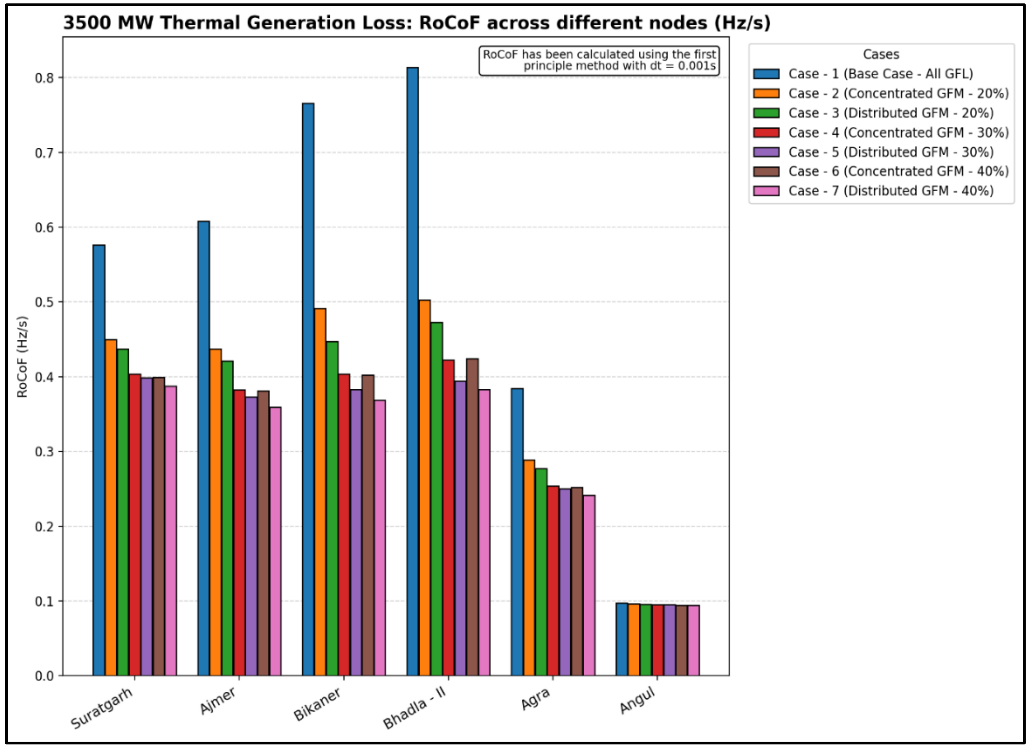
All India Simulation Study: Results

5. Frequency Response Event: Tripping of Synchronous Machines in Rajasthan

- All GFL and GFM plants are enabled for frequency response through active frequency controllers, supplying power based on available headroom.
- At t = 5 s, total 3500 MW of thermal generation in Kawai, Kalisindh, Chhabra & Rajwest thermal plants is tripped in the Rajasthan RE complex.
- Frequency and RoCoF are monitored at key buses: **Bhadla-II, Bikaner, Ajmer, Suratgarh, Agra, and Angul.**
- Simulated frequency response shows an ideal, high Power Number, unlike practical values in the Indian system.
- RoCoF is computed using the derivative method and is higher near the Rajasthan RE complex than at distant regional buses.



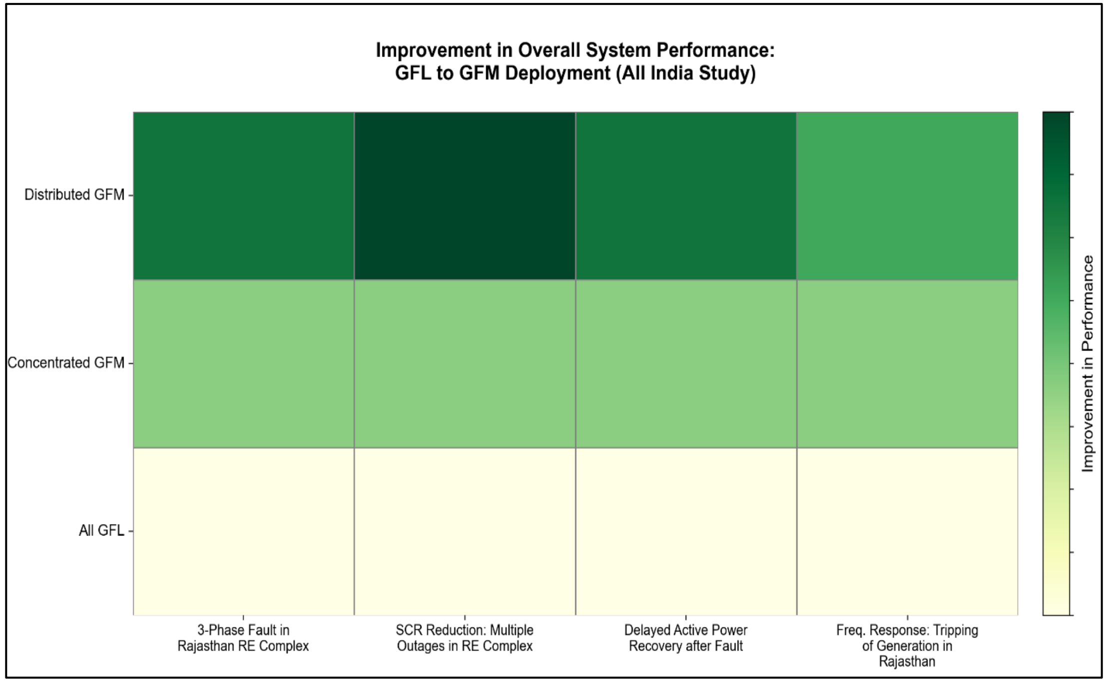


Similar observations as Study – 4: RE generation loss events!

All India Simulation Study: Results

Summary of All India Study

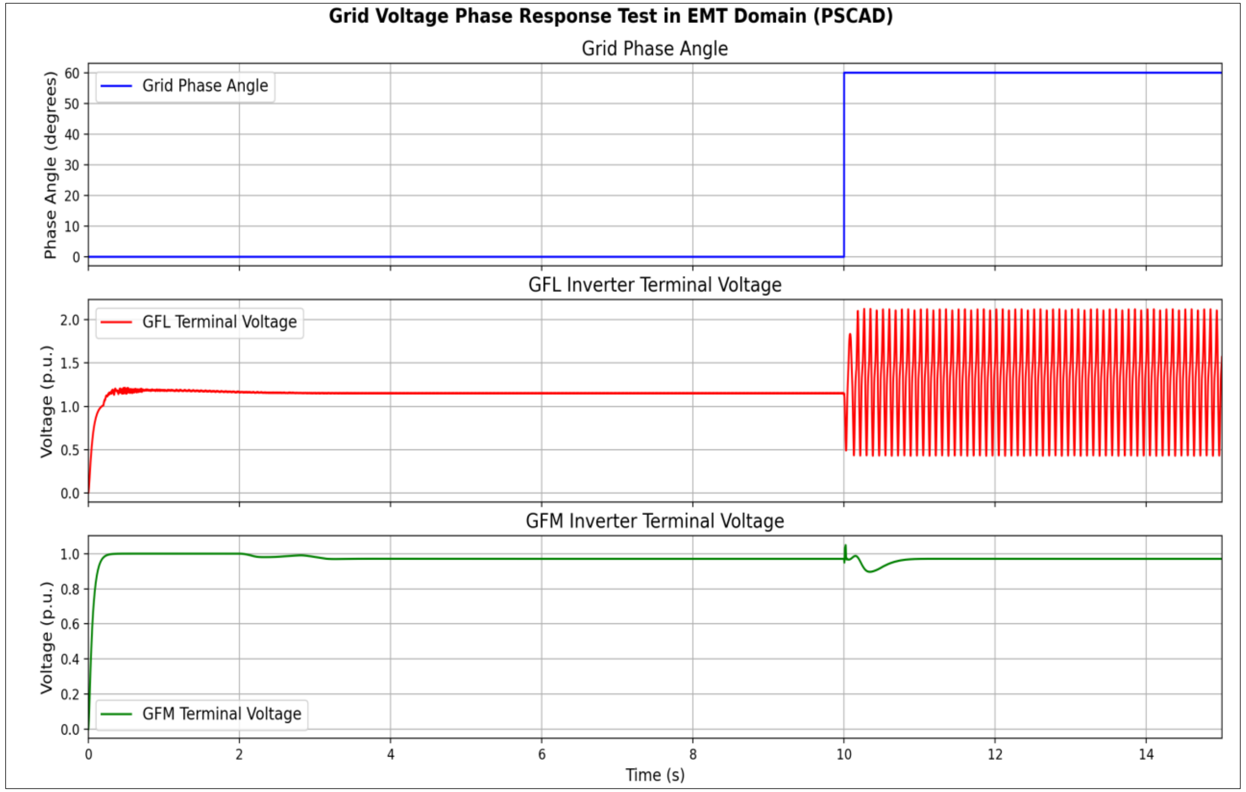
Cases	3-Phase fault in Rajasthan RE Complex	SCR Reduction: Multiple Outages in Rajasthan RE Complex	Impact of Delayed Active Power Recovery after Fault	Frequency Response Event: Tripping of Synchronous Machines in Rajasthan	Frequency Response Event: Tripping of Synchronous Machines in Rajasthan
Case – I (All GFL Case)	Worse	Worse	Worse	Worse	Worse
Case – II (Concentrated GFM Case)	Better	Better	Better	Better	Better
Case – III (Distributed GFM Case)	Better	Best	Best	Better	Better



- GFMs are observed to:
  - maintain stable operation in weak grids (low SCR), unlike PLL-based GFLs which may become unstable.
  - improve voltage stability by reducing fault voltage dips and post-fault overvoltage.
  - enhance system resilience and accelerate recovery during multiple outages and delayed GFL power recovery.
  - provide fast inertia-like response, significantly reducing RoCoF near disturbances.
- Concentrated GFM improves local voltage stability, while distributed GFM provides wider system-level benefits.
- System performance improves progressively with increasing GFM penetration

Performance Assessment of GFL and GFM: EMT Domain Study

Grid Voltage Phase Angle Jump

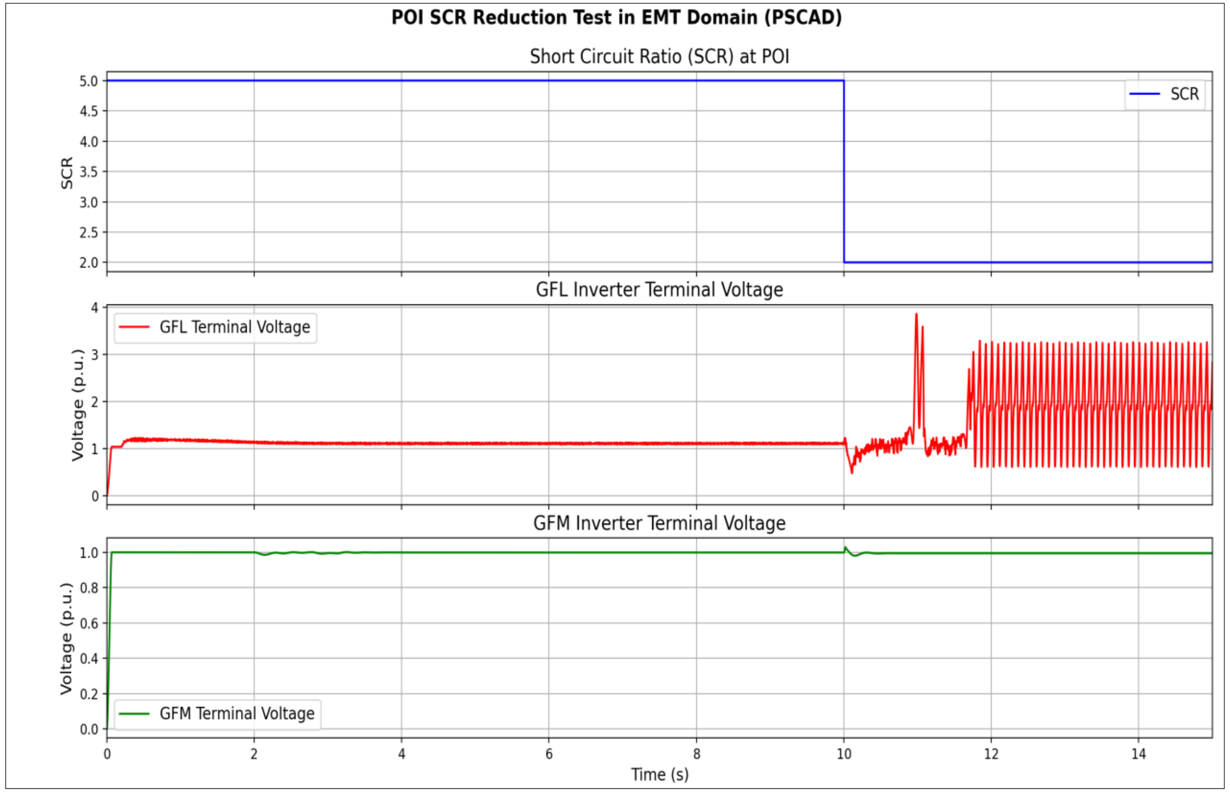


- POI bus voltage phase angle is stepped from 0° to 60° at t = 5 s.
- Simulation results show loss of stability in GFL, while GFM maintains synchronism under the phase-angle disturbance

GFL Model: *From PSCAD example library*

GFM Model: *An open-source model developed by NREL*

POI SCR Reduction



- The POI SCR is reduced from 5 to 2 at t = 5 s
- After SCR reduction, the GFL becomes unstable (possible loss of synchronism), while the GFM remains stable under weak grid conditions.

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Scope for Further Studies

Voltage Balancing Impact of GFMs

Black Start Through GFM

SSR Studies/ Frequency Scan

Impact of GFM Penetration on Protection

Effect of GFM on Power Quality

GFM in STATCOMs, HVDCs, Power Electronic Based Loads

Etc.

Contents

Global Experience with Grid Forming Inverters

Major Applications Areas of GFM:

a) Renewable Generation Systems
   - PV
   - Wind
   - Energy storage systems

b) FACTS Devices and HVDCs

c) Electric vehicles

d) Smart Loads

e) Microgrids

Region / Country	No. of Operational Projects	No. of Projects Under Construction	Total Projects
China	30	4	34
Australia	8	7	15
USA	8	3	11
Europe	4	5	9
Saudi Arabia	3	0	3

*Source: Energy Systems Integration Group (ESIG), "Installed and planned grid-forming projects," *GFM Landscape – ESIG. [Online]. Available: https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/projects*

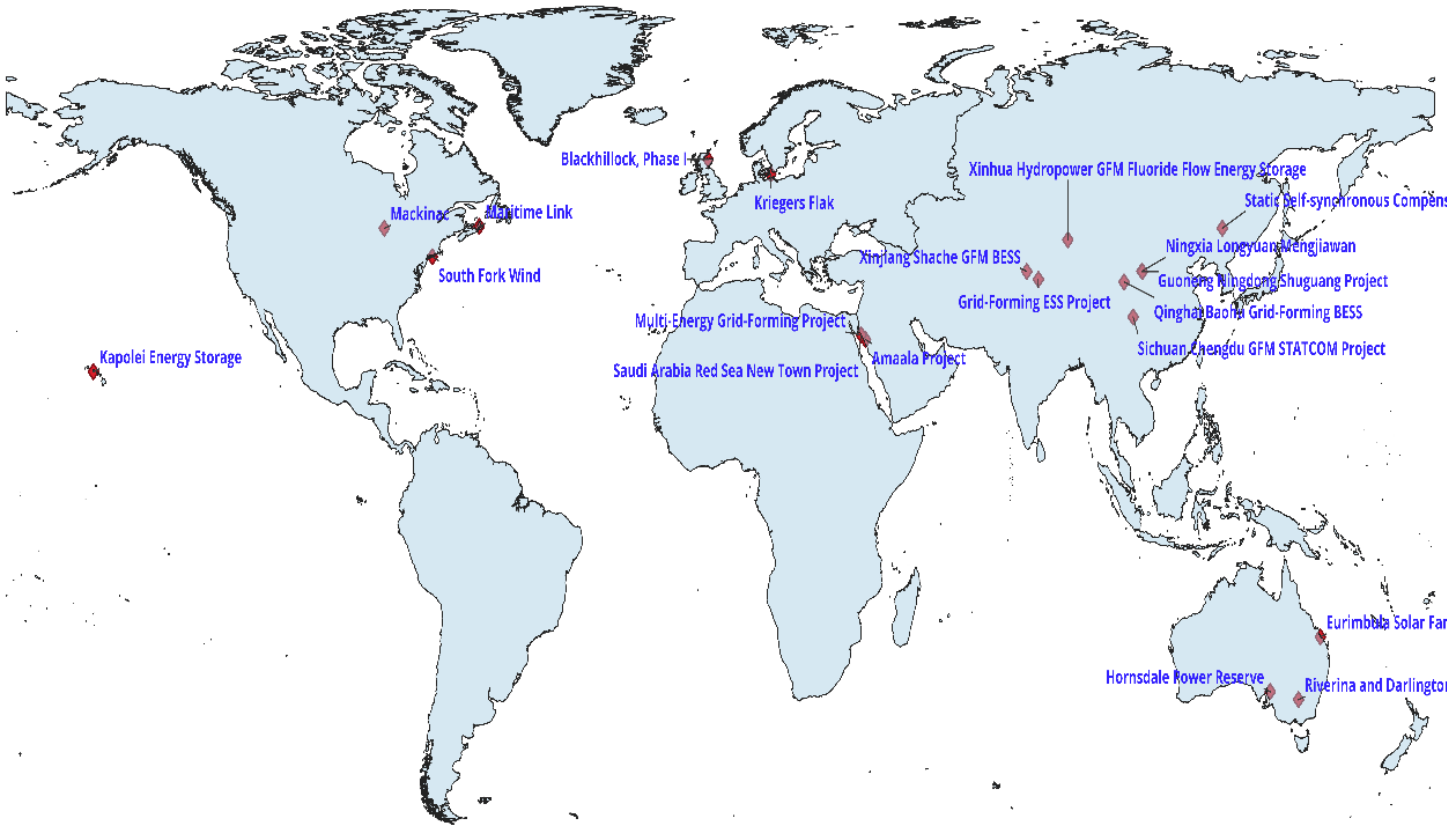
BESS inverters can enable GFM with minimal hardware changes

Adding advanced features (e.g., black-start) needs extra hardware, increasing cost.

PV and wind GFM integration is more complex due to less still DC side voltage source and is costly

Global Experience with Grid Forming Inverters

Notable GFM Projects Worldwide



Australia

- **Hornsdale Power Reserve Project (150 MW/194 MWh):** Upgraded from GFL to GFM with the capabilities of providing grid inertia service in July 2022
- **Dalrymple BESS (30 MW/8 MWh):** First transmission-connected GFM project in Australia

Great Britain

- **Blackhillock Phase-I BESS (200 MW/400 MWh):** Europe's largest transmission-connected battery projects

USA

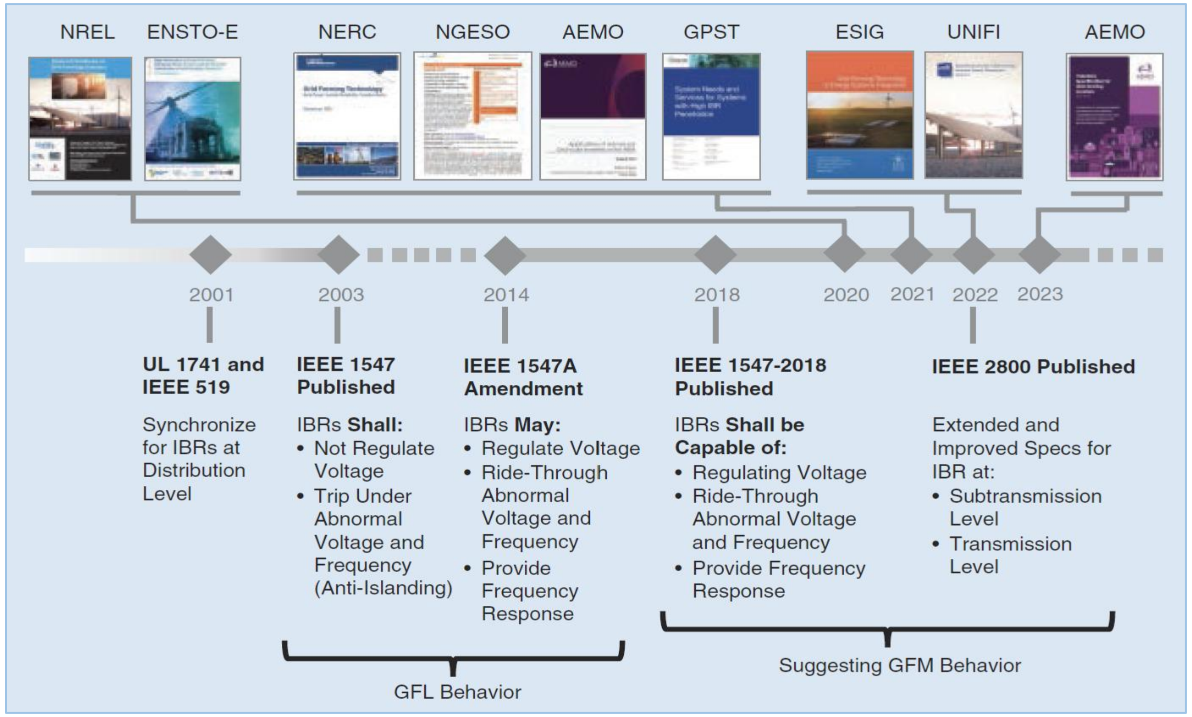
- **Kapolei BESS (185 MW/565 MWh), Hawaii:** GFM BESS providing inertia, voltage and frequency support

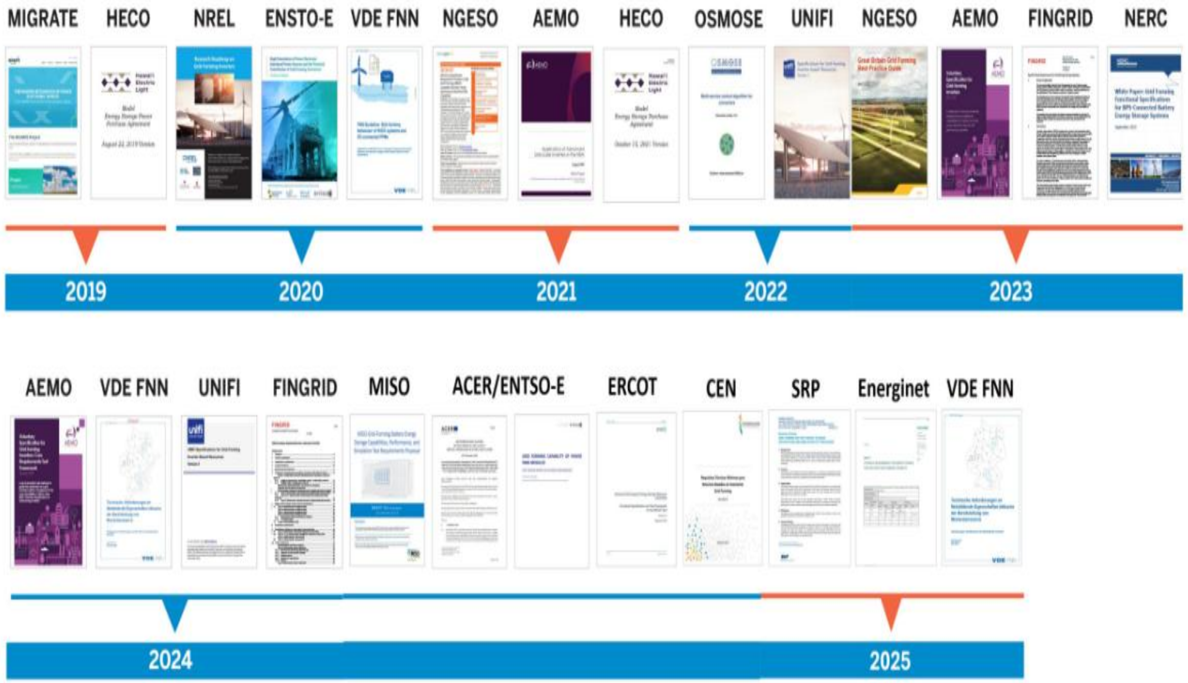
Saudi Arabia

- **Amaala Project (160 MW/760 MWh):** GFM BESS–solar microgrid enabling 24×7 renewable off-grid power in Saudi Arabia

Contents

Grid-Forming Converters - Specifications in Grid Codes and Standards





- Assume IBRs do not supply the full system load.
- Requirements are largely based on conventional inverter capabilities.
- Applicability to high-GFM or fully inverter-based systems remains uncertain.
- Interoperability between legacy IBRs and new GFM resources not assured

- Recent initiatives explicitly focus on defining GFM behaviour
- Key areas include fast inertia response and voltage-source operation
- Enhanced performance under weak grid conditions is addressed.
- Black-start capability and multi-GFM coordination are being specified

Source:
B. Bahrani et al., "Grid-Forming Inverter-Based Resource Research Landscape," IEEE Power & Energy Magazine, vol. 22, no. 2, pp. 52–63, Mar./Apr. 2024
UNIFI Consortium, "Grid-forming inverter technology specifications: A review of research reports and roadmaps," Nov. 2022.

Grid-Forming Converters - Specifications in Grid Codes and Standards

Requirements	GB Grid Code	AEMO (2023)	European Union Grid Code (Draft 2024)**	UNIFI V2 (2024)	FINGRID#	VDE-FNN 2025
Active phase jump power	✓	✓	✓(A)	✓	✓	✓
Active damping power	✓	✓	✓(A)	✓	✓	✓
Voltage jump reactive power	✓	✓	✓(A)	✓	✓	✓
Fast fault current injection	✓	✓	✓(A)	✓	✓	✓
Voltage source behaviour	✓	✓	✓(A)	✓	✓	✓
Frequency domain response	✓	✓	✓	✓(*)	✓	✓
Inertial response	✓	✓	✓High frequency: B ✓Low frequency: C	✓(***)	✓	✓
Last synchronous machine survival	✓	✓		✓	✓	✓
Weak grid operation and system strength	✓	✓	✓(A)	✓		✓
Oscillation damping	✓	✓	✓(A)	✓	✓	✓
GFM within current limits	✓	✓	✓	✓		✓
Additional Capabilities						
Headroom and energy buffer	✓	✓	✓(C)	✓(*)		✓
Current capability above continuous	✓	✓		✓		✓
Black start capability	✓	✓		✓		✓
Power quality improvement	✓	✓		✓		✓
Stability when current limit reached	✓	✓		✓		✓

- Type A: Connection point below 110 kV and maximum capacity of .8 kW or more.
- Type B: Connection point below 110 kV and maximum capacity at or above a threshold proposed by each relevant transmission system operator (TSO), which is below 1 MW.
- Type C: Connection point below 110 kV and maximum capacity at or above a threshold proposed by each relevant TSO, which is below 50 MW.
- Type D: Connection point above 110 kV or maximum capacity at or above a threshold proposed by each relevant TSO, which is below 75 MW.
- Even if not explicitly stated in the document, it can be inferred from the specifications that it is a desirable behaviour.
- ** At the present situation, GFM for type A is possible but not mandatory.
- *** In North America, this requirement is categorized under 'fast frequency response' and not explicitly defined.
- #Fingrid mandates the requirement of GFM capability for all the grid energy storage systems rated at more than 10 MW.

Source:

1. B. Bahrani et al., “Grid-Forming Inverter-Based Resource Research Landscape,” IEEE Power & Energy Magazine, vol. 22, no. 2, pp. 52–63, Mar./Apr. 2024
2. UNIFI Consortium, UNIFI Specifications for Grid-Forming Inverter-Based Resources, Version 2, 2024
3. Fingrid, "Grid code specifications for grid energy storage systems," Fingrid
4. Technical requirements for grid-forming capabilities including provision of inertia: Requirements and verifications for grid-forming units, Version 2.0, English version, Oct. 2025
5. AEMO, Voluntary Specification for Grid-forming Inverters, May 2023
6. NESO, GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

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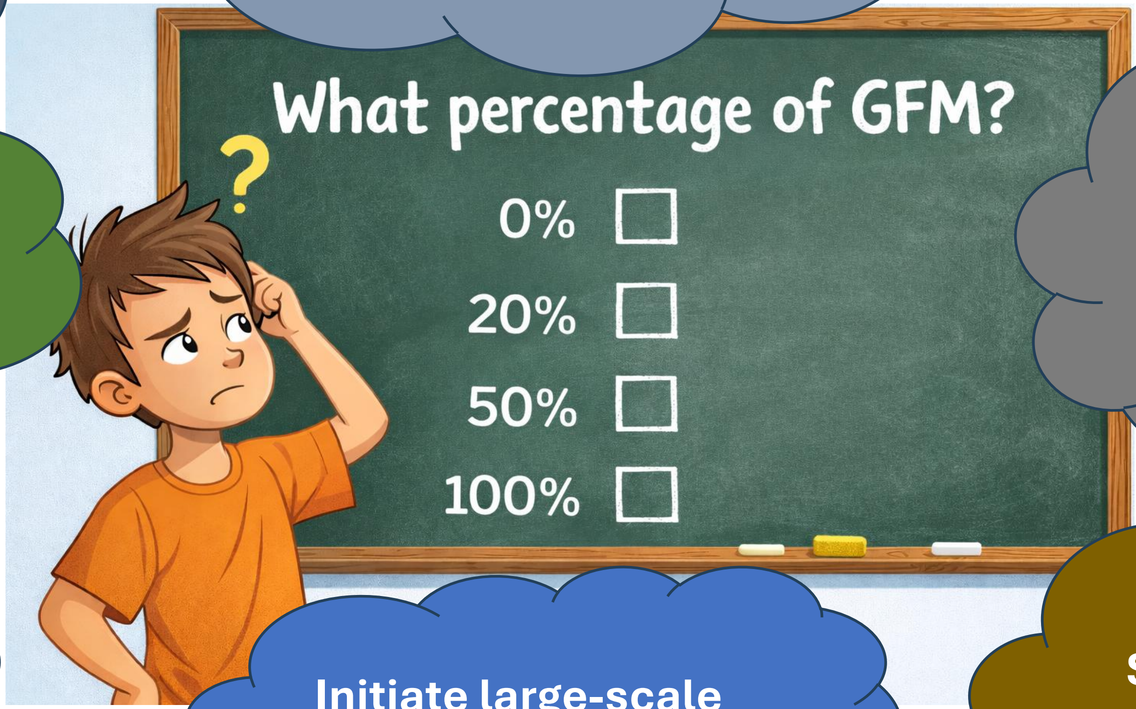
Conclusion and Way Forward

Required GFM share is ***system-specific*** and must be determined through ***detailed system studies***.

Studies indicate GFM penetration can be ***significant (often >30%)***; MIGRATE project reported ***~37% GFM*** in some systems.

GFM requirement depends on ***network strength, contingency type, and behaviour of GFL inverters and loads***.

Case studies show wide variation: ***~11% GFM*** with GFL support versus ***~23.5% GFM*** without support



Low hanging fruit: Enabling GFM in future large BESS involves ***modest incremental cost*** and offers a ***cost-effective path***

Align standards with international frameworks

Initiate large-scale pilot projects

GFMs and enabling assets (SYNCONs, STATCOMs) improve grid stability under new operating conditions

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Questions

Thank You!