

Article

PV/Wind-Integrated Low-Inertia System Frequency Control: PSO-Optimized Fractional-Order PI-Based SMES Approach

Md Shafiul Alam ^{1,*} , Fahad Saleh Al-Ismael ^{1,2,3,4}  and Mohammad Ali Abido ^{1,2,4} 

¹ K.A.CARE Energy Research & Innovation Center, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia; fsalismael@kfupm.edu.sa (F.S.A.-I.); mabido@kfupm.edu.sa (M.A.A.)

² Department of Electrical Engineering, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

³ Center for Environment & Marine Studies, Research Institute, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

⁴ Center for Renewable Energy & Power Systems, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

* Correspondence: mdshafiul.alam@kfupm.edu.sa; Tel.: +966-559105462

Abstract: A paradigm shift in power engineering transforms conventional fossil fuel-based power systems gradually into more sustainable and environmentally friendly systems due to more renewable energy source (RES) integration. However, the control structure of high-level RES integrated system becomes complex, and the total system inertia is reduced due to the removal of conventional synchronous generators. Thus, such a system poses serious frequency instabilities due to the high rate of change of frequency (RoCoF). To handle this frequency instability issue, this work proposes an optimized fractional-order proportional integral (FOPI) controller-based superconducting magnetic energy storage (SMES) approach. The proposed FOPI-based SMES technique to support virtual inertia is superior to and more robust than the conventional technique. The FOPI parameters are optimized using the particle swarm optimization (PSO) technique. The SMES is modeled and integrated into the optimally designed FOPI to support the virtual inertia of the system. Fluctuating RESs are considered to show the effectiveness of the proposed approach. Extensive time-domain simulations were carried out in MATLAB Simulink with different load and generation mismatch levels. Systems with different inertia levels were simulated to guarantee the frequency stability of the system with the proposed FOPI-based SMES control technique. Several performance indices, such as overshoot, undershoot, and settling time, were considered in the analysis.

Keywords: virtual inertia control; renewable energy resources; solar and wind energy; superconducting magnetic energy storage (SMES); fractional-order proportional integral (FOPI); frequency response



Citation: Alam, M.S.; Al-Ismael, F.S.; Abido, M.A. PV/Wind-Integrated Low-Inertia System Frequency Control: PSO-Optimized Fractional-Order PI-Based SMES Approach. *Sustainability* **2021**, *13*, 7622. <https://doi.org/10.3390/su13147622>

Academic Editors: Thanikanti Sudhakar Babu and Marc A. Rosen

Received: 17 May 2021

Accepted: 25 June 2021

Published: 7 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Due to the continuous depletion of fossil fuels, increased government incentives, technological advancements, and price drops, the utilization of renewable energy sources (RESs) as distributed generators (DGs) has increased dramatically in recent years. In power systems, several technical issues, such as low reserve generation, fault ride through capability, inertia, and high fault current, have arisen because of high-level RES integration [1]. Thus, the frequency stability issue of high-level RES-integrated systems is greatly affected. Moreover, the two main sources of renewable energy, solar and wind, are highly unpredictable. The intermittent and unpredictable RESs can be modeled with sophisticated methods to lower the risk of instability in power systems [2]. A high share of RESs complicates grid-balancing and market operations. Several dedicated devices can be installed in a RES-integrated system to provide ancillary services such as power variations, congestion reduction, grid balancing, and primary reserve [3,4]. The technical issues of RES integration with a power system could also be handled with different cutting edge technologies such

as modern control and optimization techniques, energy storage devices including batteries and supercapacitors, and fault current limiting devices [5].

The overall inertia of a power system is decreased greatly as a result of the integration of low-inertia wind and inertia-less PV systems [6]. Power electronic converter decoupling between the wind generator and the power system is responsible for the low inertia. As a result, such a low-inertia wind system cannot properly maintain the frequency stability of the power system. Moreover, solar PV with no inertia is highly responsible for the frequency deviation of the system. Therefore, high-level PV and wind penetration reduces the total inertia and augments the rate of change of frequency (RoCoF), which are responsible for the unexpected load-shedding controller activation even at small generation-load mismatch [7]. In addition, reserve power reduction due to high-level PV/wind integration causes frequency deviation [8]. In summary, inertia emulation controllers need to be designed to improve the frequency stability of RES-integrated power systems.

In order to minimize the frequency excursion of a low-inertia system, several methods have been presented in the literature, such as the auxiliary load frequency (LFC) control technique, the inertia emulation technique, the deloading technique, the droop technique, and the energy storage-based technique [9–12]. In [13], an auxiliary LFC technique was presented to control the frequency of the Egyptian grid considering high-level PV and wind integration employing the proportional-integral-derivative (PID) controller. However, the LFC technique does not consider the detailed model of the Egyptian grid; instead, it excludes tie line power flow, which needs further investigation. In general, conventional PI and PID controllers, the parameters of which were fine-tuned experimentally or tuned by Ziegler–Nichols methods, were employed in system frequency control [14,15]. However, the conventional tuning methods of PI/PID controllers may not provide satisfactory performance. In [16], a virtual inertia support technique was presented for a low-inertia microgrid with a particle swarm optimization (PSO)-based PI controller.

The superconducting magnetic energy storage (SMES) is considered a promising device for the low-inertia issue of the microgrid system in [17]. The conventional derivative approach for the virtual inertia control loop was implemented. The detailed design of feedback and proportion gains, however, were not discussed in this work. Another energy storage, the battery, was presented in [18] for frequency support of the doubly fed induction generator (DFIG)-based wind system. The battery was connected to the DC link of DFIG and controlled with the droop technique in order to reduce frequency deviation by scheduling active power exchange during system disturbances. In [19], a self-adaptive virtual inertia fuzzy controller was adopted for a high-level renewable integrated system. The proportional virtual gain was adapted by the fuzzy system, which uses the deviation of real power and frequency as its inputs. In this scheme, however, the generalized energy storage system (ESS) was considered a simple first-order system. Since the specific ESS was neither discussed nor modeled, the presented frequency support scheme needs further improvement or investigation. The sharing of active power from different energy storage devices were scheduled based on their abilities in [20] for frequency control of renewable sources. In this capability-coordinated frequency control (CCFC) approach, the total error signal was forwarded to the primary control loop of each unit based on its capabilities. The LFC for mass-less inertia PV systems was presented in [21] with PI controllers. The parameters were optimized with the hybrid optimization technique in the case of different step load changes. In order to stabilize the low-inertia PV system, another virtual inertia synthesis using a synchronverter was reported in [22] with the learning technique. The optimized virtual inertia frequency control and protection schemes were developed in [23,24] for a low-frequency interconnected power system. The combination of SMES and thyristor-controlled phase shifters (TCPS) [25] was applied in a low-inertia utility grid with the adaptive neuro-fuzzy system (ANFIS) controller. The detailed design of SMES negative feedback and proportional gains, however, was not considered. The main advantage of SMES is the quick charging/discharging ability to react to sudden changes in system dynamics. Thus, the fast-response capability of SMES could be the most

effective countermeasure against frequency deviations in a power system. The voltage and frequency stability issues of a power system are addressed in some of the literature with SMES [26–28]. Furthermore, the transient stability issues are also handled with the application of SMES [29–31]. Based on a comprehensive literature survey on SMES device applications in power systems, it is concluded that further study on virtual inertia control topologies using SMES is imperative.

In recent years, several theoretical and applied studies have been conducted on fractional-order controllers [32,33]. Better system performance is observed with fractional-order controllers over conventional PI controllers because the fractional-order controller involves additional real parameters [34]. However, in general, there is no hard and fast rule for tuning the parameters of fractional-order controllers. The tuning of fractional-order proportional integral (FOPI) controller parameters with the artificial bee colony (ABC) [35] technique has been presented, which is complex in objective function evaluation and low convergence speed. The parameter-tuning task of FOPI is formulated as an optimization problem and solved with the seeker optimization algorithm (SOA) in [36]. The harmony search (HS) algorithm is reported in [37] for FOPI parameter optimization to control the power-switched reluctance motor. However, there are no conclusive studies on the application of the virtual inertia technique using an SMES topology-based FOPI controller.

Based on several studies [17–19,25,38], it is identified that the detailed design of the PSO-optimized SMES is missing the FOPI controller to support virtual inertia for RESs. Thus, in this paper, we propose a PSO-optimized FOPI-SMES controller design approach for a two-area power system. The proposed approach can support the virtual inertia of the high-level renewable energy integrated system. The addition of this virtual inertia makes the system stable over a wide range of load–generation mismatches. Since the FOPI controller is superior to the conventional PI, the proposed technique performs better when reducing system frequency deviation. However, the design of FOPI is challenging compared to the conventional PI. Thus, this work introduces a detailed model of FOPI, SMES, and a two-area power system to find the design parameters. The dynamic model of the system presented along with SMES and FOPI is utilized to develop the frequency deviation-based cost function for the PSO algorithm. To validate the proposed optimized FOPI controller-based SMES, several case studies were considered and simulated for a wide range of load profile variations. The robustness of the proposed virtual inertia control scheme was tested under reduced system inertia. The proposed controller was compared with the conventional controller, where the improvements in several indices, such as total frequency deviation, overshoot, undershoot, and settling time, were observed. Furthermore, the performance of the non-optimized FOPI was compared with the PSO-optimized FOPI.

The manuscript is organized as follows. The dynamic model of the system including RESs is given in Section 2. The SMES modeling and PSO-based FOPI-SMES design techniques are discussed in Section 3. The simulation results are discussed in Section 4. Finally, the conclusions of this study are given in Section 5.

2. High-Level PV/Wind-Integrated System Modeling

The fractional-order PI controller for superconducting magnetic energy storage (SMES) is designed to virtually support inertia for a high-level solar PV- and wind-integrated two-area power system. An interconnected power system with low inertia due to a high-level integration of PV and wind energy sources, as shown in Figure 1, is considered in this study. The areas are connected by a tie-line, and both of them consist of thermal generating units, an industrial load, a residential load, solar PV, wind, and SMES. The measured frequency and tie-line signals are accumulated in the control and monitoring center. Since the system faces low inertia, it is expected to support the inertia via the control center, which sends control signals to the controllable energy storage devices of both areas if the communication network is available. However, in absence of a communication link, local controllers such as decentralized control, primary control, and droop control can

be employed. The net power (P_{net}) in each area in Figure 1 can be calculated using the power of (1) the thermal unit (P_{TH}), (2) the solar array (P_{SA}), (3) the wind farm (P_{WF}), (4) SMES (P_{SMES}), (5) combined industrial and other loads (P_L), and (6) the tie-line (P_{tie}). The expression for P_{net} is given below.

$$P_{net} = P_{TH} + P_{SA} + P_{WF} - P_L \pm P_{SMES} \pm P_{tie} \quad (1)$$

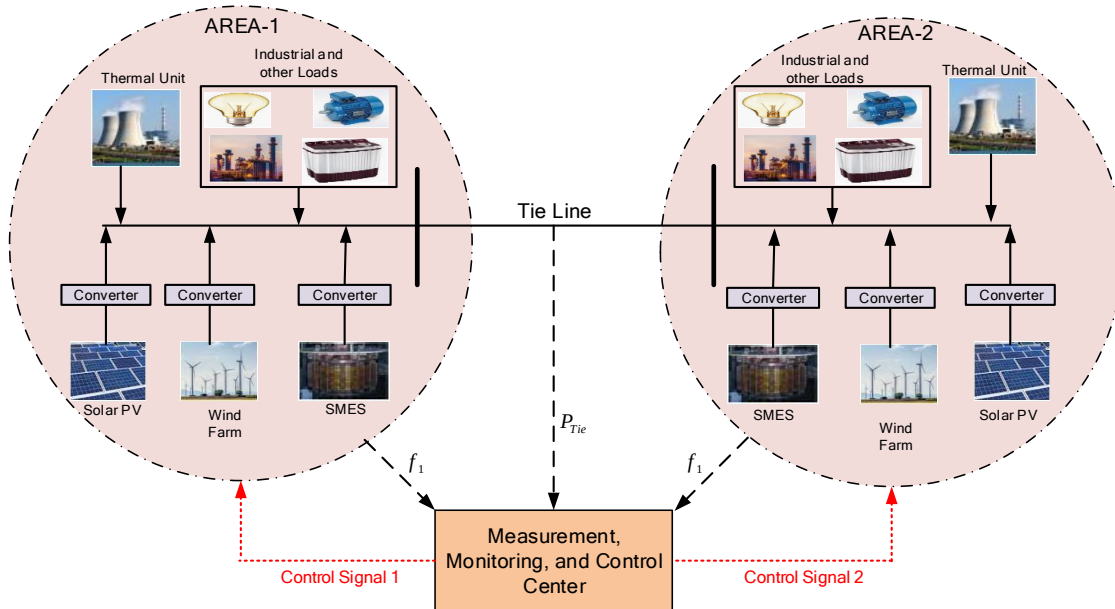


Figure 1. Two-area low inertia interconnected power system.

In general, higher-order models for thermal generating units, wind systems, solar PV, and converters, with nonlinearity are considered to precisely demonstrate the dynamic behaviors of the interconnected system. For large power systems with power electronic converters, however, simplified dynamic models are employed to study the frequency stability. The interested readers can find more details on such dynamic modeling in [39–41]. The simplified dynamic model of the two-area system can be developed as shown in Figure 2 for frequency stability analysis.

From the dynamic model, as shown in Figure 2, the frequency deviation for the k th area can be written as follows.

$$\Delta f_k = \frac{1}{2H_k s + D_k} (\Delta P_{TH,k} + \Delta P_{SA,k} + \Delta P_{WF,k} - \Delta P_{L,k} + \Delta P_{tie,k}) \quad (2)$$

where,

$$\Delta P_{TH,k} = \frac{1}{1 + sT_{t,k}} (\Delta P_{g,k}) \quad (3)$$

$$\Delta P_{g,k} = \frac{1}{1 + sT_{g,k}} (\Delta P_{AEC,k} - \frac{1}{R_k} \Delta f_k) \quad (4)$$

$$\Delta P_{WT,k} = \frac{1}{1 + sT_{wind,k}} (\Delta P_{wind,k}) \quad (5)$$

$$\Delta P_{SA,k} = \frac{1}{1 + sT_{pv,k}} (\Delta P_{pv,k}) \quad (6)$$

where H_k is the inertia constant in area k , D_k is the damping constant in area k , $\Delta P_{TH,k}$ is the incremental power of the thermal unit in area k , $\Delta P_{SA,k}$ is the incremental power of solar farm in area k , $P_{WF,k}$ is the incremental power of wind farm in area k , $T_{t,k}$ is the

turbine time constant in area k , $T_{g,k}$ is the governor time constant in area k , $T_{wind,k}$ is the wind turbine time constant in area k , and $T_{pv,k}$ is the solar system time constant in area k .

Two physical constraints, governor dead band (GDB) and generation rate constraint (GRC), affect the dynamic performance of the power system. The thermal units consist of rotating mass, which inherently has mechanical inertia; thus, it puts a constraint/limit on the output power change, which is known as GRC. The controller designed without GRC may not perform well in practical applications. To handle this issue, GRC is considered for the virtual inertia controller design in this work, as shown in Figure 2. Furthermore, the governor cannot change its valve position within a specific range of speed variation. Due to this dead-band, the tie-line power oscillation with a natural frequency of 0.5 Hz is observed. The dead-band for governor is also taken into consideration in this study to reflect the practical implementation case. The solar PV, wind, and different loads are modeled as disturbances in the dynamic model. The interested readers are directed to the literature [39] for more details on dynamic modeling of PV/wind integrated system.

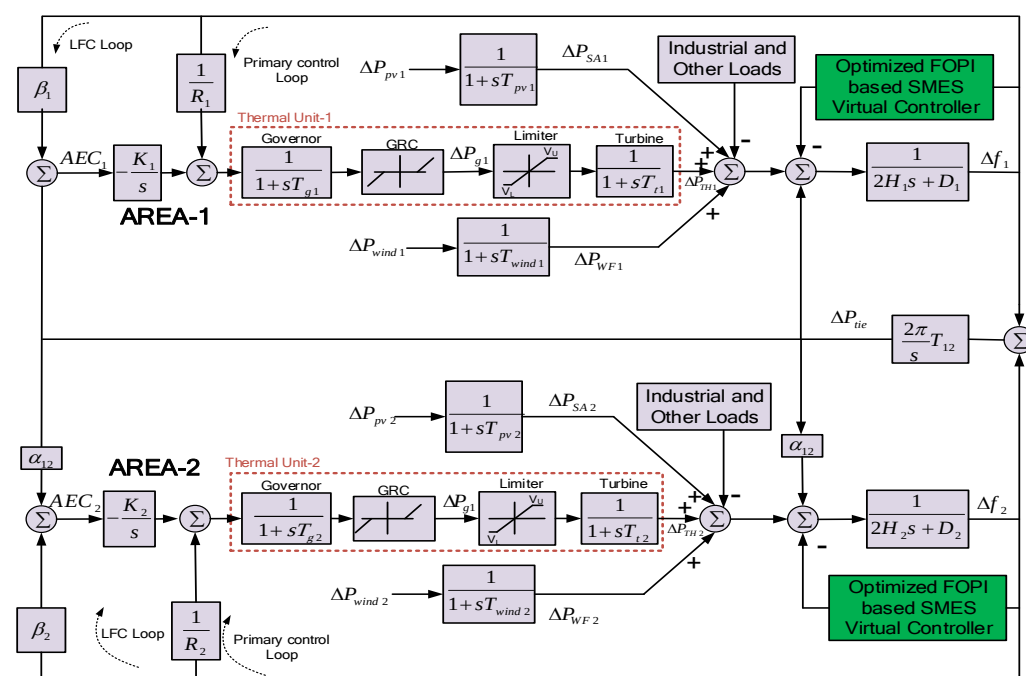


Figure 2. The dynamic model of low inertia system with the proposed controller.

3. SMES Model with FOPI Controller

SMES is a promising device for dynamic stability improvement of power systems. The SMES has several components: the power conversion system (PCS), consisting of the inverter/rectifier, and the superconducting coil which is kept under extremely low temperature [25]. The PCS also consists of three-phase transformers to allow for energy exchange between the AC grid and the superconducting coil. The harmonic contents of the signals are filtered by two cascaded six pulse bridges, as shown in Figure 3. The capability of SMES to exchange huge power within a very short duration has drawn the attention of researchers in the power system application.

In normal conditions, the SMES coil charges quickly to its pre-defined peak value. As the coil temperature is maintained below the critical value, it conducts the current with nearly zero loss. During contingencies, as the power demand is initiated by the power system, the SMES discharges power through the PCS to the grid almost instantly. While the governors of the generators support the power demand after contingencies, the SMES again charges at its preset value. The inductor DC voltage is given by the equation below [25,42].

$$E_d = 2V_{d0}\cos\alpha - 2I_D R_D \quad (7)$$

where V_{d0} is the maximum voltage of the bridge circuit, α is the triac firing angle, I_D is the superconducting coil current, and R_D is the damping resistor. Thus, the DC voltage appearing across the superconducting coil can be controlled with the variation of the triac firing angle α . If α is above 90° , the energy stored in the superconducting coil is released to the grid. In contrast, the superconducting coil charges if α is below the 90° . In this way, the superconducting coil charges and discharges through the bidirectional converter system to absorb or provide energy.

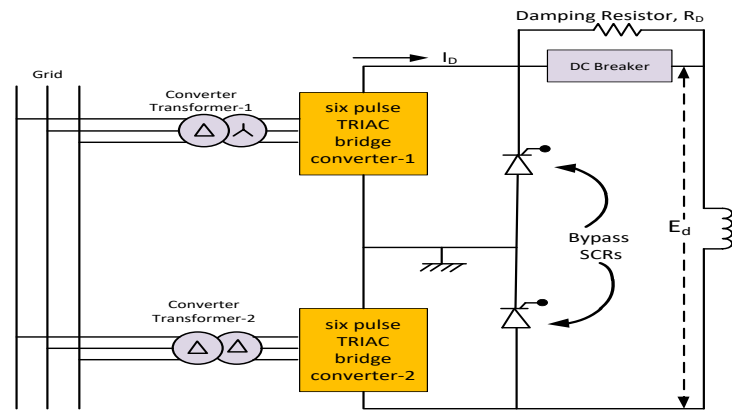


Figure 3. SMES basic configuration.

The detailed dynamic model of SMES for frequency stability studies along with the FOPI controller are shown in Figure 4. During excessive system loading, the load surpasses the generation, the E_D becomes negative, while the current I_D maintains the same direction. The incremental change in E_D is written as

$$\Delta E_D = \frac{K_{SMES}\Delta E - K_{ID}\Delta I_D}{1 + sT_{DC}} \quad (8)$$

where K_{SMES} is the SMES gain, ΔE_D is the output of the FOPI controller, K_{ID} is the negative feedback gain, ΔI_D is the incremental change in superconducting coil current, and T_{DC} is the converter delay time. The incremental change in inductor current I_D is written as

$$\Delta I_D = \frac{\Delta E_D}{sL} \quad (9)$$

The active power of SMES can be derived as follows based on Equations (8) and (9).

$$\Delta P_{SMES} = \frac{K_{SMES}(1 + sT_{DC})sL}{(1 + sT_{DC})[(1 + sT_{DC})sL + K_{ID}]}(I_D + I_{D0}) \quad (10)$$

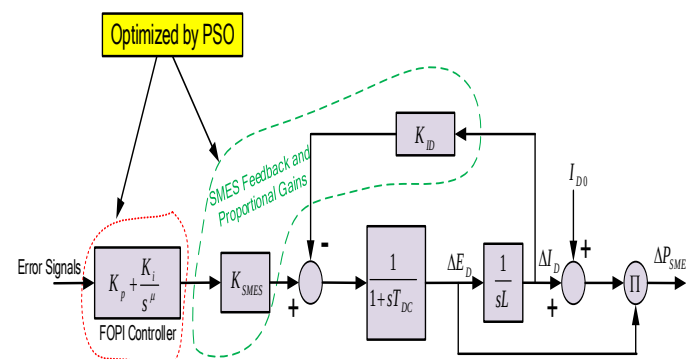


Figure 4. The dynamic SMES model along with the FOPI controller.

3.1. Controller Design

This study focuses on the optimal FOPI-SMES design based on the PSO algorithm to augment the frequency stability of the two-area power system. The fractional-order calculus involves generalized differentiation and integration of non-integer order [33,34]. The fractional-order controller is applied in several engineering fields such as automatic control and power systems due to its superiority over conventional integer order controllers.

The time domain FOPI controller can be represented as

$$u(t) = K_p \cdot e(t) + \int_t^\lambda K_i \cdot e(t) \quad (11)$$

where $e(t)$ is the error signal, K_p is the proportional gain, K_i is the integral gain, and λ is a fractional order and real number that lies between 0 and 2. The Laplace transformation gives the following transfer function for the FOPI controller.

$$C(s) = K_p + \frac{K_i}{s^\lambda}, \lambda \in (0, 2) \quad (12)$$

The conventional integer order PI and the FOPI can be understood using Figure 5 in the λ axis. The integer order controller is represented by two points on the λ axis. However, the FOPI controller can be represented by the infinite number of points between 0 and 2. Thus, it gives more degree of freedom and flexibility over the conventional integer order controller.

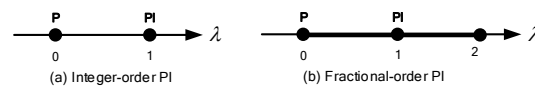


Figure 5. PI controller (fractional order and integer order).

As presented in Figure 4, the SMES virtual inertia based on FOPI is developed in this study to support the frequency of the low-inertia interconnected system. The feedback and proportional gains of SMES along with the FOPI's proportional gain, integral gain, and fractional parameter are optimized with PSO. The following subsections describe the objective function formulation and solution system with the PSO.

3.2. Description of Cost Function

The appropriate cost function is vital in the application of nature-inspired and heuristic optimization techniques in power systems. In general, the cost function is defined to minimize or maximize some variables. In this work, several FOPI gains, fractional orders, SMES feedback gains, and proportional gains are designed based on tie-line power fluctuation and area frequency deviation. For better comprehension of the optimization process, the following cost function is considered.

$$\text{Minimize: } ISE = \int_0^T (|\Delta f_1|^2 + |\Delta f_2|^2 + |\Delta P_{tie}|^2) dt \quad (13)$$

$$\text{Decision Variables: } K_{p1}, K_{i1}, \lambda_1, K_{p2}, K_{i2}, \lambda_2, K_1, K_2, K_{ID1}, K_{SMES1}, K_{ID2}, K_{SMES2} \quad (14)$$

$$\text{Constraints: } K_{p12min} \leq K_{p12} \leq K_{p12max}, K_{i12min} \leq K_{i12} \leq K_{i12max}, K_{1min} \leq K_1 \leq K_{1max}, K_{1min} \leq K_1 \leq K_{1max}, K_{ID12min} \leq K_{ID12} \leq K_{ID12max}, K_{SMES12min} \leq K_{SMES12} \leq K_{SMES12max} \quad (15)$$

where subscripts 1 and 2 are to denote area 1 and area 2 for the interconnected power system. T is the simulation time, Δf is the frequency deviation, ΔP_{tie} is tie-line power deviation, K_p is the FOPI proportional gain, K_i is the FOPI integral gain, K_{ID} is the SMES negative feedback gain, and K_{SMES} is the SMES proportional gain. Mainly, the upper and lower

limits of Equation (15) are selected based on knowledge/experience of FOPI and SMES applications in power system. The optimization algorithm is coded in a MATLAB script (.m files) environment and linked with the MATLAB Simulink (.slx files) environment.

3.3. Solution Approach with PSO

This study proposes a FOPI-based SMES virtual inertia approach in which the minimization problem described by Equation (13) is solved by the PSO. PSO, a heuristic optimization technique, was inspired by the sociological behavior of birds flocking [43]. In the PSO algorithm, several random particles that move in a search space to find the best minimum or maximum value of the cost function based on the minimization or maximization problem, respectively, are initially generated. The PSO shows outstanding performance compared to the other algorithms, as follows [44–46]:

- Since the PSO uses a numerical valued cost function, it is suitable for any nonderivative cost function optimization.
- The PSO facilitates more flexible and robust control frameworks as it uses probability rules.
- It does not fall into premature convergence.
- It has great flexibility for use in online optimization.
- It requires less time compared to other algorithms.
- It provides accurate results with very simple operations.

In recent years, the PSO has been implemented successfully to solve several power system problems such as that presented in [47,48]. The position and velocity vectors in a multi-dimensional solution space for PSO algorithm are mainly described by two equations as follows [49]:

$$v_i^k = c \left\{ v_i^{k-1} + c_1 r_1 (p_i^{k-1} - x_i^{k-1}) + c_2 r_2 (p_g^{k-1} - x_i^{k-1}) \right\} \quad (16)$$

$$x_i^k = x_i^{k-1} + v_i^k \quad (17)$$

where v_i^k and x_i^k are the velocities of i th particle for the k th iteration in a multi-dimension search space and the position of i th particle for the k th iteration in a multi-dimension search space, respectively; p_i^{k-1} and p_g^{k-1} are the individual best and global best, respectively, for the i th particle of the $(k-1)$ th iteration; r_1 and r_2 are the uniformly distributed random numbers in $[0, 1]$; and c_1 and c_2 are the learning factors used to obtain the best solution. In addition, the c is the constriction factor that is calculated from the values of c_1 and c_2 , as follows:

$$c = \frac{1}{2 - (c_1 + c_2) - \sqrt{(c_1 + c_2)^2 - 4(c_1 + c_2)}} \quad (18)$$

The maximum velocity and minimum velocity of each particle can be calculated as follows:

$$v_i^{max,min} = \pm (x_i^{max} - x_i^{min}) / N \quad (19)$$

where v_i^{max} and v_i^{min} are the maximum and minimum velocities of the i th particle, respectively; x_i^{max} and x_i^{min} are the maximum and minimum limits of the i th particle, respectively; and N is a number that takes a value between 5–10. The PSO solution steps for solving the optimization problem formulated in Section 3.2 is described below.

Step 1: Initialization of the limits of several variables and particle velocity, as described by Equations (15) and (19), respectively.

Step 2: Selection of the PSO initial parameters including c_1 , c_2 , maximum iteration, population size, etc.

Step 3: Generation of the initial population within the limits.

Step 4: Running the time domain simulation and determining the value of the objective function described by Equation (13).

Step 5: Storing the local best, the best of the current population, and the global best, the best of the total population.

Step 6: Updating the velocity of all populations using Equation (16).

Step 7: Generating a new population based on the updated particle position calculated by Equation (17).

Step 8: Stopping the optimization if the termination criteria are met. Otherwise, returning to step 4.

The overall flowchart for the PSO algorithm to design FOPI and SMES parameters is shown in Figure 6.

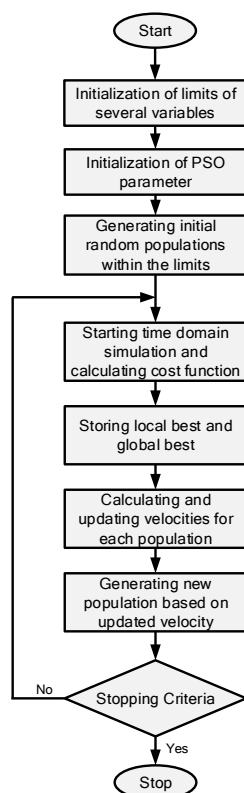


Figure 6. The PSO flowchart for optimizing control parameters.

4. Results and Discussion

The effectiveness and robustness of the proposed optimized FOPI controller in improving the frequency stability are presented in this section. The dynamic model of the system presented in Figure 2 is considered for analytical analysis. The system parameters listed in Table 1 are used to conduct computer simulations and to facilitate analyses. The total generation capacity of the two-area power is 55 MW. The rating of the energy storage device is 6 MW. The proposed energy storage with only 10.9% of the total plant capacity is capable of maintaining frequency stability in case of several load–generation mismatches. The simulations were conducted in MATLAB Simulink considering several scenarios such as light loading, medium loading, heavy loading, and reduced inertia. The system dynamic model was built in Simulink and linked with the PSO optimization code to optimally design the SMES and FOPI parameters. PSO algorithm convergence for the proposed cost function is depicted in Figure 7. As shown in Figure 7, the optimization algorithm converges at the iteration number 20 for several runs, and the corresponding optimized parameters are listed in Table 2.

The system was tested under several step load variations in both areas of the system. The frequency deviations in both areas were plotted for three cases such as (i) without any

inertia controller, (ii) with a conventional SMES controller, and (iii) with the PSO optimized FOPI-based SMES controller.

Table 1. System parameters for simulation.

Parameters	Value	
	Area-1	Area-2
Inertia (p.u. MW s)	0.079	0.11
Damping constant (p.u. MW/Hz)	0.016	0.017
Time constant of solar system (s)	1.2	1.2
Time constant of wind system (s)	1.4	1.4
Frequency bias factor (p.u. MW/Hz)	0.3585	0.3928
Valve gate maximum limit (p.u. MW)	0.5	0.5
Valve gate minimum limit (p.u. MW)	−0.5	−0.5
Synchronizing coefficient (p.u. MW/Hz)	0.09	0.09
Area capacity ratio	−0.055	−0.055
Generation rate constraint (GRC)	0.3	0.3
Thermal generator (MW)	12	15
Wind generator (MW)	8	8
PV generator (MW)	6	6
Energy storage power rating (MW)	3	3
Energy storage inductor (H)	2.65	2.65
Energy storage time constant (s)	0.05	0.05
Energy storage reference current (kA)	4.5	4.5

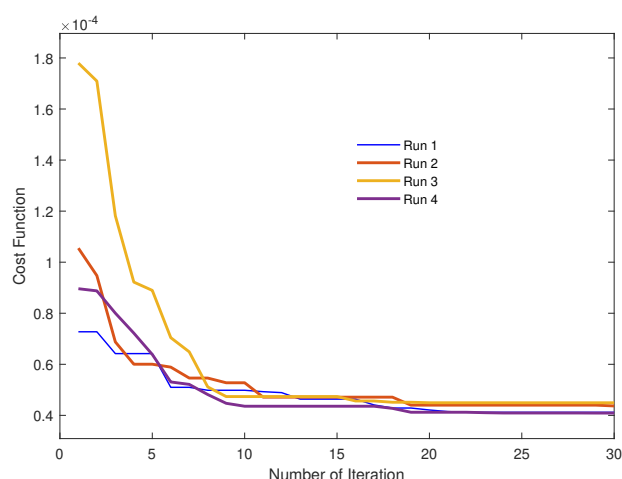


Figure 7. The convergence of the cost function.

Table 2. PSO-optimized FOPI and SMES parameters.

Optimized Parameters			
Name	Value	Name	Value
K_{p1}	6.8650	K_1	0.1931
K_{i1}	117.60	K_2	0.5000
λ_1	0.9603	K_{ID1}	2.9782
K_{p2}	21.660	K_{SMES1}	0.1300
K_{i2}	78.820	K_{ID2}	2.4879
λ_2	0.6855	K_{SMES2}	0.0410

4.1. Frequency Response Study for Step Load Change in Area 1

In this case, the studied system is simulated for default inertia (100%), as shown in Table 1. The frequency deviations for both areas are depicted in Figure 8 for low, medium, and high step load changes in area 1. The positive effect of the proposed controller is

visualized through the reduction in frequency deviations. As visualized in Figure 8a, a step load change of 0.1 p.u. in area 1 causes a significant frequency deviation in area 1 without a virtual inertia controller. The frequency deviation is around 0.42 Hz without any auxiliary controller. The conventional controller-based SMES improves the deviation to about 0.035 Hz. However, the proposed PSO optimization-based FOPI controller for SMES greatly improves the frequency deviation in area 1, which is around 0.005 Hz. It is noteworthy that the settling time is slightly increased for conventional SMES controllers while the frequency deviation is improved. However, the proposed optimized FOPI-based SMES significantly improves all indices, such as settling time, maximum undershoot, and maximum overshoot. Likewise, the frequency deviation in area 2 is very high, around 0.02 Hz, without any inertia controller, as depicted in Figure 8b. The conventional SMES controller improves frequency deviation to some extent. However, the proposed optimized FOPI-based SMES controller reduces the frequency deviation to almost zero. It is observed that, for a large step load change (0.35 p.u.) in area 1, the system cannot maintain stable operation. As visualized in Figure 8e,f, the frequency deviations in both areas continue to increase, leading to instability in the system. The application of the conventional SMES controller can maintain stable operation with some frequency deviation. On the other hand, our proposed techniques stabilize the system with almost zero frequency deviations in both areas. Thus, the system response for several load disturbances in area 1 using the proposed controller is faster, has a very small steady-state error, and is better in terms of overshoot and undershoot compared to other control strategies. The frequency deviations for several scenarios in area 1 and area 2 are given in Table 3 to clearly show the positive impact of the proposed FOPI-based SMES controller on system performance.

Table 3. Reduction in frequency deviations in area 1 and area 2 with the proposed controller.

Area	Step Load Change in p.u.	Frequency Deviation					
		Δf_1 (Hz)			Δf_2 (Hz)		
		without Inertia Controller	Conventional SMES Controller	FOPI Based SMES	without Inertia Controller	Conventional SMES Controller	FOPI Based SMES
Area-1	0.1	0.420	0.035	0.005	0.020	0.004	4.0×10^{-5}
	0.2	0.850	0.080	0.010	0.040	0.008	3.2×10^{-5}
	0.35	unstable	0.120	0.040	unstable	0.030	2.1×10^{-5}
Area-2	0.1	0.395	0.025	1.9×10^{-5}	0.320	0.030	0.010
	0.2	0.840	0.060	1.2×10^{-5}	0.630	0.090	0.012
	0.35	2.650	0.150	1.0×10^{-5}	2.125	0.106	0.025

4.2. Frequency Response Study for Step Load Change in Area 2

The load disturbances, ranging from the low to high levels, are also applied in area 2 with the system default inertia. It is noticed that the system frequency oscillates over a wide range without any inertia controller. In some cases, the oscillations are beyond the acceptable limits; thus, it requires the system frequency protection relay to operate. As depicted in Figure 9, the frequency deviation in area 1 is 0.395 Hz without any virtual inertia controller for a step load change of 0.1 p.u. The conventional SMES controller reduces the frequency deviation to 0.025 Hz, whereas the proposed optimized FOPI controller is capable of maintaining almost zero frequency deviation. Similarly, the frequency deviation in area 2 is 0.32 Hz without any auxiliary controller. The conventional SMES controller is capable of reducing the frequency deviation by 90.6%. However, the proposed optimized FOPI-based SMES controller reduces the frequency deviation by 96.87%. For the medium and high step load changes in area 2, at 0.2 p.u. and 0.35 p.u., respectively, the frequencies of both areas fall below the under-frequency relay operating setpoint of 59.5 Hz [50] without any virtual inertia controller.

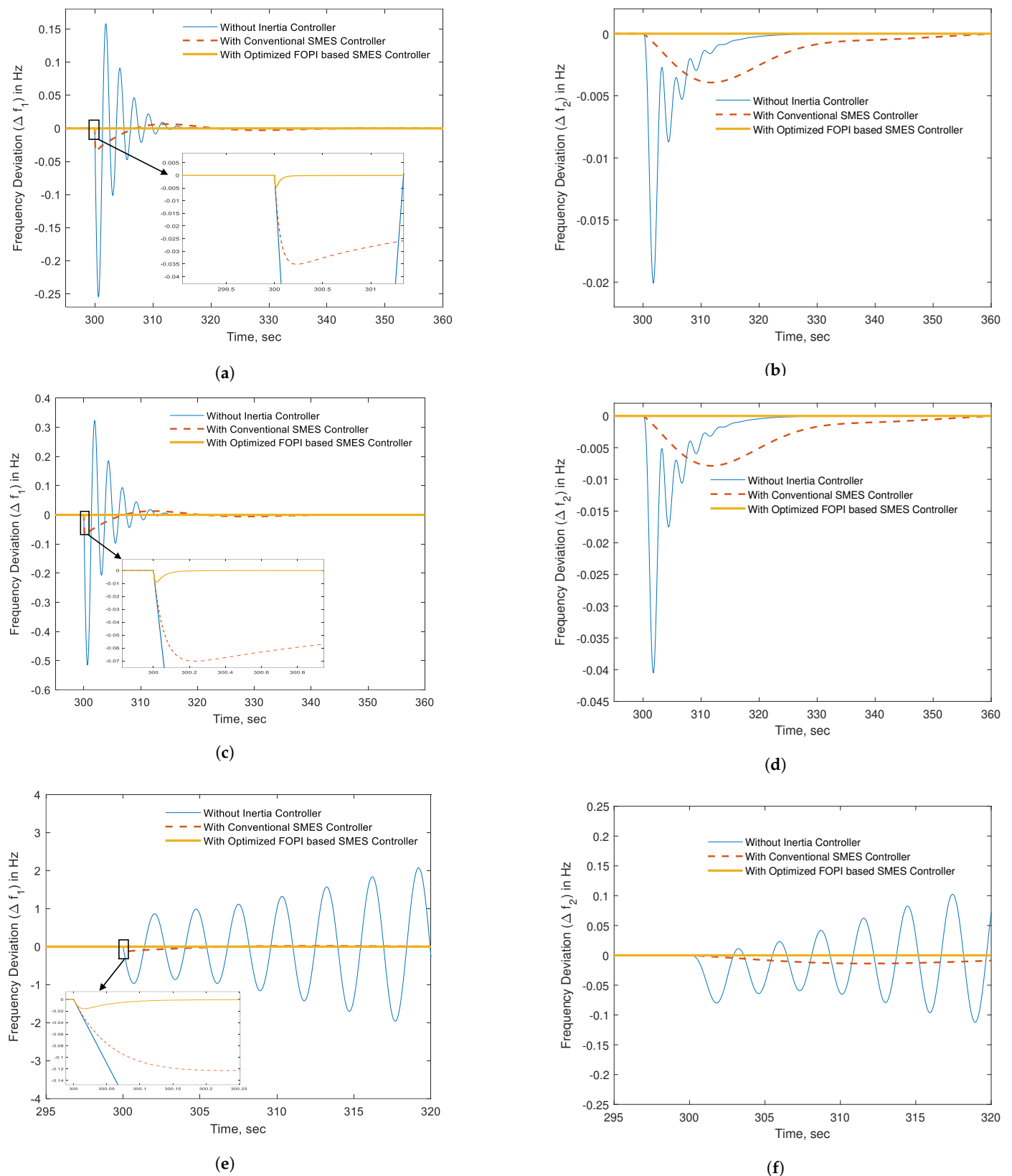
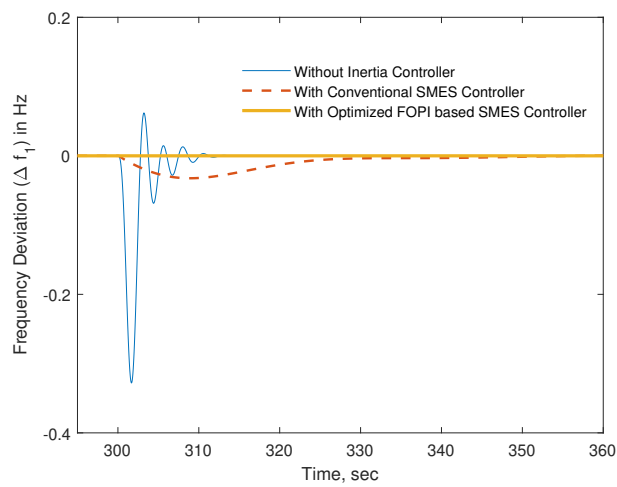
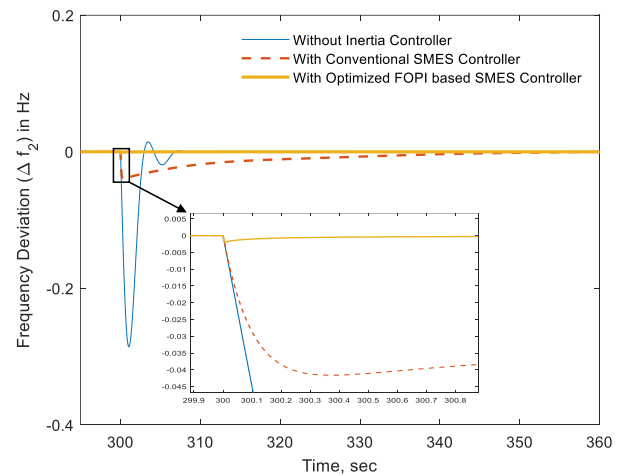


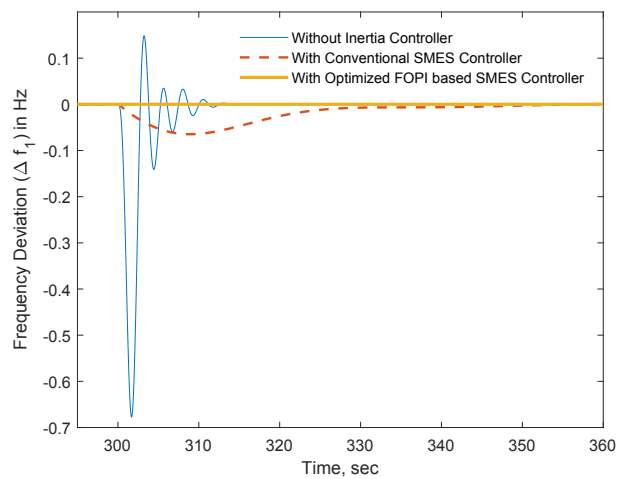
Figure 8. Performance improvement with the proposed controller for load disturbances in area 1. (a) Area 1 frequency response for a 0.1 p.u. step load change. (b) Area 2 frequency response for a 0.1 p.u. step load change. (c) Area 1 frequency response for a 0.2 p.u. step load change. (d) Area 2 frequency response for a 0.2 p.u. step load change. (e) Area 1 frequency response for a 0.35 p.u. step load change. (f) Area 2 frequency response for a 0.35 p.u. step load change.



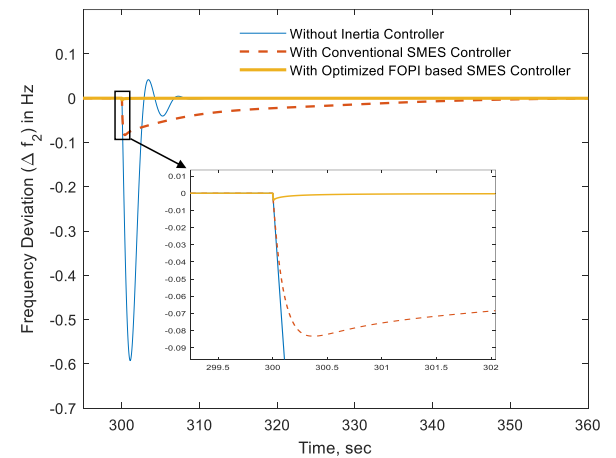
(a)



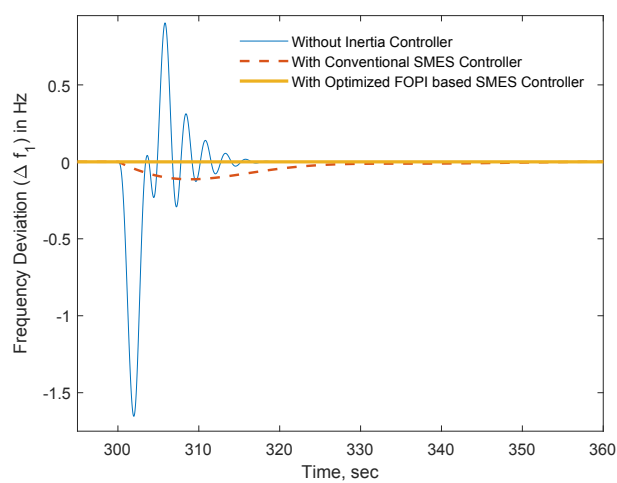
(b)



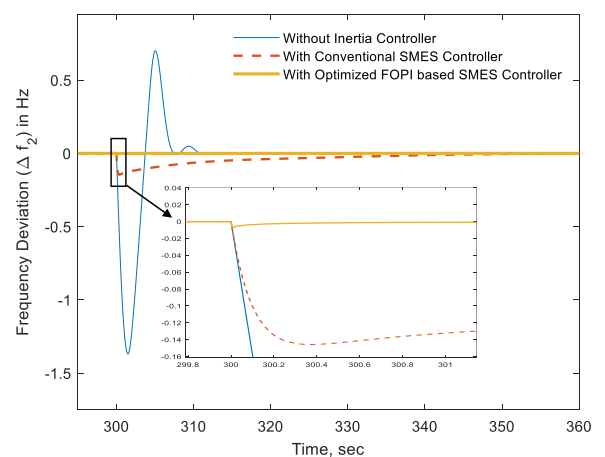
(c)



(d)



(e)



(f)

Figure 9. Performance improvement with the proposed controller for load disturbances in area 2. (a) Area 1 frequency response for a 0.1 p.u. step load change. (b) Area 2 frequency response for a 0.1 p.u. step load change. (c) Area 1 frequency response for a 0.2 p.u. step load change. (d) Area 2 frequency response for a 0.2 p.u. step load change. (e) Area 1 frequency response for a 0.35 p.u. step load change. (f) Area 2 frequency response for a 0.35 p.u. step load change.

However, the frequency deviation is well below the under-frequency relay operating point with the conventional SMES controller, as depicted in Figure 9c–f. In these figures, it is visualized that the proposed controller is capable of maintaining the frequency deviations in both areas at almost zero. Thus, the system stability and reliability are guaranteed with the proposed FOPI-based SMES controller. The overall frequency deviations for several cases are listed in Table 3.

4.3. Controller Performance with Solar PV and Wind Power Fluctuations

The effectiveness of the proposed controller was also tested with fluctuating solar and wind power in both areas. The intermittent solar and wind power disturbances considered in this study are depicted in Figure 10a,b, respectively. The solar and wind powers have mean values of 0.05 p.u. and 0.15 p.u., respectively. The solar power is integrated in area 1 at 50 s during the 150 s simulation time, which continues to inject fluctuating power during the entire simulation period. On the other hand, the intermittent wind generating unit is connected at 75 s, which is kept connected throughout the entire simulation period. As shown in Figure 10c,d, the connection of varying solar and wind powers has a detrimental effect on system frequency response without any auxiliary controller.

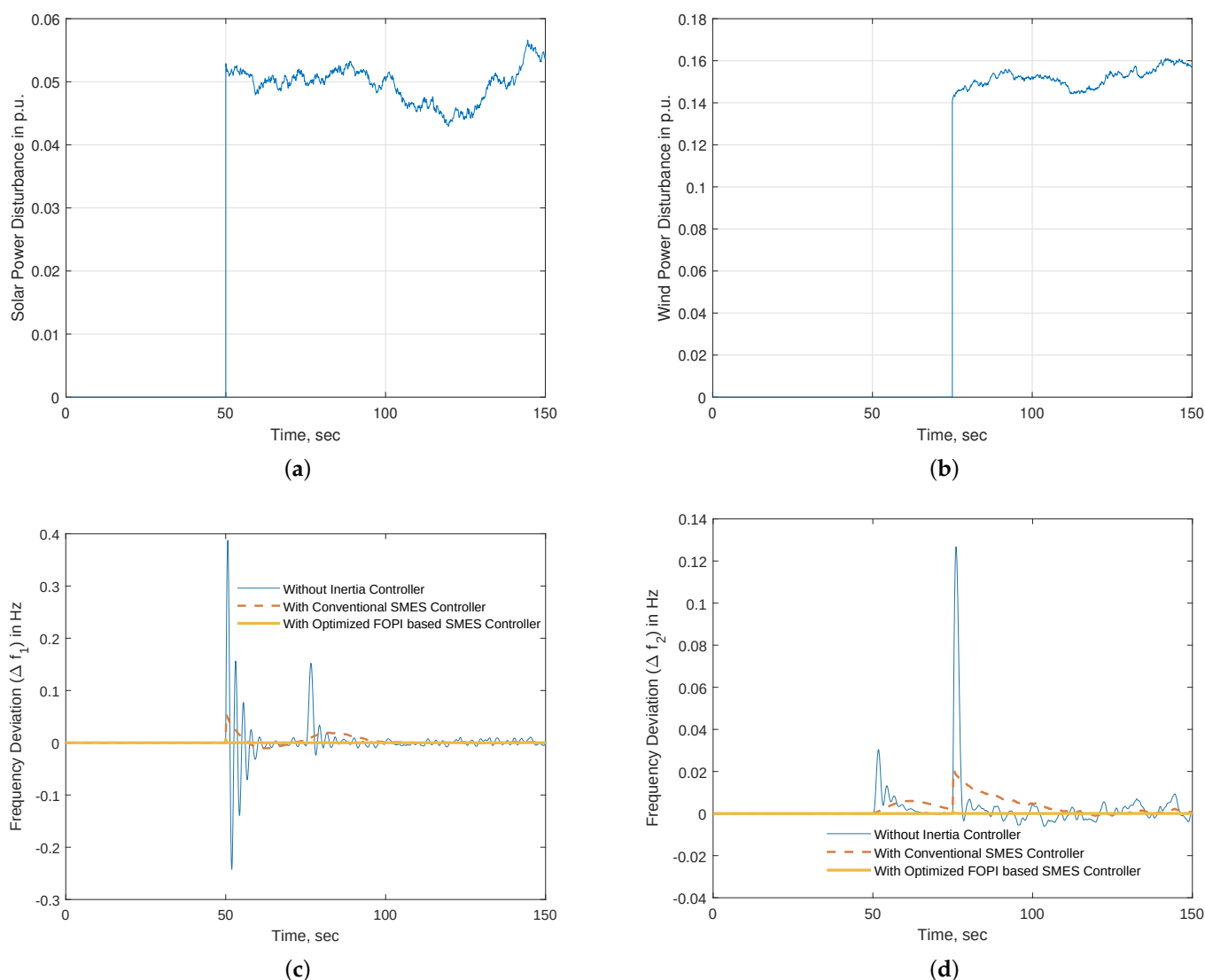


Figure 10. The frequency response for wind generation addition at 50 s and solar generation addition at 75 s. (a) Solar power disturbance. (b) Wind power disturbance. (c) Area 1 frequency response for intermittent solar and wind power. (d) Area 2 frequency response for intermittent solar and wind power.

The frequency of the system continues to vary during the entire simulation period and does not settle to a steady-state value. The conventional SMES controller slightly improves the system frequency response. On the other hand, the proposed controller performance is superior, in terms of settling time, overshoot, and undershoot, to the conventional SMES controller. The improvement of several performance indices is listed in Table 4 to demonstrate the superiority of the proposed controller.

Table 4. Improvement of the performance indices for intermittent solar and wind power integration.

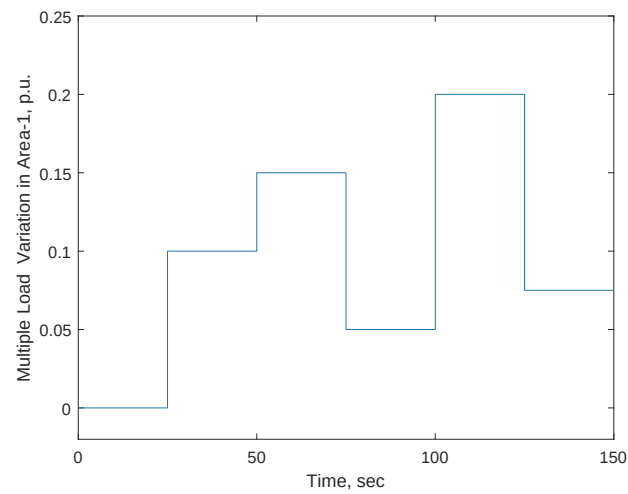
Performance Indices	without Inertia Controller	Conventional SMES	Optimized FOPI Based SMES
Maximum Overshoot, Hz	0.39	0.05	0.0100
Maximum Undershoot, Hz	0.25	0.01	0.0001
Settling Time, Sec	inf	50	2

4.4. Frequency Response Analysis for Multiple Load Changes

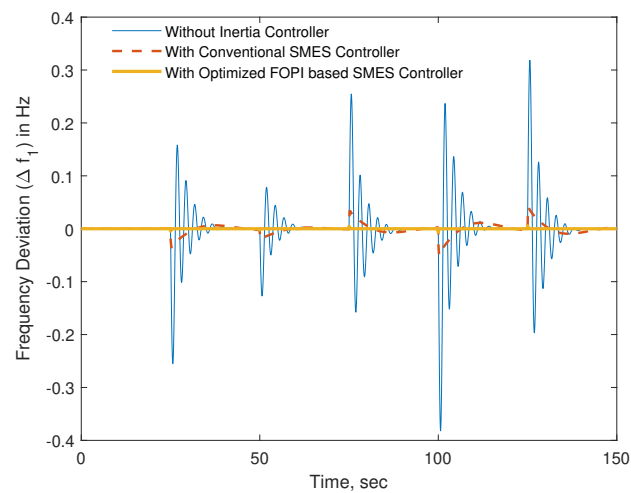
The effectiveness and robustness of the proposed control technique for virtual control of low inertia systems were also tested with multiple load change scenarios. Several step load changes were considered, as shown in Figure 11a, to investigate the system capability to bring back the frequency deviation to zero before the next changes. Better performance of the proposed FOPI-based SMES is visible from the system frequency response, as seen in Figure 11b, following the first step load change of 0.1 p.u. at 25 s. The proposed controller is faster at eliminating the frequency deviation before the beginning of the second step load change of 0.15 p.u. at 50 s compared to conventional techniques. The frequency deviations in area 1 are very high at all points of step changes without a virtual inertia controller. Although the conventional SMES controller improves the frequency response slightly, a notable improvement is achieved with the proposed technique. In this case, also, the proposed method provides a much better performance in terms of overshoot, undershoot, and settling time. The frequency response for area 2 as visualized in Figure 11c shows better performance with the proposed control technique.

4.5. The Robust Performance of the Proposed Controller with the Reduced System Inertia

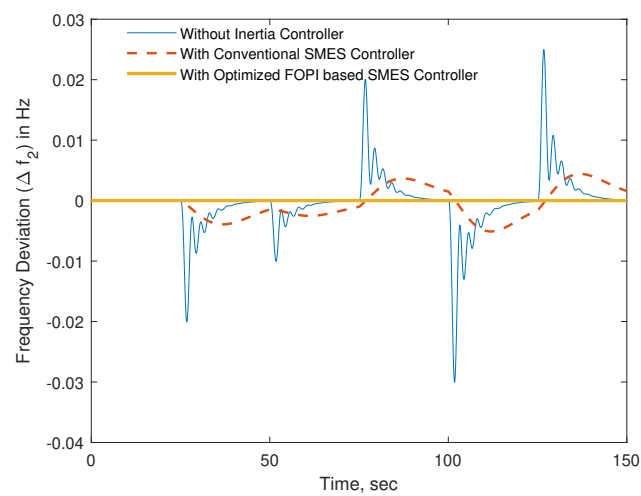
In this scenario, the robustness of the proposed controller is verified with the system inertia variations. The inertia in both areas is reduced by 50%, and a step load change of 0.15 p.u. is applied in area −1 at 50 s. The frequency response for this load change is depicted in Figure 12a,b. As depicted in Section 4.1, the system is capable of maintaining stable operation with a step load change of 0.15 p.u. in the case of default inertia (100%). However, Figure 12a,b show that the frequency deviations in both areas gradually increase, leading to instability. The system without SMES requires the under-frequency relay to start operation within 1 second of the load variation since the frequency deviation goes below 0.5 Hz, as depicted in Figure 12a. Although the area 2 frequency takes a longer time to operate under frequency relay, it is also unstable, as depicted by the increasing frequency oscillation in Figure 12b. The conventional SMES controller reduces the frequency deviations and stabilizes the system. However, the proposed control method augments the system stability greatly by reducing frequency deviations to almost zero even with 50% system inertia. The model presented in Figure 2 was also tested for very low inertia with a step load change of 0.1 p.u. in area 1. As shown in Figure 13, the controller is capable of stabilizing the model of Figure 2 for these low inertia. Furthermore, the robustness of the proposed optimized FOPI controller is compared with the non-optimized FOPI controller. The frequency deviation for the system with 15% inertia is plotted in Figure 14 with the optimized FOPI and non-optimized FOPI controller. Thus, the proposed controller is more robust compared to the conventional technique. The main limitation of the proposed technique is that the SMES is a costly solution. Further studies may be conducted on FOPI-based hybrid energy storage devices such as SMES, battery, and supercapacitor for the frequency control of low inertia PV/wind-integrated systems.



(a)

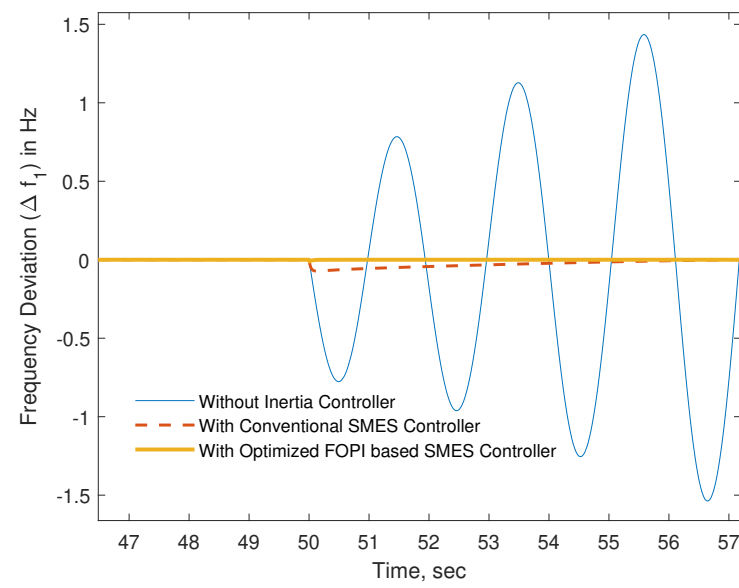


(b)

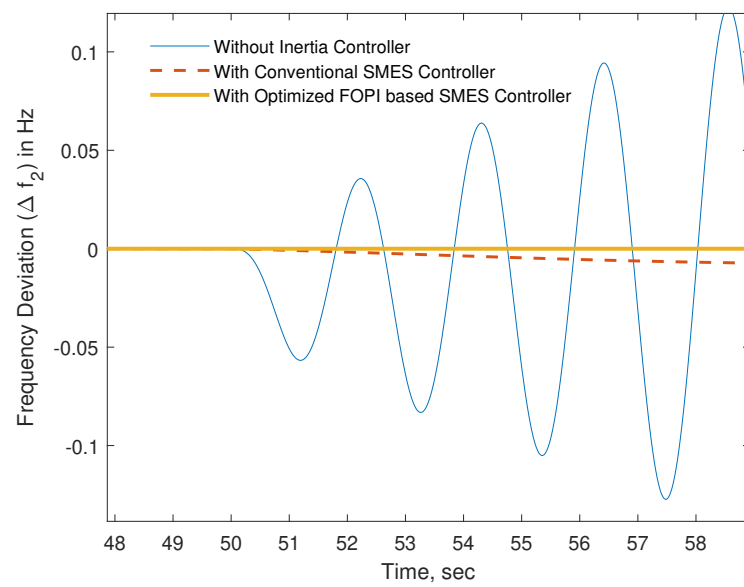


(c)

Figure 11. (a) Multiple load variations in area 1. (b) Frequency response in area 1. (c) Frequency response in area 2.



(a)



(b)

Figure 12. System response for 50% inertia (a) Area 1 frequency response. (b) Area -2 frequency response.

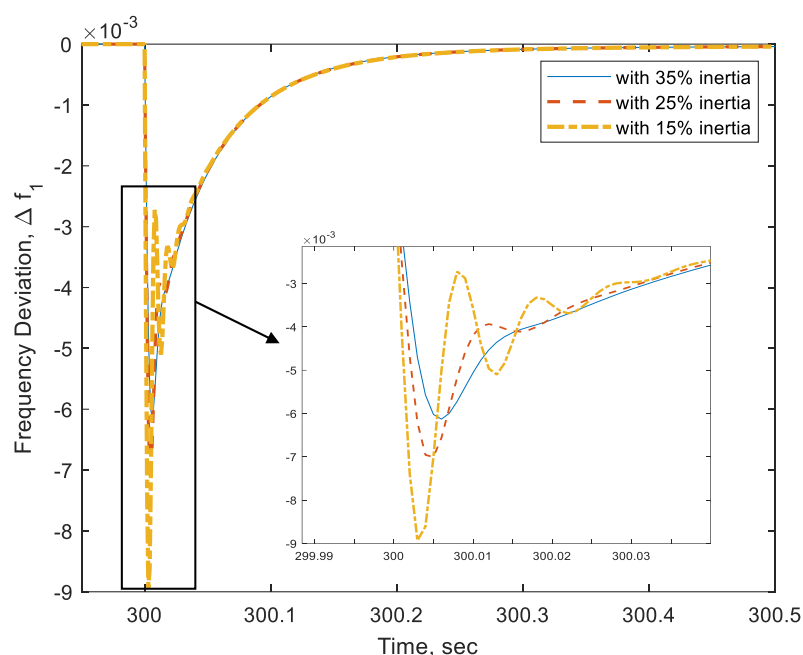


Figure 13. The system response for very low inertia.

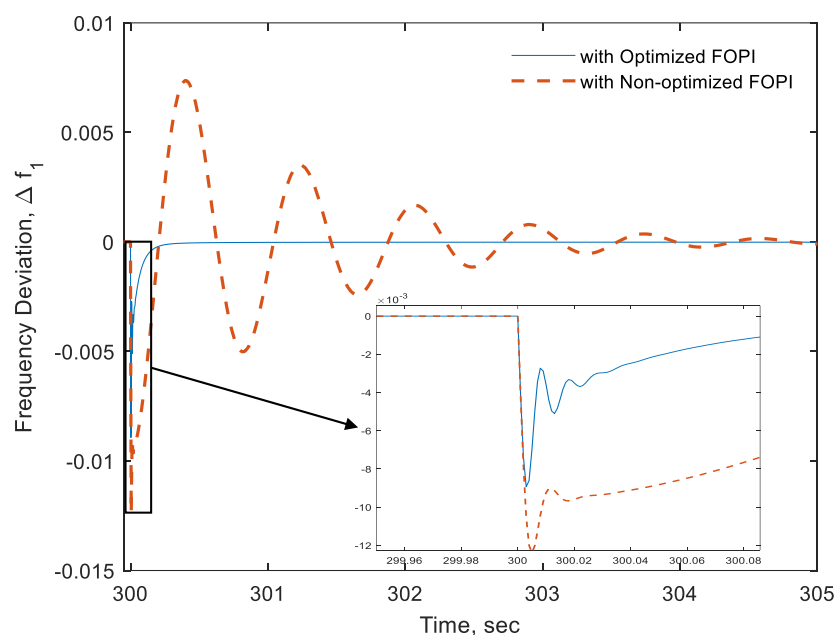


Figure 14. The frequency response comparison for the optimized and non-optimized FOPI controllers.

5. Conclusions

In this work, an optimized FOPI-based SMES virtual inertia controller is designed for a highly renewable energy integrated system. The dynamic model of the system is developed with FOPI to facilitate analysis and design of optimal parameters using PSO. The system response was analyzed with the designed virtual inertia controller considering highly fluctuating solar PV and wind energy. The system and the associated controllers were simulated in MATLAB Simulink. Small, medium, and large load disturbances were applied in the system to prove the effectiveness of the proposed energy storage-based virtual inertia control strategy. The system with default inertia and reduced inertia were tested under single and multiple load disturbances to guarantee the robustness of the proposed controller. The simulated results show promising performance in reducing system frequency deviations and in improving the frequency stability of the system. The proposed

controller is superior to the conventional controller in reducing settling time, overshoot, and undershoot, as evident from the analysis. Moreover, the simulation outcomes prove the potential benefits of FOPI controller-based energy storage in high-level renewable energy integration and endorse the green efforts to improve sustainability. Finally, a detailed large-scale DFIG offshore wind farm model with FOPI-based hybrid energy storage virtual inertia controller can be studied as future work.

Author Contributions: Conceptualization, M.S.A.; methodology, M.S.A.; formal analysis, M.S.A., F.S.A.-I. and M.A.A.; writing—original draft preparation, M.S.A.; writing—review and editing, M.S.A. and F.S.A.-I.; supervision, M.A.A.; and funding acquisition, M.S.A. and F.S.A.-I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the support provided by King Fahd University of Petroleum & Minerals (KFUPM) through the directly funded project No. DF201022. The authors also acknowledge the funding support provided by K.A.CARE Energy Research & Innovation Center (ERIC), KFUPM, Dhahran, Saudi Arabia.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RESs	Renewable energy sources
RoCoF	Rate of change of frequency
FOPI	Fractional-order proportional integral
SMES	Superconducting magnetic energy storage
PV	Photovoltaic
RE	Renewable Energy
PI	Proportional integral
PID	Proportional integral derivative
DFIG	Doubly fed induction generator
CCFC	Capacity constrained frequency control
LFC	Load frequency control
AEC	Area control error
PSO	Particle swarm optimization
GDB	Governor dead band
ANFIS	Adaptive neuro fuzzy system
TCPS	Thyristor controlled phase shifter
ABC	Ant bee colony
SOA	Seeker optimization algorithm
HS	Harmony search
WF	Wind farm
GRC	Generation rate constraint
PCS	Power conversion system
SA	Solar array
ISE	Integral squared error

References

1. Yongning, C.; Yan, L.; Zhen, W.; Zhen, L.; Hongzhi, L.; Zhankui, Z. The Characteristics and Challenge on Large-Scale Renewable Energy Grid Integration. In Proceedings of the 2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), Chengdu, China, 21–24 May 2019; pp. 1393–1398.
2. Kumar, K.P.; Saravanan, B. Recent techniques to model uncertainties in power generation from renewable energy sources and loads in microgrids—A review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 348–358. [[CrossRef](#)]

3. Samani, A.E.; D'Amicis, A.; De Kooning, J.D.; Bozalakov, D.; Silva, P.; Vandeveld, L. Grid balancing with a large-scale electrolyser providing primary reserve. *IET Renew. Power Gener.* **2020**, *14*, 3070–3078. [\[CrossRef\]](#)
4. Dadkhah, A.; Bozalakov, D.; De Kooning, J.D.; Vandeveld, L. On the optimal planning of a hydrogen refuelling station participating in the electricity and balancing markets. *Int. J. Hydrog. Energy* **2021**, *46*, 1488–1500. [\[CrossRef\]](#)
5. Alam, M.S.; Al-Ismael, F.S.; Salem, A.; Abido, M.A. High-Level Penetration of Renewable Energy Sources Into Grid Utility: Challenges and Solutions. *IEEE Access* **2020**, *8*, 190277–190299. [\[CrossRef\]](#)
6. Morren, J.; De Haan, S.W.; Kling, W.L.; Ferreira, J. Wind turbines emulating inertia and supporting primary frequency control. *IEEE Trans. Power Syst.* **2006**, *21*, 433–434. [\[CrossRef\]](#)
7. Fini, M.H.; Golshan, M.E.H. Frequency control using loads and generators capacity in power systems with a high penetration of renewables. *Electr. Power Syst. Res.* **2019**, *166*, 43–51. [\[CrossRef\]](#)
8. Ulbig, A.; Borsche, T.S.; Andersson, G. Impact of low rotational inertia on power system stability and operation. *IFAC Proc. Vol.* **2014**, *47*, 7290–7297. [\[CrossRef\]](#)
9. Saxena, P.; Singh, N.; Pandey, A.K. Enhancing the dynamic performance of microgrid using derivative controlled solar and energy storage based virtual inertia system. *J. Energy Storage* **2020**, *31*, 101613. [\[CrossRef\]](#)
10. Pradhan, C.; Bhende, C. Enhancement in primary frequency contribution using dynamic deloading of wind turbines. *IFAC-PapersOnLine* **2015**, *48*, 13–18. [\[CrossRef\]](#)
11. Ma, H.; Chowdhury, B. Working towards frequency regulation with wind plants: Combined control approaches. *IET Renew. Power Gener.* **2010**, *4*, 308–316. [\[CrossRef\]](#)
12. Khooban, M.H.; Niknam, T. A new intelligent online fuzzy tuning approach for multi-area load frequency control: Self Adaptive Modified Bat Algorithm. *Int. J. Electr. Power Energy Syst.* **2015**, *71*, 254–261. [\[CrossRef\]](#)
13. Magdy, G.; Mohamed, E.A.; Shabib, G.; Elbaset, A.A.; Mitani, Y. SMES based a new PID controller for frequency stability of a real hybrid power system considering high wind power penetration. *IET Renew. Power Gener.* **2018**, *12*, 1304–1313. [\[CrossRef\]](#)
14. Cominos, P.; Munro, N. PID controllers: Recent tuning methods and design to specification. *IEE Proc. Control Theory Appl.* **2002**, *149*, 46–53. [\[CrossRef\]](#)
15. Yang, L.; Hu, Z.; Xie, S.; Kong, S.; Lin, W. Adjustable virtual inertia control of supercapacitors in PV-based AC microgrid cluster. *Electr. Power Syst. Res.* **2019**, *173*, 71–85. [\[CrossRef\]](#)
16. Magdy, G.; Shabib, G.; Elbaset, A.A.; Mitani, Y. A novel coordination scheme of virtual inertia control and digital protection for microgrid dynamic security considering high renewable energy penetration. *IET Renew. Power Gener.* **2018**, *13*, 462–474. [\[CrossRef\]](#)
17. Kerdphol, T.; Watanabe, M.; Mitani, Y.; Phunpeng, V. Applying Virtual Inertia Control Topology to SMES System for Frequency Stability Improvement of Low-Inertia Microgrids Driven by High Renewables. *Energies* **2019**, *12*, 3902. [\[CrossRef\]](#)
18. Gomez, L.; Grilo, A.P.; Salles, M.; Sguarezi Filho, A. Combined Control of DFIG-Based Wind Turbine and Battery Energy Storage System for Frequency Response in Microgrids. *Energies* **2020**, *13*, 894. [\[CrossRef\]](#)
19. Kerdphol, T.; Watanabe, M.; Hongesombut, K.; Mitani, Y. Self-Adaptive Virtual Inertia Control-Based Fuzzy Logic to Improve Frequency Stability of Microgrid With High Renewable Penetration. *IEEE Access* **2019**, *7*, 76071–76083. [\[CrossRef\]](#)
20. Kim, J.; Muljadi, E.; Gevorgian, V.; Mohanpurkar, M.; Luo, Y.; Hovsopian, R.; Koritarov, V. Capability-coordinated frequency control scheme of a virtual power plant with renewable energy sources. *IET Gener. Transm. Distrib.* **2019**, *13*, 3642–3648. [\[CrossRef\]](#)
21. Abo-Elyousr, F.K.; Abdelaziz, A.Y. A Novel Modified Robust Load Frequency Control for Mass-Less Inertia Photovoltaics Penetrations via Hybrid PSO-WOA Approach. *Electr. Power Compon. Syst.* **2019**, *47*, 1744–1758. [\[CrossRef\]](#)
22. Yap, K.Y.; Sarimuthu, C.R.; Lim, J.M.Y. Grid Integration of Solar Photovoltaic System Using Machine Learning-Based Virtual Inertia Synthesis in Synchroverter. *IEEE Access* **2020**, *8*, 49961–49976. [\[CrossRef\]](#)
23. Rahman, F.S.; Kerdphol, T.; Watanabe, M.; Mitani, Y. Optimization of virtual inertia considering system frequency protection scheme. *Electr. Power Syst. Res.* **2019**, *170*, 294–302. [\[CrossRef\]](#)
24. Zhang, X.; Zhu, Z.; Fu, Y.; Li, L. Optimized virtual inertia of wind turbine for rotor angle stability in interconnected power systems. *Electr. Power Syst. Res.* **2020**, *180*, 106157. [\[CrossRef\]](#)
25. Pappachen, A.; Fathima, A.P. Load frequency control in deregulated power system integrated with SMES–TCPS combination using ANFIS controller. *Int. J. Electr. Power Energy Syst.* **2016**, *82*, 519–534. [\[CrossRef\]](#)
26. Ali, M.H.; Wu, B.; Dougal, R.A. An overview of SMES applications in power and energy systems. *IEEE Trans. Sustain. Energy* **2010**, *1*, 38–47. [\[CrossRef\]](#)
27. Shayeghi, H.; Jalili, A.; Shayanfar, H. A robust mixed H₂/H_{inf} based LFC of a deregulated power system including SMES. *Energy Convers. Manag.* **2008**, *49*, 2656–2668. [\[CrossRef\]](#)
28. Ngamroo, I.; Karaipoom, T. Cooperative control of SFCL and SMES for enhancing fault ride through capability and smoothing power fluctuation of DFIG wind farm. *IEEE Trans. Appl. Supercond.* **2014**, *24*, 1–4. [\[CrossRef\]](#)
29. Ali, M.H.; Park, M.; Yu, I.K.; Murata, T.; Tamura, J.; Wu, B. Enhancement of transient stability by fuzzy logic-controlled SMES considering communication delay. *Int. J. Electr. Power Energy Syst.* **2009**, *31*, 402–408. [\[CrossRef\]](#)
30. Chen, L.; Chen, H.; Yang, J.; Yu, Y.; Zhen, K.; Liu, Y.; Ren, L. Coordinated control of superconducting fault current limiter and superconducting magnetic energy storage for transient performance enhancement of grid-connected photovoltaic generation system. *Energies* **2017**, *10*, 56. [\[CrossRef\]](#)

31. Abu-Siada, A.; Islam, S. Application of SMES unit in improving the performance of an AC/DC power system. *IEEE Trans. Sustain. Energy* **2010**, *2*, 109–121. [[CrossRef](#)]
32. Podlubny, I. Fractional-order systems and $PI^\lambda D^\mu$ controllers. *IEEE Trans. Autom. Control* **1999**, *44*, 208–214. [[CrossRef](#)]
33. Li, H.; Luo, Y.; Chen, Y. A fractional order proportional and derivative (FOPD) motion controller: Tuning rule and experiments. *IEEE Trans. Control Syst. Technol.* **2009**, *18*, 516–520. [[CrossRef](#)]
34. Komathi, C.; Umamaheswari, M. Design of Gray Wolf Optimizer Algorithm-Based Fractional Order PI Controller for Power Factor Correction in SMPS Applications. *IEEE Trans. Power Electron.* **2019**, *35*, 2100–2118. [[CrossRef](#)]
35. Kesarkar, A.A.; Selvaganesan, N. Tuning of optimal fractional-order PID controller using an artificial bee colony algorithm. *Syst. Sci. Control Eng.* **2015**, *3*, 99–105. [[CrossRef](#)]
36. Kumar, M.R.; Deepak, V.; Ghosh, S. Fractional-order controller design in frequency domain using an improved nonlinear adaptive seeker optimization algorithm. *Turk. J. Electr. Eng. Comput. Sci.* **2017**, *25*, 4299–4310. [[CrossRef](#)]
37. Mosaad, M.I. Direct power control of SRG-based WECSs using optimised fractional-order PI controller. *IET Electr. Power Appl.* **2020**, *14*, 409–417. [[CrossRef](#)]
38. Alam, M.; Alotaibi, M.A.; Alam, M.A.; Hossain, M.; Shafiullah, M.; Al-Ismael, F.S.; Rashid, M.; Ur, M.; Abido, M.A. High-Level Renewable Energy Integrated System Frequency Control with SMES-Based Optimized Fractional Order Controller. *Electronics* **2021**, *10*, 511. [[CrossRef](#)]
39. Lee, D.J.; Wang, L. Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: Time-domain simulations. *IEEE Trans. Energy Convers.* **2008**, *23*, 311–320. [[CrossRef](#)]
40. Bevrani, H.; Habibi, F.; Babahajyani, P.; Watanabe, M.; Mitani, Y. Intelligent frequency control in an AC microgrid: Online PSO-based fuzzy tuning approach. *IEEE Trans. Smart Grid* **2012**, *3*, 1935–1944. [[CrossRef](#)]
41. Bevrani, H. *Robust Power System Frequency Control*; Springer: Boston, MA, USA, 2009; Volume 85.
42. Tripathy, S.; Balasubramanian, R.; Nair, P. Effect of superconducting magnetic energy storage on automatic generation control considering governor deadband and boiler dynamics. *IEEE Trans. Power Syst.* **1992**, *7*, 1266–1273. [[CrossRef](#)]
43. Eberhart, R.; Kennedy, J. A new optimizer using particle swarm theory. In Proceedings of the MHS'95, Sixth International Symposium on Micro Machine and Human Science, Nagoya, Japan, 4–6 October 1995; pp. 39–43.
44. Tasgetiren, M.F.; Sevkli, M.; Liang, Y.C.; Gencyilmaz, G. Particle swarm optimization algorithm for permutation flowshop sequencing problem. In Proceedings of the International Workshop on Ant Colony Optimization and Swarm Intelligence, Brussels, Belgium, 5–8 September 2004; pp. 382–389.
45. Engelbrecht, A. *Fundamentals of Computational Swarm Intelligence*; John Wiley & Sons Ltd.: Oxford, UK, 2005; pp. 5–129.
46. Abdel-Magid, Y.L.; Abido, M.A. AGC tuning of interconnected reheat thermal systems with particle swarm optimization. In Proceedings of the 10th IEEE International Conference on Electronics, Circuits and Systems, Sharjah, United Arab Emirates, 14–17 December 2003; Volume 1, pp. 376–379.
47. Hossain, M.A.; Pota, H.R.; Squartini, S.; Zaman, F.; Guerrero, J.M. Energy scheduling of community microgrid with battery cost using particle swarm optimisation. *Appl. Energy* **2019**, *254*, 113723. [[CrossRef](#)]
48. Aguilar, M.E.B.; Coury, D.V.; Reginatto, R.; Monaro, R.M. Multi-objective PSO applied to PI control of DFIG wind turbine under electrical fault conditions. *Electr. Power Syst. Res.* **2020**, *180*, 106081. [[CrossRef](#)]
49. Kanwar, N.; Gupta, N.; Niazi, K.; Swarnkar, A.; Bansal, R. Simultaneous allocation of distributed energy resource using improved particle swarm optimization. *Appl. Energy* **2017**, *185*, 1684–1693. [[CrossRef](#)]
50. Obaid, Z.A.; Cipcigan, L.M.; Abraham, L.; Muhssin, M.T. Frequency control of future power systems: Reviewing and evaluating challenges and new control methods. *J. Mod. Power Syst. Clean Energy* **2019**, *7*, 9–25. [[CrossRef](#)]