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FREQUENCY CONTROL OF AN ISLANDED MICROGRID WITH ELECTRIC VEHICLES USING A FRACTIONAL-ORDER CONTROLLER

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Abstract- It is anticipated that renewable energy sources (RESs) will increasingly dominate in modern electrical power systems. Nevertheless, the primary head of inertia in power systems is spinning masses, and they are absent or much reduced in renewable energy-based generating systems. As a result, the frequency of nowadays electrical grids is a crucial measurement of their reliable functioning. By considering the impacts of electric vehicles (EVs), this research intends to provide a modified control approach for load frequency regulation in a microgrid founded on a fractional-order PID (FOPID) controller. To further ensure robust efficacy, the controller's coefficients are fine-tuned using the reptile search algorithm (RSA). The proposed method outperforms comparable algorithms, taking less time to run and having high accuracy in finding optimal solutions and parameters. Different cases are investigated to see how well the suggested control method works in a time-delayed standalone microgrid. The proposed method has been proved to be efficient in time-domain features and resilient to different uncertainties as well as its fast response capability. In addition to improved performance when EVs and storage systems are presented, the suggested controller also increases the battery life of EVs, an aspect that is covered in the paper.

Keywords: Load Frequency Control, Electric Vehicles, Microgrid, FOPID Controller, Fractional-Order Controller.

1. INTRODUCTION

Due to the increasing number of RESs in the distribution grid, a new system called microgrid (MG) has emerged. Small metropolitan areas, shopping malls, and industrial centers are all examples of MGs since they are low-voltage networks with many loads, generators, and storage units for dispersed energy. Moreover, MGs can operate in two modes: network connected and isolated from the main network [1]. The primary objective of load frequency control (LFC) is to preserve the dynamical responsiveness of a power grid; it is in charge of balancing power within the system to ensure that the system's frequency stays within a restricted range. In fact, extreme fluctuations in frequency happen when the LFC capacity is insufficient to rebalance generation and demand. This issue can be exacerbated as the system operates in an isolated mode. Therefore, a suitable control mechanism has to be put in place to guarantee that the required frequency rate is reached [2].

As a result of power changes from distributed generators, operational reserves are required to make up for the resulting gap between supply and demand. Using large storage devices instead of new structures of conventional plants, which are hazardous to the environment and breathing air, can be a clean solution to compensate the power shortages. However, they are more expensive and need enormous costs to apply to this strategy [3]. EVs seem to be the future of the automobile industry since they boost energy efficiency, are ecologically friendly, and may benefit the environment by lowering emissions of greenhouse gases [4]. Hence, they are highly recommended due to their potential use as energy storage devices in grids. When EVs are plugged into the grid, they can trade their power with the system [5]. Prosperous and rational control design proposals can be considered as a robust answer to receive strong performance and stability in the MGs just like the traditional power systems [6].

Given the rapid changes in the MG's operational state and characteristics, traditional controllers are inadequate for use in the LFC of an isolated MG equipped with EVs and RESs. Therefore, they cannot guarantee the system's frequency is unaffected by the disorganized control effects of vehicle-to-grid (V2G) and other units. Consequently, it is highly desirable for the LFC to have a controller with resilient performance across a broad spectrum of system operating conditions [7]. Over the past decade, various control approaches have been introduced for the LFC in the MGs. In [6], a paper study on LFC for conventional and distribution generation power systems is applied. To design better and more influential LFCs, a novel fuzzy logic set for MGs with considering EVs is presented [7].

Additionally, to further improve the frequency responsiveness of MG, a novel controller is implemented by fusing the functions of a conventional PID controller and a two-degree-of-freedom (2-DOF) controller; this

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controller has undergone a sensitivity analysis to show that it is robust to changes in the grid's parameters [8]. An effective PID controller over LFC in a MG having an EV model is described in another research [9]. The PID controller parameters are adjusted using an ANN based on PSO. Results showed that PSO-based ANN may achieve system stability in the shortest time. The authors in [10] recommended an optimal Fuzzy Logic based-PID (FLPID) controller for LFC of isolated MG considering system uncertainties. Moreover, in [11], to control the power fluctuations in the microgrid, a New LFC method based on virtual area error in a MG including PV and the battery is implemented.

In [12], the authors advise using a hierarchical method of control for the LFC in the MG. Basic theories of type-2 fuzzy sets and systems is explained in [13]. A Robust decentralized neural network-based LFC in a deregulated environment was developed in [14]. The authors in [15] proposed a photovoltaic generation source with EVs for LFC in the modern power systems. Cascaded controllers, including ESS support, have also been studied in [16] for their potential use in power systems featuring multiple generating sources. In [17], an integer order PID (IO-PID) controller was investigated for use as a secondary strategy in a single-area MG. This was done to better understand the behavior of the system. Moreover, since the power generation from RES is uncertain and the output voltage is low, the voltage in MGs can be raised with the use of DC-DC converters. [16]. Hence, researchers have focused on the difficulty of controlling the dynamics of these non-linear systems to improve the MG's effectiveness [18, 19].

Using the V2G concept, this research examines the effectiveness of a control scheme based on a fractional order in the LFC of a delayed standalone MG system. The proposed controller design is easy to apply in many different industrial applications. RSA is also used to tune the parameters of the mentioned controller to get optimum outcomes. The remainder of the paper is broken up into the following sections: section 2 illustrates the isolated MG's details considering EVs' performance. Section 3 briefly elucidates the FOPID controller. Section 4, and section 5 elaborates on the objective function and optimization method applied in the suggested system. Eventually, the simulation results executed on MATLAB/Simulink are investigated, and the priority of the proposed method is proved in section 6.

2. PROPOSED SYSTEM SPECIFICATION

2.1. Microgrid Model

Here, the case study is an isolated MG. Figure 1 depicts the conventional design of the studied microgrid, which consists of various distributed generation sources such as photovoltaics (PVs), diesel generators, energy storage units such as flywheel energy storage systems (FESS), and batteries, electric vehicles (EVs), wind turbine generations (WTG), and also loads. Moreover, distributed management system (DMS) and MG dispatch system (MGDS) are applied to manage and control the power grid and operation of MG.

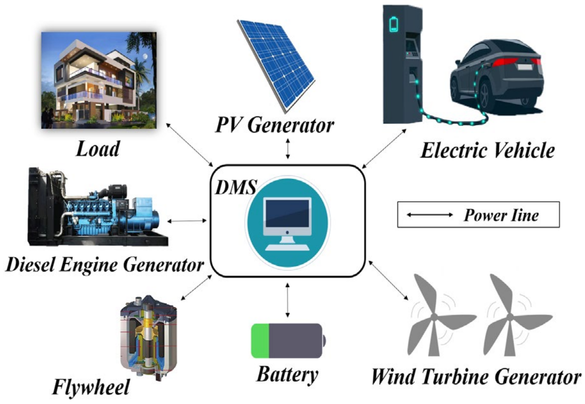

Figure 1. General scheme of the isolated Microgrids

2.2. Electric Vehicle Model

Electric drive vehicles can become an influential character of the smart grid. By using the V2G concept, the load frequency control of the MG can be accomplished. It is possible to consider an equivalent EV model of the varied numbers of EVs in each station. This model may parameterize each individual EV with a different inverter potential. An aggregated model is described in Figure 2 [3]. The whole charged or discharged powers of the EVs are determined by employing this model in a controllable phase. The number of the controllable EVs can restrain the response of the LFC signal [20].

The LFC signal delivered to the EV serves as input (Δu_e) to this model, with the EV's charging or discharging power serving as output (ΔP_E). The T_e indicates the EV's time constant, E_{max} and $E_{min,}$ respectively represent the maximum and minimum battery energy that can be controlled, $\pm\delta_e$ and $\pm\mu_e$ are correspondingly the limitations of power ramp rate and capacity of the inverter. When ΔP_E=0, an EV is in a condition of non-productivity; when ΔP_E>0, it is in the state of discharging; and when ΔP_E<0, it is in the form of charging. Discharging and charging of electric vehicles is done only in the $\pm\mu_e$ boundary. Whenever the energy of the EV becomes more than the E_{max}, the EV will particularly be discharged in the limit of $(0\sim\mu_e)$. Furthermore, when the EV energy stands under the E_{min}, the EV will exclusively be charged in the limit of $(-\mu_e\sim 0)$ [3].

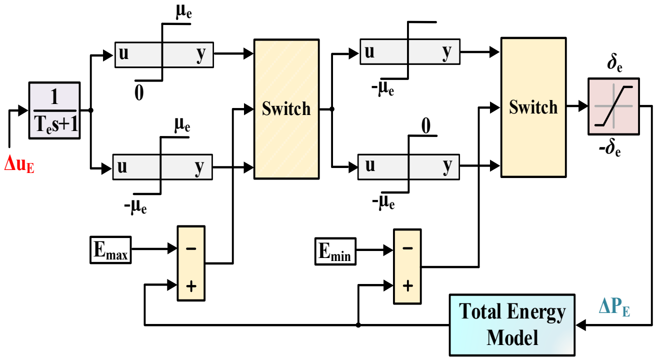

Figure 2. Equivalent model of EV in MG

2.3. Modelling of Diesel Generator

Diesel generators (DG) are often used to refer to small-scale power production devices that have the characteristics of high efficiency, rapid starting speed, and unique durability. Load demand fluctuations can be detected by DG within short intervals of time using mechanisms of the power control. The DG modifies its output through the fuel regulation while it meets power demand fluctuations. As can be seen in Figure 3, a model of a continuous transfer function depicts the connection that exists between the LFC and the output power of the DG [21]. In this model, a governor and a generator, referred to as first-order inertia plants, are included.

As shown in Figure 3, Δf indicates the variation of frequency, the dispatching LFC signal to DG is shown by Δu_{DG}, ΔX_G is the increment amount in the governor's valve position, R denotes the velocity control coefficient of the DG, T_g, and T_d are respectively governor and DG's time constants, $\pm\delta_{dg}$ show power ramp rate limits, $\pm\mu_{dg}$ represent the power increment limits and ΔP_{DG} describes the output power increment. When ΔP_{DG}=0, DG's output power holds a threshold amount that adjusts the load without grid disturbance. In such states, the frequency deviation is zero. If $\Delta P_{DG} > 0$, then the power produced by DG is in excess of the threshold value, and if $\Delta P_{DG} < 0$, then the power generated by DG is below the suggested level.

2.4. Photovoltaic Generation Model

Power is provided by photovoltaic cells from semiconductors at the time of illumination since the sunlight is on the solar cell. The output electrical power of a PV system is presented as follows [22]:

$$P_{pv} = \eta S \varphi_{PV}[1-0.005(T_a+25)] \quad (1)$$

where, η is the PV module's conversion efficiency (%), S denotes the evaluated area of the PV system (m^2), φ is the solar insolation (W/m^2), and T_a shows the ambient temperature. To synchronize the DC MG with the AC MG, power electronic interfaces inside of the PV unit is needed. An inverter and an interconnection device are good examples of power electronic devices in the photovoltaic. The transfer function [22] of a PV unit can be denoted by:

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

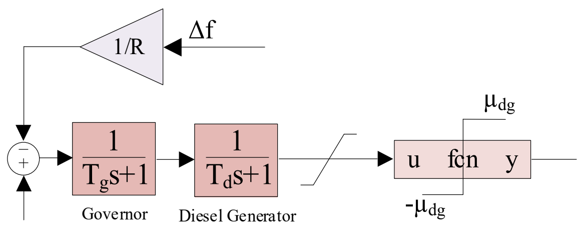

Figure 3. Diesel engine prototype

2.5. Fuel Cell Model

Generally, producing hydrogen employing the electrolyzer prepares the fuel of the fuel cell. Hydrogen breaks down into electrons and ions at the anode of the fuel cell. Hydrogen's positive ions transfer into the exchange membrane of proton ion, and electrons move in the outer circuit. In fact, the opposite reaction of the electrolyzer occurs in the fuel cell. Products of the evolution generate water and heat. Owing to recompense uncertainty of the system by cause of the intermittency of the PV and the WTG systems, A fuel cell is combined with the Energy Storage System (ESS). The transfer function [23] of a fuel cell is expressed by:

$$G_{FC} = \frac{K_{FC}}{1+sT_{FC}} = \frac{\Delta P_{FC}(s)}{\Delta P_{AE}(s)} \quad (3)$$

2.6. General Design of Time-Delayed Stand-Alone Microgrid Model

The suggested secondary LFC configuration in the isolated MG including a standard DG, two equal EVs (EV_1 and EV_2), wind Turbine generator, PV panel, Fuel Cell system, BESS, FESS, and power disturbance (ΔP_D) is depicted in Figure 4 [24]. This model of power variations includes three components: load (ΔP_L), wind power production (ΔP_W), and fluctuations in photovoltaic generation (ΔP_{PV}). In addition, H_t indicates the MG's equal inertia constant [3]. While a power disturbance appears in the isolated grid, LFC establishes to adjust the frequency variation to zero at the earliest possible time with managing the input signals. The MG system's parameters are depicted in Table 1 [7, 25].

Table 1. Specifications of microgrid system

Symbol	Values	Symbol	Values
T_g	0.1s	T_{e2}	1s
T_d	8s	μ_{e2}	0.016
R	2.5	δ_{e2}	0.01
δ_{dg}	0.001	E_{max}	0.9
μ_{dg}	0.04	E_{min}	0.8
T_{e1}	1s	T_{PV}	1.8s
μ_{e1}	0.25	K_{PV}	1
δ_{e1}	0.01	K_{WTG}	1
E_{max}	0.9	K_n	0.6
E_{min}	0.8	T_{WTG}	2s
T_{AE}	0.5s	T_{FC}	4s
K_{AE}	1/500	K_{FC}	1/100
H_t	7.11	T_{FESS}	0.1s

3. FOPID CONTROLLER

Generally, conventional PID controllers are still the simplest, robust, and the most appropriate ones in comparison with other types of controllers beneficial to industrial utilizations. Nevertheless, the system's performance decreases due to the difficulty of reaching steady-state optimal operating with a simple PID controller. Through the transient conditions, an integral element's behavior decreases the system's speed and stability. Hence, the integral part must be inactive in the transient term to increase its response [26].

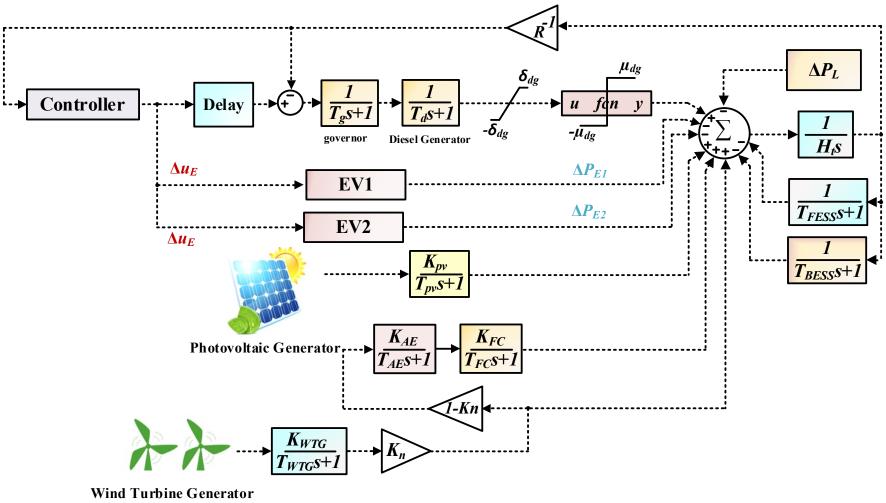

Figure 4. Overall MG scheme

Fractional-order-based controllers can improve the investigated system's dynamic performance compared to conventional controllers. In a FOPID controller, the main difference lies in the use of fractional calculus. Unlike traditional PID controllers that use integer order differentiation and integration, these controllers use fractional calculus to define the orders of differentiation and integration. The order of differentiation and integration is represented by a non-integer number, usually denoted as μ and λ respectively [18].

For this investigation, a FOPID controller is utilized, and its structure is shown in Figure 5 [18]. This controller is responsible for controlling the MG frequency. The suggested controller excels in handling perturbations and is appropriate for complex systems, making it superior to the standard PID controller. As can be seen in Figure 5, the system error is sent into the FOPID controller, and its output is the input of the DG and two EVs. The output transfer function of the proposed controller is illustrated in Equation (4). K_P show proportional, and K_D and K_I show the derivative and integral gain values, λ and μ are also two fractional-order parameters of integral and derivative [18].

$$U(s) = (K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu})\Delta F(s) \quad (4)$$

where, ΔF is the frequency fluctuation and t_{sim} is the entire time of the simulation.

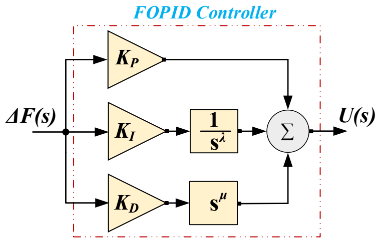

Figure 5. Structure of the FOPID controller

4. OBJECTIVE FUNCTION

Choosing the proper objective function is crucial for enhancing controller configurations across all optimization approaches. An adequate objective function ensures that the system's dynamic response is acceptable, with a minimum settling time, overshoot, and undershoot. In the investigated MG, the error signal from the frequency variations is sent into the controller, and the objective function then seeks to minimize this signal to zero within controller parameters.

In the current study, the test functions are defined as the integral of time squared error (ITSE) and the integral of squared error (ISE), and the objective function is stated as the integral of squared time squared error (ISTSE), formulated as follows [27]:

$$J_{ISTSE} = \int_0^{t_{sim}} t^2 (\Delta f)^2 dt \quad (5)$$

$$J_{ITSE} = \int_0^{t_{sim}} t (\Delta f)^2 dt \quad (6)$$

$$J_{ISE} = \int_0^{t_{sim}} (\Delta f)^2 dt \quad (7)$$

5. OPTIMIZATION PROCESS

5.1. Reptile Search Algorithm

RSA is a modified technique that attracts inspiration from the hunting strategies of crocodiles. RSA claims that its results are superior to those of competing optimization methods [28]. The RSA is distinct from previous approaches since it employs four specific techniques to provide the most up-to-date information on where solutions may be found. At the beginning of the optimization process, a collection of randomly chosen solutions (Y) is formed using Equation (8), with the most significant response being considered the ideal solution at every iteration. Equation (9) generates a set of potential solutions as follows [28].

$$Y = \begin{bmatrix} y_{1,1} & \cdots & y_{1,j} & y_{1,n-1} & y_{1,n} \\ y_{2,1} & \cdots & y_{2,j} & \cdots & y_{2,n} \\ \cdots & \cdots & y_{i,j} & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{N-1,1} & \cdots & y_{N-1,j} & \cdots & y_{N-1,n} \\ y_{N,1} & \cdots & y_{N,j} & y_{N-1,n-1} & y_{N,n} \end{bmatrix} \quad (8)$$

$$y_{ij} = rand \times (U_B - L_B) + L_B, \quad j = 1,2,...,n \quad (9)$$

where, L_B and U_B represent the bottom and upper bounds of the range, and *rand* is a number that is chosen at random. Crocodiles start their hunts with a period of discovery and investigation [28]. At this time, crocodiles have two separate walking patterns, tall walking and belly walking, each of which is influenced by the habits of the crocodile's environment. As a result of the noise these actions create, crocodiles cannot sneak up on their prey as stealthily as they would during the hunting phase. Because of this, there are several potential areas to investigate during the exploratory search and surrounding the prey. Additionally, the RSA could move between an encircling and hunting state. There are two necessities for starting the searching process: Conditions for high walking are $t<T/4$, and those for belly walking are $t<T/2$ and $t>T/4$, as shown below [28].

$$y_{(i,j)}(t+1) = \begin{cases} Best_j(t) \times -\eta_{(i,j)}(t) \times \beta - R_{(i,j)}(t) \times rand, \ t \le \dfrac{T}{4} \\ Best_j(t) \times x_{(r_1,j)} \times ES(t) \times rand, \ \ t \ge \dfrac{T}{2}, t > \dfrac{T}{4} \end{cases} \quad (10)$$

where, $Bestj(t)$ indicates the j_{th} optimum solution, t shows the iteration amount, and T is the greatest value of solutions. η denotes the hunting employee, while β controls the precision with which the explorer probes. The evolutionary sense ($ES(t)$) is a possibility proportion erratically taking on smaller values as a function of the number of repeats. Crocodiles complete their hunt by exhausting their victim so they can no longer fight back. Refer to [28] for a detailed discussion of the descriptions and equations that underpin the proposed approach.

5.2. RSA Based Proposed Controller Design

Essentially, it is needed to optimize K_P, K_D, K_I, λ and μ in order to implement the suggested controller successfully in the LFC process. Therefore, the RSA is used to specify the proposed controller's configurations in this investigation. RSA differs from GA and PSO in that it converges more quickly and can identify superior solutions without getting stuck in a rut at the regional level [28]. In addition, Table 2 shows how the objective and test functions (ISTSE, ITSE, ISE) rated the controllers' performance (FOPID, and PID). The findings show that implementing the ISTSE index leads to an increase in the proposed controllers' implementation.

Figure 6 provides a breakdown and a more in-depth illustration of the suggested controller's design method, which uses the RSA. This approach is based on the ISTSE index. The permissible range of changes to the proposed controller coefficients is displayed in Equation (11).

The initial RSA population is set to 50, and a hundred repetitions is meant to be the limit. the lowest and maximum coefficients used are 0.001 and 5, respectively. It is important to note that the suggested controller's configurations are not continually changed after their first design. Instead, the best parameters for adjusting are settled on during the design process itself, after a certain number of iterations. The recommended controller parameters are also shown in Equation (12).

$$\begin{cases} 0.001 \le K_P \le 5 \\ 0.001 \le K_D \le 5 \\ 0.001 \le K_I \le 5 \\ 0 < \lambda, \mu < 2 \end{cases} \quad (11)$$

$$\begin{aligned} &K_P = 4.1241, K_I = 3.6347, K_D = 4.6428 \\ &\lambda = 0.904, \mu = 0.1197 \end{aligned} \quad (12)$$

Table 2. Evaluative and Objective Functions' Impact on Controllers' Dynamic Behavior

Time-Domain Features		Controllers	
		Proposed	PID
Settling Time (s)	ISTSE	27.8274	36.0639
	ITSE	28.9489	37.2478
	ISE	30.1137	38.4156
Overshoot	ISTSE	9.97e-4	1.92e-3
	ITSE	1.30e-3	2.11e-3
	ISE	1.61e-3	2.38e-3
Undershoot	ISTSE	-4.99e-3	-6.3e-3
	ITSE	-7.91e-4	-6.6e-3
	ISE	-8.23e-4	-6.9e-3

6. SIMULATION RESULTS

This section describes three cases with different disturbances to compare the proposed FOPID controller's efficacy and robustness to the PID controller in the standalone MG case study. A personal laptop (Core i7 CPU, 16GB RAM) ran the simulations created in MATLAB/Simulink 2020. The outcomes are evaluated against those obtained using FOPID, and regular PID controllers. The optimization of all controllers' parameters is also performed by using the RSA.

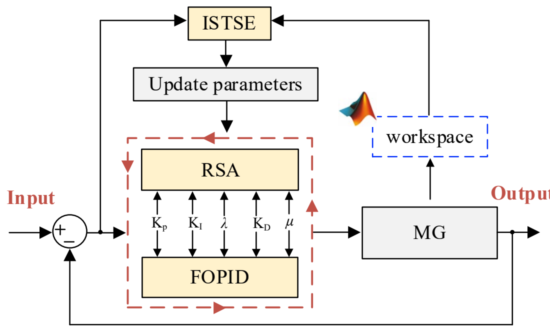

Figure 6. Suggested controller design process

6.1. Case 1

In this scenario, it is assumed that the isolated MG is operating in a steady state. After that, a load disturbance is introduced so that the priority of the FOPID controller may be compared to the PID controller. Moreover, Photovoltaic and wind turbine power variations are assumed to be constant. (ΔP_W, $\Delta P_{pv}=0$), afterward, the system undergoes a step load change ($\Delta P_L = 0.05$) at $t = 10$s. Figure 7 represents the outcomes of frequency variations of the MG with FOPID, and PID controllers. As can be observed, the suggested controller's output has a remarkable decrease in the first swing peak. Meanwhile, swifter damping frequency fluctuation of the system arises with this controller. As a result, the suggested controller is more effective in dampening the MG frequency fluctuations and has a more responsive dynamic range.

Figure 8 depicts the incremental power outputs of EVs and DGs with two controllers. As can be observed, FOPID proposed a more balanced output power in EVs and diesel generator. Consequently, the batteries' lifetime will be enhanced. Moreover, the PID controller discussed in this paper provides a high amount of settling time and overshoot, but suggested controller contributes a stable transient response with smaller overshoot and considerably lower settling time. Thus, compared to PID, the time-domain characteristics of the system (settling time, overshoot, and undershoot) are enhanced while using the presented controller, as shown in Figure 9.

6.2. Case 2

In the second scenario, step disruptions are introduced into the control system, which allows for an assessment of the overall performance of the recommended controller to be carried out in more challenging circumstances. This case investigates the performance of the MG under wind turbine and solar cell disturbance along with load changes. First, at $t=10$s, a load change ($\Delta P_L=0.05$) is applied to the MG. Then, at $t=30$s, the power fluctuations of WTG ($\Delta P_w = 0.05$) and at $t=50$s, the power disturbance of the solar cell ($\Delta P_{pv} = 0.05$) is applied to the islanded microgrid. Figure 10 reveals the frequency deviation curve with the comparison of the suggested and PID controllers. The proposed controller significantly reduces the frequency variations of the microgrid, demonstrating its superiority.

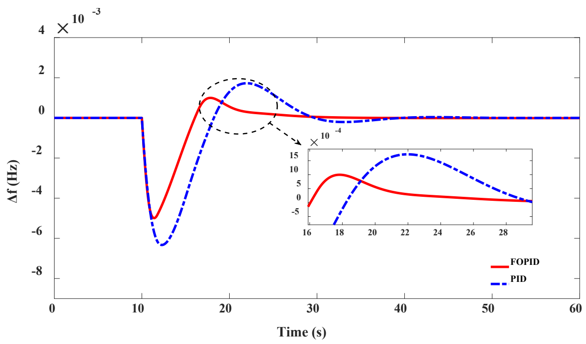

Figure 7. MG dynamic response in the first scenario

6.3. Case 3

Finally, in order to quantify the MG in more complex situations, both disturbances of the photovoltaic and wind turbine are applied to the investigated system. Moreover, fluctuating loads are also implemented as step variations. Figure 11a and Figure 11b show the wind power and the photovoltaic disturbances.

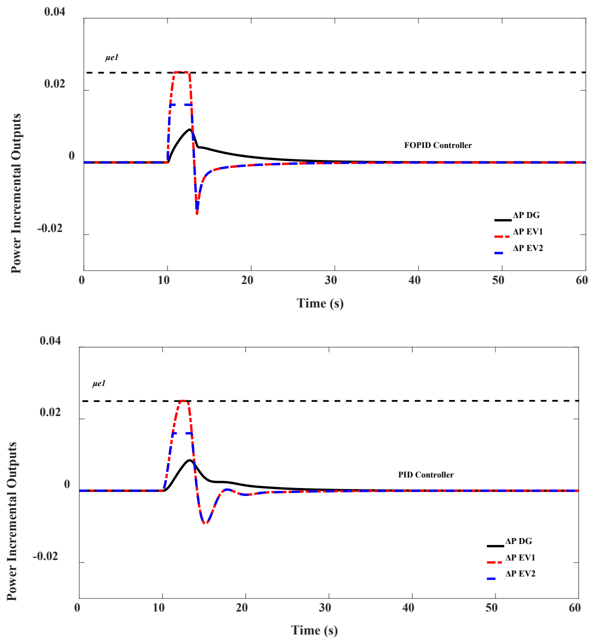

Figure 8. Power outputs of EVs and DG in each controller

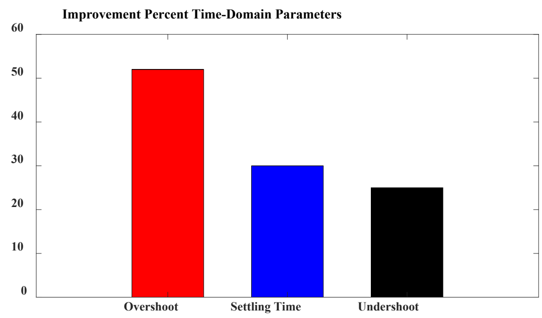

Figure 9. Time-domain feature percentage increase with proposed controller compared to identical controllers

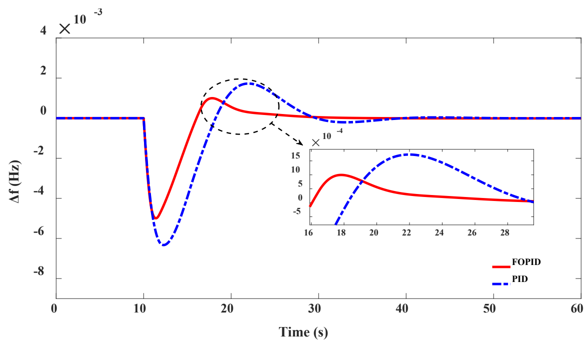

Figure 10. Frequency response to different step changes (case 2)

Moreover, the load changes curve can be seen in Figure 11c. Finally, Figure 12 shows the frequency variation of the time-delayed standalone MG. The findings indicate that the frequency deviation response of MG under these conditions is prosperous and the FOPID controller produces proper advantages in the system's dynamic behavior compared to PID controller.

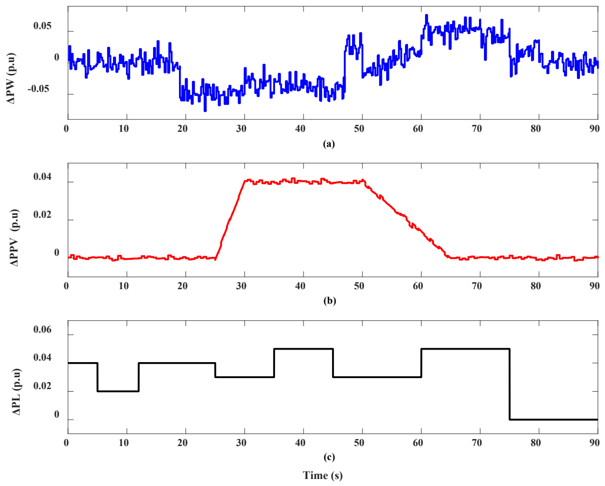

Figure 11. a) Wind Power Generation fluctuations, b) Power fluctuations waveform of PV, c) Load step changes for case 3 [7]

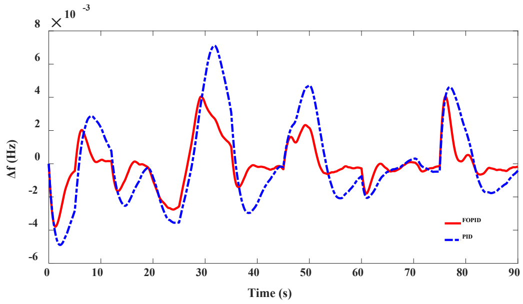

Figure 12. Frequency response of the MG in case 3

7. CONCLUSIONS

The significant factor in ensuring the frequency stability of a microgrid is the balance between generation and consumption of active power. In this paper, a FOPID controller is proposed and evaluated for LFC of a MG while including EVs and storage devices. The coefficients of the proposed controller are also optimized using the RSA approach. The design of this controller is in a way that can overcome the negative influences of different disturbances. The key benefit of the proposed controller is that it allows for optimal use of EVs capacities in the MG owing to the high quality of the controller in error-clearing without requiring rapid changes in the entry/exit of varied quantities of EVs in the LFC process. Implementing step inputs to the MG has been utilized for evaluating the proposed controller behavior analysis, and it outperforms conventional PID controller regarding settling time, undershoot, and overshoot reduction. The results reveal the system's settling time is 30% better when using the FOPID controller. Further, the suggested method's robustness is shown by the fact that the MG's overshoot and undershoot are, respectively, 52% and 25% better than PID controller.

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