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Analyzing Small-Signal Stability in a Multi-Source Single-Area Power System with a Load-Frequency Controller Coordinated with a Photovoltaic System

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Abstract: The frequency deviation from the nominal working frequency in power systems is a consequence of the imbalance between total electrical loads and the aggregate power supplied by production units. The sensitivity of energy system frequency to both minor and major load variations underscore the need for effective frequency load control mechanisms. In this paper, frequency load control in single-area power system with multi-source energy is analysed and simulated. Also, the effect of the photovoltaic system on the frequency deviation changes in the energy system is shown. In the single area energy system, the dynamics of thermal turbine with reheat, thermal turbine without reheat and hydro turbine are considered. The simulation results using Simulink/Matlab and model analysis using eigenvalue analysis show the dynamic behaviour of the power system in response to changes in the load.

Keywords: renewable energy resources; power system hydro turbine; load-frequency control; multi-source; photovoltaic system; small-signal stability; steam turbine

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1. Introduction

An essential aspect of fortifying passive defence mechanisms lies in ensuring the accessibility of energy during critical scenarios. The conventional approaches to power generation are poised to undergo a transformative shift, making room for environmentally sustainable alternatives with the integration of renewable energy sources into the power grid. The escalating demand for energy, propelled by societal growth and technological advancement, is compounded by a growing inclination towards harnessing renewable energy sources. This trend is driven by their recognized efficiency and cost-effectiveness, ushering in a transformative shift in the energy landscape. The expansion of power systems to accommodate the integration of renewable sources and the establishment of interconnections between diverse regions reflects this changing paradigm. However, this evolution introduces fresh challenges, particularly in ensuring the stability, reliability, and uninterrupted functionality of these increasingly complex systems. In tandem with this global shift towards sustainable energy, the power system is encountering new challenges and opportunities. The traditional paradigm of centralized power generation is giving way to a decentralized model, characterized by the widespread adoption of distributed generations and diverse industrial loads [1,2].

This shift not only transforms the physical infrastructure of the power grid, but also necessitates a revaluation of control strategies and grid management techniques. Renewable energy sources, like solar and wind, are intermittent, which adds a degree of unpredictability that conventional power systems were not initially built to handle [3,4]. An electric power system consists of a complex set of electromechanical devices, the main aim of which is to convert energy and transfer it from the place of production, with minimum cost and with minimum environmental impact, to the points where the consumers are located [5,6]. The power system is required to consistently fulfil the ongoing demand for both active and reactive power [7,8]. Additionally, it is imperative for the power supply to maintain frequency stability, voltage stability, and a high reliability. In contemporary times, the energy grid faces heightened complexity, attributable to the integration of distributed generators and diverse industrial loads [9,10]. The escalating integration of renewable energy generation units into electric grids poses a significant challenge for frequency stabilization, primarily attributed to the distinctive technical characteristics associated with their implementation [11,12].

Load frequency control constitutes a pivotal control loop within the power system, designed to swiftly mitigate frequency deviations to zero following a disturbance event. Also, the load should be distributed among the generators, based on their capacity. Maintaining the power exchange between the connection lines between the areas within the programmed limits is another task of this control loop [13,14]. The use of different distributed generator sources, such as wind turbine generators [15,16], solar panels [17,18], diesel engine generators [19,20], and energy storage systems [21,22], has significant advantages in improving the quality of the energy network. Nevertheless, the growing adoption of distributed generation sources presents challenges, including the intricacy of the frequency control mechanism, increased voltage instability, and heightened system sensitivity to faults within the energy network.

To date, numerous studies have been put forth concerning frequency control in energy networks, with a subset of these investigations explicitly addressing the implications arising from the incorporation of renewable power resources [23,24]. A superconducting magnetic energy storage system integration is one suggested method to improve the dynamic performance of automatic generation management after sudden load disruptions, as described in [25]. This method is primarily used in a multi-source power generation system with two zones that are connected. The quadratic performance index is adjusted using the integral square error technique in order to ascertain the integral gain of the controller.

Research into load frequency regulation within energy grids, encompassing a diverse range of energy sources such as thermal, hydro, and gas power facilities, is documented in [26]. The study delves into the determination of controller parameters, aiming to achieve optimal transient performance for the system. This is accomplished through the application of the meta-heuristic harmony search algorithm, which facilitates the exploration and optimization of the controller's settings.

The examination of load frequency regulation within a hybrid energy production framework is the focal point of scrutiny in [27]. This investigation employs first-order PID (proportional-integral-derivative) regulators to regulate and stabilize the system. The hybrid configuration of the power generation system incorporates a combination of thermal, wind, and solar energy sources. Through the utilization of these controllers, this work aims to optimize the performance and balance the load-frequency dynamics in the context of the diverse and interconnected energy generation components.

In [28], a proposal is put forth for determining the optimal settings of the PI regulator specifically tailored for load frequency regulation within a hybrid power system. This hybrid configuration encompasses both a thermal generator and a photovoltaic system. The procedure of determining the tuned controller coefficients is based on solving a time-dependent objective function, which is made easier by employing the firefly algorithm.

Research into the application of the artificial bee colony optimization framework for virtual inertia regulation within wind energy conversion systems interfaced with the grid is documented in [29]. This study delves into the intricacies of the control strategy, illustrating its efficacy through a load frequency investigation conducted across various distinct real operation situations.

In [30], a comprehensive control methodology is introduced to regulate and enhance the performance of three pivotal models within power networks. A thermal power plant's load frequency management system, an integrated photovoltaic thermal power plant's frequency variation, and an automatic voltage regulation system's output variations are all included in these models. The study explores diverse objective functions, aligned with the specific demands of the energy industry, to demonstrate the advancements in system performance parameters, including, but not limited to, maximum overshoot, steady state error, and settling time.

The analysis of small signal stability within an integrated power system is detailed in [31], employing a mathematical model that accounts for the influence of both wind and photovoltaic energy on the electrical grid. Simulation results reveal that in such an integrated energy grid incorporating wind and photovoltaic energy, the system's frequency can swiftly return to the nominal frequency, simultaneously bolstering the strength of each individual unit. This underscores the efficiency and effectiveness of the integrated system in responding to and recovering from perturbations.

In [32], an adaptive controller featuring auto-tuning parameters is described to facilitate the general performance of the power system in response to load variations. This controller exhibits a capability to effectively respond to disturbances arising from the operation of renewable production units, including, but not limited to, wave power conversion systems and solar energy systems. The adaptive nature of the controller, coupled with its auto-tuning functionality, underscores its potential to dynamically optimize system behaviour amid changing load conditions and the inherent variability associated with renewable energy integration.

Synchronous machines serve as prevalent power generators in traditional power systems. However, the integration of renewable energies, facilitated by power converters lacking inertia, notably diminishes the overall inertia of the network. This study explores the utilization of a solar photovoltaic system to augment the inertial capability of the power system. Focusing on a single-area system with diverse energy production sources, the power system equations are formulated in state space. Through the application of system mode analysis and the development of an energy network model in the Simulink/MATLAB environment, the dynamic behaviour of the energy network is simulated to assess its response to load changes.

Given the outlined problem statement and the significance of the subject matter, the paper is structured as follows: Section 2 provides an overview of the frequency load control system, elucidating the control loops within the power system; Section 3 briefly addresses the Photovoltaic system and its applications; moving on to Section 4, the paper presents the energy network model based on first-order transfer functions; the simulation of the single-area power system's performance under step changes in consumption load is conducted in Section 5 using MATLAB/Simulink software, and this section also includes a comparative analysis of the impact of various power sources on the frequency deviation of the system; and Section 6 concludes the paper by summarizing key findings and insights.

2. Load Frequency Control

When it comes to power system dynamics, conventional generators with inertial response are essential because they automatically modify rotational speed in response to variations in the system frequency. This inherent feature makes use of the kinetic energy held in rotating masses to dynamically match patterns of demand with active power supply, guaranteeing grid stability. But when renewable energy generators—which do not have these rotating masses—are integrated into the landscape, the intrinsic inertia of contemporary power systems is challenged. Transient disturbances within a power system induce instability, resulting in an imbalance between load and generation. These instabilities can significantly impact the normal operation of the power system [33,34]. Notably, the flow of active power and reactive power in the transmission network is nearly independent of each other. Active power control hinges on frequency control, while reactive power control is contingent upon voltage control. In the realm of modern energy management systems, automatic generation control emerges as a crucial function. However, various load frequency control methods grapple with challenges stemming from uncertainties, parameter variations, diverse system characteristics, and varying operating point load scenarios across a wide spectrum [35,36].

Load frequency regulation holds a pivotal role in the design and operation of modern electrical systems, ensuring high reliability [37,38]. The hierarchical execution of load-frequency regulation is determined according to the magnitude of frequency deviation [39,40]. Maintaining constant frequency and voltage is crucial for the proper functioning of the power system. The performance and reliability of the power system are intricately linked to the extent of frequency deviation [41]. Figure 1 illustrates how frequency controls are categorized according to the length and magnitude of frequency deviations. The four sections that make up frequency control levels are as [42,43]: primary control (droop control), secondary control (acting based on measurement of frequency change and power flow between areas), tertiary control (the system operator's use of various protection methods to reduce the magnitude of the frequency if the secondary control loop is not capable), and emergency control (continuous control to avoid blackouts, massive outages, or cascading failures in case of large disturbances) [44,45].

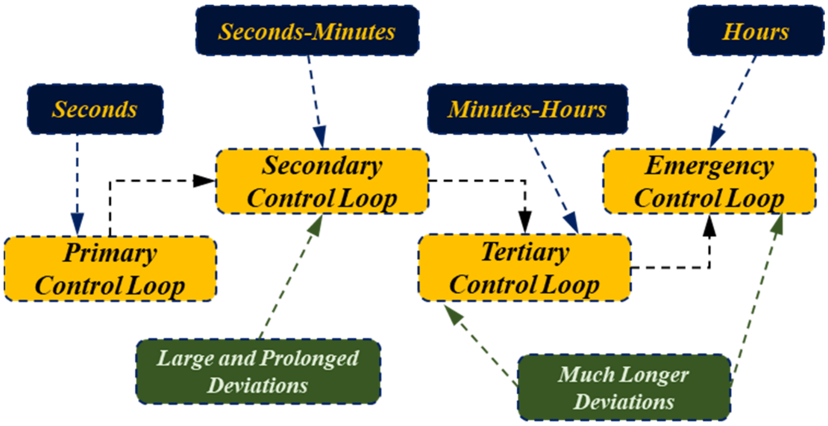

Figure 1. Classification and time range of frequency control.

The shift from traditional synchronous generators to generators controlled by electronics for the integration of renewable energy sources results in a notable decrease in system inertia, which may present challenges to the stability and dependability of the system over an extended period of time. In addition to stressing the idea of Fast Frequency response (FFR) and illuminating the changing dynamics and difficulties related to frequency control in the face of evolving power production technologies, Figure 2 graphically depicts the dynamic reaction of system frequency across various time scales. As discussed, the power system uses Primary Reserves (PRs), Secondary Reserves (SRs), and Tertiary Reserves (TRs) in a tiered manner to preserve stability in the face of disruptions. When a disturbance occurs, PRs react quickly to stabilize the frequency within a $\pm$20 MHz range. To maintain system stability, primary control must be applied before the frequency deviation rises above $\pm$200 MHz. SRs activate within a response window of 30 to 15 minutes' post-disturbance once PRs have stabilized the frequency. Their job is to replenish previously used PRs in order to maintain continuous stability, while restoring and maintaining the frequency at its nominal value. On the other hand, TRs use a manual method to neutralize and absorb the impacts of activated SRs by using tertiary control over a period of minutes to hours. Figure 3 shows a single-area energy grid with four frequency control loops along with an inertial control loop. Leveraging virtual inertia control technology boosts fortification of the total inertia of the power system and augments its frequency performance [46].

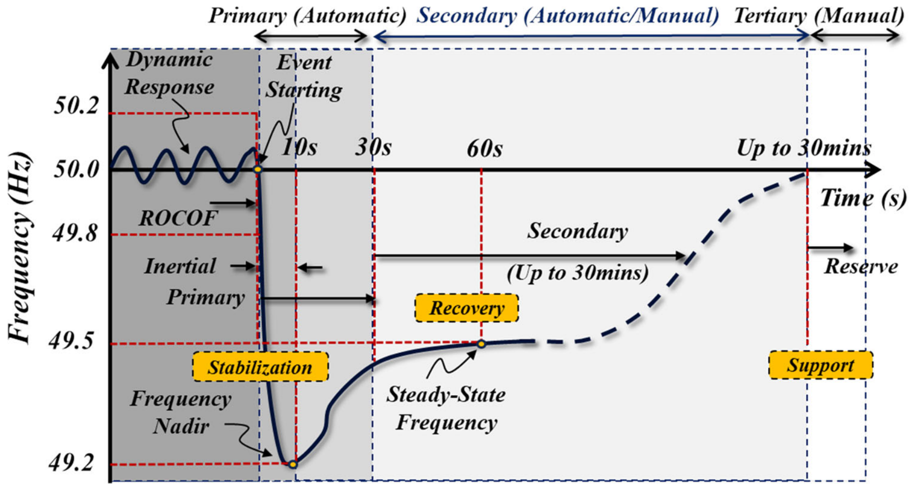

Figure 2. The dynamic reaction of system frequency across various time scales.

3. Photovoltaic System

Concerns regarding environmental issues have arisen as a result of rising energy use. Solar energy is one of the major renewable energy sources and one of the sustainable solutions to this issue. Photovoltaic solar energy, which transforms solar heat into electrical energy, and solar thermal energy, which converts solar heat into thermal energy, are the two uses of solar energy. The ever-increasing need for electrical energy has spurred the rapid development of renewable energy sources, which has accelerated the photovoltaic production. A photovoltaic system is one of the practical tools for converting solar energy into electricity [47,48]. This system represents one category within the spectrum of solar energy facilities, further classified into two types: photovoltaic units connected to the grid and those disconnected from the grid [49,50]. The general components of a photovoltaic system are: solar panels, storage batteries, inverter, control device, metal structure, and communication cables. The two main types of exploiting solar thermal energy are heat collection and electricity generation [51,52].

The transfer function of the composite circuit representing the photovoltaic system, composed of the photovoltaic plane, highest power point monitoring, filter, and inverter, is analysed with the following relationship [53,54]:

$$G_{PV}(s) = \frac{K_P}{s+p_1}\frac{s+z_1}{s+p_2}. \tag{1}$$

in which K_P is the gain of the photovoltaic system, p_1 are p_2 are poles, and z_1 is zero in the transfer function. Poles and zero are considered real and negative.

4. Small-Signal Model

To guarantee the seamless and efficient operation of the power system, the development of highly effective controllers is imperative. The optimization of these controllers relies heavily on an intricate process of modelling. The complexity of power systems, characterized by their nonlinear nature and dynamic parameters dependent on operating points, demands a meticulous approach to modelling for the design of optimal controllers. Power systems are inherently intricate, with their parameters varying as a function of the system's operating point. Moreover, the load within a power system undergoes continual fluctuations rather than remaining constant.

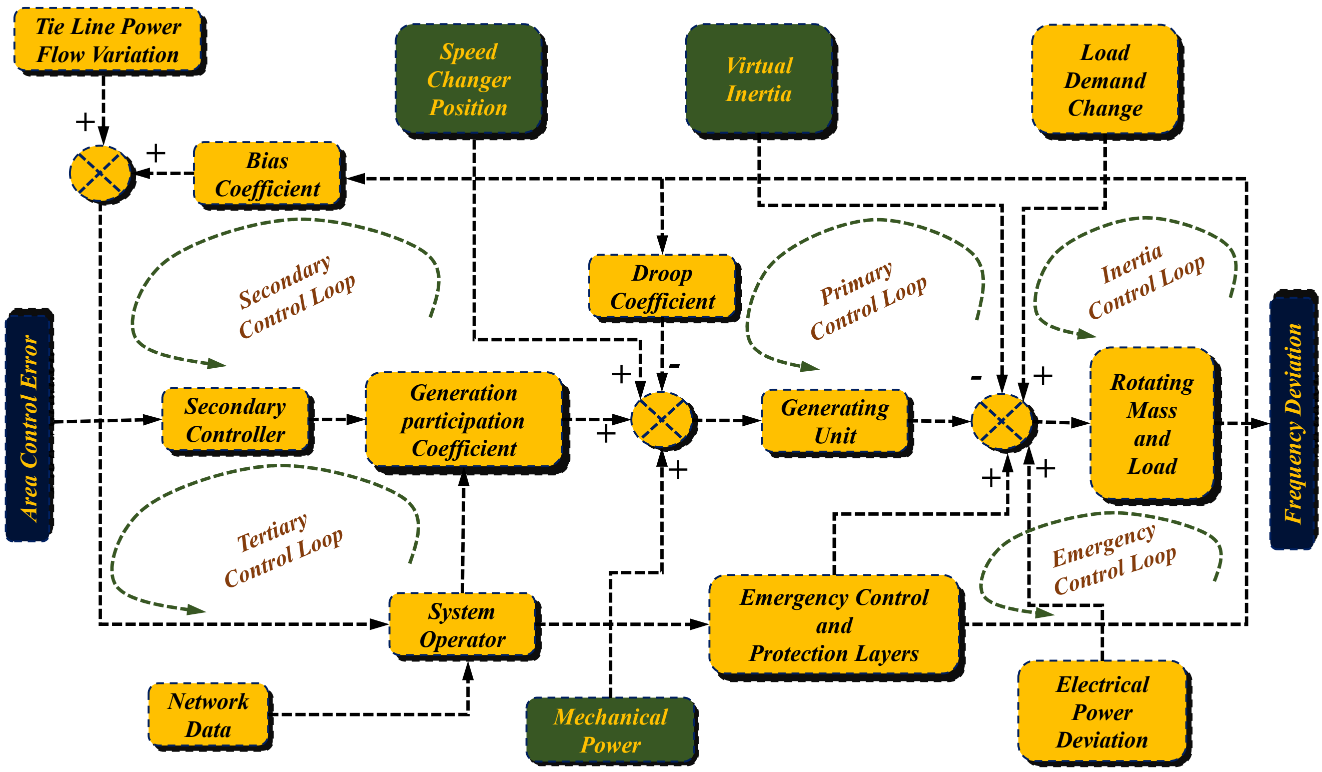

Figure 3. Control frequency in single-area energy system.

Consequently, the significance of modelling within the realm of power systems cannot be overstated. It serves as a crucial tool for comprehending system behaviour and crafting controllers capable of adapting to the ever-changing dynamics. In the unfortunate event of a power outage in the national grid, it becomes paramount to ensure the uninterrupted functionality of subsystems. The challenges arising from the frequency load control system predominantly revolve around addressing minor disturbances in demand load. The analysis of power system stability, specifically concerning minor disturbances, constitutes the focal point of small signal stability analysis. This intricate examination takes place during the operation of the power system, aiming to safeguard its stability in the face of subtle disruptions.

Small signal stability analysis hinges on a multitude of factors, including the initial operating conditions of the system, the efficacy of electrical connections interlinking various components, and the unique characteristics of control devices. By scrutinizing these elements, experts gain insights into the system's robustness and its ability to weather minor disturbances, ensuring a resilient and dependable power infrastructure. The single-area LFC is based on the block representation of the transfer function for the multi-source energy network shown in Figure 4. In this linearized structure designed for load frequency control, for the sake of simplification, a first-order delay function is employed to characterize the transfer functions of both the steam power facility and the hydro energy facility [55,56].

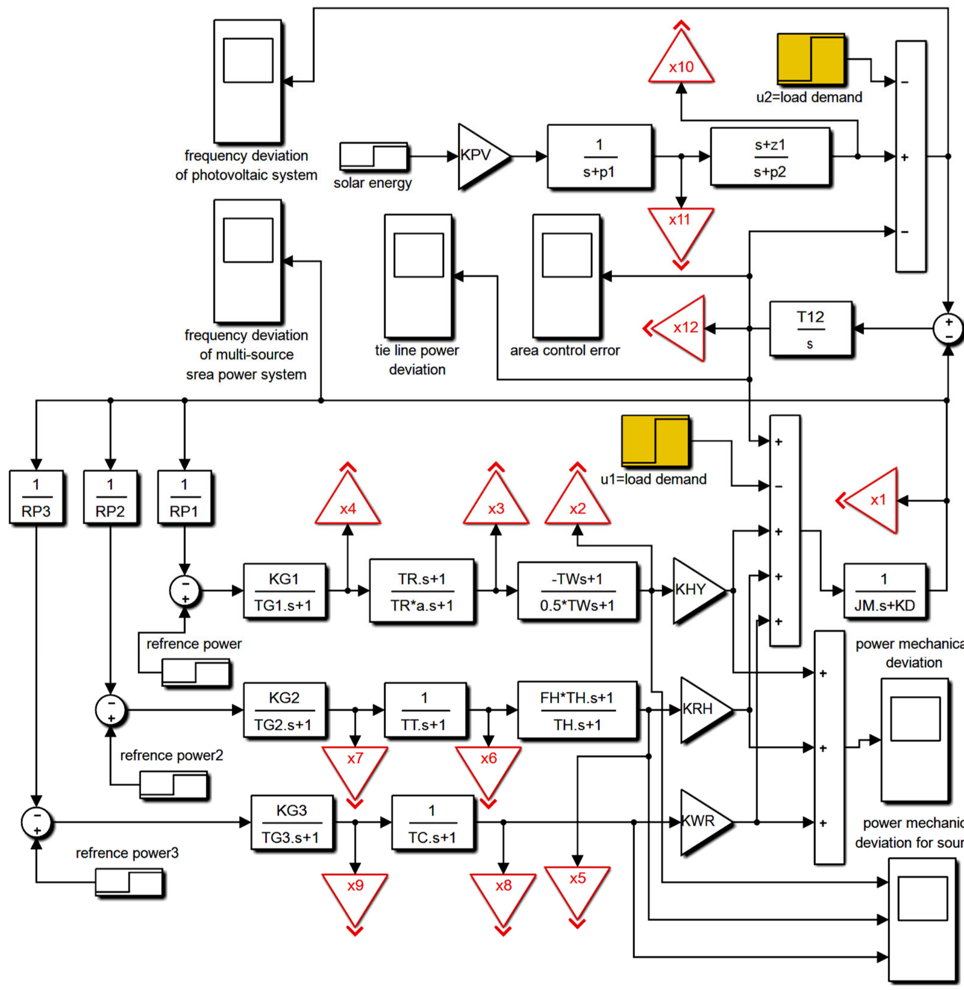

Figure 4. Block diagram of an interconnected energy system consisting of photovoltaics and various energy sources with only primary speed control.

4.1. Participation Coefficients of Generation Units

The rate of participation in load frequency control may not be the same for all manufacturers. The contribution factors of thermal units without re-heater, thermal with re-heater, and water are K_{WR}, K_{RH}, and K_{HY}, respectively. The contribution of the units in the nominal load is determined by these factors. Within a particular control area, the aggregate of membership factors is equivalent to 1 [57,58].

4.2. Rotating Mass Model

The rotor and load inertia equivalent circuit are considered with the first order differential equation [59,60]:

$$\frac{\Delta F}{\Delta P_M - \Delta P_L} = \frac{1}{J_M s + K_D}. \tag{2}$$

where K_D is the load damping constant and J_M is combined inertial constant. System frequency changes, mechanical power changes, and load changes are indicated by ΔF, ΔP_M, and ΔP_L, respectively [61,62].

The alterations in the mechanical power of the entire system are equivalent to the summation of the changes in the mechanical power of each unit, accounting for the unit's participation factor in the overall production.

$$\Delta P_M = K_{HY}\Delta P_{MH} + K_{RH}\Delta P_{MR} + K_{WR}\Delta P_{MW}. \tag{3}$$

where ΔP_{MH}, ΔP_{MR}, and ΔP_{MW} are the changes in mechanical power in generative units, water, thermal with reheater and thermal without reheater. Furthermore, the participation coefficients for hydro power plants, thermal power plants with reheaters, and thermal power plants without reheaters are denoted as $K_{HY,}$ K_{RH}, and K_{WR}, respectively.

By selecting the state variable x_1 for the system frequency changes and according to the state variables representing the mechanical power changes of the production units (x_2, x_5, and x_8), the differential equation representing the rotor and load inertia equivalent model is expressed as follows:

$$\frac{d}{dt}x_1 = -\frac{K_D}{J_M}x_1 + \frac{K_{HY}}{J_M}x_2 + \frac{K_{RH}}{J_M}x_5 + \frac{K_{WR}}{J_M}x_8 - \frac{1}{J_M}u_1. \tag{4}$$

4.3. Governor-Turbine Dynamic Model of Hydro Energy Facility

At elevated altitudes, water courses through the blades of a hydro turbine within a hydroelectric power plant, undergoing a conversion of potential energy into kinetic energy that ultimately generates electricity. A notable advantage of water turbine power plants lies in the elimination of fuel supply costs. Moreover, these installations boast a longer average lifespan compared to their thermal power plant counterparts. The hydro turbine model is considered with a transfer function having one zero ($1/T_W$) and one pole ($-2/T_W$) [63]. By selecting state variables x_2, x_3, and x_4, the first order differential equations of the generating unit with hydraulic turbine in the state space are:

$$\begin{gathered}\frac{d}{dt}x_2 = \frac{-2}{T_W}x_2 + \frac{2}{T_W}x_3 - 2\,\frac{d}{dt}x_3 = \frac{2\,K_{G1}}{\alpha\,R_{P1}T_{G1}}x_1 - \frac{2}{T_W}x_2 + \left(\frac{2}{T_W} + \frac{2}{\alpha\,T_R}\right)x_3 \\ -\left(\frac{2}{\alpha\,T_R} - \frac{2}{\alpha\,T_{G1}}\right)x_4 - \frac{2\,K_{G1}}{\alpha\,T_{G1}}u_2.\end{gathered} \tag{5}$$

where T_W represents the nominal starting time of water in the penstock, R_{P1} stands for the droop constant, T_{G1} denotes the governor time constant, and T_R represents the long reset time. Furthermore, K_{G1} is a positive coefficient associated with the governor.

$$\begin{gathered}\frac{d}{dt}x_3 = -\frac{1}{\alpha\,T_R}x_3 + \frac{1}{\alpha\,T_R}x_4 + \frac{1}{\alpha}\frac{dx_4}{dt} = -\frac{K_{G1}}{\alpha\,R_{P1}T_{G1}}x_1 - \frac{1}{\alpha\,T_R}x_3 + \left(\frac{1}{\alpha\,T_R} - \frac{1}{\alpha\,T_{G1}}\right)x_4 \\ +\frac{K_{G1}}{\alpha\,T_{G1}}u_2.\end{gathered} \tag{6}$$

$$\frac{d}{dt}x_4 = -\frac{K_{G1}}{R_{P1}T_{G1}}x_1 - \frac{1}{T_{G1}}x_4 + \frac{K_{G1}}{T_{G1}}u_2. \tag{7}$$

For further details on the extraction of the mathematical differential equation of the nonlinear dynamics, see [64,65].

4.4. Governor-Turbine Dynamic Model of Thermal Power Plant

A steam turbine could be conceptualized as a multi-dimensional regulation system with the main steam valve lifter and the reheat valve serving as its inputs [66]. By selecting state variables x_5, x_6, and x_7, the first order differential equations of the generating unit with reheat steam turbine in the state space are:

$$\frac{d}{dt}x_5 = -\frac{1}{T_H}x_5 + \frac{1}{T_H}x_6 + F_H\frac{d}{dt}x_6 = -\frac{1}{T_H}x_5 + \left(\frac{1}{T_H} - \frac{F_H}{T_T}\right)x_6 + \frac{F_H}{T_T}x_7. \tag{8}$$

$$\frac{d}{dt}x_6 = -\frac{1}{T_T}x_6 + \frac{1}{T_T}x_7. \tag{9}$$

$$\frac{d}{dt}x_7 = -\frac{K_{G2}}{T_{G2}R_{P2}}x_1 - \frac{1}{T_{G2}}x_7 + \frac{K_{G2}}{T_{G2}}u_3\,. \tag{10}$$

where T_H denotes the reheater time constant, F_H indicates the Strong pressure coefficient, T_{G1} represents the governor time constant, and T_T is the turbine time constant. In addition, K_{G2} is the governor positive coefficient, R_{P2} stands for the droop constant, and T_{G2} represents the governor time constant.

By selecting state variables x_8 and x_9, the first order differential equations of the generating unit without reheat steam turbine in the state space are:

$$\frac{d}{dt}x_8 = -\frac{1}{T_C}x_8 + \frac{1}{T_C}x_9. \tag{11}$$

$$\frac{d}{dt}x_9 = -\frac{K_{G3}}{T_{G3}R_{P3}}x_1 - \frac{1}{T_{G3}}x_9 + \frac{K_{G3}}{T_{G3}}u_4\,. \tag{12}$$

where T_C indicates the turbine time constant and R_{P3} represents the droop constant. Furthermore, K_{G3} and T_{G3} denote the governor's positive coefficient and time constant, respectively.

4.5. Governor-Turbine Dynamic Model of Thermal Power Plant

Radiation and temperature are pivotal factors influencing the energy output of solar panels [67]. Given the instantaneous variability in the output power of photovoltaic systems, their impact on the primary frequency response holds significant importance [68].

By choosing two state variables, the photovoltaic system structure is expressed in the state-space model as follows, which includes the photovoltaic panel, inverter, highest power point monitoring, and filter.

$$\frac{d}{dt}x_{10} = -p_2\,x_{10} + z_1x_{11} + \frac{d}{dt}x_{11} - p_2\,x_{10} + (z_1 + p_1)x_{11} + K_{PV}u_2. \tag{13}$$

$$\frac{d}{dt}x_{11} = -p_1x_{11} + K_{PV}u_2 \tag{14}$$

Note that all the parameters and constants in the denominator of Equations (1)–(14) are positive.

5. Simulation Results

Ensuring the quality and reliability of power supply while simultaneously maintaining stability in the power system hinges significantly on the effective control of frequency. This pivotal parameter plays a crucial role in orchestrating the seamless operation of diverse energy facilities within the overall power infrastructure.

In this section, our focus narrows down to the examination of a synergistic system. This composite configuration is comprised of a thermal energy facility equipped with a reheater, a hydro energy facility, and a thermal power plant that operates without a reheater. By scrutinizing the collective dynamics and interactions of these components, we aim to gain insights into the intricate interplay of various energy sources and their impact on frequency control within the broader context of the power system. This analysis allows us to discern the nuanced relationships and dependencies among different types of power generation facilities, shedding light on their collective role in ensuring the robustness and reliability of the power supply.

The above system is described using 13 state variables and 5 independent inputs in the state space. Information on energy production sources for simulation is given in Table 1, and information on the power system and resource participation coefficients in energy production is summarized in Table 2. The assessment of the energy grid's performance under varying loads is conducted through computer simulations utilizing MATLAB software. The study's process, focusing on simulating a power system with diverse energy sources and assessing the impact of the photovoltaic system on the load frequency control system, is illustrated in Figure 5.

Table 1. Parameters of energy production resources in the hybrid system.

Parameter	Symbol	Hydro Energy Facility	Thermal Energy Facility	
			with Reheat-Turbine	without Reheat-Turbine
Governor time constant	T_{G1}, T_{G2}, T_{G3}	0.2	0.2	0.2
Turbine time constant	T_W, T_T, T_C	1	0.3	0.3
Droop constant	R_{P1}, R_{P2}, R_{P3}	0.05	0.05	0.05
Reheater time constant	T_H	-	7	-
Strong pressure coefficient	F_H	-	0.3	-
Slope ratio	α	0.76	-	-
Long reset time	T_R	5	-	-

Table 2. Rotor and load parameters, along with the contribution coefficients of energy production sources.

Parameter	Symbol	Value
Damping coefficient	K_D	1
System inertia constant	J_M	6
Hydro power plant participation coefficient	K_{HY}	0.3
Coefficient of participation of thermal power plant with reheater	K_{RH}	0.5
Coefficient of participation of thermal power plant without reheater	K_{WR}	0.2

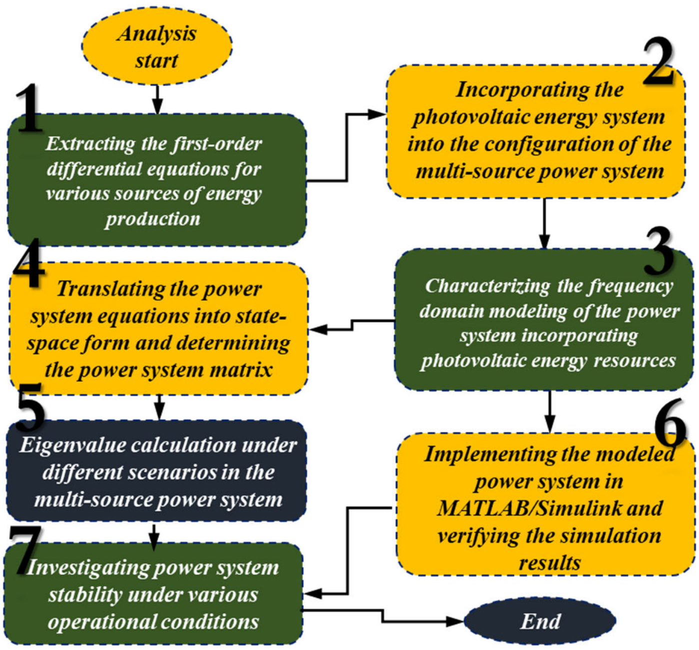

Figure 5. The process of simulating the presented power system and investigating the impact of the photovoltaic system.

Three distinct simulation scenarios are examined to illustrate the frequency fluctuations within the energy system. The first case involves load changes exclusively in the broader area of the electrical energy system, encompassing three diverse energy sources. In the second case, load changes are confined to the area of the power system incorporating the photovoltaic unit. The third case explores load changes occurring simultaneously in both areas.

5.1. Demand Step Increase without PV System

In this case, it is assumed that the power sub-system including three energy sources is subject to load demand change. Figure 6 illustrates the frequency variations within the power system, revealing a notable frequency drop exceeding 0.25 Hz. In Figure 7, alterations in the mechanical power of the entire power system are presented in response to step variation in load demand. This power is derived from the output power of three power plants, considering the participation coefficients of the individual units. Figure 8 depicts the changes in the mechanical power of each power plant unit within the energy system, specifically responding to variations in demand side. As can be seen, the steam power plant with a preheater has a lower speed compared to the other two power plants.

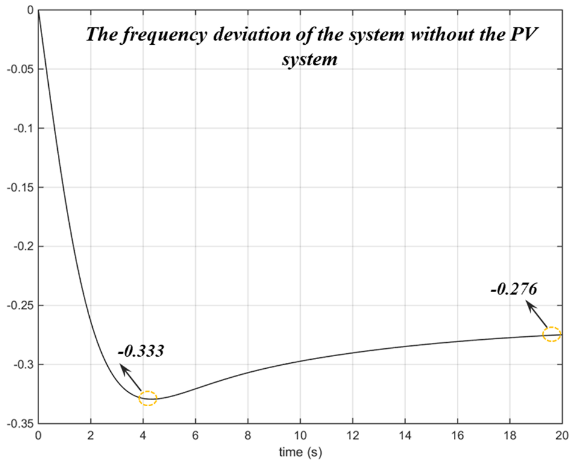

Figure 6. Power system frequency changes for step changes in load demand (without PV system).

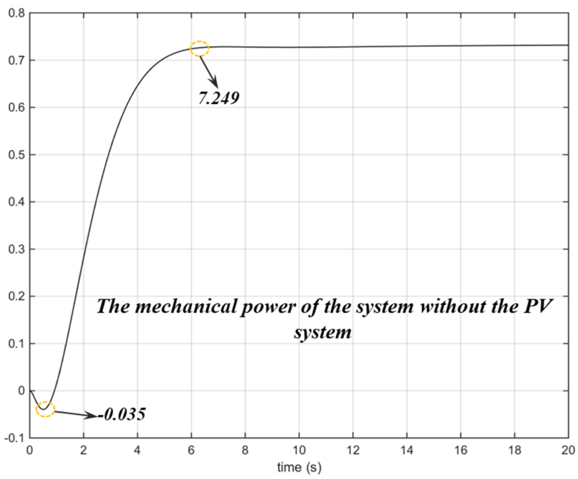

Figure 7. The variations in the mechanical power of the energy network in response to step changes in demand side (without PV system).

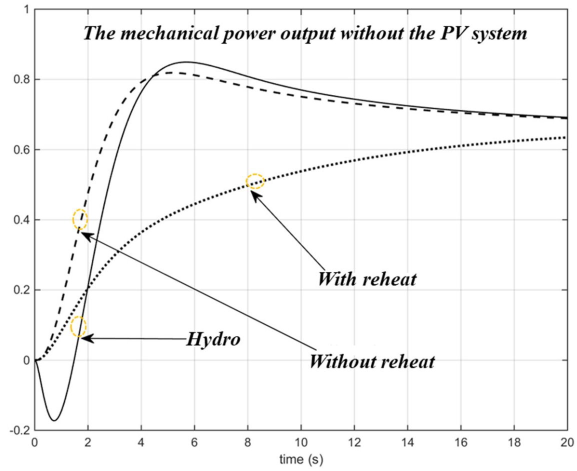

Figure 8. The variations in the mechanical power of each power unit within the power system in response to variations in demand side (without PV system).

5.2. Effect of Photovoltaic System

In this section, it is assumed that the input of the photovoltaic system is 5%. Figure 9 illustrates the frequency fluctuations in the energy grid resulting from variations in load, while Figure 10 specifically presents the frequency variations within the photovoltaic system area. Notably, the frequency changes approach nearly zero in the steady-state.

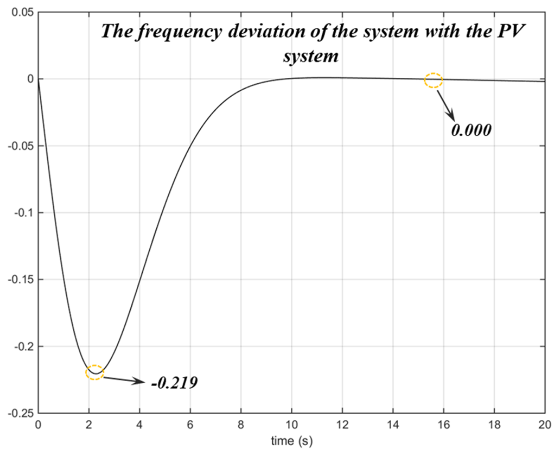

Figure 9. The frequency changes within the power grid in response to variations in demand side (with PV system).

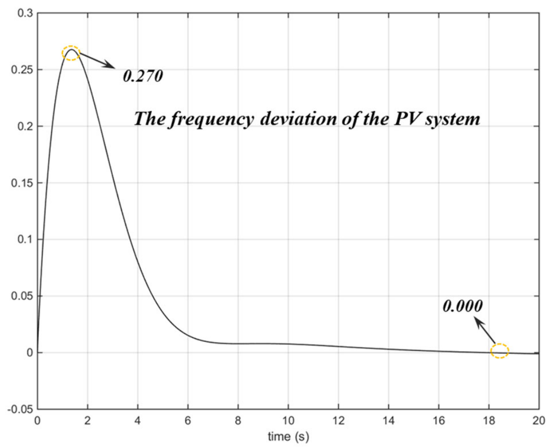

Figure 10. The frequency variations specific to the area associated with the photovoltaic system (with PV system).

6. Conclusions

The proliferation of distributed energy resources, coupled with a decline in tradition-al generators, has ushered in a transformation in the power system, marked by a discernible reduction in rotational inertia. This shift in the energy landscape has, in turn, contributed to a noteworthy decrease in overall frequency stability. Within this evolving paradigm, this paper delves into the critical challenge of load frequency control within a single-area energy grid characterized by a diverse mix of energy sources. The constituents of this singular system encapsulate a thermal energy facility featuring a reheat turbine, an-other equipped with a turbine without reheat, and a hydro power plant. The examination extends to include the incorporation of a photovoltaic unit, investigating its impact on the frequency deviation within the energy grid. The paper's findings highlight that effectively integrating renewable photovoltaic systems not only improves the environmental sustainability of overall power generation, but also alleviates frequency fluctuations within the energy system. Consequently, this integration contributes significantly to enhancing the stability and reliability of the next generation of green energy systems. Through exploration and simulation, this study aims to unravel the intricate dynamics of the energy grid, shedding light on the dynamic behaviour induced by a multi-source energy production environment. This analysis not only serves to elucidate the complex interactions among diverse power sources, but also provides valuable insights into the efficacy of load frequency regulation strategies in navigating the evolving landscape of energy resources. By addressing these pertinent issues, the paper contributes to the ongoing discourse on enhancing the resilience and adaptability of power systems in the face of emerging challenges associated with the integration of varied and decentralized energy resources.

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Nomenclature

ΔF	Frequency deviation
ΔP_M	Mechanical power deviation
ΔP_D	Demand load deviation
J_M	Combined inertial constant
K_D	Load-damping constant
ΔP_{MH}	Hydro turbine mechanical power deviation
ΔP_{MR}	Thermal with reheater turbine mechanical power deviation
ΔP_{MW}	Thermal without reheater turbine mechanical power deviation
T_W	Nominal starting time of water in penstock
T_T	Steam turbine time constant
T_R	Long reset time

References

1. Fathollahi, A.; Gheisarnejad, M.; Boudjadar, J.; Homayounzadeh, M.; Khooban, M.-H. Optimal Design of Wireless Charging Electric Buses-Based Machine Learning: A Case Study of Nguyen-Dupuis Network. *IEEE Trans. Veh. Technol.* **2023**, *72*, 8449–8458. [CrossRef]
2. Yildirim, B.; Razmi, P.; Fathollahi, A.; Gheisarnejad, M.; Khooban, M.H. Neuromorphic deep learning frequency regulation in stand-alone microgrids. *Appl. Soft Comput.* **2023**, *144*, 110418. [CrossRef]
3. Fathollahi, A.; Kargar, A.; Yaser Derakhshandeh, S. Enhancement of power system transient stability and voltage regulation performance with decentralized synergetic TCSC controller. *Int. J. Electr. Power Energy Syst.* **2022**, *135*, 107533. [CrossRef]
4. Fathollahi, A.; Gheisarnejad, M.; Andresen, B.; Farsizadeh, H.; Khooban, M.-H. Robust Artificial Intelligence Controller for Stabilization of Full-Bridge Converters Feeding Constant Power Loads. *IEEE Trans. Circuits Syst. II Express Briefs* **2023**, *70*, 3504–3508. [CrossRef]
5. Salas, V.; Olías, E.; Barrado, A.; Lázaro, A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Sol. Energy Mater. Sol. Cells* **2006**, *90*, 1555–1578. [CrossRef]
6. Ghorbani, H.; Majidi, B. Power density optimization through optimal selection of PM properties in a PM-SyncRM using FEM analysis. In Proceedings of the 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC), Shiraz, Iran, 12–14 February 2019; pp. 44–49.
7. Motaghi, A.; AaLIzadeh, M.; Abbasian, M. Reactive power compensation and reducing network transmission losses by optimal placement of parallel and series FACTS devices with fuzzy-evolutionary method. *J. Intell. Proced. Electr. Technol.* **2019**, *9*, 27–38.
8. Ghfarokhi, G.S.; Arezoomand, M.; Mahmoodian, H. Analysis and simulation of the single-machine infinite-bus with power system stabilizer and parameters variation effects. In Proceedings of the 2007 International Conference on Intelligent and Advanced Systems (ICIAS), Kuala Lumpur, Malaysia, 25–28 November 2007; pp. 167–171.
9. Rajamand, S. Load frequency control and dynamic response improvement using energy storage and modeling of uncertainty in renewable distributed generators. *J. Energy Storage* **2021**, *37*, 102467. [CrossRef]
10. Jeddi-Golfazani, M.; Vahedi, M.; Gandomkar, M. Design of robust reset controller based on optimal after reset performance to improve the performance of an industrial robot control. *J. Intell. Proced. Electr. Technol.* **2023**, *14*, 83–100.
11. Wang, W.; Yorino, N.; Sasaki, Y.; Zoka, Y.; Bedawy, A.; Kawauchi, S. A novel adaptive model predictive frequency control using unscented Kalman filter. *Electr. Power Syst. Res.* **2022**, *213*, 108721. [CrossRef]
12. Ahmed, E.M.; Mohamed, E.A.; Selim, A.; Aly, M.; Alsadi, A.; Alhosaini, W.; Alnuman, H.; Ramadan, H.A. Improving load frequency control performance in interconnected power systems with a new optimal high degree of freedom cascaded FOTPID-TIDF controller. *Ain Shams Eng. J.* **2023**, *14*, 102207. [CrossRef]
13. Li, B.; Hu, S.; Zhong, Q.; Shi, K.; Zhong, S. Dynamic memory event-triggered proportional-integral-based H∞ load frequency control for multi-area wind power systems. *Appl. Math. Comput.* **2023**, *453*, 128070. [CrossRef]
14. Rajaguru, V.; Annapoorani, K.I. Virtual synchronous generator based superconducting magnetic energy storage unit for load frequency control of micro-grid using African vulture optimization algorithm. *J. Energy Storage* **2023**, *65*, 107343. [CrossRef]
15. Mosaad, M.I.; Sabiha, N.A. Ferroresonance Overvoltage Mitigation Using STATCOM for Grid-connected Wind Energy Conversion Systems. *J. Mod. Power Syst. Clean Energy* **2022**, *10*, 407–415. [CrossRef]
16. Jafari, E.; Marjanian, A.; Solaymani, S.; Shahgholian, G. Designing an Emotional Intelligent Controller for IPFC to Improve the Transient Stability Based on Energy Function. *J. Electr. Eng. Technol.* **2013**, *8*, 478–489. [CrossRef]
17. Haghshenas, G.; Mehdi Mirtalaei, S.M.; Mordmand, H.; Shahgholian, G. High step-up boost-flyback converter with soft switching for photovoltaic applications. *J. Circuits Syst. Comput.* **2019**, *28*, 1950014. [CrossRef]
18. Bordihn, S.; Fladung, A.; Schlipf, J.; Kontges, M. Machine Learning Based Identification and Classification of Field-Operation Caused Solar Panel Failures Observed in Electroluminescence Images. *IEEE J. Photovolt.* **2022**, *12*, 827–832. [CrossRef]
19. Shojaee, M.; Azizi, S. Decentralized Robust Control of a Coupled Wind Turbine and Diesel Engine Generator System. *IEEE Trans. Power Syst.* **2023**, *38*, 807–817. [CrossRef]
20. Fathollahi, A.; Andresen, B. Multi-Machine Power System Transient Stability Enhancement Utilizing a Fractional Order-Based Nonlinear Stabilizer. *Fractal Fract.* **2023**, *7*, 808. [CrossRef]
21. Rasool, S.; Muttaqi, K.M.; Sutanto, D. A Multi-Filter Based Dynamic Power Sharing Control for a Hybrid Energy Storage System Integrated to a Wave Energy Converter for Output Power Smoothing. *IEEE Trans. Sustain. Energy* **2022**, *13*, 1693–1706. [CrossRef]
22. Keyvani-Boroujeni, B.; Fani, B.; Shahgholian, G.; Alhelou, H.H. Virtual Impedance-Based Droop Control Scheme to Avoid Power Quality and Stability Problems in VSI-Dominated Microgrids. *IEEE Access* **2021**, *9*, 144999–145011. [CrossRef]
23. Aziz, A.; Oo, A.T.; Stojcevski, A. Frequency regulation capabilities in wind power plants. *Sustain. Energy Technol. Assess.* **2018**, *26*, 47–76. [CrossRef]
24. Siti, M.; Mbungu, N.; Tungadio, D.; Banza, B.; Ngoma, L. Application of load frequency control method to a multi-microgrid with energy storage system. *J. Energy Storage* **2022**, *52*, 104629. [CrossRef]
25. 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 Proceedings of the 2014 International Conference on Advances in Green Energy (ICAGE), Thiruvananthapuram, India, 17–18 December 2014; pp. 106–111.
26. Shankar, G.; Mukherjee, V. Quasi oppositional harmony search algorithm-based controller tuning for load frequency control of multi-source multi-area power system. *Int. J. Electr. Power Energy Syst.* **2016**, *75*, 289–302. [CrossRef]

27. Koley, I.; Bhowmik, P.S.; Datta, A. Load frequency control in a hybrid thermal-wind-photovoltaic power generation system. In Proceedings of the 2017 4th International Conference on Power, Control & Embedded Systems (ICPCES), Allahabad, India, 9–11 March 2017; pp. 1–5.
28. Abd-Elazim, S.M.; Ali, E.S. Load frequency controller design of a two-area system composing of PV grid and thermal generator via firefly algorithm. *Neural Comput. Appl.* **2018**, *30*, 607–616. [CrossRef]
29. Aluko, A.O.; Dorrell, D.G.; Carpanen, R.P.; Ojo, E.E. Heuristic Optimization of Virtual Inertia Control in Grid-Connected Wind Energy Conversion Systems for Frequency Support in a Restructured Environment. *Energies* **2020**, *13*, 564. [CrossRef]
30. Ghosh, A.; Ray, A.K.; Nurujjaman; Jamshidi, M. Voltage and frequency control in conventional and PV integrated power systems by a particle swarm optimized Ziegler–Nichols based PID controller. *SN Appl. Sci.* **2021**, *3*, 314. [CrossRef]
31. He, T.; Li, S.; Wu, S.; Li, K. Small-Signal Stability Analysis for Power System Frequency Regulation with Renewable Energy Participation. *Math. Probl. Eng.* **2021**, *2021*, 1–13. [CrossRef]
32. Mokhtar, M.; Marei, M.I.; Sameh, M.A.; Attia, M.A. An adaptive load frequency control for power systems with re-newable energy sources. *Energies* **2022**, *15*, 573. [CrossRef]
33. Topno, P.N.; Chanana, S. Load frequency control of a two-area multi-source power system using a tilt integral derivative controller. *J. Vib. Control.* **2018**, *24*, 110–125. [CrossRef]
34. Rezaei, M.A.; Fathollahi, A.; Akbari, E.; Saki, M.; Khorgami, E.; Teimouri, A.R.; Chronopoulosd, A.T.; Mosavi, A.H. Reliability Calculation Improvement of Electrolytic Capacitor Banks Used in Energy Storage Applications Based on In-ternal Capacitor Faults and Degradation. *IEEE Access* **2024**, *12*, 13146–13164. [CrossRef]
35. Alhelou, H.H.; Hamedani-Golshan, M.E.; Zamani, R.; Heydarian-Forushani, E.; Siano, P. Challenges and Opportunities of Load Frequency Control in Conventional, Modern and Future Smart Power Systems: A Comprehensive Review. *Energies* **2018**, *11*, 2497. [CrossRef]
36. Shahgholian, G.; Fattollahi, A. Improving Power System Stability Using Transfer Function: A Comparative Analysis. *Eng. Technol. Appl. Sci. Res.* **2017**, *7*, 1946–1952. [CrossRef]
37. Khadanga, R.K.; Kumar, A.; Panda, S. A modified Grey Wolf Optimization with Cuckoo Search Algorithm for load frequency controller design of hybrid power system. *Appl. Soft Comput.* **2022**, *124*, 109011. [CrossRef]
38. Oshnoei, S.; Fathollahi, A.; Oshnoei, A.; Khooban, M.H. Microgrid Frequency Regulation Based on a Fractional Order Cascade Controller. *Fractal Fract.* **2023**, *7*, 343. [CrossRef]
39. Ma, M.; Zhang, C.; Liu, X.; Chen, H. Distributed Model Predictive Load Frequency Control of the Multi-Area Power System After Deregulation. *IEEE Trans. Ind. Electron.* **2017**, *64*, 5129–5139. [CrossRef]
40. Parmar, K.S.; Majhi, S.; Kothari, D. Load frequency control of a realistic power system with multi-source power generation. *Int. J. Electr. Power Energy Syst.* **2012**, *42*, 426–433. [CrossRef]
41. Pandey, S.K.; Mohanty, S.R.; Kishor, N. A literature survey on load–frequency control for conventional and dist-ribution generation power systems. *Renew. Sustain. Energy Rev.* **2013**, *25*, 318–334. [CrossRef]
42. Aluko, A.O.; Carpanen, R.P.; Dorrell, D.G.; Ojo, E.E. Robust State Estimation Method for Adaptive Load Frequency Control of Interconnected Power System in a Restructured Environment. *IEEE Syst. J.* **2021**, *15*, 5046–5056. [CrossRef]
43. Fattollahi, A.; Dehghani, M.; Yousefi, M.R. Analysis and Simulation Dynamic Behavior of Power System Equipped with PSS and Excitation System Stabilizer. *Signal Process. Renew. Energy* **2022**, *6*, 99–111.
44. Alam, M.S.; Chowdhury, T.A.; Dhar, A.; Al-Ismail, F.S.; Choudhury, M.S.H.; Shafiullah, M.; Hossain, M.I.; Hossain, M.A.; Ullah, A.; Rahman, S.M. Solar and wind energy integrated system frequency control: A critical review on recent developments. *Energies* **2023**, *16*, 812. [CrossRef]
45. Bevrani, H.; Golpîra, H.; Messina, A.R.; Hatziargyriou, N.; Milano, F.; Ise, T. Power system frequency control: An updated review of current solutions and new challenges. *Electr. Power Syst. Res.* **2021**, *194*, 107114. [CrossRef]
46. Kerdphol, T.; Rahman, F.S.; Mitani, Y. Virtual Inertia Control Application to Enhance Frequency Stability of Interconnected Power Systems with High Renewable Energy Penetration. *Energies* **2018**, *11*, 981. [CrossRef]
47. Abrazeh, S.; Mohseni, S.-R.; Zeitouni, M.J.; Parvaresh, A.; Fathollahi, A.; Gheisarnejad, M.; Khooban, M.-H. Virtual Hardware-in-the-Loop FMU Co-Simulation Based Digital Twins for Heating, Ventilation, and Air-Conditioning (HVAC) Systems. *IEEE Trans. Emerg. Top. Comput. Intell.* **2023**, *7*, 65–75. [CrossRef]
48. Saravanan, S.; Babu, N.R. Maximum power point tracking algorithms for photovoltaic system—A review. *Renew. Sustain. Energy Rev.* **2016**, *57*, 192–204. [CrossRef]
49. Mohammadzamani, F.; Hashemi, M.; Shahgholian, G. Adaptive control of nonlinear time-delay systems in the presence of output constraints and actuators faults. *Int. J. Control.* **2023**, *96*, 541–553. [CrossRef]
50. Hussein-Sachit, A.; Fani, B.; Delshad, M.; Shahgholian, G.; Golsorkhi- Esfahani, A. Analysis and implementation of second-order step-up converter using winding cross coupled inductors for photovoltaic applications. *J. Sol. Energy Res.* **2023**, *8*, 1516–1525.
51. Josia, H. Off-grid solar PV system design and analysis in isolated island for sustainable energy access: A case study in sukun island, indonesia. *J. Sol. Energy Res.* **2023**, *8*, 1609–1621.
52. Katche, M.L.; Makokha, A.B.; Zachary, S.O.; Adaramola, M.S. A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. *Energies* **2023**, *16*, 2206. [CrossRef]
53. Zeng, G.-Q.; Xie, X.-Q.; Chen, M.-R. An Adaptive Model Predictive Load Frequency Control Method for Multi-Area Interconnected Power Systems with Photovoltaic Generations. *Energies* **2017**, *10*, 1840. [CrossRef]

54. Bakeer, A.; Magdy, G.; Chub, A.; Bevrani, H. A sophisticated modeling approach for photovoltaic systems in load frequency control. *Int. J. Electr. Power Energy Syst.* **2022**, *134*, 107330. [CrossRef]
55. Hassan, S.M.U.; Ramli, M.A.M.; Milyani, A.H. Robust Load Frequency Control of Hybrid Solar Power Systems Using Optimization Techniques. *Front. Energy Res.* **2022**, *10*, 902776. [CrossRef]
56. Fattollahi-Dehkordi, A.; Shahgholian, G.; Fani, B. Decentralized Synergistic Control of Multi-Machine Power System Using Power System Stabilizer. *Signal Process. Renew. Energy* **2020**, *4*, 1–21.
57. Tavakoli, M.; Pouresmaeil, E.; Adabi, J.; Godina, R.; Catalão, J.P. Load-frequency control in a multi-source power system connected to wind farms through multi terminal HVDC systems. *Comput. Oper. Res.* **2018**, *96*, 305–315. [CrossRef]
58. 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*, 16070. [CrossRef]
59. Sarker, M.A.; Kamrul-Hasan, A.K.M. Load frequency control in power system. *J. Sci. Eng.* **2016**, *10*, 23–30.
60. Bhuyan, S.; Dey, S.H.N.; Paul, S.; Chaine, S. Analysis of Frequency Regulation for a Hydro-Thermal System with ALFC-DR Model. In Proceedings of the 2021 1st International Conference on Power Electronics and Energy (ICPEE), Bhubaneswar, India, 2–3 January 2021; pp. 1–5.
61. Zimmer, G. Modelling and simulation of steam turbine processes: Individual models for individual tasks. *Math. Comput. Model. Dyn. Syst.* **2008**, *14*, 469–493. [CrossRef]
62. Shankar, R.; Bhushan, R.; Chatterjee, K. Small-signal stability analysis for two-area interconnected power system with load frequency controller in coordination with FACTS and energy storage device. *Ain Shams Eng. J.* **2016**, *7*, 603–612. [CrossRef]
63. Kumar, M.; Hote, Y.V. Graphic RCRA-PIDA tuning based on maximum sensitivity for automatic generation control of thermal and hydro power systems. *IET Gener. Transm. Distrib.* **2020**, *14*, 6427–6439. [CrossRef]
64. Tunç, C. Stability and bounded of solutions to non-autonomous delay differential equations of third order. *Nonlinear Dyn.* **2010**, *62*, 945–953. [CrossRef]
65. Tunc, C. On some qualitative behaviors of solutions to a kind of third order nonlinear delay differential equations. *Electron. J. Qual. Theory Differ. Equ.* **2010**, 1–19. [CrossRef]
66. Aghadavoodi, E.; Shahgholian, G. A new practical feed-forward cascade analyzes close loop identification of combustion control loop system through RANFIS and NARX. *Appl. Therm. Eng.* **2018**, *133*, 381–395. [CrossRef]
67. Padiachy, V.; Mehta, U. Novel Fractional-Order Proportional-Integral Controller for Hybrid Power System with Solar Grid and Reheated Thermal Generator. *Solar* **2023**, *3*, 298–321. [CrossRef]
68. Rajan, R.; Fernandez, F.M. Small-signal stability analysis and frequency regulation strategy for photovoltaic sources in interconnected power system. *Electr. Eng.* **2021**, *103*, 3005–3021. [CrossRef]