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Design of Integrated Power System Using Virtual Inertia Control

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Abstract

Modernization and integration of renewable energy sources have made power networks dynamically more complicated, calling for the creation of effective and flexible control mechanisms. With an emphasis on grid stability, energy optimisation, and response to changing conditions, this research examines the crucial role that automatic control systems play in power systems. To examine the potential and constraints of existing control systems, the study combines case studies, simulations, and data analysis. According to the study, automatic control systems are essential for preserving grid stability since they continuously monitor grid conditions and carry out control actions to avert interruptions. Additionally, by effectively allocating power producing resources and incorporating renewable energy sources into the grid, these systems maximise energy usage. Simulations show that control systems are capable of successfully responding to dynamic load fluctuations and fault conditions. The resilience and adaptability of control systems are improved by the incorporation of cutting-edge technology like artificial intelligence (AI) and the internet of things (IoT). While Internet of Things (IoT) devices offer real-time data for better decision-making, AI algorithms optimise control strategies. Additionally, the study pinpoints problems like grid complexity and cybersecurity risks and suggests fixes including cutting-edge algorithms and security precautions.

Keywords: Automatic Control Systems, Power Systems, Grid Stability Energy

1. Introduction

In the modern world, renewable energy sources (RESs) are gradually becoming integrated into the power networks of utility companies. RESs stand for "renewable energy sources." RES have many benefits, including the absence of pollutants that are damaging to the environment, the availability of an unending supply, and a low overall cost [1,2]. However, as a result of RES, utility grids may encounter a variety of difficulties and concerns. Because it produces a reduction in the inertia of power systems that are interconnected, the incorporation of RES into modern power systems that are interconnected is one of the challenges that must be surmounted before the problem can be solved. Power converters are the mechanism of choice for making the connection between renewable energy sources and the utility grid in the vast majority of instances. Because of the implementation of these converters, it has been proved that the overall inertia of the power system is reduced. Because of this, the frequency and voltage stability of the power supply are both thrown off as a direct consequence of the disruption. The biggest obstacle that prevents the broad adoption of renewable energy sources in today's linked power networks is the reduction in the inertia of power systems, which is the result of the previous barrier. In recent years, there has been a parabolic growth in the demand for electrical energy all over the world. This need has led to an increase in the production of electrical energy. This rise may be linked to rapid industrialization, the evolution of technology, and the extensive use of power in our day-to-day lives. The transmission of electrical energy from the locations at which it is generated to the consumers of that energy by means of complex power distribution networks has arisen as an essential component of modern life. This transmission takes place from the point at which it is generated to the users of that energy. To satisfy this continuously growing demand while preserving the dependability and consistency of electrical grids is a formidable obstacle for the power industry, which is now struggling to meet this task. Figuring out how to efficiently manage and control the dynamic and complicated nature of today's power systems is the challenge at hand here.

The current power systems of today can be characterized by two words: intricate and dynamic. These are the defining qualities of today's modern power systems. They are made up of a vast selection of interconnected components, such as generators, transformers, transmission lines, substations, and distribution networks, among many other things. The transmission of electricity from power plants to residential regions, commercial establishments, and industrial settings is accomplished through the collaborative efforts of these components. However, there are a number of challenges that must be conquered with regard to this operation. The dynamic nature of power networks is caused by the interaction of a number of different elements. The ebb and flow of consumer demand, the inclusion of renewable energy sources, and the incidence of unplanned disturbances such as faults or equipment breakdowns are all components that fall under this category. These dynamic changes have the potential to generate imbalances in the equation between supply and demand, which can ultimately lead to variations in frequency, instability in voltage, and substantial disruptions in electrical service. This can all be traced back to the original supply and demand equation.

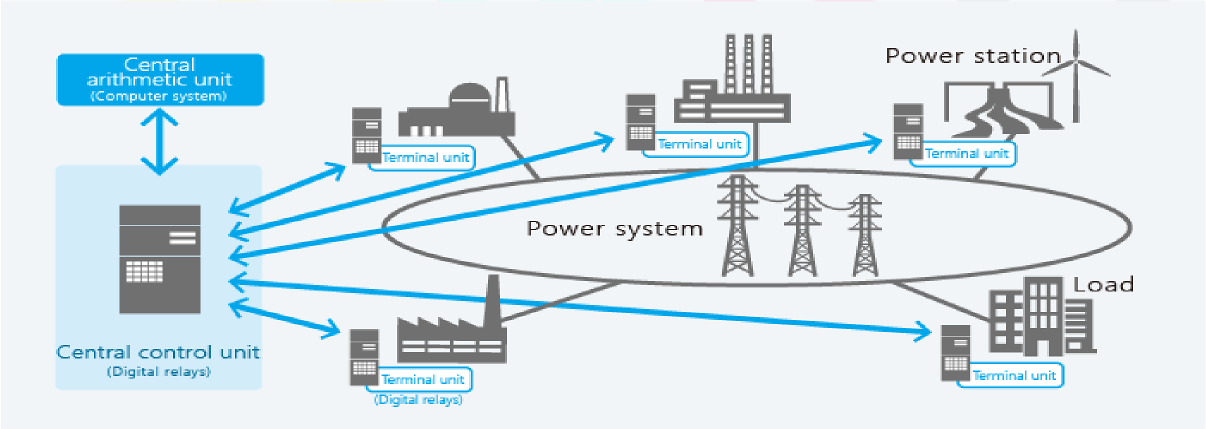

Figure.1 Power system monitoring and control systems

1.1 The Role of Automatic Control Systems

A sophisticated control mechanism that can react in real-time to changing conditions, maintain the stability of the grid, and maximize energy utilization is needed to address the dynamic and complex character of modern power systems. In this situation, automatic control systems become crucial to managing the power grid.

Power systems place a great deal of emphasis on automatic control systems, a fusion of hardware and software elements. They serve as the watchful defenders of electrical networks, making certain that electrical energy is generated, transmitted, and distributed in an efficient and trustworthy manner. Electrical grid stability is maintained via automatic control mechanisms. To avoid voltage collapses, frequency deviations, and blackouts, they continuously monitor grid conditions, spot deviations, and immediately take corrective action. Energy Optimization These systems efficiently distribute power generation resources, control load distribution, and incorporate renewable energy sources into the grid to maximize energy consumption. Response to Load Variations Because automatic control systems are responsive to dynamic load variations, the grid is able to smoothly handle changes in electricity demand.

An advanced network of hardware and software components called an automatic control system is used in power systems to monitor, manage, and control the production, transmission, and distribution of electrical energy. For electrical grids to operate steadily and dependably, these control systems are essential. They are crucial to preserving the reliability of power systems, maximizing energy efficiency, and adapting to sudden changes in load and generation.

1.2 Components

1. Sensors and Measurement Devices

The electrical grid is filled with numerous sensors and measurement tools that are used by automatic control systems. These sensors keep an eye on things like voltage levels, current flows, frequency, temperature, and the condition of the equipment. The basis for the decision-making process in the control system is real-time data from these sensors.

2. Data Acquisition

Continuously acquired and transferred to a central control center are measurements and sensor data. The control system gets access to precise and current data regarding the state of the power system thanks to this data acquisition mechanism.

3. Supervisory Control and Data Acquisition (SCADA) Systems

A crucial part of power system automatic control systems are SCADA systems. They give operators a centralized interface via which they may visualize data, manage numerous machines, and monitor the power system. Real-time decision-making and responsiveness to grid circumstances are made possible by SCADA systems.

4. Control Algorithms and Logic

The software of the control system has embedded control algorithms and logic. Based on the information gathered from the sensors and the operator's input, these algorithms carry out operations. Voltage and frequency regulation, load shedding, and fault isolation and isolation are all examples of control techniques.

5. Communication Infrastructure

Sensors, SCADA systems, and control centers are connected by robust communication infrastructure, which frequently uses high-speed fiber-optic networks. For rapid reactions from the control system, quick and trustworthy communication is crucial.

6. Control Centers:

The brain of the automatic control system is the control center. In these centers, skilled engineers and operators monitor grid conditions and make crucial choices. When necessary, operators can manually enter the control procedure.

7. Automated Control Actions

Without the need for human intervention, automatic control systems can carry out a variety of control operations. The output of generators can be adjusted, voltage and frequency can be regulated, malfunctioning equipment can be isolated, and power flows can be rerouted, among other things.

8. Adaptive and Predictive Control

Adaptive and predictive control methodologies are used in several contemporary control systems. These techniques forecast future grid conditions using sophisticated algorithms and data analysis, then modify control measures as necessary.

9. Integration of Advanced Technologies

With the incorporation of cutting-edge technologies like artificial intelligence (AI) and the internet of things (IoT), automatic control systems are changing. Control tactics can be improved by AI algorithms, while IoT devices offer more data sources for better decision-making.

10. Grid Resilience and Reliability

The dependability and resilience of the grid are strongly impacted by automatic control systems. They support stable grid conditions, the prevention and mitigation of interruptions, and the efficient use of energy to satisfy consumer demand. Power systems' complicated and crucial automatic control mechanisms maintain a consistent and dependable supply of electrical energy. To control the dynamic and complicated character of contemporary power networks, they mix technology, software, data analysis, and human skills. In the face of constantly shifting conditions and demands, these systems are essential for preserving the stability and effectiveness of electrical networks.

2. Literature Review

Naladi Ram Babu et al. (2023) have published a comprehensive review article that aims to provide an extensive analysis of the existing literature and a thorough bibliography on investigations related to automatic generation control (AGC) and load frequency control. The article covers various perspectives on control, including frequency and power control, and discusses different optimization strategies, such as numerical approaches, heuristics, and meta-heuristic techniques, for determining optimal values of secondary controllers in AGC.

A review delves into AGC studies in the context of power transmission, focusing on factors like inertia and phase-locked loops in high voltage direct current (HVDC) systems and accurate HVDC models. It also explores the integration of AGC literature with flexible alternating current transmission system (FACTS) devices in loaded transmission lines and the incorporation of energy storage devices to address intermittent power generation from renewable energy sources (RES). Additionally, the article covers various performance index criteria (PIC), including standard PIC and hybrid peak area (HPA)-PIC, used for controller optimization with algorithms.

Kyoungho Ahn et al. (2023) conducted a study evaluating the effectiveness of an Eco-Cooperative Automated Control (Eco-CAC) system in a large-scale network, considering a mix of internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), and battery-only electric vehicles (BEVs) in a microscopic traffic simulation environment. The results highlight that the Eco-CAC system effectively reduces vehicle fuel and energy consumption, travel time, total delay, and stopped delay in heavily congested conditions. However, the outcomes vary depending on the composition of vehicles. Notably, the maximum energy consumption savings for BEVs occurred at a 10% market penetration rate (MPR) of connected automated vehicles (CAVs) in mild congestion, while the maximum savings for future vehicle compositions occurred at a 50% CAV MPR in no congestion.

The system also reduced fuel consumption for ICEVs and HEVs under certain conditions but increased total fuel consumption in others. The study emphasizes that the effectiveness of the Eco-CAC system is influenced by traffic conditions, network configuration, CAV MPR, and vehicle composition. Haonan Xie et al. (2023) discuss the impact of energy and climate crises on the decarbonization of electric power systems. They highlight the role of carbon-neutral, intelligent system technologies, and digital transformation in this decarbonization process. Pengcheng Chen et al. (2022) present a novel dynamic event-triggered scheme for load frequency regulation, specifically addressing periodic denial-of-service (DoS) attacks and deception attacks using a decentralized output-based control algorithm. The proposed strategy adjusts trigger parameters based on the frequency trend of the DoS attack, ensuring power system stability while increasing the probability of effective transmission during DoS attacks and reducing network bandwidth usage. The article outlines the design of output-based load frequency controllers and validates the proposed approach through simulations in a three-area power system.

Muhammad Majid Gulzar et al. (2022) offer a comprehensive review of various load frequency control (LFC) structures in diverse power system configurations. The review covers single-area, multi-area, and multi-stage power systems, highlighting different controller types and techniques. The article provides a graphical comparative analysis of various controllers and strategies, outlining potential areas for future research and emphasizing the need for improved LFC design in complex power system environments.

Pavel Matrenin et al. (2022) focus on building a model for medium-term load forecasting in electric power systems using ensemble machine learning methods. They conduct a comparative study of different models and highlight the benefits of isolating features from time series data to improve forecast reliability and expand the use of information technologies in power system planning and management. Ahmadreza Eslami et al. (2022) review the applications of artificial intelligence (AI) techniques in harmonic analysis and their superiority over traditional methods, particularly in varying operating conditions. The article suggests opportunities for further research in combining AI techniques, ensemble learning, optimal structures, training algorithms, and deeper comprehension of harmonic analysis.

Jaime Fernando Venegas-Zarama et al. (2022) provide a literature review on the factors influencing the management of Virtual Power Plants (VPPs) in power systems. The review covers various aspects, including concepts and definitions, VPP operation, planning, interaction with systems, programming methods, mathematical techniques, software tools, and international VPP projects. The goal is to enhance understanding of VPPs' role in power systems, sustainability, and their interaction with the power market.

I. Kh. Siddikov et al. (2022) address the improvement of neuro-fuzzy systems for power flow regulation in electric power facilities. They propose an optimization model focused on minimizing power losses in distribution elements of electric power systems, aiming to optimize operations and prevent emergencies. Y N Barykina et al. (2022) examine electric power systems, their properties, and elements. The article analyzes the relationship between functions and properties of energy systems, emphasizing the concept of reliability in fulfilling their functions.

Oleg Kryukov et al. (2020) analyze the operational properties of electric drives in gas pipelines under stochastic disturbances. They introduce a new method for implementing invariant control in gas air-cooling devices, which helps stabilize gas temperature on compressor stations. Maedeh Mahzarnia et al. (2020) discuss power system resilience and its importance in reducing the likelihood of blackouts during High-Impact, Low-Probability (HILP) events. They categorize resilience measures into planning, response, and restoration phases, review approaches and techniques in each category, and address the challenges posed by high renewable energy penetration.

Yasser Ahmed Dahab et al. (2020) present an adaptive load frequency control (LFC) technique for power systems. The technique involves on-line tuning of an integral controller using Electro-Search optimization (ESO) with a modification called the 'balloon effect' to regulate system frequency effectively, especially in the presence of load changes, uncertainties, and renewable energy sources. Ana Fernández-Guillamón et al. (2019) review the evolving dynamics of power systems and the challenges posed by renewable generation units with electronic converters, affecting grid inertia. They discuss the concept of inertia and damping factor values, comparing scenarios with traditional and current generation mixes, and examine the contributions of wind and photovoltaic power plants to frequency control strategies.

Meysam Gheisarnejad et al. (2019) propose a novel fuzzy proportional integral derivative (PID) controller with filtered derivative action and fractional order integrator (fuzzy PIλDF controller) to address automatic generation control (AGC) in power systems. They conduct time domain simulations to demonstrate the controller's effectiveness in terms of performance and stability under various conditions. Sensitivity analysis is also performed to assess robustness.

3. Research Objectives

This research paper aims to achieve the following objectives:

1. Investigate the current state of automatic control systems in power systems, including their architectures, components, and applications.
2. Evaluate the impact of automatic control systems on the stability, reliability, and efficiency of power grids.
3. Analyze challenges and limitations associated with the implementation of advanced control mechanisms in power systems.
4. Identify potential solutions and future directions for the enhancement of automatic control systems in the power industry.

4. Methodology

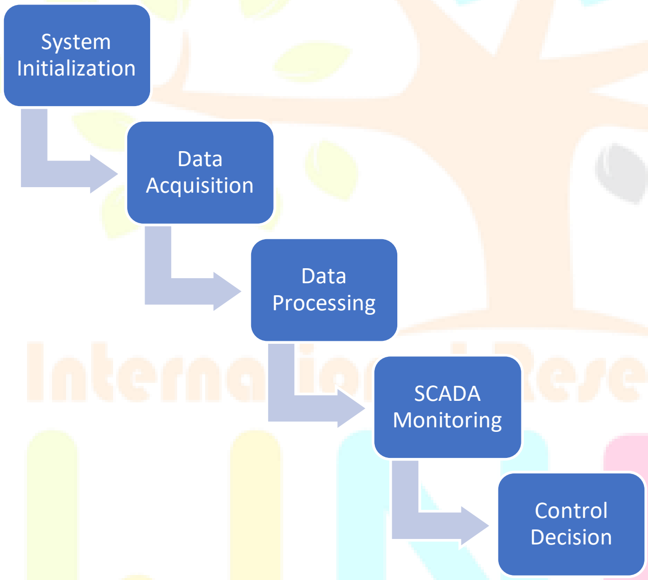

Figure 2. High-level overview of the processes involved in an automatic control system in power systems

4.1 Simulation Software

The usage of simulation software is essential for modeling and assessing the behavior of both the power systems and the control systems in the context of your research on automatic control systems in power systems. Here is a description of the stated simulation software programs and how they were used:

1. PSS/E (Power System Simulator for Engineering)

A popular simulation programme for power system modelling and analysis is PSS/E. It was used to develop dynamic power system models. These models feature depictions of transmission lines, transformers, generators, and other parts. The simulation of many operating situations and contingencies, such as load variations, faults, and disturbances, is possible with PSS/E. The software allows for the examination of voltage profiles, transient responses, and power system stability under various circumstances.

2. DIgSILENT

Another simulation software programme is DIgSILENT, which is renowned for its capacity for power system analysis and simulation. It was used to simulate and examine the interactions between the various parts of the power system. For fault analyses, load flow simulations, and transient analysis, DIgSILENT makes it easier to create intricate models. The programme offers a platform for evaluating how control systems affect the performance and stability of power systems.

3. MATLAB Simulink

MATLAB Power systems and control systems, among other dynamic systems, can be modelled and simulated using the flexible simulation framework known as Simulink. Simulink was used to construct dynamic models for both the automatic control systems and the power systems. The power system models can now incorporate control algorithms, feedback loops, and signal processing methods. Simulink provides a visible and adaptable method for simulating intricate interactions between control techniques and power system components.

4.1.2 Steps Simulation Software Utilized:

Dynamic Models: Dynamic models of the parts of the power system were created and included in each of these simulation software programmes. These models incorporate algebraic and differential equations that describe the behaviour of transformers, generators, and other components.

Test Case construction: The simulation software allowed for the construction of numerous test cases, including load variations, faults, and disturbances, to gauge how the power system would react in various situations. This aids in evaluating the transient responses and system stability.

Simulation software was utilised to incorporate control system models into the power system models in order to conduct a thorough study. As a result, control techniques, such as PID controllers and other automatic control systems, can be evaluated.

Performance Evaluation: The software made it easier to assess the effectiveness of control strategies for preserving grid stability, controlling voltage and frequency, and responding to system disturbances by running simulations using the integrated power and control system models.

Utilising simulation tools like PSS/E, DIgSILENT, and MATLAB Simulink was crucial in the development of dynamic models, scenario testing, and analysis of automatic control system performance in power systems. For the purpose of researching the interaction between control techniques and power system dynamics, these technologies offered a realistic and controlled environment.

4.2 Automatic Control System Architectures

Power systems rely on complex control frameworks to maintain stable operation, adapt to changing loads, and effectively handle interruptions. This section gives an overview of the various control system architectures frequently used in power systems, talks about the function of SCADA systems, and looks at how cutting-edge technologies like the Internet of Things (IoT) and Artificial Intelligence (AI) can be incorporated into control systems.

4.2.1 Control System Architectures in Power Systems

There are various different types of power system control architectures, each with particular features and purposes:

1. Centralized Control

A single central controller oversees the whole power system in centralised control schemes. A hierarchical structure with different levels of control, such as primary, secondary, and tertiary control, each in charge of particular duties, is frequently used. The reliability and capacity of centralised control systems to coordinate intricate operations throughout the electrical grid are well established.

2. Distributed Control

Distributed control architectures disperse control tasks among diverse power system components and subsystems. Due to the decentralised nature of control duties, this method provides more redundancy and fault tolerance. Managed control is especially useful for microgrids and renewable energy sources.

3. Hierarchical Control

Centralised and dispersed control are both combined in hierarchical control structures. They have various degrees of control, each in charge of particular duties but with differing levels of autonomy. Power systems that are huge and complicated can be managed effectively thanks to hierarchical control.

4.3 Role of Supervisory Control and Data Acquisition (SCADA) Systems

4.3.1 SCADA Overview

Power system control architectures depend heavily on Supervisory Control and Data Acquisition (SCADA) systems. SCADA systems make it possible to monitor, collect data from, and control remote equipment and processes in real-time. They collect information from sensors and remote terminal units (RTUs) and offer operators a graphical interface for power grid monitoring and management.

4.3.2 Functions of SCADA in Power Systems

SCADA systems play a critical role in power system operations by:

- Monitoring voltage levels, current flows, and equipment status.
- Detecting faults and disturbances in real time.
- Providing operators with situational awareness.
- Executing control commands to adjust system parameters, switch devices, and restore service after disruptions.

5. Integration of Advanced Technologies

5.1 IoT in Control Systems

Architectures for the control of power systems now incorporate elements of the Internet of Things (IoT). Many different types of IoT devices, including sensors and smart metres, gather a tonne of real-time data from power grid assets. Demand response, predictive maintenance, and grid resilience are all supported by this data.

5.2 Control Systems with AI

Control systems are progressively using machine learning and artificial intelligence (AI). In order to optimise power generation, distribution, and demand, AI algorithms can analyse enormous datasets. Predictive maintenance, fault finding, and adaptive control all involve machine learning models. The addition of IoT and AI technology improves the capabilities of power system control structures, enabling more intelligent decision-making, more efficient grid operation, and responsiveness to changing energy landscapes.

There are many different types of power system control architectures, including centralised, distributed, and hierarchical designs. SCADA systems are essential for monitoring and managing power grids, and their combination with IoT and AI technologies has opened up new possibilities for efficiency and adaptability. In the context of contemporary power systems, where grid stability and sustainability are critical, these developments are essential.

6. Challenges and Future Directions

Power systems that use automatic control have come a long way, yet there are still issues and restrictions. These problems are identified in this section, along with suggested remedies and future research objectives. It also takes into account how modernising the grid and integrating renewable energy would affect control systems.

6.1 Challenges and Limitations

Grid Complexity

Challenge: With the integration of renewable energy sources, distributed generation, and changing demand patterns, modern power networks are getting more and more complex.

Limitation: Operational difficulties may result from existing control systems' inability to cope with this complexity.

Cybersecurity Threats

Problem: Power grids are more vulnerable to cybersecurity threats as a result of the rising reliance on digital control systems.

Limitation: Control system flaws could potentially cause disruptions and jeopardise grid security.

Scalability

Challenge: As power systems grow and incorporate microgrids and dispersed energy resources, scalability becomes a challenge.

Limitation: To accommodate additional assets and maintain stability, control systems must be scalable.

Real-time Data

Problem: Effective control depends on accurate real-time data, but data collection and transmission may be constrained.

Limitation: The performance of the control system can be hampered by inaccurate or delayed data.

Model Accuracy

The difficulty is that the decision-making process depends on the accuracy of power system models used in control systems.

Limitation: It can be difficult to create precise models for various grid arrangements.

6.2 Potential Solutions and Future Research Directions

Utilising machine learning and AI, create sophisticated control algorithms that can change to the complexity of the grid. Examine the application of neural networks and reinforcement learning to adaptive control. Protect control systems from dangers by putting in place strong cybersecurity safeguards. Explore blockchain technology for secure data sharing and decentralized control. Create scalable control system architectures that permit the seamless integration of additional assets. Create standardised interfaces and protocols to enable interoperability.

Improve communication and data collecting technologies to guarantee the availability of reliable real-time data. Look into the usage of 5G networks and edge computing for real-time data transmission. In order to more properly represent grid dynamics, improve modelling methods for the electricity system. Create hybrid models that integrate data-driven and physics-based methodologies.

7. Result and Discussion

7.1 Control System model

The researched two-area interconnected contemporary power system that is integrated with the VIC method is shown in Figure 3 as its structural layout. The tie-line, a power transmission line, has been used to connect the two sites. A thermal power plant, a load, and a VIC based on ESS are present in each area. In areas 1 and 2, respectively, photovoltaic (PV) solar and wind farms have also been added. The first section features an 8 MW solar farm, while the second part has a 6 MW wind farm. The frequency and tie-line power of the two zones are handled by the system controller. The control signals are then produced for each location. The low-order models of the individual generation units may be regarded as appropriate for regulating interconnected power systems to simulate the examined system [1]. Figure 3 depicts the linear model of the investigated two-area interconnected power system using VIC technology. Additionally, Table 1 presents the model parameters. Every area has a residential load, which the model treats as a disturbance. Solar and wind farms are also considered disruptions.

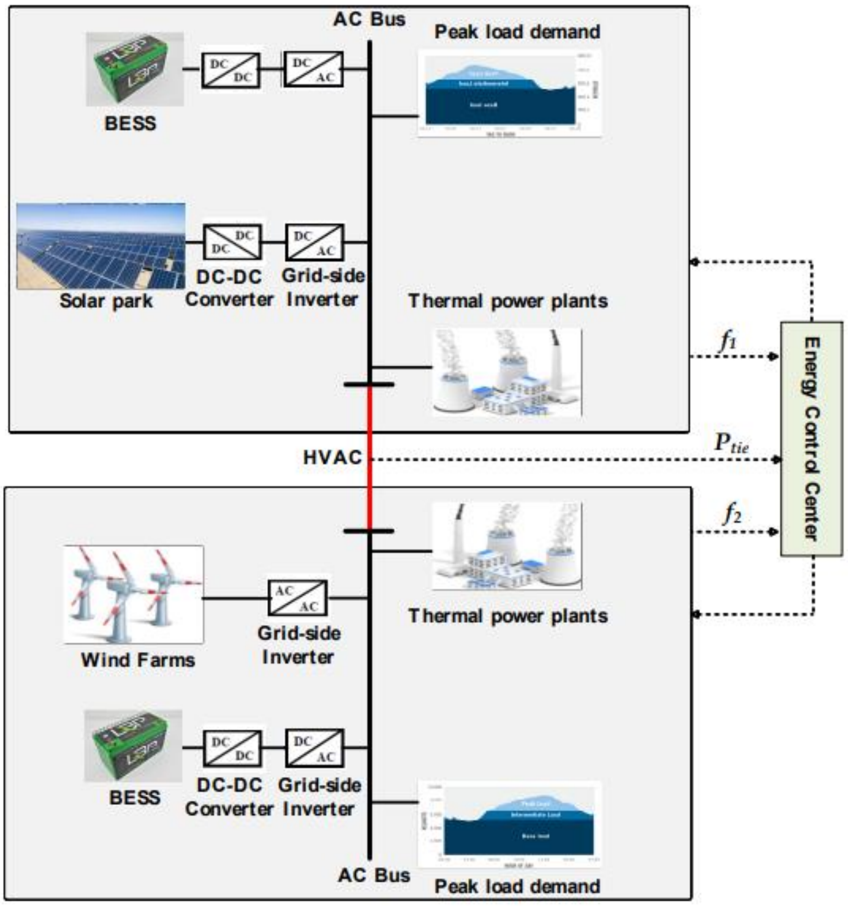

Figure 3. The basic structure of the proposed two-area interconnected power system

The Matlab/Simulink platform is used to simulate the proposed two-area linked power system with the VIC approach and the proposed iFOI controller, as illustrated in Figure 4. Four scenarios or instances were created out of the results. In the first case, the system experiences a step-change in load with a consistent RESs profile. In the second case, a step load adjustment with a random RES profile is taken into account. In the third scenario, the system has a random load and a consistent RES profile. The system experiences a random load change with a random RESs profile in the fourth example. For each situation, three controllers are contrasted. The proposed iFOI, the FOI that is designed alongside the proposed controller in this work, and the standard I controller are the three controllers that are being compared [1]. The following few paragraphs include the results in depth and the comments.

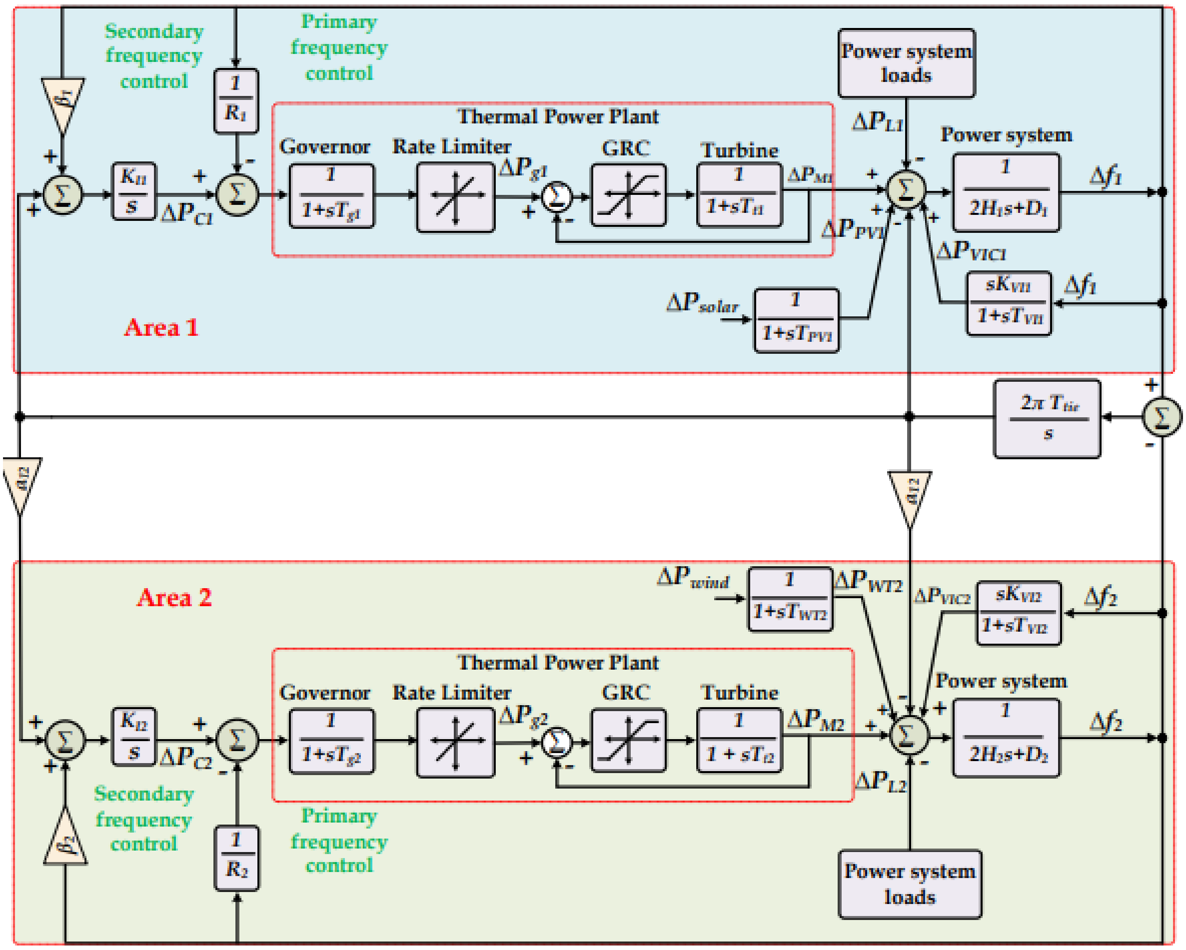

Figure 4. The dynamic model of the studied interconnected two-area power system.

According to Figure 5, which is provided in terms of the integral and fractional order of the parameters, a FOPID controller consists of five parameters, including two additional parameters of integral and fractional order. The FOPID's entire transfer function is provided in (15). It has been demonstrated that, when compared to a conventional PID, these factors can make the controller's transient time, stability, and steady-state error longer.

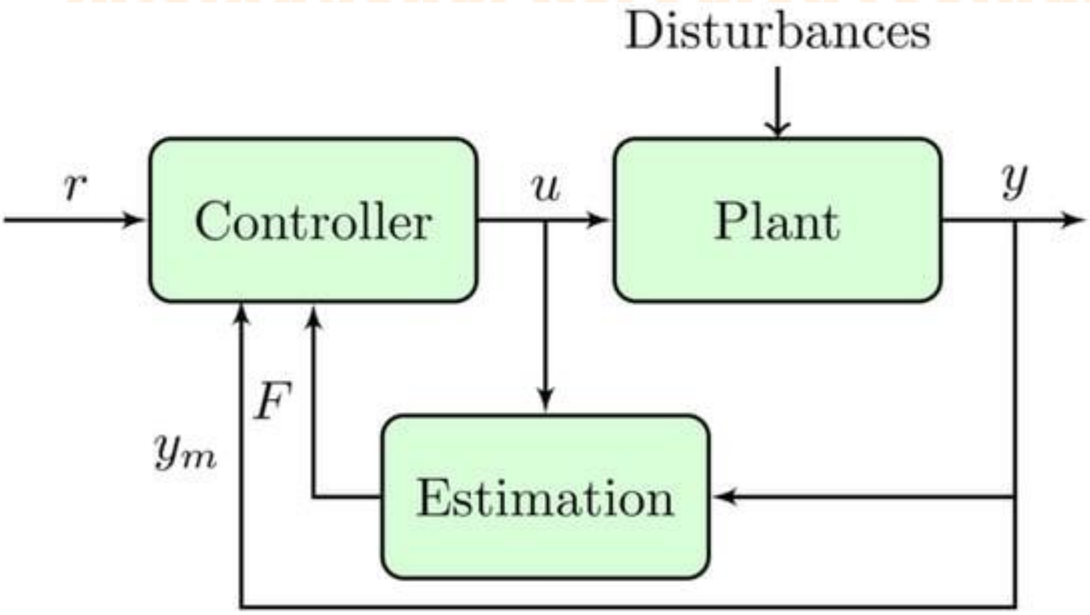

Figure.5 The structure of the ultra-local model.

8. Conclusion

In this study, an improved iFOI controller with virtual inertia control was developed for the LFC of a modern, two-area interconnected power system. The suggested iFOI controller is best built in this case using a metaheuristic optimisation technique known as grey wolf optimisation, which also offers the lowest possible frequency and tie-line power variations. By comparing the suggested optimal iFOI controller's performance to that of existing control methods used in the literature, such as the integral controller and the FOI controller, its efficacy is demonstrated. Under load/RESs fluctuations, the two-area power system's performance has been evaluated. The simulation results generated by the MATLAB software revealed the effectiveness and robustness of the suggested optimal iFOI controller based on the GWO when compared to existing control approaches from the literature for various circumstances. Despite this, the iFOI received the best feedback in the two sectors. Furthermore, the frequency deviations remained within the advised limits. The outcomes of every scenario demonstrate that the proposed iFOI outperforms both the integral controller and the FOI controller in terms of the interconnected system's overall performance. On the other hand, the integral square error has been employed to analyse the objective functions for the controllers used with the scenarios under study. It is clear that in each situation, the proposed iFOI has the lowest value of the objective function in comparison to the other two controllers.

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