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Frequency Control of Interlinked Microgrid System Using Fractional Order Controller

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ABSTRACT

As renewable energy resource (RES) penetration levels increase within a grid, power networks become more vulnerable to low inertia issues. Additionally, the proliferation of electric vehicles (EVs) has already made a substantial impact on grid dynamics. To ensure reliable frequency regulation in networked microgrid systems, this study introduces a fractional-order controller that integrates tilt-integral-derivative with filter and hybrid fractional-order controllers into a unified entity. The proposed controller adeptly manages various disturbances and frequency control within interconnected microgrid systems, comprising renewable resources, energy storage units, and synchronous generators. Furthermore, the utilization of the particle swarm optimization algorithm is used for optimizing controller settings in microgrid systems. Existing EVs contribute additional functionality to interconnected microgrid systems. A case study is conducted considering installed photovoltaic (PV) panels, wind turbines, and distributed EVs in a multi-area interconnected microgrid. Simulation results underscore the effectiveness of the proposed controller, demonstrating its superiority over existing controllers in the literature in terms of enhancing system dynamic performance.

Index Terms—Electric vehicles, interlinked microgrid system, renewable energy resources (RESs), FO controller

I. INTRODUCTION

The modern time of industrial revolution and overexploitation of non-renewable energy resources have infringed the weather pattern and increased the global temperature, which has become a new challenge for the existence of humanity and life on earth. The demand for energy increases day by day due to the large population. So, it is necessary to install distributed energy resources widely [1]. Furthermore, the load could be utilized in a grid-connected or islanded mode as per the requirement [2]. The future project of the world is renewable energy development, which will be led by a hybrid fractional order (FO) controller. The load frequency control (LFC) plays a pivotal role in upholding the stability of interconnected grids amidst load disruptions and variations in renewable energy sources (RESs). Previous studies have addressed frequency regulation in isolated microgrid (MG) systems [3, 4]. Given the widespread adoption of electric vehicles (EVs), it is imperative to explore how their energy storage systems could enhance LFC and MG stability. Electric vehicle fleets can function as distributed energy storage systems, capable of aggregating to discharge power during peak demand periods. Nevertheless, the complexity of control characteristics in large-scale power systems with numerous interconnected regions necessitates optimal planning. Various configurations and combinations of controllers, such as proportional (P), integral (I), derivative (D), and tilt (T) controllers, have been proposed for LFC systems [5–8]. In [9], the traditional PI controller for LFC is used. When the time delay of the communication system is taken into account, MG has instability problems. The LFC parameters in connected MG have been designed using various control theories. A model-free controller has been designed using a PID approach for the closed-loop system [10]. In [11], the Harris Hawks optimization method is used to optimize the PI parameters. These controllers are straightforward solutions, but they fall short of completely reducing power system disturbances. The artificial-bee-colony optimizer has been used to develop and optimize the regulation of EVs utilizing the tilted integral derivative (TID) controller in [12]. The ideal modified FO controller for EVs based on multi-area interconnected power networks has already been provided by the authors in [13]. The particle swarm optimizer (PSO) technique has also been used to optimize virtual inertial

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controllers [14]. The authors of [15] have presented a proportional, integrator, and filtered derivative terms (PIDF) plus filter controller in parallel control structure. Additionally, [16, 17] have created an enhanced automatic generation control approach utilizing FO-PID. Additionally, other FO-based controllers have been given and contrasted for resolving LFC problems in [18, 19]. Nevertheless, most of the controllers discussed require substantial effort during the parameter tuning phase. Specifically, the heightened risk of converging to a local minimum diminishes the reliability of metaheuristic optimization techniques. Furthermore, appropriately calibrating numerous parameters poses a significant challenge in attaining optimal outcomes. An enhanced control scheme has been introduced in the literature to further enhance LFC performance. In [19], the TIDF controller was suggested and optimized via differential evolution. Slap Swarm Optimizer Algorithm (SSA) has been used in [20] to tune the PI-TDF controller. The butterfly optimizer algorithm has been used to optimize dual-stage controllers in [21] using the manta ray foraging optimizer to develop hybrid FO controllers. Additionally, cascaded fractional-order PID controller-fuzzy logic control (FOPID-FLC) have been developed utilizing the imperialist competitive optimizer algorithm in order to dampen the grid [22].

In the preceding discourse, several controllers have been presented for interconnected MG power systems. However, the adoption of FO-based controllers provides notable advantages in alleviating system oscillations and preserving system frequency. Moreover, they provide robust solutions in terms of response time and frequency regulation.

The following points sum up the key major contributions of this paper:

- A new robust FO controller is suggested for enhancing the frequency stability of the MG-based interlinked power system.
- Electric vehicles assist in providing extra functionality for an interlinked microgrid system. Consequently, EVs can help to achieve a new PSO program is created for optimizing the suggested controller's parameter settings, providing additional damping of the frequency and tie-line power oscillations.
- The proposed controller is implemented while taking into account the various impacts of load fluctuations, unpredictable conditions of RESs penetration, and uncertainties.
- The design of the suggested controller also takes the generation rate limitations (GRC) into account in interlinked MG Systems.

The remaining portions of the paper are arranged as follows: The mathematical modeling of the interlinked MG system, including the numerous generation sources, is presented in Section II. In Section III, the suggested HybFO-TIDF controller is shown. The simulation results and comments of the suggested controller are discussed in Section IV. In Section V, the paper's conclusion is presented.

II. MATHEMATICAL MODELING

The system configuration of the interlinked MG system is shown in Fig. 1. The Simulink model is shown in Fig. 2 where thermal power plants, wind turbines, EVs, energy storage devices, and connected loads are all connected in area 1 and area 2, respectively. To mitigate fluctuations in the area frequency and tie-line power, each region is managed by its own local LFC. In order to ensure the stable regulation of system frequency and tie-line power in the examined system, the proposed controller also oversees the coordination between EVs and other power generation resources in each area. The parameters of the system configuration have been taken from [23].

A. Electric Vehicles Modeling

The in-depth dynamic model of EVs, which was used in this study for the analysis of frequency response, is depicted in Fig. 3. The relationship between the open circuit voltage (V_{oc}) and the state of charge (SOC) of connected EVs is also frequently expressed using the Nernst equation, as shown below.

$$Voc\left(SOC\right)=Vnom+S\frac{RT}{F}\ln\left(\frac{SOC}{Cnom-SOC}\right) \tag{1}$$

Here, Voc(SOC), Vnom, and Cnom represent the open-circuit voltages of EVs, and they are functions of the EVs' SOC, nominal voltages, and nominal capacities (in Ah), respectively. Furthermore,

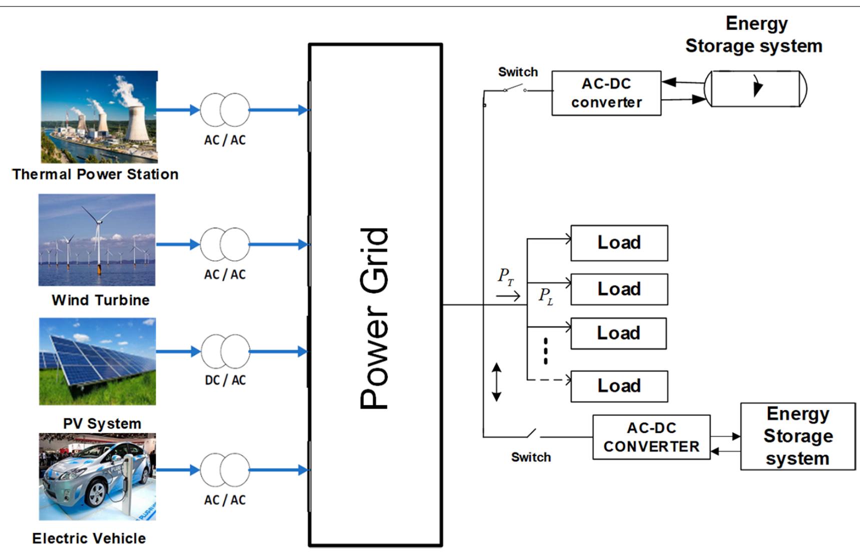

Fig. 1. System configuration of the interlinked MG system.

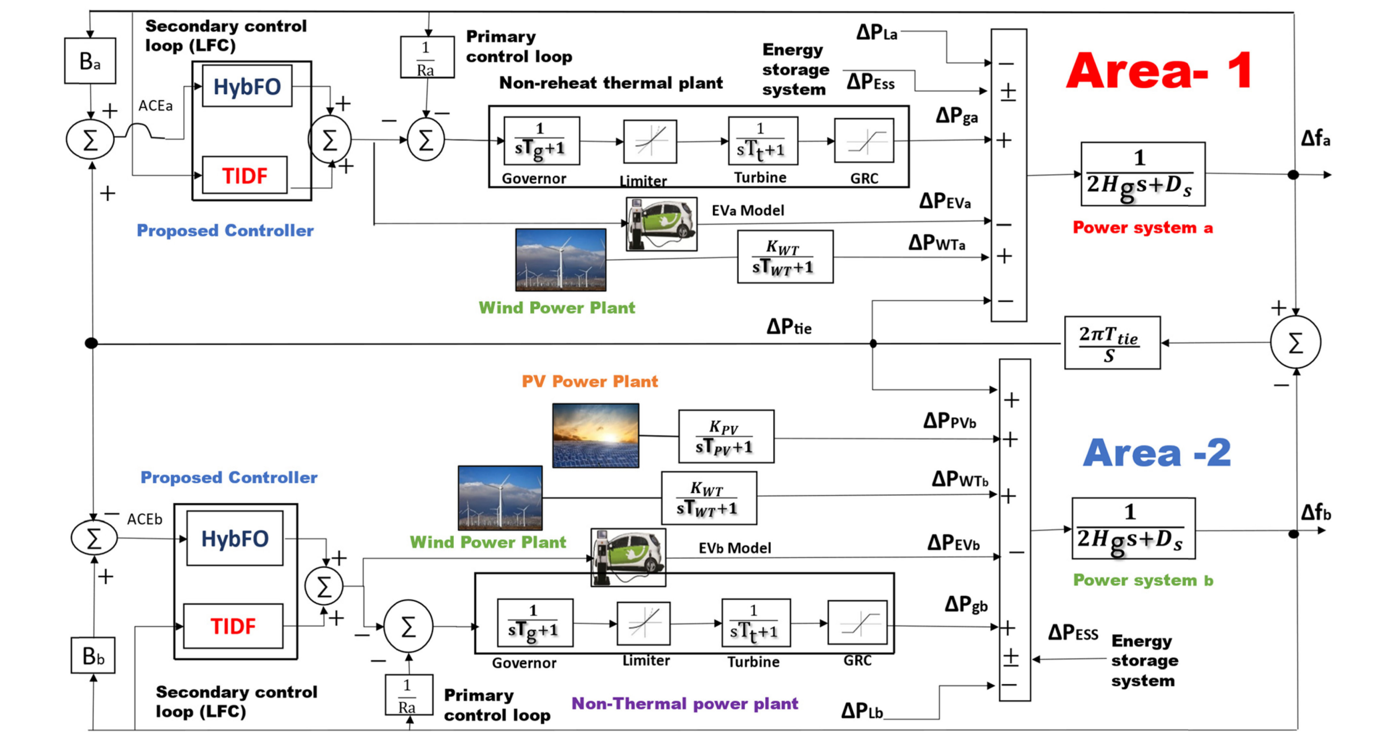

Fig. 2. The model of the studied grid using the interlinked MG system.

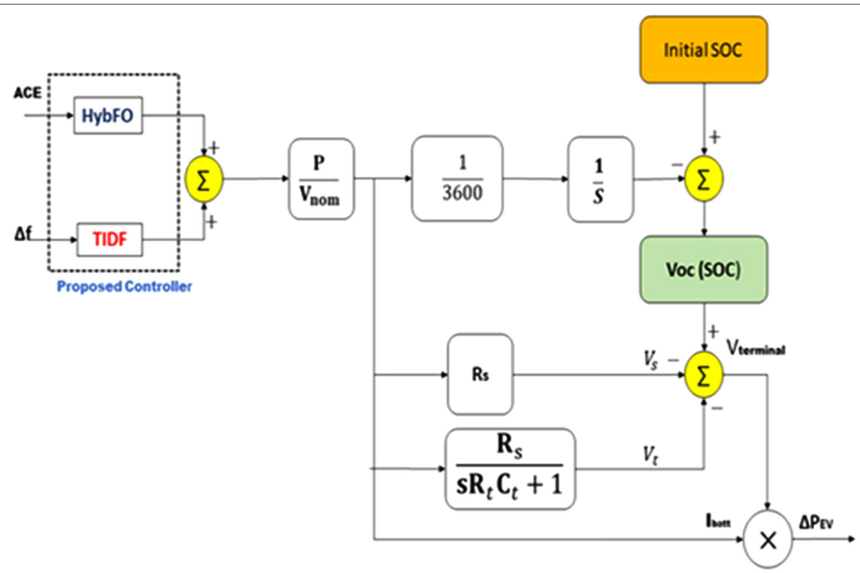

Fig. 3. Dynamic modeling of connected electric vehicles.

S represents the sensitivity parameter value indicating the relationship between Voc and the SOC of connected EVs [13]. On the other hand, R, F, and T denote the gas constant, Faraday constant, and the temperature, respectively.

B. Modeling of Wind Power Plants

Modeling of wind power plants describes the generation system of wind energy. It can be expressed in a first order transfer function [14], where K_{WT} and T_{WT} are the gain and time constants.

$$G_T(s) = \frac{Kw}{sTw + 1} \tag{2}$$

C. Modeling of PV Power Plants

Modeling of photovoltaic (PV) power plants describes the generation system of solar energy. It can be expressed in a first-order transfer function $G_{PV}(s)$ [15], where, K_{PV} and T_{PV} are the gain and time constant for the PV system.

$$G_{PV}(s) = \frac{1}{sT_{PV} + 1} \tag{3}$$

D. Modeling of Non-reheat Thermal Plants

The modeling of governor and turbine is given in 4a and 4b respectively

$$G_G(s) = \frac{1}{sT_G + 1} \tag{4-a}$$

$$G_t(s) = \frac{1}{sT_t + 1} \tag{4-b}$$

E. Modeling of Energy Storage System

The transfer functions of the energy storage systems are given as follows.

$$G_{ESS}(s) = \frac{K_{ESS}}{1 + sT_{ESS}} \tag{5}$$

F. Generation Rate Constraints

Incorporating GRC into the model alters the dynamic response, leading to increased settling time and greater overshoot compared to when GRC is not present in the system. The study considers a generation rate of 0.1 per unit (p.u.) MW per minute, equivalent to 0.00017 p.u. MW per second [24].

III. PROPOSED CONTROLLER

Novel advancements are necessary to broaden the applications of FO control systems. Conventional controllers rely on a singular feedback signal, the ACE signal, leading to a sluggish response in the LFC system. Moreover, the exclusive use of the ACE feedback signal results in inadequate mitigation of diverse disturbances.

The FOPID controller is used to amalgamate the benefits of an integer-order PID and the FO controller. The FOPID controller can be expressed as follows:

$$C(s) = \frac{Y(s)}{R(s)} = K_p + \frac{K_i}{s} + Kd\, s^{\mu} \tag{6}$$

In this context, λ and μ denote the orders related to the integral and derivative terms respectively within the range of [0, 1]. It has been confirmed that these terms, λ and μ, can deliver superior performance and improved dynamic responses when compared to PID controllers [23]. TID controllers have found applications in FO control systems for LFC. Equation (7) representing the TID controller is as follows:

$$C(s) = \frac{Y(s)}{R(s)} = K_t s^{-1/n} + \frac{K_i}{s} + Kd\, s \tag{7}$$

where K_t, K_i, K_d stands for the tilt, integral, and derivative terms gain respectively. The optimization process involves adjusting both the gain and FO to optimize and ensure stable performance in the entire system. Meanwhile, n is chosen between 2.0 and 5.0 [8], [19].

The HybFO controller can be articulated as follows:

$$C(s) = \frac{Y(s)}{R(s)} = K_t s^{-1/n} + \frac{K_i}{s} + Kd\, S^{\mu} \tag{8}$$

The mathematical formulation of the controller is given in (9) and in Fig. 4.

$$Y(s) = (K_{t1} s^{-1/n} 1 + \frac{K_{i1}}{s} + Kdl \frac{N_c s}{s + N_c})\Delta fx + (K_{t2} s^{-(1/n)_2}) + \frac{K_{i2}}{s} + Kd2\, s^{\mu 1})ACEx \tag{9}$$

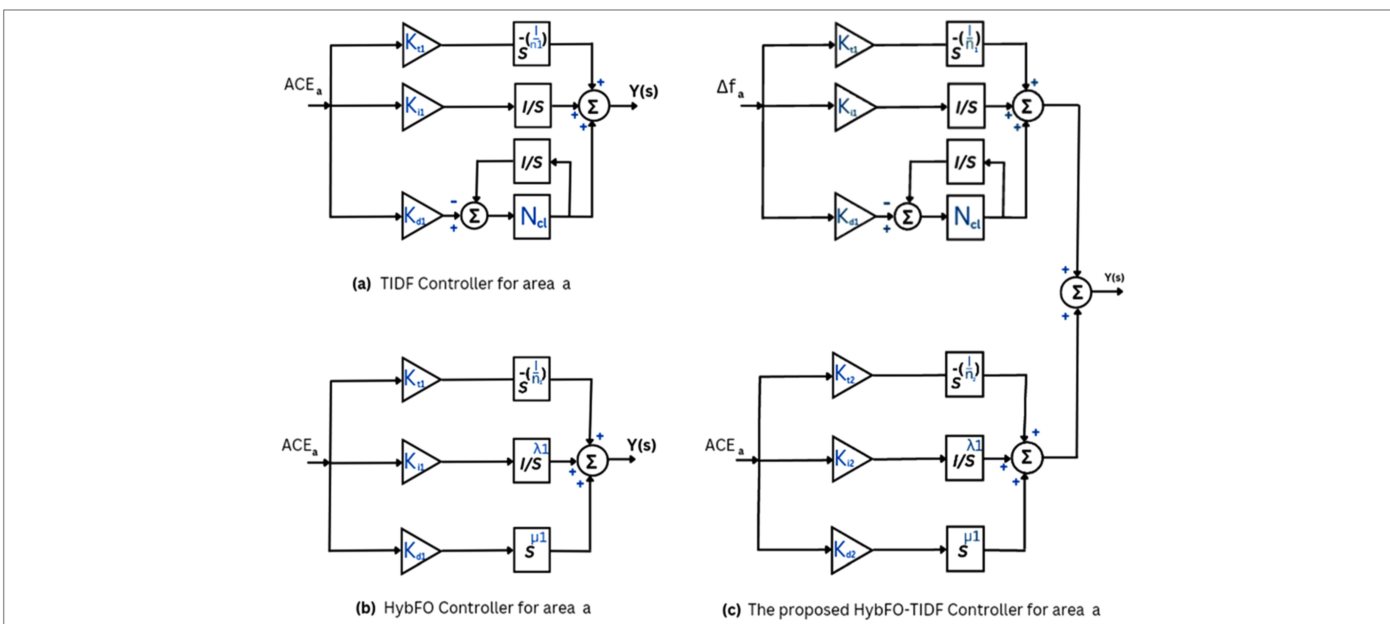

Fig. 4. The schematic of the studied controller.

IV. Simulation Calculation and Optimization Process

The accomplishment of the new combined controller and the operation of the PSO are analyzed using the chosen multi-interconnected grid model while considering different scenarios of renewable energy penetrations and load changes. The analyzed scenarios are executed through MATLAB/SIMULINK programming code. The PSO algorithm [25] is coded into a (.m file) and embedded into the SIMULINK platform of the interconnected MG models under scrutiny to streamline optimization procedures. It effectively discerns optimal parameters within predetermined upper and lower bounds. The selection of gain upper and lower bounds are shown below:

$$K_{min\ t} \leq K_{t1}, K_{t2}, K_{t3}, K_{t4} \leq K_{max\ t}$$

$$K_{min\ i} \leq K_{i1}, K_{i2}, K_{i3}, K_{i4} \leq Kmax_{\ i}$$

$$K_{min\ d} \leq K_{d1}, K_{d2}, K_{d3}, K_{d4} \leq K_{max}$$

$$n_{min} \leq n_1, n_2, n_3, n_4 \leq n_{max}$$

$$\lambda_{min} \leq \lambda_1, \lambda_2 \leq \lambda_{max}$$

$$\mu_{min} \leq \mu_1, \mu_2 \leq \mu_{max}$$

$$N_{min\ c} \leq N_{c1}, N_{c2} \leq N_{max\ c}$$

In this approach, $K_{min\ t}$, $K_{min\ i}$, and $K_{min\ d}$ are chossen to be 0, whereas, $K_{max\ t}$, $K_{max\ i}$, and $K_{max\ d}$ are chosen to be 5. The values of n_{min} are 2 and n_{max} is 5, respectively. The λ_{min}, and μ_{min} are chosen to be 0 and λ_{max} and μ_{max} values are 1. Additionally, the parameter N_{minc} and $N_{max\ c}$ are to be 5 and 500, respectively.

A. SCENARIO 1: Results and Discussion

A simulation result is performed for interlinked MG system for various cases and compared with other controllers. In all cases, it is found the proposed controller is superior in all aspects of frequency regulation of MG.

1) Case 1: 5% Step Load Change in Area-2

In this case, the interlinked MG system is subjected to a 5% load change at the beginning of the simulation in region B. The frequency regulation of both regions is illustrated in Fig. 5a and b, respectively. The results indicate that the suggested controller yields minimum frequency deviation when compared to conventional controllers

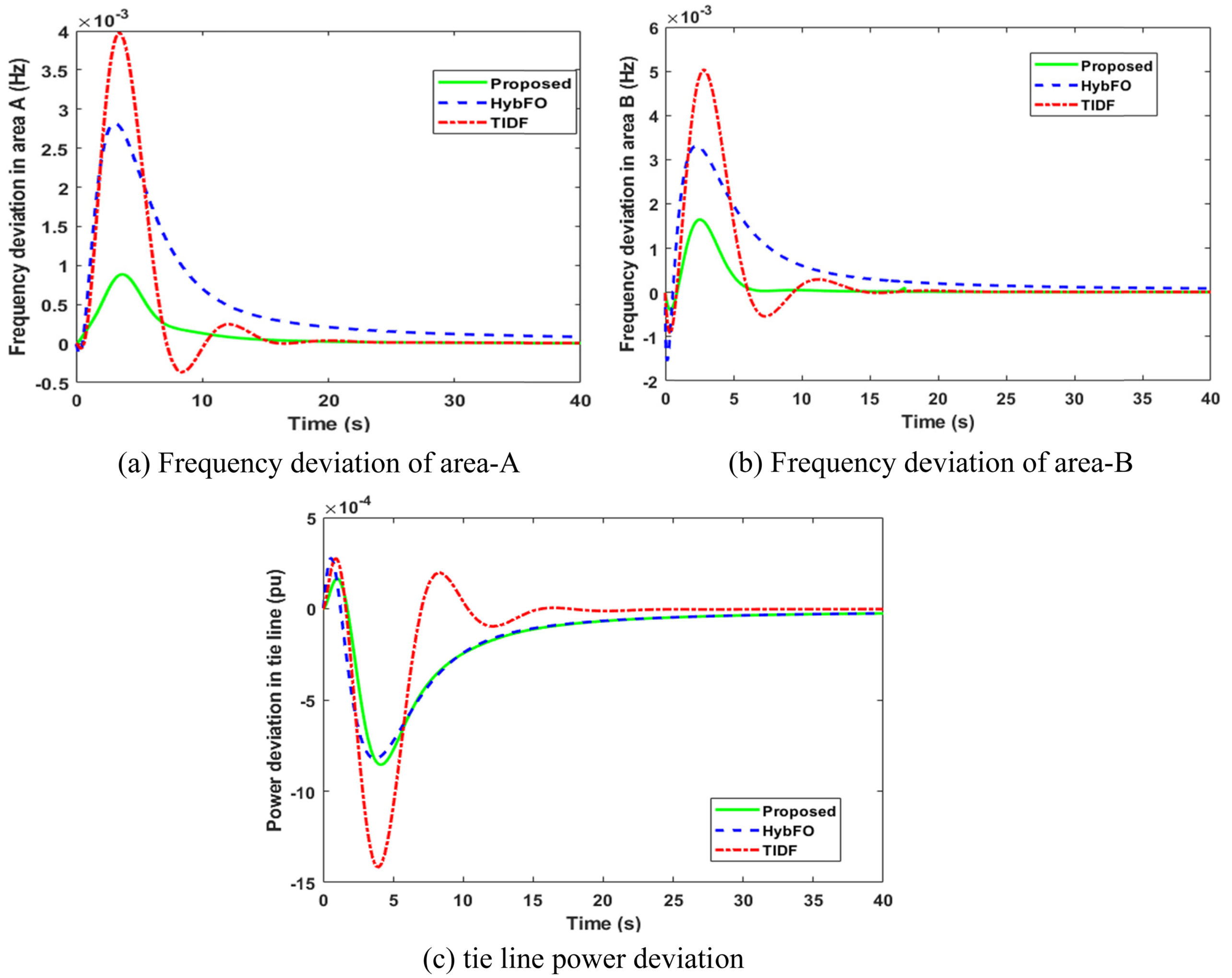

Fig. 5. Dynamic response of studied system.

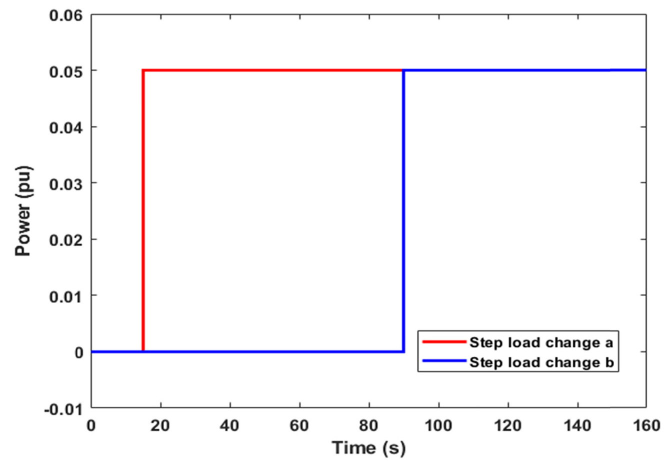

Fig. 6. Power generation for scenario 1 (case 2).

such as TIDF and HybFO. Furthermore, Fig. 5c proves the superiority of the proposed controller for tie line power deviation.

2) Case 2: 5% Step Change in Load Both Areas

In this instance, the interconnected MG system experiences step-load disturbances in both regions, as depicted in Fig. 6, with a 5% change in region A at $t=15s$ and 5% in region B at $t=90s$. To check the system efficacy of the controller utilizing the optimized HybFO-TIDF combination controller, comparisons are conducted with traditional TIDF and HybFO controllers separately. As depicted in Fig. 7, it is evident that the proposed controller having quicker performance in maintaining the system frequency and tie-line power deviation to their schedule value as compared to others techniques. This novel collaborative approach involving the HybFO-TIDF in a single entity and EVs contribute significantly to optimizing the requisite power from diverse sources.

B. Scenario 2: Impact of Renewable Energy Resources Disorder

The objective of this scenario is to illustrate the efficacy of the proposed method involving the combination of HybFO-TIDF and the contribution of EVs influencing the dynamic response of an interlinked MG system amid disturbances in RES. The analyzed system takes into consideration the intermittent characteristics RES and their fluctuations, such as those seen in wind and PV generations. These sources are crucial components in interconnected power systems, particularly in microgrids. Further in this particular scenario, the proposed coordination of LFC and EV utilizing the optimized HybFO-TIDF controller based on PSO is assessed under challenging conditions involving significant variations in load and RES. Further, PV generated power is introduced into the systems at t = 10s in area B, while the wind power is injected at t = 70s into area A. Additionally, a sudden step-load increase of 5% is introduced into area B at t = 40s, as illustrated in Fig. 8. The frequency deviation is depicted in

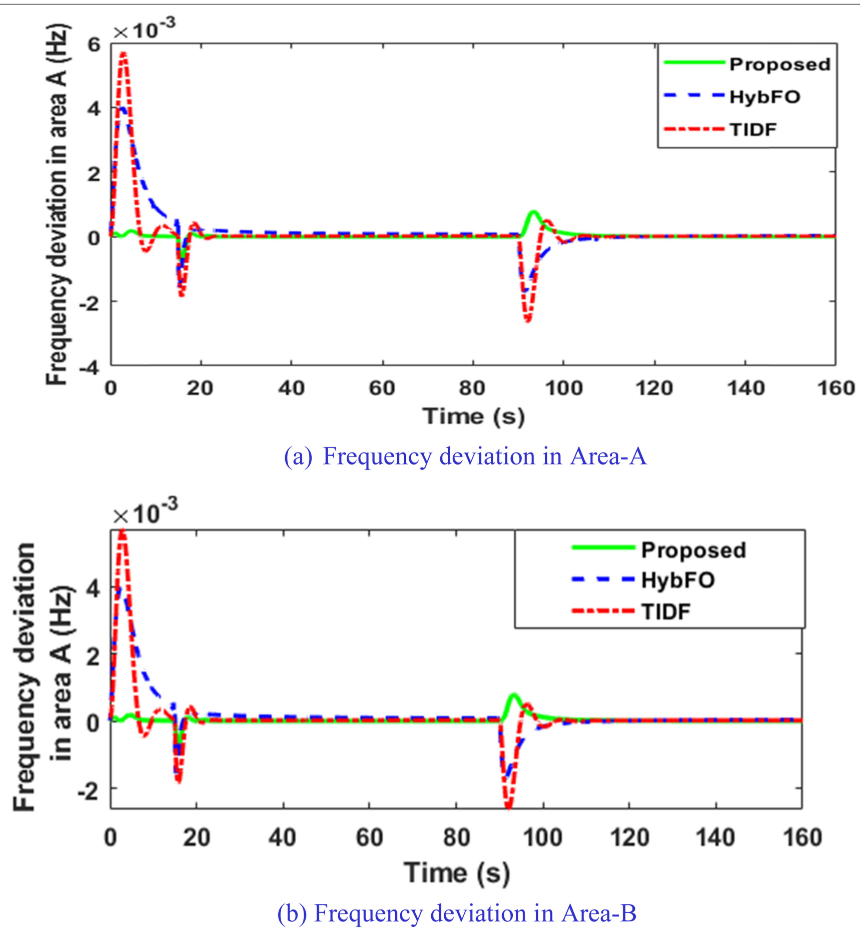

Fig. 7. System response of interlinked MG system.

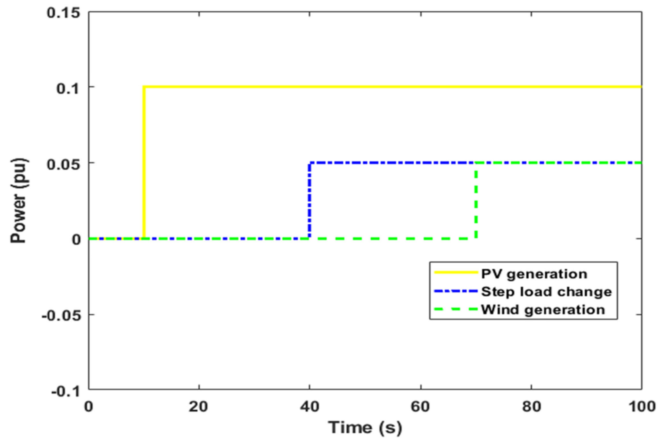

Fig. 8. Power generation and demand for scenario 2.

Fig. 9, revealing that each region has augmented its generation to adjust the tie-line power and meet its load demand, resulting in an increased tie-line power approaching zero.

C. Scenario 3: Renewable Energy Resources and System Uncertainties

The suggested parallel HybFO-TIDF controller combination's robustness for real-time applications is examined for an interconnected MG system with uncertain system characteristics. This scenario operates the investigated power system under the same circumstances as scenario 2 but reduces system inertia by 30% and changes all other system parameters proportionately. The objective of this scenario is to evaluate the stability of the studied systems across different uncertainty scenarios. The dynamic responses of the analyzed system to fluctuations in frequency and tie-line power are depicted in Fig. 10. Nonetheless, the proposed HybFO-TIDF controller demonstrates superior regulation of frequency and control of tie-line power, particularly when LFC and EVs collaborate. By synchronizing

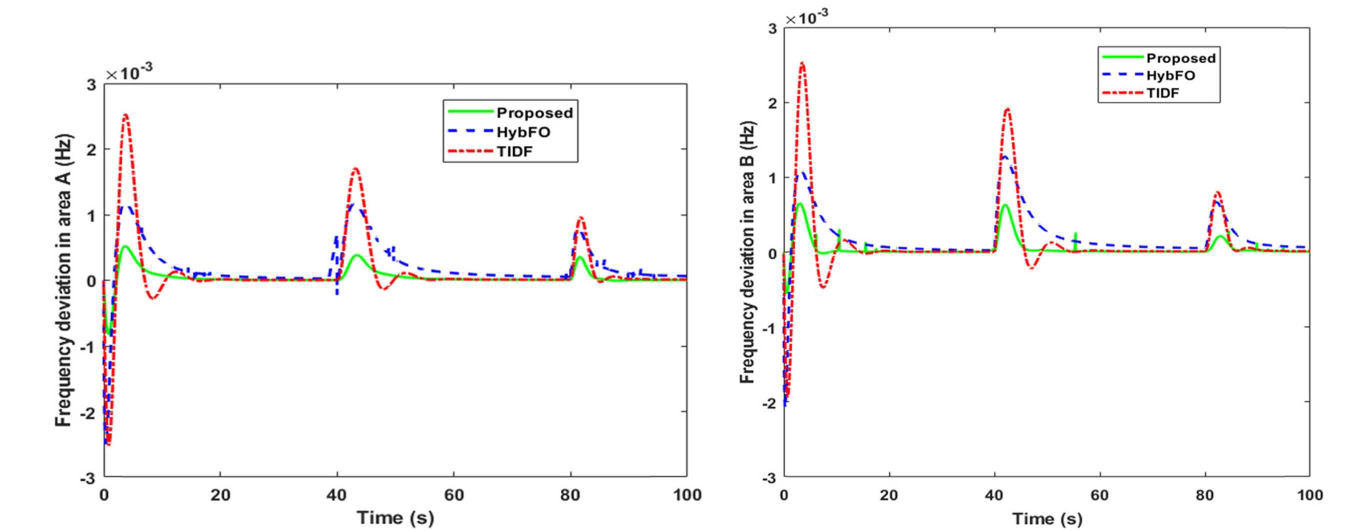

Fig. 9 Frequency deviation of area A and B for different generation scenario and demand.

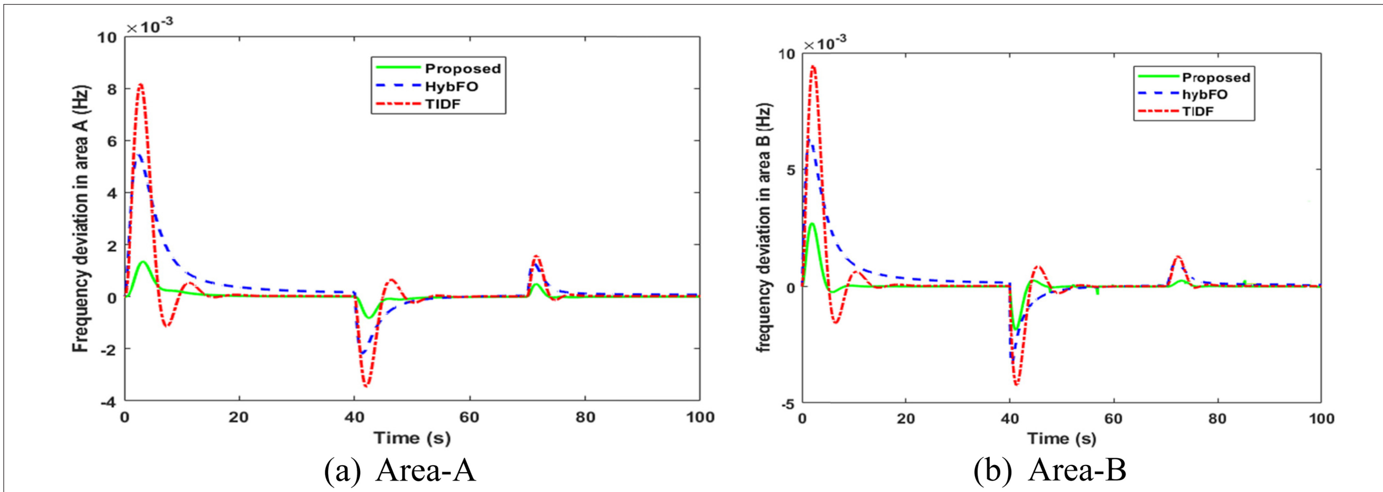

Fig. 10. System response with +30% variation in nominal parameters.

TABLE I. PERFORMANCE INDICES FOR VARIOUS CASES

		Performance Indices			
Scenario	**Controller Technique**	**Integral Square Error (ISE)**	**Integral Absolute Error (IAE)**	**Integral Time Square Error (ITSE)**	**Integral Time Absolute Error (ITAE)**
No. 1 (Case 1)	TIDF	0.0001067	0.0396	0.000358	0.1818
	HybFO	0.00007899	0.5282	0.0003451	0.4566
	Proposed	0.0002202	0.0169	0.0004271	0.1204
No. 1 (Case 2)	TIDF	0.0002095	0.06177	0.0006997	0.3548
	HybFO	0.0001548	0.07463	0.0006355	0.6227
	Proposed	0.00002289	0.02736	0.00009896	0.2285
No. 1 (Case 3)	TIDF	0.003057	0.5361	0.4657	76.56
	HybFO	0.001903	0.5779	0.2859	82.6
	Proposed	0.0002601	0.1871	0.03912	26.57

LFC and involving EVs, the suggested combined controller exhibits robust performance. Furthermore, it effectively executes LFC actions in the presence of various disturbances and uncertainties, commonly encountered during the real-world operation of interconnected MG systems. The various performance indices of the studied system are shown in Table I. From Table I, it is evident that the proposed approach is better than other techniques, and it is clear that with the proposed approach, the performance indices obtained from various cases are superior to the other method.

V. CONCLUSION

This study investigates a hybrid controller for interconnected MGs combining the advantages of two controllers, TIDF and HybFO, into a unified system to reduce frequency deviation and fluctuations in tie-line power. Incorporating EVs and other renewable energy resources into the MG system aids in optimizing the parameter settings of the proposed controller, offering additional damping of frequency and tie-line power oscillations. The initial feedback signal utilizes the ACE, empowering the proposed controller to reduce the low-frequency oscillations of signals. Conversely, the second feedback signal employs frequency deviation, playing a crucial role in alleviating high-frequency signals. The studied system has been examined for various types of case studies, and its performance has also been also compared with the existing available controller. The proposed controller achieves the best performance indices indicators which demonstrate the superiority of the suggested controller in all scenarios examined across a range of performance goals.

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