DESIGN AND ANALYSIS OF ARCTIC PUFFIN OPTIMIZATION BASED CASCADE PI-PDF CONTROLLER FOR FREQUENCY CONTROL OF ISLANDED MICROGRID

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Abstract -*Microgrid is a concept of innovative work for addition of renewable energy sources (RES) into a distribution system. A microgrid is a version of small-scale utility grid, which can work autonomously or in colligation with the main grid. This study investigates the combination of renewable energy sources into an islanded microgrid (MG) model to increase the efficiency and diminish carbon emission.The growth of renewable energy sources (RES) in Micro Grids has expanded the strike of damping on network stability. This gives climb to a lot of issues in the power system, along with power inconstancy from fluctuating RES, reduction of frequency regulation, and over supply from grid connected assigned generators. This analysis shows a cascaded hybrid load frequency controller for a micro grid that send frequency variation caused by change in load. A performance comparison was carried out between various controllers, including the integral (I), proportional–integral (PI), proportional–integral–derivative with filtering (PIDF), and the newly developed PIPDF controller. The results show that the PIPDF controller significantly improves efficiency, reducing the ISE value by 97.12%, 72.46%, and 68.50% relative to the I, PI, and PIDF controllers, respectively.Different operating conditions were examined, including changes in load, shifts in demand* response, the effect of time delays*and challenging environmental situations.*

Key Words:**Micro Grid (MG), Renewable Energy Sources (RES), Demand Response (DR),Arctic Puffin Optimization (APO), Integral Square Errors (ISE), Proportional Integral Proportional Derivative Filter (PIPDF).**

1. Introduction

The accelerating pace of urbanization, driven by population growth and industrialization, has led to increasing energy demands and environmental pollution. By the mid-21st century, two-thirds of the global population is expected to live in urban areas, underscoring the urgent need for sustainable solutions. The transportation sector, which significantly contributes to CO_2 emissions with its expanding carbon footprint, is under increasing pressure to adopt eco-friendly practices. Renewable Energy Sources (RES), Electric Vehicles (EV), and Demand Response (DR) have emerged as crucial strategies for reducing emissions and fostering sustainability.

This study investigates the role of EV and DR in Load Frequency Control (LFC) within micro grids, ensuring stability among load variations, time delays, and renewable energy fluctuations. The proposed Arctic Puffin Optimization (APO) algorithm, combined with a cascade PIPDF controller, is evaluated against conventional I, PI, and PIDF controllers. Simulation results indicate that the PIPDF controller, optimized by the APO algorithm, achieves superior performance, reducing ISE error by up to 97.01% compared to the traditional PIPDF controller.

Moreover, leveraging micro grids with RES creates a sustainable ecosystem by reducing carbon footprints, ensuring energy reliability, and benefiting local communities. This integrated approach highlights the potential of advanced controllers, DR, EV, and RES in achieving sustainability in urban energy systems. Various scenarios, including load changes, time delays, demand response variations, and the integration of renewable sources, have been examined to ensure comprehensive analysis and applicability. This study emphasizes the importance of adopting advanced technologies and strategies to create a more sustainable and eco-friendly future for urban areas.

2.Literature Review

The critical role of Load Frequency Control (LFC) in Microgrid (MG) systems has catalysed a plethora of research, exploring a spectrum of methodologies to enhance its efficacy. The scholarly discourse encompasses a diverse array of controllers, each with its unique attributes and applications. These methodologies have been meticulously documented and are synthesized in a comprehensive table within the literature.

To enhance the effectiveness of LFC, various control approaches have been explored in the literature. Traditional controllers such as Proportional-Integral (PI) and Proportional-Integral-Derivative Filter (PIDF) have been widely used due to their simplicity and flexibility [1]. However, their performance is often inadequate in handling complex dynamics and nonlinearities in modern microgrids. To address these limitations, optimization-based methods have been employed for tuning controller parameters.

In [2], Arctic Puffin Optimization (APO) was combined with a PIPDF controller to design and analyze an effective solution for LFC in the systems. In [3], Genetic Algorithm (GA) was utilized to optimize the controller gains for the proposed hybrid systems. The simulation results highlight the effectiveness of GA-based controllers in achieving reduced settling time, overshoot, and oscillations. In [4], Particle Swarm Optimization (PSO) was combined with Bacterial Foraging Optimization Algorithm (BFOA) to address the LFC problem in a hybrid system, aiming to prevent sub-optimal solutions and accelerate convergence time. In [5], the Social Spider Optimizer (SSO) was employed to fine-tune the proposed Proportional–Integral–Derivative (PID) controllers by optimizing their settings. The effectiveness of the SSO-based approach was demonstrated on an isolated hybrid microgrid system.

In [6], the Whale Optimization Algorithm (WOA) was enhanced with quasi-oppositional-based learning theory to improve its convergence speed, accuracy, and reliability, and was applied for the first time to address the LFC problem. In [7], a Class Topper Optimization (CTO)-based PID controller was proposed for load frequency control of power systems with nonlinearities. Its performance was compared with CTO-based PI, ID, PSO-based PID controllers. In [8], the optimization techniques used in energy management system was observed. In [9], we got to know about the controller parameters tuning of algorithm and its practical application to load frequency control of a power system. [10], how electric vehicle was integrated to a microgrid for the various purpose we know from this paper. Reference [11], examines load frequency control in three interconnected microgrid models that incorporate a thermal power plant, a supercapacitor, an electric vehicle, a photovoltaic system, and a wind turbine. [12], this study presents an improved cascaded controller-based approach for frequency stabilization in a two-region interconnected power system that includes electric vehicles. The proposed controller utilizes a cascade structure integrating a fractional-order proportional-integrator and a proportional-derivative controller with a filter term to address frequency regulation challenges in a hybrid power system with renewable energy sources.[13], it is forecasted that by 2050, approximately 66% of the world's population will stay in cities. Transportation accounts for 24% of direct CO_2 emissions resulting from fuel combustion. While aviation currently contributes approximately 3% of total CO_2 emissions, the industry is expanding at an annual rate of 6%.[14], for the system uncertainties the performance of LFC control strategy is useful. [15], To overcome these challenges in an isolated AMG, the load-frequency control (LFC) strategy and a flexible load control mechanism can be implemented. The LFC method is crucial in an isolated AMG, as it helps maintain frequency stability within predefined limits by minimizing the imbalance between generated power and load demand.[16], The key benefits of MGs include enhanced power quality, a dependable power supply, greater operational flexibility, lower feeder capacity requirements, minimized transmission losses, higher integration of renewable energy sources (RESs), and ultimately, reduced environmental pollution. [17], in this paper we got the idea state of charge of battery energy storage system in microgrid and its contribution towards the electric vehicle. [18], the strong control of microgrid frequency fluctuation with storage system was proposed in this paper. An overlook on control outcome in renewable energy integration was learned through this paper, [19]. [20], this paper elaborated the flexile load control and demand response capacity can enhance or diminish the load in the LFC control.

3.Investigated System

The structure of the Autonomous Microgrid (AMG) discussed in the schematic is a complex network integrating various distributed generation sources, including both AC and DC power generators. These generators connect to the AC bus via suitable Power Electronic Converters (PECs). Wind Turbine Generators (WTG) and Diesel Engine Generators (DEG) form the AC generation, while photovoltaic solar units represent the DC generation, both linking to the AC bus through DC/AC converters.

A distinguishing feature of the AMG is the incorporation of battery storage and electric output power, also connected to the AC bus via DC/AC converters. The system includes a demand response mechanism for electric vehicle Grid-to-Vehicle (G2V) loads, classified as controllable loads, while terminal loads are considered constant within the AMG framework.

The Autonomous Microgrid Control Centre (AMCC) manages the coordination of the AMG's various components. Its main role is to monitor and regulate the operations of the AMG's diverse elements, ensuring smooth functionality under changing conditions. This centralized control is vital for maintaining the AMG's stability and efficiency, especially given the variable energy demands and the intermittent supply from renewable sources.

Fig1.Investigated MG system

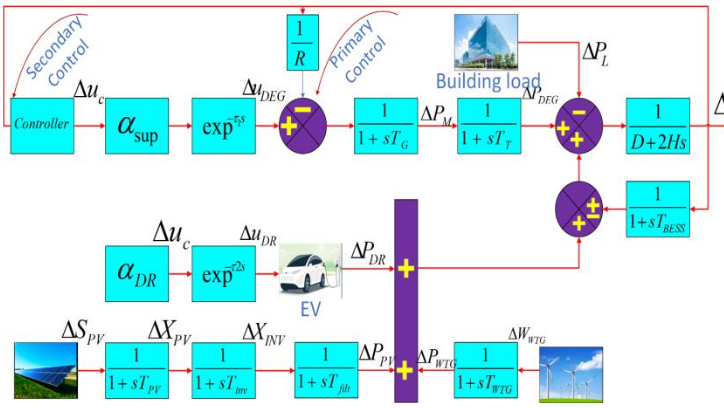


Table 1 : Parameters related to the studied MG

Parameter	Value	Parameter	Value	Parameter	Value
C_{kwh}	15	T_{WT}	1.5	M	0.2
$N_{control}$	72	T_{PV}	1.8	D	0.012
$N_{initial}$	100	T_{fil}	0.004	T_{EAC}	1
$N_{control\_in}$	22	T_{inv}	0.04	T_{T}	0.1
N_{plug_out}	50	T_{BESS}	0.1	T_{G}	0.08
		C_{kw}	3	R	3

3.1. Renewable Energy Model

The A photovoltaic (PV) model that shown in Fig 2. exhibits a nonlinear voltage current relationship across various conditions. Near its Maximum Power Point (MPP), it acts similar to a controlled current source, with solar irradiance significantly influencing its current output.

Changes in irradiance mainly affect the PV current, whereas temperature increases reduce the operating voltage and overall power output. In frequency stability studies, PV systems are often simplified using a first-order transfer function with time constant Tpv and gain Kpv, where Tpv is the time for PV current to settle after a disturbance. The PV model comprises the PV system, an inverter (time constant T_{INV} and gain one), and a first-order filter (time constant T_{FIL}). Random irradiance fluctuations are simulated, with PV power then integrated into the MG.

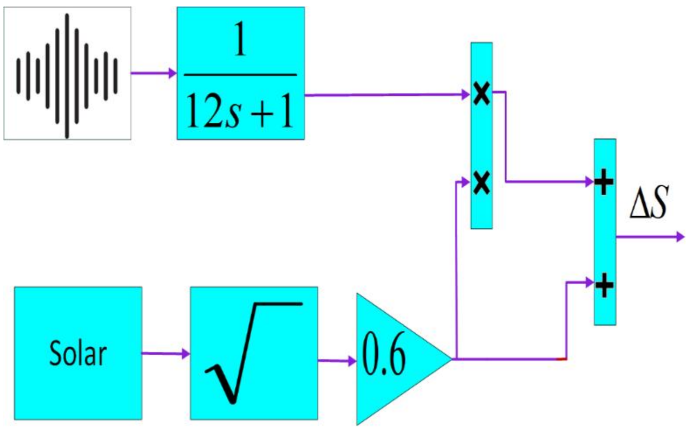
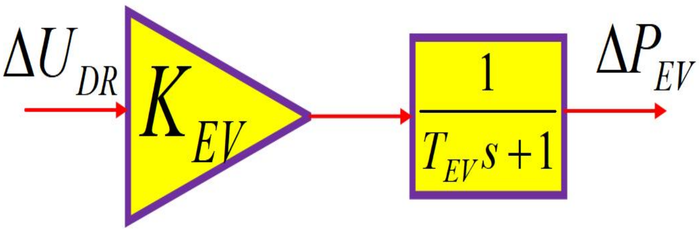


Fig2. Noised based PV model.

The wind turbine model that pictured in Fig 3. despite its inherent complexity and nonlinearity, is simplified in the



MG analysis using a first-order linear approximation. To simulate natural fluctuations, random wind speed variations within a specified range are applied as inputs. This model is represented by a first-order transfer function with a time constant (T_{WTG}) and a gain of one, allowing the turbine to inject power into the microgrid. This linear simplification, as suggested in previous studies, facilitates the effective investigation of the wind turbines impact on Load Frequency Control (LFC) while minimizing model complexity.

3.2. Electric Vehicle Model in Micro Grids

Electric Vehicles (EVs) are increasingly recognized as an

Fig3. Noised based WT model

integral part of microgrid systems, offering not only transportation solutions but also serving as dynamic elements within the grid. These vehicles have the dual capability of charging from and discharging back into the grid, making them controllable loads that can participate in Demand Response (DR) programs. This is particularly relevant in settings such as electric vehicle parking lots, where a fleet of EVs can be managed to contribute to LFC. By responding to control signals, EVs can actively-engage in grid services, thereby enhancing the overall stability of the system.

In the context of an AMG, we consider a scenario where 100 EVs are modelled. The State Of Charge (SOC) of these EVs is represented using uniform distribution functions, with the current SOC ranging between 40% and 100%, and the expected SOC set between 80% and 100%. For the purpose of this model, the SOC parameters, including the minimum SOC (SOCmin), lower threshold SOC (SOClow), higher threshold SOC (SOChigh), and maximum SOC (SOCmax), are assumed to be 60% and 90%, respectively.

The response frequency model of EVs operating in Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) modes is characterized using a first-order transfer function. This function includes a delay time of 0.04 seconds, reflecting the response time of EVs in these modes. The operational mode of the EVs, whether charging or discharging, is determined by the frequency deviation signal and the DR commands issued by the EV aggregator.

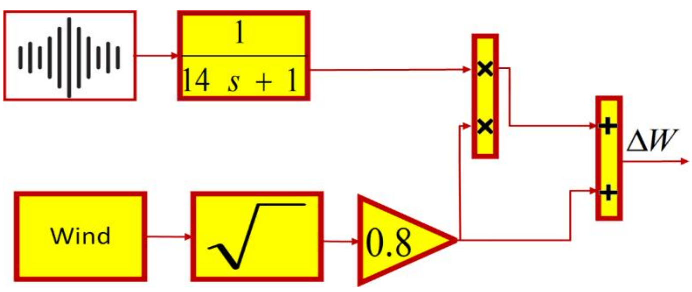


Fig4. V2G model of EV.

4. Proposed Controller

The basic model of controller such as integral controller (I) and proportional integral controller (PI) are taken into account to examined the microgrid. To avoid the noise due to derivative controller we also take other controller PIDF using an additional filter. For a better performance and solve the frequency deviation we take another cascaded controller proportional integral proportional derivative controller with a filter.The PIPDF Controller boosts system stability by integrating dual proportional terms, an integral term, a derivative term, and filtering. It enhances flexibility, reduces steady-state error, predicts errors to minimize overshoot, and decreases noise sensitivity for precise, robust control. Here the 'n' is considered as 100. We also observed the integral of squared error (ISE) that is decreasing by using of the best controller.

5. Objective function

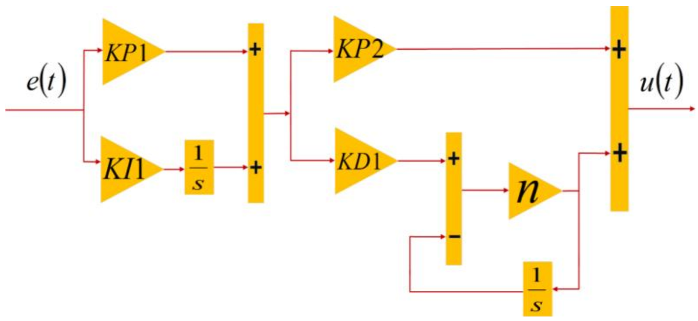
Designing an optimal controller with metaheuristic methods requires selecting a suitable objective function. The chosen multi-objective function ensures fast frequency response, robustness against uncertainties, minimal control cost, and computational simplicity. It consists of a weighted sum of two key parts: one to minimize frequency deviation and another to reduce ISE error, achieving maximum stability with minimal expense. This objective function optimizes the parameters of the I, PI, PIDF controller using the APO algorithm. To validate its performance, the PIPDF cascade controller is evaluated, demonstrating efficient control based on the defined objective function. The main objective function of this work is to find out the ISE error and maximum overshoot and maximum undershoot.Integral Square Error (ISE) is a performance metric in control systems that quantifies the cumulative squared error over time, emphasizing larger errors, and is commonly used to evaluate controller effectiveness. The Integral Square Error (ISE) is a measure used in control systems to evaluate the performance of a controller by assessing the error over time. For a two-area microgrid system in load frequency control (LFC), the ISE can be calculated as the integral of the square of the error signal (which is the difference between the desired and actual frequency) over a period.

The formula for the ISE in a two-area microgrid system can be written as:

$$\text{ISE} = \int_0^{\infty} e^2(t)\,dt$$

Where e(t) is the error signal that can be obtained by the difference of desired output and actual output of the system, the integral runs from 0 to infinity.

Fig5. Cascaded PIPDF controller.



6. Overview of Arctic Puffin Optimization (APO)

Optimization involves finding the best possible solution by maximizing or minimizing an objective function within specific constraints. The Arctic Puffin Optimization (APO) algorithm is a metaheuristic optimization method inspired by the survival and hunting behaviours of Arctic puffins. It consists of two main phases: aerial flight (exploration) and underwater foraging (exploitation).In summary, the Arctic puffin's behaviours—collective aerial searching, swooping to feed, group foraging, intensified underwater searching, and hazard avoidance form the basis of the Arctic Puffin Optimization (APO) algorithm. These behaviours are modelled to effectively address global optimization challenges through coordinated exploration and exploitation strategies.

6.1. Mathematical model and basic principles: -

- **Population initialization: -**

Arctic puffins exhibit strong collectivism, whether during migration or at their habitat, always moving in groups and collaborating. Each Arctic Puffin represents a potential solution participating in the optimization. The generation process of initializing the population is described by the following equation:

X_i^t = rand*(ub-lb) + lb, i = 1,2,3,....N (1)

where X_i^trepresents the position of the ith Arctic Puffin; rand generates a random number between 0 and 1; ub and lb represent the upper and lower bounds, respectively; N is the number of individuals in the population.

- **Aerial flight for exploration: -**

Arctic puffins use flight and foraging strategies to survive in challenging environments, adapting between ocean and air. They employ two key strategies: aerial searching to locate prey and plunge diving to catch it. These behaviours showcase their adaptability to diverse conditions, crucial for survival and reproduction. This analysis explores these strategies and their importance.

- **Strategy of aerial search: -**

Arctic puffins use coordinated, low-altitude flight for efficient prey scouting and predator vigilance. In favourable conditions, they accelerate towards water to catch prey. Puffins rely on the Levy flight coefficient for long-distance, efficient exploration, covering vast areas and staying near food sources. To evade predators like seagulls, they employ rotational flight tactics. This aerial strategy enhances global search capabilities, helping locate optimal fishing spots and improving the algorithm's exploration efficiency.

- **Strategy of swooping predation: -**

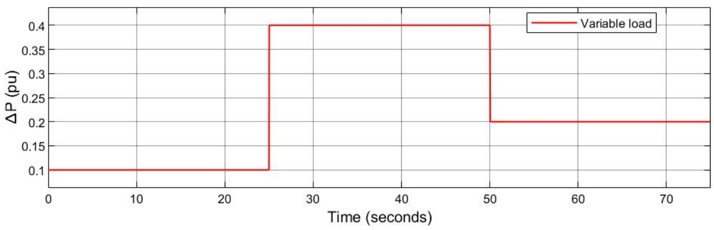
Swooping is crucial for Arctic puffins in hunting, allowing swift flight adjustments for capturing prey. This tactic, vital in competitive feeding, boosts survival success. A velocity coefficient simulates swooping, adjusting puffins' movements. Incorporating swooping in the model enhances their adaptability, speed prioritization, and prey capture efficiency, mirroring natural predation.

- **Underwater foraging for exploitation: -**

Arctic puffins use cooperative foraging by gathering around schools of fish near the water's surface. This teamwork enhances hunting efficiency and success, as they collectively surround and capture prey. Puffins on the sea surface also observe others to locate diving hotspots and food resources, increasing their chances of successful predation through collaboration and shared strategies. When Arctic puffins detect predators nearby, they use specific calls to alert others, signaling the presence of danger. These warning calls prompt other puffins to become alert and move away from the hazardous area. Simultaneously, puffins swiftly adjust their positions, swimming along a larger, safer path to evade predators. This behavior showcases their adaptability and teamwork in reacting to potential dangers in their environment.

7. Results and Discussion

When the MG system is exposed to load disturbances and/or RES uncertainties, severe problems such as frequency deviations may occur due to energy imbalance between generation and load. The variable nature of RES, such as changes in solar radiation and wind speed, can



lead to significant frequency-power oscillations that need to be avoided. For this purpose, the used different types of controllers for MG islanding is optimized using APO optimization algorithm, and the defined objective function is used to determine the optimal control coefficients of the used controllers. Three optimized controllers, namely I, PI, PIDF, PIPDF, are applied to the MG system for comparison. Our approach adopted a scenario-based evaluation, considering a range of scenarios that encompassed variations in load, renewable energy generation, and the two vital system parameters changes. Various scenarios are examined below.

- Scenario 1: Multiple load disturbances
- Scenario 2: Demand response variations
- Scenario 3: Impact of time delay
- Scenario 4: Performance under harsh condition

Scenario 1: Variable load disturbances: -

To evaluate the performance of the used controller and its robustness against uncertainties in demand and load changes, variable load changes have been applied to the distribution network in this scenario. To do so, the pattern of variable load changes at different time intervals over a period of 75 second has been considered. The pattern of load changes where the minimum and maximum values of load changes are 0.1 and 0.4 p.u , respectively. In first zero

Controllers	Maximum overshoot	Minimum undershoot	ISE
I	60.30%	60.40%	97.12%
PI	22.25%	22.24%	72.46%
PIDF	6.15%	6.26%	68.50%

second the load is minimum 0.1 p.u and after 25 sec the load is increased to 75% of the initial load then the load variation is constant up to 50 sec then we decreased the load up to 50%.Then the load is constant through the 75 sec. we observed the model which leads to variation in frequency. We noted the KP, KI, KD, and objective values of the function. The demand response of the first scenario is 0.6 for thermal power and 0.4 for EV. We calculate the maximum overshoot and minimum undershoot and ISE error in all the used controllers such as I, PI, PIDF, PIPDF.

Fig6. Variable building load in 1st scenario
Fig7. Frequency variation response of the system load variation.
Table2: Optimal parameters of LFC controllers observed in MG

Method	Controller	KI_1	KP_1	KD_1	KP_2	ISE	Objective Value
APO	I	1.9988	-	-	-	0.1982	0.19822
	PI	1.9646	1.9894	-	-	0.0207	0.020652
	PIDF	1.9983	1.9947	0.099336	-	0.0181	0.018100
	PIPDF	1.9982	1.9915	0.088766	1.9543	0.0057	0.0057039

Table 3: Different types of errors for scenario 1: -

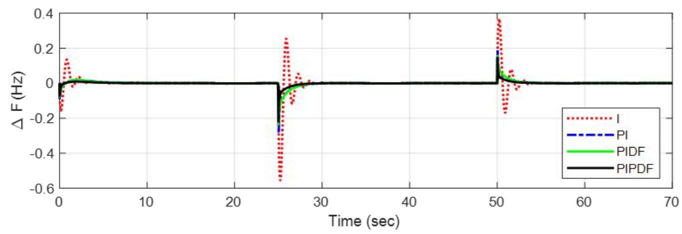
Controllers	Maximum overshoot	Minimum undershoot	ISE
I	0.3688	-0.5551	0.1982
PI	0.1883	-0.2827	0.0207
PIDF	0.1560	-0.2345	0.0181
PIPDF	0.1464	-0.2198	0.0057

Table 4: Decreasing percentage error with respect to PIPDF controller for scenario 1: -

Scenario 2:Demand response variations:

Another important factor in controlling the frequency of the microgrid is demand Response under different conditions. In scenario 2, the effect of demand Response on LFC in the MG has been observed. To examine the effects of these changes on frequency control, the DR system has been considered. Therefore the participation coefficients for building load and EV are 0.8 ,0.2 respectively. In this scenario, DR has been applied to various loads that have the ability to participate in the

Controllers	Maximum overshoot	Maximum undershoot	ISE
I	0.3610	-0.5442	0.1788
PI	0.1703	-0.2563	0.0195
PIDF	0.1266	-0.1906	0.0177
PIPDF	0.1149	-0.1730	0.0051



demand response program, and their power is variable over time. The load change pattern is the same as the previous scenario, and the effect of time delay has not been considered.

Table 5: Different types of errors for scenario 2:

Controllers	Maximum overshoot	Minimum undershoot	ISE
I	0.3884	-0.5863	0.2579
PI	0.2056	-0.3087	0.0239
PIDF	0.1692	-0.2543	0.0197
PIPDF	0.1584	-0.2380	0.0069

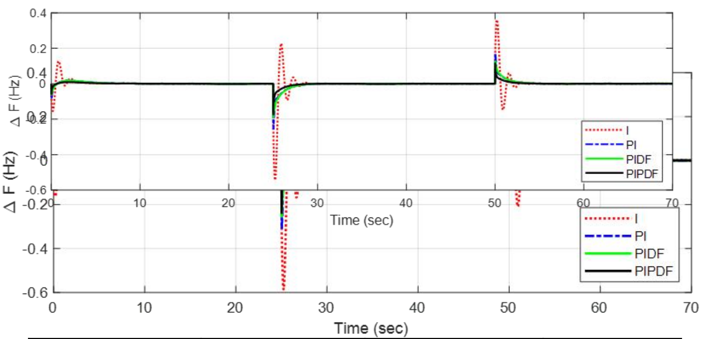


Fig8. Frequency variation response of the system for demand response.

Scenario 2:Time delay impact: -

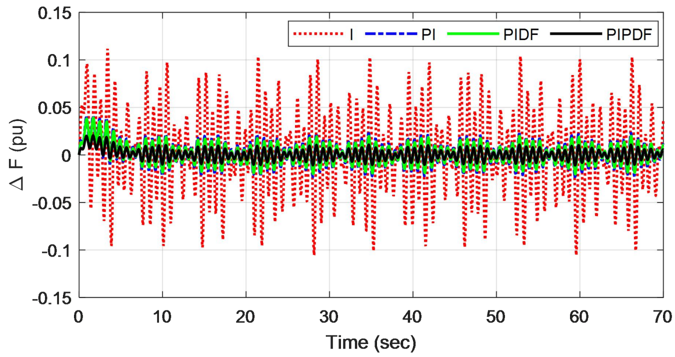
One of the main challenges in frequency control of microgrid load is the time delay in transmitting control signals between different components of the system. Time delay can reduce the quality of microgrid frequency control and thus increase instability in the system. In fact, since microgrid frequency load control should be dynamically and quickly adjusted, any time delay in the controller path can reduce control accuracy. This can lead to increased microgrid frequency oscillations and fuel consumption costs. Therefore, reducing time delay in the controller path can significantly improve the performance of microgrid frequency load control and improve the quality of electricity for consumers. In this scenario, a time delay has been considered for the control sections to evaluate the performance of the designed controller in LFC microgrid. The time delay of 10,20,30 and 40 ms have been taken for the control section of demand response, EV and diesel generator respectively.

Table 6: Different types of errors for scenario 3: -

Controllers	Maximum overshoot	Maximum undershoot	ISE
I	68.17%	68.21%	97.14%
PI	32.53%	32.50%	73.84%
PIDF	9.24%	9.23%	71.18%

Table 7: Decreasing percentage error with respect to PIPDF controller for scenario 3: -

Fig9. Frequency variation response of the system for



time delay.

Scenario 4: Performance under harsh condition: -

In this scenario we observed how the different controllers react under harsh condition with the change of sinusoidal wave as the load instead of step load. Since load variation changes over time, it serves as an appropriate representation of load uncertainty. In addition to handling these variations, the designed controller should ensure that frequency fluctuations remain minimal in amplitude.

$\Delta_{PD} = 0.006\sin(5.2t) + 0.01\sin(7t) - 0.02\sin(8t)$

We have considered three sinusoidal wave load here, the first sinusoidal wave load has 0.006amplitude and the frequency is 5.2Hz, and remaining two wave have amplitude of 0.01 and 0.02, frequency of 7,8Hz respectively. From this case we observed that the PIPDF controller that we use, delivered the best performance sinusoidal wave load and control the frequency deviation.

Table 11: Different types of errors for scenario 5: -

Controllers	Maximum overshoot	Minimum undershoot	ISE
I	0.1116	-0.1055	0.1427
PI	0.0412	-0.0236	0.0104
PIDF	0.0391	-0.0203	0.0079
PIPDF	0.0205	-0.0110	0.0023

Table 8: Decreasing percentage error with respect to PIPDF controller for scenario 5: -

Fig10. Frequency variation response of the system under harsh condition.

Controllers	Maximum overshoot	Maximum undershoot	ISE
I	81.63%	89.57%	98.38%
PI	50.24%	53.38%	77.88%
PIDF	47.57%	45.81%	70.88%

8. Conclusion

In this analysis we observed the frequency variation of the microgrid system. Considering various scenarios such as load fluctuation, changing the time delay, taking different values of demand response and under harsh condition.Here the APO algorithm and cascade controller PIPDF is used to achieve efficiency in controlling the micro grid's frequency response. The performance of this controller is compared tothree I, PI, PIDF controllers in four scenarios. Based on the simulation results in different scenarios, the APO algorithm was able to optimally design the PIPDF controller with the aim of reducing ISE error. In this analysis we examined that the PIPDF shows the better result as compared to other controllers, the ISE error also decreasing 97.12%, 72.46%, 68.50% respectively.

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