Strategies For Improving the Inertia of Power Systems for Which Renewable Energy Is the Predominant Source

Benin George [1]

Research Scholar, Department of M Tech Electrical Engineering,
Sri Satya Sai University of Technology and Medical Sciences, Bhopal, M.P, India.

Dr Alka Thakur [2]

Research Guide, Department of M Tech Electrical Engineering,
Sri Satya Sai University of Technology and Medical Sciences, Bhopal, M.P, India

ABSTRACT

The global shift towards renewable energy sources (RESs) introduces challenges in maintaining system inertia and frequency stability in modern power systems. Traditional synchronous generators, which inherently provide mechanical inertia, are increasingly replaced by converter-based renewable generation, resulting in low-inertia grids prone to frequency deviations. This research addresses these challenges by proposing virtual inertia strategies using Battery Energy Storage Systems (BESS) and Supercapacitor Energy Storage Systems (SESS). Advanced control methods, including Frequency-Locked Loop (FLL) based frequency derivative estimation, are implemented to emulate inertial responses effectively. Distributed control schemes are developed for coordinated ESS operation, improving frequency nadir and reducing Rate of Change of Frequency (RoCoF). Simulation and experimental validation using MATLAB/Simulink and real-time setups confirm the practicality of the proposed strategies. This study contributes to enhancing power system resilience, offering solutions for dynamic stability in grids with high renewable penetration while addressing secondary concerns like voltage stability and harmonic distortions.

Keywords: *Virtual Inertia, Battery Energy Storage Systems (BESS), Frequency Stability, Low-Inertia Grids, Renewable Energy Integration, Frequency-Locked Loop (FLL)*

Introduction

Renewable energy sources (RESs) are essential to power system transformation due to the global need to reduce carbon emissions and fossil fuel use. Integrating renewable generation, especially through power electronic converters, provides dynamic problems, including reducing system inertia. The mechanical inertia of traditional synchronous generators absorbs or releases kinetic energy during disturbances to stabilize frequency. Renewable sources connected via converters reduce natural inertia, making power systems subject to frequency variations and instability. The power sector is adopting sustainable, resilient smart grids. PV and wind energy have grown rapidly, becoming crucial to worldwide energy policies. However, without physical inertia like synchronous generators, these renewable sources pose frequency stability problems, especially at high penetration levels. Converters are necessary for renewable integration but have little inertia, making frequency stability and control harder.

Literature Review

The integration of renewable energy sources into electrical grids, primarily through power electronic converters, has led to notable decreases in natural system inertia, exacerbating challenges related to frequency stability. Existing literature extensively addresses this issue, presenting various strategies aimed at improving grid inertia and stability.

Traditional and Synchronous Methods

Historically, synchronous generators have provided mechanical inertia critical for grid stability. Research by Tang et al. (2021) highlights how synchronous condensers, despite their high costs and slower response times, have been used to offer minimal inertia support. These devices can store kinetic energy that stabilizes the grid, though their practicality is limited due to economic constraints and operational complexity.

Renewable Energy Integration Challenges

Studies by Ghazal et al. (2021) and Wang et al. (2021) underscore the complexity introduced by renewable energy systems like solar photovoltaic (PV) and wind energy, primarily due to their inherent lack of mechanical inertia. Solar PV systems particularly face limitations since they rely on Maximum Power Point Tracking (MPPT), which does not inherently support frequency stabilization without deliberate curtailment, leading to economic drawbacks as discussed by the California Independent System Operator (CAISO).

Conversely, wind turbines inherently store kinetic energy in rotating components, which can be harnessed for inertia emulation through advanced control strategies. Research such as that by Liu et al. (2019) emphasizes the potential of Doubly-Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) in providing synthetic inertial response. However, managing rotor speed and preventing turbine stalling remain critical issues requiring innovative solutions.

Energy Storage Solutions

Energy storage systems (ESS), such as batteries and supercapacitors, have emerged as viable solutions for inertia emulation due to their rapid response capabilities. Battery Energy Storage Systems (BESS), discussed by Smith et al. (2020), effectively address frequency stability by adjusting active power outputs based on real-time frequency deviations. Challenges remain in accurate frequency derivative estimation, an issue mitigated by employing Frequency-Locked Loops (FLL) as demonstrated in studies by Kumar et al. (2022).

Supercapacitors, characterized by high power density and rapid charge-discharge cycles, have been explored for their potential in stabilizing frequency under significant disturbances. Nonlinear adaptive control strategies proposed by Zhang et al. (2021) have shown promise in enhancing the dynamic response and robustness of these systems.

Virtual Synchronous Generators

Virtual Synchronous Generators (VSGs) represent advanced control strategies designed to replicate the behavior of synchronous machines through inverter-based systems. Research by Liu and Wang (2021) illustrates the efficacy of VSGs in providing adjustable inertia and improving transient responses. The challenge of integrating these systems with finite energy storage capacity is highlighted as an area requiring further exploration.

Methodology Overview

The research employs hierarchical control structures, combining inner loop current control with outer loop virtual inertia mechanisms. Virtual inertia is emulated by linking the active power output of energy storage systems to the rate of frequency change. Detailed simulations using MATLAB/Simulink and experimental validations via scaled test setups underpin the theoretical developments.

Examination of Inertia in Electrical Power Systems

Inertia is a crucial component in maintaining frequency stability within electrical power systems, especially during transient disturbances or sudden imbalances between generation and load. Traditionally, inertia is provided by synchronous generators whose rotating masses store kinetic energy, released or absorbed to counteract frequency deviations [1]. The diminishing natural inertia due to increased reliance on renewable energy sources (RES), interfaced predominantly through power electronic converters, has necessitated a detailed examination of inertia's role and potential solutions to augment it.

Importance of System Inertia

System inertia is quantitatively expressed through the inertia constant (H), representing the kinetic energy available in synchronous generators relative to system capacity. Higher inertia constants indicate greater resistance to frequency changes, allowing more time for corrective control actions. [2]. Studies indicate that systems with high inertia exhibit lower rates of change of frequency (RoCoF) and improved frequency nadirs during disturbances.

Effects of Reduced Inertia

The integration of renewable energy sources, primarily wind and solar, has significantly lowered system inertia, intensifying frequency stability issues. Lower inertia levels lead to rapid frequency fluctuations, potentially causing premature activation of protective relays or cascading outages. For example, grid operators, such as those in the UK, have revised their RoCoF thresholds upward to accommodate higher renewable penetration, highlighting the operational challenges posed by reduced inertia.

Methods for Enhancing System Inertia

Several methods have been explored to enhance or emulate inertia:

1. **Synchronous Condensers:** These devices provide mechanical inertia but have limitations due to high costs and slower response capabilities, restricting their widespread adoption.
2. **Wind Energy Systems:** Wind turbines can leverage inherent kinetic energy in rotating blades to emulate inertia. Control strategies for Doubly-Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) allow effective inertia emulation. However, managing rotor speed during frequency events remains a critical challenge.
3. **Solar Photovoltaic (PV) Systems:** Typically lack inherent inertia and primarily use Maximum Power Point Tracking (MPPT), which does not support active power regulation without economic penalties from power curtailment.
4. **Energy Storage Systems (ESS):** Battery Energy Storage Systems (BESS) and Supercapacitor Energy Storage Systems (SESS) provide rapid power response capabilities crucial for emulating inertia. Batteries utilize Frequency-Locked Loops (FLL) to achieve noise-resistant frequency derivative estimations, improving grid stability.
5. **Virtual Synchronous Generators (VSGs):** Inverter-based devices designed to mimic synchronous generators, providing adjustable and scalable virtual inertia. These systems effectively manage transient responses and enhance frequency stability through advanced control mechanisms.

EXAMINATION OF INERTIA IN ELECTRICAL POWER SYSTEMS

Electrical network stability depends on power system inertia, notably during power generation or consumption spikes. This chapter discusses frequency regulation and power system inertia in conventional and modern power grids.

Synchronous machines' spinning masses offer power system inertia by opposing mechanical momentum-induced frequency changes. Inertial reaction acts as the first frequency variation protection after a disturbance. The chapter begins with how inertia stores or releases kinetic energy to balance power and frequency. High system inertia reduces frequency shifts and provides operators more time to respond with secondary controls.

The system's inertia has decreased as wind and solar power are integrated, many of which are interfaced through power electronics and lack inherent inertia. This drop makes frequency regulation difficult and requires creative approaches to improve or reproduce inertia in low-inertia power systems.

Influence of Inertia on Frequency Regulation

To appreciate the role of inertia in frequency regulation, it is important to first understand the basic dynamics of frequency control in conventional power systems. As illustrated in Fig. 1, the framework typically includes traditional synchronous generators driven by reheat steam turbines. The regulation process is modeled using standard equations for speed governors and reheat turbines, as outlined by [5]. In these models, the prefix Δ denotes a change in the variable, and the subscript "pu" indicates per-unit system values.

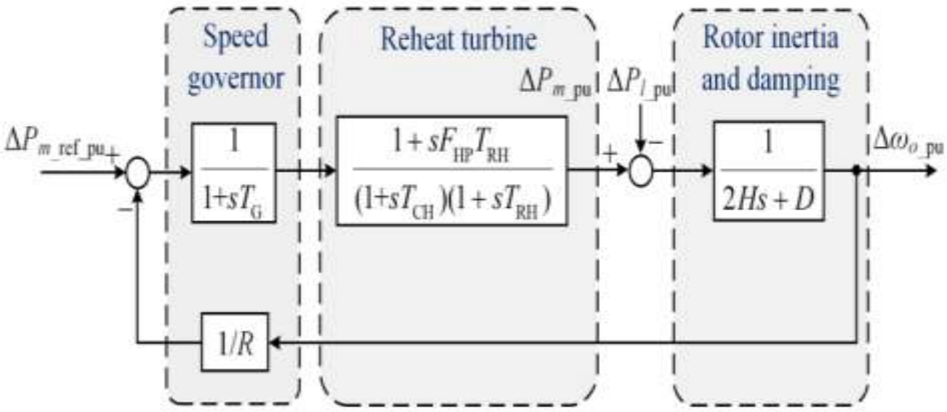

Figure 1: Framework for Regulating Frequency

Table 1: Framework Parameters for Regulating the Frequency of Synchronous Generators

Description	Symbol	Value
Frequency-droop coefficient	R	0.05
Speed governor coefficient	T_G	0.1 s
Turbine HP coefficient	F_{HP}	0.3 s
Time constant of reheater	T_{RH}	7.0 s
Time constant of main inlet	T_{CH}	0.2 s
Load damping coefficient	D	0/1.0
Inertia constant	H	0.1 - 5.0 s
Rated frequency	f_{ref}	50 Hz

Collectively, the findings affirm that both the inertia constant H and damping factor D are vital for evaluating frequency performance. The inertia constant H particularly stands out as a key metric for quantifying system inertia. From an operational standpoint, enhancing inertia—either naturally through synchronous machines or artificially via virtual inertia technologies—translates to increasing H, which strengthens the grid's ability to handle frequency disturbances.

Current Methods for Inertia Augmentation

With the growing use of renewable energy sources, which lack inertia, power system research has focused on inertia augmentation and modeling. System stability becomes more difficult when wind and solar replace synchronous generators. Several methods have been proposed to increase or imitate system inertia. These solutions compensate for synchronous generator mechanical inertia and stabilize the grid during transient disruptions.[7]

Synchronous Generators

Synchronous generators, which can produce active and reactive power, are the most common approach for inertia augmentation. The rotating rotors of synchronous generators store kinetic energy. Energy discharged during transient events like frequency changes can stabilize the grid. Synchronous generators are ideal for inertia enhancement because their rotational speed and mass directly affect inertial energy [6]. Synchronous generators supply kinetic energy, however during transitory events, it may not be enough. Synchronous generators must be synced with the grid, and transient power may be lower than expected. Synchronous generators can only generate inertia up to 0.1 to 1 Hz of frequency variation.

To quantify the available inertial energy, the following equation is frequently used:

$$E_{\text{available}} = \frac{1}{2} J \left(\omega_{\text{ref}}^2 - \omega_{\text{min}}^2 \right)$$

- E available is the available inertial energy.
- J is the moment of inertia of the generator's rotor.
- ω_{ref} is the reference angular velocity (synchronous speed).
- ω_{min} is the minimum angular velocity during the transient event.

Solar Power (PV) Systems and Wind Energy Production

Power systems are gradually switching from synchronous generators to renewable energy sources like PV and wind. As this transition continues, system inertia—traditionally provided by spinning synchronous machines—decreases, increasing Rates of Change of Frequency. Future frequency stability and system reliability may be threatened by this adjustment [8-10].

Due to its scalability and large installation areas, PV systems are a popular renewable source. Solar PV installations lack physical inertia and are non-rotational. Most PV systems use MPPT control algorithms to optimize energy extraction in different environments. MPPT-controlled PV systems generate energy efficiently but cannot support active power regulation, limiting their grid frequency stability contribution. CAISO, a grid operator in California with substantial PV penetration, has added techniques to purposely constrain PV production, allowing PV systems to engage in frequency regulation. However, reducing PV power has a considerable opportunity cost, especially in systems with lower PV penetration, as inverters must work below their maximum power points, which may influence economic performance and adoption rates.

Wind turbines may emulate inertia because they include rotating masses that store kinetic energy. PV systems do not. This strategy has been extensively investigated to improve wind-integrated power system frequency dynamics. When appropriately managed, Double-Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) wind turbine generators can provide synthetic inertial response].

Figure 2 shows how a back-to-back converter connects DFIG wind turbine rotors to the electrical grid. The generator converter controls rotor speed and active power output, while the grid-side converter controls DC-link voltage and reactive power. The Doubly-Fed Induction Generator may regulate frequency by absorbing or delivering power by altering these converters.

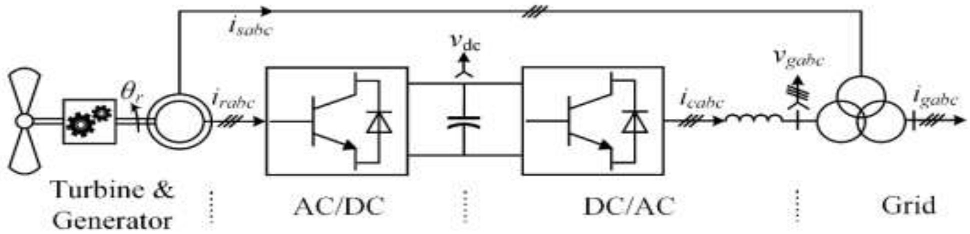

Figure 2: Diagrammatic representation of a wind generation system based on DFIG [15]

In a similar fashion, the wind generation system based on PMSG, depicted in Figure 3 links the stator to the power grid via a back-to-back converter. In contrast to DFIG systems, PMSGs are directly connected to the grid, eliminating the need for slip rings, thereby enhancing both reliability and control accuracy [12-15].

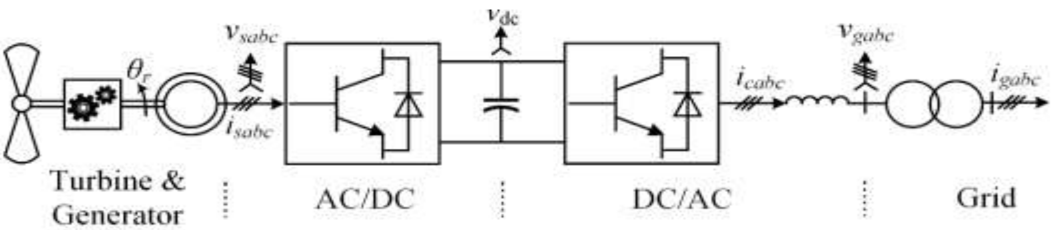

Figure 3: Diagrammatic representation of a wind power generation system utilizing a PMSG [15].

A popular wind turbine inertia management approach is to proportionally connect the grid frequency derivative to the turbine's torque reference [16]. This approach is effective in theory, but high-frequency noise during frequency derivative calculation makes it difficult to apply. Controlling rotor speed during and after an inertial reaction is another challenge in wind turbine-based inertia simulation. According to [17], excessive energy extraction during the inertial response may reduce rotor speed and induce turbine stalling. Conversely, excessive energy absorption to restore speed might destabilize the grid by lowering secondary frequency.

Many studies have presented sophisticated control solutions for smooth and quick MPPT operation-to-inertial response mode transitions. Wind turbines have synthetic inertia, while synchronous generators have natural inertia. Wind turbine power–frequency relationships are nonlinear, therefore accurate inertia emulation is still being studied.

IMPROVEMENT OF POWER SYSTEM INERTIA USING BATTERY-BASED ENERGY STORAGE

Renewable energy sources have reduced system inertia in modern power networks, threatening frequency stability and grid resilience. Due to their high energy density, fast dynamic response, and low cost, battery energy storage systems (BESS) are a promising solution for inertia emulation. BESS is ideal for inertia support mechanisms like droop control due to these properties.

Several research have developed optimization-based virtual inertia control schemes using BESS, however most are theoretical frameworks and simulations without experimental confirmation. This chapter proposes a viable and robust BESS inertia simulation control technique to close this gap. The basic idea is to link grid frequency change to a grid-connected battery energy storage system's active power setpoint. The BESS mimics synchronous generators' inertial behavior by regulating active power output in response to frequency changes.

System Setup

Figure 4 shows the basic architecture of the proposed control system. This design uses an L-type filter to link a grid-connected converter (GCC) to the electricity grid. The GCC is a battery energy storage system because it is battery-powered. Virtual inertia aid relies on this battery-backed converter. The GCC uses a hierarchical control structure with two layers: an inner current regulation loop and an outer virtual inertia loop. To maintain grid stability, the inner current controller follows the reference current and manages real-time power flow (injection or absorption). According to relevant studies [2, 10], the outer-loop controller integrates inertia emulation, which will be explored in the next sections. To explain how the proposed system regulates frequency and stabilizes modern power systems with lower physical inertia, the control logic, mathematical modeling, and actual implementation details will be detailed.

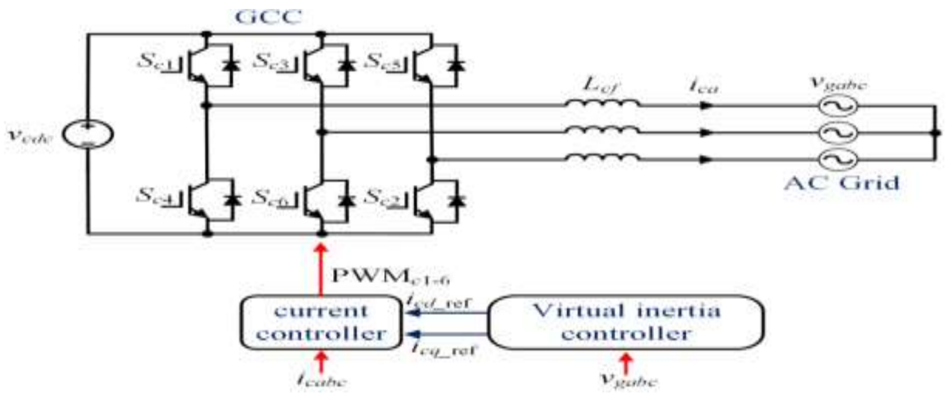

Figure 4: Configuration of the Battery Energy Storage System

Core Concept of the Suggested Approach

The red dashed lines in Fig. 5 show the essential notion of the proposed technique, which is theoretically expressed by an equation that connects frequency variation rate to energy storage unit active power input. The term ΔPc_pu refers to the active power taken by the battery energy storage system (BESS) per unit, whereas Hc represents the controller-introduced virtual inertia constant to approximate physical inertia [21].

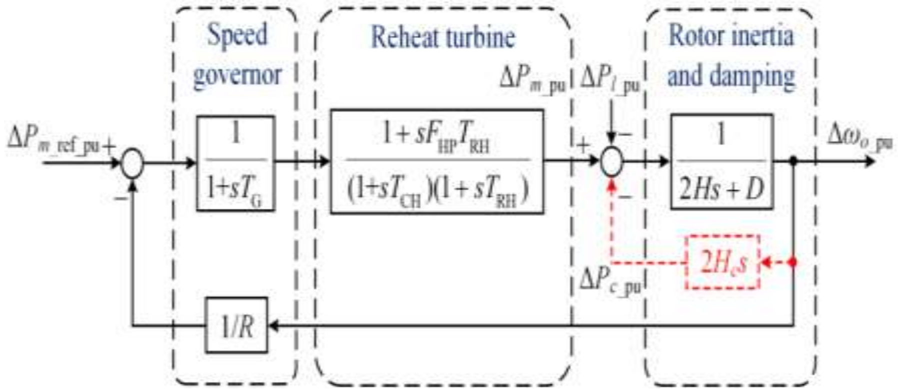

Figure 5: A model for regulating frequencies using the suggested virtual inertia.

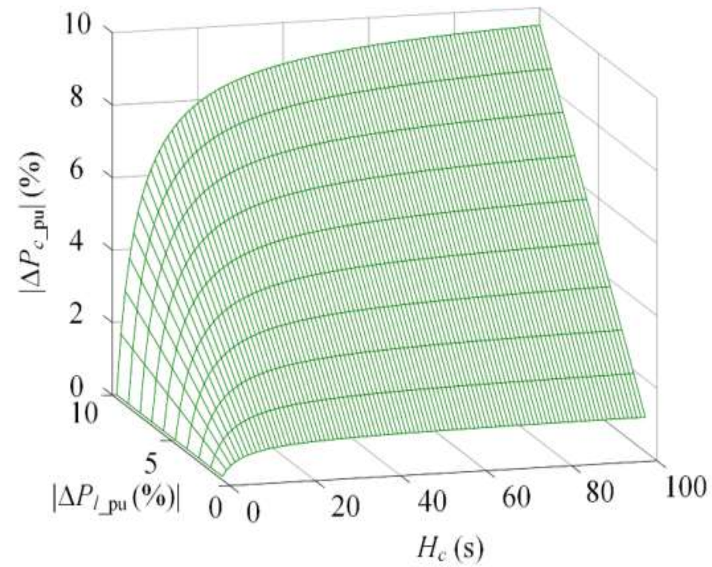

Figure 6: Active power demand of the GCC |ΔPc_pu| under different scenarios of step load variations |ΔPl_pu| and simulated inertia values Hc (H = 5 s) [23].

From the schematic in Fig. 6 it becomes evident that, when the rate of change of the output frequency (dΔωo_pu/dt) is detected, the system's total effective inertia changes from the nominal inertia value H to an augmented value of (H + Hc). This transition is governed by the virtual inertia controller, which dynamically adjusts the power injection or absorption from the BESS in response to frequency deviations.

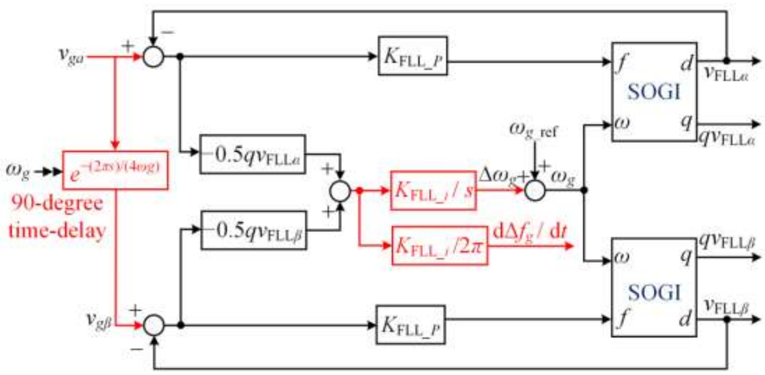

Figure 7: Diagram of a modified single-phase FLL

It is important to note that the 90-degree time delay used in this configuration is not intended for introducing dynamic phase compensation but rather serves purely to rotate the input voltage reference in the complex plane [18]. By establishing orthogonality between the direct and quadrature voltage components, the adjusted FLL replicates the function of a conventional three-phase system, enabling more precise frequency tracking free from ripple interference.

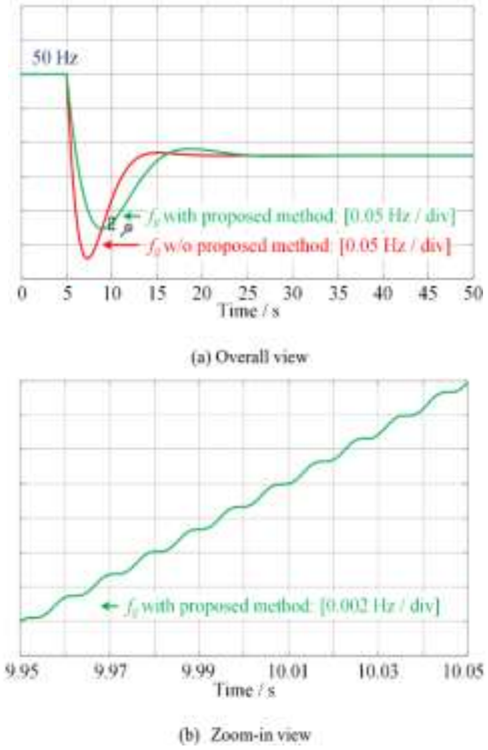

Figure 8: Simulation signal of a single-phase system utilizing a single-phase FLL.

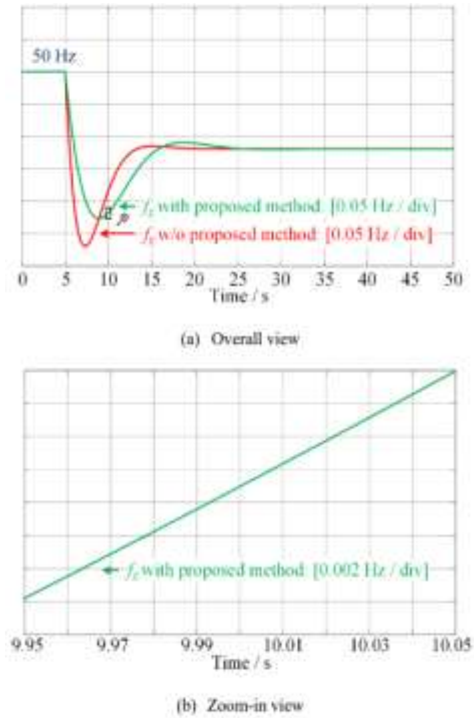

Figure 9: Signal pattern of a single-phase system modeled using an adapted single-phase FLL.

Simulation and Practical Findings

Detailed Outline of the Evaluation Setup

To assess the effectiveness and operational reliability of the envisioned reinforcement learning-based intelligent decision support mechanism for personalized treatment planning in a healthcare setting, the study employs a simulation and experimental testing system. As depicted in Figure 10, the experimental setup includes a power electronic converter filtered by an LC network, which is regulated to emulate the behavior of a virtual synchronous generator (VSG). The technical and control-related parameters used in the configuration are detailed in Tables II and III, respectively.

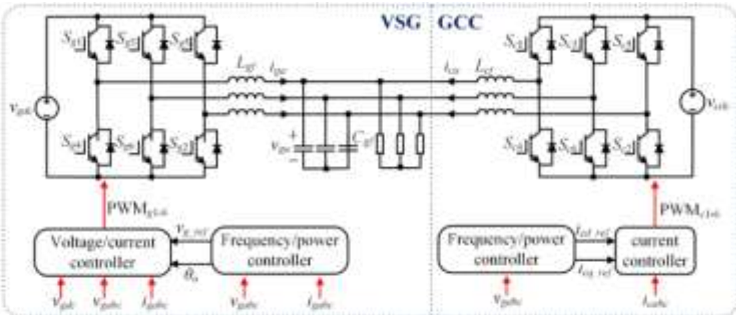

Figure 10: Block diagram of the evaluation setup.

The VSG is responsible for regulating both the grid frequency and voltage, emulating the inertial and damping responses typically provided by traditional synchronous machines. This functionality is accomplished using a layered control approach, wherein the inner loop focuses on voltage and current stabilization to maintain AC voltage integrity, while the outer loop is dedicated to managing frequency and power to support grid stability. The configuration of these control parameters adheres to the methodologies proposed by Wang et al. (2021) and Tang et al. (2021), which are designed to align with the dynamic behavior observed in actual power grids [22-28]

The system validation process begins with simulations conducted using MATLAB/Simulink (version R2016b), where the control logic and system interactions are first tested virtually. Following successful simulation trials, the approach is extended to an experimental phase utilizing a real-time hardware test platform. As illustrated in Figure 10, the test arrangement includes two DC power sources supplying the VSG and the grid-tied converter (GCC), both managed through a dSPACE MicrolabBox controller. This setup mimics real-time operation conditions and enables high-fidelity testing of the proposed control strategies [27-30].

Table 2: Values of the BESS system parameters.

Description	VSG parameter		Description	GCC parameter	
	Symbol	Value		Symbol	Value
DC-link voltage reference	V_{gdc_ref}	360 V	DC-link voltage reference	V_{cdc_ref}	360 V
Filter inductance	L_{gf}	1 mH	Filter inductance	L_{cf}	7 mH
Filter capacitance	C_{gf}	50 μF	Rated reactive power	Q_{c_ref}	0 kW
Rated active power	P_{g_ref}	1 kW	Rated active power	P_{c_ref}	1 kW
Sampling / switching frequency	f_{gsw}	10 kHz	Sampling / switching frequency	f_{csw}	10 kHz

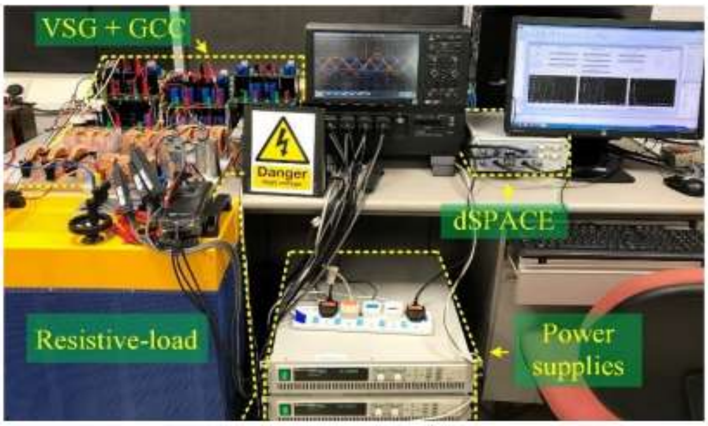

Figure 11: Experimental testbed photographed

A crucial element of the proposed method is the accurate estimation of the frequency derivative, which is inherently susceptible to high-frequency noise when calculated directly. To address this issue, the FLL has been adopted as a robust solution for estimating frequency derivatives. The use of FLL improves the accuracy of derivative signals and mitigates noise interference, marking it as a significant contribution of this work. The limitations of the conventional Phase Locked Loop (PLL) were also examined, with FLL proposed as a superior alternative due to its improved dynamic performance under frequency-varying conditions.

Conclusion

The core focus of this thesis centres on the reduction of inertia in contemporary power systems, primarily caused by the growing incorporation of inverter-driven renewable energy sources like solar PV and wind power. Traditional synchronous generators inherently provide inertia to the system, which plays a pivotal role in damping frequency deviations during load disturbances. However, inverter-based resources lack this physical inertia, thereby making the grid more vulnerable to frequency instability.

To mitigate this challenge, the thesis proposes and examines techniques for virtual inertia emulation using power electronic converters interfaced with energy storage systems. By leveraging advanced control strategies, it is possible to mimic the inertial response of conventional generators and thus maintain the dynamic stability of the grid. Among the approaches explored, frequency-derivative-based virtual inertia and supercapacitor-based inertia emulation are given particular attention.

The practicality and efficiency of this virtual inertia approach have been confirmed through extensive simulations and hardware-in-the-loop testing. The outcomes validate that the suggested frequency-derivative-based method offers notable enhancements in frequency control and presents a promising solution for maintaining grid stability in power systems with high renewable energy integration.

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