FREQUENCY STABILIZATION WITH SOLAR PV INTEGRATION IN TWO-AREA INTERCONNECTED MICRO GRID SYSTEM

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ABSTRACT

Microgrids (MGs) are becoming more reliant on Renewable Energy Sources (RESs) to meet consumer demand but the fluctuating output of RESs, combined with the unpredictable behaviour of loads can contribute to frequency instability. The incorporation of additional renewable energy sources enhances the system's inertia, contributing to frequency stabilization. This work examines the frequency regulation (FR) in a microgrid system with two-area control, incorporating a variety of energy sources such as electric vehicles (EVs), fuel cells, wind turbines, energy storage systems, conventional generators, and solar PV systems. A solar photo voltaic (PV) system, equipped with an inverter was integrated into the existing microgrid for evaluation of microgrid's performance and analysed its operation with and without the PV system, specifically examining deviations in frequency and power. Classical controllers, including PI, PID, and I, are implemented in Area-1 and Area-2 of the microgrid to enhance frequency and power stability. Magnitude of frequency and power fluctuations were tabulated to compare the performance in Area-1 and Area-2 of Micro Grid with photo voltaic (PV) and without PV systems.

Keywords: *Solar PV System, Frequency Regulation, Storage System, Distributed Energy Systems, Renewable Energy Sources, Single Area System, Two-Area Interconnected Syste*

1. INTRODUCTION

The electrical power system has undergone significant transformations as a result of increasing demand, the rapid exhaustion of non-renewable energy sources, and the introduction of new deregulation policies. The prolonged dependence on fossil fuel energy in recent decades has not only drained these resources but has also intensified environmental issues such as climate change, atmospheric pollution, and the greenhouse effect[1] . Consequently, Renewable Energy Sources (RESs) have gained traction as alternatives for power generation with traditional sources of energy. These challenges include voltage instability, frequency regulation issues, and reliability concerns. A power system is made up of interconnected control areas connected by tie lines. The generators within each control area coordinate their speeds (either speeding up or slowing down) to ensure stability in frequency and power angle under both steady-state and dynamic conditions. Load Frequency Control (LFC) is responsible for regulating generator power output in response to fluctuations in system frequency and tie line power flow, keeping them within designated limits. Lifestyle changes, increased energy consumption, industrial expansion, and environmental concerns have made Renewable Energy Sources (RES) a vital and flexible option. However, the inherently variable nature of RES generation, influenced by weather and other factors, can present challenges when integrated into large-scale energy systems. Microgrids are being adopted in Renewable Energy Systems to boost reliability and manage the variability of sources like solar and wind [2]. MG's offer several advantages, such as efficient

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and affordable clean energy, increased local resilience, and improved power system performance. They are effective in providing electricity to remote regions with limited infrastructure [3]. However, the intermittent and unpredictable nature of RESs complicates MG operation, particularly due to fluctuations in power and frequency that need careful management [4]. Storage devices serve as an important solution to frequency regulation issues (FRI) when there is a mismatch between energy demand and generation, especially given the variability of RESs [5]. A micro-grid typically incorporates a range of Distributed Energy Resources (DERs) such as Fuel cells, Wind turbines, Solar Photo Voltaic systems, storage units, and connected loads [6]. Different Microgrids (MGs) integrate various Distributed Energy Resources depending on their design, operation, and the types of generation technologies they use [7]. DERs can include Renewable Energy Sources (RES) such as Wind Turbine Generators (WTGs) and Photo Voltaic systems (PVs), as well as conventional resources like Diesel Engine Generators (DEGs) [8]. While WTGs and PVs provide intermittent power and their output cannot be controlled, DEGs can enhance system reliability. The Lyapunov stability method is a widely employed approach for determining the stability characteristics of nonlinear electrical systems[9] .Although DERs are crucial, the reliable operation of MGs, especially in islanded mode, also depends on Energy Storage Systems (ESSs) [10]. MGs can also operate independently from the main power grid during outages or power quality issues. Microgrids face greater challenges in maintaining stable frequency compared to traditional power systems. These challenges arise from the lower rotational inertia of microgrid components and the intermittent nature of many distributed energy resources within microgrids [11].

Extensive research has been conducted on frequency control strategies for microgrids [6-50]. Electric vehicles (EVs) are poised to be a cornerstone of the future automotive industry, offering a sustainable alternative with substantial reductions in greenhouse gas emissions and energy consumption. Beyond their transportation function, EVs can serve as energy storage units for the power grid, capable of bidirectional power exchange. During charging, EVs draw power from the grid, while during discharging, they can contribute to the grid as power producers [12]. This dual role makes EVs valuable assets for enhancing the operation of microgrids. Various LFC strategies, including traditional control methods, decentralized control, and advanced optimization techniques along the effectiveness of energy storage systems and demand response programs in mitigating frequency deviations in load frequency control including emerging trends and research gaps in the field, offering insights into potential future directions for LFC research and development were addressed in [13]. The quick response of power electronic devices in MGs helps to stabilize the power system and reduce frequency fluctuations [14]. Employing modeling method to analyse behavior of conventional power systems during primary frequency control and improve response strategies is discussed in [15].

Microgrids utilize several frequency control methods, including control by droop, virtual inertia, secondary control, and energy storage systems, to ensure stability. Frequency control in Single-Area microgrids helps to sustain stable power supply and frequency in a specific region, facilitating effective energy management while reducing the intricacies associated with decentralized networks [16]. Early research on load frequency control (LFC) focused on single-area conventional power systems, analyzing simplified models of gas, hydro and thermal power plants. Numerous studies have explored LFC strategies in one-area interconnected power systems [17],[18]. Additionally, the LFC design systems for single-area power systems analyzed different turbine types [19],[20]. System dynamics involving various turbine types have also been considered [21]. A significant challenge in wide-area LFC is communication delay, which can negatively impact system performance and even lead to instability. To address this issue, delay compensation strategies developed for load frequency control in single-area systems have been suggested in [22],[20]. Microgrids with two-area frequency control can better maintain power balance, distribute loads more effectively, and react quickly to disturbances, resulting in a more reliable and stable system[23]. The complexities of load frequency control in interconnected power grids with two control areas [24], while [25] introduces an LFC strategy for a system with a discrete frequency regulation in hybrid power systems incorporating non-conventional energy sources is proposed in [26]. Additionally, [27] and [28] explore multi-source systems and the role of energy storage, such as ultra-capacitors, in regulating frequency in systems with thermal and solar thermal power. The study in [29] considered Bio-Diesel (BD), wind turbines (WTs), fuel cells (FCs), solar-thermal (ST) plants and water heaters (WHs). Research in [30][31][32][33][34]] examined systems with photovoltaics (PV), diesel generators (DG), FCs, AEs and/or WTs, along with flywheel and battery energy storage. Micro-grid stability involving ST, DG, WTs, AE, FC, and battery storage was investigated in [35], while studies in [36],[37] addressed frequency issues with electric vehicles (EVs), DG, and WTs. The multi-source interconnected micro-grid system, as described in [38], includes various Distributed Energy Systems (DESs) like Ship Diesel Generator [39], Electric Vehicle Model [40] Diesel Generator , Biodiesel Generator [41], Fuel Cell and Aqua Electrolyser [42], Wind Turbine Generator [34], Biogas Generator , and Battery Energy Storage System [43], with their respective transfer function models derived from corresponding references.

The introduction provides a comprehensive overview of load frequency control (LFC) studies involving conventional and non-conventional energy sources, and storage in one-area and two-area systems. Research motivation is outlined in the second section, followed by a description of the proposed system, which includes the addition of a solar photovoltaic (PV) system, in the third section. The fourth section details the controllers employed for frequency regulation in microgrids. The fifth section presents the results of the proposed system and compares it to existing systems, while the sixth section summarizes the conclusions of the work.

2. MOTIVATION FOR THE WORK

Addition of Non-Conventional Sources of Energy to generation of power is considered to be the since the traditional sources for power generation are shrinking from day to day due to rise in power demand. Usage of non-conventional sources of energy results in no carbon emissions thereby causing no harm to the environment. Integrating a high penetration of renewable energy into the grid can pose challenges such as frequency instability, voltage issues, and reduced power quality concerns [44]. To overcome these challenges and maximize the penetration of RES, innovative approaches and novel methodologies are required. Energy storage systems play a vital role in incorporating renewable energy sources into the power grid. They stabilize frequency and handle sudden load changes. High-power-density storage technologies like supercapacitors, SMES, and fly wheel energy storage (FES) can be combined with battery storage for efficient energy management [45]. Single-area microgrids face challenges like instability, system-wide failures, and limited flexibility, driving the shift towards two-area and multi-area systems [7]. A two-area system in microgrids increases stability, control, and fault tolerance by using decentralized management and optimizing load distribution. It also provides flexibility for both grid-connected and islanded modes, supporting greater efficiency and scalability [46]. LFC plays a crucial role in Micro Grids and integrating RES into LFC strategies is a key focus of current research.

3. PROPOSED SYSTEM

Solar PV system, including an inverter and interconnection device to the micro grid in addition to the microgrid system [39] is considered in the investigation, and the overall micro-grid system is illustrated in the block diagram. The dynamic modeling and control of Solar PV systems with grid-tied inverters are crucial for maintaining system stability, enhancing power flow, and improving energy efficiency. In microgrids that include multiple Distributed Energy Resources (DERs), these inverters play a key role in converting transforming the DC power generated by solar panels into the AC format used in the electrical grid, supplying either the grid or local loads, whether in grid-connected or islanded modes.

3.1. Solar PV System

The efficiency of a solar photovoltaic cell in converting solar energy into electricity is influenced by factors like irradiance levels, temperature, and the electrical load it's connected to. The relationship between the voltage and current produced by a solar cell is described by its nonlinear I-V characteristics, which can be modeled using a simplified equivalent circuit consisting of a current source, a diode, series and parallel resistances. The power generated by a Solar PV system is expressed as:

$$P_{pv} = V_{pv} * I_{pv} \quad (1)$$

where

V_{pv} = The terminal voltage of the PV array

I_{pv} = Current of the PV array.

A more detailed model involves solving nonlinear equations that describe the relationship between irradiance, temperature, and electrical output.

The dynamic behavior of a PV system can be modeled using a first-order transfer function that describes the relationship between input irradiance and output voltage or power [26].

$$G_{pv}(s) = \frac{K_{pv}}{1+sT_{pv}} \quad (2)$$

K_{pv} represents the system gain and T_{pv} is the time constant, reflecting the PV system's output response to environmental changes.

3.2. Inverter

The inverter's role is to convert the direct current (DC) produced by the PV panels into alternating current (AC), making it compatible for grid integration. Inverter models typically utilize modulation techniques, such as Pulse Width Modulation (PWM), along with filters to ensure a smooth AC waveform. The inverter's dynamic performance is often described using a transfer function [27], which illustrates the relationship between the DC input voltage and the AC output power.

For dynamic control analysis, the inverter's response can be modeled by:

$$G_{inv}(s)=\frac{K_{inv}}{1+sT_{inv}} \quad (3)$$

where K_{inv} represents the gain and T_{inv} is the time constant representing the inverter's dynamic performance.

3.3. Interconnection Device

The dynamic model of the interconnection device has a significant impact on control strategy of a PV system within a microgrid. It facilitates the secure, stable, and optimizing the integration of solar power into the electrical grid ensuring synchronization while safeguarding the system against grid faults. For a first-order approximation [27], the interconnection device's response to grid conditions and the inverter's output can be expressed using a transfer function:

$$G_{itv}(s)=\frac{K_{int}}{1+sT_{int}} \quad (4)$$

In this equation K_{int} denotes the system gain of the interconnection device, while T_{int} represents the time constant that defines its dynamic behaviour.

The complete solar PV system, including the inverter and interconnection device, can be modeled as

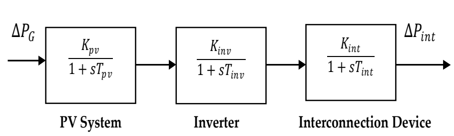

Figure 1: Solar PV system with Inverter and Interconnection Device

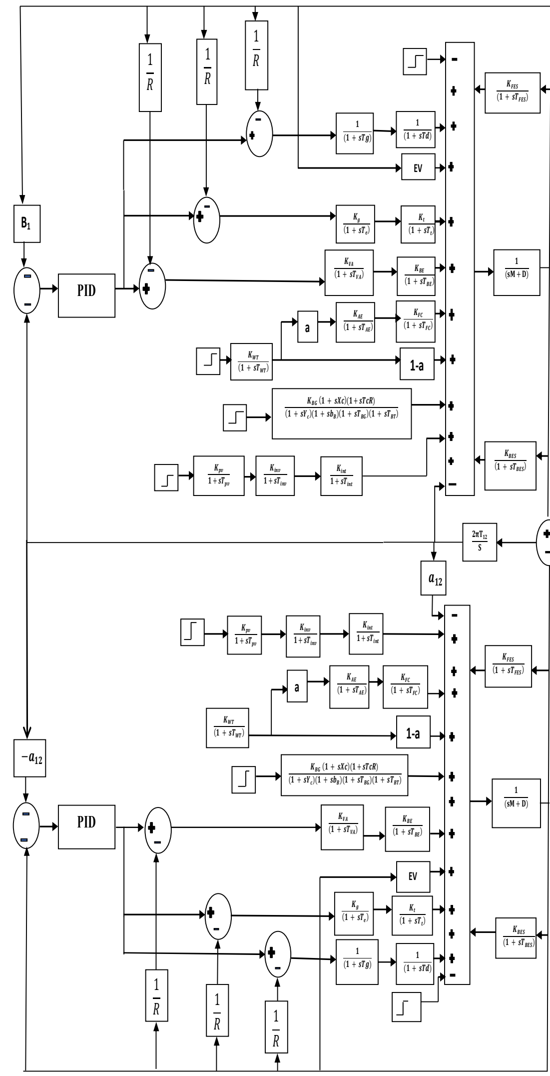

Figure 2: Block Diagram for Proposed Micro Grid System with Solar PV System

4. CLASSICAL CONTROLLERS FOR LFC CONTROL IN TWO-AREA INTERCONNECTED MICRO GRID SYSTEM

Proportional (P), Proportional Integral (PI), Proportional, Integral Derivative (PID) and Integral (I) controllers are commonly utilized in control systems to manage different processes by modifying inputs in response to error signals, which represents the deviation from the actual output. In microgrids, PI, PID, and I controllers are essential for keeping frequency levels stable. Microgrids typically include distributed energy resources (DERs) such as solar panels, wind turbines, and battery storage systems [29]. Changes in power generation and demand within these systems can result in frequency variations, which, if not adequately controlled,

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may lead to instability and a decline in power quality. The main purpose of frequency controllers in microgrids is to keep the frequency within acceptable ranges, despite these fluctuations.

Table 1. Comparison of Classical Controllers with their Advantages and Disadvantages

S.NO	Controllers Type	Advantages	Disadvantages
1	Proportional Derivative Controller (PD)	Enhances system stability without impacting the steady-state error.	Amplifies high-frequency noise.
2	Proportional Integral Derivative Controller (PID)	Improves steady-state performance.	Restricted range of stable operating conditions
3	Proportional Derivative (PD) controller	Greater resilience and quicker reaction to changes	PID controllers exhibit a linear relationship between the error and the control output

PID has three tunable parameters (K_p , K_I and K_D) and the I controller has one tunable knob (K_I). PI, PID and I controllers are implemented in both the areas of Micro Grid for frequency stabilization in both the configurations that is Interconnected Micro Grid with PV system and without PV system. The values for the adjustable parameters of the traditional controllers used in the simulation were taken from reference [39].

5. SIMULATION RESULTS

To evaluate performance of Micro Grid system for 2 percent step natured disturbance in both the areas, to observe the deviations taking place in frequency and power in Area 1 and Area 2 for both setups, without the use of any controllers. Deviation in frequency of Area 1 and Area 2 of Microgrid System integrated with PV ( )without integrated PV system (- - - -) was shown in figure 3,4 and power deviation of tie-line in figure 5 respectively.

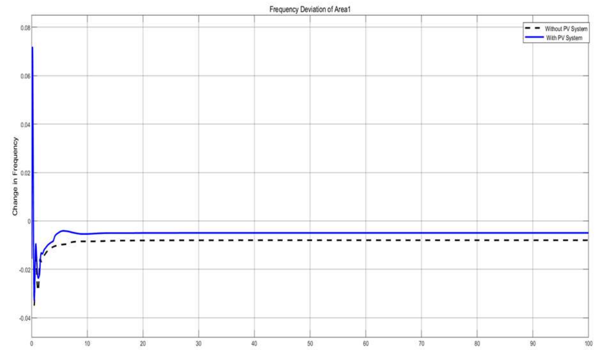

Figure 3: Frequency Deviation in Area 1 of Two Area Interconnected Microgrid system

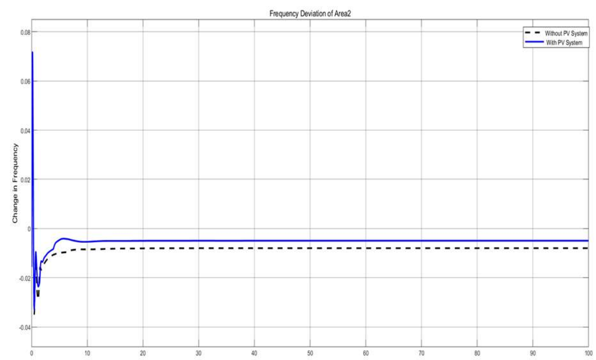

Figure 4: Frequency Deviation in Area 2 of Two Area Interconnected Microgrid system

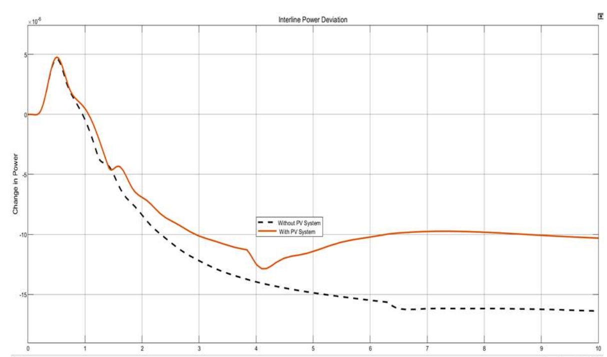

Figure 5: Tie-line power change in Interconnected Microgrid system

Table 2: Deviations in Frequency and Tie line Power of Micro Grid for 2% step natured disturbance in the system

Parameter	Micro Grid Without PV System	Micro Grid with PV System
Δf (Area-1)	$-7.979*10^{-3}$	$-4.943*10^{-3}$
Δf (Area-2)	$-7.979*10^{-3}$	$-4.943*10^{-3}$
ΔP (Tie-line)	$-1.662*10^{-5}$	$-1.030*10^{-5}$

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Examination of the values presented in Table 2 reveals that the interconnected microgrid with a photovoltaic (PV) system exhibits lower deviations in frequency and power compared to the interconnected microgrid without a PV system. This improvement can be attributed to the increased system inertia resulting from the addition of a new power generation source, which enhances the microgrid's ability to respond to disturbances.

Frequency Deviation of both the areas and Inter Tie-line power of Micro Grid without PV system and with PV system with the inclusion of PID controller was depicted in figures 6,7 and 8 respectively.

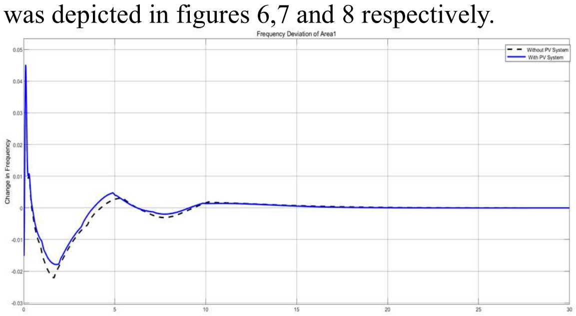

Figure 6: Frequency Deviation in Area 1 and Area 2 of Two Area Interconnected Microgrid system using PID controller

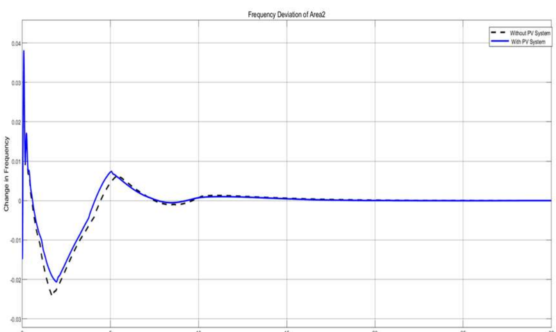

Figure 7: Frequency Deviation in Area 1 and Area 2 of Two Area Interconnected Microgrid system using PID controller

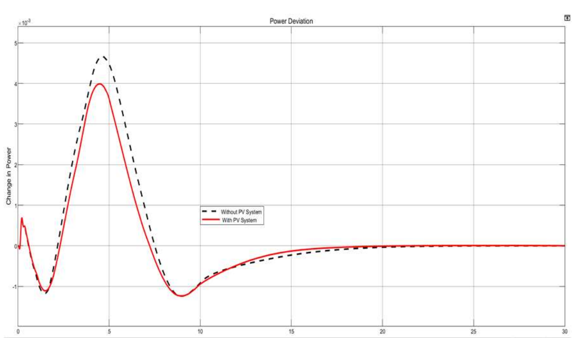

Figure 8: Tie-line power deviation in Interconnected Microgrid system with PID Controller

Figures 9,10 represents the Frequency Deviation of two areas for both the configurations using PI controller. Tie-line power change is depicted in figure 11.

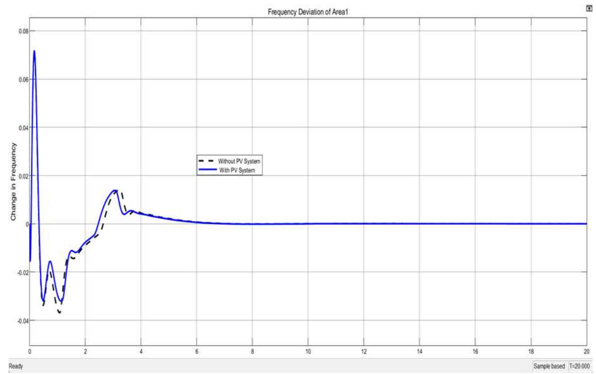

Figure 9: Frequency Deviation in Area 1 and Area 2 of Two Area Interconnected Microgrid system using PI controller

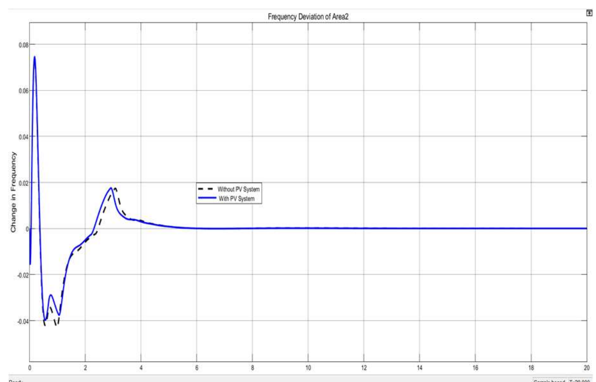

Figure 10: Frequency Deviation in Area 1 and Area 2 of Two Area Interconnected Microgrid system using PI controller

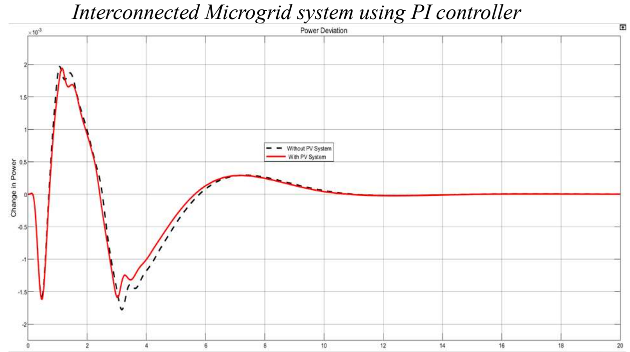

Figure 11: Tie-line power deviation in Interconnected Microgrid system with PI Controller

The depiction of Frequency Deviation for both the areas with Integral Controller is shown in figures 12,13 and Tie-line power deviation in figure 14 respectively.

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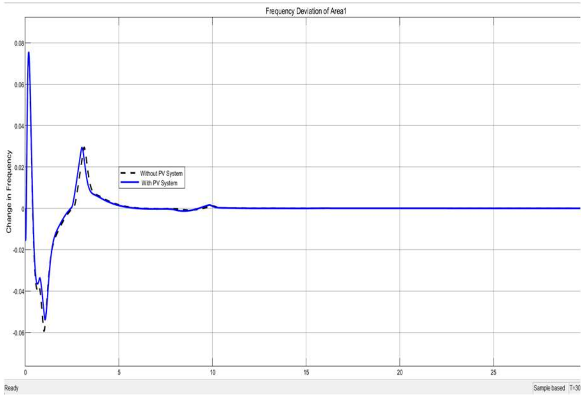

Figure 12: Frequency Deviation in Area 1 and Area 2 of Two Area Interconnected Microgrid system using I controller

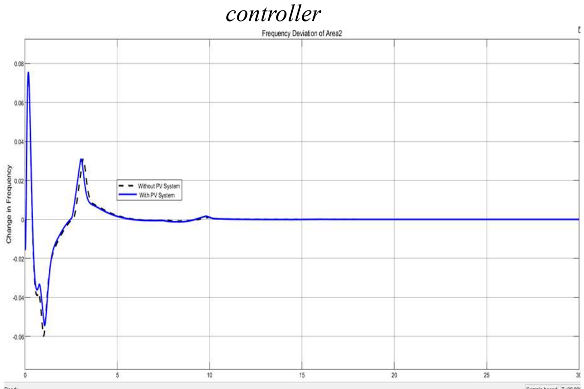

Figure 13: Frequency Deviation in Area 2 of Two Area Interconnected Microgrid system using I controller

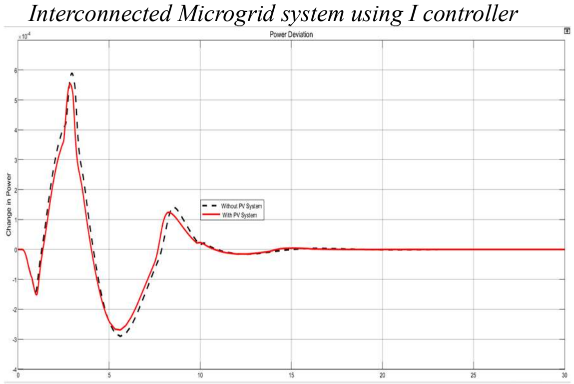

Figure 14: Tie-line power deviation in Interconnected Microgrid system with I Controller

6. NOVEL CONTRIBUTIONS

Previous studies mainly explored frequency stabilization in single-area microgrid systems or simplistic two-area models lacking diverse renewable energy sources and storage, our research undertakes a comprehensive examination of frequency stabilization in a complex two-area interconnected microgrid system. This system integrates a varied mix of renewable energy sources, including solar PV, wind turbines, and bio-diesel generators, supplemented by electric vehicles and ship diesel generators. Additionally, it incorporates aqua electrolysers for hydrogen production as well as energy storage systems to enhance stability. Notably, our findings reveal significant improvements in frequency stabilization and robustness when accounting for solar PV variability, electric vehicle integration, and coordinated energy storage system control, offering a more realistic and resilient approach to microgrid frequency stabilization.

6.1. Applied Implications of the Work

The proposed frequency stabilization strategy for two-area interconnected microgrid systems with solar PV integration offers numerous applications, spanning remote community power, enhancing resilience in islanded microgrids, supporting electric vehicle adoption, optimizing renewable energy farms, improving smart city power quality, and stabilizing off-grid industrial power systems and grid-scale energy storage. Real-world implementation possibilities include integrating solar PV farms into existing infrastructure, designing resilient microgrids for critical infrastructure, developing community-scale renewable energy projects, and enhancing grid stability in areas with high electric vehicle adoption. Future research directions include assessing scalability, exploring applications in alternative microgrid configurations, and developing advanced control strategies for optimal frequency stabilization. This research has significant potential to address real-world challenges and opportunities in renewable energy integration, electric vehicle adoption, and resilient microgrid design.

6.2. Current Limitations and Future Directions

A: This research on frequency stabilization in two-area microgrid systems with solar PV integration identifies open issues and limitations, including simplified modeling and neglected electric vehicle charging strategies. Future research directions include advanced control strategies, optimization techniques, and experimental validation.

7. CONCLUSIONS

Integrating a solar photovoltaic (PV) system with an inverter into the existing multi-source interconnected microgrid can substantially enhance its overall performance. By expanding the energy mix with a renewable source like solar, the microgrid becomes less reliant on fossil fuel-powered generators. This shift not only reduces fuel costs but also mitigates greenhouse gas emissions. To minimize or eliminate deviations of frequency and power in a microgrid, proportional-integral (PI), proportional-integral-derivative (PID), and integral (I) controllers are commonly employed. For identical values of K_p, K_i, and K_d (controller parameters) obtained from literature reviews, the microgrid system incorporating a photovoltaic (PV) system consistently outperforms the one without PV. This superior performance is demonstrated by faster settling times, reduced frequency and power deviations from observation of results. Tuning process of classical controllers can be explored as future work to enhance frequency and power stabilization in interconnected microgrid systems. A coordinated control strategy for energy storage systems mitigates frequency fluctuations in two-area microgrid systems with solar PV integration. This research reveals solar PV variability's substantial impact on frequency stability and energy storage optimization benefits, contributing to resilient microgrid development.

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APPENDIX

Table 3. System Parameter values and Terminology

Notations/Symbols	*Description*	*Numerical Values*
R, T_g and T_d	Governor Regulation parameter and Time constants of ship diesel generator (s)	3,0.5, 0.25
R, K_g, K_t, T_e and T_t,	Governor Regulation constant, Gains and time constants of diesel generator	2.5,1, 1, 0.1 s, 8 s
R, K_{VA}, K_{BE}, T_{VA} and T_{BE},	Governor Regulation constant, Gains and time constants of bio-diesel generator	2.4,1, 1, 0.05 s, 0.5 s
Y_C, X_C, K_{BG}, T_{CR}, T_{BG}, and T_{BT}	Admittance, reactance, Gain, and time constants of bio-gas turbine	1,0.6,0.5, 0.05, 0.01 s, 0.23 s, 0.2 s
K_{WT}, T_{WT}	Gain and Time constant of Wind Turbine	1, 1.5s
T_{AE} and K_{AE}	Time constant and Gain of aqua-electrolyzer	0.5 s ,1/500
T_{FC} and K_{FC}	Time constant and Gain of fuel cell	4 s ,1/100
T_{BES} and K_{BES}	Time constant and Gain of battery energy storage	0.1 s, −1/300
T_{FES} and K_{FES}	Time constant and Gain of flywheel energy storage system	0.1 s, −1/100
K_{PV}, T_{PV}		1.8s,1
	Time constant and Gain of PV system	
K_{inV}, T_{inV}		0.04,1
	Time constant and Gain of Inverter	
K_{int}, T_{int}		0.004, 1
	Time constant and Gain of Interconnected system	
D and M	Damping and Inertia constants of MG system.	0.2, 0.012
T_{12}		0.0867s
	Time constant of Synchronizing power	
Δ		----
P_{tie} *and* f	Change (or) Deviation	----
μ_E	Tie-line power and Frequency	0.025
δ_E	Capacity Limit of Inverter	0.01
E_{max}	Ramp rate limit of power	
E_{min}		0.95
	Maximum EV energy limit	0.80
T		
	Minimum EV energy limit	1s
K_p, K_I *and* K_D		
	Time Constant of EV	Area1: 0.3700,0.9990,0.5810 Area2: 0.2660, 0.2199,0.9970
K_p *and* K_I	Gains of PID controller	
		Area1: 0.9900,0.8690 Area2: 0.2277,0.9980
K_I	Gains of PI controller	
		Area1: 0.9980 Area2: 0.9050
	Gains of I controller	