Contribution of Multi-Energy Storage System To Enhance Microgrids Frequency Stability

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Abstract— This paper deals with the use of a hybrid energy storage system (HESS) coordinated with High Voltage Direct Current (HVDC) Link to enhance Multiple Microgrids active power management and frequency control in presence of renewable energies. An optimal automatic Load Frequency Control (LFC) loop was proposed to cope with frequency fluctuations in case of isolated and interconnected microgrids frequency including a mix of renewable sources. A novel two-stage optimal active power management and frequency regulation scheme was developed, which allows the use of the multi-storage system to support the frequency regulation and reduce the conventional LFC ability by using the stored energy in each devices. The investigated storage system comprise : Redox-Flow Batteries (RFBs), Superconducting Magnetic Energy Storage System (SMES) and Fuel Cell (FC). The proposed control strategy includes two stages: in the first stage, an optimal LFC loop was used to handles frequency deviation; in the second stage, frequency feedback is used to regulate the HESS power output to further reduce frequency deviation in case of wind and solar fluctuations. In order to design a robust and effective controller, a recently nature inspired metaheuristic algorithm named Marine Predator Algorithm (MPA) was employed to optimize the PIDN controller parameters. The proposed strategy can manage the storage system to better participate in power system dispatch and LFC control. A comparative study was performed and the obtained results prove the effectiveness and validly of the proposed method to enhance dynamic microgrid frequency regulation in case of multiple interconnected microgrid with a large share of green power.

Keywords— **Autonomous Microgrid; Frequency Control; Marine Predator Algorithm (MPA); Multi Energy Storage System; PIDN Controller.**

I. INTRODUCTION

Modern power systems can includes various kind of new technologies such green power, artificial intelligence (AI), and smart grids that improve efficiency and reliability. These systems utilize advanced monitoring and communication technologies to optimize electricity distribution and reduce waste. Presently, power system face many challenges especially in small and remote areas of power generation such microgrids (MGs). Microgrid can be operate in isolated mode or connected mode with the main grid. In most cases, the microgrid is managed independently from the main grid. It can include a variety of distributed energy resources (DG) like wind farm, solar PV panels, and storage batteries to provide power to a smaller community or facility. Microgrids are often used for increased reliability, energy efficiency, and cost savings [1]. A modern microgrid typically incorporates advanced technology and control systems to optimize energy generation, storage, and distribution. It often includes smart meters, grid management software, and sophisticated monitoring capabilities to maximize efficiency and reliability. These modern microgrids are being increasingly utilized in residential, commercial, and industrial settings to enhance energy resilience and sustainable practices [2-3]. In dynamic behavior, MG stability refers to the ability of the system to maintain reliable and consistent power supply despite changes in energy generation or load.

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Maintaining stability is crucial for the efficient and continuous operation of the microgrid [4-5]. In addition, energy storage solutions, such as batteries and pumped hydro storage, play a critical role in balancing supply and demand in isolated system, especially with the increasing reliance on intermittent renewable energy sources. Furthermore, the integration a hybrid energy storage system into microgrids presents both challenges and opportunities. HESS could serve as energy storage units, allowing excess energy to be stored during low-demand periods and released back to the grid when needed. As loads continue to grow, the concept of decentralized energy production, where local energy generation meets local consumption, is gaining traction. This shift can enhance energy security and promote sustainability by reducing reliance on traditional centralized power plants. Overall, the evolution of microgrids towards innovative technologies not only addresses environmental concerns but also paves the way for a more resilient and interconnected energy future.

Moreover, a large interconnected multi-area microgrid can support frequency control by using HVAC or HVDC transmission links, which refers to the coordination and management of multiple small power supply areas across different geographic sectors to ensure stability and balance of power supply and load. This involves monitoring and controlling the frequency of each microgrid to avoid fluctuations and maintain a reliable and resilient power system. Advanced control algorithms and communication technologies are often used to enable seamless coordination and operation of interconnected multi-area microgrids [6-7]. Also, energy storage devices can be used to support microgrid supply and participate in frequency regulation during disturbances [8-10]. They can help manage the intermittency of solar and wind power by storing excess energy for later use [11-12]. Moreover, storage system play a vital role in reducing peak demand by providing stored energy during periods of high electricity consumption [13].

Several works proposed the use of storage system to enhance the energy management system (EMS) and monitoring of MG, In reference [14], authors have proposed a review of energy storage system in microgrid systems. In reference [15], Peña Asensio, *et al.* have proposed an effective method to show the contribution of battery energy storage systems in microgrid. In references [16, 17 and 18], authors have suggested the use of artificial intelligence to enhance microgrid energy management and control system. In [19], authors, have discussed the contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand. Also, In reference [20], authors have presented the contribution of wind-hydro pumped storage systems in meeting Lebanon's electricity demand. Furthermore, A lot of published work have also suggested various energy storage devices and artificial intelligence (AI) techniques including optimization algorithm to enhance microgrid dynamic behaviours in case of load changes or green power integration [21-22]. On the other hand, many researcher have proposed the use of coordinated control strategy that involves the integration of emerging technologies with AI, especially the connexion of wind farm and PV array with High Voltage Direct Current (HVDC) transmission link, such presented in references [23, 24, 25 and 26]. The main aim of using the HVDC link was to reduce power fluctuations due to the RESs and enhance frequency regulation system.

It is in this context that, this paper address the use of coordinated technology and effective energy storage devices as robust solution to enhance dynamic microgrid stability, making a mix of storage system the key components in building a more resilient and reliable energy infrastructure supported with HVDC transmission line. The layout of this paper is divided into five sections. Section one comprises this Introduction. Section two presents islanded and interconnected multi-microgrid model. Section three illustrates the two-stage acive power management and frequency control approach including the contribution of HESS. Section four focuses to the presentation and discussion of the results with a comparative study. Finally, the last section is devoted to the conclusion of this paper.

II. Multi-Microgrid Model

In the context of renewable energy integration, the microgrid serves as a crucial component in enhancing energy resilience and sustainability. The microgrid can be modelled as a small isolated area that includes a mix of distributed generation units with multiple load model as shown in Fig.1. the invistigated microgird includes Diesel Generator (DG), Wind Farm (WF), Solar PV Generator (SPG) , Load and hybrid energy storage system that comprise: Redox-Flow Batteries (RFBs), Superconducting Magnetic Energy Storage System (SMES) and Fuel Cell (FC). An optimal LFC loop based PIDN controller was installed in the microgrid to enhance frequency stability using the Fuzzy Logic control and the Marine Predator Algorithm (MPA) as optimization tool. The main idea was to reduce the operational regulation capacity in presence of RESs by using a hybrid energy storage system. The proposed method allows the use of HESS as supply unit during load variation, and also as smooth frequency regulation system to cope with wind and solar intermittent.

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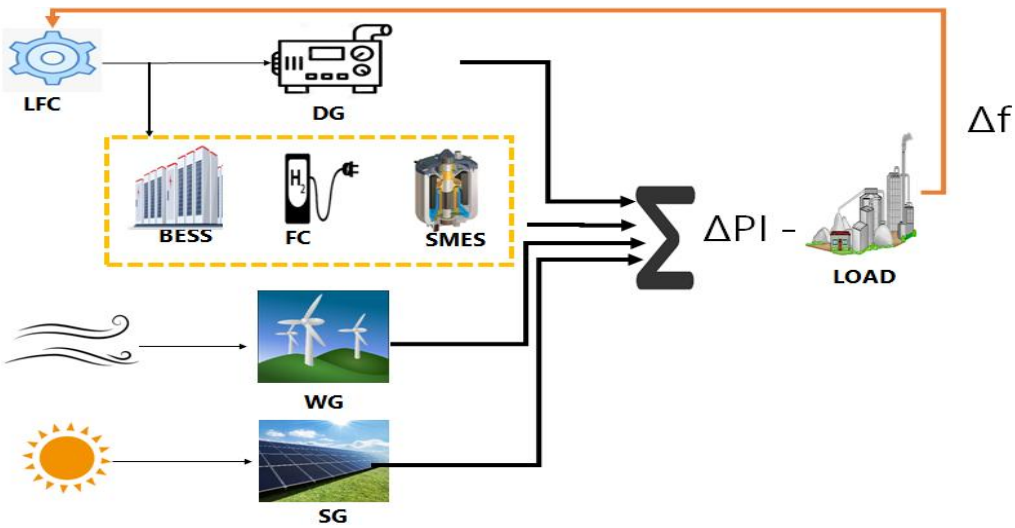

Fig.1. Single Area Microgrid Model.

During the Simulation, the study was extended to an interconnected multi-microgrid topology (MMG), that was created in the aim to increase the renewable sources penetration and enhance microgrid stability by using the HVDC interline power exchanges as given in Fig.2. A centralized load frequency control LFC loop was installed to coop with system fluctuations, which was coordinated with a hybrid energy storage system that was used for smooth regulation. In addition, an intelligent power management system was also considered to ensure MMG power equilibrium and satisfy the load in each microgrid, even load variations or supply units power decrease. The proposed coordinated strategy that involves artificial intelligence can be further extended in case of microgrid connected utility grid in the aim to support the conventional regulation system and reduce the capacity of LFC system. Using this method, power system operator can increase the penetration ratio of green power integration in the electrical network, together with minimization of production cost and CO_2 gas emission. It also, should noted that the storage system play a vital role in this strategy, which is used for both power management to supply load and system control to support the secondary frequency regulation loop.

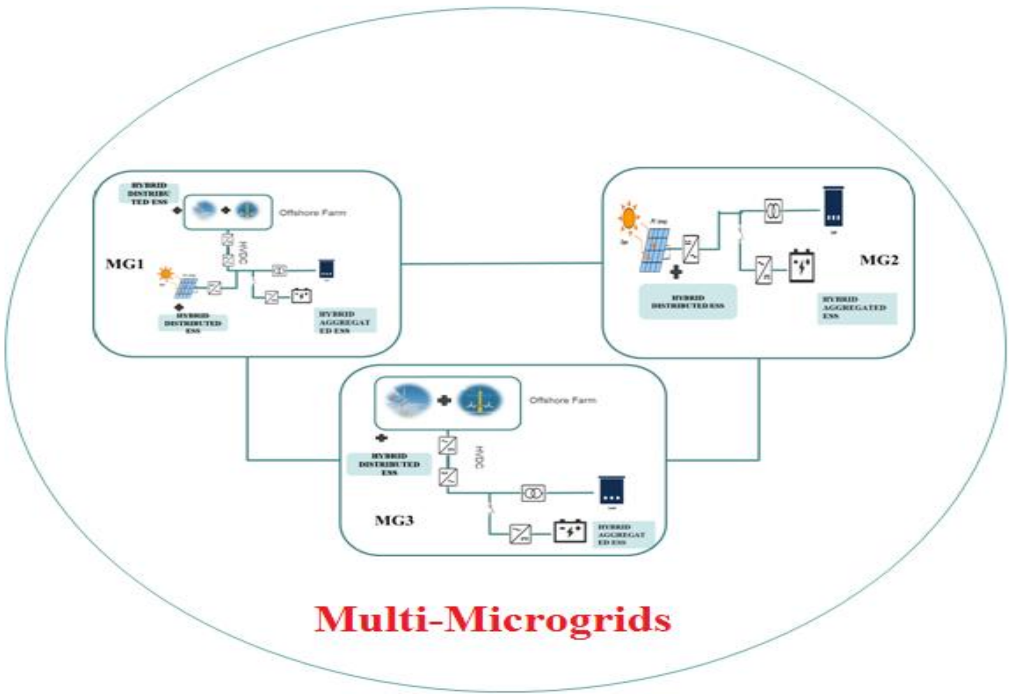

Fig.2. Interconnected Multi-Microgrid (MMG) Model.

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III. Optimal LFC Scheme Using MPA

In this section, an optimal secondary load frequency controller named LFC loop was proposed to cope with frequency deviation during disturbances. This system was coordinated with both HVDC transmission line and hybrid energy storage system that combines SMES, RFB and FC as presented in Fig.3. In addition, an optimal EMS system was employed to ensure RESs power maximization in order to face load variations. The proposed strategy of this paper includes three stages, at the first stage a Fuzzy Logic method was used to ensure active power management in each microgrid. Then, at the second stage, and if the MG was isolated, the LFC loop type Flat Frequency Control (FFC) was equipped with a PIDN controller, where this latter parameters were optimized using the newly Marine Predator Optimization Algorithm. Finally, at the third stage, and in case of multi area interconnected microgrid a Tie-Line Bias Control (TBC) is activated to ensure frequency stability and suppress the tie-lines power flow oscillations.

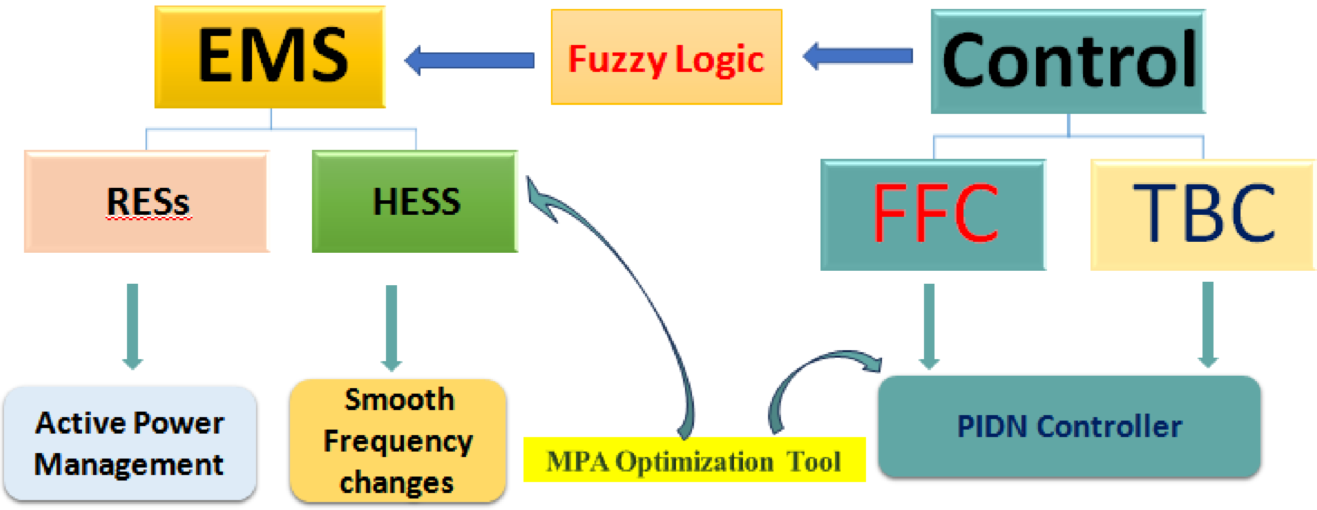

Fig.3. Multi-Stage Active Power Management and Control of Multi-Microgrid (MMG) Model.

A. Marine Predator Algorithm (MPA)

Nowadays, Nature-inspired and Bio-inspired is a class of optimization algorithm that is widely used to solve many engineering topic. This kind of optimization algorithms have gained significant popularity in various engineering fields due to their ability to efficiently solve complex issue [27-28]. These methodologies draw inspiration from natural phenomena and biological processes to develop innovative solutions for engineering issues. These algorithms have the ability to mimic the adaptive and evolutionary characteristics found in nature, allowing for the optimization of complex systems in a more efficient and effective manner [29]. Moreover, the application of nature-inspired algorithms extends beyond traditional engineering problems and has been successfully utilized in diverse areas such as data science, power system, and control [30-32]. By harnessing the power of nature-inspired optimization techniques, researchers and practitioners can tackle challenging optimization problems with greater accuracy and speed. As technology continues to advance, the integration of nature-inspired algorithms into various fields is expected to grow, paving the way for new advancements and breakthroughs in optimization and problem-solving methodologies. In this part, a novel metaheuristic optimization algorithm called Marine Predators Algorithm (MPA) was proposed and presented [30]. The MPA algorithm is a new nature-inspired optimization that follows the rules in optimal foraging strategy and encounters rate policy between predator and prey in marine ecosystems [30-32]. The main process of MPA is divided into three phases considering different velocity ratio and at the same time mimicking the entire life of a predator and prey. These steps are defined based on the rules governed on the nature of predator and prey movement while mimicking the movement of predator and prey in nature. More details are available on reference [30]. The MPA Flowchart is depicted in Fig.4.

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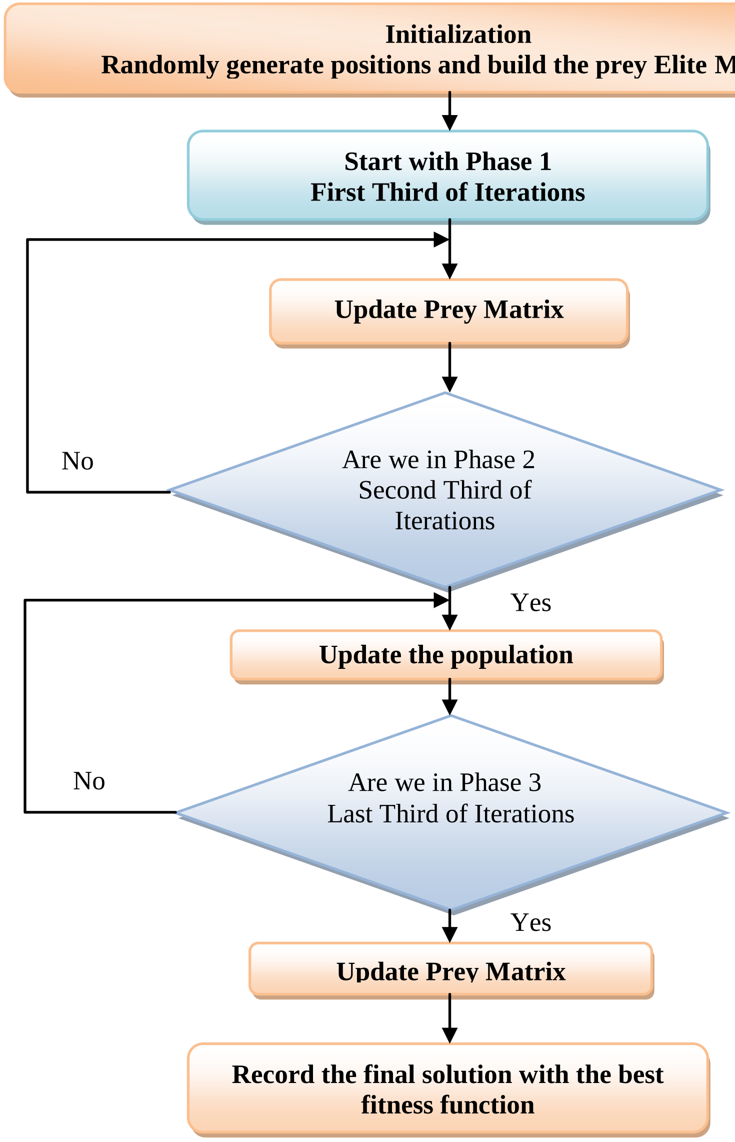

Fig.4. Flowchart of Marine Predators Algorithm [30].

B. *Objective Function*

In order to handle frequency deviation and ensure optimal microgrid power managment with maximization of a mix of green power units, the Area Control Error (ACE) was calculated as given in Eq.1, where, the Integral Time multiply Absolute Error (ITAE) given in Eq. 2 was used as fitness function subject to the PIDN controller parameters upper and lower limits in Eq.3.

$$ACE_{MG} = \beta_f \, \Delta f_{MG} \tag{1}$$

$$ObjFun = \int_{0}^{tsim} t.\left(\left|\Delta f + \Delta Ptie\right|\right).dt \tag{2}$$

$$\begin{gathered} K_{P\,min} \le K_P \le K_{P\,max} \\ K_{i\,min} \le K_i \le K_{i\,max} \\ K_{d\,min} \le K_d \le K_{d\,max} \\ N_{min} \le N \le N_{max} \end{gathered} \tag{3}$$

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IV. SIMULATION RESULTS

In this section, an isolated and interconnected microgrid was considered for the simulation. in the first case study, an islanded microgrid was simulated, which includes: wind farm, PV generator, CSP unit, and hybrid storage system. In order to show the robustness of the proposed controller to ensure system stability various scenarios have been simulated and presented involving load variation, storage system integration and HVDC link tied-offshore wind farm. The MPA optimization algorithm was used to find the best controller parameter in the aim to enhance frequency control as show in Fig.5, Fig.6 and Fig.7. Then in, the study was extended to a three area interconnected microgrid, where, the HVDC system was used as path between the three areas to ensure system stability and support the load in each area.

A. Islanded Microgrid

It is clear from the presented results that the frequency deviation was reduced the most effectively during load change in case of optimal LFC controller, where, it can be observed that the system frequency can be enhanced using the contribution of the hybrid storage system to support the power generation, also in case of large offshore wind farm the used of the HVDC transmission link can help to minimize frequency fluctuation the most effectively, where, the system remain to the nominal stable state.

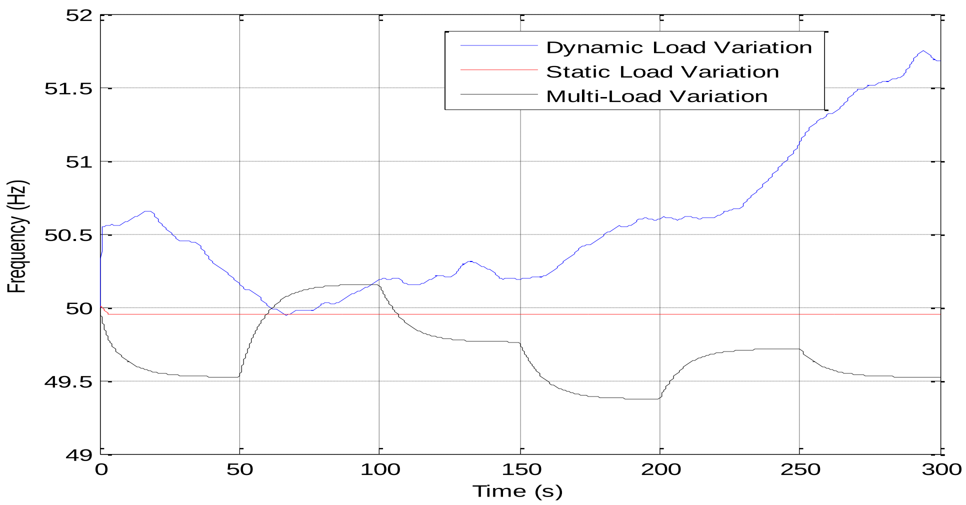

Fig.5. Frequency Fluctuations in Case of Multiples Load Changes.

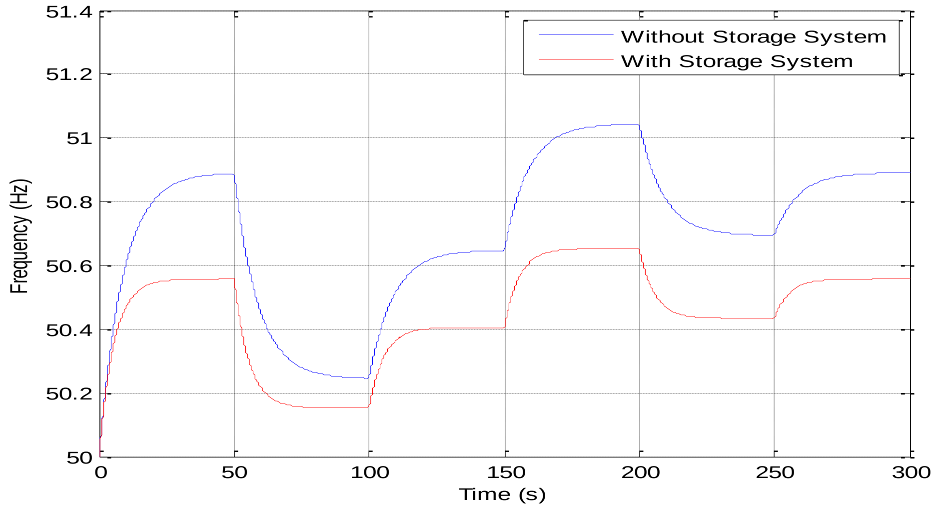

Fig.6. Contribution of Storage System to Reduce Frequency Fluctuations in Case of Multiples Load Changes.

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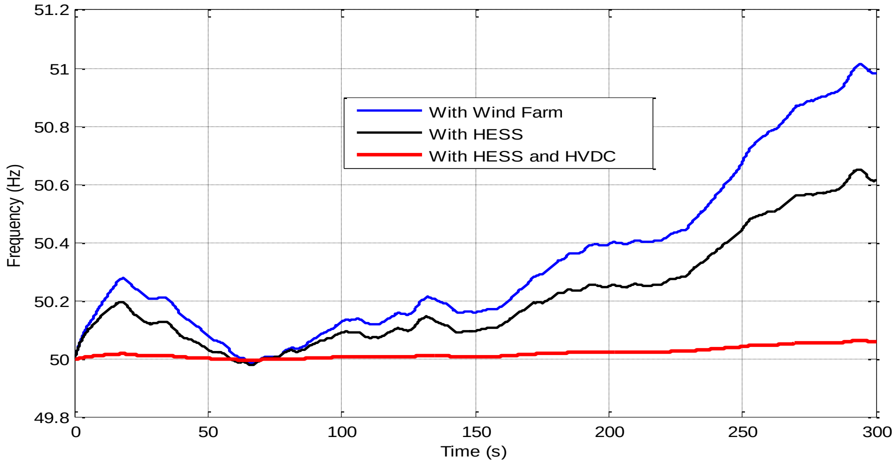

Fig.7. Contribution of HVDC Device to Reduce Frequency Fluctuations in Case of Dynamic Load Changes.

B. Interconnected Multi-Microgrid

In this part, a three areas interconnected microgrids MMG was simulated. A centralized TBC control system was used to ensure frequency stability coordinated with the HVDC tie-line device. The simulation results presented in Figs. 8, 9 and 10, shows the validity of the proposed strategy to cope with various perturbations in case of islanded and interconnected microgrids.

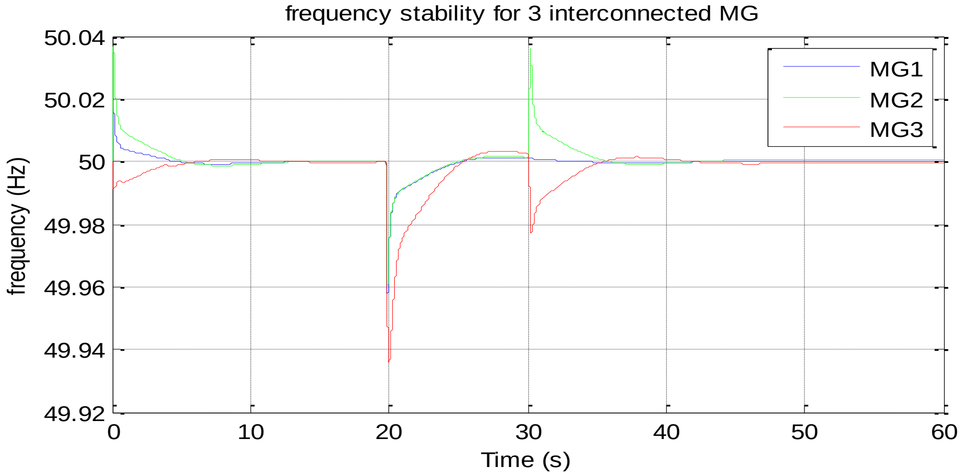

Fig.8. Frequency Deviation Without Storage System .

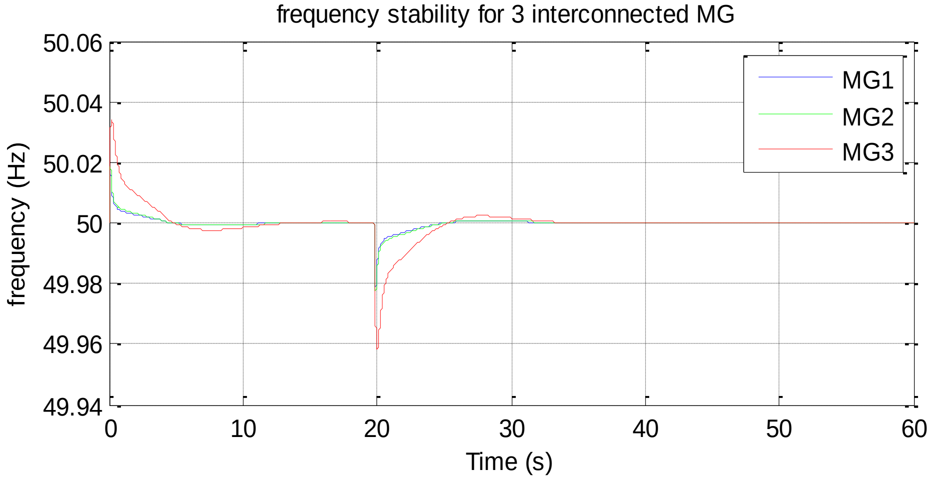

Fig.9. Frequency Deviation With Storage System.

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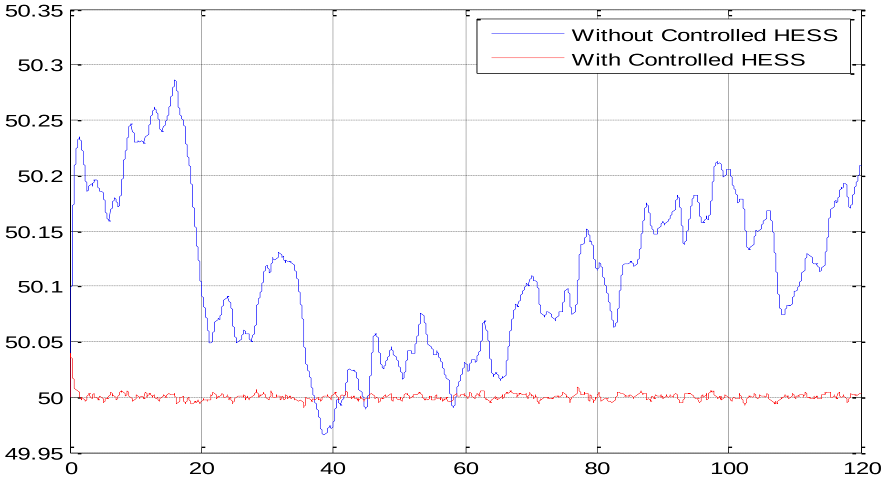

Fig.10. Contribution of HESS to reduce Frequency Deviation in Presence of RESs.

It can be observed that the load change can affect the frequency stability of the microgrid. It is crucial to consider the impact of load changes on dynamic behaviour of the microgrid. When the load fluctuates, it can lead to variations in the power generation and consumption within the microgrid especially in presence of wind and solar fluctuations, affecting the overall frequency stability. To address this issue, implementing a robust smart LFC controller can quickly respond to load changes. Moreover, integrating a hybrid energy storage systems within the microgrid can provide additional support in mitigating the impact renewable sources and load changes on frequency stability. HESS can store excess energy during low load periods and discharge it during high load periods, helping to balance the power supply and demand within the microgrid, which can ensure reliable frequency stability under varying load conditions. Also, in case of multi-area MG system the HVDC transmission line can help the LFC loop to handle with frequency fluctuations.

V. Conclusions

This paper have analyzed frequency stability and control of islanded and interconnected microgrid usinga multi-stage active power management and control strategy based optimal load frequency control loop coordinated with storage system and HVDC link. A new optimization algorithm called Marine Predator Algorithm (MPA) was employed to find the best PID controller during disturbances. This study was based on the calculation of the active power and frequency deviations during faults. Various scenarios have been simulated and presented including load change and storage system integration. Moreover, this analysis plays a crucial role in supporting dynamic frequency regulation and stability improving to ensure good power quality. Finally, and as perspectives, in the near future , a new optimal strategy will be implemented to find the optimal placement and sizing of the renewable sources in power system connected with microgrids and nanogrids systems.

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