Improving the Grid System Stability with High Renewable Energy Penetration using Virtual Inertia

. Abdullah Al-Badi, Ahmed Al-Farsi , Hassan Yousef , Abdelsalam El Haffar, Razzaqul Ahshan

Sultan Qaboos University

College of Engineering

Department of Electrical & Computer Engineering

Outline

- Introduction
- Problem Statement
- Objective
- Methodology
- Developed Models
- Simulation Results
- Conclusion and Future work

Introduction

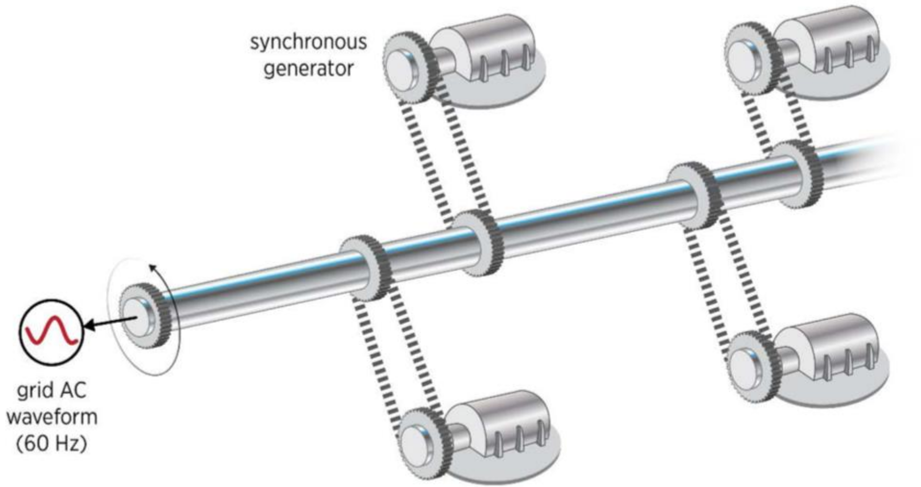
- In order to maintain operational security of the power system its frequency must stay within a predefined range. If the frequency is not held near its nominal value, protection systems begin to activate in order to protect machinery, and to keep the power system operational.

- Synchronous generators help the power system to resist changes in system frequency due totheir kinetic energy. However, as renewable production begins to replace conventional production, the ability of the system to resist these changes decreases.

Introduction

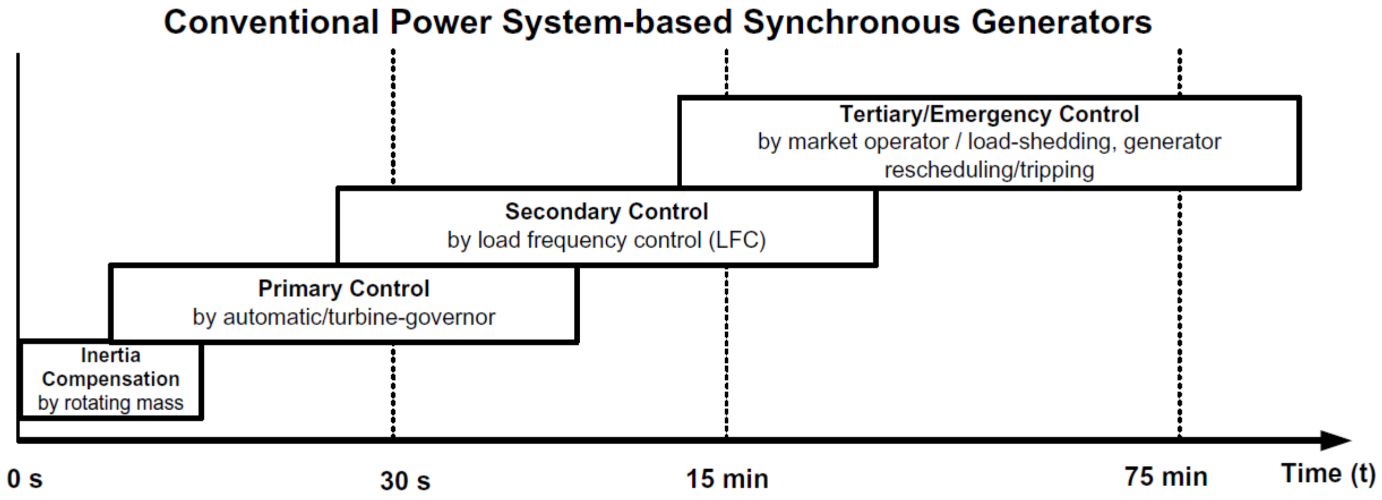
- Inertia in power systems refers to the energy stored in large rotating generators and some industrial motors, which gives them the tendency to remain rotating, this energy can be tapped for a few seconds to provide the grid time to respond to power plant or other system failures.

The Concept of Synchronous Generators Working Together in an Electrical Grid



In a power grid, inertia is derived from hundreds or thousands of generators that are synchronized, meaning they are all rotating in lock step at the same frequency

Timescale of Frequency Dynamic Control for Conventional Power Systems



Clean Energy

- The demand for clean energy in the modern power system increases, driven by factors such as fuel prices, laws, and regulations
- The modern power system is moving from a synchronous machine-based system towards an inverter-dominated system, with large-scale penetration of renewable energy sources (RESs) like wind and photovoltaics.

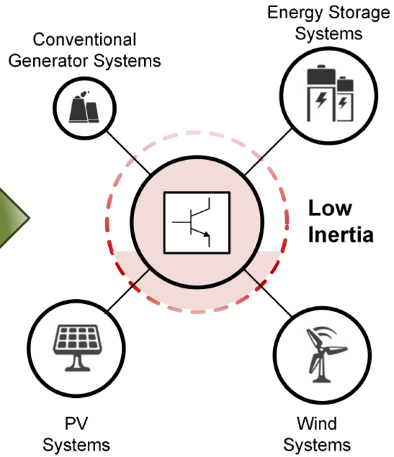
Power System Stability

- Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a disturbance.

- Countries are transitioning from conventional power systems towards converter-interfaced generators. With this transformation, thus making the system dynamic response progressively faster and more complex.

Future Power Stations

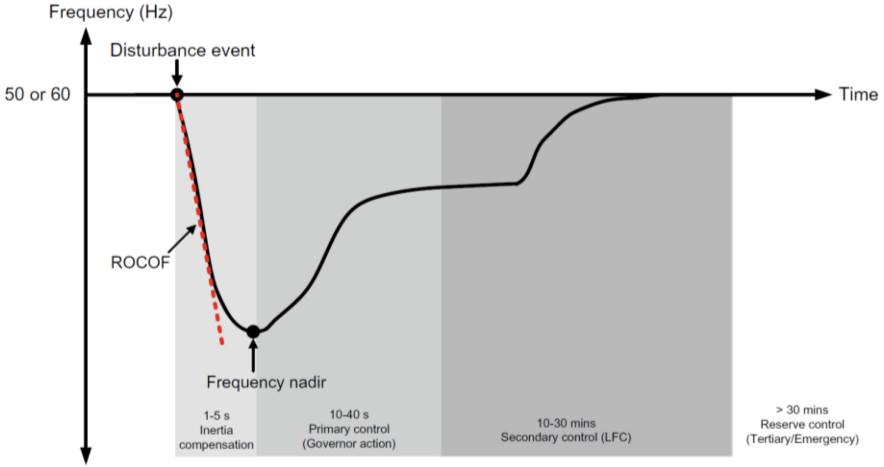
Conventional Power Stations



Modern wind turbines are operated as variable speed and interfaced through back-to-back converters, completely decoupling the inertia from the grid. Similarly, PV systems and BESSs have a DC-DC converter and an inverter in the front-end, and do not contribute to the inertial response

Source: U. Tamrakar, D. Sharestha and M. Maharjan, " Virtual Inertia: Current Trends and Future Directions," *Applied Sciences*, vol. 7, no. 7, pp. 654, 2017, doi: 10.3390/app7070654

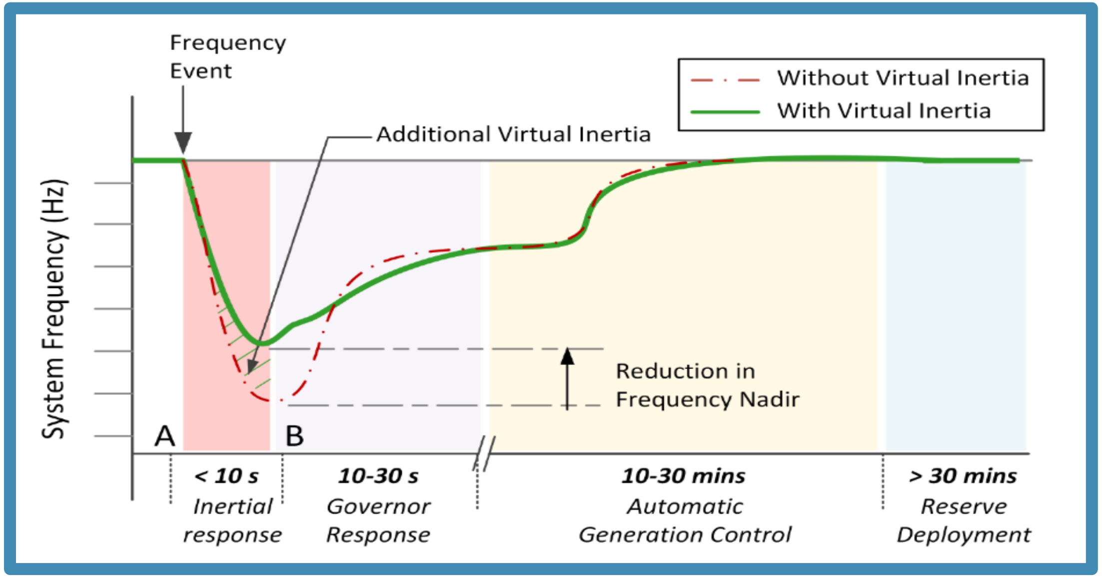
Frequency response in a power system following a Frequency Event



- Whenever there is an imbalance between the generation and consumption in a power system, the generators cannot respond instantaneously. The kinetic energy stored in the rotors is responsible for counteracting this imbalance through inertial response until the primary control respond
- The governor response is the primary control action typically 10–30 s
- The automatic generation control is the secondary control action typically 10–30 min

Source: U. Tamrakar, D. Sharestha and M. Maharjan, " Virtual Inertia: Current Trends and Future Directions," *Applied Sciences*, vol. 7, no. 7, pp. 654, 2017, doi: 10.3390/app7070654

Frequency response in a power system following a Frequency Event with Renewable



Source: Tamrakar, U.; Shrestha, D.; Maharjan, M.; Bhattarai, B.P.; Hansen, T.M.; Tonkoski, R. Virtual Inertia: Current Trends and Future Directions. *Appl. Sci.* **2017**, *7*, 654. https://doi.org/10.3390/app7070654

Concept of Virtual Inertia

The frequency variation in a power system after a frequency disturbance can be approximated by the swing equation:

$$P_{gen} - P_{load} = \frac{d(E_{K.E.})}{dt} = \frac{d(\frac{1}{2}J\omega_g^2)}{dt}$$

$$\frac{2H}{f}\frac{df}{dt} = \frac{P_{gen} - P_{load}}{S_g}$$

$$H_i = \frac{E_{kinetic}}{S_{SGi}} = \frac{J_S\omega^2}{2S_{SGi}}$$

For synchronous generators

$$H = \frac{\sum_i (H_i S_{SGi})}{S_{PS}}$$

H: Inertia Constant, second

J: System moment of inertia, kg.m2

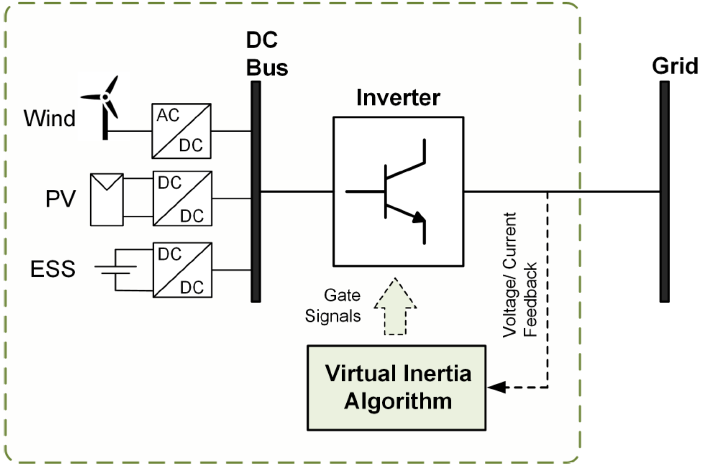
Inertia considering generators+ CIGs:

$$H_{eq} = \frac{\overbrace{\sum_{i=1}^{N_{SG}} H_{SG,i} S_{B,i}}^{(SGs)} + \overbrace{\sum_{j=1}^{N_{CIG}} H_{CIG,j} S_{B,j}}^{(CIGs)}}{\sum_{i=1}^{N_{SG}} S_{B,i} + \sum_{j=1}^{N_{CIG}} S_{B,j}}$$

CIG: converter-interfaced generation

Source: U. Tamrakar, D. Sharestha and M. Maharjan, " Virtual Inertia: Current Trends and Future Directions," *Applied Sciences*, vol. 7, no. 7, pp. 654, 2017, doi: 10.3390/app7070654

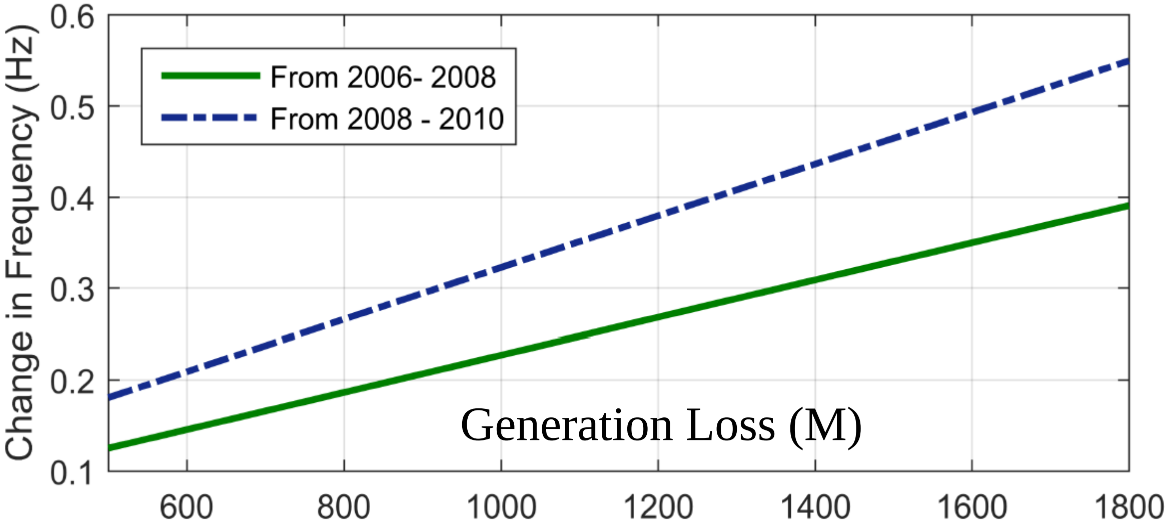
Concept of Virtual Inertia



Why most of modern wind turbines are not contributed to the inertia?

Source: U. Tamrakar, D. Sharestha and M. Maharjan, " Virtual Inertia: Current Trends and Future Directions," *Applied Sciences*, vol. 7, no. 7, pp. 654, 2017, doi: 10.3390/app7070654

Power System Inertia



The change in frequency per generation loss is increasing yearly with increased RES penetration for ERCOT

Source: Electricity Reliability Council of Texas (ERCOT). Future Ancillary Services in ERCOT; ERCOT: Taylor, TX, USA, 2013.

Renewable Energy Projects in Oman

WIND Farms

JBB (100 MW, 2026)

Duqm Wind (200 MW, 2026)

Dhofar I (50 MW, 2019)

Dhofar II (100 MW, 2026)

Ras Madrakah (200MW, 2027)

Wind(200MW, 2029)

Total = 850 MW

PV Power Plants

IBRI (500 MW, 2021)

PV, Manah I & II 2025 (1000 MW)

IBRI II PV(500MW, 2026)

Al Kamil PV(500MW, 2027)

PV(1000 MW, 2029)

Total = 3500 MW

The Sultanate aims to raise the level of renewable energy contribution to the total energy demand to reach 20% by 2030.

The intermittent nature of renewables with this level of contribution may lead to grid instability, especially when weather fluctuations occur.

Renewable Energy Development Plan – MIS and Duqm

	2023	2024	2025	2026	2027	2028	2029
Contracted Projects	MW						
Ibri II Solar IPP[a]	500	500	500	500	500	500	500
Total Contracted Capacity	500	500	500	500	500	500	500
Planned Projects							
Manah I Solar IPP [a]			500	500	500	500	500
Manah II Solar IPP [a]			500	500	500	500	500
Ibri III Solar IPP					500	500	500
JBB Wind IPP [b]					100	100	100
Duqm Wind IPP [b]					200	200	200
Ras Madrakah Wind IPP [b]					200	200	200
MIS Solar IPP 2027					500	500	500
Barka WTE IPP						140	140
Solar PV IPPs 2029							1000
Wind IPP 2029							200
Total Planned Capacity	-	-	1000	1000	2500	2640	3840
RE Day Peak Contribution[a]	**460**	**460**	**1250**	**1250**	**2413**	**2540**	**3464**
RE Night Peak Contribution	**-**	**-**	**-**	**-**	**287**	**414**	**536**

Source: NPWP's 7-YEAR STATEMENT (2023-2029)

Objective

- Analyze the impact of renewable energy sources on power system inertia and the rate of change of frequency (RoCoF) of the main interconnected system (MIS)
- Developed solution to enhance the system inertia
- Test the developed solution under high level of renewable penetration on the MIS

Renewable Energy Development Plan – MIS and Duqm

	2023	2024	2025	2026	2027	2028	2029
	MW						
Contracted Capacity	7,511	6,823	6,823	6,823	6,823	5,323	3,305
Capacity Contributions from:							
Non - Firm Contracts	380	200	200	200	200	200	200
RE Capacity Contribution (Day)	460	460	1,250	1,250	2,413	2,540	3,464
RE Capacity Contribution (Night)	-	-	-	-	287	414	536
Procurement Plans and Spot Market	-	428	790	1,137	1,020	2,529	4,682
Total Capacity Available during Day Peak	**8,351**	**7,911**	**9,063**	**9,410**	**10,456**	**10,592**	**11,653**
Total Capacity Available during Night Peak	**7,891**	**7,451**	**7,813**	**8,160**	**8,330**	**8,466**	**8,725**

Source: NPWP's 7-YEAR STATEMENT (2023-2029)

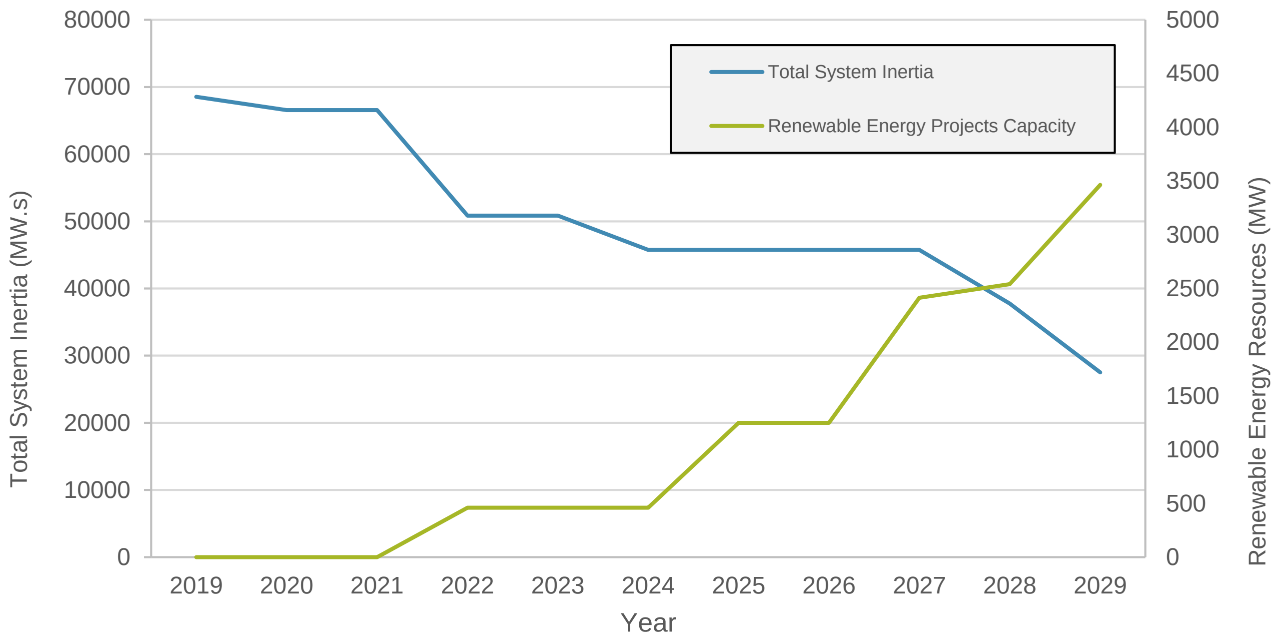
Challenges

The high-level penetration of RES to the system

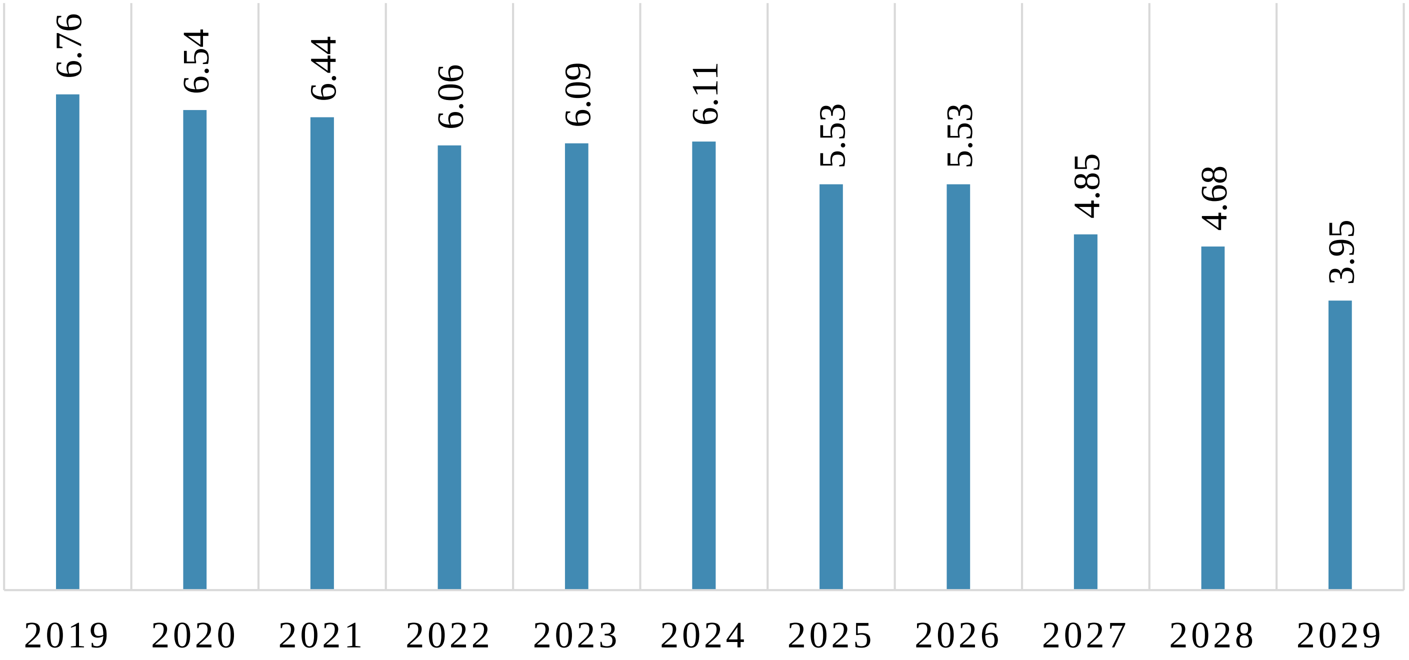
- ❑ Reduction of the system **overall inertia**.
- ❑ Increasing the rate of change of frequency (**ROCOF**) that can activate load-shedding controller, even at **small load-generation mismatch**.

Many techniques have been proposed to mitigate the effects of low inertia on the frequency of modern grids (RES and conventional power systems).

MIS Inertia Level Estimation



MIS Inertia Constant (H) Estimation



Transmission Security Standard

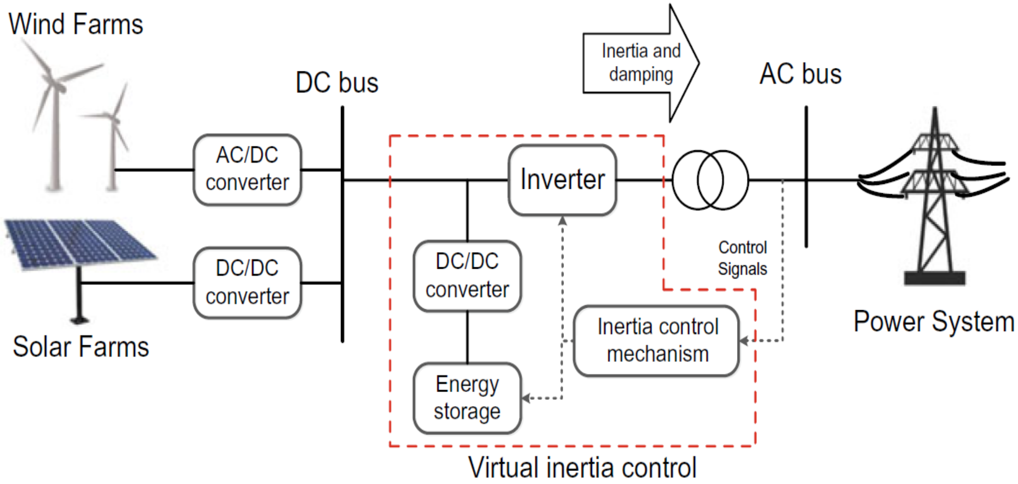
Table 2.1 – OETC licensed transmission system – system parameter values

Quality of Supply – System Parameter values													
Parameter	Unacceptable conditions	Stretched conditions		Disturbed conditions		Normal conditions			Disturbed conditions		Stretched conditions		Unacceptable conditions
		Low	High	Low	High	Low	Target	High	Low	High	Low	High	
	<	≥	<	≥	<	≥		≤	>	≤	>	≤	>
Frequency Hz	47.50	47.50	49.50	49.50	49.95	49.95	50.00	50.05	50.05	50.50	50.50	51.50	51.50
		Less than 60 seconds									Less than 60 seconds		
Voltage kV	380	380		390			400	410			420		420
	198	198		209			220	231			242		242
	119	119		125			132	139			145		145

MICROGRID STABILITY CONTROL STRATEGIES

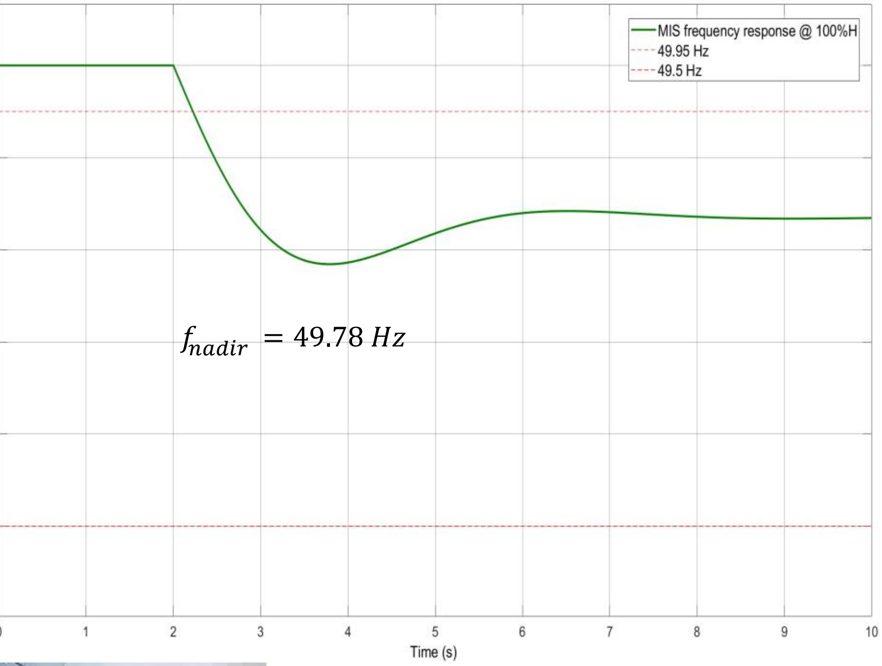
The power output from a virtual inertia control module can be described as

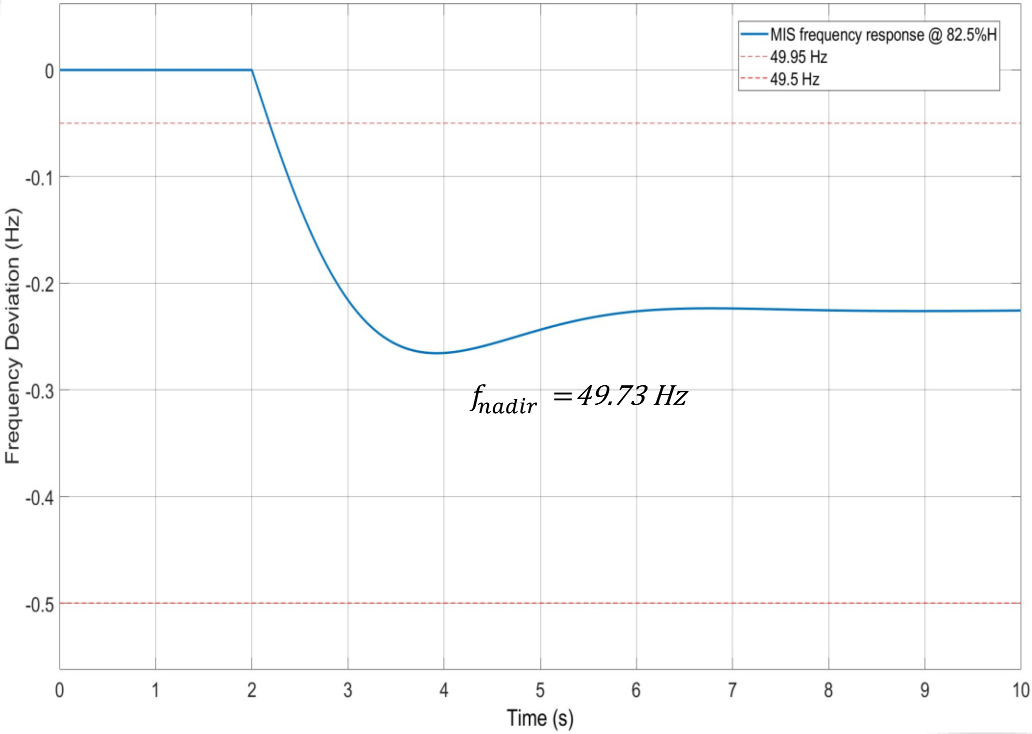
$$P_{VI} = K_{VI}\frac{d\Delta f}{dt} + D_{VI}\Delta f + P_0$$



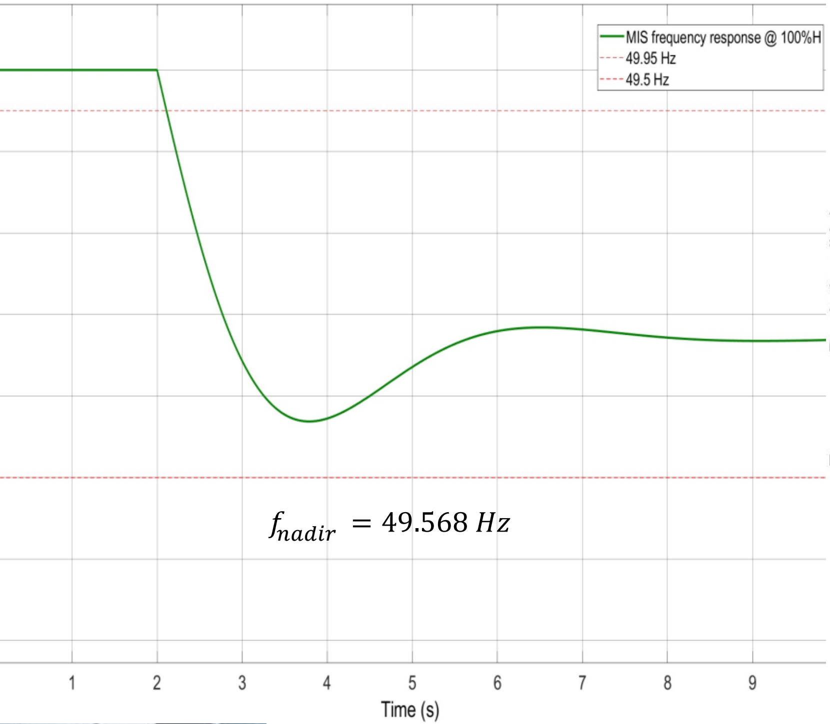
$d\Delta f/dt$ represents the Rate of Change of Frequency (ROCOF)
f_0 denotes the system's standard frequency.
K_{VI} the virtual inertia constant.
D_{VI} the virtual damping coefficient.
P_{Inv} the power output from a virtual inertia control
P_0 the primary power directed to the inverter

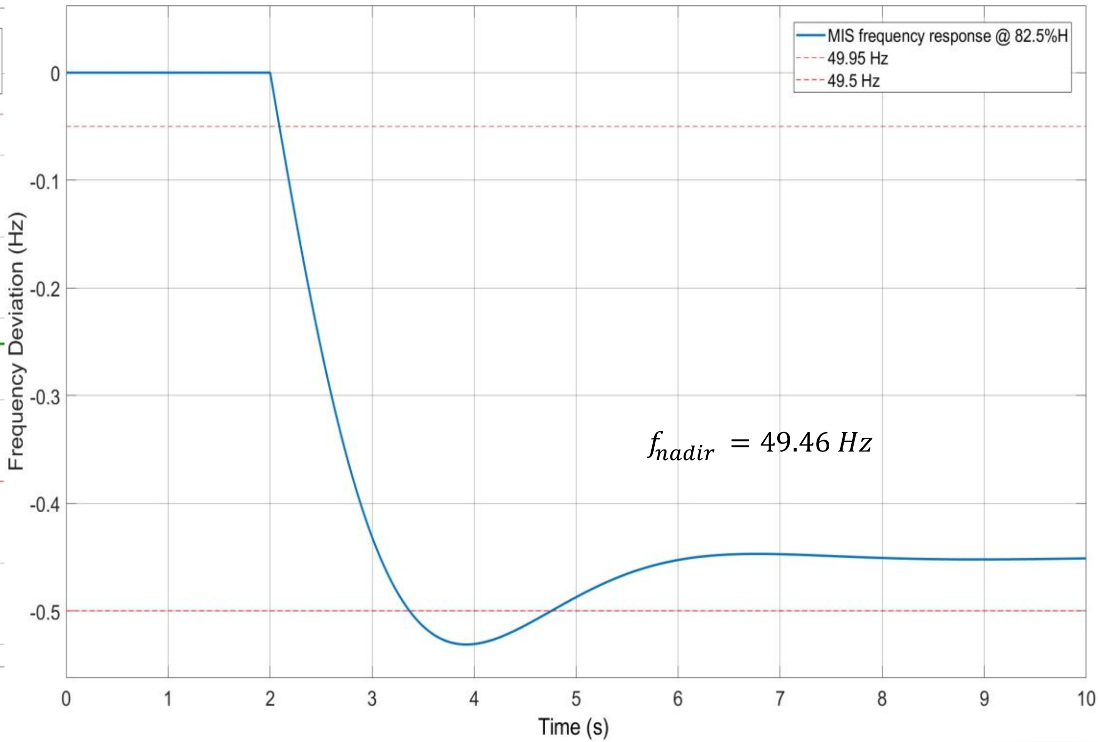
MIS Frequency Response for 5% Step Load
(a) at 100% Inertia, (b) at 82.5% Inertia



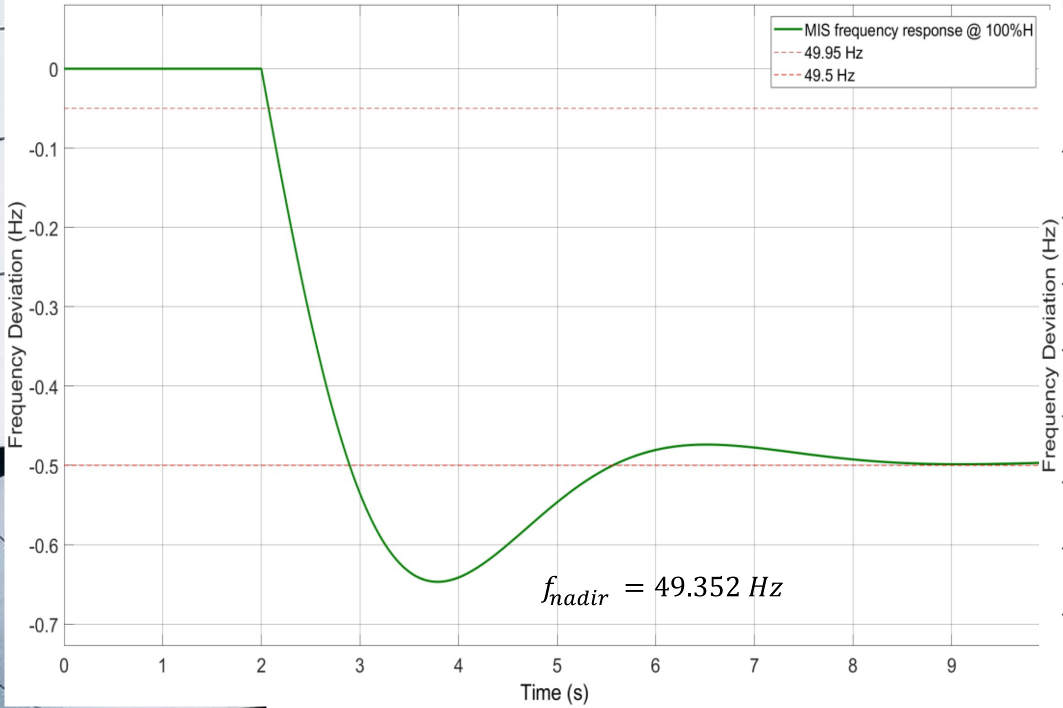


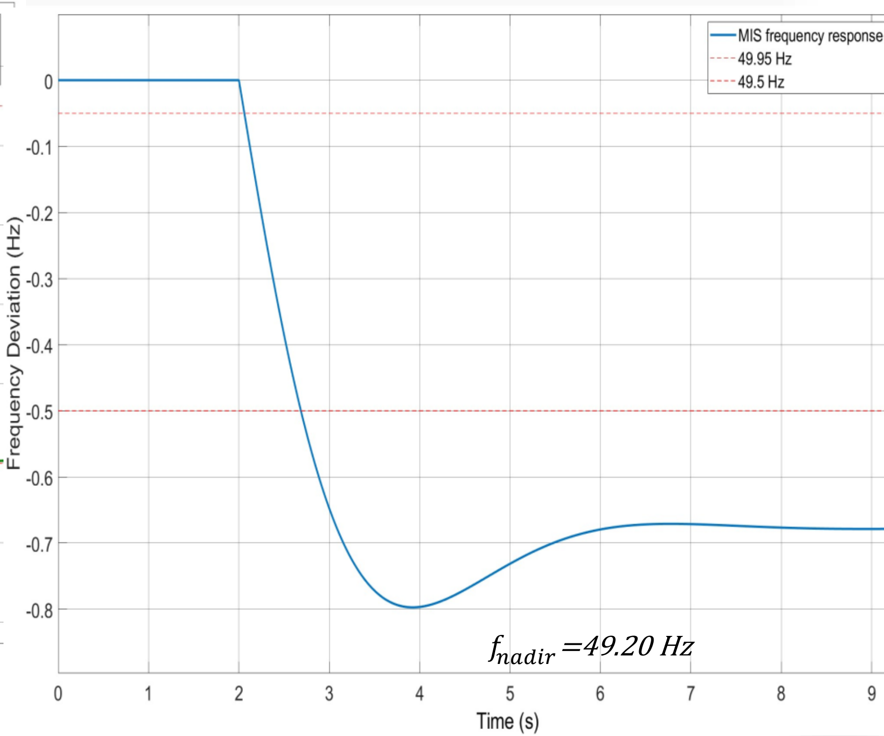
MIS Frequency Response for 10% Step Load (a) at 100% Inertia, (b) at 82.5% Inertia





MIS Frequency Response for 15% Step Load (a) at 100% Inertia, (b) at 82.5% Inertia

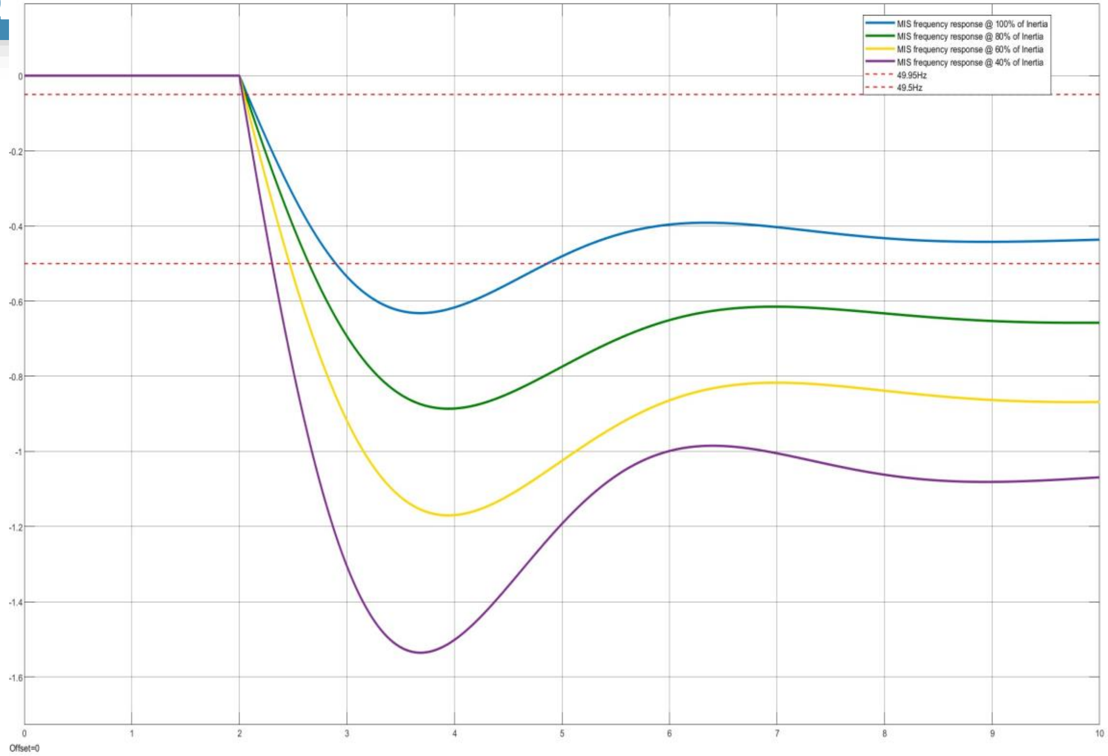




Summary of MIS Frequency Response Simulations-2025

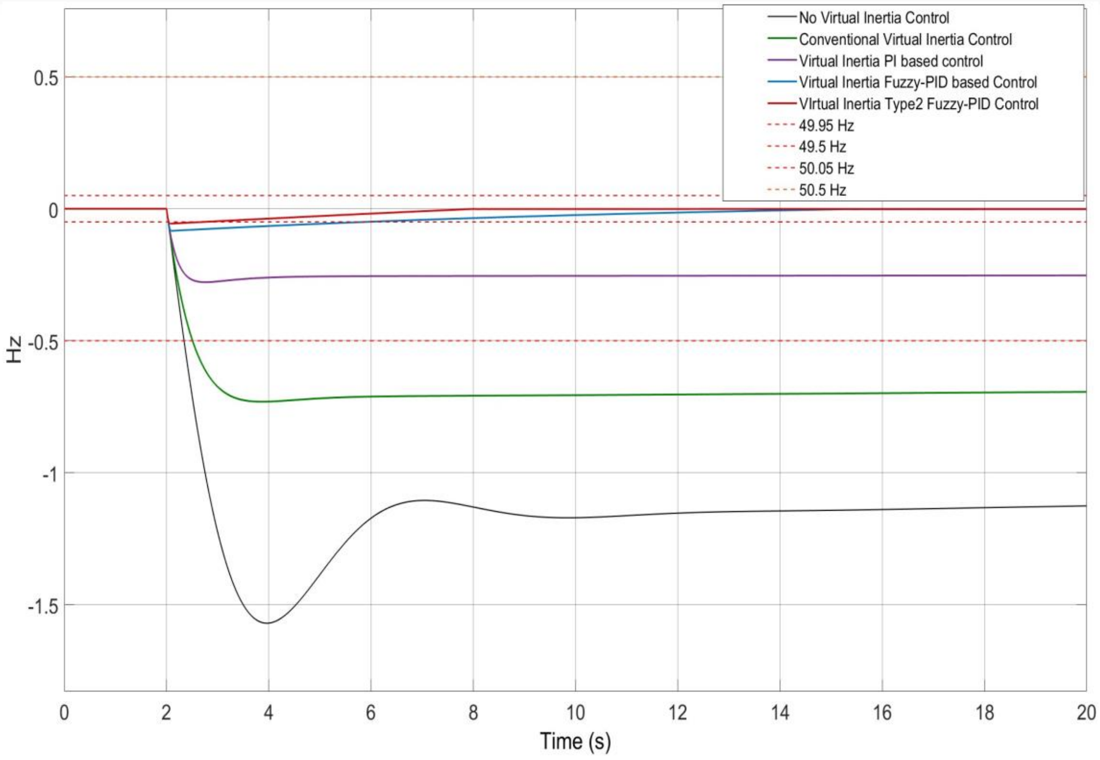
Step Load	100% Inertia	82.5% Inertia
5%	49.78	49.73
10%	49.568	49.46
15%	49.352	49.20
20%	49.093	48.94
30%	48.7	48.342

MIS Frequency Response for 15% addition of sudden load

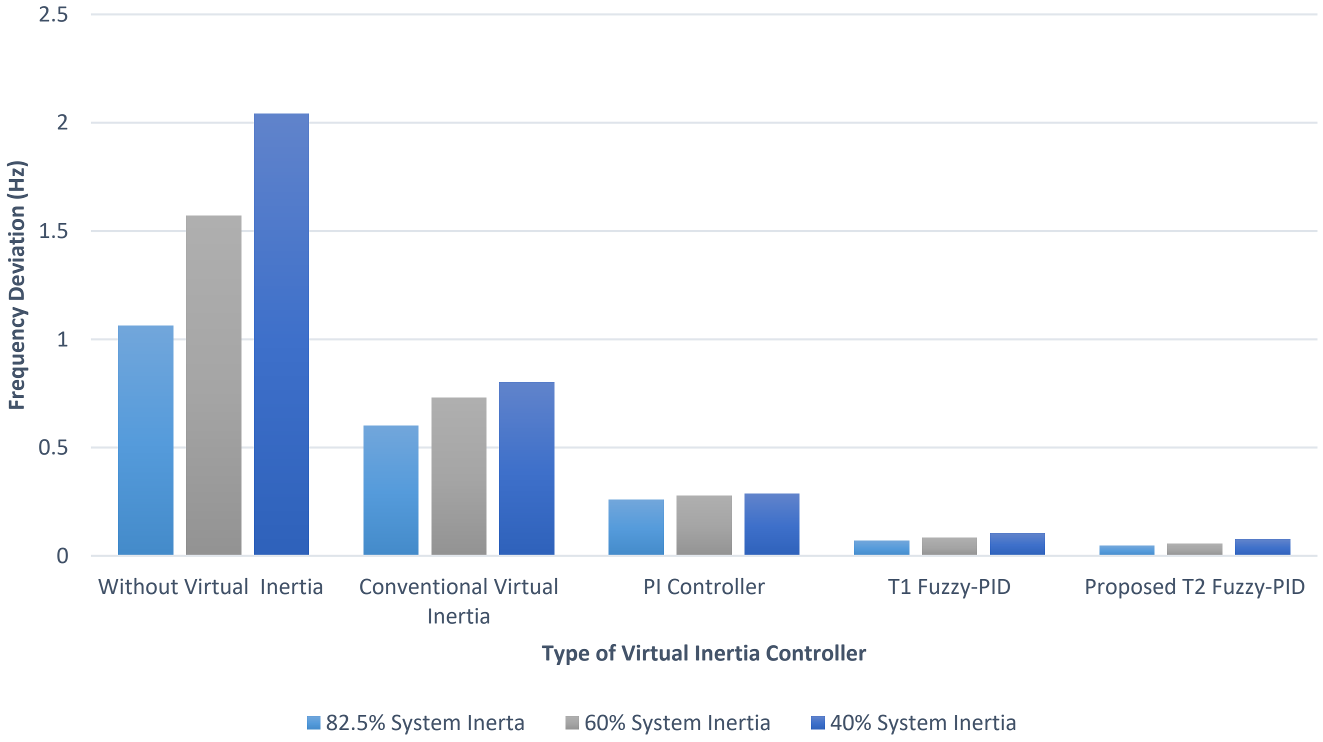


MIS Frequency Response for 15% sudden load addition at Different Levels of System Inertia

MIS Frequency Response for 20% addition of sudden load at 60% System Inertia



MIS Frequency Deviation at 20% Step Load with Different Types of VI Controllers



Conclusion and Recommendations

- The impact of renewable energy on the MIS inertia was studied.
- The research identified a reduction in grid inertia resulting from the growing use of inverter-based generators, which do not contribute inertia to the grid.
- Adopting the principle of virtual inertia and its implementation in the MIS to improve the frequency response is recommended.
- The study developed a virtual inertia control system utilizing Type 2 fuzzy logic controllers, presenting a promising approach to managing the challenges posed by high levels of renewable energy penetration.

Thank you