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Optimization of Control Parameters for Battery Energy Storage Systems (BESS) for Contribution to Power System Frequency Regulation

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Abstract :

The increasing penetration of non-synchronous renewable energy sources has significantly reduced system inertia, posing serious challenges to power system frequency stability. Battery Energy Storage Systems (BESS) have emerged as an effective solution for providing fast frequency support through virtual inertia and primary frequency control. This paper proposes a hybrid frequency control strategy for BESS that integrates virtual inertia control and virtual droop control to enhance both transient and steady-state frequency response. In addition, a novel Repeatable Optimization Algorithm (ROA) is developed to optimally tune the control parameters of the proposed BESS model and the associated PID controller. The effectiveness of the proposed approach is validated through detailed MATLAB/Simulink simulations on both single-area and four-area interconnected power systems under severe load disturbances. Comparative studies with several well-known optimization algorithms demonstrate that the proposed ROA achieves faster convergence, reduced frequency deviation, improved RoCoF, and shorter settling time. The results confirm that the proposed control and optimization framework provides a robust and efficient solution for frequency regulation in low-inertia power systems.

Keywords: Frequency Control, Battery Energy Storage Systems (BESS), Inertial Response, Rate of Change of Frequency (RoCoF).

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1. Introduction

In recent years, power systems worldwide have experienced considerable growth. Due to the intermittent nature and uncertain output of renewable energy sources, their widespread integration into the grid places much higher demands on frequency regulation [1]. Additionally, the gradual decommissioning of large fossil-fuel power plants impacts frequency control performance, which depends on the balance between instantaneous load, generation, and system inertia. A key challenge associated with reduced inertia is maintaining frequency stability, defined as the power system's ability to preserve frequency following a severe disturbance that creates a substantial mismatch between generation and demand.

the rotating masses of synchronous generators and loads. During any contingency in the power system, this kinetic energy is released to counteract frequency drops and prevent the system from falling below safe limits [6]. Consequently, IR represents a fast-acting frequency response and is critical for maintaining system stability, particularly in the initial moments following a disturbance. In large power systems, significant amounts of renewable energy are often integrated from different regions, and the increasing share of non-synchronous generation introduces a system-level inertia deficit. This can lead to extreme events such as blackouts, exemplified by the 2016 South Australia outage [7]. Non-synchronous generation connected via inverters does not inherently contribute to grid inertia; however, with suitable

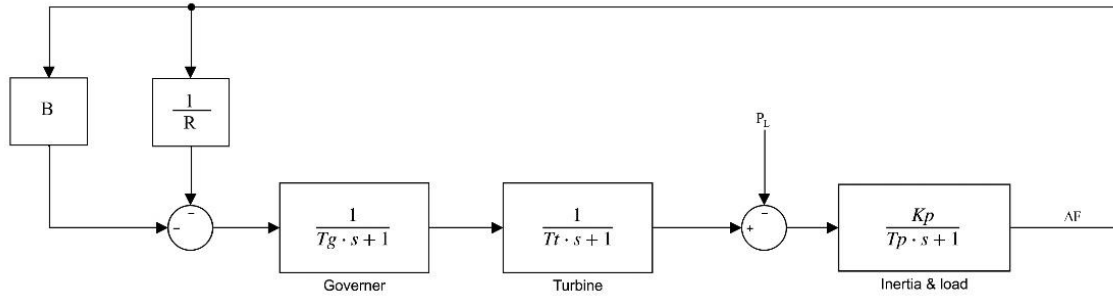


Fig. 1. Main Components of the Overall Model

Fluctuations in load demand led to variations in system frequency and power flows across transmission lines relative to their nominal levels [2]. As a result, frequency stability has become a critical issue for power system operators. Load Frequency Control (LFC) refers to the process of keeping the system frequency within its designated range despite changing load conditions. The stability of the power system depends significantly on LFC to maintain power balance among interconnected regions under varying demand [3].

As reported in [4], frequency response is typically categorized into Inertial Response (IR), Primary Frequency Control (PFC), Secondary Frequency Control (SFC), and Tertiary Frequency Control (TFC). The three key metrics used to evaluate power system frequency response are the Nadir Frequency, Steady-State Frequency, and Rate of Change of Frequency (RoCoF) [5]. Primary and Secondary Frequency Control are provided by the turbine governor and Automatic Generation Control (AGC), respectively. Primary Frequency Control itself consists of two rapid responses: Inertial Response and Governor Control. Inertial Response arises from the kinetic energy stored in

control strategies, it can provide synthetic or emulated inertia, thereby enhancing the frequency response dynamics.

A promising solution to compensate for reduced system inertia is Battery Energy Storage Systems (BESS), which assist in power system frequency regulation by providing virtual (or synthetic) inertia. Battery Energy Storage Systems are rapidly being developed for power system applications. The primary advantage of using energy storage systems is their short-term power supply, which typically delivers power within a few seconds and sustains it for several minutes to several hours [8]. BESS are well-suited to provide power in the timeframe between the inertial response of synchronous generators and the frequency-dependent response of synchronous generators, HVDC, and peak-time reserve power plants. The power provided in this timeframe is valuable as it reduces the risk of cascading failures and damage to the power system due to low frequency or a high RoCoF [9]. When battery energy storage systems are employed for grid frequency regulation, they greatly enhance the grid's frequency response and lessen the reliance on conventional units held in

reserve for frequency control. Within this framework, an appropriate control method can further boost the frequency-regulating capability of BESS and substantially decrease the required storage capacity configuration [10]. In recent years, the significant deployment of Battery Energy Storage Systems (BESS) has played a crucial role in power system operation. For example, the world's largest BESS, with a capacity of 100 MW/129 MWh, was built by Tesla in South Australia in November 2017 to support the power grid. It is expected that the total installed BESS capacity globally will reach 100 to 167 GWh by 2030 [11]. Paper [12] proposes a Virtual Inertia Control (VIC) strategy based on a fractional-order derivative and a controller parameter tuning method. The proposed control and tuning method are applied to a Battery Energy Storage System (BESS) in a low-inertia power system with renewable energy integration. Paper [13] investigates the use of a Battery Energy Storage System (BESS) to improve the frequency response characteristics of a low-inertia power system following a disturbance or active power mismatch. A simple control strategy for BESS is proposed to improve the system's inertial and primary frequency response. In paper [14], for frequency control in a power distribution system with a high resistance/inductance ratio, the mechanism between the rate of change of frequency and the Required Reactive Power (RRP) of the networks is analyzed, showing that RoCoF is proportional to RRP. In [15], frequency dynamics under time-varying inertia are modeled as a nonlinear switching system, where the frequency dynamics under each state are described by nonlinear oscillation equations, and the different states represent different inertia levels. In [16], a Fast Frequency Response (FFR) controller is proposed to maintain the frequency within predefined thresholds while reducing the operational costs associated with Battery Energy Storage Systems (BESSs).

Recent studies have investigated various aspects of BESS control and frequency regulation in low-inertia systems. Adaptive parameter optimization under high renewable penetration has been shown to improve frequency stability using improved metaheuristic methods [17]. Hybrid energy storage sizing considering dynamic

frequency constraints offers a systematic approach to grid support [18]. Integrated strategies for hybrid ESS combining virtual inertia and droop-like control have demonstrated significant enhancements in frequency regulation performance [19-20]. Additionally, the impact of BESS on frequency stability in weak grids with high converter share has been analyzed, confirming the capability of controlled storage to improve frequency response [21].

The main advantages of using BESS for frequency control stem from three key points. First, it replaces gas turbine reserves that are maintained for fast startups in case of any disturbance. Second, its fast response replaces online reserve generators and acts as a complementary PFC. Third, it supports the system's inertial response and serves as a substitute for reduced inertia. To facilitate frequency support, the battery storage system must meet the following conditions: 1) Rapid energy delivery/absorption in response to observed frequency deviations; 2) Consideration of specific constraints, including power output limits and State of Charge (SoC) limits; and 3) Having a designed response that considers operational costs (internal energy level and degradation cost). Therefore, an optimization problem needs to be formulated to consider all the above requirements.

Motivated by the increasing frequency stability challenges in low-inertia power systems, this paper makes the following key contributions:

(i) A hybrid BESS-based primary frequency control strategy is proposed by combining virtual inertia control and virtual droop control, enabling simultaneous improvement of RoCoF, frequency nadir, and steady-state frequency deviation.

(ii) A novel heuristic optimization technique, referred to as the Repeatable Optimization Algorithm (ROA), is developed to optimally tune the parameters of the proposed BESS model and the PID controller under practical operational constraints.

(iii) The effectiveness and robustness of the proposed approach are demonstrated through extensive simulation studies on both single-area and multi-area interconnected power systems, and its superiority is verified via comparative analysis with several widely used optimization algorithms reported in recent literature.

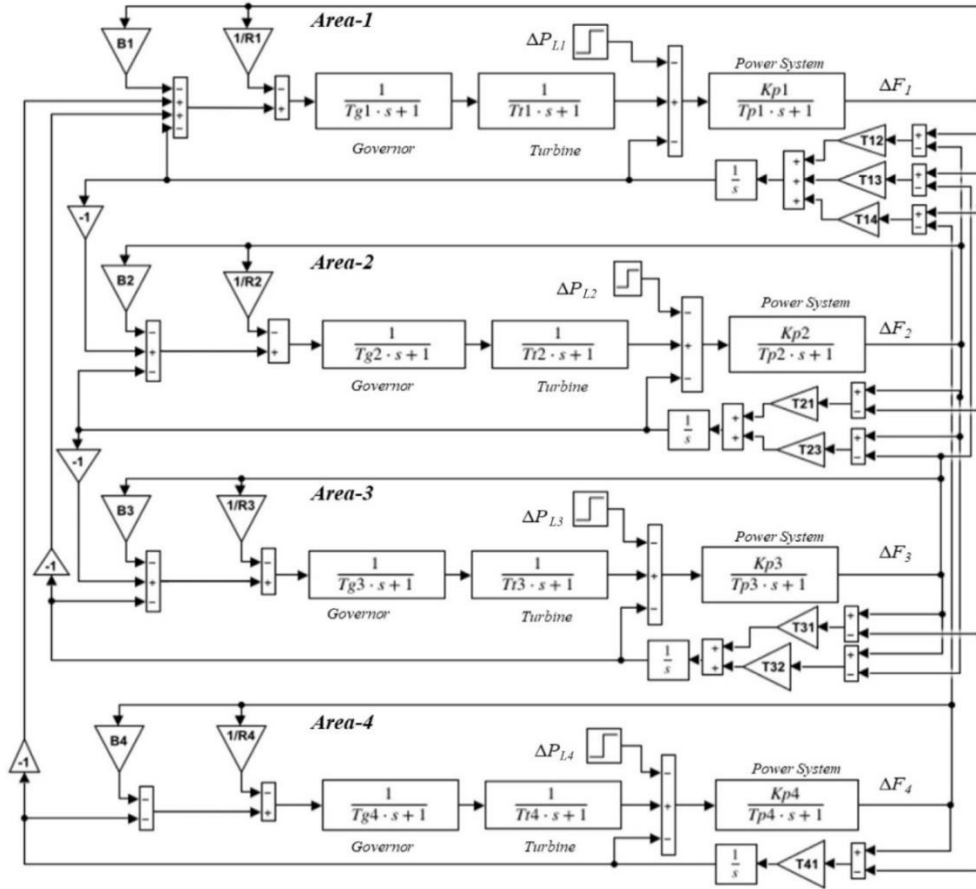


Fig. 2. Four-Zone LFC Model

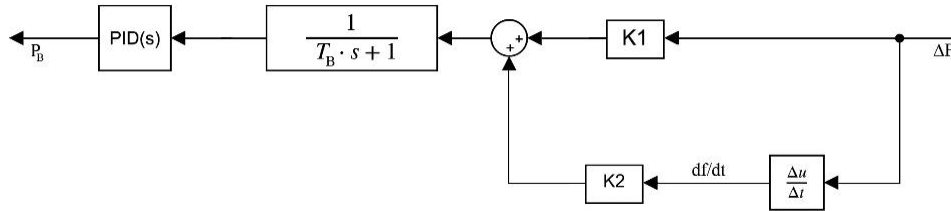


Fig. 2. BESS Control Block Diagram

The main sections of the paper are as follows: The first section will cover system and battery modeling. The next section will deal with controller design and then the optimization algorithm. Then, the simulation results for a single-area and a four-area system will confirm the applicability of the controller and the effectiveness of the proposed innovative optimization algorithm.

2. System Model

2.1. LFC Model

This model is derived from the swing equation

governing the behavior of the system's synchronous generator ensemble [22]:

$$\frac{df}{dt} = \frac{f_0}{2H_{sys}S_{tot}} (\Delta P_g - \Delta P_l) \quad (1)$$

$$H_{sys} = \frac{\sum_{i=1}^N S_{ni} H_i}{S_{tot}} \quad (2)$$

$$S_{tot} = \sum_{i=1}^N S_{ni} \quad (3)$$

$$H_i = \frac{1}{2} \frac{J \omega_n^2}{S_{ni}} = \frac{E_{ki}}{S_{ni}} \quad (4)$$

$$E_{k,sys} = S_{tot} H_{sys} = \sum_{i=1}^N S_{ni} H_i \quad (5)$$

Where:

- f_0 is the system frequency before the event [Hz].
- H_{sys} is the system's cumulative inertia [s].
- S_{tot} is the total rated power of the generators.
- $\Delta P_{g,i}$ is the difference between generation before and after the event.
- ΔP_L is the change in load.
- S_{ni} is the rated power of generator i .
- H_i is the inertia constant of generator i .

For a synchronous generator, H is defined as the ratio between the stored kinetic energy at nominal speed and the generator's rated apparent power. J is the generator's moment of inertia, and ω_n is the nominal angular speed of the rotor. Instead of expressing the inertia of a power system, it is often easier to calculate the kinetic energy stored in the rotating masses of the system.

Based on these assumptions, a linear power system model is formulated, where an equivalent power plant represents all synchronous generators in the system, divided into thermal and hydro units [23]. The model incorporates system inertia, the transfer function of conventional power plants, the Primary Frequency Control (PFC) scheme, and frequency-sensitive loads. The primary elements of the model are illustrated in Fig.1.

A four-area interconnected power system based on Load Frequency Control (LFC) is shown in Figures 2 and 3.

A detailed four-area thermal power system has been designed in the MATLAB/Simulink environment, as shown in Fig. 3.

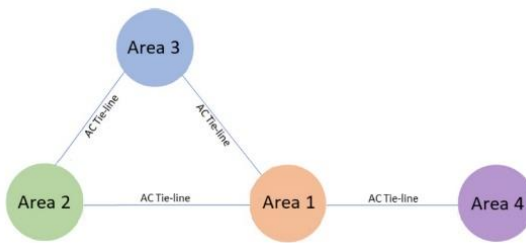


Fig. 3. Four-Zone System Connection Model

In this model, for each area i :

$$G_G(s) = \frac{K_g}{1 + sT_g} \quad (6)$$

$$G_P(s) = \frac{K_p}{1 + sT_p} \quad (7)$$

$$G_T(s) = \frac{K_t}{1 + sT_t} \quad (8)$$

In this context, K_G , K_T , and K_P denote the gains of the speed governor, turbine, and overall power system, respectively. The corresponding time constants for the speed governor, turbine, and power system are represented by T_G , T_T , and T_P , respectively. ΔP_D is the change in load demand, ΔP_{tie} is the change in tie-line power, Δf is the system frequency deviation, and T_{21} , T_{12} , T_{13} , T_{31} , T_{23} , T_{32} , T_{14} , and T_{41} are the tie-line synchronization coefficients. Area Control Error (ACE) is the controller input, B is the frequency bias parameter, and R is the governor speed regulation parameter. The objective functions Integral Time Absolute Error (ITAE), Integral Time Square Error (ITSE), Integral Square Error (ISE), and Integral Absolute Error (IAE) are calculated from (9)-(12), where t is the simulation time and n is the number of areas. ACE is dependent on frequency and tie-line power deviations [24]:

$$J_{ITAE} = \int_0^t t. \sum_{i=1}^n |ACE_n| dt \quad (9)$$

$$J_{ITSE} = \int_0^t t. \sum_{i=1}^n (ACE_n)^2 dt \quad (10)$$

$$J_{ISE} = \int_0^t \sum_{i=1}^n (ACE_n)^2 dt \quad (11)$$

$$J_{IAE} = \int_0^t \sum_{i=1}^n |ACE_n| dt \quad (12)$$

2.2. Energy Storage System

The battery, also referred to as a Battery Energy Storage System (BESS) in this study, can respond to power changes at high speed, ensuring frequency control. The concept involves emulating the inertia of synchronous generators, allowing for an immediate adjustment in active power in response to any given Rate of Change of Frequency (RoCoF) in the system.

The dynamic model for the BESS is shown in Fig. 4, adopted from [25], with the difference that the contribution from the frequency derivative is, in fact, similar to the instantaneous synchronous inertia response. The component related to Δf is similar to the level of Primary Frequency Control (droop control) and corresponds to the PFC level, while the component related to RoCoF (df/dt) is aimed at simulating a virtual inertia. The two input signals are weighted with factors K_P and K_D . The

primary control of the battery is modeled as a first-order transfer function, which is suitable for power system stability studies [26].

If σ_B is the equivalent droop of the BESS and P_B is the nominal active power of the BESS, the BESS's virtual regulating energy will be given by $E_{BESS} = -(P_B/f_0\sigma_B)$ and the BESS's virtual inertial response coefficient will be $k_{BESS} = (2H_{BESS}P_B/f_0)$. The BESS is designed with the constraint that the maximum allowable energy discharge must be equal to the maximum allowable energy charge [27].

In the case of conventional power plants, the reserved band for Δf is $(\frac{\Delta P_{MAX}}{P_n}) = 10\%$, while the BESS uses 100% of its band. As a result, a new equivalent droop value can be calculated, which for the BESS imposes its reserve saturation at the same frequency deviation as a conventional unit, but with $(\Delta P_{MAX}/P_n)_B = 1$. The reserve saturation frequency is calculated as (13) and (14) [27]:

$$\Delta f_{MAX} = \frac{\Delta P_{MAX}}{P_n} f_0 \sigma_p \quad (13)$$

$$\sigma_B = \frac{\Delta f_{MAX}}{f_0} \left(\frac{P_n}{\Delta P_{MAX}} \right)_{BESS} = 0.05 \quad (14)$$

Using this updated value, the equivalent regulating energy of the BESS can be determined by accounting for its share of the total power contributing to Primary Frequency Control (PFC), denoted as **PB**. This BESS model effectively captures the key dynamics during a disturbance and allows assessment of its influence on the grid. A specific contribution of this work is the application of an Energy Storage Law (ESL) to estimate the BESS's virtual inertia $H_{virtual}$, which is then used to compute K_{BESS} based on the saturation assumption for RoCoF values exceeding 1 Hz/s [28].

The concept is to mimic the inertial response of synchronous generators, enabling an immediate adjustment of active power for any given Rate of Change of Frequency (RoCoF) in the system. Consequently [28]:

$$H_{BESS} = \frac{f_0}{2|df/dt|_{MAX}} \quad (15)$$

2.2.1. Rate of Change of Frequency

RoCoF is a meaningful metric for indicating a system's ability to cope with a sudden power imbalance. A higher RoCoF means less time is available for the system operator to stop the frequency decline. A time interval of 100

milliseconds to 2 seconds is defined for RoCoF measurement. The European Network of Transmission System Operators for Electricity (ENTSO-E) standard specifies that the allowable RoCoF can obtain a value between 0.5 and 1 Hz/s. To represent the RoCoF frequency indicators, it is defined based on the classic swing equation as follows [29]:

$$2H \frac{d\Delta f(t)}{dt} = \Delta P_m(t) - \Delta P_L(t) - \Delta P_{tie}(t) \quad (16)$$

$$Rocof = \frac{\Delta P_m(t) - \Delta P_L(t) - \Delta P_{tie}(t)}{2H} \quad (17)$$

Where $\Delta P_{tie}(t)$, $\Delta P_L(t)$, $\Delta P_m(t)$ represent the mechanical power, electrical power, and tie-line power, respectively.

2.2.2. Nadir Frequency

Nadir Frequency mainly depends on the total system inertia and the ability of power sources to provide a primary frequency response. According to the North American Electric Reliability Corporation (NERC) and The Union for the Coordination of the Transmission of Electricity (UCTE) standards, the minimum allowable frequency for a system is 800 mHz. Considering the time dependency of the governor response, the Nadir Frequency can be written as (18) [30]:

$$\Delta f_{nadir} = \frac{(\Delta P_L + \Delta P_{tie})^2 T_d}{4HR} \quad (18)$$

where R is the additional power received through the governor and T_d is the governor's response time. In (18), it is assumed that the mechanical power increases as a linear function of time via the governor [31]. To simultaneously meet both the Nadir Frequency and RoCoF standards, the lower limit for virtual inertia is selected in the optimization problem for each area.

2.3. Inertial Response Controllers for BESS

During a disturbance in the power system, the balance between generation and load is disrupted, and the system frequency initially changes at a rate determined by the total system inertia [26]. When a power mismatch occurs, the deficit is first compensated by the rotational inertia, followed by the activation of a primary frequency regulation response. The overall model is built on the concept of a uniform or average frequency, which smooths out inter-generator oscillations while preserving the general frequency behavior. This approach

assumes that generators maintain rotor angle stability relative to each other (grid synchronism), a phenomenon consistently observed in real power systems [32]. If generation exceeds load, the BESS enters a charging mode, absorbing energy from the grid to prevent the frequency from exceeding its permissible limits. Conversely, in the case of a sudden load increase, the BESS discharges power to the grid, mitigating the risk of a sharp frequency drop that could trigger under-frequency load shedding.

Frequency control depends on the rate of change of frequency. The frequency droop coefficient is calculated using (19):

$$R_{droop} = \frac{1}{K_{droop}} = \frac{\Delta f}{\Delta p} \quad (19)$$

Δp is the change in active power of the battery and is determined by K_{droop} , where K_{droop} is the frequency droop and Δf is the frequency change. For contingencies where the frequency is low, K_{droop} is positive, and the BESS will be in a discharging state. For an over-frequency event, K_{droop} becomes negative, and the BESS will be in a charging state. The change in active power is related to RoCoF according to (20):

$$\Delta P = K_{rocof} \frac{df}{dt} \quad (20)$$

Here, K_{rocof} represents the rate at which the frequency varies. The frequency control mechanism enables the battery to release energy in a regulated manner. Droop control functions similarly to the proportional component of a generator's speed governor, helping to minimize the steady-state frequency error, though it cannot completely eliminate the frequency's rate of change. Conversely, virtual inertia control influences the dynamic frequency variation but is unable to correct the steady-state frequency offset.

2.3.1. Hybrid Control Method of Virtual Droop and Virtual Inertia

The power converter in an energy storage system can replicate the droop behavior of conventional frequency-regulating units. As a result, both Virtual Droop Control and Virtual Inertia Control are capable of taking part in Primary Frequency Control (PFC). In this analysis, the nonlinear characteristics of the generator and the storage system are disregarded.

Thus, integrating the strengths of virtual droop

control and virtual inertia control enables the BESS to be used more effectively for enhancing frequency regulation performance. The hybrid control scheme applied to BESS for contributing to an area's primary frequency control is illustrated in Fig. 5.

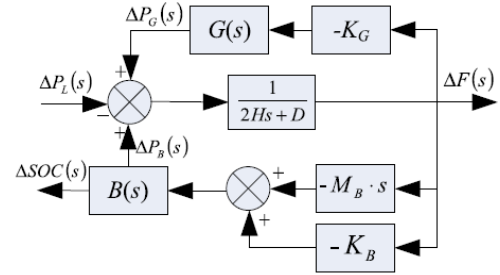


Fig. 5. Model of Primary Frequency Regulation in a Regional Power System Incorporating BESS through a Combined Virtual Inertia and Virtual Droop Control Strategy

Equations (21) and (22) define how the variables presented in the figure are related to one another:

$$\begin{cases} \Delta P_G(s) = -K_G \cdot G(s) \cdot \Delta F(s) \\ \Delta P_B(s) = -(K_B + M_B \cdot s) \cdot B(s) \cdot \Delta F(s) \end{cases} \quad (21)$$

$$\Delta P_G(s) + \Delta P_B(s) - \Delta P_L(s) = \Delta F(s)(2Hs + D) \quad (22)$$

The transfer functions of the traditional generation units and the energy storage system are denoted by $G(s)$ and $B(s)$, respectively. K_G refers to the regulation gain of the conventional unit, while K_B corresponds to the virtual droop control gain. In addition, ΔP_L represents the load disturbance, and Δf denotes the resulting frequency deviation. The parameter D is the damping coefficient of the system, H is the inertia constant of the synchronous generator, and M_B serves as the virtual inertia coefficient, allowing the Power Conversion System (PCS) to behave as an equivalent first-order inertial element for frequency control purposes. The formulations for $G(s)$ and $B(s)$ are provided in equations (23) and (24):

$$G(s) = \frac{1 + F_{HP} T_{RH} \cdot s}{(1 + T_G \cdot s)(1 + T_{CH} \cdot s)(1 + T_{RH} \cdot s)} \quad (23)$$

$$B(s) = \frac{1}{(1 + T_{PCS} \cdot s)} \quad (24)$$

Where T_G , T_{CH} , and T_{RH} are the time constants of the turbine, steam chest, and reheat, respectively. The high-pressure power fraction of the reheat turbine is given by F_{HP} . T_{PCS} is the PCS

time constant.

Based on the above equations, the system frequency change can be expressed as (25) and (26):

$$\Delta F(s) = \frac{-\Delta P_L(s)}{K_G \cdot G(s) + K_B \cdot B(s) + M_B \cdot s \cdot B(s) + 2H \cdot s + D} \quad (25)$$

$$\begin{cases} df_0 = \lim_{s \rightarrow \infty} s \cdot [s \cdot \Delta F(s)] = \frac{-\Delta p_L}{2H + M_B} \\ \Delta f_s = \lim_{s \rightarrow 0} s \cdot \Delta F(s) = \frac{-\Delta p_L}{K_G + K_B + D} \end{cases} \quad (26)$$

Here, df_0 denotes the initial frequency rate-of-change difference, and Δf_s represents the steady-state frequency deviation. The size of the step change in load is indicated by Δp_L .

From equation (26), it is evident that df_0 does not depend on the droop control of the energy storage system; instead, it is determined by H and is inversely related to M_B . When the load shifts to a fixed value, a higher virtual inertia coefficient of the storage system results in a smaller initial frequency deviation rate. Conversely, Δf_s is unaffected by the virtual inertia control. Under a load disturbance, increasing the droop coefficient of the energy storage system leads to a reduction in the steady-state frequency deviation.

This indicates that the BESS output is proportional to the rate of change of the frequency deviation, and this rate reaches its maximum at the instant the disturbance occurs. When the load disturbance is positive, the system frequency begins to drop, and both the generator and the energy storage system start supplying power. The initial output of the BESS at the moment of disturbance is expressed by equation (27):

$$P_{B0} = \frac{M_B}{2H + M_B} \Delta p_L \quad (27)$$

The power supplied by the BESS and the generator slows down the rate at which the system frequency deviates, which consequently reduces the BESS output. When the total output from both the BESS and the generator surpasses the load disturbance, the system frequency starts to recover rather than continue falling, resulting in a positive rate of change of frequency deviation. Based on the behavior observed for virtual droop control and virtual inertia control, the following two conclusions can be made:

1. Virtual droop control can effectively reduce the absolute values of Δf_m and Δf_s , but it has

no effect on the absolute value of the rate of change of frequency.

2. Virtual inertia control has a positive effect on Δf_m and the absolute value of the rate of change of frequency, but it has no effect on Δf_s .

Traditional droop control is the most widely adopted strategy for enabling BESS to contribute to power grid frequency regulation and is applicable to nearly all types of battery energy storage systems. To enhance frequency regulation performance while preserving the battery's State of Charge (SoC), some studies have incorporated an SoC balancing mechanism within droop control, commonly referred to as the Battery SoC Holder (BSH) [1, 33].

Given the above, a comprehensive control mode including virtual inertia control and virtual droop control can be proposed. A method for configuring energy storage capacity is formed, and the energy storage output is as follows:

$$P_E = \begin{cases} M_B \cdot \frac{d\Delta f}{dt}, & \frac{d\Delta f}{dt} < 0 \\ K_B \cdot \Delta f, & \frac{d\Delta f}{dt} > 0 \end{cases} \quad (28)$$

This model takes into account both the strengths and limitations of virtual inertia and virtual droop control. It should be noted, however, that it does not address scenarios in which the system experiences continuous minor disturbances, during which the frequency may fluctuate unpredictably.

3. Design of a PID Controller

PID controllers are crucial in frequency regulation, serving as a key approach in power systems to ensure the balance between generation and load [34–36]. By modulating the generators' output power, they maintain equilibrium among generators within each control area, keeping the system frequency at its target value, such as 50 Hz or 60 Hz. The proposed controller achieves a response time of just a few seconds, significantly enhancing system stability. In addition, the PID parameters are tuned using the Repeatable Optimization Algorithm (ROA), which is straightforward to implement; its process is illustrated in Fig. 6.

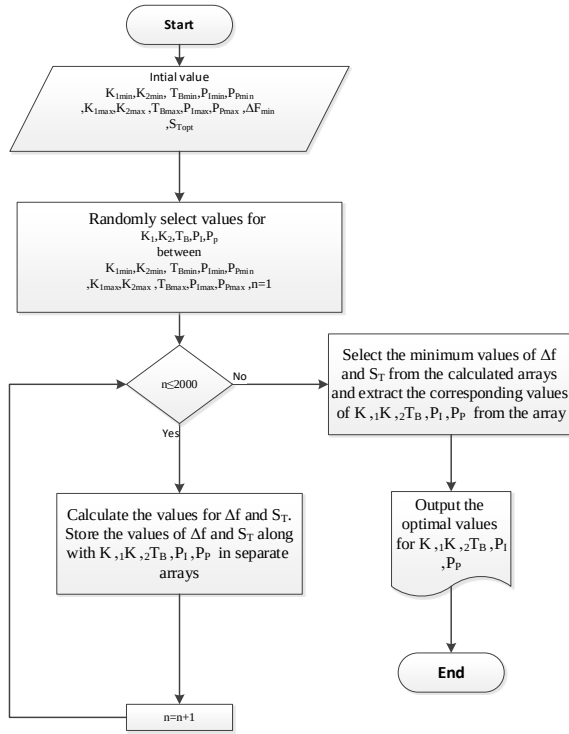


Fig. 6. ROA Flowchart

The results show that using the ROA can significantly reduce computation time. To achieve the optimal performance of the PID controller, the ROA is used to calculate the optimal controller coefficients, as shown in Fig. 7.

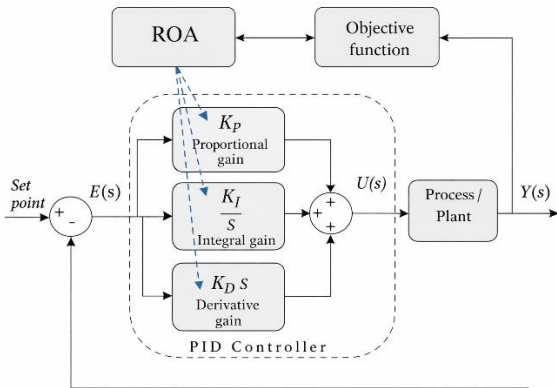


Fig. 7. Block Diagram of PID Optimization with ROA

In a PID controller, the output's transfer function is given by the following equation, where $U(s)$ represents the control signal, and $E(s)$ is the error signal. The parameters K_p , K_i , and K_d are the proportional, integral, and derivative coefficients, respectively [37]:

$$U(s) = \left(K_p + \frac{K_i}{s} + K_d s \right) \cdot E(s) \quad (29)$$

The constraints for the controller coefficients are given in (30), (31), and (32), where larger constraints require more iterations, leading to longer computation times. The minimization of the objective function J for the controller is subject to the following constraints:

$$K_{P,min} \leq K_P \leq K_{P,max} \quad (30)$$

$$K_{I,min} \leq K_I \leq K_{I,max} \quad (31)$$

$$K_{D,min} \leq K_D \leq K_{D,max} \quad (32)$$

The main purpose of the controller is to reduce the deviation (error) between the actual output and the desired setpoint. Using this error signal, the objective function, together with the optimization algorithm, adjusts the controller parameters for optimal performance.

3.1. ROA for Parameter Limits

I. Set the initial values for the variables K_{1min} , K_{2min} , T_{Bmin} , P_{1min} , P_{pmin} , K_{1max} , K_{2max} , T_{Bmax} , P_{1max} , P_{pmax} , N_{max} , and set $n=1$.

II. While $n \leq N_{max}$:

- * Randomly select values for the variables K_1 , K_2 , T_B , P_1 , P_P between their respective bounds.
- * Calculate the values for Δf and ST .
- * Store the values of Δf and ST along with K_1 , K_2 , T_B , P_1 , and P_P in separate arrays.
- * If ST decreases, then set $ST_{opt} = ST$
- * If Δf decreases, then set $F_{min} = \Delta f$
- * Increment the value of n by one.

III. Select the minimum values of Δf and ST from the calculated arrays and extract the corresponding values of K_1 , K_2 , T_B , P_1 , and P_P from the array.

IV. Output the optimal values for K_1 , K_2 , T_B , P_1 , and P_P .

Unlike conventional population-based metaheuristic algorithms such as GA, PSO, ALO, and DA, which rely on stochastic operators including crossover, mutation, or velocity updates, the proposed Repeatability Optimization Algorithm (ROA) employs a deterministic bounded-search mechanism with adaptive step refinement. This structure significantly reduces algorithmic complexity and enhances convergence repeatability. Moreover, ROA avoids the sensitivity to initial population distribution commonly observed in metaheuristic techniques, resulting in more stable and predictable convergence behavior. These characteristics make the proposed method particularly suitable for real-time controller tuning in power system frequency regulation applications.

4. Simulation Results

The simulations were performed in MATLAB/Simulink 2021b using the ode23 solver with a variable step size to model the transfer functions of the power systems under study. The Repeatabile Optimization Algorithm (ROA) was implemented. The ROA works by first establishing bounds for the BESS model parameters. These chosen bounds must prevent a divergent increase in Δf or excessive recovery time, as well as avoid frequency oscillations. A simple program can be used to separately calculate the upper and lower bounds for each parameter.

Then, within the ROA, these parameter bounds, the step size for each parameter, the maximum allowed Δf , and the maximum acceptable frequency recovery time are set. The initial values are set to the lower bounds. The value of K_1 is first varied from the lower to the upper bound with a step of ΔK_1 . If Δf decreases, K_1 is set as the optimal value, and Δf is updated to the new value. The other parameters are then optimized sequentially according to the flowchart in Fig. 7, by examining the effect of their changes on Δf and the recovery time. To increase the accuracy of the response, the step sizes are reduced in the next stage, and the process is repeated. This continues until there is no further change in the values of Δf and the recovery time, at which point the optimized values are output.

In scenarios with reduced system inertia, both the Nadir Frequency and RoCoF are adversely affected because the system has less regulating energy to maintain stability following a disturbance. To address this, a BESS is introduced. For the BESS, a sensitivity analysis is performed by varying the regulating energy and the dynamic pole constant. Using a real-world case as a reference, each area has a rated capacity of 2000 MW with a nominal load of 1000 MW [38–41]. Within each area, turbines, generators, and speed and load control systems are installed.

4.1. Case 1: Using 10% Step Load Perturbation (SLP) on a Single-Area Power System

A single-area thermal power system without nonlinearities, as shown in Fig. 1, is considered, with parameters given in Table 1. The change in frequency is presented in Fig. 8. At time $t=2s$, the load suddenly increases by 200 MW. The time at which Δf reaches its maximum value is $t=2.55s$. The frequency sharply drops with the sudden load increase, decreasing to 39.534 Hz, and at time $t=7.5s$, the frequency stabilizes at 44.083 Hz, and

the power changes become zero.

Table 1. Single-Area System Parameters

R [Hz/pu]	B [pu/Hz]	T_P [s]	K_P [Hz/pu]
2.4	0.425	20	120

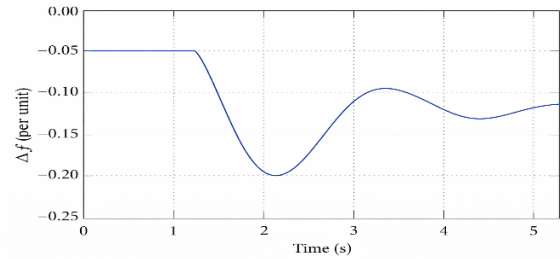


Fig. 8. Frequency Changes in Terms of Per Unit

This section presents the simulation results following the integration of the Battery Energy Storage System (BESS) and the optimal tuning of its control parameters using the proposed Repeatabile Optimization Algorithm (ROA). The coordinated hybrid virtual inertia–droop structure, when optimally configured, substantially enhances both transient and steady-state frequency performance by reducing the maximum frequency deviation, suppressing RoCoF, and shortening the settling time.

With the integration of the Battery Energy Storage System (BESS) and the optimization of its parameters using the mentioned algorithm, the frequency change is presented in Fig. 9. The improvement in transient frequency response is mainly attributed to the virtual inertia component, which suppresses the initial RoCoF immediately after the disturbance. On the other hand, the reduction in steady-state frequency deviation is primarily achieved by the droop control component. Therefore, the coordinated hybrid structure enables simultaneous enhancement of both dynamic and steady-state performance indices. In this scenario, with a sudden load increase of 200 MW at time $t=2s$, the settling time for Δf_1 is $t=2.013s$, and it decreases by 0.0035 units. With the ROA and parameter optimization, the frequency deviation becomes nearly zero at time $t=2.35s$, and the frequency reaches 49.925 Hz. The optimized parameters of the BESS model are provided in Table 2.

Table 2. Optimized Parameters BESS Model

I_{PID}	P_{PID}	T_B	K_2	K_1
8.42	0.71	0.003	0.04	72.51

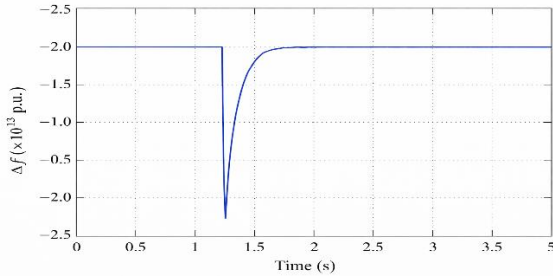


Fig. 9. Frequency Changes with BESS in Terms of Per Unit

Based on the provided text, [Table 2](#) serves to demonstrate the superior performance of the proposed model. It compares its optimization algorithm with other methods described in the referenced articles.

Specifically, the text highlights that the proposed model's effectiveness in improving frequency response and RoCoF time is showcased by the optimized parameters and frequency output. The comparison is made against other studies that used similar but less comprehensive approaches.

The text points out two examples from the referenced literature:

- Article [\[42\]](#) compensated for frequency drop by considering only virtual inertia in its BESS model.
- Article [\[43\]](#) improved frequency changes by considering both virtual inertia and droop for its BESS model.

In essence, [Table 3](#) and the accompanying text argue that the proposed model, by incorporating a new optimization algorithm, achieves more successful and significant improvements in frequency stability than the methods used in the other papers. To provide a clearer quantitative assessment, the percentage improvement achieved by the proposed method is calculated. Compared with the conventional approach in [\[42\]](#), the proposed method reduces the maximum frequency deviation by approximately 5% and decreases the settling time by nearly 12%. This confirms the superior damping and transient support capability of the hybrid virtual inertia–droop structure.

Table 3. Comparison of Frequency Performance Indices

	$F_{min}(Hz)$	$T_s(s)$
This paper	49.95	0.32
[24]	49.75	1.2
[26]	49.55	1.41
[33]	49.4	1.35
[42]	49.7	2.5
[43]	49.65	5

4.1.1. Comparison of the ROA with Other

Optimization Techniques

The Repeatable Optimization Algorithm (ROA) is evaluated against several recent optimization methods, including the Genetic Algorithm (GA), Dragonfly Algorithm (DA), Ant Lion Optimization (ALO), Whale Optimization Algorithm (WOA), and Particle Swarm Optimization (PSO).

The optimized parameter values, minimum objective function (F_{min}), settling time (T_s), and computation time (in seconds) for each technique are shown in [Table 4](#) and [Table 5](#).

Table 4. Comparison of Optimized Parameters of the BESS Model

Algorithm	K_1	K_2	T_B	P_{PID}	I_{PID}
ROA	72.51	0.04	0.002	0.71	8.42
GA	77.67	0.082	0.002	0.28	10.17
DA	68.42	0.05	0.008	0.64	11.2
ALO	76.69	0.079	0.004	0.52	10.68
PSO	71.351	0.04	0.002	0.72	8.542

Table 5. Comparing the Response of the Proposed Algorithm with other Algorithms

	$F_{min}(Hz)$	$T_s(s)$	Solution time
ROA	49.95	0.32	3200
GA	49.8	0.2	3600
DA	49.75	0.41	7800
ALO	49.7	0.65	8400
PSO	49.78	0.32	6500

Since we have $E_{BESS} = -(P_B/f_0\sigma_B)$, then $P_B = -(E_{BESS} * f_0\sigma_B)$.

Thus, for P_{BESS} , we will have:

$$P_B \approx 72.51 * 50 * 0.05 \approx 181 \text{ MW.}$$

The required BESS power rating (approximately 181 MW) remains within practical operational limits for utility-scale battery systems. This indicates that the proposed strategy not only improves frequency stability but also remains technically feasible from an implementation perspective.

4.1.2. Quantitative Performance Improvement Analysis

A quantitative comparison further highlights the superiority of the proposed ROA-based approach. In terms of frequency deviation from the nominal value (50 Hz), the proposed method reduces the steady-state deviation by approximately 75% compared to GA, nearly 80% compared to DA, approximately 83.3% compared to ALO, and nearly 77% compared to PSO.

Although GA exhibits a slightly shorter settling time, the ROA achieves significantly better steady-state accuracy while maintaining competitive dynamic performance. Compared to DA and ALO,

the proposed method reduces the settling time by approximately 21.9% and nearly 50.8%, respectively.

From a computational efficiency perspective, the ROA demonstrates remarkable improvement. The solution time is reduced by nearly 59% compared to DA, 62% compared to ALO, 50.7% compared to PSO, and 11% compared to GA.

These results confirm that the proposed algorithm achieves a superior balance between dynamic performance, steady-state accuracy, and computational efficiency, making it a highly suitable candidate for practical real-time frequency regulation applications.

Power System

A four-area interconnected thermal power system without nonlinearities, as shown in [Fig. 3](#), is considered. The system parameters are given in [Table 6](#).

Table 6. Four-Area System Parameters

Area	R [Hz/pu]	B [pu/Hz]	T_P [s]	K_P [Hz/pu]
1	2.4	0.425	20	120
2	2.7	0.425	25	112.5
3	2.5	0.425	20	125
4	2.0	0.425	15	115

To verify the stability of the system, a severe scenario is analyzed in which each area experiences a 10% Step Load Perturbation (SLP). The resulting frequency variation is illustrated in [Fig. 10](#).

4.2. Case 2: Using 10% SLP on a Four-Area

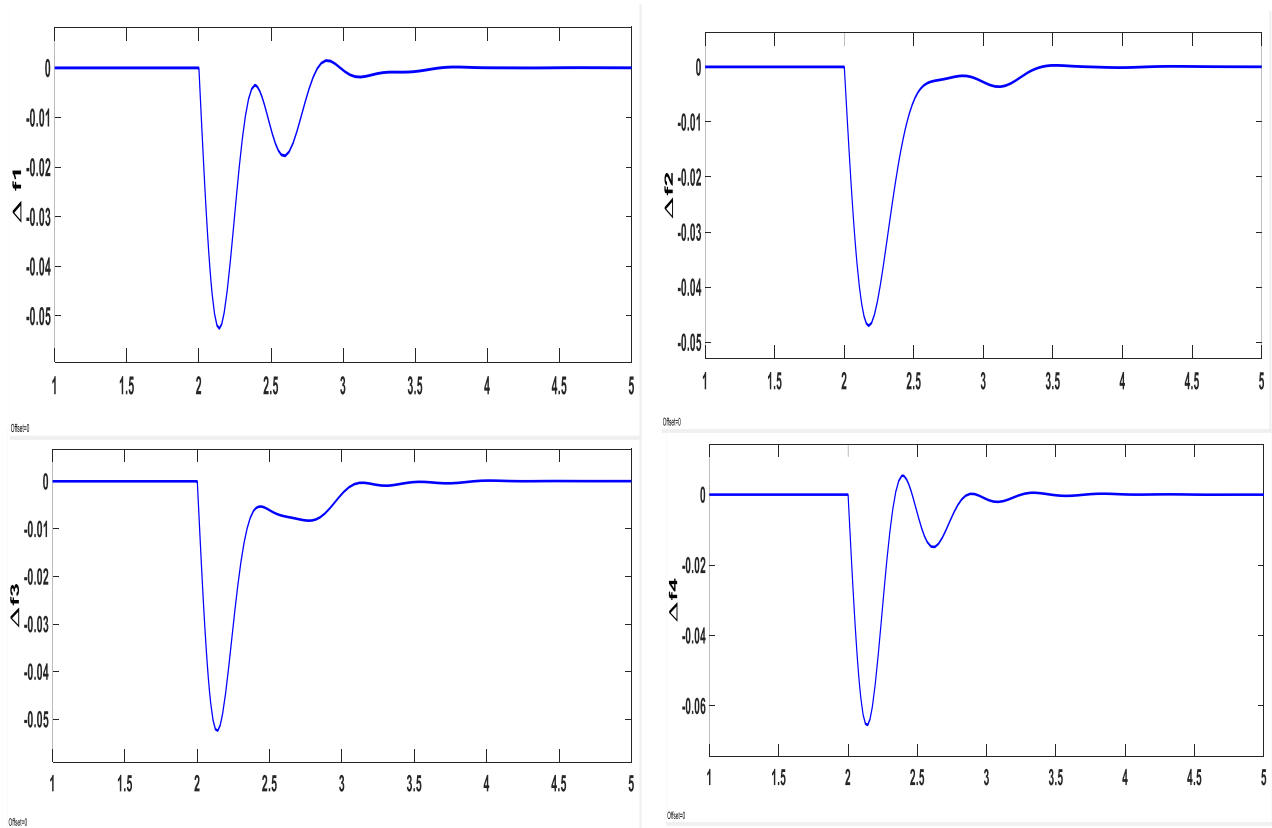


Fig. 10. Frequency Changes in a Four-Zone System

At time $t=2$ s, the load suddenly increases by 200 MW. The time when the frequency deviation reaches its maximum value is $t=2.14$ s for Δf_1 , with a decrease of 2.625 Hz. For Δf_2 , the decrease is 2.35 Hz; for Δf_3 , it is 2.625 Hz; and for Δf_4 , the

decrease is 3.275 Hz. Overall, the lowest frequency reaches 46.725 Hz. This indicates that the frequency experiences a rapid decline due to the sudden load increase. By $t = 4$ s, the frequency settles at 49.8 Hz.

With the installation of the Battery Energy Storage System (BESS) and the optimization of its parameters using the algorithm, the change in frequency is presented in [Fig. 11](#).

With a sudden load increase of 200 MW at time

$t=2s$, the settling time for the frequency deviations (Δf_1 , Δf_2 , Δf_3 , and Δf_4) is $t=2.013s$. The frequency reaches 49.883 Hz. At $t=2.38s$, the frequency deviation becomes almost zero, and the frequency stabilizes at 50 Hz.

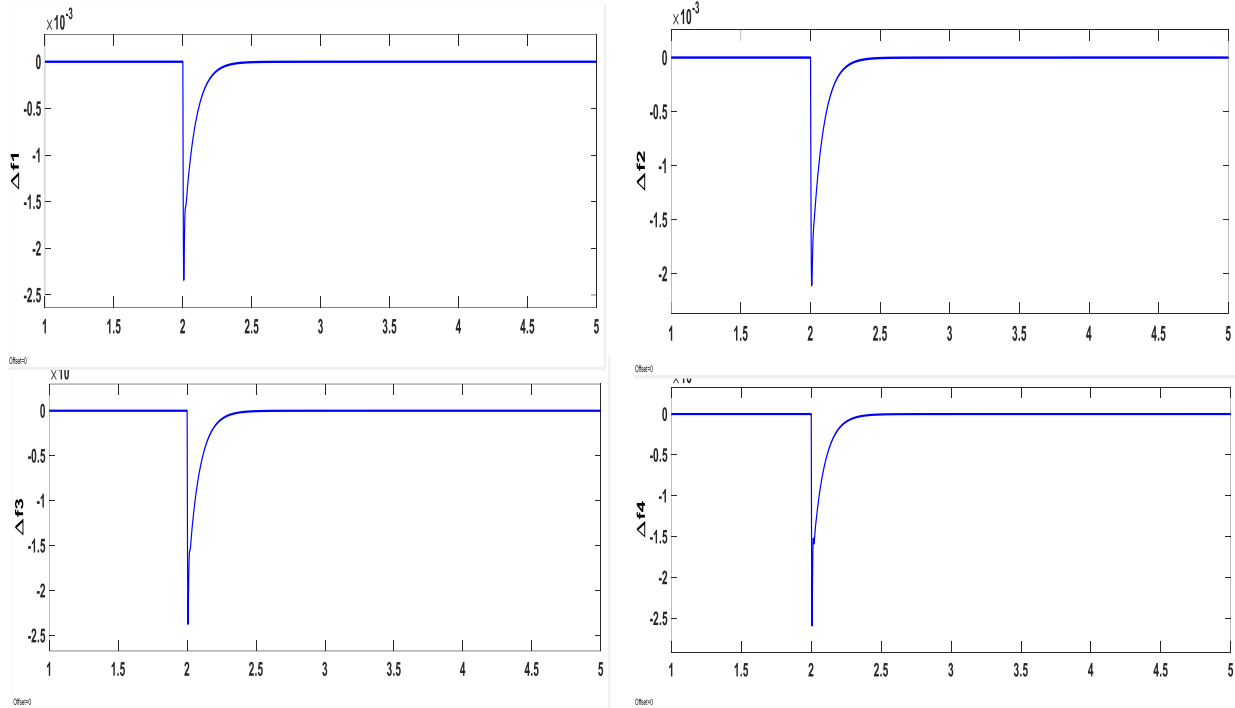


Fig. 11. Frequency Changes in a Four-Zone System after Battery Placement in Terms of Per Unit

4.3. Comparative Performance Evaluation

To further validate the effectiveness and robustness of the proposed hybrid BESS control strategy optimized using the Repeatable Optimization Algorithm (ROA), a comprehensive comparative performance evaluation is conducted against several widely used metaheuristic optimization techniques, including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Lion Optimization (ALO), and Dragonfly Algorithm (DA).

For a fair comparison, all optimization algorithms were implemented under identical operating conditions, system parameters, disturbance magnitude (10% step load perturbation), and controller parameter constraints. The same objective function and termination criteria were used for all algorithms. In addition, population size and iteration limits were selected consistently to ensure comparable computational effort. The optimized parameter sets obtained using each algorithm are summarized in [Table 4](#), while the corresponding performance indices—including minimum frequency deviation (F_{min}), settling time (T_s), and computational time—are presented

in [Table 5](#).

The results clearly demonstrate that the proposed ROA-based approach achieves one of the lowest frequency deviations while maintaining competitive settling time and significantly reduced computational burden. In particular, the ROA exhibits faster convergence characteristics compared to GA, ALO, and DA. Although some algorithms may achieve comparable settling time in certain cases, they generally require higher computational effort or produce larger steady-state deviations. From a dynamic performance perspective, the improvement in frequency response using the proposed method can be attributed to the coordinated tuning of the virtual inertia gain, droop coefficient, and PID parameters. The ROA effectively balances transient damping (influencing RoCoF and frequency nadir) and steady-state regulation performance. As a result, the system experiences:

- Reduced maximum frequency deviation,
- Improved frequency nadir,
- Lower RoCoF,
- Shorter settling time.

Compared to conventional optimization

techniques, the proposed ROA demonstrates more stable convergence behavior and reduced sensitivity to initial parameter selection. This characteristic is particularly important for practical implementation in power systems, where fast and reliable parameter tuning is required. Furthermore, the computational efficiency of the proposed algorithm makes it suitable for real-time or near-real-time frequency regulation applications. The reduced solution time, as observed in [Table 5](#), confirms that the ROA can provide high-quality solutions without excessive computational overhead.

Overall, the comparative analysis verifies that the proposed hybrid BESS control strategy combined with ROA-based parameter optimization offers a robust, computationally efficient, and dynamically superior solution for frequency regulation in modern low-inertia power systems.

The observed improvements are also consistent with the theoretical relationship derived from the swing equation. According to the classical frequency dynamics model, the initial RoCoF is inversely proportional to the equivalent system inertia. By introducing virtual inertia through the BESS control loop, the effective inertia of the

system is increased, thereby reducing the initial frequency slope. Similarly, the droop component directly influences the steady-state frequency deviation by modifying the power-frequency characteristic of the system. Therefore, the simulation results are not only numerically superior but also analytically justified based on fundamental power system dynamics.

An increase in K_2 leads to distortion in the recovery time, while a further decrease has no effect on the output response. An increase in TB leads to distortion in the recovery time and an increase in oscillations in tie-line power, whereas a decrease leads to an increase in recovery time and an increase in the time for tie-line power to reach zero. An increase in PP leads to an increase in recovery time and an increase in oscillations in tie-line power, while a further decrease leads to an increase in the time for tie-line power to reach zero.

An increase in PI leads to an increase in frequency drop, while a decrease leads to an increase in recovery time and an increase in the time for tie-line power to reach zero. The changes for the system parameters K_1 , K_2 , TB, PI, and PP are shown in [Fig. 12](#).

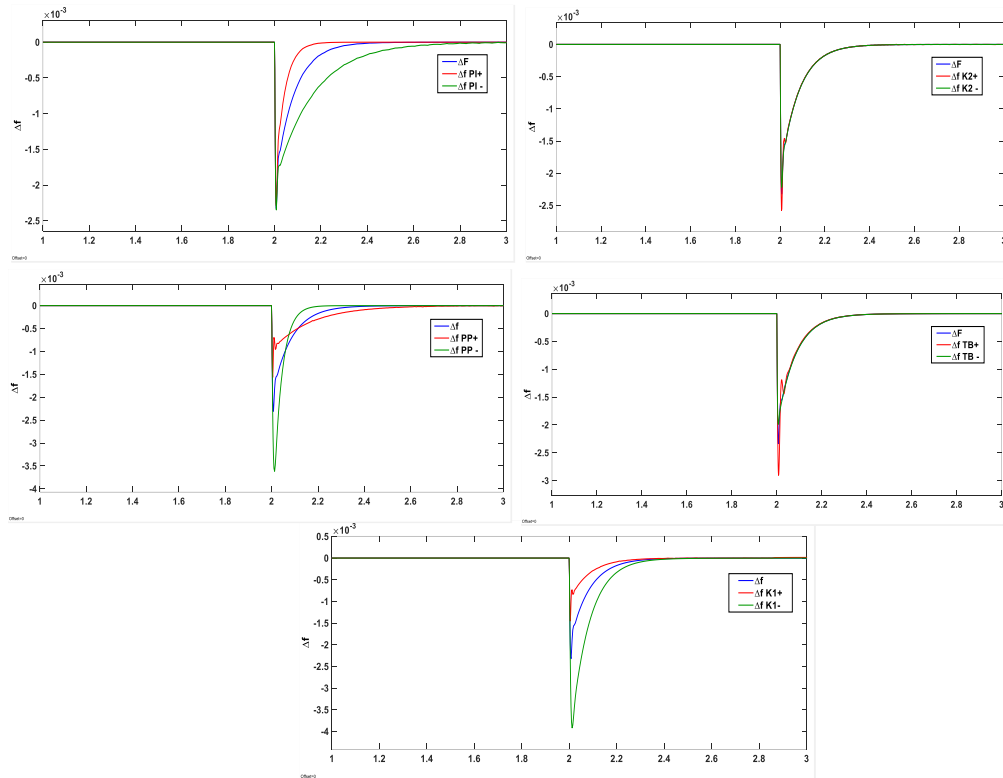


Fig. 12. Frequency Changes in Sensitivity Analysis of System Parameters

It should be noted that the present study assumes linear turbine dynamics without explicitly

incorporating Generation Rate Constraint (GRC) nonlinearities. In practical power systems, GRC

limits the ramping capability of thermal units, which may slightly increase settling time and deepen the frequency nadir. However, since the proposed hybrid BESS control primarily provides fast initial support through virtual inertia, its effectiveness in reducing RoCoF and frequency deviation is expected to remain valid. Future work will extend the analysis by incorporating nonlinear GRC effects for further validation.

5. Conclusion

This paper proposed a hybrid primary frequency control framework for low-inertia power systems integrating Battery Energy Storage Systems (BESS). The proposed approach combines virtual inertia control and virtual droop control to simultaneously enhance transient and steady-state frequency performance. A novel Repeatable Optimization Algorithm (ROA) was developed to optimally tune the BESS and PID controller parameters under predefined operational constraints.

Comprehensive simulation studies were carried out on both single-area and four-area interconnected power systems under severe load disturbances. The results demonstrated that the coordinated hybrid control significantly improves frequency nadir, reduces RoCoF, minimizes steady-state deviation, and shortens settling time compared to conventional approaches. Quantitative comparisons with established optimization algorithms—including GA, PSO, ALO, and DA—confirmed the superiority of the proposed ROA in terms of convergence speed, steady-state accuracy, and computational efficiency.

The analytical interpretation based on the swing equation further validates that the performance enhancement is directly linked to the increase in effective system inertia and improved droop characteristics achieved through optimized BESS control. In particular, the proposed method reduced the maximum frequency deviation to 49.95 Hz and achieved a settling time of 0.32s in the single-area case, demonstrating a substantial improvement over benchmark techniques.

Overall, the proposed hybrid BESS control strategy combined with ROA-based parameter optimization provides a robust, computationally efficient, and practically implementable solution for frequency regulation in modern power systems with high renewable penetration and reduced inertia.

Future work will focus on incorporating nonlinear turbine constraints such as GRC, battery

degradation models, state-of-charge limitations, and hardware-in-the-loop experimental validation to further enhance the practical applicability of the proposed framework.

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