



Stability Enhancement of Utility-scale Renewable Energy Plants in Weak Grids

[Project Summary]

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- ☐ **Introduction**
- ☐ Grid-following Inverters
- ☐ Grid-forming Inverters
- ☐ Power-Synchronized Grid-following Inverters
- ☐ Synchronous Condenser (SynCon)
- ☐ Project Summary

Introduction Projected System Strength in the NEM

System strength determines how a power system can **securely and reliably operate** upon various contingencies.

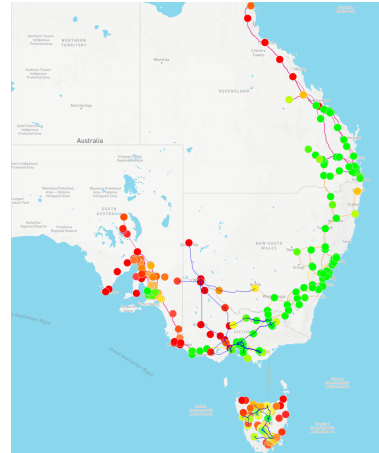


Figure 1: 2018-19

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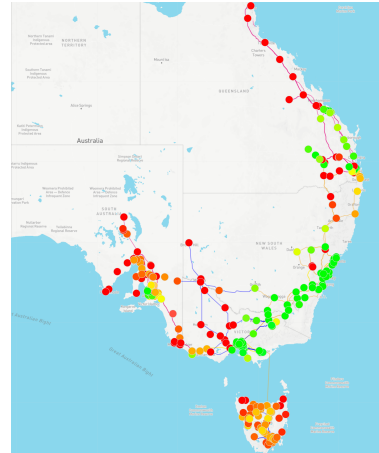


Figure 2: 2028-29

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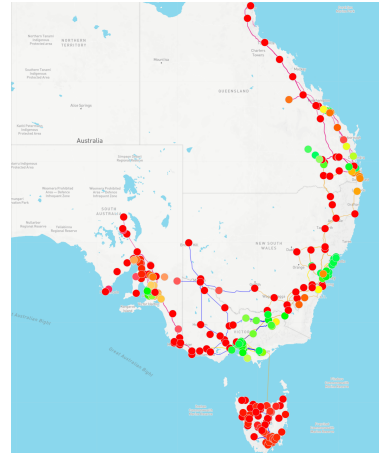


Figure 3: 2038-39

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Most of these **low system strength areas overlap with REZs**, which means more farms will be integrated into these weak areas.

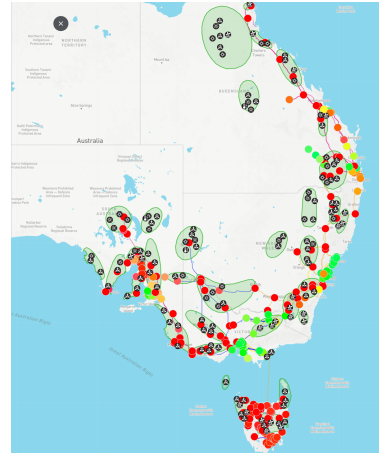


Figure 4: 2038-39

Low System Strength Problems

As identified by **TB-671-2016-B4-62 CIGRE Working Group Report**, integration of renewable energy farms into networks with low system strength can cause:

- control interactions and instability,
- failure to ride-through disturbances and faults,
- electromechanical oscillatory stability,
- islanding issues,
- sub-synchronous oscillatory behavior,
- inability of farms to inject their maximum power.

Project Aims:

- **classify/describe stability issues** likely to happen in weak grids,
- **identify grid properties/value-range/scenarios** under which above issues are likely to be encountered,
- propose innovative **allocation, sizing, and control strategies** for grid-strengthening assets such as **SynCons and grid-forming inverters**,
- enhance the **industry understanding of the interaction** of farms with other assets in the network such as grid-forming inverters and SynCons.

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Project Outcomes:

- **increased penetration of solar/wind farms** unlocking future investments,
- **maximised generation capacity** of existing farms located in weak networks,
- **increased reliability/security** of the grid as the renewable energy penetration grows.

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Project Budget:

The project duration was **two and a half years** and started in July 2020, and the studies were primarily done at **Monash University**. The **total budget was \$1.36M**, and the funding requested from **ARENA is \$559k (41%)**. Monash Grid Innovation Hub provided **\$100k as cash contribution**. The combined **in-kind contribution** of all partners were **\$708k**.

Project Tasks

Task1 - Grid Classification & Test-Bed

- ☐ Weak Grid Classification
- ☐ Quantification of Stability Conditions for Wind/Solar Farms
- ☐ Test-bed Development based on Northwestern Victorian Grid

Task2 - Grid-Strengthening Solutions

- ☐ Synchronous Condensers: Allocation and Sizing
- ☐ Grid Forming Inverters: Control, Allocation, Sizing, and Black-start Capability

Task3 - Internal Controllers & Interactions

- ☐ Farm Voltage Control for Damping Northwestern Victoria Oscillations
- ☐ Farm Synchronisation with Weak Grids
- ☐ Interaction of Wind/Solar Farms, SynCons and Grid Forming Inverters



HITACHI



ARENA



Australian Government
Australian Renewable
Energy Agency

Research Areas of the Project:

Grid Following Inverters (GFLIs)

- Nonlinear Transient Stability Analysis of GFLIs
- Small-Signal Synchronization Stability Enhancement of GFLIs
- Output Power Capability of GFLIs
- Modeling, Analysis, Stability Enhancement, and Impedance Measurement of GFLIs

Grid Forming Inverters (GFMI)s

- Generalized VSG for GFMI)s
- H_{∞} -based Control for GFMI)s
- Multivariable Control for GFMI)s
- Grid-Forming Capabilities for Wind Farms
- Adaptive Control for VSGs
- Virtual Resistance for Post-fault Oscillation Damping of GFMI)s

Power-Synchronised Grid Following Inverters (PSGFLI)s

- Optimization-based PSGFLI)s
- Linear-Parameter Varying control (LPV-PSGFLI)
- Impedance-based Stability Analysis and Transient Stability Analysis of LPV-PSGFLI)s
- Enhanced frequency control (ePSGFLI)
- Double synchronous reference frame control (DS-PSGFLI)

Synchronous Condensers (SynCons)

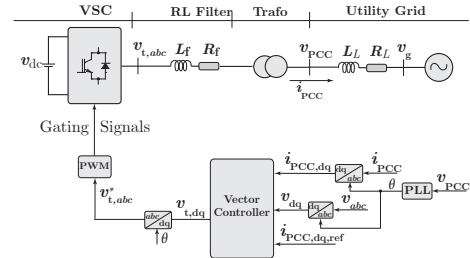
- Optimal Allocation and Sizing of SynCons
- A Data-Driven SynCon Exciter Controller Design
- Quantifying Stability in Inverter-based Weak Grids



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- ☐ Grid-forming Inverters
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Advantages

- the most common type of inverters in power systems worldwide
- Simple structure
- Well-established control technique
- Good performance in strong grids
- Stable under various disturbances (frequency deviations)



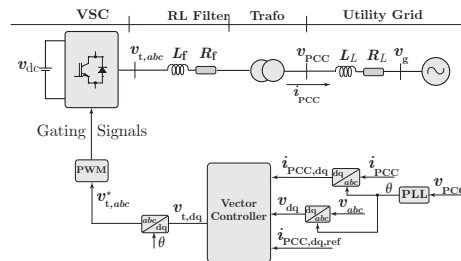
Simplified model of a grid-following inverter

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Disadvantages

- Poor performance in weak grids
- Small signal instability issues (e.g., PLL).
- needs an external grid $\Rightarrow$ Low system strength $\Rightarrow$ failed synchronization

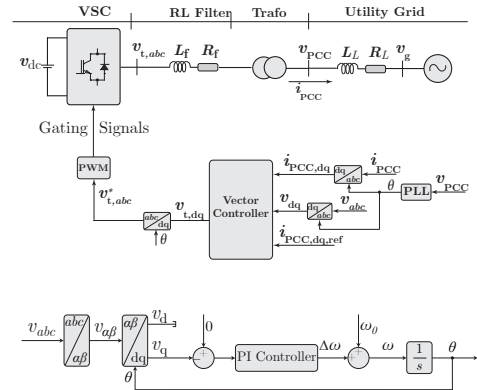


Simplified model of a grid-following inverter

Nonlinear Stability Analysis

Motivations

- Nonlinear control system $\Rightarrow$ linear methods not sufficient
- System strength relies on both the grid and inverter control
- PLL causes the majority of instabilities



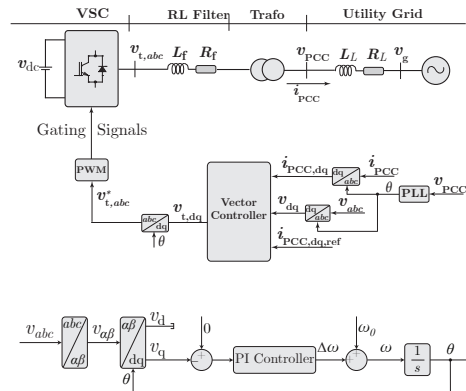
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Objectives

1. A nonlinear method to assess PLL-equipped systems stability
2. A nonlinear controller to expand PLLs capabilities



Nonlinear Stability Analysis: Methodology

Procedure

1. Derivation of the system model (PLL+ grid)

Nonlinear Stability Analysis: Methodology

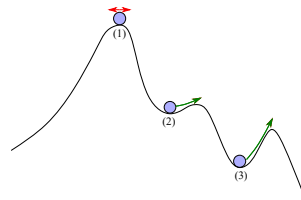
Procedure

1. Derivation of the system model (PLL+ grid)
2. Stability Analysis:
 - Finding the equilibrium points ((1), (2), and (3))
 - Determining which equilibrium point is stable (points (2) and (3))
 - Evaluating the disturbance tolerance of the stable equilibrium points, i.e., their **domain of attraction** (point (3) is more robust) by **utilising Lyapunov's Second Theorem**

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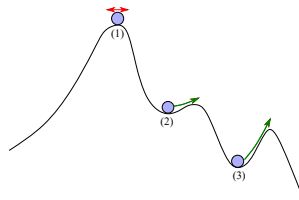
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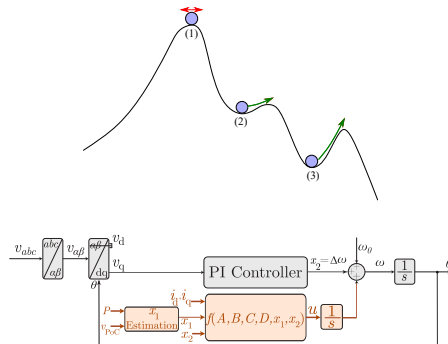
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[1] M. Z. Mansour, S. P. Me, S. Hadavi, B. Badrzadeh, A. Karimi and B. Bahrani, "Nonlinear Transient Stability Analysis of Phased-Locked Loop-Based Grid-Following Voltage-Source Converters Using Lyapunov's Direct Method," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 3, pp. 2699-2709, June 2022.

[2] M. Z. Mansour, M. H. Ravanji, A. Karimi and B. Bahrani, "Small-Signal Synchronization Stability Enhancement of Grid-Following Inverters via a Feedback Linearization Controller," in IEEE Transactions on Power Delivery, vol. 37, no. 5, pp. 4335-4344, Oct. 2022.

Output Curve Capability: Impact of PLL Dynamics and Grid Strength

Output Capability Curve (OCC):

- defines the permitted active-reactive operating region for any generating unit in a system,
- can be represented by equations (complex approach),
- can graphically illustrate the results of these derived equations (simple approach).

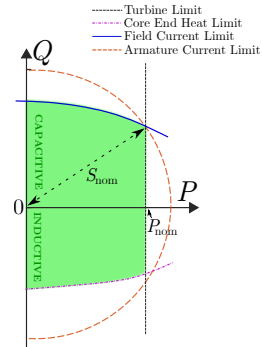


Figure 5: OCC of a typical synchronous generator.

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The OCC is remarkably limited by:

- thermal limits,
- stability (PLL) limits,
- energy resource limits,
- voltage limits and
- static limits.

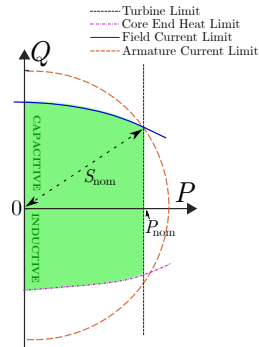


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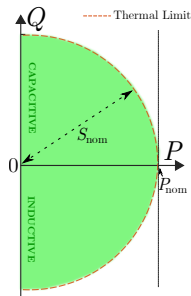


Figure 6: OCC of a typical voltage source with only thermal limit.

M.H. Ravanji, W. Zhou, N. Mohammed and B. Bahrani, "Comparative Analysis of the Power Output Capabilities of Grid-Following and Grid-Forming Inverters Considering Static, Dynamic, and Thermal Limitations," Under review.

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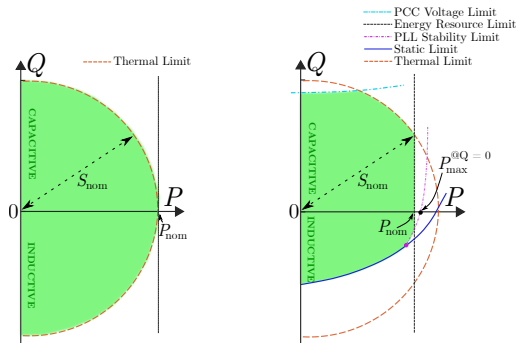


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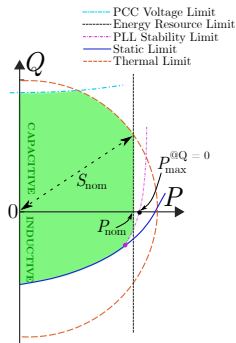


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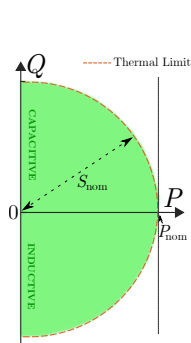


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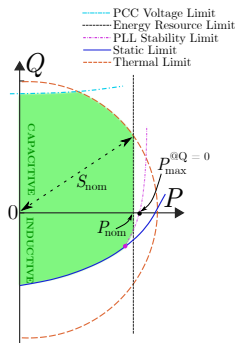


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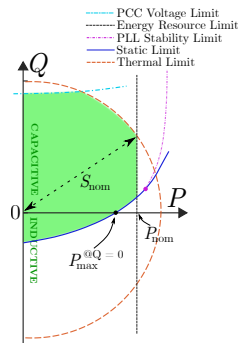


Figure 8: OCC when connected to a weaker grid.

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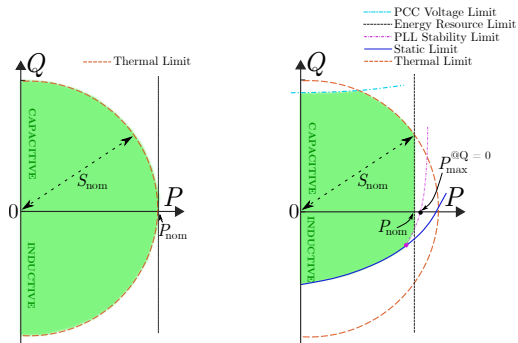


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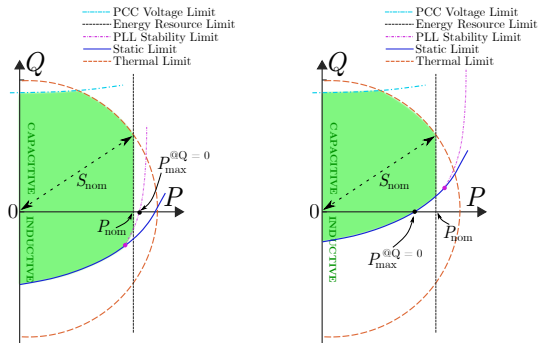


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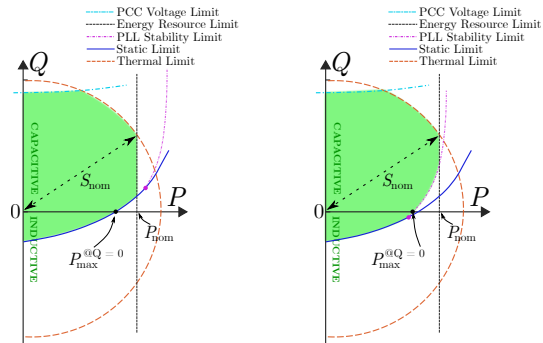


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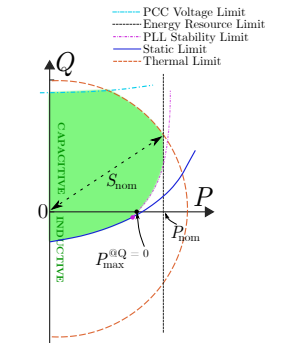


Figure 9: OCC when the PLL is also not tuned.

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Output Curve Capability: Maximizing the GFLI Transferable Power

In previous slides, it is shown that the **OCC can be significantly limited**. These limits are categorised into **two categories**:

1. caused by the inverter itself (limits 1-3)
2. caused by the grid (limits 4 and 5)

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Suggested solutions for Increasing the GFLI Maximum Transferable Power

- by changing the PLL gains the PLL stability limit can be pushed rightward in the OCC of a GFLI
- Proposing an auxiliary controller to provide the optimal Q_{ref} for the conventional control.

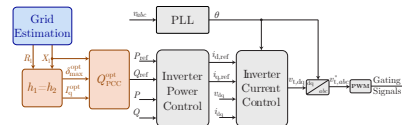


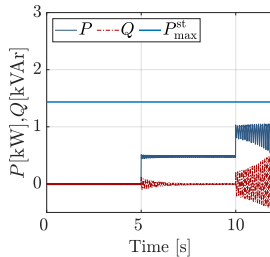
Figure 10: The proposed auxiliary controller for maximising the static limit.

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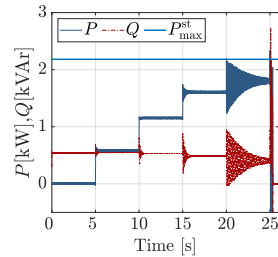
OCC: Auxiliary controller for maximising the static limit

Experimental results

- Considering a weak grid with SCR=1.2
- Inverter rated power is 2.2 kW
- Two cases are compared without and with the auxiliary controller
- It can be seen the proposed auxiliary controller increases the IBR maximum transferable power to the grid



Results without the auxiliary controller



Results with the auxiliary controller



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Introduction

Challenges in inverter-dominant power systems

- Reduced inertia and system strength
- Reduced fault current
- Control interactions and oscillations

A simplified grid-forming inverter.

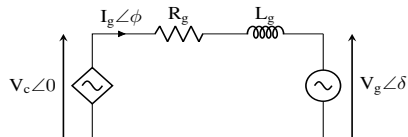


Figure 11: Simplified model of a grid-forming inverter.

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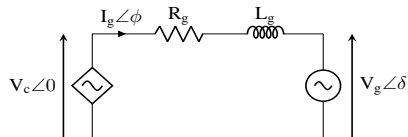


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- GFMLs are capable of **providing system strength and inertia** to the power system.

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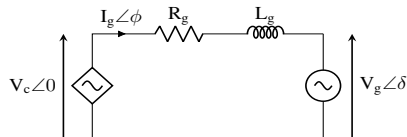


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Grid-forming inverters

- **Superior** performance of GFMI in weak grids over GFLI.
- GFMI are capable of **providing system strength and inertia** to the power system.
- GFMI are capable of operating in **grid-connected (GC) and standalone (SA)** modes.

A simplified grid-forming inverter.

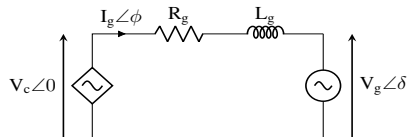
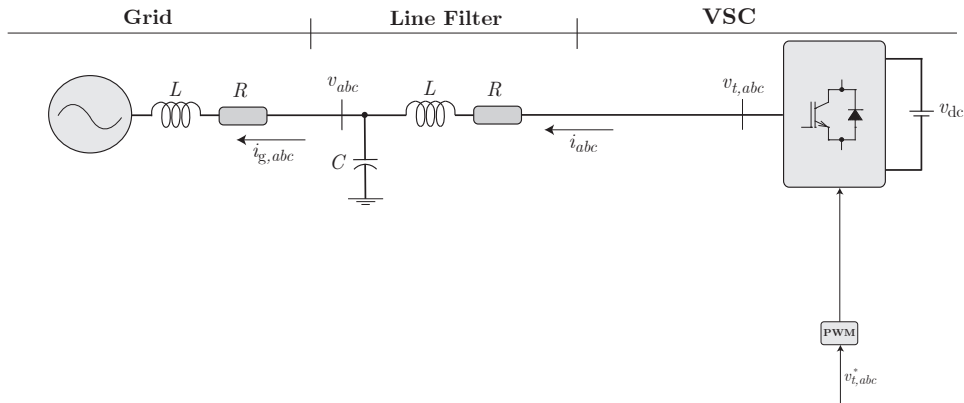
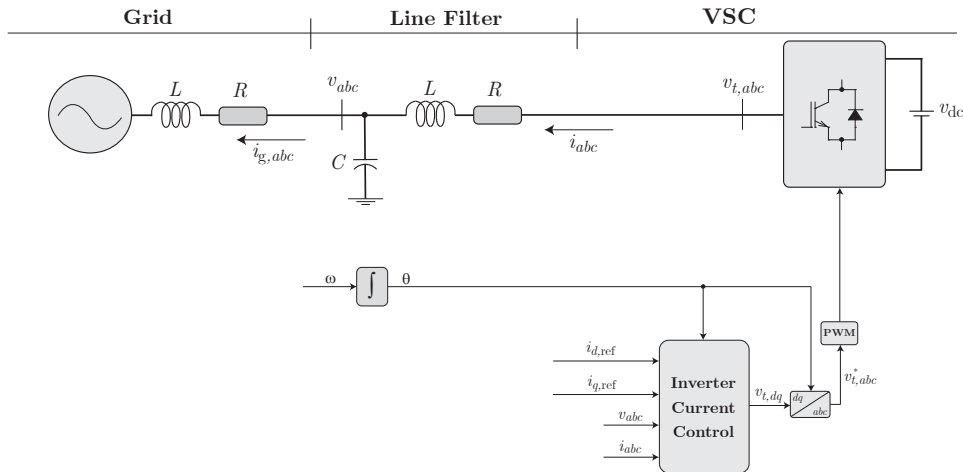


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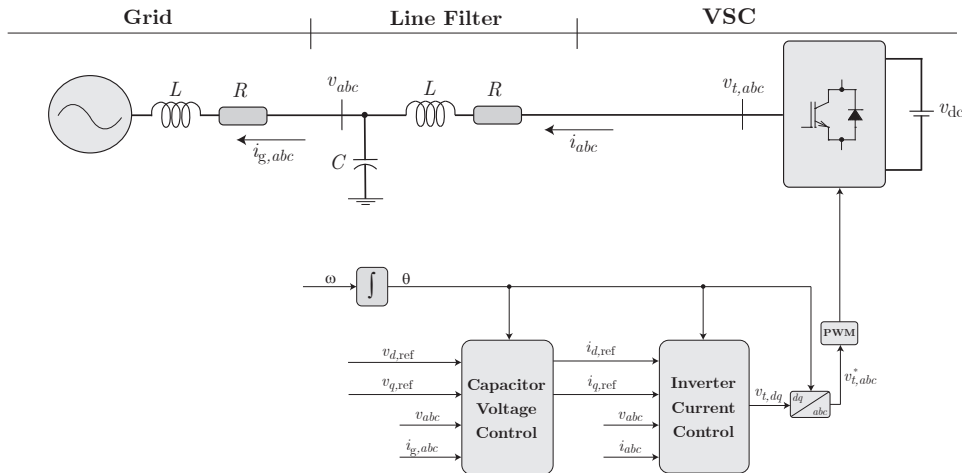
Generic Control Structure



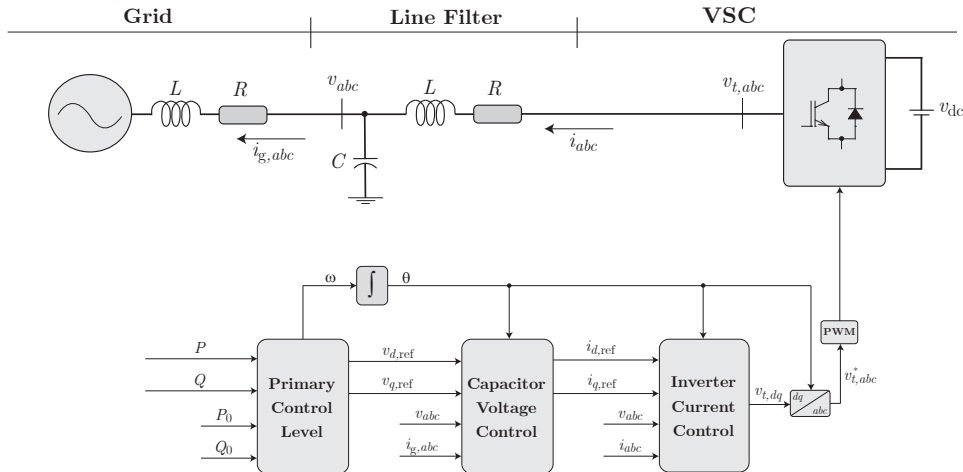
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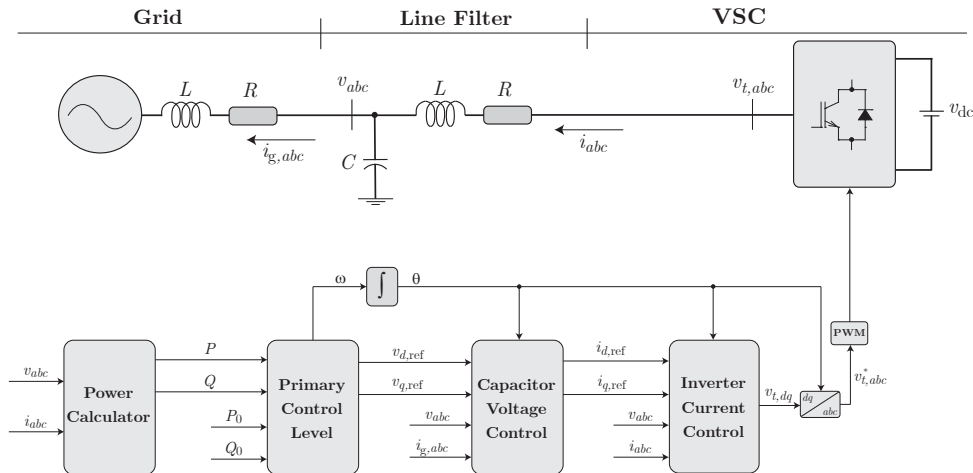


Generic Control Structure



Generic Control Structure





Control of the Conventional VSG: Dynamic Response

Virtual Synchronous Generator (VSG) Control

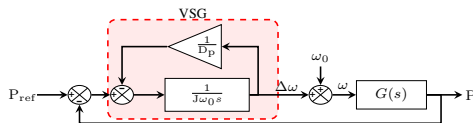


Figure 12: Virtual Synchronous Generator (VSG) Control

$$K_{\text{vsg}}(s) = \frac{D_p}{(\tau_i s + 1)},$$

- D_p is the droop coefficient.
- τ_i is set based on the required virtual inertia provision.

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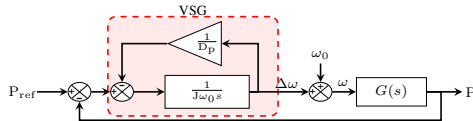


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Dynamic Response with Virtual Synchronous Generator (VSG) Control

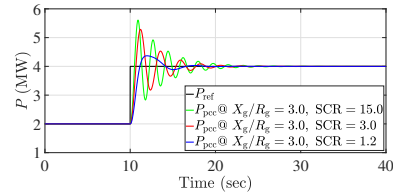


Figure 13: VSG performance in grid-connected mode: Effects of SCR when $X_g/R_g = 3.0$,

- as SCR is decreased, the overshoot and rise time are increased.

Adaptive VSG: Challenge & Motivation

Challenge

- Performance of VSG is strongly related to:
 - Grid strength SCR
 - X_g/R_g ratio

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Motivation

1. Can we design a fully controllable VSG with fixed dynamic performance:
 - ⇒ settling time?
 - ⇒ overshoot?
 - ⇒ damping ratio?
2. Is it possible to keep the exact control structure of the conventional VSG?

Adaptive VSG: Methodology

1. Consider the power flow equations with RL model of the grid

$$P_{\text{pcc}} = \frac{3}{R_g^2 + X_g^2} [R_g (V_i^2 - V_i V_j \cos \theta_{ij}) + X_g V_i V_j \sin \theta_{ij}], \quad (1)$$

$$Q_{\text{pcc}} = \frac{3}{R_g^2 + X_g^2} [X_g (V_i^2 - V_i V_j \cos \theta_{ij}) - R_g V_i V_j \sin \theta_{ij}], \quad (2)$$

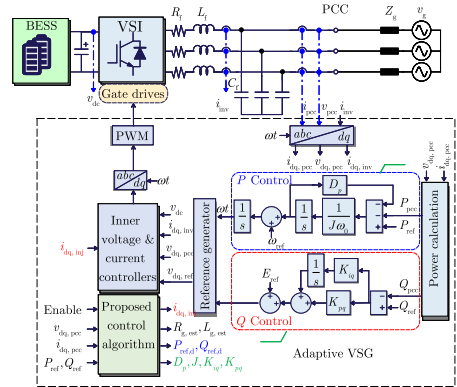


Figure 14: Proposed Adaptive VSG.

N. Mohammed, M. H. Ravanji, W. Zhou and B. Bahrani, "Online Grid Impedance Estimation-Based Adaptive Control of Virtual Synchronous Generators Considering Strong and Weak Grid Conditions," in IEEE Transactions on Sustainable Energy, vol. 14, no. 1, pp. 673-687, Jan. 2023.

Adaptive VSG: Methodology

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$$Q_{\text{pcc}} = \frac{3}{R_g^2 + X_g^2} [X_g (V_i^2 - V_i V_j \cos \theta_{ij}) - R_g V_i V_j \sin \theta_{ij}], \quad (2)$$

2. Linearize the power flow equations

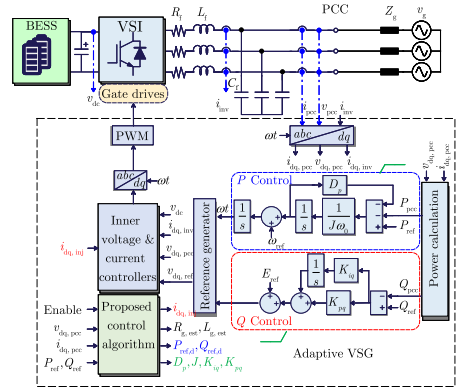


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Adaptive VSG: Methodology

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2. Linearize the power flow equations

3. Define the desired performance (e.g., T_s , ζ) for the VSG

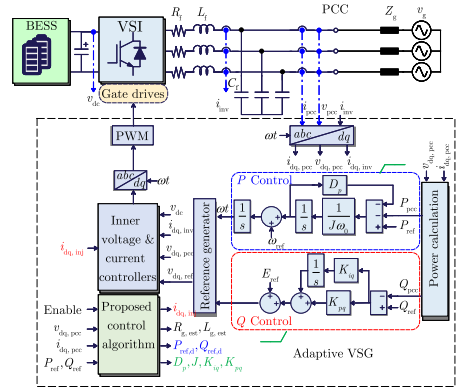


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Adaptive VSG: Methodology

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$$P_{\text{pcc}} = \frac{3}{R_g^2 + X_g^2} [R_g (V_i^2 - V_i V_j \cos \theta_{ij}) + X_g V_i V_j \sin \theta_{ij}], \quad (1)$$

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2. Linearize the power flow equations
3. Define the desired performance (e.g., T_s , ζ) for the VSG
4. Estimate the grid impedance (R_g , X_g) in real-time by the VSG itself by 75 Hz inter-harmonic injection.

$$R_g \cong \Re \left[\frac{v_{\text{res}}(75 \text{ Hz})}{i_{\text{res}}(75 \text{ Hz})} \right], \quad L_g \cong \frac{1}{\omega_0} \Im \left[\frac{v_{\text{res}}(75 \text{ Hz})}{i_{\text{res}}(75 \text{ Hz})} \right]. \quad (3)$$

5. Tune of the VSG adaptively: (J , D_p , K_{pq} , K_{iq})

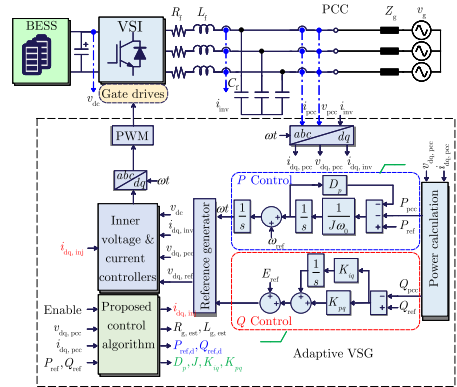


Figure 14: Proposed Adaptive VSG.

N. Mohammed, M. H. Ravanji, W. Zhou and B. Bahrani, "Online Grid Impedance Estimation-Based Adaptive Control of Virtual Synchronous Generators Considering Strong and Weak Grid Conditions," in IEEE Transactions on Sustainable Energy, vol. 14, no. 1, pp. 673-687, Jan. 2023.

Adaptive VSG: Verification in a weak grid with SCR= 2.5

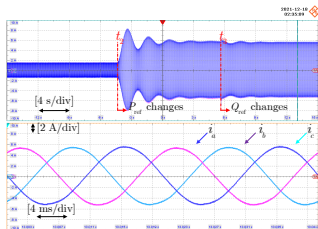


Figure 15: (left) PCC current of the conventional VSG, (middle) (left) PCC current of the adaptive VSG, (right) PCC power waveforms of the conventional and adaptive VSG.

Adaptive VSG: Verification in a weak grid with SCR= 2.5

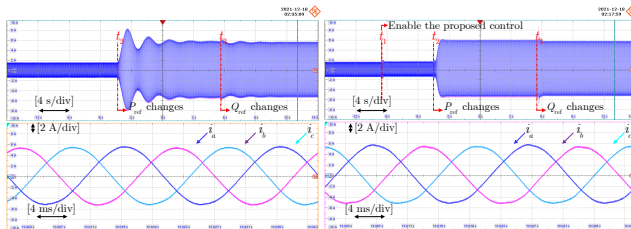


Figure 15: (left) PCC current of the conventional VSG, (middle) (left) PCC current of the adaptive VSG, (right) PCC power waveforms of the conventional and adaptive VSG.

Adaptive VSG: Verification in a weak grid with SCR= 2.5

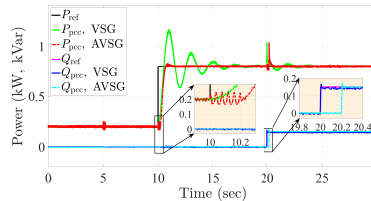
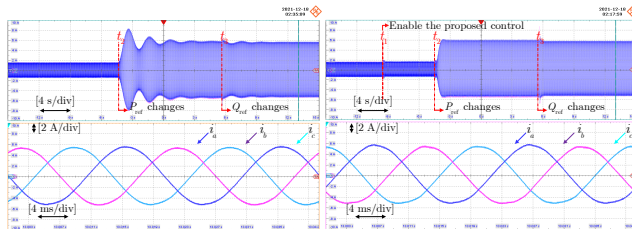


Figure 15: (left) PCC current of the conventional VSG, (middle) (left) PCC current of the adaptive VSG, (right) PCC power waveforms of the conventional and adaptive VSG.

Adaptive VSG: Verification in a strong grid with SCR=6.74

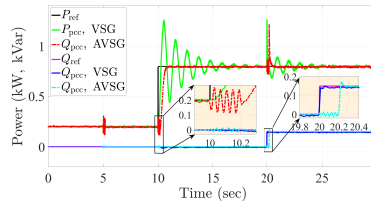
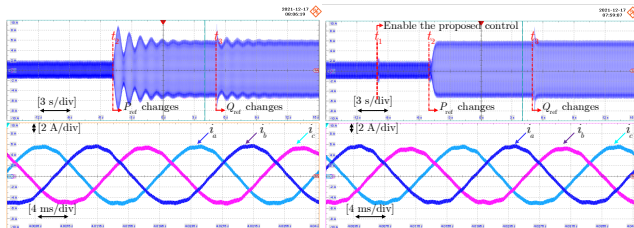


Figure 16: (left) PCC current of the conventional VSG, (middle) (left) PCC current of the adaptive VSG, (right) PCC power waveforms of the conventional and adaptive VSG.

Generalized VSG and Compensated Generalized VSG: Methodology

Generalized Virtual Synchronous Generator Control (GVSG)

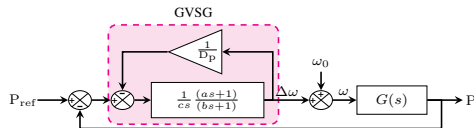


Figure 17: Generalized Virtual Synchronous Generator Control (GVSG)

- a , b , and c are controller gains.
- The proposed controller does not result in a very high initial RoCoF.
- It allows setting a desired $P - \omega$ droop coefficient.

D. B. Rathnayake, R. Razzaghi, and B. Bahrani, "Generalized Virtual Synchronous Generator Control Design for Renewable Power Systems," in *IEEE Transactions on Sustainable Energy*, vol. 13, no. 2, pp. 1021-1036, April 2022.

Generalized VSG and Compensated Generalized VSG: Methodology

Generalized Virtual Synchronous Generator Control (GVSG)

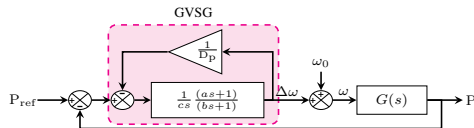


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Compensated GVSG Control

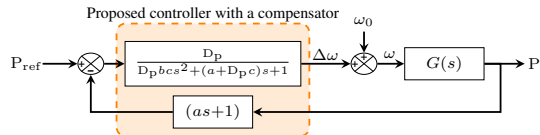


Figure 18: Control block diagram of the proposed controller with a damping correction loop.

- The step response of the GVSG still results in an overshoot.
- The zero in the closed-loop transfer function results in an undesirable overshoot.
- Solution: adding a damping correction loop

GVSG and CGVSG: Experimental Validation

Strong grid (SCR = 10.6)

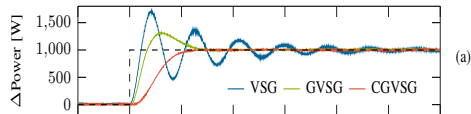


Figure 19: Experimental results for a step change in active power for SCR = 10.6.

Weak grid (SCR = 1.9)

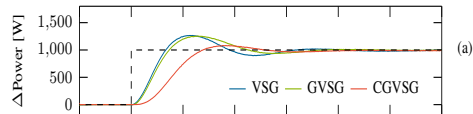


Figure 20: Experimental results for a step change in active power for a SCR = 1.9.

- Excellent performance in **strong/weak grids**.
- CGVSG has the **lowest** overshoot and settling time.
- **Grid strength impact** on the GVSG and the CGVSG is marginal.

$\mathcal{H}_\infty$ -based Control Design of VSG: Methodology

Challenges in CGVSG control design

- Difficult to specify the performance specifications, such as overshoot and rise time, in the control design stage.
- Only simplified parametric models could be used in the control design.
- Cannot design controllers for multiple GFMI s simultaneously.

D. B. Rathnayake, S. P. Me, R. Razzaghi and B. Bahrani, "H ∞ -based Control Design for Grid-forming Inverters with Enhanced Damping and Virtual Inertia," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2022.

$\mathcal{H}_\infty$ -based Control Design of VSG: Methodology

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- Difficult to specify the performance specifications, such as overshoot and rise time, in the control design stage.
- Only simplified parametric models could be used in the control design.
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Controller Structure

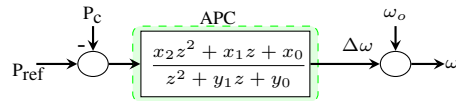


Figure 21: Control block diagram of the proposed controller.

D. B. Rathnayake, S. P. Me, R. Razzaghi and B. Bahrani, "H ∞ -based Control Design for Grid-forming Inverters with Enhanced Damping and Virtual Inertia," in IEEE Journal of Emerging and Selected Topics in Power Electronics, 2022.

$\mathcal{H}_\infty$ -based Control Design of VSG: Experimental Validation

Step in Power Reference in Grid-connected Mode.

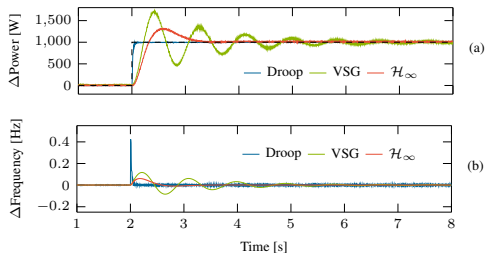


Figure 22: Experimental results for the droop, the VSG, and the proposed controller when a step change in active power is applied in the GC mode: (a) active power output and (b) frequency.

$\mathcal{H}_\infty$ -based Control Design of VSG: Experimental Validation

Step in Power Reference in Grid-connected Mode.

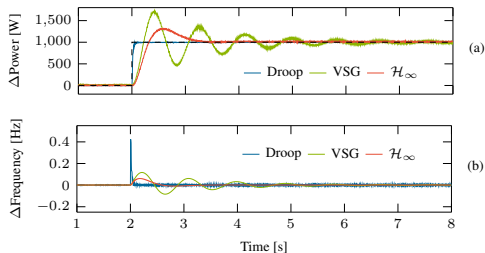


Figure 22: Experimental results for the droop, the VSG, and the proposed controller when a step change in active power is applied in the GC mode: (a) active power output and (b) frequency.

Load Change in Standalone Mode.

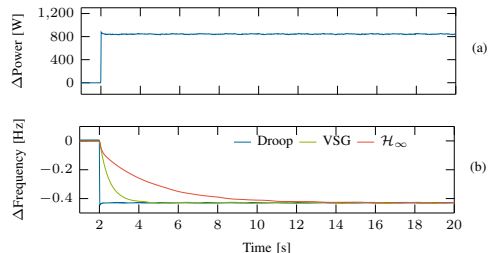


Figure 23: Experimental results for the droop, the VSG, and the proposed controller when subjected to a load change in the SA mode: (a) load real power and (b) system frequency.

Multivariable Control Design of VSG: Methodology

Proposed Controller Structure

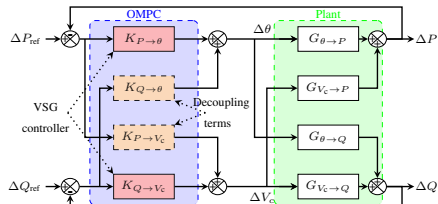


Figure 24: Small-signal diagram of proposed MIMO control

$$\begin{bmatrix} \Delta\theta \\ \Delta V_c \end{bmatrix} = \underbrace{\begin{bmatrix} K_{P \rightarrow \theta} & K_{Q \rightarrow \theta} \\ K_{P \rightarrow V_c} & K_{Q \rightarrow V_c} \end{bmatrix}}_K \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix},$$

D. B. Rathnayake and B. Bahrani, "Multivariable Control Design for Grid-Forming Inverters With Decoupled Active and Reactive Power Loops," in *IEEE Transactions on Power Electronics*, vol. 38, no. 2, pp. 1635-1649, Feb. 2023.

Multivariable Control Design of VSG: Methodology

Proposed Controller Structure

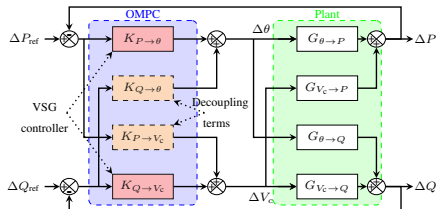


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Controller Structure

$$K = \begin{bmatrix} \frac{(x_1^{1,1}z + x_0^{1,1})(z+1)}{(z + y_0^{1,1})(z-1)} & \frac{x_1^{1,2}z + x_0^{1,2}}{z + y_0^{2,2}} \\ \frac{(x_1^{2,1}z + x_0^{2,1})(z+1)}{(z + y_0^{1,1})(z-1)} & \frac{x_1^{2,2}z + x_0^{2,2}}{z + y_0^{2,2}} \end{bmatrix}$$

- Loop Shaping-based Multivariable Control Design
- A controller **similar to VSG control** is pursued.

Multivariable Control Design of VSG: Experimental Validation

P and Q Decoupling

- The decoupling capability of the **virtual impedance method is limited**.
- The coupling effect of the **proposed MIMO is minimal**.
- The **rise-time** of the active power is **not affected** by the decoupling.

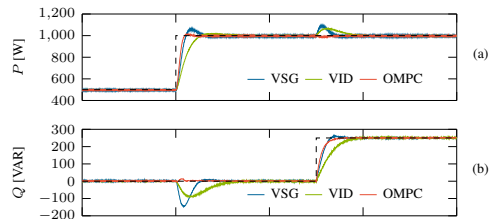


Figure 25: Experimental results of the VSG, VID, and OMPC with zero steady-state error Q controller (K_{ZSEQ}) during step changes of $P_{\text{ref}} = 500$ W at $t = 2$ s and $Q_{\text{ref}} = 250$ VAR at $t = 5$ s: the (a) active power and (b) reactive power.

Multivariable Control Design of VSG: Experimental Validation

Ride-through during ω disturbance

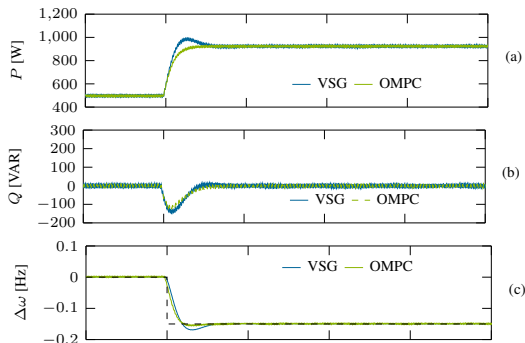


Figure 26: Experimental results of the VSG and OMPC with zero steady-state error Q controller (K_{ZSEQ}) during a grid-frequency drop of -0.15 Hz at $t = 1$ s: the (a) active power, (b) reactive power, (c) frequency deviation generated by the controller, and (d) d-axis and q-axis PCC voltage reference deviation.

Multivariable Control Design of VSG: Experimental Validation

Ride-through during ω disturbance

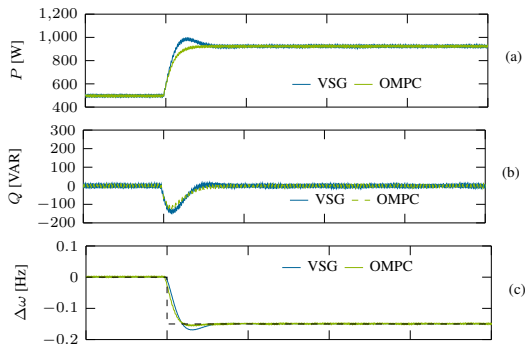


Figure 26: Experimental results of the VSG and OMPC with zero steady-state error Q controller (K_{ZSEQ}) during a grid-frequency drop of -0.15 Hz at $t = 1$ s: the (a) active power, (b) reactive power, (c) frequency deviation generated by the controller, and (d) d-axis and q-axis PCC voltage reference deviation.

Ride-through during V disturbance

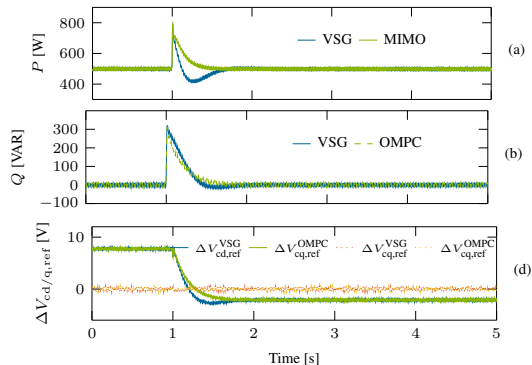


Figure 27: Experimental results of the VSG and OMPC with zero steady-state error Q controller (K_{ZSEQ}) during a grid voltage sag of -13 V at $t = 2$ s: the (a) active power, (b) reactive power, (c) frequency deviation generated by the controller, and (d) d-axis and q-axis PCC voltage reference deviation.

Virtual Resistance for Postfault Oscillation Damping: Background

Challenges

- Inverters are **vulnerable** during faults and fault recoveries.
- **Poorly-tuned** controllers in cascaded loops might lead to undesired interactions/oscillations.
- This is typically more pronounced in weak networks.
- **Trigger protection** devices $\Rightarrow$ lead to unnecessary disconnections and instability.

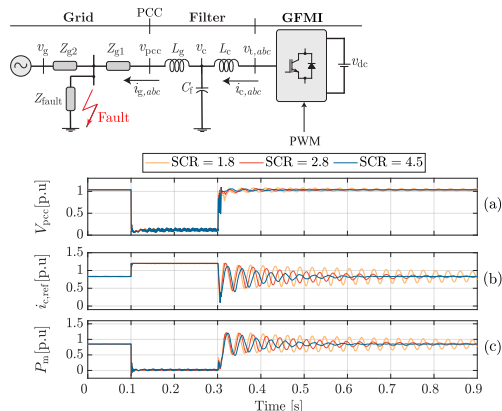


Figure 28: Fault recovery with different SCRs

S. P. Me, S. Zabihi, F. Blaabjerg and B. Bahrani, "Adaptive Virtual Resistance for Postfault Oscillation Damping in Grid-Forming Inverters," in *IEEE Transactions on Power Electronics*, vol. 37, no. 4, pp. 3813-3824, April 2022, doi: 10.1109/TPEL.2021.

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- This is typically more pronounced in weak networks.
- **Trigger protection** devices $\Rightarrow$ lead to unnecessary disconnections and instability.

Motivation

- Damping mechanism to suppress the oscillations.
- **Virtual resistance** can do the job.

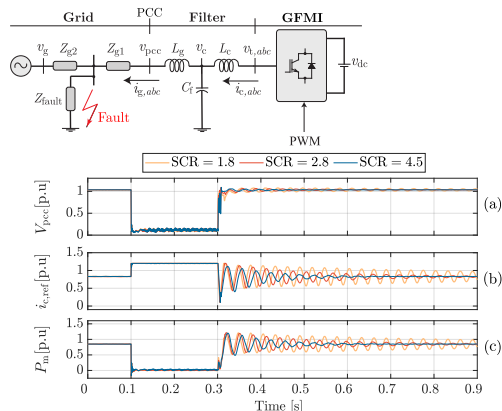
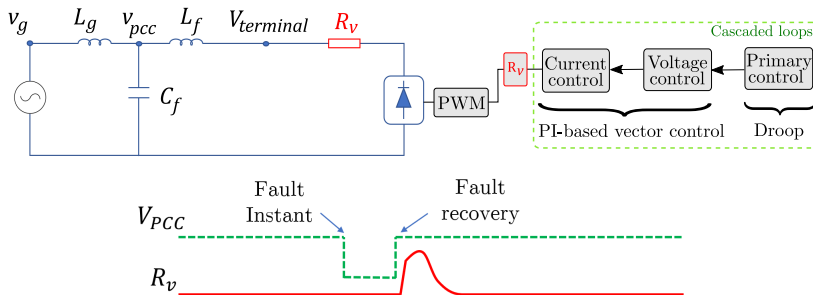


Figure 28: Fault recovery with different SCR values

S. P. Me, S. Zabihi, F. Blaabjerg and B. Bahrani, "Adaptive Virtual Resistance for Postfault Oscillation Damping in Grid-Forming Inverters," in *IEEE Transactions on Power Electronics*, vol. 37, no. 4, pp. 3813-3824, April 2022, doi: 10.1109/TPEL.2021.

Virtual Resistance for Postfault Oscillation Damping: Fixed-value



- Virtual Resistance (VR) is well-known in the literature for **oscillation damping**.
- A **small** fixed R_v is not sufficient to damp the oscillation in **weak** grids.
- A **large** fixed R_v requires **higher active current**.

Virtual Resistance for Postfault Oscillation Damping: Adaptive-value

- Need to be **adaptive** as grid's topology is dynamic.
- Dynamic** virtual resistance, only added in the fault-recovery process.
- The measured power, P_m , is passed through a filter network to form the VR value, R_v .
- More VR is used in the early stage of fault recovery.
- Less VR is used in the later stage of fault recovery.
- The operation of the AVR is governed by a state machine.

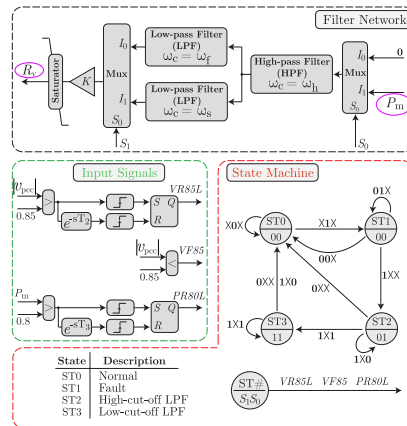


Figure 28: The state machine calculating the adaptive VR (AVR)

Virtual Resistance for Postfault Oscillation Damping: Simulation Results

Without Virtual Resistance

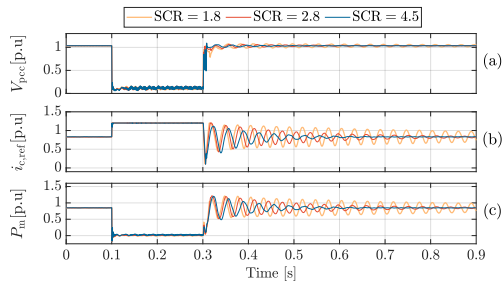


Figure 29: Fault recovery with different SCRs

Virtual Resistance for Postfault Oscillation Damping: Simulation Results (cont.)

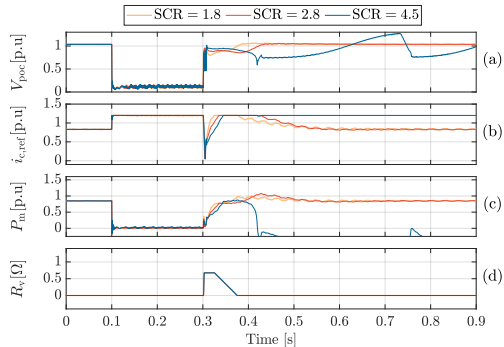


Figure 30: Fault recovery with fixed virtual resistance (Sim.).

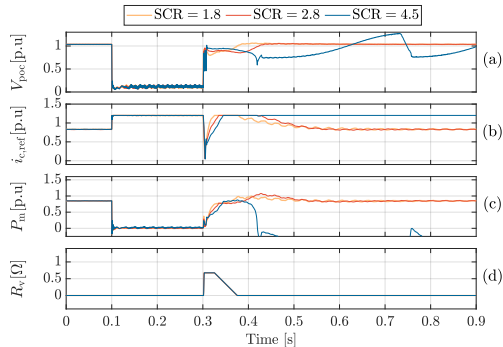


Figure 30: Fault recovery with **fixed** virtual resistance (Sim.).

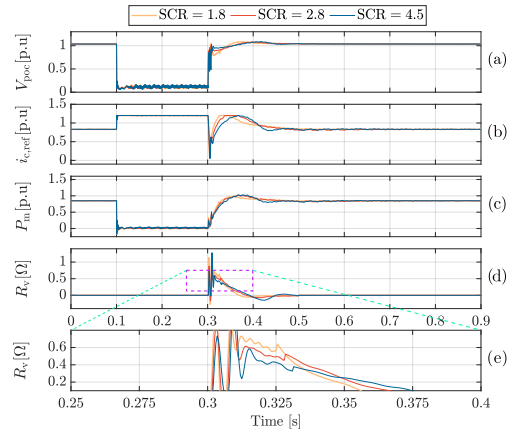


Figure 31: Fault recovery with **adaptive** virtual resistance (Sim.).



- ☐ Introduction
- ☐ Grid-following Inverters
- ☐ Grid-forming Inverters
- ☐ **Power-Synchronized Grid-following Inverters**
- ☐ Synchronous Condenser (SynCon)
- ☐ Project Summary

Optimization-based Control (Configuration v1)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids

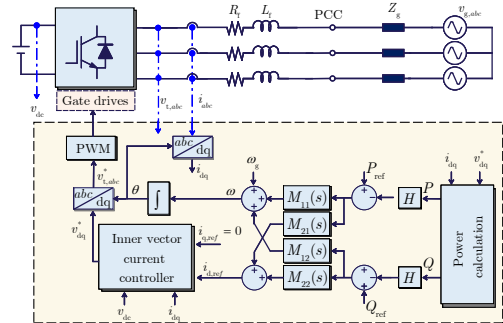


Figure 32: Power-Synchronized Grid-Following Inverters

Optimization-based Control (Configuration v1)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids

Disadvantages

- Offline optimization-based power controller
- Controller bandwidth depends on the operating point of the system
- Oscillatory operation under unbalanced grid voltage

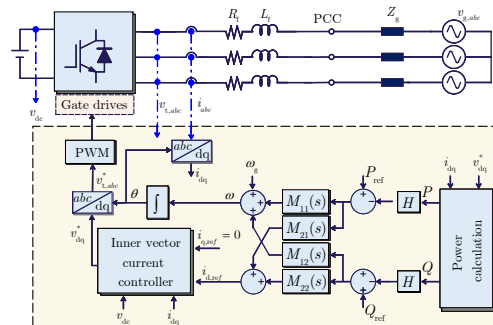
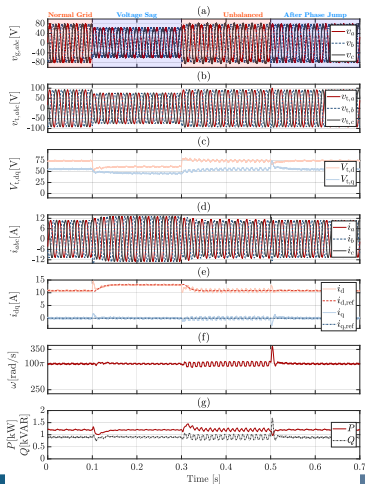


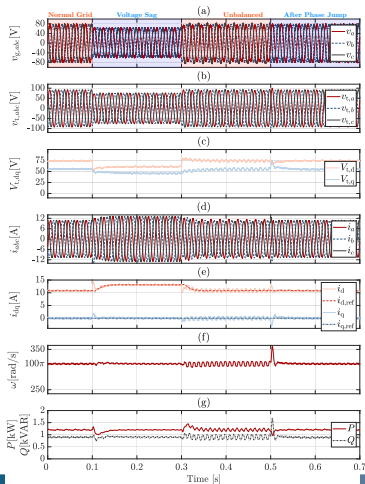
Figure 32: Power-Synchronized Grid-Following Inverters

Optimization-based Control (Configuration v1): Experimental Validation

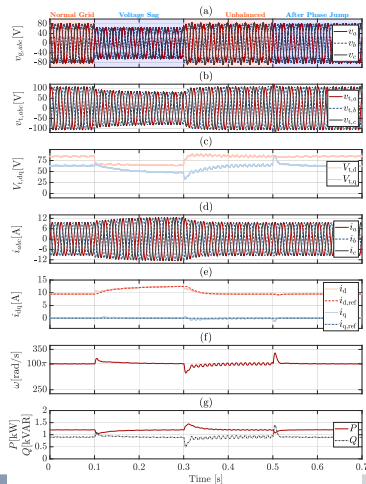
In a strong grid with SCR= 6.4



In a strong grid with SCR= 6.4



In a weak grid with SCR= 0.9



Linear Parameter-Varying Control (Configuration v2)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids
- Real-time tuning of the power controller

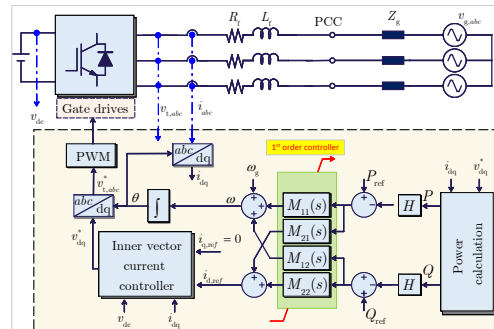


Figure 33: Linear Parameter-Varying Control PSGFLIs

M. Zarif Mansour, M. H. Ravanji, A. Karimi and B. Bahrani, "Linear Parameter-Varying Control of a Power-Synchronized Grid-Following Inverter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 2, pp. 2547-2558, April 2022.

Linear Parameter-Varying Control (Configuration v2)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids
- Real-time tuning of the power controller

Disadvantages

- Unstable operation under large Frequency deviations
- Oscillatory operation under unbalanced grid voltage

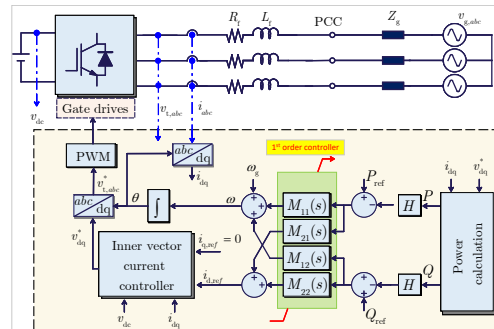


Figure 33: Linear Parameter-Varying Control PSGFLIs

M. Zarif Mansour, M. H. Ravanji, A. Karimi and B. Bahrani, "Linear Parameter-Varying Control of a Power-Synchronized Grid-Following Inverter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 2, pp. 2547-2558, April 2022.

Enhanced Frequency Control (Configuration v3)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids
- Real-time tuning of the power controller
- Stable operation even under large grid frequency deviations

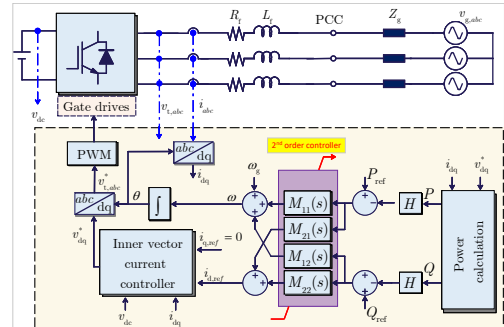


Figure 34: Enhanced Frequency control for PSGFLIs

N. Mohammed, M. H. Ravanji, W. Zhou and B. Bahrani, "Enhanced Frequency Control for Power-Synchronized Grid-Following PLL-less Inverters," Under review.

Enhanced Frequency Control (Configuration v3)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids
- Real-time tuning of the power controller
- Stable operation even under large grid frequency deviations

Disadvantages

- Oscillatory operation under unbalanced grid voltage

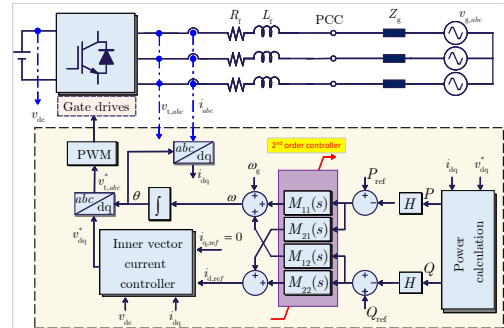
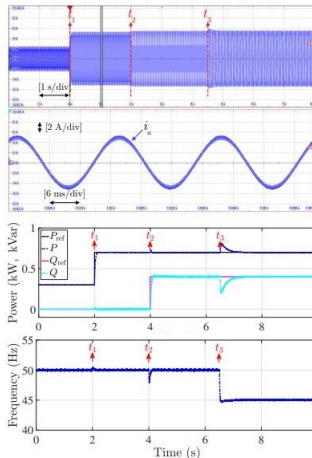


Figure 34: Enhanced Frequency control for PSGFLIs

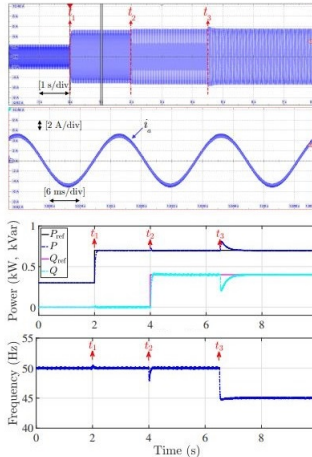
N. Mohammed, M. H. Ravanji, W. Zhou and B. Bahrani, "Enhanced Frequency Control for Power-Synchronized Grid-Following PLL-less Inverters." Under review.

Enhanced Frequency Control (Configuration v3): Experimental Validation

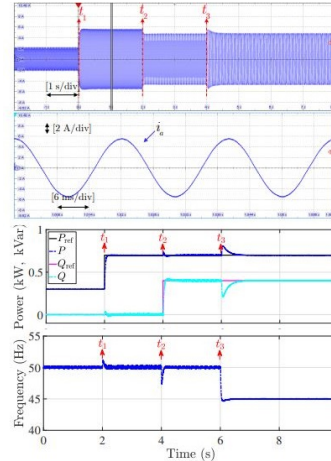
In a strong grid with SCR= 7.4



In a strong grid with SCR= 7.4



In a weak grid with SCR= 1.38



Double-Synchronous Control (Configuration v4)

Advantages

- A PLL-less control strategy
- Excellent performance in strong and weak grids
- Real-time tuning of the power controller
- Stable operation even under large grid frequency deviations
- Free-of-oscillation under unbalanced grid voltage

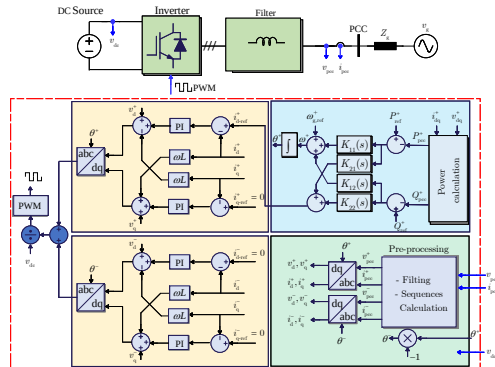


Figure 35: Double-Synchronous-Reference-Frame-Based for PSGFLIs

N. Mohammed, W. Zhou and B. Bahrani, "Double-Synchronous-Reference-Frame-Based Power-Synchronized PLL-Less Grid-Following Inverters for Unbalanced Grid Faults," Under review.

- ☐ Introduction
- ☐ Grid-following Inverters
- ☐ Grid-forming Inverters
- ☐ Power-Synchronized Grid-following Inverters
- ☐ **Synchronous Condenser (SynCon)**
- ☐ Project Summary

Introduction

Synchronous Condensers (SynCons) are synchronous machines without a prime mover.

Advantages

- Contribution of short-circuit power
- Voltage support (exciter)
- Providing inertia

Drawbacks

- Installation/operation costs
- Lead-time



Figure 36: <https://new.siemens.com/>

Optimal Allocation and Sizing

Procedure

- An objective function based on operational costs and voltage deviation is formulated.
- A meta-heuristic algorithm, such as GA, is used in one study.
- A convex optimisation approach is used in another study.

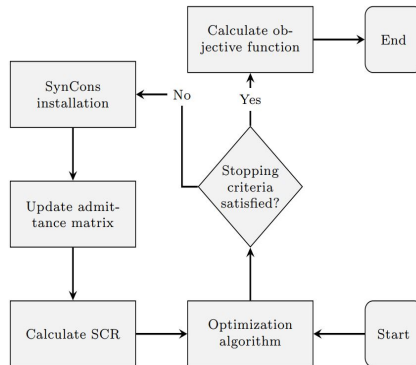


Figure 37: Flowchart of existing optimization procedures

S. Hadavi, M. Z. Mansour and B. Bahrani, "Optimal Allocation and Sizing of Synchronous Condensers in Weak Grids With Increased Penetration of Wind and Solar Farms," in *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 11, no. 1, pp. 199-209, March 2021.

S. Hadavi, J. Saunderson, A. Mehrizi-Sani and B. Bahrani, "A Planning Method for Synchronous Condensers in Weak Grids Using Semi-Definite Optimization," in *IEEE Transactions on Power Systems*, vol. 38, no. 2, pp. 1632-1641, March 2023, doi: 10.1109/TPWRS.2022.3174922.

Optimal Allocation and Sizing: Fault Ride Through Test

Fault Ride Through (FRT) Test without SynCons

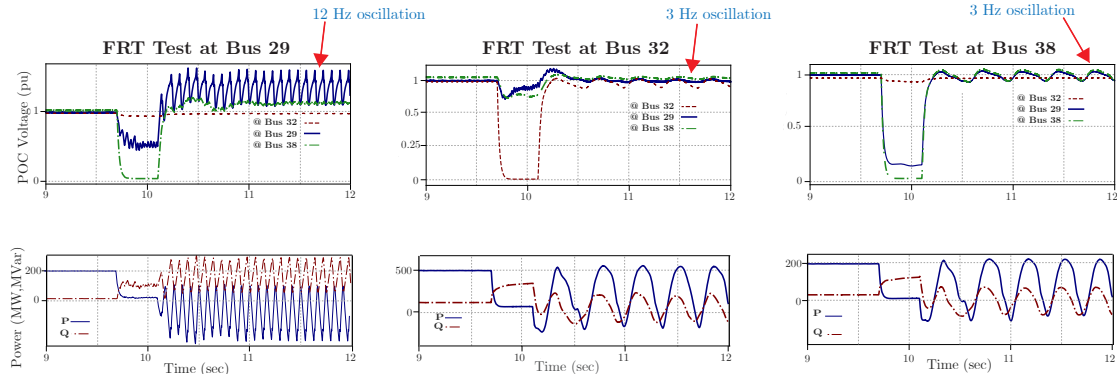


Figure 38: Fault Ride Through (FRT) Test without SynCons

Optimal Allocation and Sizing: Fault Ride Through Test

Fault Ride Through (FRT) Test with optimal SynCons

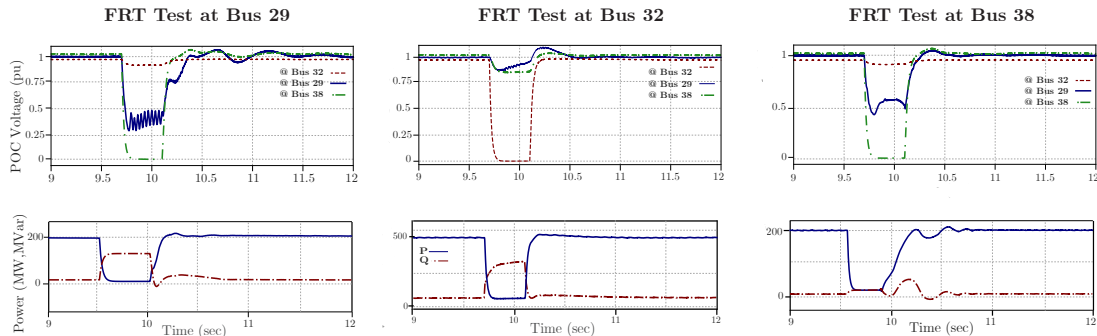


Figure 39: FRT test results with meta-heuristic approach

Optimal Allocation and Sizing: Fault Ride Through Test

Fault Ride Through (FRT) Test with optimal SynCons

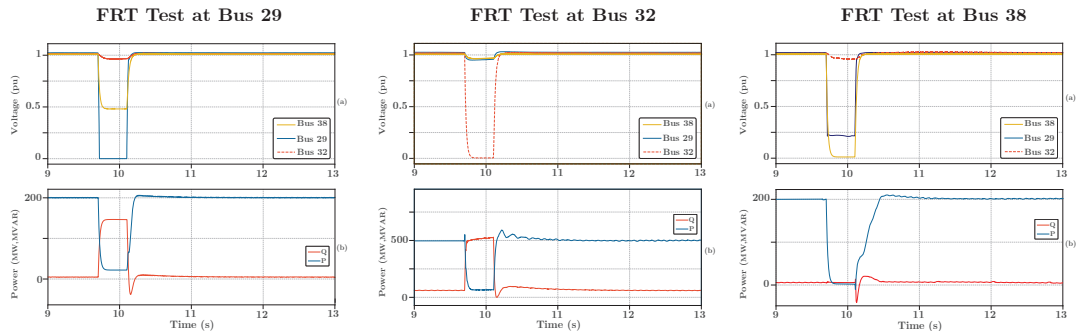


Figure 39: FRT test results with convex approach

A Data-Driven SynCon Exciter Control: Methodology

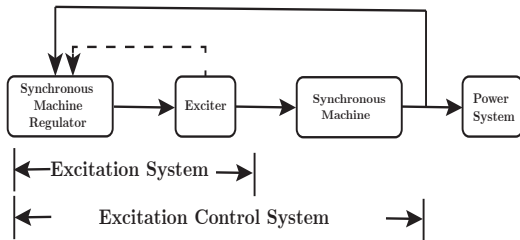


Figure 40: Block diagram of excitation control system

Particularly in weak grids, the exciter type and its tuning influence:

- response time,
- interaction with nearby farms,
- SSO in power systems.

S. Hadavi, D. B. Rathnayake, G. Jayasinghe, A. Mehrizi-Sani and B. Bahrani, "A Robust Exciter Controller Design for Synchronous Condensers in Weak Grids," in *IEEE Transactions on Power Systems*, vol. 37, no. 3, pp. 1857-1867, May 2022.

A Data-Driven SynCon Exciter Control: Methodology

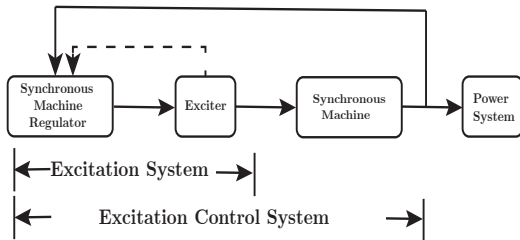


Figure 40: Block diagram of excitation control system

Particularly in weak grids, the exciter type and its tuning influence:

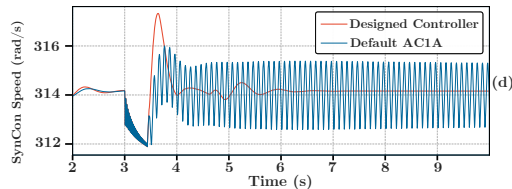
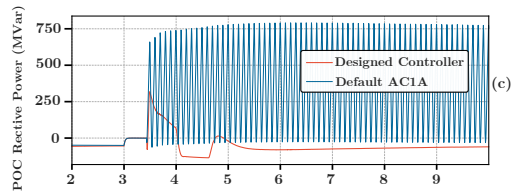
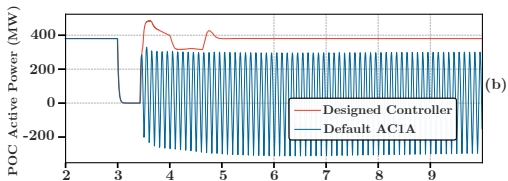
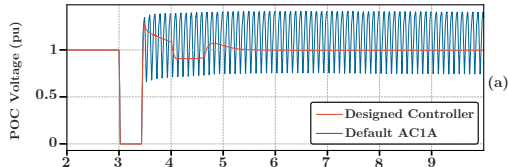
- response time,
- interaction with nearby farms,
- SSO in power systems.

Solutions

- a robust exciter controller, designed based on the system's frequency-domain model
- Considering system's model for different SCR and X/R ratios,

S. Hadavi, D. B. Rathnayake, G. Jayasinghe, A. Mehrizi-Sani and B. Bahrani, "A Robust Exciter Controller Design for Synchronous Condensers in Weak Grids," in *IEEE Transactions on Power Systems*, vol. 37, no. 3, pp. 1857-1867, May 2022.

A Data-Driven SynCon Exciter Control: Large Disturbance Tests



Simulation results when the FRT test is applied at PoC at $t=3$ s with a duration of 430 ms with the optimal designed exciter control and AC1A exciter



- ☐ Introduction
- ☐ Grid-following Inverters
- ☐ Grid-forming Inverters
- ☐ Power-Synchronized Grid-following Inverters
- ☐ Synchronous Condenser (SynCon)
- ☐ **Project Summary**

- For grid-following inverters (GFLIs), an **index to determine the stability** margin is proposed.
- A **modified PLL** is proposed for GFLIs that expands the stability margin of the system considerably.
- A **new breed of grid-following** inverters based on power synchronisation is proposed.
- A number of **control strategies for grid-forming** inverters (GFMLs) are proposed.
- Output capability curves for grid-forming and grid-following inverters are determined.
- Two **allocation** techniques and an **exciter** control design for SynCons are also proposed.

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Thank you for your attention!

Q/A