

Article

Design and Implementation of Maiden Dual-Level Controller for Ameliorating Frequency Control in a Hybrid Microgrid

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Abstract: It is known that keeping the power balance between generation and demand is crucial in containing the system frequency within acceptable limits. This is especially important for renewable based distributed hybrid microgrid (DHμG) systems where deviations are more likely to occur. In order to address these issues, this article develops a prominent dual-level “proportional-integral-one plus double derivative {PI–(1 + DD)} controller” as a new controller for frequency control (FC) of DHμG system. The proposed control approach has been tested in DHμG system that consists of wind, tide and biodiesel generators as well as hybrid plug-in electric vehicle and an electric heater. The performance of the modified controller is tested by comparing it with standard proportional-integral (PI) and classical PID (CPID) controllers considering two test scenarios. Further, a recently developed mine blast technique (MBA) is utilized to optimize the parameters of the newly designed {PI – (1 + DD)} controller. The controller’s performance results are compared with cases where particle swarm optimization (PSO) and firefly (FF) techniques are used as benchmarks. The superiority of the MBA-{PI – (1 + DD)} controller in comparison to other two strategies is illustrated by comparing performance parameters such as maximum frequency overshoot, maximum frequency undershoot and stabilization time. The displayed comparative objective function (J) and J_{FOD} index also shows the supremacy of the proposed controller. With this MBA optimized {PI – (1 + DD)} controller, frequency deviations can be kept within acceptable limits even with high renewable energy penetration.



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1. Introduction

A drastic demand with larger depletion of fossil fuels is resulting in utilization of nonconventional resources in modern power network. In fact, the transformation of low carbon energy system and its’ utilization policies has been presented [1,2]. In this circumstance, to provide the sustainable electricity islanded microgrid system integrated with nonconventional resources is believed to be the cost effective solution due to small scale, energy security and on-site distributed energy. However, mismatch between total generation and demand may be frequently encountered in hybrid microgrid system which leads to power and frequency fluctuation. To avoid this problem in the modern power system network, the automatic frequency control (AFC) plays a significant role in maintaining the balance between the demand and generation through the control of system frequency and power sharing. Mostly, the frequency change is regulated via primary control and secondary control. In primary control, the governor has a control mechanism to change the speed and thereby to change the frequency [3]. However, the secondary control has played a key role in regulating the frequency in the wake of large deviations or events in

a slower time scale [4]. For this reason, the secondary controller has a larger impact on system performance and has to be an optimal controller. There are different optimization approaches and strategies that can be used to achieve this objective.

Many studies were carried out for FC of microgrids with distributed generators to enhance the system's transient performance against faults or other sudden changes. A robust control strategy [5,6], pole placement tools, structure distinction methodology [7] and feedback loop technique [8] were anticipated in order to contain the system response (i.e., frequency) in a better fashion. However, these strategies lead to demerits of upper order complex design which is not fruitful for operating scenarios.

Another approach to take care of the frequency regulation issue is to utilize the algorithmic techniques tuned controller [9]. Popular genetic optimization technique (GA) [10] is successfully utilized to manage the frequency regulation issue with proportional integral (PI) and proportional integral with derivative (PID) controllers. To optimally select the parameters of PI and PID controllers, organic Rankine cycle (ORC) solar-thermal-energy storage based microgrid frequency response model with PSO technique has been utilized and its dynamic response is compared [11]. For the enhancement of transient phenomenon, differential evolution (DE) technique based PI controller was developed in [12]. However, these strategies improve the system performance but create uncertainty due to their slow convergence. Additionally, due to the uncertainty in power networks, flower pollination technique (FPT) tuned classical PID controller is leveraged for sustainable frequency response model [13]. Here, the same FPT tool has been investigated for tuning the two-degree of freedom (2DOF)-PID controller to contain the system frequency under wind/solar thermal/diesel/ultracapacitor etc. based distributed microgrid system [14]. To yield desired performance, a cascaded proportional-integral with proportional derivative (PI-PD) controller structure is used to meet the frequency control assignment for microgrid power network [15]. A number of studies have been observed where firefly (FF) and cuckoo search (CS) techniques have been widely used to contain the frequency of Wind-PV-diesel based renewable microgrid power system [16,17]. The sine cosine technique (SCT) based cascade proportional-derivative with PID (PD-PID) controller method has presented in [18] for frequency regulation of renewable wind-diesel-fuel cell-battery based microgrid. The work in [19] presented PID control structure to strengthen the frequency stabilization of wind-super conducting magnetic energy (SMES) storage-nonrenewable diesel units based microgrid network.

With the gradual development of controller's fractional order (FO) based PID, controller has been added to control the microgrid network. Wang et al. [20] leveraged multi-objective (MO) technique to optimally tune the higher FOPID controller's parameters for better frequency response of microgrid. In the control process of frequency response microgrid model, a kriging based noninteger FO control strategy is developed to tune the controller parameters in less time [21]. The cascaded noninteger FO three degree of freedom (3DOF) controller is applied to adjust control signal of the associated system to enhance frequency stabilization of microgrid power system [22]. However, these control strategies suffer from higher controller parameter with larger run time, suitability issue and complexity. To overcome these problems, several authors have leveraged different structural fuzzy logic (FL) approaches [23–27]. Lal et al. and Rajesh et al. [23,24] have considered wind-solar PV-conventional diesel based microgrid network using fuzz-PID controller where application different recently utilized renewable sources with bio sources needs to explore. To shape the self-frequency restoration of distributed generation, a single input type-two fuzzy integral controller is considered [25]. Nithilasaravanan K. et al. [26] developed a wind-solar thermal based frequency response model. A self-tuned noninteger fuzzy-PID has been leveraged to restore the system frequency. An adaptive neuro-fuzzy interface system (ANFIS) controller for restoring microgrid frequency regulation is established by Karimipouya et al. in [27]. However, these techniques faced different problems such as pre-knowledge fuzzy parameters setting and higher computational analysis.

Hence, an alternative path to solve such problem is to utilize a newly established topical optimization algorithm grounded on mine bomb explosion in a specified area named as Mine Blast Optimization Technique (MBA) [28]. The benefits of this optimization technique are that it reduces the calculation, has faster convergence rate and achieves better optimal results for solving concentrated engineering problem [29]. Besides, in order to improve the system dynamics a maiden dual level “proportional-integral-one plus double derivative $\{PI - (1 + DD)\}$ controller” controller has been developed for the first time due to its better performance in respect of tuning disturbance rejection ratio, lesser elapsed time under different scenarios. Thus, in this paper a new strategy is proposed in which the recently developed MBA technique is utilized to tune the parameters of novel “proportional-integral-one plus double derivative $\{PI - (1 + DD)\}$ controller” for FC in microgrids with high renewable energy penetration.

Based on the above literature survey, the prime contributions and novel aspects of the current research work are outlined below:

1. To develop a distributed hybrid microgrid (DH μ G) model consisting of wind, tidal and biodiesel generators, hybrid plug-in electric vehicle and nonsensitive electric water heater.
2. Implementation of novel dual-level $\{PI - (1 + DD)\}$ controller to achieve the system dynamic by controlling the tuning parameters.
3. To study the dynamic responses of $\{PI - (1 + DD)\}$, CPID and PI controller separately to find the best one.
4. Extensive tests have been performed to compare system dynamics of the proposed controller with other classical PI/CPID controllers in terms of peak frequency deviations, stabilization time and objective function J index.
5. To explore the dynamic performance of MBA, PSO and FF techniques using the best controller obtained in (3).
6. To exemplify and validate that the proposed strategy is under real-time wind data.

In the present article, the following segments are organized to articulate the above-mentioned objectives. Section 2 is focused around the system configuration whereas the description of proposed controller and optimization technique are illustrated in Section 3; the simulation results are presented in Sections 4 and 5 is intended to describe the conclusions of the work.

2. Investigated System Modeling

In order to control the system efficiently, it is necessary to determine and locate the hybrid system components and to formulate the variable production resources and consumption. Figure 1 shows a distributed hybrid microgrid (DH μ G) system comprising of distributed generation system (DG) with load demand.

The DG system contains WPS (Wind Power System), TPGS (Tidal Power Generation System), BDPG (Bio-diesel Power Generator) HPEV (Hybrid Plug-in Electric Vehicle) and EWH (Electric Water Heater System). Table 1 shows a set of nominal parameters in terms of Gain (K) and time constant (T) for the said hybrid power system. The optimal parameters values are reported in the annexure. Power generating units with nonsensitive load of the proposed system are as follows:

Table 1. Symbols and their corresponding values.

Symbol	Nomenclature	Value
ΔP_{DL}	Net demanded load of DH μ G	-
ΔF	frequency deviation (Hz) of DH μ G	-
ΔP_G	Net generated power of DH μ G	-
D_{lg}	Microgrid damping coefficient	0.1
M_{lg}	Microgrid inertia constant	0.12

Table 1. Cont.

Symbol	Nomenclature	Value
K_{CEX}	Gain of engine delay of BDPG	1
T_{CEX}	Constant time engine delay of BDPG	0.5 s
K_{IVRx}	Gain of inlet valve regulator delay of BDPG	1
T_{IVRx}	Constant time of inlet valve regulator delay of BDPG	0.05 s
K_{WPSx}	Gain of wind	1
T_{WPSx}	Time constant wind	5s
K_{TPGSx}	Gain of collector governor and turbine of TPGS	1
T_{TPGSx}	Constant time of collector governor and turbine of TPGS	0.08 s
T_{HPEVx}	Time constant of HPEV	0.2 s
K_{CEWHx}	Gain of EWH	1
T_{EWHx}	Time constant of EWH	0.1 s
t_{sim}	Simulated run time of DH μ G	100 s

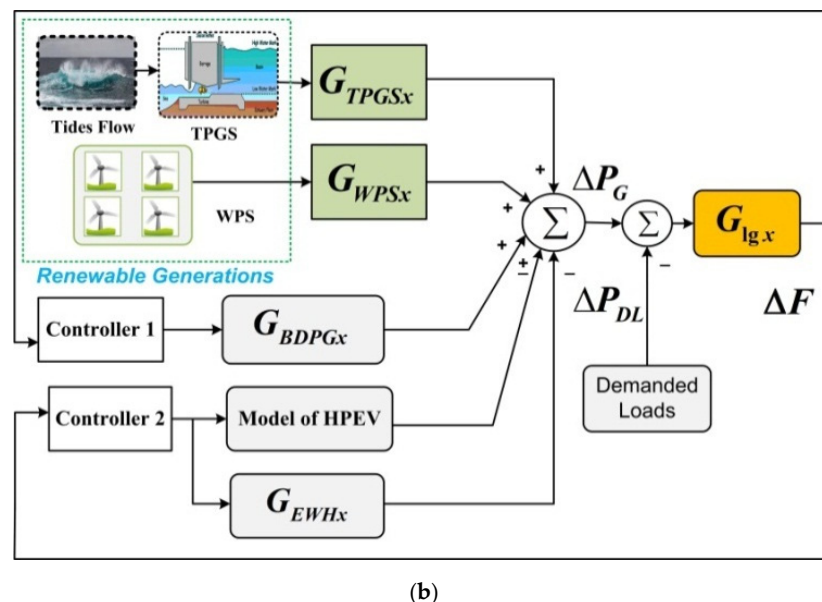
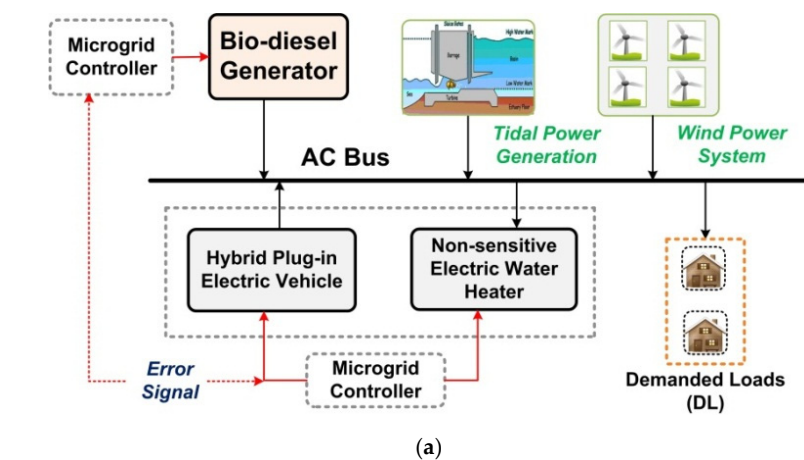


Figure 1. (a) Schematic diagram of the proposed system, (b) Block diagram depiction of proposed microgrid simulink model.

2.1. Mathematical Modeling of Generating Units

2.1.1. Wind Power System (WPS)

Power generation from wind farms has been rapidly growing in the past few decades. The kinetic energy present in the wind is being converted into clean electrical energy by the wind turbines. Meanwhile, as the wind rotates the blades of the turbine, a rotor then

grabs the kinetic energy positively existing in the wind. Mechanical output power trapped from the wind power system can be depicted as [30]:

$$P_{WPS}^{Mech} = 0.5\rho \cdot V_{WPS}^3 \cdot S_b \cdot C_P(\lambda, \beta) \quad (1)$$

Taking into account that ρ , V_{WPS} , S_b and C_P signify the air density, intermittent wind velocity, turbine's blade swept area and the power conversion coefficient respectively. The expression of wind turbine power coefficient which is defined in dimensionless form is as follows [30]:

$$10C_P = 5.17 \left(\frac{1160}{\lambda + 0.08\beta} - \frac{40.6}{1 + \beta} - 0.8\beta - 50 \right) e^{\left(-\frac{21}{\lambda} \right)} + 0.068\lambda \quad (2)$$

$$\lambda = \frac{\omega_B \cdot R_B}{V_{WPS}} \quad (3)$$

The internal function λ and β are the tip-speed ratio and blade pitch angle, respectively. R_B and ω_B are the blade radius and angular speed. A real-time recorded datasheet (provided by National Institute of Wind Energy, India) of Akkanayakanpatti [31] wind power station is considered in this work as shown in Appendix A. Based on the wind power system's cut-in and cut-out speed variables the power generation from WPS with its complete transfer function model could be represented as below [32]:

$$P_{WPS} = \begin{cases} 0, & V_{WPS} < V_{cut-in} \mid V_{WPS} > V_{cut-out} \\ P_{rated}, & V_{rated} \leq V_{WPS} \leq V_{cut-out} \\ (0.001312 V_{WPS}^6 - 0.04603 V_{WPS}^5 + 0.3314 V_{WPS}^4 \\ + 3.687 V_{WPS}^3 - 51.1 V_{WPS}^2 + 2.33 V_{WPS} + 366), & else \end{cases} \quad (4)$$

$$\Delta P_{WPS} = \begin{cases} 0, & V_{WPS} < V_{cut-in} \mid V_{WPS} > V_{cut-out} \\ 0, & V_{rated} \leq V_{WPS} \leq V_{cut-out} \\ ([0.007872 V_{WPS}^5 - 0.23015 V_{WPS}^4 + 1.3256 V_{WPS}^3 \\ + 11.061 V_{WPS}^2 - 102.2 V_{WPS} + 2.33] \cdot \Delta V_{WPS}), & else \end{cases} \quad (5)$$

$$G_{WPSx}(s) = K_{WPSx} \cdot \left(\frac{1}{sT_{WPSx} + 1} \right)$$

where V_{cut-in} and $V_{cut-out}$ are the cut-in and cut-out wind velocities in m/s. K_{WPSx} and T_{WPSx} are the gain and constant time of wind generation system.

2.1.2. Tidal Power Generation System (TPGS)

The sea based TPGS is an evolving sustainable unit, generate electrical power from sea tides with global mounted capacity of 511 MW. In operational point of view the TPGS is same as WPS where the mechanical power trapped from the TPGS (P_{TG}) could be illustrated as [33]:

$$P_{TG}^{Mech} = \frac{1}{2} \rho_G \cdot V_{TG}^3 \cdot \pi R_b^2 \cdot C_{TG}(\mu, \beta) \quad (6)$$

Taking into account that C_{TG} signifies the power conversion coefficient as a function of tip speed ratio (μ) and controlled pitch angle (β). The parameters ρ_G , V_{TG} , R_b , are the density of water, velocity of tides and turbine blade area, respectively. The mathematical equation of C_{TG} can be modeled as follows [33]:

$$C_{TG}(\mu, \beta) = \left(K_1 \left(\frac{K_2}{\gamma + K_6\beta} - \frac{K_7}{\beta^3 + 1} - K_3\beta - K_4 \right) \right) \exp \left(-K_5 \left(\frac{1}{\gamma + K_6\beta} - \frac{K_7}{\beta^3 + 1} \right) \right) \quad (7)$$

where

$$\mu = \frac{R_b \cdot \omega_b}{V_{TG}} \quad (8)$$

The linearized transfer function of modeled TPGS could be estimated as [33]:

$$G_{TPGSx}(s) = K_{TPGSx} \cdot \left(\frac{1}{sT_{TPGS} + 1} \right) \quad (9)$$

The considered parameters of TPGS have illustrated in Table 1 where a constant time of 0.01 s is assumed to interface the power.

2.1.3. Bio-Diesel Power Generator (BDPG)

Biodiesel extracted from transesterification method favorably utilized for less carbon emitted power generation. A biodiesel plant converts crop's biowaste to biodiesel through blended form. This plant is independently proficient in delivering the deficiency of power and could minimize the power mismatch between generation and demand. The linearized transfer function formulation of the biodiesel plant comprising inlet valve control unit and biodiesel combustion engine is expressed by:

$$\Delta W_{BDPG} = W(s) - (R^{-1} \cdot \Delta F) \quad (10)$$

$$\Delta P_{GCE} = \Delta P_{IVR} \times \left\{ K_{IVR} \cdot \left(\frac{1}{T_{IVRS} + 1} \right) \right\} \quad (11)$$

$$\Delta P_{BDPG} = \Delta P_{GCE} \times \left(\frac{K_{CE}}{T_{CES} + 1} \right) \quad (12)$$

where ΔW_{BDPG} and $W(s)$ are the change in input error of BDPG and the output control signal of the controller. The droop constant is represented by R (Hz/p.u. MW). K_{GCEx} , T_{GCEx} are the gain and constant time delay of BDPG.

2.1.4. Hybrid Plug-in Electric Vehicle (HPEV)

HPEV's are a good alternative for uncontracted power demands. Figure 2 portrays HPEVs' participation in idle mode. The value of gain K_{HPEV} is a function of the State of Charge (SOC) [34]. HPEVs do not participate in frequency control when SOC is between SOC_A and SOC_B . The maximum and minimum output power reserve of HPEVs are marked by $\Delta P_{\max}^{HPEV}$, ΔP , and $\Delta P_{\min}^{HPEV}$ respectively [34].

$$\Delta P_{\max}^{HPEV} = + \left\{ \left(\frac{1}{N_{HPEV}} \right) \cdot \Delta P_{HPEV} \right\} \quad (13)$$

$$\Delta P_{\min}^{HPEV} = - \left\{ \left(\frac{1}{N_{HPEV}} \right) \cdot \Delta P_{HPEV} \right\} \quad (14)$$

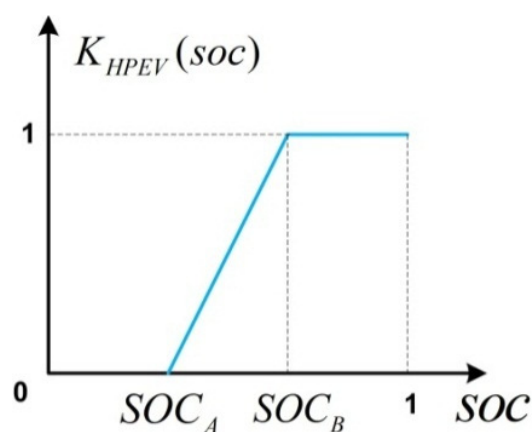


Figure 2. Characteristic of K_{HPEV} vs. SOC in idle mode case.

In Equations (13) and (14) N_{HPEV} is the number of HPEVs connected and ΔP_{HPEV} represents incremental generation change of HPEV. The charging and discharging capability of HPEV are supposed 5 KW further; it may extend to 50 KW [34]. The HPEVs will not bestow frequency control if SOC is less than the minimum required SOC_A . If SOC is in the range of 50% to 70%, K_{HPEV} value equals to 1 [34]. HPEV power output according to microgrid control error signal (ES) is provided as [35]:

$$\Delta P_{HPEV} = \begin{cases} K_{HPEV} \cdot ES, & |K_{HPEV} \cdot ES| \leq \Delta P^{\max} \\ \Delta P^{\max}, & |K_{HPEV} \cdot ES| > \Delta P^{\max} \\ \Delta P^{\min}, & |K_{HPEV} \cdot ES| < \Delta P^{\min} \end{cases} \quad (15)$$

where the constant time values are depicted in Table 1.

2.2. Controllable Electric Water Heater (EWH) Modeling

Besides the different generation units to take care of load demands for optimal frequency stabilization, a controllable plug-in electric water heater (EWH) is considered in the proposed model. The first order EWH model is adopted here as follows:

$$G_{EWHx}(s) = K_{EWHx} \cdot \left(\frac{1}{T_{EWHx}s + 1} \right) \quad (16)$$

where the gain and constant time values of EWH is represented by K_{EWHx} and T_{EWHx} .

2.3. Dynamic Modeling of Power System and Load

By addressing all the system components, the effective load-generator dynamics ($G_{lgx}(s)$) for sustainable microgrid power systems could be estimated as (17):

$$G_{lgx}(s) = \frac{K_{lgx}}{sM_{lgx} + D_{lgx}} \quad (17)$$

K_{lgx} , M_{lgx} and D_{lgx} are the gain, inertia value (s) and damping cofactor (p.u./Hz) of hybrid microgrid system.

Considering single load-generator model [36] for low-inertia ($H = 0.1s$), the assigned ΔF can be expressed as [36]:

$$\Delta F = \left(\frac{K_{lgx}}{sM_{lgx} + D_{lgx}} \right) \cdot \Delta P_G \quad (18)$$

$$\begin{aligned} \Delta P_G &= \Delta P_{RGs} + \Delta P_{BDPG} \pm \Delta P_{HPEV} - \Delta P_{EWH} = \Delta P_{DL} \rightarrow 0 \\ \text{where; } \Delta P_{RGs} &= \sum_{i=1}^n \text{Renewable generation's power} \\ &= (\Delta P_{WPS} + \Delta P_{TPGS}) \end{aligned} \quad (19)$$

$$\Delta P_D = \Delta P_G - \Delta P_{DL} \quad (20)$$

The detailed values of the considered system parameters are presented in Table 1.

3. Proposed Dual-Level PI – (1 + DD) Controller Design

In this work, a novel proportional-integral with one plus double derivative PI – (1 + DD) controller is proposed and implemented to control and maintain the frequency of generated power supply at the time of unexpected load-generation changing condition. Utilization of only droop method is insufficient for advanced control purpose [37]. Thus, the secondary control loop is needed for better control of frequency fluctuation of the distributed power network. The architecture of the proposed PI – (1 + DD) utilized in this research work encloses two levels. The first level leverages proportional integral (PI) while the second level is constructed by double derivative controller as displayed in Figure 3. The controller

is performed using the input error signal (ΔF). The formulation of PI – (1 + DD) controller with its transfer function modeling can be written as:

$$U_c(s) = \Delta F \times \{PI - (1 + DD)\} \quad (21)$$

$$G_{\{PI-(1+DD)\}}s = \left(K_P + \frac{K_I}{s}\right) \cdot (1 + K_{Di}s + K_{Di}s); \text{ i.e.; } i = (1, 2 \dots) \quad (22)$$

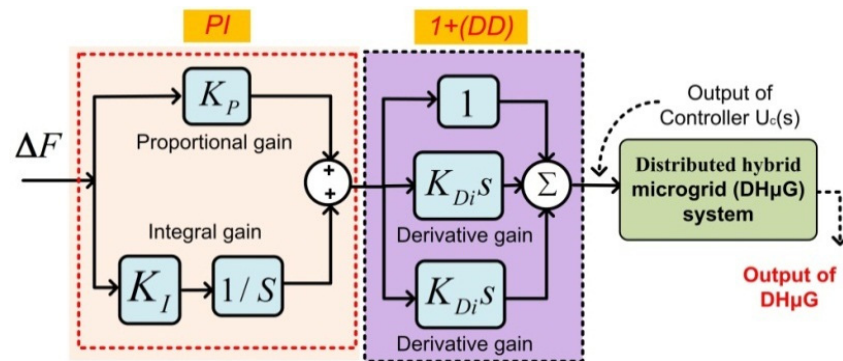


Figure 3. Control structure of the proposed dual level PI – (1 + DD) controller.

From the arrangement shown in Figure 3, PI – (1 + DD) controller structure has five independent tuning parameters: four tunable controller gains and one constant gain of 1. These gain parameters provide better flexibility in controller design. The advantages of the proposed PI – (1 + DD) controller are the enhancement of system stability by reducing the peak deviation and improvement of transient response where PID controller is not so effective under transient operation.

4. Mine Blast Algorithmic Technique (MBA)

The MBA is a population-based optimization method based on the landmine explosion concept [28]. At the time of mine bomb explosion, a large number of shrapnel pieces spread at random distances. The casualties are calculated. The mine bomb explosion based casualties are treated as the fitness of the objective function at the mine bomb location. The flowchart of MBA is displayed in Figure 4. The variable upper and lower bound parameters (U_B and L_B) are selected. Initially, different considered parameters such as: designed variables (N_V), no of counts (N_C), iteration number (I_M) and reduction factor (R_d) are taken. Hence the first targeted point Q_0 is given by [28]:

$$Q_0 = L_B + \{rand \cdot (U_B - L_B)\} \quad (23)$$

where $rand$ is the randomly distributed number between 0 and 1. The present position of landmine for g th iteration expressed as (24) [28]:

$$Q_g = [Q_m] \quad (24)$$

where $m = 1, 2, 3 \dots N_V$.

In every iteration, the mine bomb explosion at location Q_r causes consequent explosion at position Q_{r+1} .

$$Q_{r+1} = Q_{er(r+1)} + Q_r \left(e^{-\sqrt{\frac{M_{r+1}}{D_{r+1}}}} \right) \quad (25)$$

The r value will be in between (0-infinite).

$$Q_{er(r+1)} = D_r + \{rand \cdot \cos(\theta)\} \quad (26)$$

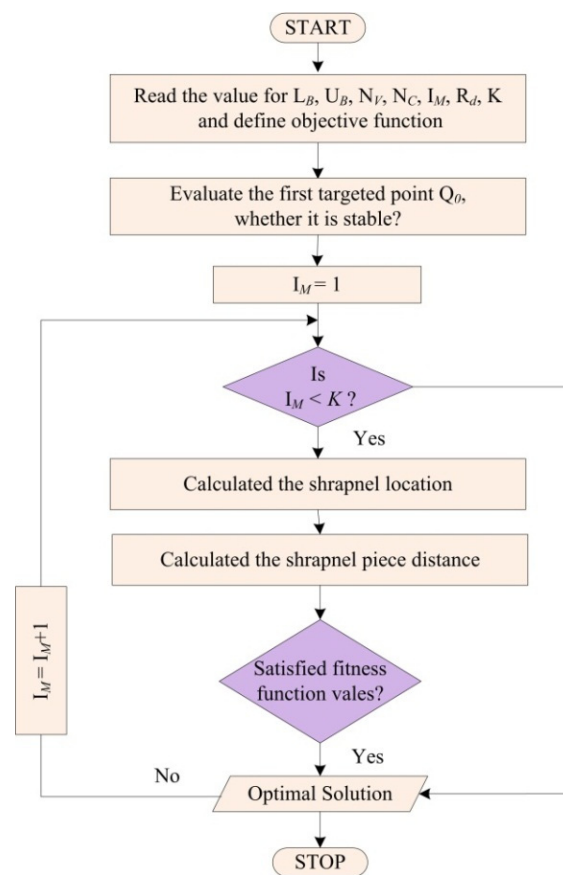


Figure 4. Flow diagram of MBA.

The covered distance (D_{r+1}) could be expressed as [28]:

$$D_{r+1} = \left[(Q_{r+1} - Q_r)^2 + (f_{r+1} - f_r)^2 \right]^{0.5} \quad (27)$$

where f is the function.

The direction of shrapnel pieces is expressed as (28) [28];

$$M_{r+1} = \left(\frac{f_{r+1} - f_r}{Q_{r+1} - Q_r} \right) \quad (28)$$

The initial distance (D_0) after explosion could be formulated as:

$$D_0 = (U_B - L_B) \quad (29)$$

The distance in search space could be calculated using (30).

$$D_{r+1} = D_r \cdot (|rand|)^2 \quad (30)$$

where Equation (31) depicted the mine bomb blasting can be formulated as:

$$Q_{er(r+1)} = D_{r+1} \cdot \cos(\theta) \quad (31)$$

To find global minima location, the initial distance travel by shrapnel pieces should reduce slowly. Hence the distance (D_r) is calculated as [28]:

$$D_r = \frac{D_r - 1}{e^{\frac{I_M}{K_d}}} \quad (32)$$

In this study, MBA was used to optimize gains of the proposed dual level {PI-(1+DD)} controller and other conventional controllers. The considered parameters of MBA techniques are depicted in Appendix A. On the other hand, the main aim of these above-mentioned algorithms is to minimize the objective function, i.e., integral square error (ISE) as denoted as J , presented in (33), which has been optimized by considering three different algorithms.

$$J = \int_0^{t_{sim}} \{(\Delta F)^2 \cdot dt\} \quad (33)$$

where ΔF is the frequency change for the simulated response time (t_{sim}).

5. Simulation Studies

A systematic investigation under various scenarios is essential to evaluate the performance of the proposed control strategy to reduce the problems related to frequency through other subsystem power contributions in a distributed hybrid microgrid (DHμG) system. In this paper, two different scenarios are considered. Where Scenario 1 deals with comparison of system frequency deviation with constant load demand where renewable power generation is zero. This renewable power zero may happen due to climatic condition or due to maintenance issues. Whereas in Scenario 2, a concurrent random real-time wind data based renewable power generation and load demand is considered. To validate the proposed work in real-time scenario this Scenario 2 is considered. MATLAB® Simulink® R2015a (Natick, MA, USA) software has been used to simulate DHμG incorporating renewable based generations to observe the effect of proposed two level PI – (1 + DD) controller-based MBA technique. The following subsections present the result analysis by taking the different scenarios. Finally, the real-time validation is done by considering real-recorded natural wind velocity data where the dynamic responses have also been analyzed.

5.1. Scenario 1: Nonavailability of All Renewable Power Generations

In this scenario, the hybrid microgrid system is verified by considering disturbance as 40% constant load change while all the renewable resources are off due to maintenance purpose. The corresponding system frequency deviation and other subsystem's power sharing simulated comparison graphs are displayed in Figure 5a–c. Three controllers named PI, CPID and {PI – (1 + DD)} are taken one at a time as a secondary controller of the unified frequency control loop to find the best one. These controllers have been performed individually and optimized the controller gains parameters using MBA. The tuned values of associated controller's parameters are represented in Table 2. The responses are presented in Figure 5 and Table 2, which clearly illustrate that the maximum frequency overshoot (+ MFO), undershoot (– MFU) and stabilization time (ST) of frequency decisively gets reduced with the MBA optimized proposed PI – (1 + DD) based control technique. Table 2 shows that + MFO, –MFU and T_{ST} considering proposed {PI – (1 + DD)} controller are reduced by 94.46%, 85.37% and 27.37% and are reduced by 71.42%, 56.69% and 19.39% compared to PI and CPID controllers. The observations validate the supremacy of the proposed {PI – (1 + DD)} controller over other employed controllers. By observing the comparisons of three different controllers' objective function, (J) are plotted in Figure 5d and corresponding performance figure of demerits (J_{FOD}) values are also evident in that {PI – (1 + DD)} controller gives better result. As a result, the PI – (1 + DD) controller is carried out in further studies.

$$J_{FOD} = \{(+MFO)^2 + (-MFU)^2 + (T_{ST})^2\} \quad (34)$$

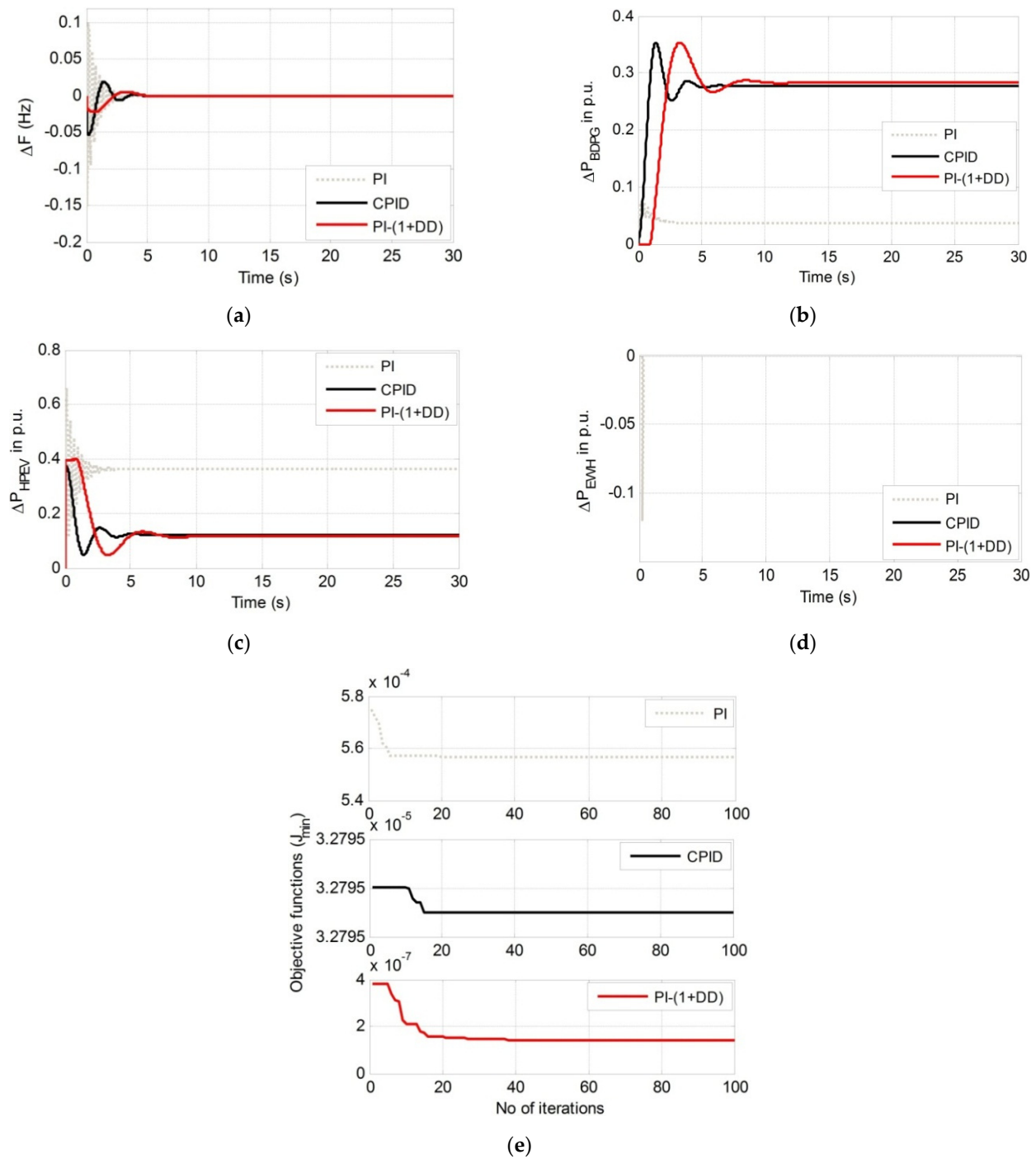


Figure 5. Comparison of the dynamic response of PI, CPID with the proposed (a) frequency deviation (ΔF), (b) power sharing of BDPG, (c) power sharing of HPEV, (d) power sharing of EWH and (e) objective functions (J).

Table 2. Controllers' gains with comparative performance parameters under 100 iterations.

Controllers		PI	CPID	PI – (1 + DD)
Maximum Frequency Overshoot (+MFO)				
ΔF (in Hz)		0.0975	0.0189	0.0054
Maximum Frequency Undershoot (-MFU)				
ΔF (in Hz)		0.1525	0.0515	0.0223
Stabilization time (T_{ST})				
ΔF (in s)		6.019	5.423	4.371
Minimum value of J (J_{min})				
		5.56×10^{-4}	3.28×10^{-5}	1.40×10^{-7}
Figure of demerits (J_{FOD})				
		36.261	29.411	19.106
Optimized controllers' values				
Controller-1	K_{P1}	3.012	0.512	0.306
	K_{I1}	2.008	12.53	10.04
	K_{D11}	-	0.107	0.509
	K_{D12}	-	-	0.107
Controller-2	K_{P2}	11.11	5.061	1.517
	K_{I2}	20.01	5.005	4.115
	K_{D21}	-	1.627	1.113
	K_{D22}	-	-	2.229

Bold indicate superior output.

5.2. Scenario 2: Availability of Concurrent Random Renewable Generations with Load Perturbation

The comparative performance evaluation of the suggested algorithmic techniques is analysed in terms of frequency deviation and other subsystem output power in Figure 6b–e under real-time wind data and other collective random disturbances as depicted in Figure 6a. The real-time wind data and its corresponding change in wind power are plotted in Figure 6a. Three tools named PSO, FF and MBA are taken as an optimization technique of the unified frequency control model to find the best one. These optimization techniques have been performed individually and optimized the proposed best PI – (1 + DD) controller gains parameters. Table 3 lists the controller parameter values for different optimization techniques for Scenario 2. The system dynamic responses clearly demonstrated that MBA:{PI – (1 + DD)} technique is much better than PSO:{PI – (1 + DD)} and FF:{PI – (1 + DD)} techniques. It can be ascertained from Figure 6b that change in frequency subsides prolifically under MBA technique, ensuring the better stable response. Further, exploration under real-recorded weather data illustrates the competency of the suggested technique.

Table 3. PI – (1 + DD) controller's parameters for the selected scenario (Scenario 2).

Techniques		PSO	FF	MBA
Optimized Controllers' Values				
Controller-1	K_{P1}	5.031	10.01	0.308
	K_{I1}	30.42	25.18	2.072
	K_{D11}	0.501	0.497	0.505
	K_{D12}	0.108	0.117	0.104

Table 3. Cont.

Techniques		PSO	FF	MBA
Optimized Controllers' Values				
Controller-2	K_{P2}	4.518	4.621	4.502
	K_{I2}	4.119	4.115	4.124
	K_{D21}	1.114	1.108	1.163
	K_{D22}	2.217	2.229	2.231

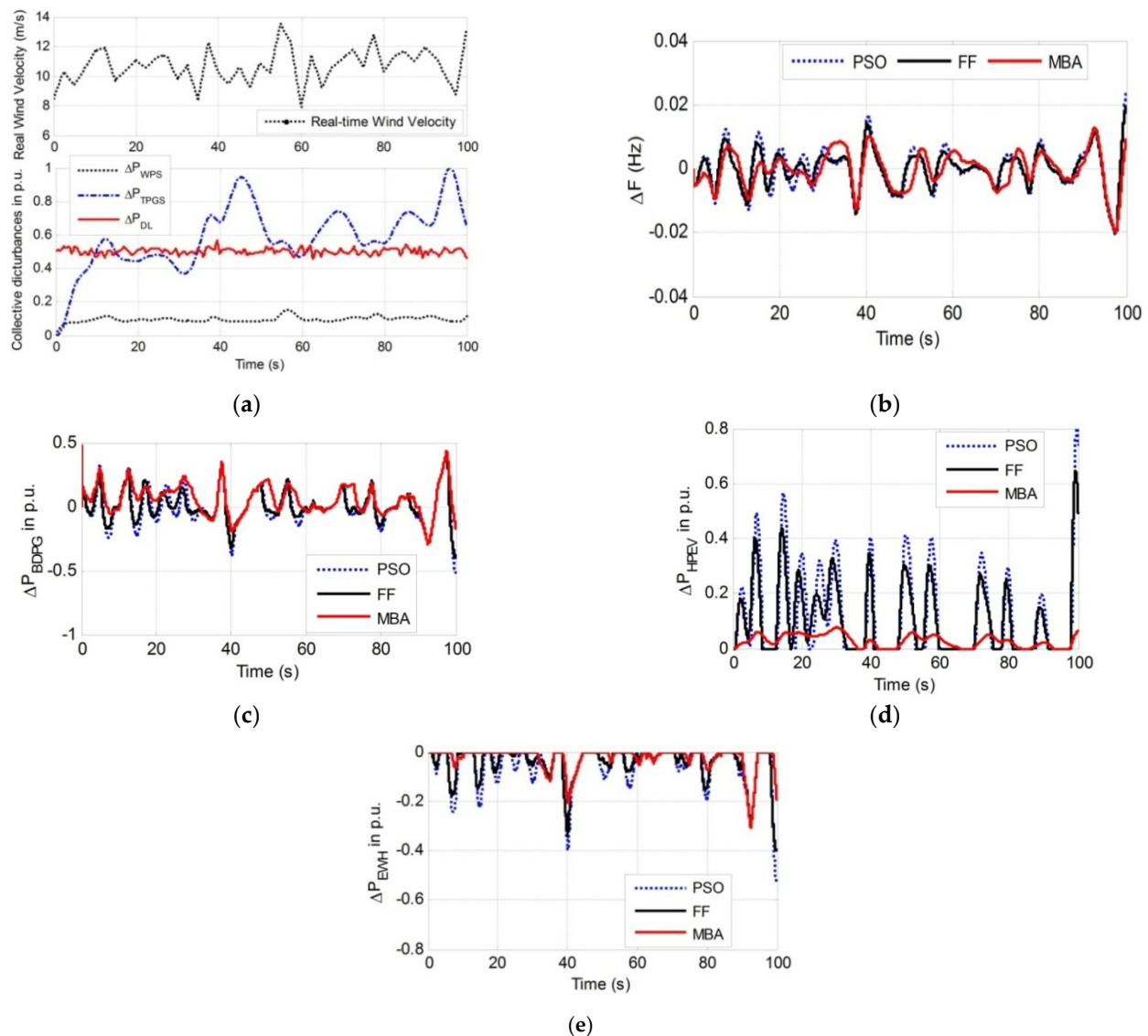


Figure 6. Comparison of the dynamic response when PI – (1 + DD) controller is optimized with PSO, FF with MBA (a) Real-time data based multiple random disturbances (b) frequency deviation, (c) power contribution of BDPG, (d) power contribution of HPEV, and (e) power output of EWH.

6. Conclusions

In this paper, a novel two level PI – (1 + DD) controller was proposed for ameliorating the microgrid dynamic oscillations consisting of different new renewable energy resources. The combination of renewable power generating units such as wind, tidal and biodiesel units in addition to hybrid plug-in electric vehicle and nonsensitive electric water heater is studied. As a novelty, first time two level PI – (1 + DD) controller concept has

been proposed to incorporated in renewables based distributed microgrid power system at different scenarios. To improve the system dynamics, a system is designed to regulate power contributions of different subsystems and nonsensitive load by incorporating PI – (1 + DD) controller under different scenarios. The outcome of the simulation reveals that MBA:PI – (1 + DD) control strategy is much more effective to bring reduction in magnitude of maximum frequency overshoot (+ MFO), undershoot (– MFU), stabilization time (T_{ST}) and estimated figure of demerits (J_{FOD}) index values. The analysis of the comparative J_{FOD} values shows the percentage improvement of J_{FOD} with proposed PI – (1 + DD) controller compared to traditional PI and CPID are 47.31% and 35.03% respectively. As an after stage, MBA technique has applied and compared with other technique such as PSO and FF. Further, a real-recorded wind data has been considered for real-time validation of the proposed control strategy. It is inferred that this proposed controller with MBA optimization technique is capable to improve the dynamic performance of the studied DH μ G system. Simulation results recognized that the proposed novel two level frequency controller can be utilized in microgrids with high renewable energy penetration to keep frequency within acceptable limits and drastically improve the frequency control. The proposed control strategy performs better than other controller designs and optimization techniques.

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Appendix A

WPS: Recorded date: 1 July 2016, Min^m flow of wind: 7.4804 (meter/s); Max^m flow of wind: 14.08 m/s; Average flow of wind: 10.922 m/s; SD: 1.1895.

MBA: No search shrapnel pieces = 20, $I_M = 100$, $R_4 = 297.17$, design variable (N_V) = 4.

References

- Chen, Q.; Gu, Y.; Tang, Z.; Wei, W.; Sun, Y. Assessment of low-carbon iron and steel production with CO₂ recycling and utilization technologies: A case study in China. *Appl. Energy* **2018**, *220*, 192–207. [\[CrossRef\]](#)
- Foumani, K.M. Smith-Miles The impact of various carbon reduction policies on green flowshop scheduling. *Appl. Energy* **2019**, *249*, 300–315. [\[CrossRef\]](#)
- Bevrani, H.; Hiyama, T. *Intelligent Automatic Generation Control*; CRC Press: Boca Raton, FL, USA, 2017.
- Aftab, M.A.; Hussain, S.S.; Latif, A.; Das, D.C.; Ustun, T.S. IEC 61850 communication based dual stage load frequency controller for isolated hybrid microgrid. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106909. [\[CrossRef\]](#)
- Rahmani, M.; Sadati, N. Hierarchical optimal robust load-frequency control for power systems. *IET Gener. Transm. Distrib.* **2012**, *6*, 303–312. [\[CrossRef\]](#)
- Yazdizadeh, A.; Ramezani, M.H.; Hamedrahmat, E. Decentralized load frequency control using a new robust optimal MISO PID controller. *Int. J. Electr. Power Energy Syst.* **2012**, *35*, 57–65. [\[CrossRef\]](#)
- Liao, K.; Xu, Y. A robust load frequency control scheme for power systems based on second-order sliding mode and extended disturbance observer. *IEEE Trans. Ind. Inform.* **2017**, *14*, 3076–3086. [\[CrossRef\]](#)
- Ojaghi, P.; Rahmani, M. LMI-based robust predictive load frequency control for power systems with communication delays. *IEEE Trans. Power Syst.* **2017**, *32*, 4091–4100. [\[CrossRef\]](#)
- Latif, A.; Hussain, S.M.S.; Das, D.C.; Ustun, T.S. State-of-the-art of controllers and soft computing techniques for regulated load frequency management of single/multiarea traditional and renewable energy based power systems. *Appl. Energy* **2020**, *266*, 114858. [\[CrossRef\]](#)

10. Das, D.C.; Roy, A.K.; Sinha, N. GA based frequency controller for solar thermal–diesel–wind hybrid energy generation/energy storage system. *Int. J. Electr. Power Energy Syst.* **2012**, *43*, 262–279. [\[CrossRef\]](#)
11. Das, D.C.; Sinha, N.; Roy, A.K. Automatic generation control of an organic rankine cycle solar-thermal/wind-diesel hybrid energy system. *Energy Technol.* **2014**, *2*, 721–731. [\[CrossRef\]](#)
12. Rout, U.K.; Sahu, R.K.; Panda, S. Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system. *Ain Shams Eng. J.* **2013**, *4*, 409–421. [\[CrossRef\]](#)
13. Hussain, I.; Ranjan, S.; Das, D.C.; Sinha, N. Performance analysis of flower pollination algorithm optimized PID controller for wind-PV-SMES-BESS-diesel autonomous hybrid power system. *Int. J. Renew. Energy Res.* **2017**, *7*, 643–651.
14. Hussain, I.; Das, D.C.; Sinha, N.; Latif, A.; Hussain, S.M.S.; Ustun, T.S. Performance Assessment of an Islanded Hybrid Power System with Different Storage Combinations Using an FPA-Tuned Two-Degree-of-Freedom (2DOF) Controller. *Energies* **2020**, *13*, 5610. [\[CrossRef\]](#)
15. Dash, P.; Saikia, L.C.; Sinha, N. Flower Pollination Algorithm Optimized PI-PD Cascade Controller in Automatic Generation Control of a Multi-area Power System. *Int. J. Electr. Power Energy Syst.* **2016**, *82*, 19–28. [\[CrossRef\]](#)
16. Latif, A.; Das, D.C.; Ranjan, S.; Hussain, I. Integrated demand side management and generation control for frequency control of a microgrid using PSO and FA based controller. *Int. J. Renew. Energy Res.* **2018**, *8*, 188–199.
17. Latif, A.; Pramanik, A.; Das, D.C.; Hussain, I.; Ranjan, S. Plug in hybrid vehicle-wind-diesel autonomous hybrid power system: Frequency control using FA and CSA optimized controller. *Int. J. Syst. Assur. Eng. Manag.* **2018**, *9*, 1147–1158. [\[CrossRef\]](#)
18. Gorripotu, T.S.; Ramana, P.; Sahu, R.K.; Panda, S. Sine Cosine Optimization Based Proportional Derivative-Proportional Integral Derivative Controller for Frequency Control of Hybrid Power System. In *Computational Intelligence in Data Mining*; Springer: Singapore, 2020; pp. 789–797.
19. Alattar, A.H.; Selem, S.I.; Metwally, H.; Ibrahim, A.; Aboelsaud, R.; Tolba, M.A.; El-Rifaie, A.M. Performance enhancement of micro grid system with SMES storage system based on mine blast optimization algorithm. *Energies* **2019**, *12*, 3110. [\[CrossRef\]](#)
20. Wang, H.; Zeng, G.; Dai, Y.; Bi, D.; Sun, J.; Xie, X. Design of a fractional order frequency PID controller for an islanded microgrid: A multi-objective extremal optimization method. *Energies* **2017**, *10*, 1052. [\[CrossRef\]](#)
21. Pan, I.; Das, S. Kriging based surrogate modeling for fractional order control of microgrids. *IEEE Trans. Smart Grid* **2015**, *6*, 36–44. [\[CrossRef\]](#)
22. Guha, D.; Roy, P.K.; Banerjee, S. Equilibrium optimizer-tuned cascade fractional-order 3DOF-PID controller in load frequency control of power system having renewable energy resource integrated. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12702. [\[CrossRef\]](#)
23. Lal, D.K.; Barisal, A.K.; Tripathy, M. Load frequency control of multi area interconnected microgrid power system using grasshopper optimization algorithm optimized fuzzy PID controller. In Proceedings of the 2018 Recent Advances on Engineering, Technology and Computational Sciences (RAETCS), Allahabad, India, 6–8 February 2018; pp. 1–6.
24. Rajesh, K.S.; Dash, S.S. Load frequency control of autonomous power system using adaptive fuzzy based PID controller optimized on improved sine cosine algorithm. *J. Ambient Intell. Humaniz Comput.* **2019**, *10*, 2361–2373. [\[CrossRef\]](#)
25. Gheisarnejad, M.; Mohammadi-Moghadam, H.; Boudjadar, J.; Khooban, M.H. Active power sharing and frequency recovery control in an islanded microgrid with nonlinear load and non dispatchable DG. *IEEE Syst. J.* **2019**, *14*, 1058–1068. [\[CrossRef\]](#)
26. Nithilasaravanan, K.; Thakwani, N.; Mishra, P.; Kumar, V.; Rana, K.P.S. Efficient control of integrated power system using self-tuned fractional-order fuzzy PID controller. *Neural Comput. Appl.* **2019**, *31*, 4137–4155. [\[CrossRef\]](#)
27. Karimipouya, A.; Abdi, H. Microgrid frequency control using the virtual inertia and ANFIS-based Controller. *Int. J. Ind. Electron. Control Optim.* **2019**, *2*, 145–154.
28. Sadollah, A.; Bahreininejad, A.; Eskandar, H.; Hamdi, M. Mine blast algorithm-a new population based algorithm for solving constrained engineering optimization problems. *Appl. Soft Comput.* **2013**, *13*, 2592–2612. [\[CrossRef\]](#)
29. Sadollah, A.; Bahreininejad, A.; Eskandar, H.; Hamdi, M. Mine blast algorithm for optimization of truss structures with discrete variables. *Comput. Struct.* **2012**, *102*, 49–63. [\[CrossRef\]](#)
30. Shang-Guan, X.; He, Y.; Zhang, C.; Jiang, L.; Spencer, J.W.; Wu, M. Sampled-data based discrete and fast load frequency control for power systems with wind power. *Appl. Energy* **2020**, *259*, 114202. [\[CrossRef\]](#)
31. Wind Speed Data. Available online: http://niwe.res.in:8080/NIWE_WRA_DATA/DataTable_D4.jsf (accessed on 21 April 2021).
32. Khooban, M.H.; Dragicevic, T.; Blaabjerg, F.; Delimar, M. Shipboard microgrids: A novel approach to load frequency control. *IEEE Trans. Sustain. Energy* **2018**, *9*, 843–852. [\[CrossRef\]](#)
33. Kumar, A.; Sankar, G. Quasi-oppositional harmony search algorithm based optimal dynamic load frequency control of a hybrid tidal-diesel power generation system. *IET Gener. Transm. Distrib.* **2018**, *12*, 1099–1108. [\[CrossRef\]](#)
34. Debbarma, S.; Dutta, A. Utilizing electric vehicles for LFC in restructured power systems using fractional order controller. *IEEE Trans. Smart Grid* **2017**, *8*, 2554–2564. [\[CrossRef\]](#)
35. Arya, Y. Effect of electric vehicles on load frequency control in interconnected thermal and hydrothermal power systems utilising cf-foidf controller. *IET Gener. Transm. Distrib.* **2020**, *14*, 2666–2675. [\[CrossRef\]](#)
36. Kundur, P. *Power System Stability and Control*; Reprint; Balu, N., Lauby, M.G., Eds.; McGraw-Hill: New York, NY, USA, 2009; pp. 309–366.
37. Ustun, T.S.; Aoto, Y. Analysis of Smart Inverter’s Impact on the Distribution Network Operation. *IEEE Access* **2019**, *7*, 9790–9804. [\[CrossRef\]](#)