

IMPROVEMENT OF LOAD FREQUENCY CONTROL FOR EVS AND RESS INTEGRATED HYBRID POWER SYSTEMS

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Abstract

The purpose of the study is to resolve the emergent issue by optimising the parameters of fractional order controllers (FOCs) using the Mountain Gazelle Optimiser (MGO) and validate the strategy on real-time simulator using the platform OPAL-RT. This paper implements load frequency control (LFC) in multi-area, multi-source power systems (MSPSs), encompassing thermal power plants (TPPs), hydro power plants (HPPs), and gas power plants (GPPs), as well as the integration of renewable energy sources (RESS) and electric vehicles (EVs). On the other hand, this study also takes system uncertainties such as load disturbances and nonlinearities such as governor dead band (GDB) and generation rate constraints (GRC). The superiority of MGO in optimization has been assessed in comparison to various other metaheuristic optimization technique (MOT), such as Particle Swarm Optimisation (PSO), Grey Wolf Optimisation (GWO), and Archimedes Optimisation Algorithm (AOA). The result analysis in case-1 shows that the value of objective function for MGO is 63.89%, 81.16%, 75.47%, and 95.6% less in comparison to WOA, PSO, GWO, and AOA, respectively. Similarly, in case-2 the value of the objective function for MGO-tuned fractional order proportional integral derivative (FOPID) controller is 3.8%, 11.93%, and 97.77% less in comparison to the tilt integral derivative (TID), PID, and IC, respectively. The sensitivity analysis in terms of parameter variations and stability analysis through the Bode plot also has been done for the real feasibility of the controller. System stability with respect to frequency is substantially improved by the MGO-based FOPID controller compared to other controllers.

Keywords: Electric Vehicles; Fractional Order Controllers; Load Frequency Control; Load Perturbations; Mountain Gazelle Optimizer; Renewable Energy Sources

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Nomenclature & Symbols

Acronym	Definitions
FOC	Fractional Order Controller
MGO	Mountain Gazelle Optimiser
LFC	Load Frequency Control
MSPS	Multi-Source Power System
TPP	Thermal Power Plant
HPP	Hydro Power Plant
GPP	Gas Power Plant
RES	Renewable Energy Source
EV	Electric Vehicle
GDB	Governor Dead Band
GRC	Generation Rate Constraint
MOT	Metaheuristic Optimization Technique
PSO	Particle Swarm Optimisation
GWO	Grey Wolf Optimisation
AOA	Archimedes Optimisation Algorithm
FOPID	Fractional Order Proportional Integral Derivative
TID	Tilt Integral Derivative
PS	Power System
MPC	Model Predictive Control
SPP	Solar Power Plant
WPP	Wind Power Plant
N_1 and N_2	Fourier Coefficients
P_w	WPP Output Power
ρ	Density of Air in Kg/m ³
A_T	Swept Area (m ²)
V_w	Rated Speed of the Wind (m ²)
C_P	Parameter of rotor blades
λ_T	Ideal Tip-speed ratio (TSR)
λ_I	Intermittent TSR
r_T	rotor radius
ΔP_{solar}	changing output power of the solar system
P_{solar}	output power of the solar system
SoC	state of charge
R_{EV}	Droop coefficient of EVs
K_{EV}	Aggregator EVs gain
T_{EV}	EVs battery time constant
$D_{t_f}^\alpha$	FO operator
t_0 and t_f	time limits
α	order of the operator
K_T	tilt gain in the TID controller
K_P	Proportional gain of the PID controller
K_I	Integral gain of the PID controller
K_D	Derivative gain of the PID controller
μ & λ	fraction of derivative and integral
n	tilt fractional component
NFL	No Free Lunch

Acronym	Definitions
TSM	Territorial Solitary Males
MH	Maternity Herds
BMH	Bachelor Male Herds
MSF	Migration To Seek For Food
$male_{gazelle}$	Position vector of the best global solution (adult male)
ri_1 and ri_2	Random integers 1 or 2
BH	Young male herd coefficient vector
F	Related to computation time
Cof_r	randomly selected coefficient vector
ri_3 and ri_4	integer and random numbers 1 or 2
X_{rand}	The vector position of a gazelle
$X(t)$	The position of the gazelle vector in the current iteration
ri_5 and ri_6	integers 1 or 2 that are chosen randomly
D	Position vector for best solution
u_b and l_b	problem's upper and lower limits
r_7	integer between 0 and 1 chosen at random
Δf_1	Frequency fluctuations of areas 1
Δf_2	Frequency fluctuations of areas 2
ΔP_{tie}	Tie-line power fluctuation
ITSE	Integral of Time Multiplied Squared Error
MSLP	Multistep Load Perturbation
RLP	Random Load Perturbation
SLP	Step Load Perturbation
US	Undershoot
ST	Settling time
OS	Overshoot
N_C	No. of EVs in charging mode
N_D	No. of EVs in discharging mode

Introduction

Several factors have increased the significance of PSs analysis in recent times. Nowadays, these include the extensive integration of RESs and EVs into conventional power plants, the introduction of uncertainties like GRC and GDB, and the diverse nature of load variations (Ahmed *et al.*, 2022; Raj & Shankar, 2023). As people's needs increase and they utilize more RESs, EVs, and storage systems, the complexity of current power networks has escalated. The incorporation of RESs results in a persistent decline in the system's inertia, hence impacting its stability and causing increased frequency fluctuations. EVs are swiftly evolving from a niche market to a predominant mode of transportation. As their quantity increases, their batteries dispersed throughout the grid present

considerable promise beyond mobility: enhancing power system stability, especially in frequency management (Kumar & Prasad, 2024). Under typical conditions, LFC is crucial for the different PS zones to regulate frequency and manage tie line power deviations. Figure 1 presents the analysis of the MSPS model under consideration.

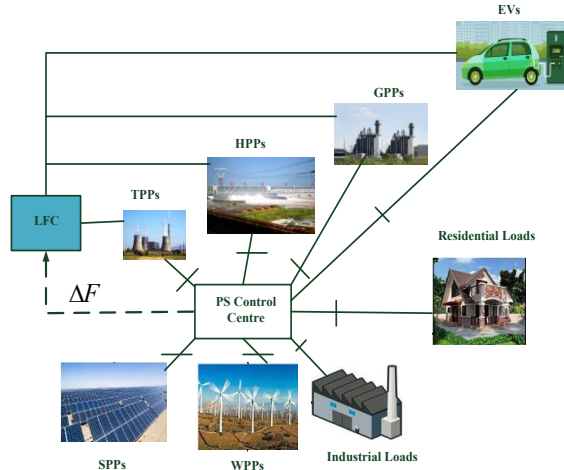


Figure 1. The structure of the analysed PS

Literature Survey

Several PS topologies have been developed to address the problem of frequency stability, specifically single-area PSs (Topno & Chanana, 2018), multi-area interconnected PSs (Chen *et al.*, 2018), deregulated PSs (Tasnin *et al.*, 2018), and multi-area PSs that are connected while taking nonlinearities into account (Jagatheesan *et al.*, 2018; Nguyen *et al.*, 2018). Moreover, several control techniques, such as robust control methods (Eltamaly *et al.*, 2021), MPC (Nandi *et al.*, 2020), artificial intelligence control such as fuzzy logic control (Danaeefar, 2019) and the Multiverse optimized fuzzy-PID controller (Kumar & Suhag, 2017b), have been used to address the LFC issue with PSs. On the other hand, FOCs are becoming more common because they are flexible and can be set up in a lot of different ways, so researchers have more curiosity in FOCs (Kumar & Suhag, 2017b; Danaeefar, 2019). In (Magdy *et al.*, 2018; Morsali *et al.*, 2018), different electrical systems have been subjected to the FOCs. FOCs offer several benefits, such as increased lifetime, improved disturbance rejection, and the ability to modify the settings of a closed-loop system. And because of this, a lot of researchers think that the TID controller handles LFC issues in various situations (Topno & Chanana, 2018). In (Kasireddy *et al.*, 2018; Magdy *et al.*, 2018; Morsali *et al.*, 2018), a hybrid controller is

suggested, utilising the benefits of both TID and FOPID controllers. Consequently, many cascaded controllers have improved power networks' frequency stability (Elmelegi *et al.*, 2021; Mohamed *et al.*, 2020a; Prakash *et al.*, 2019). Numerous research studies have used two controllers in tandem, such as an adaptive MPC and an arrangement of a linear quadratic Gaussian controller & an MPC controller (Mohamed *et al.*, 2015; Mohamed *et al.*, 2020b). Previously, conventional optimisation techniques have been employed to choose the fine-tuned parameters for the controllers (Soleimani & Mazloun, 2018). However, these algorithms have to deal with a number of problems when trying to find the best parameters. These include slump, death traps in local minimums, the need for many rounds, and relying on starting conditions. To overcome these obstacles, the researchers created MOTs such as the Archimedes optimization algorithm (Ahmed *et al.*, 2022), moth-flame optimization (Nandi *et al.*, 2020), Gravitational Search algorithm (Danaeefar, 2019), Multiverse optimized algorithm (Kumar & Suhag, 2017b), moth swarm algorithm (Magdy *et al.*, 2018), GWO Algorithm (Kumar & Suhag, 2017a), genetic algorithms (Soleimani & Mazloun, 2018), PSO algorithm (Jagatheesan *et al.*, 2016), and ant colony optimization (Ali *et al.*, 2021). Furthermore, significant emphasis has been placed on implementing different optimisation methods to address technological challenges, including the LFC issue. This shows the reasons behind the author's motivation to select the MGO (Abdollahzadeh *et al.*, 2022) to tune the FOC's fine parameters for this research. A great deal of research is currently being conducted on related topics.

Problem Statement and Proposed Solution

The primary observation derived from the existing research is that the systems analysed are restricted to conventional resources only. Most of the current research for LFC studies has not considered the integration of RESs (such as SPPs & WPPs) and EVs in the PSs. Conversely, LFC techniques that depend on the expertise of the controller designer, such as MPC and fuzzy logic control, yield the desired performance; nevertheless, they exhibit some design deficiencies and require considerable effort. Additionally, traditional IC, PI, and PID controllers encounter considerable challenges when dealing with system uncertainties. Most prior research has inadequately addressed various robustness evaluations, such as fluctuations in system parameters, system nonlinearities, and

system defects. Based on the above observations, this paper proposes the FOCs in a multisource-based two-area interconnected PS with a significant penetration of RESs as well as integration of EVs for the LFC analysis. It takes into consideration nonlinearities, system uncertainties, and different load patterns. The result analysis in case-1 shows that the value of the objective function for optimization technique MGO is 63.89%, 81.16%, 75.47%, and 95.6% less in comparison to WOA, PSO, GWO, and AOA respectively. Similarly, in case-2 the value of the objective function for MGO tuned FOPID controller is 3.8%, 11.93%, and 97.77% less in comparison to TID, PID, and IC, respectively.

Contribution and paper organization

In summary, this article primarily contributes the following:

- I. The performance of the MGO has been compared to other algorithms (such as PSO, WOA, GWO, and AOA) based on the LFC of the analysed PSs, proving its superiority.
- II. The superior and efficient performance of the FOPID based on MGO with other

controllers (i.e., IC, PID, and TID) has been confirmed.

- III. The FOPID's robust performance and efficacy are demonstrated by evaluating a variety of load perturbances on the analysed PSs.
- IV. RESs fluctuations, integration of EVs, and other system non-linearity are taken into consideration by the FOPID controller with system uncertainties such as GDB and GRC.
- V. The sensitivity analysis based on parameter variations and stability analysis has been done to determine the feasibility of controllers and optimization techniques.
- VI. Validation of system with different controllers through OPAL-RT.

The succeeding sections of the paper are organised in the following manner. A detailed explanation of the resources and model employed by the PS under investigation is provided in Section 2. Section 3 presents the controllers structure, the preferred optimisation approach (MGO), and the controller design methodologies. Section 4 subsequently analyses the results of the simulation with OPAL-RT validation. The conclusion is elaborated upon extensively in Section 5.

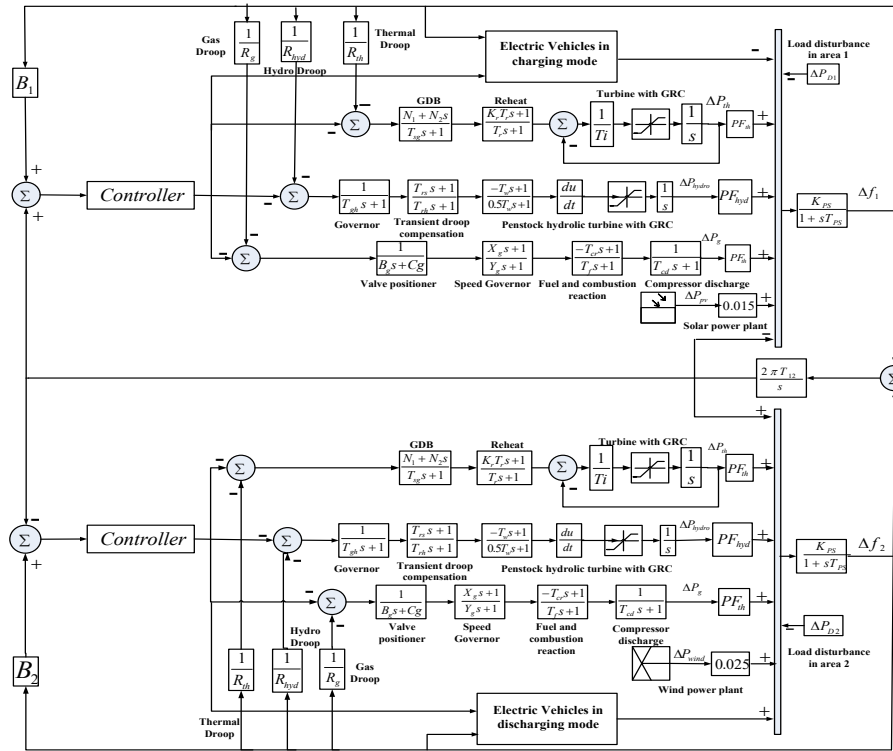


Figure 2. The analysed power system model

Model configuration and resources used

Figure 2 illustrates the two interconnected-area PSs. Each area has TPPs, HPPs, and GPPs, as well as EVs in charging and discharging modes in areas 1 and 2. Additionally, an SPP connects to area 1, while a WPP connects to area 2. The system's non-linearity is considered, as well as the physical limitations of the PS, which include the GRC and GDB of the TPPs and the GRC of the HPPs. An HPP of 500 MW, a GPP of 240 MW, and a TPP of 1000 MW, each with a nominal load of 1740 MW and a capacity rating of 2000 MW, are dispersed throughout each area. The system under analysis's specifics and parameters are detailed in (Morsali *et al.*, 2018). The GRC has been established at 10% pu/min (0.0017 pu.MW/s) for TPPs with both increasing and decreasing rates. Additionally, the HPP demonstrates a GRC of 270% pu/min (0.045 pu. MW/s) when operating at increasing rates and 360% pu/min (0.06 pu. MW/s) when operating at decreasing rates. The GDB's non-linearity equations can be linearly depicted in terms of rate of change and speed change. The Fourier series has been employed to develop the equation for the GDB with a 0.5% oscillation, as outlined below:

$$GDB = \frac{N_1 + N_2 s}{T_{sg} s + 1} \quad (1)$$

Where N_1 and N_2 are the Fourier coefficients, and obtained as $N_1 = 0.8$ and $N_2 = -0.2/\pi$, respectively. The following is a comprehensive discussion of RESs and EVs.

The WPPs model

The wind generation plant unit is being studied, using the MATLAB/SIMULINK environment through equation (2) (Magdy *et al.*, 2019). The effect of natural airflow is created by the white noise block. It acts as a variable velocity, and it amplifies the wind speed to match the prevailing conditions. Figure 3 displays the fluctuation in the raw power output of the WPPs.

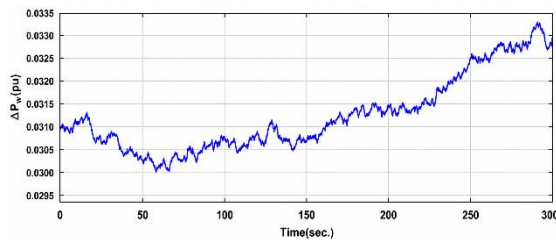


Figure 3. A WPP's fluctuating power output

The equation for wind-generated power is as follows:

$$P_w = \frac{1}{2} \rho A_T V_w^3 C_P(\lambda, \beta) \quad (2)$$

Where P_w , ρ , A_T , V_w , & C_P are the output power, density of air in kg/m^3 , swept area by the rotor in m^2 , rated speed of the wind in m/s , and the parameter of rotor blades, respectively. Equation (3) (Magdy *et al.*, 2019) will be utilised to ascertain the values, noting that C_1 through C_7 represent the parameters for the turbine.

$$C_P(\lambda, \beta) = C_1 \times \left(\frac{C_2}{\lambda_1} - C_3 \beta - C_4 \beta^2 - C_5 \right) \times e^{\frac{C_6}{\lambda_1}} + C_7 \lambda_T \quad (3)$$

Where, λ_T shows the ideal tip-speed ratio (TSR), which may be determined from equation (4) and β represents the pitch angle.

$$\lambda_T = \lambda_T^{OP} = \frac{\omega_T \times r_T}{V_w} \quad (4)$$

Where λ_1 & r_T represents the intermittent TSR and rotor radius, respectively. Table 1 shows the parameters of the WPPs.

Table 1. The parameters of the WPPs

Used parameters	Value	Used parameters	Value
P_w	750 Kw	C_5	5
V_w	15 m/s	C_3	0.4
r_T	22.9 m	C_7	0.1405
A_T	1684 m^2	C_2	116
λ_T	22.5 rpm	C_6	21
ρ	1.225 Kg/m^3	C_4	0
C_1	-0.6175		

The SPPs Model

Weather situations dictate the solar power output, rendering it unpredictable. As a result, the substantial variations in frequency induced by the power production of solar plants degrade the stability of the system. It is imperative to calculate the SPP's output power, which is subject to variation based on the level of insolation. The insolation and other circumstances in the PV system model are shown in real-time using the white noise

block with MATLAB/SIMULINK (Magdy *et al.*, 2019). The variations in solar radiation make it necessary to calculate the changing output power of the solar system using equation (5). Figure 4 illustrates the observed fluctuations in the real-world power output of the PV system model.

$$\Delta P_{Solar} = 0.6\sqrt{P_{Solar}} \quad (5)$$

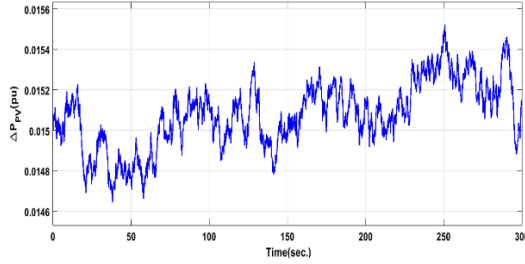


Figure 4. An SPP's fluctuating power output

The EV system model

The EV system model as shown in Figure 5 illustrates the battery charger is a component, and it contributes to grid-load balance (Kumar & Prasad, 2024). Disturbances may occasionally arise due to the abrupt connection of EVs to the charging or discharging system, as well as performance gains, and these are exactly proportionate to their SoC. The frequency range limit, as well as the charging and discharging capability, is -10 to 10 millihertz and -5 to 5 kilowatts, respectively. The deadband droop characteristics are limited to ± 10 millihertz to avoid any negative impact caused by abrupt separation of EVs in the main frequency controlling unit (Shukla *et al.*, 2024). The R_{EV} , K_{EV} , and T_{EV} of the aggregate model are considered equivalent to conventional units at 2.4 Hz/p.u.MW, 1, and 1, respectively.

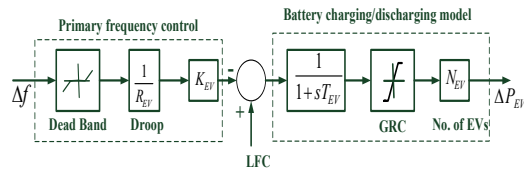


Figure 5. The EV system model

Configuration of controllers

The FOPID controller is presently employed to address LFC issues in contemporary PSs incorporating RESs and nonlinearities, and it is categorised within the FOCs' family. Flexibility to change closed-loop system parameters, improved

disturbance rejection, and better resilience are just a few of the many benefits offered by FOCs in the control system. For its design purposes, FOCs make use of FO calculus. The FOCs and the PID controller intended to handle LFC have a similar fundamental structure and design. A non-integer order of the integral and derivative terms is utilised to represent the FOCs. An FO operator is required for the extension of integer-order differentiation and integration to be applicable to the FO notion. The

FO operator can be assessed by ${}_{t_0}D_{t_f}^\alpha$, where t_0 and t_f show the time limits of the computation process of the operators, and α denotes the order of the operator (Daraz *et al.*, 2020). Additionally, there are other ways to depict the FO operator, including the following:

$${}_{t_0}D_{t_f}^\alpha = \begin{cases} \alpha > 0 \rightarrow \frac{d^\alpha}{dt^\alpha} \\ \alpha < 0 \rightarrow \int_{t_0}^{t_f} dt^\alpha \\ \alpha = 0 \rightarrow 1 \end{cases} \quad (6)$$

The proposed system has employed the oustaloup approach. This method aims to calculate the FO differential term s^α with high-order analogue filters by use of the following equation:

$$s^\alpha = K \prod_{n=1}^N \frac{s + \omega_k'}{s + \omega_k} \quad (7)$$

N denotes the quantity of poles and zeros. The following formula can be used to calculate the frequencies of the filter variable, poles, and zeroes:

$$\omega_k = \omega_b \left(\frac{\omega_h}{\omega_b} \right)^{\frac{k+N+\frac{1}{2}(1+\alpha)}{2N+1}}; \omega_k' = \omega_b \left(\frac{\omega_h}{\omega_b} \right)^{\frac{k+N+\frac{1}{2}(1-\alpha)}{2N+1}}; k = \omega_h^\alpha \quad (8)$$

The frequency range is defined as [0.001, 1000] rad/s, and the filter level is denoted by $(2N + 1)$. The FO calculus is used to create the TID and FOPID controllers, which are widely acknowledged as two of the most common FOCs. The TID controller provides additional advantages, including improved disturbance rejection, heightened sensitivity to variations in system parameters, and streamlined adjustment (Kumari & Shankar, 2018). The transfer function of all four used controllers is generally formulated as follows:

$$\left\{ \begin{array}{l} IC = \frac{K_I}{S} \\ PID = K_P + \frac{K_I}{S} + K_D S \\ FOPID = K_P + \frac{K_I}{S^\lambda} + K_D S^\mu \\ TID = \frac{K_T}{S^n} + \frac{K_I}{S} + K_D S \end{array} \right. \quad (9)$$

Where K_T denotes the tilt gain in the TID controller, and K_P , K_I , & K_D represent the PID controller's proportion, integral, and differential coefficients, respectively, as well as the μ & λ represents the fraction of derivative and integral. The tilt fractional component provides robustness against parameter uncertainty, facilitates adjustment, and improves the system's ability to tolerate shocks. Thus, the FOPID can achieve good dynamic performance under different patterns of load disturbance.

MGO optimization technique

A variety of MOT algorithms have been designed by the researchers to precisely modify the optimal parameters of the controller for LFC. An approach to addressing this issue is accomplished by utilising the NFL theorem (Lockett, 2020). Researchers can apply the NFL theory to create novel optimisation algorithms, and it can effectively address and enhance various conditions. This study explores MGO, a novel MOT that draws inspiration from the social dynamics and collective behaviours of mountain gazelles in their natural habitat. The MGO algorithm is utilised to determine the parameters of the controller. The four primary criteria employed in the MGO strategy, which is dependent on the social and communal existence of mountain gazelles, are TSM, MH, BMH, and MSF. In order to conclude the exploration and exploitation phases of the MGO technique, these four procedures are implemented as follows:

Mechanism 1- TSM: Upon reaching adulthood, male mountain gazelles establish solitary territories, demonstrating a high degree of territoriality, with significant distances often separating these areas. The adult male territory has been modelled using equation (10).

$$TSM = male_{gazelle} - [(r_1 \times BH - r_2 \times X(t)) \times F] \times Cof_r \quad (10)$$

Mechanism 2- MH: During the mountain gazelle's life cycle, mother herds are very important because they give birth to strong male gazelles. Male gazelles can also help with birthing gazelles

and are sometimes seen trying to mate with females. Equation (11) is used to describe this behaviour.

$$MH = (BH + Cof_{1,r}) + (r_{i3} \times male_{gazelle} - r_{i4} \times X_{rand}) \times Cof_{1,r} \quad (11)$$

Mechanism 3- BMH: As male gazelles reach maturity, they typically establish territories and assert dominance over female gazelles. Equation (12) quantitatively formulates this behaviour of gazelles.

$$BMH = (X(t) - D) + (r_{i5} \times male_{gazelle} - r_{i6} \times BH) \times Cof_r \quad (12)$$

Mechanism 4- MSF: Mountain gazelles engage in considerable migration and foraging year-round, consistently seeking new food sources. In contrast, mountain gazelles are agile and adept at significant jumps. This mathematical representation of gazelle behaviour is derived from equation (13) shown herein.

$$MSF = (ub - lb) \times r_7 + lb \quad (13)$$

The four BMH, MH, TSM, and MSF procedures have been applied to each gazelle in order to generate new generations of gazelles. The population increases with each generation, denoting one replication in the recent time span. All gazelles are arranged in ascending order after each era as well. Only the best-trained, economical, and sensible gazelles remain in the community. Older or feebler individuals have killed off the gazelle population entirely. The mature male gazelle in charge of his region is considered the best. Figure 6 shows the MGO algorithm flowchart. The FOPID controller receives input signals based on the tie-line power fluctuation signal using the frequency fluctuations of areas 1 and 2 from Δf_1 , Δf_2 , and ΔP_{tie} , respectively. For the purpose of comparing the IC, PID, TID, and FOPID controllers, it is imperative to effectively modify a specific number of parameters for each controller. Choosing the objective function is a critical step in this procedure. The controller's performance is evaluated in this investigation by calculating the integral of time-weighted squared error (ITSE). This may be formalised as a restricted optimisation problem, as illustrated below:

$$ITSE = \int_0^T t [\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2] dt \quad (14)$$

Adjusted settings for the suggested controller: K_{T1}/K_{P1} , K_{I1} , K_{D1} , K_{T2}/K_{P2} , K_{I2} , K_{D2} , n_1/λ_1 , n_2/λ_2 , N_{C1}/μ_1 , N_{C2}/μ_2

$$\text{Subject to: } \begin{cases} K_{T\min} \leq K_{T1,2} \leq K_{T\max} \\ K_{I\min} \leq K_{I1,2} \leq K_{I\max} \\ K_{D\min} \leq K_{D1,2} \leq K_{D\max} \\ n_{\min} \leq n_{1,2} \leq n_{\max} \\ N_{C\min} \leq N_{C1,2} \leq N_{C\max} \end{cases}$$

The MGO tunes the controller's gains for the optimal controller parameters. This can be demonstrated as follows: the controllers' gains are possessed by each gazelle, and the no. of gazelles is equivalent to the population size. Using TSM, MH, BMH, and MSF as the initial possible choices for the controller parameters, the MGO starts the search process. At this stage, the random position of each object, a potential solution in the search space, is likewise initialized. Each object's TSM, MH, BMH, and MSF are updated after using equation (14) to estimate the fitness of the original population. K_T , K_P ,

K_I , and K_D have been fine-tuned to these gains in the range of $[-5, 5]$. On the other hand, the range of values for the FO operators' μ and λ is $[0, 1]$. While this is going on, the tilt fractional component n has been fine-tuned to fall anywhere between $[0, 5]$.

Results Analysis

The results of the system's simulation were obtained using the MATLAB software. The laptop used for the simulation is equipped with a 64-bit CPU and i3 processor, which operates at a clock speed of 2.4 GHz. The Simulink model of the PS under analysis is connected to the MGO code to carry out the optimisation process. In addition, the performance of the PS being studied, which includes the FOPID controller, is correlated with IC, PID, and TID controllers in different scenarios. Additionally, the simulation is organised in the following way:

Case 1: Validation and effectiveness of MGO

Case 2: System response based on a different controller

Case 3: System response based on Multistep Load Perturbation (MSLP)

Case 4: System response based on Random Load Perturbation (RLP)

Case 5: System response based on RESs penetration

Case 6: System response based on integration of Electric Vehicles

Case 7: Sensitivity analysis regarding system parameter variations and stability analysis

Case 8: Validation of system with different controllers through OPAL-RT

Case 1: Validation and effectiveness of MGO

By comparing the MGO's performance with the results of four optimization methods from the literature, namely AOA, GWO, WOA, and PSO, its effective performance is verified. A further 1% SLP is applied to area-1 to enhance the analysed PS by fine-tuning the parameters of the TID controller. Consequently, the population size is 30 and the max iterations are 50, set as inputs. The fine-tuned parameters for the TID are displayed in Table 2 for each of the five optimization methods that were used: AOA, GWO, PSO, WOA, and MGO.

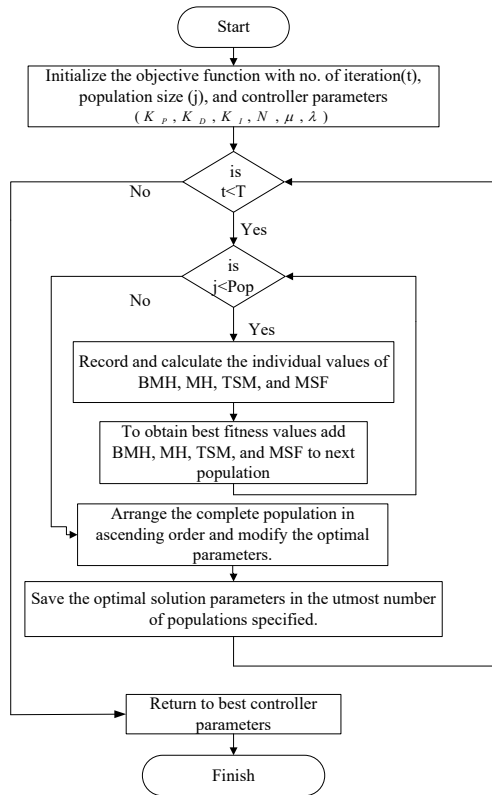


Figure 6. The MGO flow chart

Table 2. Parameters of TID based on several optimization approaches

Algorithm	Area-1				Area-2			
	K_{T1}	K_{I1}	K_{D1}	n_1	K_{T2}	K_{I2}	K_{D2}	n_2
AOA	0.0890	1.8154	3.2980	0	-0.0082	-0.0039	-1.2384e-04	1.209
GWO	-4.0034	4.7419	3.7204	1.0370	2.6476	0.0163	2.0175	1
PSO	5	-4.468	4.3230	1	-0.0948	1.6918	1.7294	1
WOA	1.5706	0.5472	2.0113	0.1009	1.8991	2.8283	3.3044	0.063
MGO	5	0.7989	2.7685	0.4928	1.2564	-0.5659	3.5682	0.645

Through a convergence curve comparison with the other four optimization approaches, Figure 7 demonstrates the superiority of MGO. The system responses in terms of frequency and tie line power deviation, as well as quality and quantity analysis, are illustrated in Figure 8 and Table 3, which are the result of the implementation of a TID controller utilising the five optimisation algorithms—GWO, AOA, WOA, PSO, and MGO. On the other side, the MGO-based TID controller performs well and is capable of reducing the US, ST, OS, and ITSE index, as shown in Table 3.

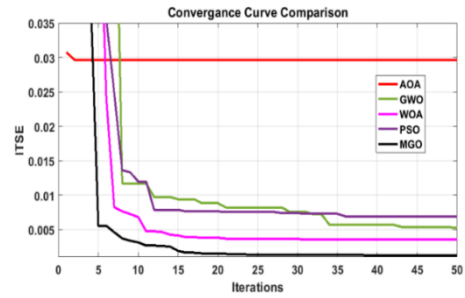


Figure 7. The curve of convergence for the various optimization methods

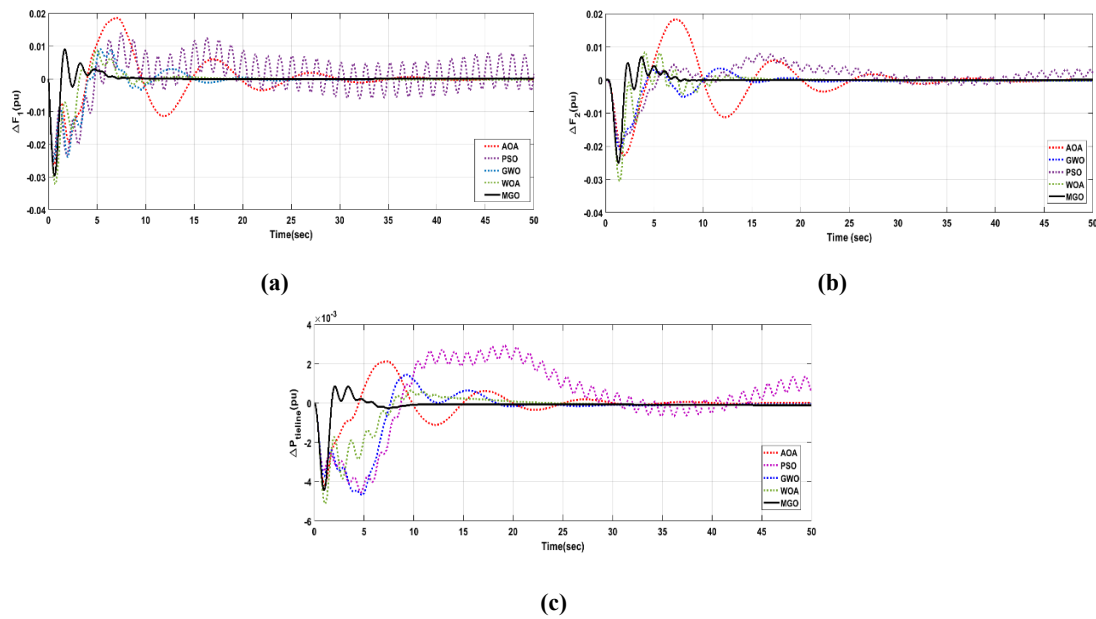


Figure 8. Responses from the TID controller using various optimisation techniques for (a) ΔF_1 ; (b) ΔF_2 ; (c) ΔP_{tie} .

Table 3. Performance evaluation of the dynamic system with five optimisation methods

MOT	Difference measure	OS (Hz)	US (Hz)	ST (s)	Rise time (RT) (s)	ITSE
AOA	ΔF_1	0.0185	-0.0264	37.8895	0.0018	0.0296
	ΔF_2	0.0182	-0.0227	38.4972	0.0919	
	ΔP_{tie}	0.0021	-0.0011	33.6420	0.0013	
GWO	ΔF_1	0.009	-0.025	17.7810	0.0019	0.0053
	ΔF_2	0.0035	-0.0209	19.9292	0.0756	
	ΔP_{tie}	0.0014	-0.0047	27.0170	0.0554	
PSO	ΔF_1	0.0139	-0.0238	49.9792	0.0173	0.0069
	ΔF_2	0.0080	-0.0012	49.6294	0.2539	
	ΔP_{tie}	0.0032	-0.000516	49.9215	0.1016	
WOA	ΔF_1	0.0087	-0.0321	15.1692	0.0031	0.0036
	ΔF_2	0.0084	-0.0304	15.8296	0.0574	
	ΔP_{tie}	0.00062	-0.0051	23.5472	0.0685	
MGO	ΔF_1	0.008	-0.029	6.7113	5.2983e-04	0.0013
	ΔF_2	0.0069	-0.025	7.3368	0.0729	
	ΔP_{tie}	0.0006	-0.00442	8.2729	0.0772	

Case 2: System response based on a different controller

In this scenario, area 1 is treated with the 1% SLP, but the RESs illustrated in Figure 2 are not included in the system. Table 4 displays the parameters for the MGO-based controllers tuned in this case. Figure 9 and Table 5 illustrate the superior and smooth performance of the FOPID controller, providing a qualitative and quantitative performance comparison with the IC, PID, and TID controllers. While PID and TID controllers

can improve the power system's dynamic oscillations, the IC is unable to accomplish this, as seen in Figure 9. However, even at optimal LFC values, the system oscillation time decreases. In terms of OS, US, ST, and ITSE, the results demonstrate that the FOPID controller, which was used to resolve the LFC, achieved superior results than the IC, PID, and TID controllers. The 3-D diagram has been shown in Figure 10 for better understanding the effectiveness of FOPID in comparison to other controllers.

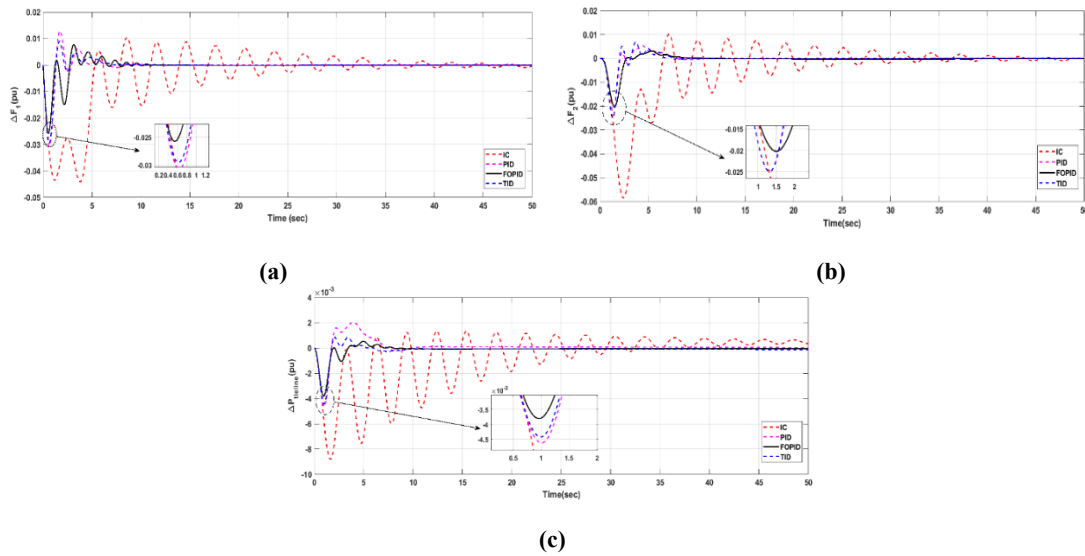


Figure 9. The outputs of various controllers for (a) ΔF_1 ; (b) ΔF_2 ; (c) $\Delta P_{\text{tie line}}$

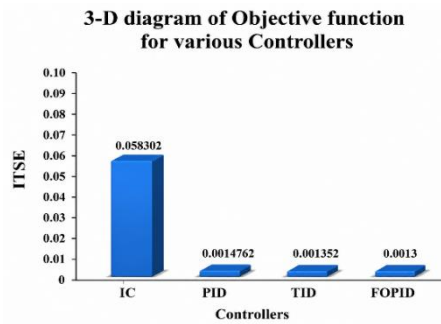


Figure 10. 3-D diagram of ITSE for various controllers

Table 4. The fine parameters of the controllers

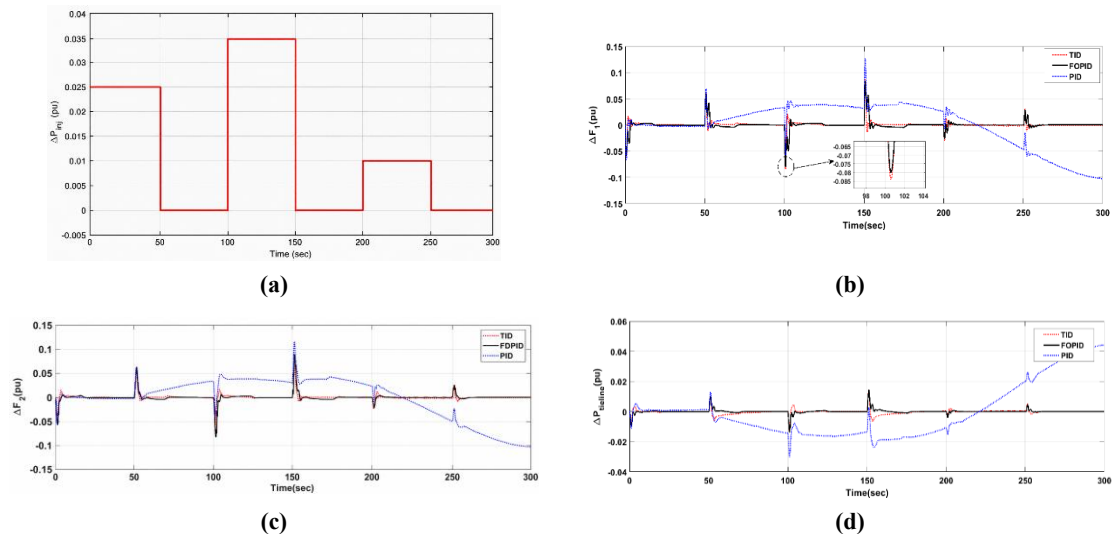
Algorithm	Area-1				Area-2			
	K_{T1}	K_{I1}	K_{D1}	n_1	K_{T2}	K_{I2}	K_{D2}	n_2
IC	-	0.109	-	-	-	-0.022	-	-
TID	5	0.798	2.769	0.492	-	1.256	-0.56	3.568
PID	2.442	4.366	2.485	-	391.321	-1.22	0.005	3.666
FOPID	0.543	4.367	3.766	0.573	0.9992	0.404	-0.06	1.340

Table 5. Evaluation of various controllers' effects on the dynamic system

Controller	Difference measure	OS (Hz)	US (Hz)	ST (s)	Rise time (RT) (s)	ITSE
IC	ΔF_1	0.0104	-0.0440	45.0977	0.0058	0.058302
	ΔF_2	0.0103	-0.0585	43.4322	0.1511	
	$\Delta P_{\text{tipeline}}$	0.0014	-0.0060	49.1368	0.0652	
PID	ΔF_1	0.0126	-0.0308	7.7907	8.9598e-04	0.0014762
	ΔF_2	0.0058	-0.0250	9.5035	0.0198	
	$\Delta P_{\text{tipeline}}$	0.0022	-2.7788e-04	9.9100	0.0044	
TID	ΔF_1	0.00895	-0.029	6.7113	5.2983e-04	0.001352
	ΔF_2	0.0069	-0.025	7.3368	0.0729	
	$\Delta P_{\text{tipeline}}$	0.00085	-0.0044	8.2729	0.0772	
FOPID	ΔF_1	0.0077	-0.0258	10.6114	0.0016	0.0013
	ΔF_2	0.0032	-0.0202	9.3886	0.1014	
	$\Delta P_{\text{tipeline}}$	0.00053	-0.0038	7.9280	0.0480	

Table 6. The fine parameters of the controllers for MSLP & RLP

Controllers	Area-1					Area-2				
	Kt1/Kp1	Ki1	Kd1	n1/ λ 1	Nc1/ μ 1	Kt2/Kp2	Ki2	Kd2	n2/ λ 2	Nc2/ μ 2
PID	1.342	3.566	3.23	-	493.521	-2.32	1.0032	4.56	-	335.6
TID	4.414	4.572	3.26	0.27	-	-0.19	0.2422	3.857	0.9934	-
FOPID	0.64	4.25	3.8	0.5	0.9785	0.50	-0.05	1.35	0.4123	0.67

**Figure 11. The outputs of various controllers for MSLP (a) ΔP_L ; (b) ΔF_1 ; (c) ΔF_2 ; (d) $\Delta P_{\text{tipeline}}$** **Case 3: System response based on MSLP**

The MSLP, illustrated in Figure 11(a), is implemented in area 1 of the two-area PS indicated in Figure 2 to simulate a real-world load variation. Several unanticipated changes in loading or forcible shutdowns of production units were part of the MSLP. The system response of the analysed PS is illustrated in Figures 11(b)-11(d) when the parameters are tuned using the MGO algorithm, based on PID, TID and FOPID control techniques, as shown in Table 6. The FOPID controller achieves minimal OS and US compared to the TID controller across all system loading variations. The MGO-implemented FOPID controller improves the

stability of the system. The recommended FOPID based on MGO is a valuable and efficient substitute for the LFC since it provides the best damping operation for forced-producing unit outages or loading changes.

Case 4: System response based on RLP

The power system depicted in Figure 2's area 1 applies the RLP, as illustrated in Figure 12(a), subsequent to a study of the effectiveness of the FOPID over other controllers. RLPs are a series of sudden activation or deactivation events of units, characterised by unpredictable changes in load. Figures 12(b)-12(d) depict the system response of

the system under investigation when the controller parameters are tuned using the MGO algorithm, and it is taken from Table 6. When faced with abrupt and gradual variations in load, the FOPID controller beats the other controllers.

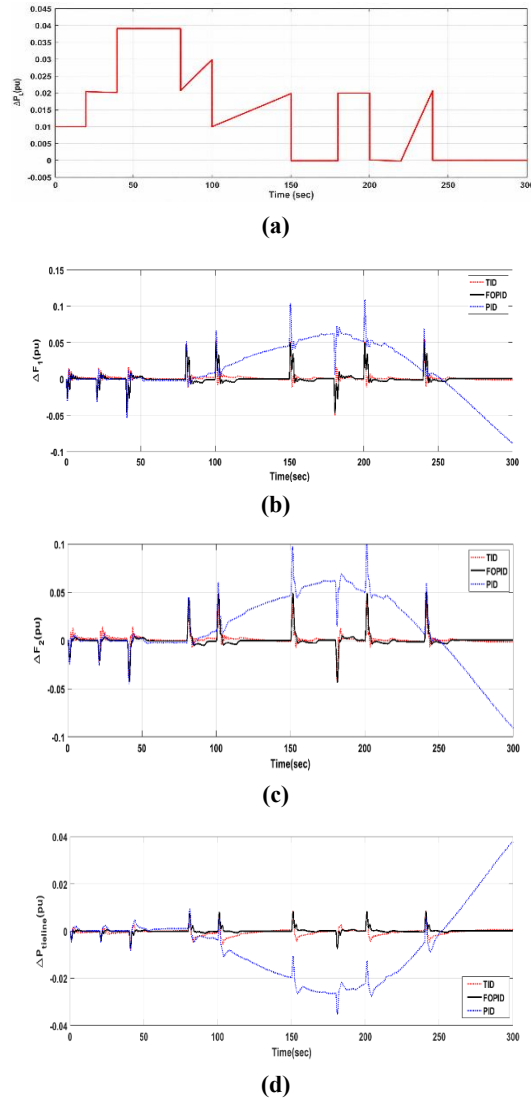


Figure 12. The outputs of various controllers for RLP
(a) ΔP_L ; (b) ΔF_1 ; (c) ΔF_2 ; (d) $\Delta P_{\text{tie line}}$

Table 7. The controllers' optimal parameters for RES penetration

Controllers	Area-1					Area-2				
	K_{t1}/K_{p1}	K_{i1}	K_{d1}	$n1/\lambda1$	$Nc1/\mu1$	K_{t2}/K_{p2}	K_{i2}	K_{d2}	$n2/\lambda2$	$Nc2/\mu2$
PID	5	5	5	-	493.46	5	5	5	-	485.94
TID	5	4.4365	3.6593	0.07	-	4.9981	4.9264	4.9997	0.0093	-
FOPID	4.3793	4.4525	4.9999	1	1	4.9723	4.6714	4.9985	0.9695	0.9999

Table 8. The tuned parameters of controllers on integration of EV in charging mode

Controllers	Area-1					Area-2				
	K_{t1}/K_{p1}	K_{i1}	K_{d1}	$n1/\lambda1$	$Nc1/\mu1$	K_{t2}/K_{p2}	K_{i2}	K_{d2}	$n2/\lambda2$	$Nc2/\mu2$
TID	-3.643	-3.672	-1.0351	0.003	-	5	5	5	0	-
FOPID	-4.999	-5.000	-4.988	0.91	0.971	4.957	5	5	0.992	0.0715

Case 5: System response based on RESs penetration

The moment RESs and step load disturbances are present in this case study. In Figure 2, the TID, PID, and FOPID controllers' effectiveness vary with respect to the parameters set by the MGO algorithm. The 50 MW SPP is connected to area 1 and turns off after 150 seconds. The 70 MW WPP is connected to area 2 and turns on after 250 seconds. Furthermore, the 1% SLP connects in area 1 after 10 seconds, whereas the 3% SLP connects in area 2 after 200 seconds. The TID, PID, and FOPID parameters tuned by the MGO algorithm are shown in Table 7. The FOPID controller is more effective in regulating fluctuations in RESs than the PID and TID controllers, as illustrated in Figure 13.

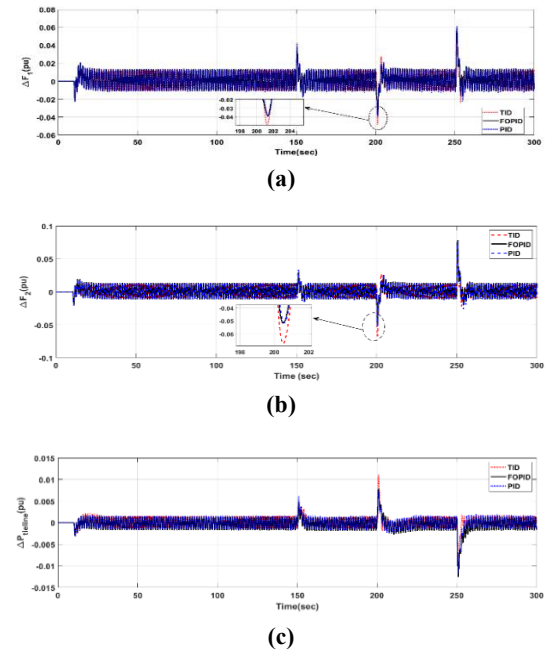


Figure 13. Impact of RESs and SLP on the system's response for (a) ΔF_1 ; (b) ΔF_2 ; (c) $\Delta P_{\text{tie line}}$

Case 6: System response based on integration of EVs

The efficacy of the FOPID is now being evaluated under the integration of EV in the investigated system Figure 2 charging and discharging mode after an evaluation of the performance with other controllers under various load perturbations. The EVs are connected to the grid at all times, according to their individual usage patterns. Therefore, at any given point, certain EVs may be in the process of charging while others may be discharging, as depicted in Figure 5. The variability in the quantity of EVs either charging or discharging has an impact on the dynamics of the systems. So, we look at the effects of EVs when charging and when discharging separately to get a complete picture of this issue.

Case 6(a): System response in charging mode of EVs

In this scenario, there are $N_C = 300$ EVs in charging mode and $N_D = 200$ EVs in discharging mode. As a result, most EVs are connecting to the grid for power. The analysis also includes the application of a 2% SLP in area-1 at $t = 10$ s. Figure 14 illustrates the system response in comparison to other control strategies. Table 8 displays the tuned parameters which are determined by the algorithm. The FOPID exhibits superior performance, as evidenced by the analysis.

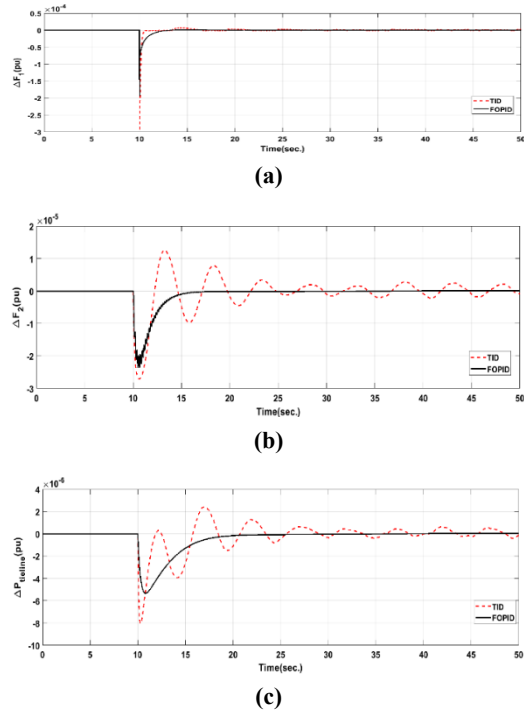


Figure 14. System response after integration of EV (charging mode) and SLP for (a) ΔF_1 ; (b) ΔF_2 ; (c) $\Delta P_{\text{tie line}}$

Case 6(b): System response in discharging mode of EVs

In this scenario, there are $N_D = 300$ EVs in discharging mode and $N_C = 200$ EVs in charging mode. As a result, most EVs are connecting to the grid to supply power. The analysis also includes the application of a 2% SLP in area-1 at $t = 10$ s. Figure 15 illustrates the system response for various control strategies. Table 9 displays the tuned parameters that were determined by the algorithm. The FOPID exhibits superior performance, as evidenced by the analysis.

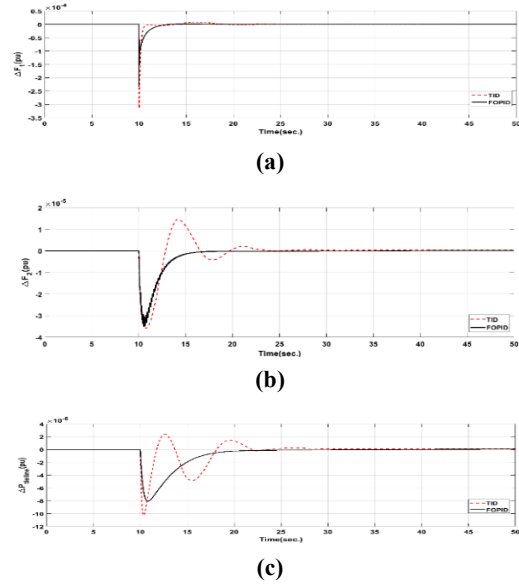


Figure 15. System response after integration of EV (discharging mode) and SLP for (a) ΔF_1 ; (b) ΔF_2 ; (c) $\Delta P_{\text{tie line}}$

Case 7: Sensitivity analysis regarding system parameter variations and stability analysis

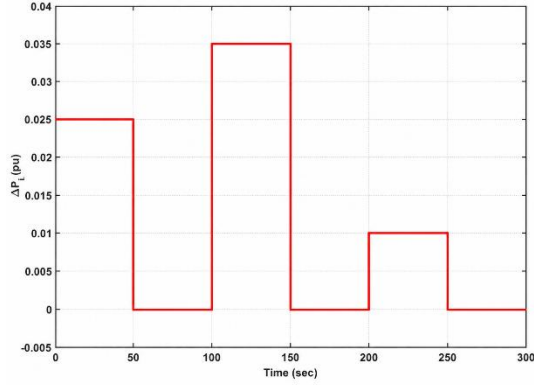
The evaluation of the system response of the investigated system, Figure 2, has been considered in TPPs, GPPs, HPPs, penetration of MSLP, and changes in parameters of up to $\pm 50\%$. The parameters considered are T_{sg} , T_t , T_{gh} , X_g , and Y_g . The system is working under MSLP in area -1, as illustrated in the load graph in Figure 16(a). Table 6 contains the parameters of the controller, and they have been fine-tuned by the MGO algorithm. The system is recovering faster in the case of FOPID for MSLP with parameter variations of $\pm 50\%$. The FOPID controller demonstrates excellent performance, as depicted in Figures 16(b)-(d).

The stability analysis of the analysed model controlled by FOPID has been performed by plotting a Bode plot, and it has been done through the simulation and coding of the model in MATLAB. The obtained Bode plot is illustrated in Figure 17. The phase margin and gain margin are

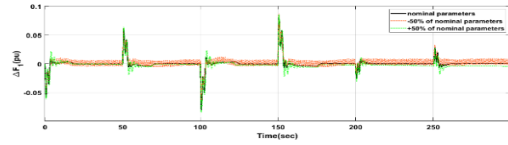
Table 9. The tuned parameters of controllers on integration of EV in discharging mode

Controllers	Area-1					Area-2				
	Kt1/Kp1	Ki1	Kd1	n1/ λ 1	Nc1/ μ 1	Kt2/Kp2	Ki2	Kd2	n2/ λ 2	Nc2/ μ 2
TID	-4.999	-4.999	-1.473	5.4e-6	-	4.992	1.768	4.979	0.010	-
FOPID	-5	-5	-5	0.91	0.974	5	5	5	1	0.0657

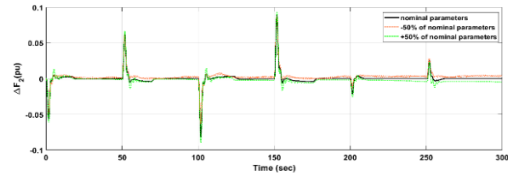
positive. This demonstrates the consistent functioning of both the controller and the system.



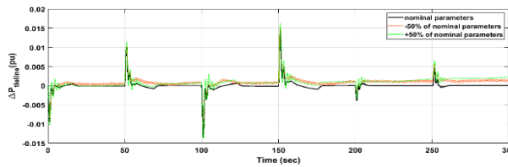
(a)



(b)

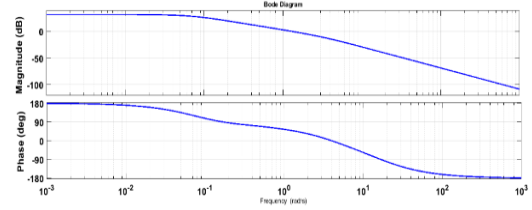


(c)



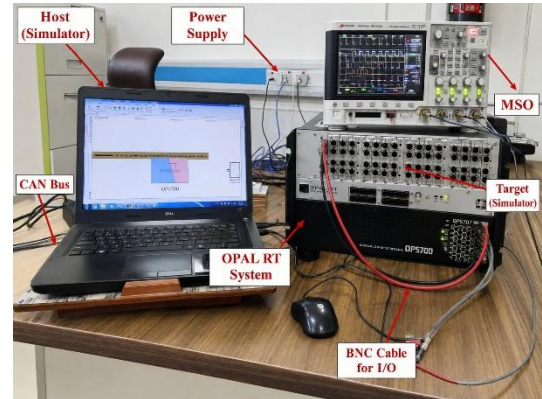
(d)

Figure 16. System performance of MSLP in area-1 and $\pm 50\%$ system parameter variations with a FOPID controller (a) ΔP_L ; (b) ΔF_1 ; (c) ΔF_2 ; (d) ΔP_{tie}

**Figure 17.** Bode Plot

Case 8: Validation of system with different controllers through OPAL-RT

The validation of the analysis of the system with different controllers has been performed on OPAL-RT, a real-time simulator (RTS). Figure 18 shows the experimental setup, which includes a power supply, a host and target simulator, an OPAL-RT 5700, and a Mixed Signal Oscilloscope (MSO).

**Figure 18.** The OPAL-RT 5700 experimental setup

In the seven different cases that have been discussed so far, the experiments are done in all operating situations, just like they were in case-2, case-3, and case-4 of the simulation results. The frequency and tie line power variation in both areas are shown in Figures 19 (a-c), which matches the simulation results shown in Figures 9 (a-c). The optimal parameters of the controllers for RTS on

OPAL-RT are taken from Table 4. The OPAL-RT results show a similar response as the simulation and validate the feasibility of the controller with the MGO optimization technique for the case-2.

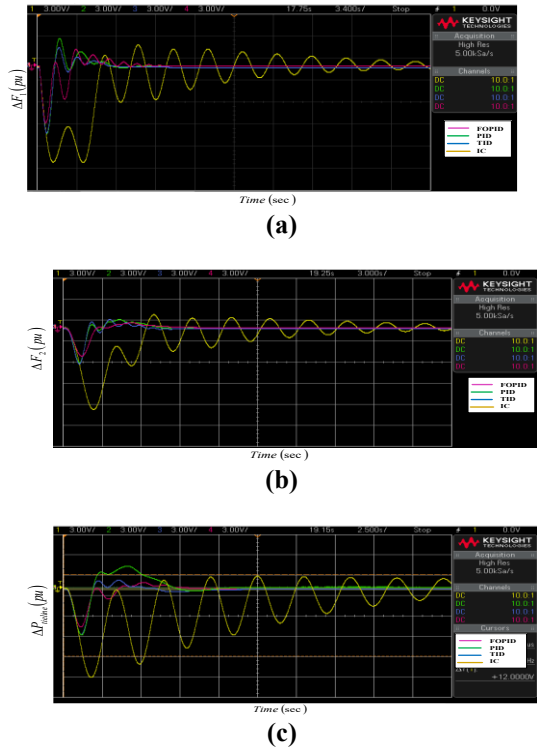


Figure 19. The outputs of various controllers from OPAL-RT for (a) ΔF_1 ; (b) ΔF_2 ; (c) $\Delta P_{\text{tie line}}$

Conclusion

A two-area interconnected multi-source PS with non-linearities has been considered for analysis of LFC. The modern PS is a mix of RESs, EVs, and conventional power plants. So, the penetration of RESs, integration of EVs, and all possible load variations with GRC and GDB have been considered for study with controllers. The convergence curve displays the superiority of MGO as compared to other MOTs. The parameters of the TID have been tuned by the MGO, which has given the best undershoots and overshoots compared to other MOTs. The FOPID controller outperforms other controllers in terms of ST, OS, US, and fitness value. The parameter variation of the examined system has been considered, and the response of the system for the FOPID is displayed. The stability analysis has also been done with the Bode plot. The validation of the system with different controllers has been also performed on the OPAL-RT 5700 real-time simulator. The result analysis in case-1

shows that the value of the objective function for optimization technique MGO is 63.89%, 81.16%, 75.47%, and 95.6% less in comparison to WOA, PSO, GWO, and AOA, respectively. Similarly, in case-2 the value of the objective function for the MGO-tuned FOPID controller is 3.8%, 11.93%, and 97.77% less in comparison to TID, PID, and IC, respectively. Overall, the MGO and FOPID is best and studied for load frequency problems with the integration of RESs and EVs. It has the potential to be implemented in the future for systems with FACTS units and three-area systems.

Ethical Approval

Not applicable, as the study did not involve human or animal participants.

Consent to Participate

Not applicable.

Consent for Publication

All authors reviewed the final version of the manuscript and agreed to its submission and publication.

Author Contributions

Anil Kumar contributed to the methodology, investigation, formal analysis, simulation, data visualization, and writing of the original draft. Amit Kumar contributed to the conceptualization, supervision, validation, and writing—review and editing. Saurabh Chanana contributed to the supervision, validation, and writing—review and editing. All authors reviewed and approved the final version of the manuscript.

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Competing Interests

The authors declare that there are no financial or non-financial conflicts of interest related to this study.

Data Availability

All relevant data supporting the findings of this research are included in the manuscript; no additional data are required.

Declaration of Generative AI

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

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