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Analysis of the Impact of Energy Storage Units on Frequency Regulation Stability in Hydrothermal Power Plant Using State Space Modeling

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Abstract

Energy storage systems have been considered in the last few years to improve the performance of energy grids. In a typical power system, an instantaneous balance between generated and consumed power must be maintained, without storing energy. As a result, the power generation must follow the load curve, and due to the variability of electrical demand, the operation of the energy grid may not be economically efficient. Balancing total generated power with total demand, while accounting for losses, requires optimal performance of the electric power system. Consequently, one of the critical components in any energy network is its ability to regulate load frequency effectively. This study investigates the effect of an energy storage system on enhancing load frequency regulation performance in an interconnected energy network comprising two-area steam and hydropower plants. Initially, the energy grid model, incorporating a superconducting magnetic energy storage (SMES) unit, is expressed in state space using first-order differential equations. Subsequently, the effect of the energy storage system on the power network is explored through system mode analysis. Results from time-domain simulations conducted in MATLAB demonstrate the effectiveness of the system mode investigation and its responsiveness to load fluctuations, confirming the reliability of the approach.

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1 Introduction

The sustainability of the power supply has become a critical requirement for supporting social activities, especially in remote areas with limited access to electricity. The growth of industrial centers, along with the sharp increase in power demand and the environmental impact of fossil fuel-based energy, has accelerated the adoption of renewable energy sources [1, 2]. Over recent years, these sources have advanced rapidly, playing a crucial role in the energy system, while the cost of renewable energy technologies has significantly decreased. As the integration of renewable power resources into modern power systems increases, the absence of inertia in these energy production units has weakened the transient behavior and stability of the grid. This makes energy storage systems even more crucial for power networks with low prevailing inertia [3, 4]. Distributed energy sources have unique characteristics, which influence the dynamic behavior of power plants in distinct ways. If not properly controlled, these sources can lead to challenges such as low-frequency oscillations, voltage fluctuations, and frequency deviations. Additionally, the growing number of power production units can potentially result in instability within the power system [5, 6].

The discrepancy between the net energy production and the load need in energy networks yields voltage and frequency fluctuations. The operating point in a connected energy grid is changing because of load fluctuations, and may cause deviations in the nominal frequency of the network and the planned swap energy between areas [7,8]. Frequency load management is therefore a critical component in ensuring the proper functioning and regulation of an electric power grid. The purpose of this regulator is to handle the frequency deviations and maintain the system's standard frequency by utilizing a secondary regulator [9, 10]. Load frequency regulation aims to ensure a continuous balance between the generated power and the demanded power in real-time. The increasing integration of renewable energy sources has heightened the need for this management strategy, as it must account for uncertainties in system operation due to the variable nature of renewable energy production [11, 12].

Interconnection of power systems has become necessary due to the development of industrial centers and the increase in load demand. The ability to meet the total load demand, including transmission losses, through the total generation capacity directly impacts the performance of the interconnected energy grids [13, 14]. The implementation of a multi-area power system introduces dynamic changes over time, which can lead to variations in the standard frequency and fluctuations in the energy exchanged across transmission lines between areas [15, 16].

The rapid involvement of renewable power production units into energy grids has caused various disturbances due to the lack of inertia because of the substitute of sources by synchronous generators. Additionally, the periodic nature of renewable sources has led to frequency and voltage fluctuations. As a result, the use of energy storage units has become crucial for the effective integration of renewable power production units, ensuring grid stability and reliable energy supply [17,18]. Reducing greenhouse gas emissions and improving the stability of the power network are among the advantages of renewable power depository technology. Energy storage systems help address power fluctuations by storing excess energy from renewable power production units. This stored energy can then be released during periods of energy shortage or surplus, ensuring a stable and reliable power supply while maximizing the efficiency of renewable energy integration into the grid [19, 20].

The elevated involvement of renewable power production units has made frequency variations a problem for the transient stability of the system. Power storage systems can perform well in frequency regulation for microgrid systems [21, 22]. There are various types of power repository units like super-conducting magnetic energy storage (SMES) [23, 24], electric batteries [25, 26], fuel cells [27, 28] and redox flow batteries [29, 30] that are employed to enhance the performance and reliability of power systems. The prominent advantages of superconducting magnetic energy storage (SMES), such as fast response time, low power losses in the superconducting coil, long lifespan, the ability to be deployed in strategic locations, and its capability to manage both reactive and active power, have made it a popular choice for addressing instabilities in the electrical grid [31, 32]. SMES also offers superior dynamic performance compared to other energy storage devices and is used to improve energy quality and transient stability [33, 34].

1.1 Research background review

When the load demand fluctuates in a generation unit, a temporary imbalance between input and output power occurs, necessitating the use of an energy storage system to compensate for this transient event. Extensive research has been conducted on the significance and application of frequency regulation systems, and investigations in this area continue to evolve [35, 36]. Various energy storage technologies have been explored to mitigate frequency oscillations in power grids [37,38].

A frequency regulation model for an interconnected energy network incorporating multiple energy storage units is presented in [39], considering all stages of the frequency control process. This model examines the impact of communication delays and state-of-charge management on the area control error, providing insights into their effects on system stability and performance.

The application of SMES to support the secondary loop in frequency load management and enhance network frequency resilience is presented in [40]. In this approach, a proportional-integral controller is optimally designed using a particle swarm optimization framework to minimize frequency deviations in the energy grid. The studied energy network includes conventional generation plants alongside renewable power production units, such as solar and wind power plants. Simulation results demonstrate the improved resilience of the energy grid under various scenarios with increased integration of renewable energy sources. An adaptive coordination control method is proposed in [41] for energy sources in a hybrid generation system to enhance frequency stability. The optimal design of the proportional-integral-derivative (PID) regulator is achieved using the Gray Wolf optimization framework, which estimates the additional power from renewable energy sources. This method effectively mitigates frequency oscillations, optimizing the utilization of renewable power production units while simultaneously reducing frequency fluctuations in the energy grid.

A dispersed frequency load management strategy is presented in [42] for a multi-zone energy grid including photovoltaic system and battery energy storage system. To ensure asymptotic stability, the proportional-integral controller gains are determined using linear matrix inequality technique. Simulation outcomes exhibit that the regulator is robust to frequency fluctuations caused by photovoltaic system changes.

The nonlinear dynamics of the battery due to changes in the battery state of charge for primary frequency regulation in an isolated microgrid is investigated in [43]. A coordinated and adaptive load frequency control system for battery charging management is presented, which uses parameter adjustment methods and a natural-based genetic optimization framework. This approach is designed to enhance the frequency/load regulation system's effectiveness in addressing challenges associated with the nonlinear characteristics of battery energy storage systems.

The load frequency management system in a two-zone energy grid including hydro, thermal, and gas power plants has been studied in [44] considering the energy storage system. Small signal stability analysis has been used to examine frequency deviation in each zone. A proportional controller is employed to mitigate oscillations, while an integral controller – optimized using the harmonic search-based technique - is implemented to achieve effective regulation. Additionally, an energy storage system is integrated to enhance the transient response of the grid.

1.2 Highlights and structure of the paper

To effectively manage frequency and energy flow across interconnection lines following a disturbance, a load frequency control system is essential. Among various energy storage technologies, superconducting magnetic energy storage (SMES) stands out as a highly suitable option for frequency regulation in energy grids due to its fast response time and efficiency. In this paper, the influence of the SMES unit on improving the implementation of the load frequency regulation strategy in a two-zone connected hydrothermal electric energy grid is investigated. The energy network representative under study is developed and simulated using Simulink-MATLAB. The key highlights of this study include the following:

- Qualitative and quantitative comparison of a conventional controller and a power storage unit in the frequency and load management system of a two-zone energy grid
- Investigation of the influence of the power depository on the transient behavior of each zone due to changes in the consumed load.
- Determination of the system frequency because of shifts in the characteristics of each zone
- Combination of production power plants to study the behavior of the load frequency control system

2 Superconducting Magnetic Energy Storage

Due to the unpredictable and intermittent nature of renewable power production units, the electrical power storage system plays a crucial role in enhancing the reliability of the energy grid. Its integration significantly improves power stability and consistency [45,46]. The complexity of power storage systems has led to an increased demand for electrical power. In Superconducting Magnetic Energy Storage (SMES), energy is stored in the form of a magnetic field created by a direct current flowing through superconducting coils [47,48]. The resistive losses during the formation of the magnetic field in the superconducting coil are negligible due to the coil's near-zero resistance. In this power storage unit, the energy conversion process is limited to transforming alternating current (AC) into direct current (DC), with no significant thermodynamic losses involved in the conversion between these power forms [49,50]. During normal operation, the superconducting coil is charged up to its rated current from the network. When the network requires power, the coil discharges. Since the power losses in the SMES coil are negligible, it achieves high efficiency. SMES units can rapidly switch states – from charging to discharging and vice versa – in just a few seconds. This ability provides a fast response and long operational lifetime compared to other power storage devices, such as battery energy storage. Unlike batteries, whose lifespan is significantly reduced under repeated charge-discharge cycles, SMES units are better suited for providing inertial support due to their durability and efficiency [51, 52]. Due to the advantages of SMES, this storage unit can provide effective support for grid inertia [53, 54]. It serves as a reliable solution to reduce fluctuations in output power, enhance transient stability, and improve frequency control. Additionally, SMES can be utilized to improve the energy quality of grid-connected renewable power production units. The control algorithms employed in SMES devices are simple and require minimal hardware for implementation, making them cost-effective and efficient for integration into the energy grid [55,56]. The SMES unit is considered with a first-order transfer function as follows, where K_{SMES} and T_{SMES} are its gain and time constant, respectively [57]:

$$G_{\text{SMES}}(s) = \frac{\Delta P_{\text{SMES}}}{\Delta f(s)} = \frac{K_{\text{SMES}}}{T_{\text{SMES}}s + 1} \tag{1}$$

3 System Under Study

Figure 1 pictures the general configuration of a hierarchical control system in three levels along with the tasks of each level. Two preliminary and secondary regulation loops are employed to manage the frequency in the energy grid. The primary regulation loop is responsible for preventing frequency transients that can cause steady-state errors. The secondary regulation loop, which focuses on frequency and load regulation, is tasked with maintaining frequency stability. The primary goal of the frequency and load regulation system is to adjust the generator output power in each area to counteract changes in grid frequency and fluctuations in line energy exchanges between areas [58, 59].

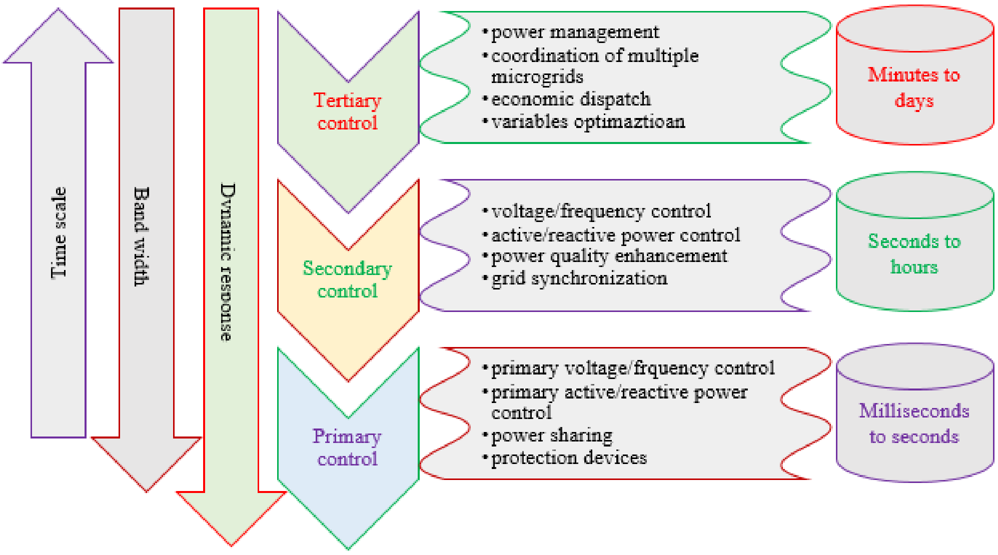

Fig. 1. The role of control loops in hierarchical control in a power system.

Figure 2 depicts the load frequency control representative of the two-area energy grid under study, which includes both a hydropower unit and a steam power unit. In this model, a separate SEMS is considered for each area. Also, the load changes in each area are the system inputs. β_S and β_H are frequency bias coefficients, and R_S and R_H are governor speed management coefficients of thermal and hydro energy plants [60, 61]. The input and output signals of SEMS are area control error and power, respectively. The output signal is then added to the sum of the load changes and mechanical power changes of each area.

The transfer function of the hydro energy unit and the transfer function of the steam energy plant are illustrated by $G_H(s)$ and $G_S(s)$ where T_{GH} and T_{GS} are the time constants of governor, T_{RS} is the hydro turbine speed governor reset time, T_W is the starting time of water in the hydro turbine, T_{RH} is the time constant of the transient droop, T_T is the time constant of the steam turbine, K_{RE} is the fraction of power generated by high pressure section and T_{RE} is time constant of reheater [62, 63].

$$G_H(s) = \underbrace{\left(\frac{1}{T_{\mathrm{GH}}s+1}\right)}_{\text{hydro governor}} \times \underbrace{\left(\frac{T_{\mathrm{RS}}s+1}{T_{\mathrm{RH}}s+1}\right)}_{\text{transient droop compensation}} \times \underbrace{\left(\frac{-T_W s+1}{0.5T_W s+1}\right)}_{\text{penstock hydraulic turbine}} \tag{2}$$

$$G_S(s) = \underbrace{\left(\frac{1}{T_{\mathrm{GS}}s+1}\right)}_{\text{thermal governor}} \times \underbrace{\left(\frac{K_{\mathrm{RE}}T_{\mathrm{RE}}s+1}{T_{\mathrm{RE}}s+1}\right)}_{\text{reheat}} \times \underbrace{\left(\frac{1}{T_T s+1}\right)}_{\text{steam turbine}} \tag{3}$$

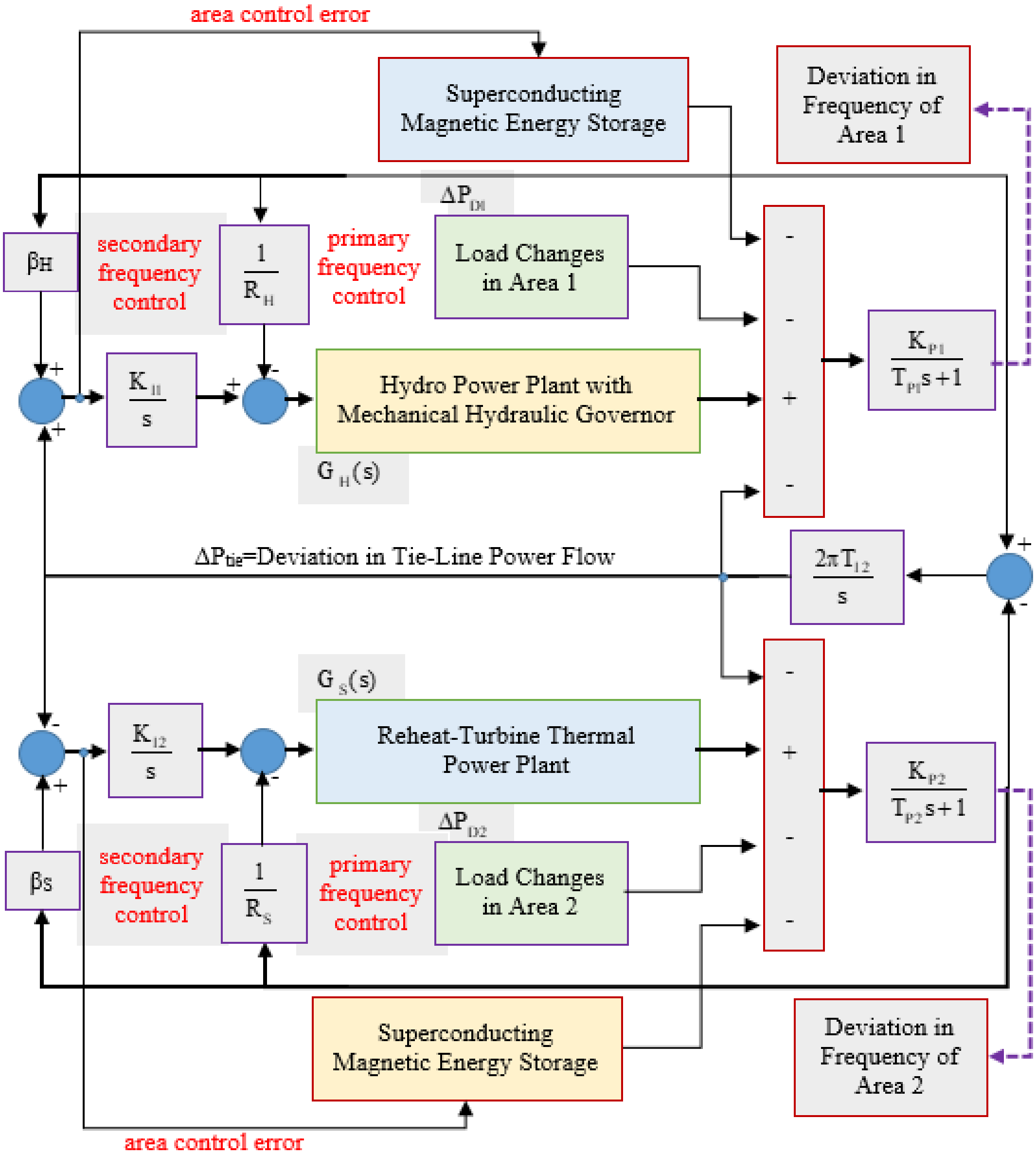

Fig. 2. Load frequency control model of the two-area power system under study.

The two variables, frequency deviation and transmission line power exchange, together constitute the area control error, which is used as a feedback variable in the load frequency control loop, and is defined as follows:

$$\mathrm{ACE} = \beta_i \Delta f_i + \Delta P_{\mathrm{tie}} \tag{4}$$

where β_i is the frequency bias coefficient and ΔP_{tie} is the power exchange variation between the two areas. The power system in each area is represented by a first-order transfer function, where K_{P1} and K_{P2} are the gains and T_{P1} and T_{P2} are their time constants [64,65].

In a single-area power system, the system output frequency changes in terms of two inputs can be considered as follows:

$$\Delta F(s) = H_{\mathrm{FD}}(s)\Delta P_D(s) + H_{\mathrm{FC}}(s)\Delta P_C(s) \tag{5}$$

where $H_{\mathrm{FD}}(s)$ and $H_{\mathrm{FC}}(s)$ are the transfer functions corresponding to the load change and setpoint change inputs of the system. If a controller with transfer function $G_C(s)$ and an energy storage with transfer function $G_{\mathrm{SMES}}(s)$ are used, the frequency changes will change as follows:

$$\begin{aligned}\Delta F(s) = {} & H_{\mathrm{FD}}(s)\big[\Delta P_D(s) + G_{\mathrm{SMES}}(s)\Delta F(s)\big] \\ & - H_{\mathrm{FC}}(s)G_C(s)\Delta F(s)\end{aligned} \tag{6}$$

Therefore, the transfer function of the entire system is equal to:

$$\begin{aligned}H(s) &= \frac{\Delta F(s)}{\Delta P_D(s)} \\ &= \frac{H_{\mathrm{FD}}(s)}{1 + H_{\mathrm{FD}}(s)G_{\mathrm{SMES}}(s) + H_{\mathrm{FC}}(s)G_C(s)}\end{aligned} \tag{7}$$

Given that the transfer function representing the first-order SMES is considered, and according to the above relationship, in the steady state, the time constant and gain of the SMES transfer function will not affect the steady state value of the frequency changes.

To write the equations of the system under study in state space, it is necessary to select 11 state variables, including four state variables for the hydro unit, four state variables for the thermal unit, one state variable for the power transferred between the two areas, and two state variables for the controller outputs. If the energy storage units are considered with a transfer function of order 1, then two state variables are also considered for the output of the SEMS units. Therefore, the power system under study will have order 13. The first-order equations of the system under study, without considering the SEMS effect in the state space, are expressed as follows:

$$\begin{aligned}\frac{d}{dt}\underbrace{\begin{bmatrix} X_S \\ X_H \\ X_T \\ X_C \end{bmatrix}}_{X} = {} & \underbrace{\begin{bmatrix} A_{SS} & A_{SH} & A_{ST} & A_{SC} \\ A_{HS} & A_{HH} & A_{HT} & A_{HC} \\ A_{TS} & A_{TH} & A_{TT} & A_{TC} \\ A_{CS} & A_{CH} & A_{CT} & A_{CC} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} X_S \\ X_H \\ X_T \\ X_C \end{bmatrix}}_{X} \\ & + \underbrace{\begin{bmatrix} -\frac{K_{P1}}{T_{P1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{K_{P2}}{T_{P2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}}_{B} \underbrace{\begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \end{bmatrix}}_{U}\end{aligned} \tag{8}$$

where the state variable vector X consists of the state variable vectors of the hydro unit X_H, the thermal unit X_S, the power transferred between the two areas X_T, and the controller outputs X_C. The system matrix A also consists of the corresponding submatrices. The input vector consists of two inputs representing the load changes in each area. In this study, unit 1 includes a thermal power plant with four state variables x_1 to x_4 and unit 2 includes a hydro power plant with four state variables x_5 to x_8. The inter-area variable (x_9) includes the power transferred between the two areas. The two variables related to the output of the integral controllers are x_{10} and x_{11}. Therefore, the four diagonal matrices A_{SS}, A_{HH}, A_{TT}, and A_{CC} will be related to the intrinsic variables of the thermal power plant, the hydro power plant, the inter-regional variable and the control system respectively. The non-diagonal elements of the system matrix A are related to the relationships between the subsystems that make up the main system.

4 Analysis of Simulation Results

Maintaining synchronism between different components is crucial for stabilizing a power system after a disturbance. To achieve this, electric power must be generated in accordance with the demand of consumption loads while simultaneously accounting for system losses. Various external conditions during power system operation can lead to frequency deviations from the nominal value, impacting overall system stability. Time constants and inertia constants are important factors affecting the dynamic behavior of the power system. The primary function of the load frequency control system is to maintain the system frequency at its the nominal value while ensuring that power exchange with other areas according to the specified limits. To verify the simulation results, the model of the studied system was also implemented in MATLAB Simulink as shown in Figure 3. The parameters of the system under study have been selected according to Table 1.

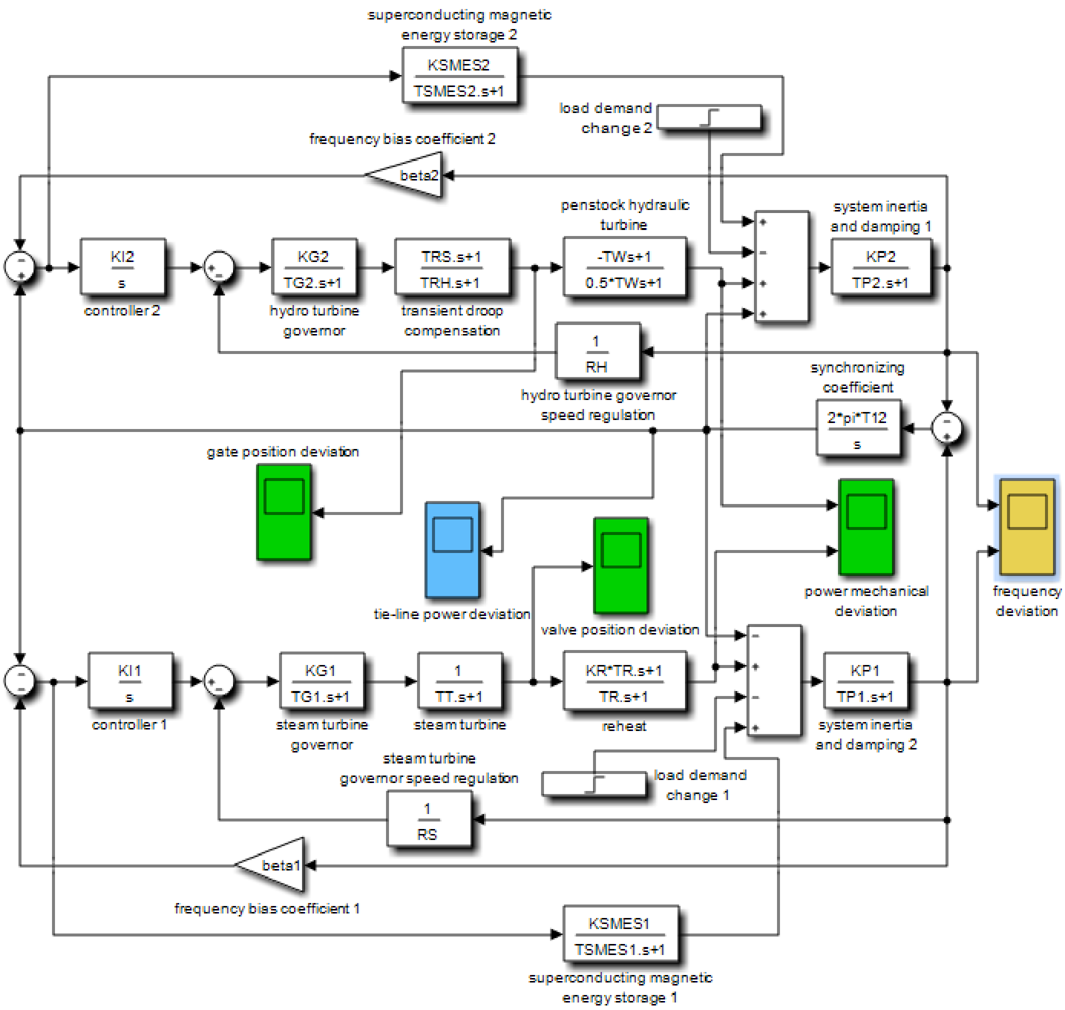

Fig. 3. Implementation of the two-area power system under study in MATLAB Simulink with energy storage effect.

4.1 Without super-conducting magnetic energy storage

The system modes for single-area and dual-area configurations, excluding the energy storage system, are presented in Table 2. The table also specifies the damping coefficients of the oscillatory modes. As observed, the oscillatory mode in the thermal power plant model exhibits a higher damping coefficient compared to that in the hydropower plant. Additionally, in the two-area power system, all three oscillatory modes in the controlled state have damping coefficients below 0.5, whereas in the uncontrolled state, one of the two oscillatory modes falls below this threshold. Furthermore, the system modes for both single-area and two-area configurations are located on the left side of the imaginary axis, indicating system stability. With the addition of the steady-state controller, response changes will tend to zero. Figures 4 and 5 show the response of output frequency changes of area 2 (hydropower plant) and mechanical power changes of the hydropower unit to step changes of load in area 2, respectively. As observed, frequency changes in the controlled system tend towards zero and mechanical power changes in the controlled system tend towards 1. Figures 6 and 7 show the responses of frequency changes and mechanical power output in the thermal unit for step changes in the consumption load in area 2. Figures 8 and 9 show the changes in frequency and mechanical power output in the thermal unit for step changes in the load consumption in area 1. These results confirm the effectiveness of the controller design in handling step changes in load for both areas, ensuring that the responses stabilize at zero in the steady state.

Table 1. Parameters of the system under study.

Sub system	Symbol	Value
Steam power plant	K_{G1}	1
	T_{G1}	0.2
	T_T	0.3
	T_R	7
	K_R	0.3
	K_{P1}	1
	T_{P1}	10
	R_S	0.2
	β_S	0.431
Hydro power plant	K_{G2}	1
	T_{G2}	0.2
	T_{RS}	5
	T_{RH}	9.5
	T_W	1
	K_{P2}	1
	T_{P2}	6
	R_H	0.2
	β_H	0.431
Inter-area synchronizing constant	T_{12}	0.0867
Superconducting Magnetic Energy Storage	K_{SMES1}	2
	T_{SMES1}	0.4
	K_{SMES2}	2
	T_{SMES2}	0.2
Integral controller	K_{I1}	0.2
	K_{I2}	0.1

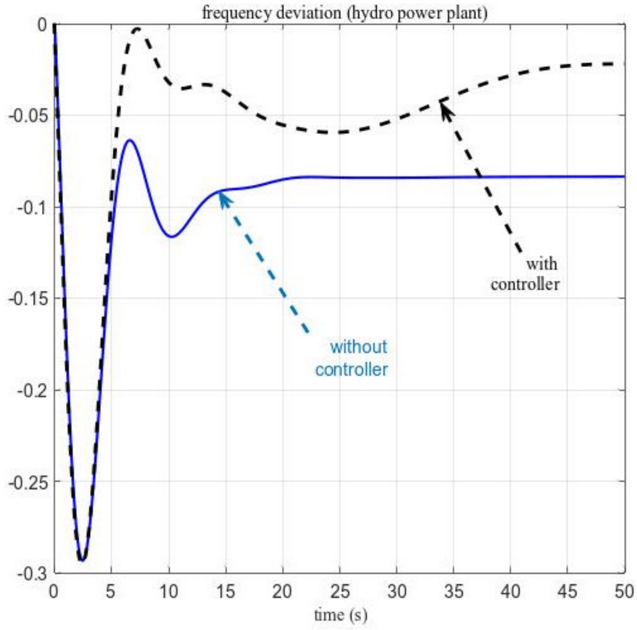

Fig. 4. Frequency changes of the output of the hydro unit in the two-area system for step changes of the load in area 2.

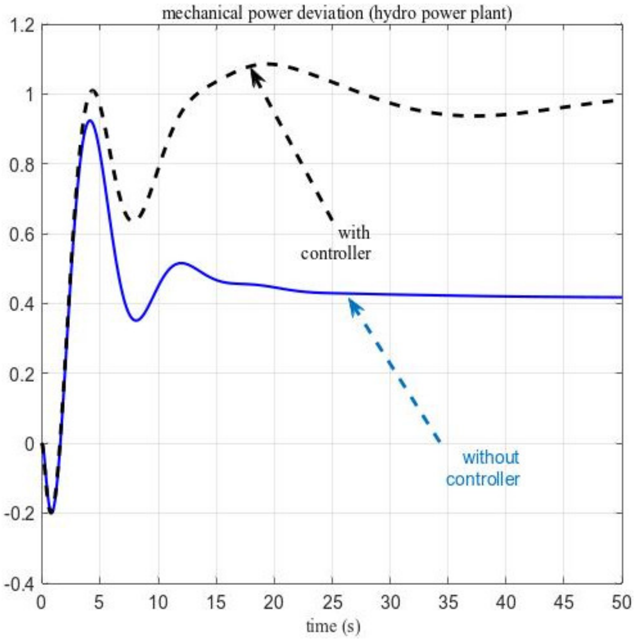

Fig. 5. Mechanical power changes of the output of the hydro unit in the two-area system for step changes of the load in area 2.

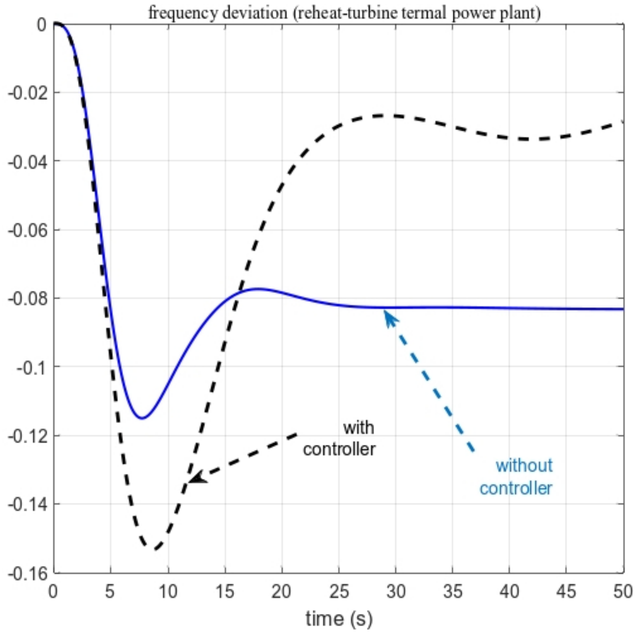

Fig. 6. Frequency changes of the output of the thermal unit in the two-area system for step changes of the load in area 2.

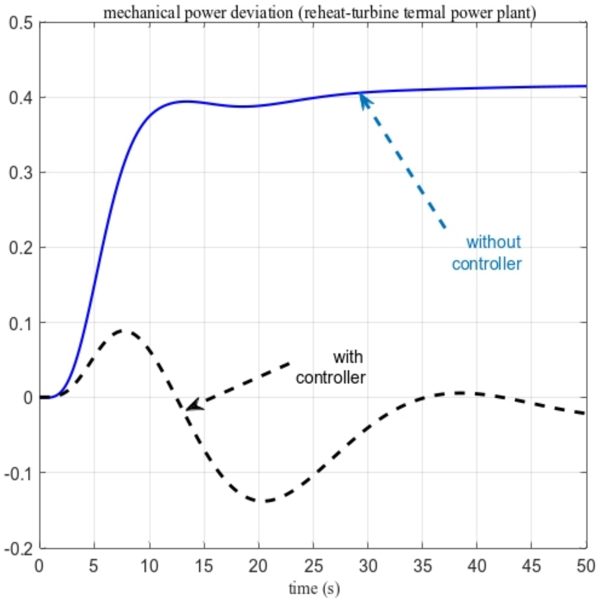

Fig. 7. **Mechanical power changes of the output of the thermal unit in the two-area system for step changes of the load in area 2.**

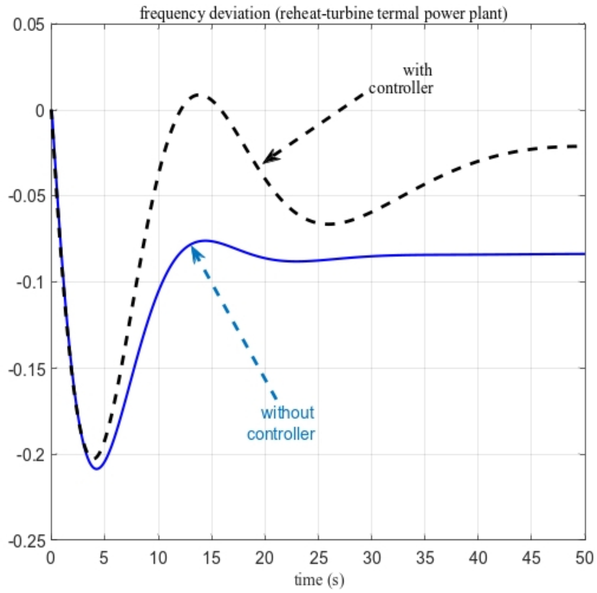

Fig. 8. **Frequency changes of the output of the thermal unit in the two-area system for step changes of the load in area 1.**

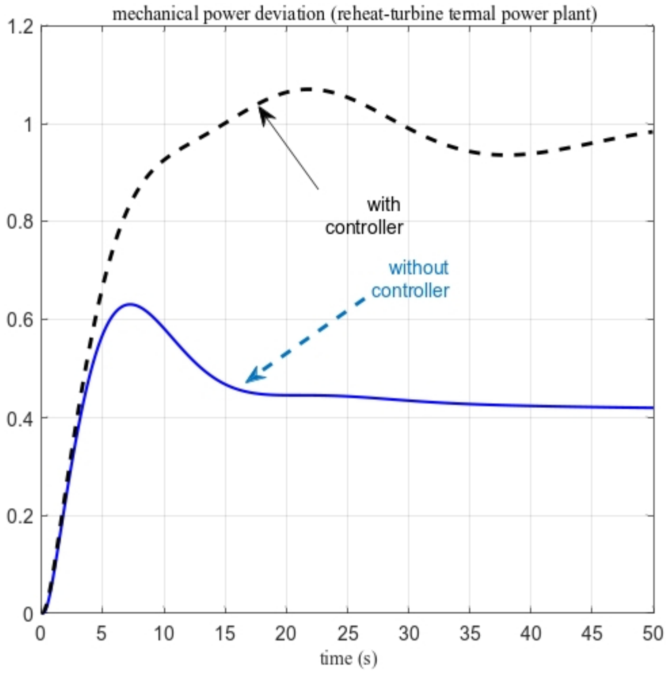

Fig. 9. **Mechanical power changes of the output of the thermal unit in the two-area system for step changes of the load in area 1.**

Table 2. System mods not including super-conducting magnetic energy storage

Single-area		Two-area	
Thermal	Hydro	Without controller	With controller
-5.2386	-6.2203	-5.2382	-5.2375
-2.9558	-0.2066	-6.2181	-6.2150
$-0.1909 \pm j0.2363$	$-0.4225 \pm j0.8004$	-2.9581	-2.9598
(0.6284)	(0.4668)	$-0.3223 \pm j0.8264$	$-0.3415 \pm j0.7997$
		(0.3633)	(0.3927)
		$-0.2085 \pm j0.3250$	$-0.1741 \pm j0.3030$
		(0.5400)	(0.4980)
		-0.2882	$-0.0642 \pm j0.1744$
		-0.0838	(0.3455)
			-0.0227
			-0.2536

4.2 Energy storage effect

To investigate the effect of SEMS, three cases have been investigated. In the first case, stepwise load changes are considered in zone 1. In the second case, stepwise load changes are applied in zone 2. In the third case, load changes occur simultaneously in both zones. For each case, the simulation results show the frequency changes in both areas and the changes in the mechanical power output of the generating units. Figures 10 and 11 correspond to the first case, Figures 12 and 13 to the second case, and Figures 14 and 15 to the third case.

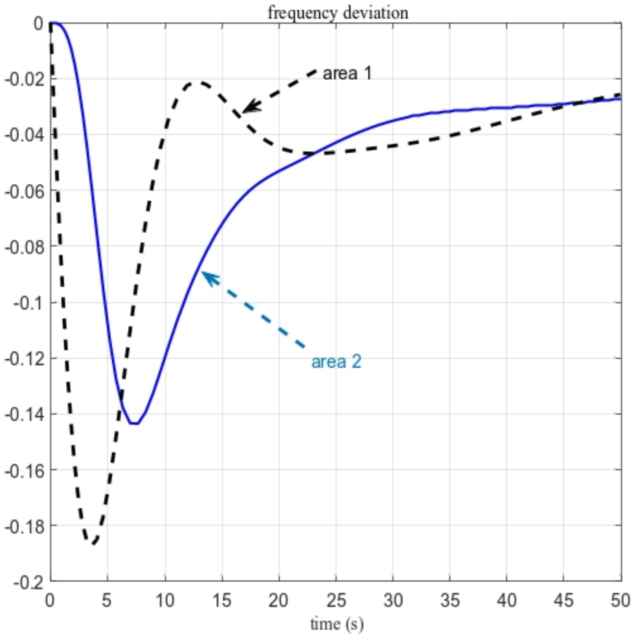

Fig. 10. Frequency changes of areas for step changes of load in area 1 with SEMS effect.

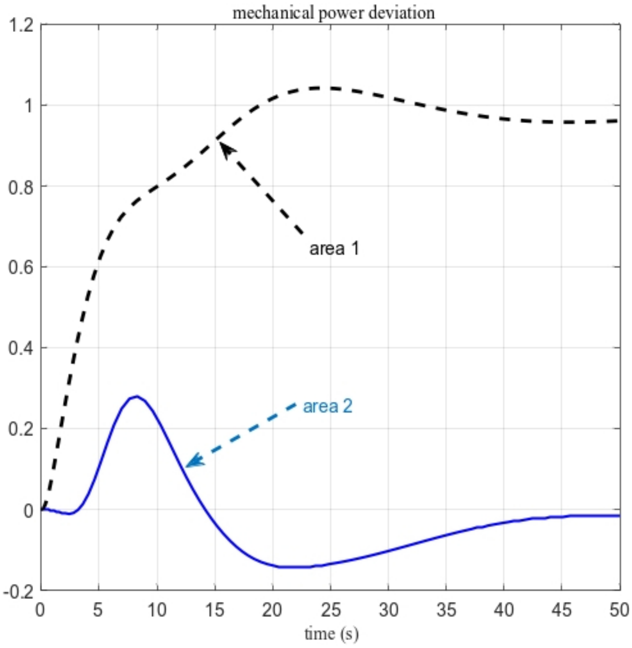

Fig. 11. Changes in the mechanical power output of the generating units for step changes in the load in area 1 with SEMS effect.

The simulation results show that the use of SMES improves the dynamic performance of the load frequency control system. Moreover, SMES can be effectively placed either one or both areas. However, the improvement in dynamic performance when using SMES in both areas, compared to a single area, is minimal. Therefore, from an economic perspective, it is more efficient to place SMES in each area separately. The results further show that adding SMES accelerates the damping of oscillations and reduces response overshoot. Moreover, the simulations reveal that SMES significantly decreases settling time, ensuring that the responses remain smooth and free from ripples.

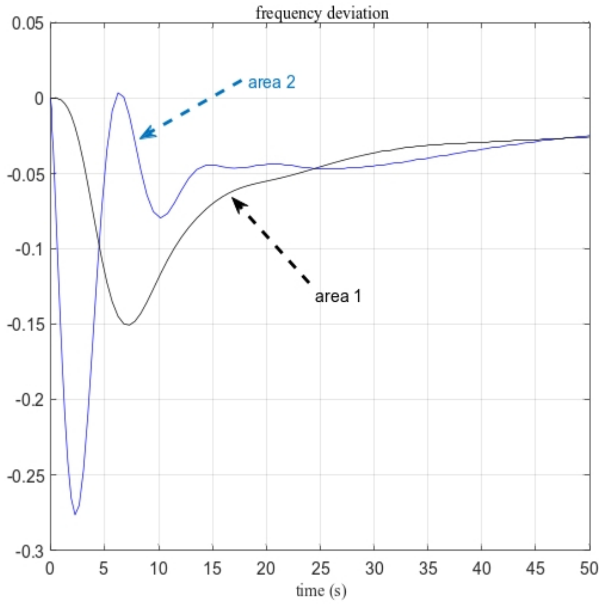

Fig. 12. Frequency changes of areas for step changes of load in area 2 with SEMS effect.

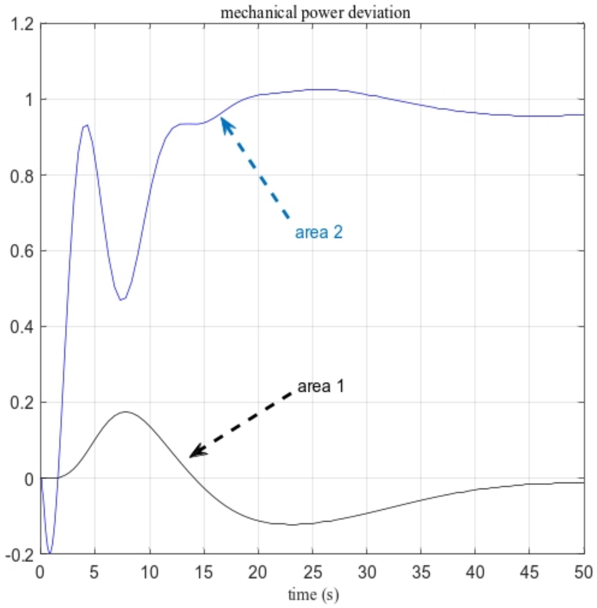

Fig. 13. Changes in the mechanical power output of the generating units for step changes in the load in area 2 with SEMS effect.

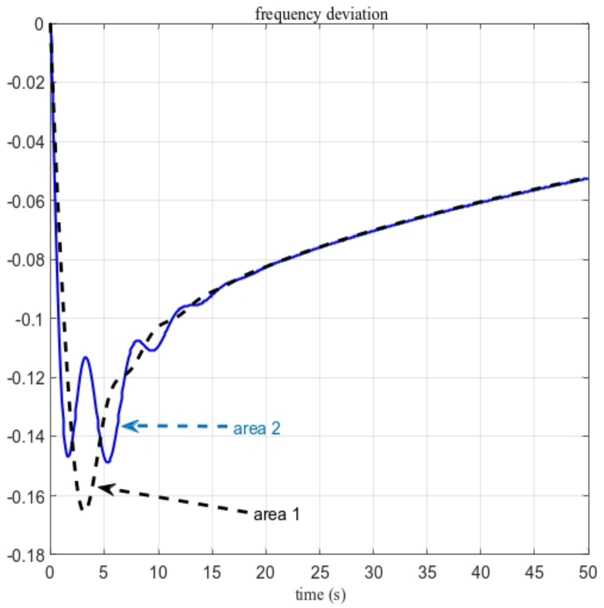

Fig. 14. Frequency changes of generating units for simultaneous load step changes in both areas with SEMS effect.

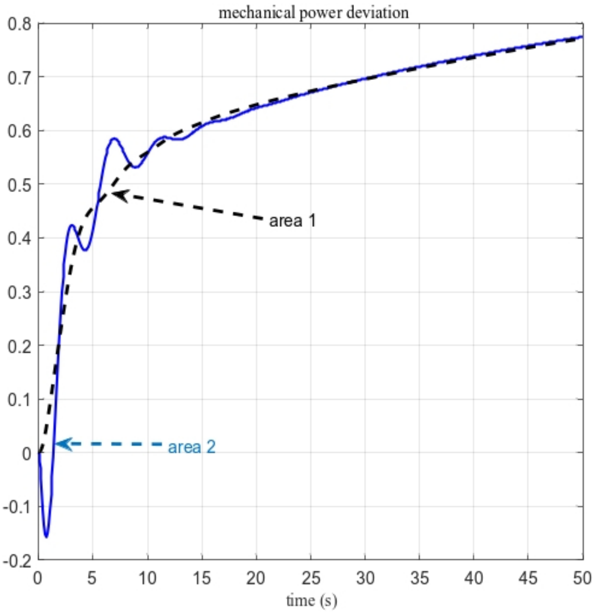

Fig. 15. Changes in mechanical power output of generating units for stepwise changes in simultaneous load in both areas with SEMS effect.

5 Conclusion

Frequency stability is crucial for the stable and reliable operation of power systems, which represents the fundamental position of power systems for generating power and supplying the required load. However, the unpredictable nature of renewable energy sources, the randomness of load demand, and the lack of system inertia pose significant challenges to maintaining frequency stability. To address sudden load variations and ensure the continuous supply of required power, the integration of an active energy source within the power system is essential. Superconducting magnetic energy storage (SEMS) is an advanced energy storage system capable of delivering an unlimited number of charge and discharge cycles with a faster response time and a longer lifespan compared to other energy storage technologies. This study explores the application of an SMES unit in enhancing the dynamic stability of a power system. The two-zone power system under study includes a hydro unit and a boiler unit. The effect of SEMS on the stability of frequency regulation in a hydrothermal power system is analyzed using state-space system modeling. Simulation results show that the integration of SMES enhances the system's response to frequency variations and effectively reduces power fluctuations between the two areas.

References

[1] Rajamand S. Load frequency control and dynamic response improvement using energy storage and modeling of uncertainty in renewable distributed generators. Journal of Energy Storage. 2021;37:102467.

[2] Sharifiyana O, Dehghani M, Shahgholian G, Mirtalaei SMM, Jabbari M. Nonisolated boost converter with new active snubber structure and energy recovery capability. Journal of Circuits, Systems and Computers. 2023;32(05):2350084.

[3] Magdy G, Bakeer A, Alhasheem M. Superconducting energy storage technology-based synthetic inertia system control to enhance frequency dynamic performance in microgrids with high renewable penetration. Protection and Control of Modern Power Systems. 2021;6(4):1–13.

[4] Daraz A, Alrajhi H, Basit A, Afzal AR, Alahmadi AN, Khan IA. Load frequency stabilization of distinct hybrid conventional and renewable power systems incorporated with electrical vehicles and capacitive energy storage. Scientific Reports. 2024;14(1):9400.

[5] Zamani M, Shahgholian G, Fathollahi A, Mosavi A, Felde I. Improving interarea mode oscillation damping in multi-machine energy systems through a coordinated PSS and FACTS controller framework. Sustainability. 2023;15(22):16070.

[6] Sedghisigarchi K, Feliachi A. Impact of fuel cells on load-frequency control in power distribution systems. IEEE Transactions on Energy Conversion. 2006;21(1):250–256.

[7] Saini N, Ohri J. Optimal and Robust Load Frequency Control for Hybrid Power System Integrated with Energy Storage Device by Sine Cosine Algorithm. Wireless Personal Communications. 2024;138(3):1955–1983.

[8] Khosravi A, Chatraei A, Shahgholian G, Kargar SM. System identification using NARX and centrifugal compressor control through the intelligent, active method—Case study: K-250 centrifugal compressor. Asian Journal of Control. 2022;24(6):3345–3364.

[9] Khan MRB, Pasupuleti J, Jidin R. Load frequency control for mini-hydropower system: A new approach based on self-tuning fuzzy proportional-derivative scheme. Sustainable Energy Technologies and Assessments. 2018;30:253–262.

[10] Parmar KS, Majhi S, Kothari D. Load frequency control of a realistic power system with multi-source power generation. International Journal of Electrical Power & Energy Systems. 2012;42(1):426–433.

[11] Zhang Y, Shi X, Zhang H, Cao Y, Terzija V. Review on deep learning applications in frequency analysis and control of modern power system. International Journal of Electrical Power & Energy Systems. 2022;136:107744.

[12] Shankar R, Pradhan S, Chatterjee K, Mandal R. A comprehensive state of the art literature survey on LFC mechanism for power system. Renewable and Sustainable Energy Reviews. 2017;76:1185–1207.

[13] Montazeri M, Yousefi M, Shojaei K, Shahgholian G. Design of fast variable structure adaptive fuzzy control for nonlinear state-delay systems with uncertainty. IETE journal of research. 2022;68(6):4577–4589.

[14] Panda S, Mohanty S, Rout PK, Sahu BK, Parida SM, Samanta IS, et al. A comprehensive review on demand side management and market design for renewable energy support and integration. Energy Reports. 2023;10:2228–2250.

[15] Fani SARAS. Investigation Various Types of Frequency Support Methods and Inertial Control Techniques in Power Systems Based on Variable Speed Wind Turbines. Technovations of Electrical Engineering in Green Energy System. 2024;3(10).

[16] Ranjan M, Shankar R. A literature survey on load frequency control considering renewable energy integration in power system: Recent trends and future prospects. Journal of Energy Storage. 2022;45:103717.

[17] Calero F, Cañizares CA, Bhattacharya K, Anierobi C, Calero I, de Souza MFZ, et al. A review of modeling and applications of energy storage systems in power grids. Proceedings of the IEEE. 2022;111(7):806–831.

[18] Aghadavoodi E, Shahgholian G. A new practical feed-forward cascade analyze for close loop identification of combustion control loop system through RANFIS and NARX. Applied Thermal Engineering. 2018;133:381–395.

[19] Magdy G, Bakeer A, Nour M, Petlenkov E. A new virtual synchronous generator design based on the SMES system for frequency stability of low-inertia power grids. Energies. 2020;13(21):5641.

[20] Gholami M, Mallaki M, et al. Increase Flexibility and Improve Resilience in Smart Microgrids by Coordinating Storage Resources and Distributed Generation During Contingencies. Journal of Southern Communication Engineering. 2022;12(45):45–60.

[21] Li J, Xiong R, Yang Q, Liang F, Zhang M, Yuan W. Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system. Applied Energy. 2017;201:257–269.

[22] Fathollahi A, Andresen B. Deep deterministic policy gradient for adaptive power system stabilization and voltage regulation. e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2024;9:100675.

[23] Rajaguru V, Annapoorani KI. Virtual synchronous generator based superconducting magnetic energy storage unit for load frequency control of micro-grid using African vulture optimization algorithm. Journal of Energy Storage. 2023;65:107343.

[24] Uddin Mufti M, Lone SA, Iqbal SJ, Mushtaq I. Improved load frequency control with superconducting magnetic energy storage in interconnected power system. IEEJ Transaction. 2007;2:387–397.

[25] Coban HH, Rehman A, Mousa M. Load frequency control of microgrid system by battery and pumped-hydro energy storage. Water. 2022;14(11):1818.

[26] Liu L, Matayoshi H, Lotfy ME, Datta M, Senjyu T. Load frequency control using demand response and storage battery by considering renewable energy sources. Energies. 2018;11(12):3412.

[27] Bagherian Farahabadi H, Rezaei Firozjaee M, Mohammadpour Mir A, Youneszadeh R. Fuel cell power system conceptual design for unmanned underwater vehicle. Hydrogen, Fuel Cell & Energy Storage. 2023;10(1):33–50.

[28] Stambouli AB, Traversa E. Fuel cells, an alternative to standard sources of energy. Renewable and sustainable energy reviews. 2002;6(3):295–304.

[29] Çelik E, Öztürk N, Houssein EH. Influence of energy storage device on load frequency control of an interconnected dual-area thermal and solar photovoltaic power system. Neural Computing and Applications. 2022;34(22):20083–20099.

[30] Ozgoli HA, Yazdani H. Integration of a vanadium redox flow battery with a proton exchange membrane fuel cell as an energy storage system. Iranian Journal of Hydrogen & Fuel Cell. 2017;1:53–68.

[31] Abraham RJ, Das D, Patra A. AGC study of a hydrothermal system with SMES and TCPS. European Transactions on Electrical Power. 2009;19(3):487–498.

[32] Poisson O, Rioual P, Meunier M. Detection and measurement of power quality disturbances using wavelet transform. IEEE transactions on Power Delivery. 2000;15(3):1039–1044.

[33] Zargar MY, Mufti MUD, Lone SA. Adaptive predictive control of a small capacity SMES unit for improved frequency control of a wind-diesel power system. IET Renewable Power Generation. 2017;11(14):1832–1840.

[34] Mishra DK, Panigrahi TK, Mohanty A, Ray PK. Effect of superconducting magnetic energy storage on two agent deregulated power system under open market. Materials Today: Proceedings. 2020;21:1919–1929.

[35] Yang J, Zhong Q, Liu X, Shi K, Ghias AM, Dong ZY. Decentralized Periodic Event-Triggered Load Frequency Control for Multiarea Power Systems. IEEE Transactions on Systems, Man, and Cybernetics: Systems. 2024;.

[36] Fathollahi A, Andresen B. Enhancing Transient Stability in Multi-Machine Power Systems through a Model-Free Fractional-Order Excitation Stabilizer. Fractal & Fractional. 2024;8(7).

[37] Jafari E, Marjanian A, Solaymani S, Shahgholian G. Designing an emotional intelligent controller for IPFC to improve the transient stability based on energy function. Journal of Electrical Engineering and Technology. 2013;8(3):478–489.

[38] Khalil AE, Boghdady TA, Alham M, Ibrahim DK. A novel multi-objective tuning formula for load frequency controllers in an isolated low-inertia microgrid incorporating PV/wind/FC/BESS. Journal of Energy Storage. 2024;82:110606.

[39] Cañizares CA, Bhattacharya K, Sohm D, et al. Frequency regulation model of bulk power systems with energy storage. IEEE Transactions on Power Systems. 2021;37(2):913–926.

[40] Magdy G, Shabib G, Elbaset AA, Mitani Y. Optimized coordinated control of LFC and SMES to enhance frequency stability of a real multi-source power system considering high renewable energy penetration. Protection and Control of Modern Power Systems. 2018;3(4):1–15.

[41] Salama HS, Magdy G, Bakeer A, Vokony I. Adaptive coordination control strategy of renewable energy sources, hydrogen production unit, and fuel cell for frequency regulation of a hybrid distributed power system. Protection and Control of Modern Power Systems. 2022;7(3):1–18.

[42] Lan Y, Illindala MS. Robust Distributed Load Frequency Control for Multi-Area Power Systems with Photovoltaic and Battery Energy Storage System. Energies. 2024;17(22):5536.

[43] Faragalla A, Abouzeid SI, Abdel-Rahim O, Orabi M, Abdelhameed EH. Adaptive and coordinated load frequency control for isolated microgrids considering battery state of charge dynamics. Journal of Energy Storage. 2025;112:115467.

[44] Shankar R, Chatterjee K, Bhushan R. Impact of energy storage system on load frequency control for diverse sources of interconnected power system in deregulated power environment. International Journal of Electrical Power & Energy Systems. 2016;79:11–26.

[45] Yang B, Wang J, Zhang X, Yu L, Shu H, Yu T, et al. Control of SMES systems in distribution networks with renewable energy integration: A perturbation estimation approach. Energy. 2020;202:117753.

[46] Abdollahi SA, Faramarzi S, Mafi M, Ranjbar SF, Motavalli Sofiani S. Proposing a Hydrogen Liquefaction Cycle for Geothermal Energy Storage in an Innovative Multi-Generation System. Hydrogen, Fuel Cell & Energy Storage. 2025;12(1):1–8.

[47] Guo W, Hong Y, Lan J, Yang Y. Multi-Functional Device Based on Superconducting Magnetic Energy Storage. Energies. 2024;17(13):3175.

[48] Arsénio Costa AJ, Morais H. Power Quality Control Using Superconducting Magnetic Energy Storage in Power Systems with High Penetration of Renewables: A Review of Systems and Applications. Energies (19961073). 2024;17(23).

[49] Ngamroo I, Taeratanachai C, Dechanupaprittha S, Mitani Y. Enhancement of load frequency stabilization effect of superconducting magnetic energy storage by static synchronous series compensator based on H∞ control. Energy Conversion and Management. 2007;48(4):1302–1312.

[50] Turky RA, Abdelsalam TS, Hasanien HM, Alharbi M, Ullah Z, Muyeen S, et al. Adaptive controlled superconducting magnetic energy storage devices for performance enhancement of wind energy systems. Ain Shams Engineering Journal. 2023;14(7):102343.

[51] Vyas G, Dondapati RS. Investigation on the structural behavior of superconducting magnetic energy storage (SMES) devices. Journal of Energy Storage. 2020;28:101212.

[52] Penthia T, Panda AK, Patnaik N, Mohanty PR. Performance of SMES system with non-linear dynamic evolution control approach for pulsed power load compensation. IET generation, transmission & distribution. 2020;14(10):1872–1881.

[53] Sang W, Guo W, Dai S, Tian C, Yu S, Teng Y. Virtual synchronous generator, a comprehensive overview. Energies. 2022;15(17):6148.

[54] Khaleel M, Yusupov Z, Nassar Y, El-khozondar HJ, Ahmed A, Alsharif A. Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems. e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2023;5:100223.

[55] Devotta J, Rabbani M. Application of superconducting magnetic energy storage unit in multimachine power systems. Energy Conversion and Management. 2000;41(5):493–504.

[56] 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(20):3902.

[57] Wang D, Ma N, Wei M, Liu Y. Parameters tuning of power system stabilizer PSS4B using hybrid particle swarm optimization algorithm. International Transactions on Electrical Energy Systems. 2018;28(9):e2598.

[58] Gulzar MM, Iqbal M, Shahzad S, Muqeet HA, Shahzad M, Hussain MM. Load frequency control (LFC) strategies in renewable energy-based hybrid power systems: A review. Energies. 2022;15(10):3488.

[59] Fani B, Mesrinejad F, Yaghoubi S, Alhelou H. Improved dynamic performance in interconnected power system using secondary frequency control. International Journal of Smart Electrical Engineering. 2023;12(02):127–133.

[60] Kalyan CHNS, Rao GS. Impact of communication time delays on combined LFC and AVR of a multi-area hybrid system with IPFC-RFBs coordinated control strategy. Protection and Control of Modern Power Systems. 2021;6(1):1–20.

[61] Rahman A, Saikia LC, Sinha N. Load frequency control of a hydro-thermal system under deregulated environment using biogeography-based optimised three-degree-of-freedom integral-derivative controller. IET generation, transmission & distribution. 2015;9(15):2284–2293.

[62] Ali T, Asad M, Touti E, Graba BB, Aoudia M, Abbas G, et al. Terminal voltage and load frequency control in a real four-area multi-source interconnected power system with nonlinearities via OOBO algorithm. IEEE Access. 2024;.

[63] AboRas KM, Ragab M, Shouran M, Alghamdi S, Kotb H. Voltage and frequency regulation in smart grids via a unique Fuzzy PIDD2 controller optimized by Gradient-Based Optimization algorithm. Energy Reports. 2023;9:1201–1235.

[64] Deepak M. Improving the dynamic performance in load frequency control of an interconnected power system with multi source power generation using superconducting magnetic energy storage (SMES). In: 2014 International Conference on Advances in Green Energy (ICAGE). IEEE; 2014. p. 106–111.

[65] Khan IA, Mokhlis H, Mansor NN, Illias HA, Daraz A, Ramasamy A, et al. Load frequency control in power systems with high renewable energy penetration: A strategy employing PIλ (1+ PDF) controller, hybrid energy storage, and IPFC-FACTS. Alexandria Engineering Journal. 2024;106:337–366.