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LOAD FREQUENCY CONTROL IN HYBRID SMART GRID WITH BESS IN MATLAB

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Abstract: The integration of renewable energy sources like wind into conventional thermal power systems poses significant challenges to grid frequency stability due to variable generation and fluctuating loads. Load variations cause critical frequency deviations that threaten grid stability, making effective frequency stabilization essential for reliable operation. This mini project develops a MATLAB/Simulink model for load frequency control (LFC) in a hybrid smart grid. This Paper investigates Load Frequency Control (LFC) of two different configurations of a Hybrid Smart Grid Model . The first Configuration follows LFC by connecting a Hydroelectric Microgrid in islanding mode . While, the second one is a BESS integrated grid tied mode . The proposed Combination of systems subjects to supply external extra voltage that is proportional to the voltage fluctuation developed that might develop due to a fault or internal external factors .

***Index Terms* -** Introduction, Literature Survey, Block Diagram , Results& Dsicussions , Conclusion , Future Scope , References.

I. Introduction

With increasing involvement of renewable and distributed energy sources, the conventional electrical grid has evolved into the intelligent and decentralized concept of smart grid. As opposed to the conventional power generation system, smart grid is characterized by the incorporation of distributed generation units, sophisticated communication system, intelligent monitoring, and control system to provide reliable, efficient, and sustainable power generation.Hydroelectric microgrid has become one of the most popular forms of distributed generation sources in smart grids because of its efficiency, relatively lower cost of operation, and environmentally friendly nature. A microgrid is defined as a small-scale power system which consists of distributed generation, energy storage systems, and load. According to various circumstances, a microgrid can be operated in either a grid-tied or an islanding manner. Under usual conditions, a microgrid operates in a grid-tied mode. Under this condition, the microgrid is connected to the utility network through the point of common coupling (PCC), thus providing bidirectional power flow from the utility network to the distributed generation system. The utility network serves as an infinite bus. In this case. The shift from grid-connected mode to an islanded mode can either be intentional or unintentional. In the case of an intentional switch, this happens during the scheduled maintenance period. In an unintended shift, the causes include faults in the transmission system, faulty equipment, or malfunction of protection systems. After disconnecting from the utility grid, the microgrid will have to operate independent of the grid. This means that there is nothing from the utility grid supporting the microgrid, and any small difference in power generation and consumption will affect the frequency. There exist various merits of hydroelectric power generation when used in microgrids due to the quick responding nature of the governor and its capability of controlling mechanical input power. Nevertheless, in some cases, a hydroelectric plant may not be able to handle the rapid changes in loads, especially in cases of disturbance. In such a case, the imbalance between generation and load leads to frequency fluctuations, long settling time, and poor power quality. Consequently, a suitable LFC scheme is necessary for constant balancing between power generation and power consumption.

Load Frequency Control is one of the basic ancillary services. that ensure the balance between the generation of active power and electric load. The increase in the load without a simultaneous increase in the generation results in the decrease in the system frequency, while increased generation results in an increase in the system frequency. Traditional Automatic Generation Control (AGC) is designed to adjust the turbine governor behavior in order to reduce such deviations. Yet, the growing penetration of distributed generation [6,8]complicates the frequency control problem due to more rapid changes in power generation. In this research, hydroelectric microgrid is simulated in MATLAB/Simulink in order to study frequency characteristics of the hydroelectric microgrid in grid connected and islanded operation. In grid-connected mode of operation, the hydroelectric microgrid supplies and consumes electrical energy from the utility grid at the point of common coupling (PCC). In case of islanded operation, the generation of hydroelectric microgrid solely provides electrical energy to the local load through Load Frequency Control. The suggested model is analyzed under various loading conditions for the dynamic analysis of frequency response, settling time, overshoot, and steady state of the system in both cases. The simulation results confirm the efficiency of the Load Frequency Control scheme for frequency stabilization and reliable performance of the hydropower smart microgrid under changing operational conditions. Moreover, the suggested model allows for a flexible simulation tool for further implementation of BESS, solar PV generation, wind energy conversion system, and intelligent control algorithm for smart grid. [1-4]

literature survey

As more and more renewable energy resources and distributed generation are added to the power system, it is becoming a smart grid with intelligence. But the intermittent nature of the renewable energy sources poses serious deviations in frequency because of the fluctuation in power generation and load demand. Thus, the development of Load Frequency Control (LFC) has been a must for ensuring the stability, reliability and power quality of the grid. In recent years, Battery Energy Storage Systems (BESS), advanced controls and intelligent control algorithms are more frequently used as part of modern LFC strategies to enhance frequency regulation during dynamic operating conditions.[5,6]

A. Jeya Veronica and N. Senthil Kumar (2021) provided a detailed review of frequency regulation techniques of microgrid. Their work includes primary, secondary and tertiary frequency control methods, and the comparison of the conventional PID method, droop control method, fuzzy logic method, adaptive control method and intelligent control method. The authors found that incorporation of fast response energy storage systems can greatly improve frequency stability particularly under islanded mode of operation, where the system inertia is relatively low.[7]

Majid Gulzar et al. (2022) conducted a review on load frequency control strategies for renewable energy based hybrid power system. The study points out that uncertainty is added to the system with the addition of renewable generation due to the intermittency of this generation, which reduces the effectiveness of the conventional controllers. Different optimization methods such as fuzzy logic, neural networks, genetic algorithms, particle swarm optimization, adaptive controllers, etc. were tested. The authors noted that BESS plays a crucial role in enhancing transient response, minimizing overshoot, and decreasing settling time during load disturbances.[6]

The researchers have recently carried out a comprehensive review on recent advances in Load Frequency Control for smart grid in Renewable and Sustainable Energy Reviews, 2024. Classical PI/PID controllers, robust control, adaptive control and model predictive control, AI and reinforcement learning (RL) were all reviewed. It also covered the frequency regulation effects due to integration of renewable energy, communication delays, cyber-security issues, and energy storage technologies. The research results showed that integrating energy storage and smart control has a great potential for enhancing grid resilience and stability.[5]

A detailed survey on Load Frequency Control (LFC) with integration of Renewable Energy Sources is presented in the Journal of Energy Storage (2022). The paper presented various controller structures of conventional and renewable-based power system and concluded that Battery Energy Storage Systems were one of the most viable solutions for tackling frequency oscillations associated with renewable intermittency. The authors also talked about some future research avenues that include hybrid energy storage systems, advanced optimization techniques, etc.[8]

In Alexandria Engineering Journal (2023) recent research work was given relating to the state of the art for the Load Frequency Control of Flexible Hybrid Power Systems. According to the study, traditional PID controllers are not enough to ensure frequency stability in today's smart grid with high penetration of renewable energy. It found that hybrid controllers with Battery Energy Storage Systems can restore frequency faster, suppress oscillations and provide better dynamic performance in different operating conditions.[9]

This recent paper in Electronics (2026) was about Battery Energy Storage Systems in AC microgrids. The authors talked about the economic and technical advantages of BESS such as peak shaving, load leveling, frequency regulation and support for renewables. They pointed out that the BESS can be considered a fast-response power supply that can deliver the required power within milliseconds to provide compensation for load fluctuations, which makes it very suitable for Load Frequency Control (LFC) application in the smart grid.[10]

Research Gap

Several studies have studied the problem of load frequency control in renewable energy generation in combination with battery energy storage systems (BESS) in thermal power plants and wind farms, photovoltaic (PV) systems, and multi-area interconnected networks, but most studies have been conducted in the context of one of these four types of power plants. The number of studies on a hybrid smart grid (HEMG) with a hydroelectric micro-grid coupled with a Battery Energy Storage System (BESS) is relatively small, which is an HEMG operating in both grid connected and islanded mode. In addition, there are numerous studies that have considered advanced optimization methods but not given practical configurations for a system in Simulink that can be implemented in the classrooms or for prototypes. Hence, a simple and simulation based hybrid smart grid model using BESS for effective frequency stabilization under various operating scenarios still exists.[5,6,8,9]

Motivation of the Present Work

The present work proposes a MATLAB/Simulink model of a hybrid smart grid system consists of a utility-based grid, a hydroelectric micro-grid, Battery Energy Storage System (BESS), industrial loads, residential loads, and a load frequency control mechanism, based on the identified research gap. The proposed system is to be used both in grid connected and in islanded mode. The BESS is used to quickly absorb or deliver active power during load disturbances, to reduce frequency deviations and enhance system stability as a whole. The performance of the proposed configuration is tested by dynamic simulations under different operating conditions.

II. BLOCK DIAGRAM

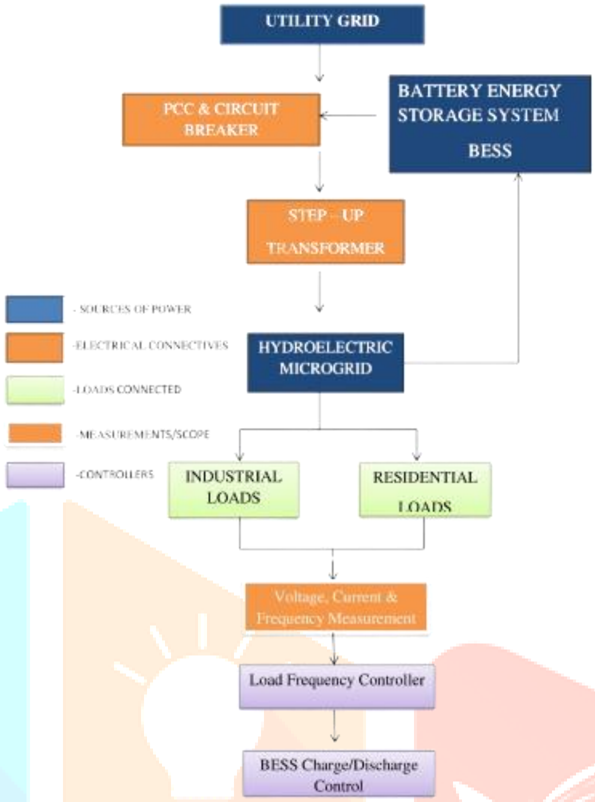

Fig-1:block diagram

The functional block diagram of the proposed Load Frequency Control (LFC) of a Hybrid Smart Grid with a Battery Energy Storage System (BESS) is shown in figure 1. This system includes a utility grid, a Point of Common Coupling (PCC), circuit breaker, step-up transformer, hydroelectric microgrid, Battery Energy Storage System (BESS), industrial and residential loads, voltage current frequency measurement unit and a Load Frequency Controller (LFC). The proposed design is deployed in both Grid connected and Islanded mode, which provides a reliable power supply while maintaining stability of the frequency under fluctuating loads [11,12]

3.1UTILITY GRID

During grid connected operation the electrical power comes from the utility grid as the main source. Supplies power to the hybrid smart grid and to the hydroelectric microgrid during periods of high demand. The nominal voltage and frequency are maintained by the utility grid, and it is sharing the load with the distributed generation system under normal operation conditions [11,13].

3.2 POINT OF COMMON COUPLING (PCC) & CIRCUIT BREAKER

The Point of Common Coupling (PCC) is a point of connection where the utility grid meets the hybrid microgrid. The mode of the system is controlled by a three-phase circuit breaker installed at the PCC. If the breaker is kept closed, then the microgrid is connected to the grid. When the utility power goes out, or when the utility is scheduled to be shut down, the breaker will open to disconnect the microgrid from the main grid, but to continue serving the loads in the microgrid area. In the event of a utility disturbance or a scheduled utility outage, the breaker will open to separate the microgrid from the main grid, while maintaining service to the local loads within the microgrid area [12], [14].

3.3 BATTERY ENERGY STORAGE SYSTEM

The Battery Energy Storage System is through a bidirectional power conversion system comprising of a battery bank, bidirectional DC-DC converter and DC-AC inverter connected to the Point of Common Coupling. When loads surge, the BESS can quickly inject active power, and when loads are light the BESS can absorb excess power. The BESS has fast-dynamic response, which results in minimal frequency deviations, oscillations, and improvement in the transient stability of the hybrid smart grid [10], [15] and [16].

3.4 STEP – UP TRANSFORMER

A step-up transformer is used to electrically isolate and match the voltage of the utility grid to the hydroelectric microgrid. It regulates the voltage levels to ensure optimal power transmission efficiency and reduce power transmission losses and enhance system reliability [11], [13].

3.5 HYDROELECTRIC MICROGRID

The micro-grid is a hydroelectric distributed generation source for the proposed hybrid smart grid. It transforms hydraulic energy into electrical energy and delivers power to the industrial and domestic loads. In the islanded mode, the hydroelectric microgrid works autonomously with the assistance of the BESS to balance out the load and generation demand.[12,17].

3.6 INDUSTRIAL AND RESIDENTIAL LOADS

The electrical energy produced is fed to industrial and residential loads on the hybrid microgrid. Changes in these loads result in changes in the power balance and hence deviations of system frequency. The coordinated operation of the hydroelectric microgrid and the Battery Energy Storage System [8, 10] compensate these disturbances.[13,15]

3.7 DEMONSTRATING THE MEASUREMENT OF VOLTAGE, CURRENT AND FREQUENCY.MEASUREMENT OF VOLTAGE, CURRENT AND FREQUENCY.

A measurement unit is connected to the load bus and constantly reads the system voltage, system current and frequency. These measured parameters are feed to the “Load Frequency Controller” for real time monitoring and analysis. Accurate measurement can be used to quickly detect frequency deviations from generation or load demands [11, 14].

3.8 LOAD FREQUENCY CONTROLLER (LFC)

Continuous comparison of system frequency and the nominal reference frequency is made in the Load Frequency Controller, which is fixed at 50 Hz. According to the frequency error obtained, control signals are calculated to control power exchange between Battery Energy Storage System. The controller reduces the frequency error in the steady state, enhances the transient response and recovers the system frequency after disturbances [12, 15, 16].

3.9 BESS CHARGE/DISCHARGE CONTROL

The charge/discharge controller is used to control the charging and discharging of the Battery Energy Storage System (BESS) based on the control signals generated by the Load Frequency Controller. The controller sends instructions to the BESS when frequency falls to discharge stored energy into the grid. On the other hand, if the frequency increases due to surplus power generation, the BESS will store the energy by charging the battery bank. This coordinated operation helps to make the frequency control more efficient, to make the system more stable, and to make the hybrid smart grid more reliable [10],[15],[16].

The overall working of the proposed system is described below:

The proposed smart grid is a hybrid, where the utility grid, hydroelectric micro grid and Battery Energy Storage System are connected at a common Point of Common Coupling. Normally, the utility grid and hydropower generation provide power to industrial and residential load. Continuous monitoring of the system voltage, current and frequency, followed by a comparison of the measured frequency with the nominal frequency of 50 Hz. Load Frequency Controller generates corrective control signals to the Battery Energy Storage System whenever there is a deviation from the set frequency and load. A bidirectional converter enables the BESS to inject or absorb active power from the system, thereby restoring the nominal frequency of the system. In an islanded configuration, the hydroelectric microgrid and BESS collaborate to ensure steady and reliable power supply while balancing power generation and load [11]–[17].

IV. RESULTS AND DISCUSSION

4.1 Working of The System

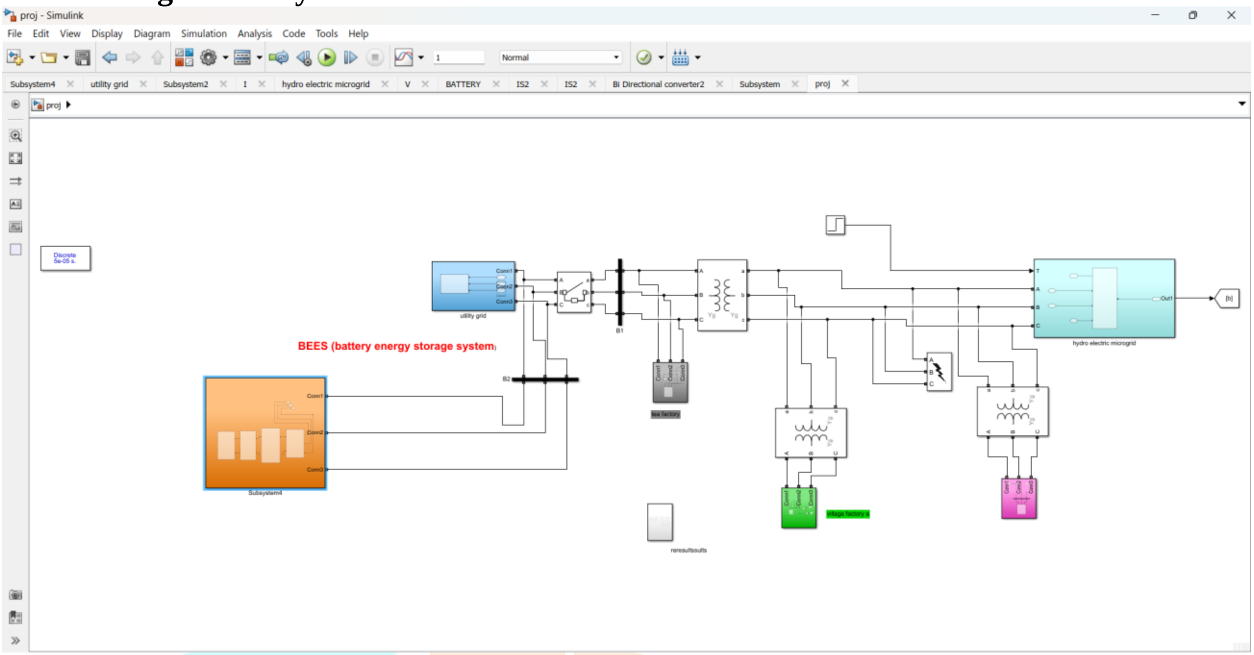

Fig-2:Simulation Circuit

The proposed hybrid smart grid comprises a utility network, a Hydro Microgrid and Battery Energy Storage System (BESS) with the aim to optimize the operation of the grid in both grid connected and island operating modes in terms of Load Frequency Control (LFC). The entire system is then modeled and analyzed in the MATLAB/Simulink environment, where dynamic performance of the system under load disturbances and frequency deviations is evaluated [12, 15].

In normal grid connected mode, the electrical energy is provided to the industrial and residential loads through Point of Common Coupling (PCC) by both the utility grid and the hydroelectric microgrid. The PCC's circuit breaker stays open, enabling a bidirectional flow of power between the microgrid and the grid. The step-up transformer is used to match the voltage and for electrical isolation to facilitate the transfer of power from the interconnected sources to the distribution network [12], [18].

The Battery Energy Storage System is connected at the PCC via a bidirectional power converter which consists of a DC-DC converter and a DC-AC inverter. When it is in steady-state the BESS is either in standby or runs based on the state of charge. If a sudden rise or fall in the load demand takes place, the power balance between generation and load is upset, causing a deviation of the system frequency frequency from its nominal value of 50 Hz [11, 19].

Measurement block is used to continuously monitor the voltage, current and frequency of the system. The measured parameters are given to the LFC which compares the actual system frequency with the reference frequency. The frequency error is fed into the controller for generating the suitable control signals for the BESS [11, 20].

When the frequency of the system drops in response to increased load demand or reduced generation, the controller tells the BESS to discharge stored energy by sending a signal to the bidirectional converter to send active power to the grid. The controller, on the other hand, discharges the excess electrical energy from the system to the battery when the frequency increases due to less load demand. Such fast response to the power imbalance allows the BESS to synchronize the frequency, reduce the oscillations and enhance the transient stability within a very short period of time [19, 20].

Islanded operation is when the circuit breaker trips to isolate the hybrid microgrid from the electricity grid. During this mode, hydroelectric microgrid is the main power generation source, the Battery Energy Storage System delivers active power support instantly to match generation and load. The hydroelectric micro grid, Load Frequency Controller, and BESS work in a coordinated way to provide continuous power generation, improve frequency regulation, and supply better power reliability even without the support of the utility grid [15], [20], [16].

In general, the proposed control strategy could effectively utilize the fast dynamic response of the Battery Energy Storage System to compensate the frequency fluctuations under different load conditions, which helps to enhance the stability, reliability and operational performance of hybrid smart grid [12]–[20].

4.2 Results of the Simulation Model

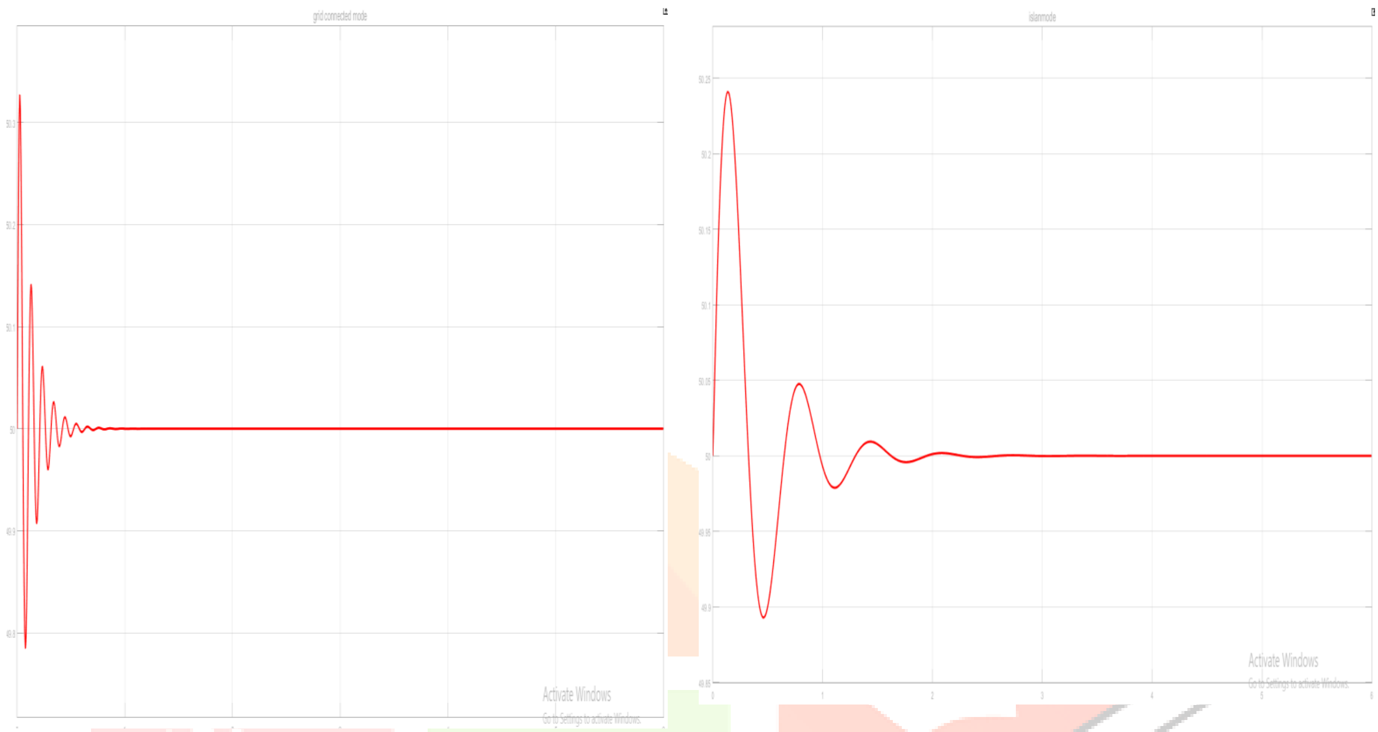

Fig-3:frequency dip at Fault & frequency stabilization at islanding mode.

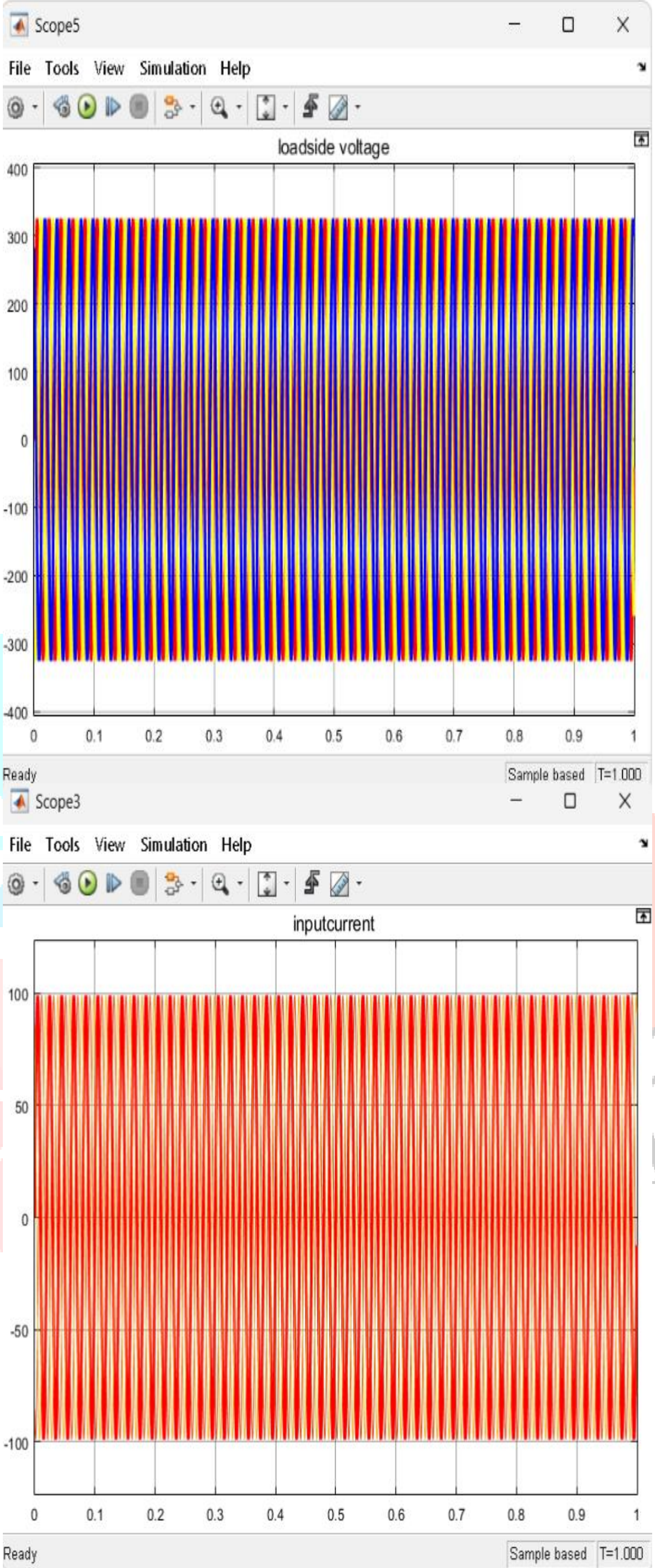

Fig-3:frequency stabilization at BESS integrated Grid Connected mode

MATLAB/Simulink simulations were performed to analyze the performance of the Battery Energy Storage System (BESS) in the proposed hybrid smart grid for different operating conditions to evaluate the effectiveness of the BESS in maintaining the system frequency. The simulation has been conducted in two phases: islanding under grid disturbance and grid connected with BESS support. The results obtained confirm the ability of the proposed control approach to ensure better frequency stability, suppress oscillations and guarantee reliable power supply.

A. Current and voltage sharing between the power supply and the load Control of these parameters.

Figure 3 shows the frequency response of the hybrid smart grid when the utility power grid is disconnected from the microgrid due to a fault, resulting in the microgrid running in the islanding mode. Following the disturbance, there is a large frequency deviation due to the rapid mismatch between the power generation and load demand. This results in the frequency oscillations in the system before the onset of corrective action by the controller.

The integrated BESS can inject or absorb active power quickly depending on the frequency error, which results in a compensation for power imbalance. As in the simulation, the oscillations slowly fade out, and the system frequency approaches the nominal operating frequency. The BESS provides a great deal of damping which helps to reduce settling times and eliminates extended frequency excursions. The obtained result confirms that the presented LFC strategy improves the dynamic stability of the microgrid system during islanded mode operation and keeps the power supply to the loads unaffected [12,11,18,15].

B. Grid-Connected Operation with BESS

The voltage waveform on the load side and current waveform at the input of the hybrid smart grid are shown in Figure 4 in the grid-connected operation mode with BESS support. The voltage waveform is balanced and sinusoidal during all parts of the simulation, demonstrating the hydroelectric microgrid's synchronization with the utility grid. The input current also shows a sinusoidal waveform with minimal distortion, further confirming the power exchange between the grid and microgrid.

It operates via a bidirectional converter and constantly measures the frequency of the system and its energy consumption, the BESS. Under normal operating conditions, the battery is charged and discharged as needed to help regulate power fluctuations and frequency. This synchronized power deployment reduces voltage variations, allows for better voltage quality, and increases overall grid reliability. The simulation validates the proposed system in case of varying load conditions and to support seamless grid integration [11]–[20] and confirms the effectiveness of the proposed system in maintaining stable electrical parameters.

Overall Performance Analysis

The simulation results show that the performance of the hydroelectric microgrid and hybrid smart grid with a BESS is significantly enhanced in terms of the load frequency control. Under islanding conditions, the BESS can offer rapid frequency support through active power balancing, minimizing frequency deviations and enhancing transient stability. When connected to the utility grid, coordinated operation of the utility grid, hydroelectric microgrid and BESS maintains stable voltage, balanced current and reliable grid frequency regulation. Thus, the proposed system is capable of improving the power quality, reliability of operation and overall stability of the smart grid which can be applicable in modern power systems based on renewable energy sources [11-20].

V. CONCLUSION

In this paper, a Battery Energy Storage System (BESS) assisted load frequency control (LFC) scheme for a hybrid smart grid with the hydroelectric microgrid system in both grid-connected and islanded modes were modeled and simulated. The proposed system was designed and simulated in MATLAB/Simulink to check its ability to maintain the frequency of the system while operating under different operating conditions, load disturbances and fault scenarios.

The dynamic performance of the hybrid smart grid with the integration of the BESS can be improved significantly as shown by the simulation results, which provide fast active power support during frequency deviations. In grid-connected mode, both the utility grid and hydroelectric microgrid provide power to the load, and the BESS acts as a buffer to avoid high transient power imbalances, resulting in a stable voltage and current profile. The hydroelectric microgrid, equipped with BESS, is able to stabilize frequency oscillations and maintain the nominal frequency after disturbances on the grid, resulting in an improved level of system stability in islanding conditions. The results obtained validate that the proposed control strategy successfully reduces the frequency deviations, reduces settling time and improves reliability performance of the hybrid power system.

The model developed shows that the hydroelectric microgrid and BESS can be used as a practical and efficient solution for future smart grid with high penetration of renewables. The planned system enhances the operation flexibility, continuity of power supply during any disturbance in the grid, and contributes to better power quality and frequency regulation. Thus, the proposed method can be used as a promising method for frequency control in modern Hybrid Smart Electrical Grids and future Distributed Electrical Power Generation Systems [11]–[20].

VI. FUTURE SCOPE

Advanced methods of intelligent control, like Model Predictive Control (MPC), Fuzzy Logic Control, Artificial Neural Networks (ANN), and Reinforcement Learning can be used in future works to further enhance the frequency regulation performance. The proposed model can be extended by incorporating other renewable energy sources like photovoltaics, wind generation and also taking into account electric vehicle charging stations, demand response strategies and real-time implementation in hardware via OPAL-RT or Hardware-in-the-Loop (HIL) platforms. The improvements will facilitate the development of smart grid systems that are more resilient, intelligent and sustainable in order to operate effectively under various operating conditions [12]–[15].

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