Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

OPTIMAL CONTROL DESIGN FOR FREQUENCY REGULATION IN ELECTRIC POWER SYSTEM WITH LOW INERTIA

Adrian Jonathan Pakpahan[1], Herlambang Setiadi[2]

[1]*Department of Electrical Engineering, Faculty of Advanced Technology and Multidiscipline, Universitas Airlangga*
[2]*Department of Electrical Engineering, Faculty of Advanced Technology and Multidiscipline*

***Abstract*— Electricity is a very important element in this era because almost all aspects of modern life depend on electricity. Therefore, electricity plays a very important role in improving people's quality of life and maintaining an efficient and productive life. An efficient and reliable electrical system is essential to ensure adequate electricity availability and maintain system reliability. Therefore, planning, designing and operating electrical systems must be carried out carefully to ensure stability, reliability and efficiency. However, a decrease in frequency in the electrical system sometimes occurs when there is a sudden change in load. This can affect system stability. Therefore, Load Frequency Control (LFC) and Linear Quadratic Regulator (LQR) analysis is needed to maintain the stability of the electrical system frequency. The combination of these two techniques, namely LFC with LQR modeling, provides a better solution for maintaining frequency stability and optimizing electrical system performance. LFC analysis regulates power generation settings automatically to compensate for fluctuations in load demand and maintain a stable frequency, while LQR is a control technique used to minimize system errors and optimize system performance. Therefore, LFC with LQR results in system performance increasing very significantly with a faster response, undershoot that can be reduced to 0.001 and a better settling time of 300s in area-1 and 450s in area-2 and rise time reaching 270s in area-1 and 405s in area-2 as well as the use of LQR can maintain the system frequency at its nominal limit and the presence of New Renewable Energy (EBT) has an effect in the form of a greater undershoot level than without EBT.**

***Keywords*—Electricity, Frequency Drop, Frecuency Stability, Load Frequency Control, Linier quadratic Regulator.**

I. INTRODUCTION

Electric power is needed for household needs and various industries (Nwankwo & Njogo, 2013). Consequently, continuous power generation with uninterrupted service is required to meet customer demands. Power generation centers must be able to respond to varying load demands, ensuring capacity matches electricity consumption (Elektro et al., 2013). The unique challenge in operating an electrical power system lies in maintaining a balance between generated and consumed power, commonly referred to as load. Generator capacity is contingent upon installed generator system capacity and equipment availability. Electric power systems are expected to deliver electricity to consumers at nearly constant frequencies (Plc et al., 2021). Deviations from the nominal frequency must remain within permissible tolerances, typically 50Hz ±2%. To maintain this tolerance, active power output or system output must balance with active power load (Anwar, 2017). Increased load or sudden changes can lower system frequency, and disruptions to generators or system tripping can also lead to inconsistent frequencies (Djalal et al., 2018).

Electric power systems encounter disturbances or transient disturbances such as network faults, short circuits, and minor disturbances like minimal load changes (Abdilah et al.). Minimal disturbances are referred to as dynamic disturbances. Frequency stability in the power system is crucial for monitoring and understanding frequency response at workstation areas. In reality, frequency values are always variable around their operating points (Barklund et al., 2008). Therefore, frequency stability is a key parameter in power system stability under minor disturbances.

Rapid industrial development requires more energy to support industrial processes. The use of conventional energy sources can harm the environment (Bull, 2001). The transition from conventional to renewable energy sources is increasingly adopted worldwide (Dincer, 2000). However, the presence of renewable energy sources poses new challenges to the power system (Yu et al., 2019).

Generators have rotors with mass and inertia (Rahmawati & Fajri, 2019) that affect their ability to withstand disturbances. Higher inertia enhances a generator's capability to maintain stable frequency amidst load changes. Conversely, renewable energy sources like wind and solar lack significant mass in the system, resulting in less stable frequencies due to low inertia.

Frequency stability in electrical systems depends significantly on system inertia. During disruptions such as power outages or load increases, generator inertia stabilizes the system frequency (Atiqah et al., 2023). Higher system inertia leads to more stable system frequencies, whereas lower inertia results in less stable frequencies. Therefore, besides load changes, the presence of low-inertia renewable energy sources can influence power system frequency stability (Nur et al., 2022).

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

In addition to load changes, modern power systems integrate renewable energy sources such as wind and solar. While this has positive impacts, it introduces challenges like uncertainty and low inertia. Low system inertia can cause unstable frequency fluctuations during load changes or system disturbances. System inertia acts as a frequency stabilization mechanism. When fluctuations occur in the system load or conventional power sources are disconnected, generator inertia provides kinetic energy to stabilize the power system frequency.

However, according to (Teknologi, 2015), renewable energy sources like photovoltaic or wind turbines connected via inertless inverters can lead to more frequent and rapid frequency fluctuations. This is because inverters lack frequency stabilization mechanisms found in conventional systems using generators with inertia.

The instability of frequency can be addressed through Load Frequency Control (LFC) using various methods. According to (Kumar Sharma et al., 2008), PI control processing can be implemented. In LFC, a PI controller modulates active power signals and adjusts active power supply to balance with active power demand. This control method stabilizes system frequency by regulating generator speed to remain constant despite load fluctuations. PI control processing adjusts proportional and integral constants based on system characteristics to optimize controller response. Using PI controllers minimizes frequency instability in the power system over the long term.

In addition to PI processing, according to (Siswanto et al., 2016), PID processing can also be used. In LFC applications, the P signal is used for quick responses to load changes, the I signal handles errors in the P response over the long term, and the D signal reduces response changes due to sudden load changes. Thus, PID control helps mitigate frequency instability in the power system.

Apart from PID methods, Pole Placement processing can also be employed (Seleksi et al., 2017). Pole placement is a control method used to address frequency instability in power systems through Load Frequency Control (LFC). This method adjusts the pole position of the control system to achieve desired responses. However, pole placement requires deep knowledge of power systems and considerable time to design an appropriate control system. Tuning the pole placement process can be challenging, especially for complex and large systems.

This thesis analyzes frequency stability using Load Frequency Control (LFC) with the Linear Quadratic Regulator (LQR) method. LQR is an optimal control technique for linear dynamic systems. When applied to address frequency instability with LFC, LQR can design optimal controllers to improve system responses to disturbances and enhance overall system performance. This optimal control method minimizes a mathematically defined objective function using adjustable weight matrices. Therefore, LQR offers better control performance in stabilizing the system and improving frequency response compared to conventional methods.

II. LITERATURE REVIEW

A. *Control System of Active Power and Frequency*

Active power has a crucial relationship with frequency values in an electrical system, as system loads in the form of active power constantly fluctuate over time. Maintaining frequency within allowable tolerance limits requires that the supply of active power in the system matches the demand for active power.

The fundamental principle in rotor dynamics establishes a direct relationship between the mechanical torque driving the generator and its rotational speed. This relationship dictates that system frequency regulation is essentially the regulation of the mechanical torque driving the generator or the control of active power output from the generator.

According to this principle, the system's rotational speed (ω) inversely affects frequency (f); as rotational speed decreases, frequency decreases, and conversely, as rotational speed increases, frequency increases. This relationship underscores the critical role of mechanical torque control in stabilizing system frequency amidst varying load conditions.

B. *Frequency Standard*

The frequency standard referenced is IEEE C37.102-2006 (System & Committee, 1995). IEEE, or the Institute of Electrical and Electronics Engineers, is an international professional organization focused on the development and standardization in technology fields, particularly in electrical and electronics engineering, communications, computers, and related technologies. IEEE plays a significant role in producing technical standards that serve as references in industries, such as the IEEE 802.11 standard for wireless local area networks (Wi-Fi) and the IEEE 802.3 standard for Ethernet networks. Additionally, IEEE publishes numerous scientific journals, conferences, and other resources contributing to the advancement of knowledge and technology. IEEE C37.102-2006 standard is used for systems operating at a frequency base of 60 Hz.

C. *Governor Model*

A well-functioning electrical power system is one that can sustainably meet load demands while maintaining stable frequency. Changes in electrical load demand are inevitable within the system. The fluctuating electrical load demand over time can lead to unstable electrical frequencies.

The regulation of electrical frequency is managed by governors, which adjust the amount of fuel entering the combustion chamber in response to changes in electrical frequency signals. When the electrical load increases, the frequency decreases, prompting the governor to increase fuel input to the main driving engine to raise the frequency back to the allowable standard limits of 50Hz ± 2%. Conversely, when

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

the electrical load decreases, the frequency increases, and the governors of the power generators must reduce fuel input to the main driving engines to lower the frequency within the allowable standard limits.

The primary function of governors is to regulate the flow of fluid entering the turbine through valve opening mechanisms. The operation of these governors depends on Load Frequency Control (LFC) output. When the electrical load on the generator suddenly increases, the electrical power demanded exceeds the mechanical power input to the generator. This power deficit is balanced by the kinetic energy stored in the rotating system. The turbine speed and generator frequency decrease due to the reduction in kinetic energy (Nasional, n.d.). The governor turbine detects these speed changes and adjusts the turbine input valve position to alter mechanical power output. This action moves the rotating ball and provides mechanical response in reaction to speed changes.

D. Prime Mover Model

The prime mover or mechanical power source can take various forms of turbines, such as hydraulic turbines utilizing waterfalls, steam turbines powered by coal combustion, gas, nuclear fuel, and gas turbines. Models for turbines relate to the relationship between changes in mechanical power output ΔPm and changes in steam valve position ΔPv. Different turbine types exhibit varying characteristics. For instance, in Steam Power Plants, the turbine used is the steam turbine. Steam turbines are fundamental components in steam power plants. The main components of such a system include the boiler, condenser, boiler feed pump, and the turbine itself. Steam, serving as the working fluid, is generated by the boiler, a device that converts water into steam. According to (Rangga Akbar, 2002), the simplest model for the prime mover in steam turbines without reheating can be expressed with a single turbine time constant (τT).

E. Generator Model

A synchronous generator is an electrical power generation machine that converts mechanical energy into electrical energy based on Faraday's law. It is called synchronous because the rotational speed of its magnetic field is synchronized with the rotation of its rotor. The principle of operation is that when there is a change in the magnetic field around a conductor, an electromotive force (EMF) is induced in that conductor, which opposes the change in the magnetic field. For large-capacity synchronous generators, they are commonly referred to as alternators. The generator itself consists of two main parts: the moving part (rotor), which includes the stator core, stator windings, slots, and stator housing, and the stationary part (stator), which consists of the pole core and the field coil/enhancer coil.

F. Load Model

Power systems have various types of electrical loads consisting of different devices. Resistive loads such as lighting and heating do not depend on the electrical frequency. Frequency changes can affect the performance of electric motors as loads (Pawitra et al., 2022). The sensitivity to frequency changes in a load depends on the composite speed characteristics of all driven devices.

G. Photovoltaic (PV) Model

Energy is divided into two main categories: conventional energy and renewable energy. Conventional energy sources, such as coal and petroleum, are limited and non-renewable, whereas renewable energy is derived from natural resources that can be replenished, such as sunlight, wind, water, and biomass. A significant advantage of using renewable energy is its sustainability and environmental friendliness. Renewable energy not only replenishes naturally but also has lower environmental impacts compared to conventional energy sources. The use of renewable energy can help reduce greenhouse gas emissions and mitigate negative impacts on ecosystems (Qazi et al., 2019).

Concrete examples of renewable energy sources involve technologies like solar panels for electricity generation, wind turbines in wind power plants, harnessing river flows or waterfalls for electricity generation (hydropower), and utilizing biomass from organic waste to produce energy. In addition to environmental benefits, renewable energy also provides energy security and potential job creation in the renewable energy sector, making it an increasingly important choice for the future. The most widely used renewable energy source is solar energy, largely due to its abundant and readily available nature. Solar PV systems are also straightforward to install.

H. Load Frequency Control

According to (Fahreza et al., 2019), the operational objective of Load Frequency Control (LFC) is to maintain a relatively stable frequency, balance the load among generators, and control the exchange of power schedules among interconnected grids. Changes in frequency and real power of the interconnected grids are perceived, which are measured by the rotor angle deviation δ, i.e., the error $\Delta\delta$ that needs to be corrected. Error signals, Δf and $\Delta Ptie$, are amplified, mixed, and converted into a real power command signal ΔPv, which is sent to the main drive to request torque increase.

Therefore, the main drive induces changes in the generator output by ΔPg, which will adjust the values of Δf and $\Delta Ptie$ within specified tolerances. The first step in the analysis and design of the control system is mathematical system modeling. Two common methods are transfer function method and state variable approach. The state variable approach can be applied to describe both linear and nonlinear systems. To use transfer functions and linear equations, the system must first be linearized. Accurate assumptions and estimations are made to linearize the mathematical equations that describe the system, and a transfer function model is obtained for the components.

I. Automatic Generation Control (AGC)

Several models are used as mathematical representations for implementing frequency and voltage control in synchronous generators. The models used in frequency control include the generator model, load model, prime mover model, and governor

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

model. All these models are integrated into a control model for load frequency control (LFC).

Automatic Generation Control (AGC) is an automatic control system used in power plant operations to monitor and adjust the power output of generators with the aim of maintaining the frequency of the electrical system at desired levels. Its objective is to ensure the stability of the electrical system frequency, which is a crucial indicator of power balance between production and consumption in the electrical system.

AGC gathers data from the electrical system, including the load demanded by consumers and the power generated by power plants, and uses this information to control power plants to produce power as needed. AGC monitors load fluctuations and the frequency of the electrical system, automatically adjusting the power output of power plants to maintain the frequency at the desired level.

AGC operates using automatic controllers, such as integral controllers, which generate signals sent to generators to adjust power output and maintain frequency at the desired level. AGC can also be used to allocate load among various power plants in interconnected systems to achieve cost savings and optimize energy production. AGC plays a crucial role in maintaining the stability of the electrical system and preventing widespread power outages.

J. Linear Quadratic Regulator (LQR)

The Linear Quadratic Regulator (LQR) is an optimal control method widely used across various fields such as industry, robotics, and engineering. Its primary advantage lies in providing optimal solutions for control problems defined in state-space. Due to its state-space basis, the LQR method is particularly effective in solving control problems in Multi Input Multi Output (MIMO) systems. According to Susanto & Ahdan (2020), LQR is a control technique whose model and type of control are linear, making it one of the most commonly applied control methods.

In the Linear Quadratic Regulator (LQR), P is a symmetric positive semidefinite matrix that is part of the solution to the Riccati differential equation. The Riccati equation is a matrix differential equation that arises in optimal control theor. Q is a symmetric real positive semidefinite matrix determining the error, while R is a symmetric real positive definite matrix. Symmetric means the elements along the main diagonal (from top-left to bottom-right) are symmetric with respect to the diagonal axis. Positive semidefinite means the matrix does not yield negative numbers but can include zero. On the other hand, positive definite means the matrix does not yield negative numbers and cannot include zero.

The LQR control method works by selecting the best values for the Q and R matrices, which affect the system's response according to desired specifications. The relationship between the weight matrices Q and R and the dynamics of the closed-loop system is highly complex. In practice, the effects of these weight matrix pairs on the closed-loop system behavior cannot be predicted straightforwardly. Often, an approach involves trying various pairs of weight matrices within a certain range and selecting the pair that produces the desired dynamic response. The initial weighting values for Q and R typically start at 1 and are adjusted based on the resulting system response (Zakaria & Dharmawan, 2017).

III. METHODOLOGY

In the upcoming research, the chosen approach is dynamic modeling, a method used to construct mathematical models of dynamic systems, including physical, biological, economic, or other systems. Dynamic modeling aims to understand the behavior and interactions among components within the system, as well as to observe the responses generated by simulations of the constructed models. The process of using dynamic modeling methods involves the application of specialized software designed to dynamically model electrical systems. In this method, the initial steps include designing a circuit that needs to be detailed, including determining the components to be used, the relationships between these components, and determining the parameters of each component. Once the circuit is planned, the next step is to create a mathematical model that describes the relationships between variables in the circuit. The goal is to determine the behavior of the components and the interactions among the components that have been created.

Understanding of the system is gained through simulation using software, where the dynamic system can be analyzed under various conditions. This process involves evaluating the output signals from the designed circuit. The simulation results are evaluated and analyzed to understand the system's behavior, identify critical points, and observe the system's response to disturbances or fluctuations. The advantage of this simulation method lies in its ability to provide a comprehensive overview of the system's response, enabling detailed analysis of system changes or signal over time, including responses to input changes, disturbance handling, and system performance evaluation such as frequency response.

The system consists of two areas comprising the generator model, load model, prime mover model, and governor model interconnected with photovoltaic (PV) as the input. There is a disturbance (PL1) occurring in area-1, while no disturbance (PL2) occurs in area-2, both of which have been modeled in block diagram form and will be represented in a state space model implemented in Simulink.

The first step to represent the state space model is to formulate the mathematical equations for each state variable in the system. After modeling the state space from the mathematical equations of each state variable, the next step is to implement it in Simulink using $\dot{x} = Ax + BU$ and $y = Cx + DU$, where A represents the system matrix, B represents the input matrix, C represents the output matrix, and $\dot{x}$ represents the state variable parameter matrix.

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

IV. RESULTS

In the research to be conducted, there are several parameter values.

Parameter	Area-1	Area-2
R	0,05	0,0625
D	0,6	0,9
H	5	4
τg	0,2s	0,3s
τT	0,5s	0,6s
Common base	1000 MVA	1000 MVA

R = Speed setting
D = Load coefficient
H = Inertia constant
τg = Governor time constant
τT = Turbine time constant
common base = Common base power

In order to understand the dynamics of electrical systems, four significant case studies in Load Frequency Control (LFC) will be discussed. These four case studies include: Load Frequency Control (LFC) response without the implementation of Linear Quadratic Regulator (LQR), Load Frequency Control (LFC) response with the implementation of Linear Quadratic Regulator (LQR), Load Frequency Control (LFC) response using Renewable Energy Sources (RES) without the implementation of Linear Quadratic Regulator (LQR), and Load Frequency Control (LFC) response with the implementation of Renewable Energy Sources (RES) together with Linear Quadratic Regulator (LQR).

Each subsection will provide in-depth information on how the use of LQR control method and integration with Renewable Energy Sources (RES) impact Load Frequency Control (LFC) systems. Through comparison and analysis of these case studies, it will illustrate how each approach affects the performance and stability of electrical systems.

A. Linear Quadratic Regulator (LQR) Modeling

Linear Quadratic Regulator (LQR) is an optimal control method that has been widely used in various fields. LQR itself is not a controller but a method to design a gain feedback controller. Essentially, LQR is part of the solution to the Riccati differential equation that yields a solution matrix. The solution matrix of this equation is called P. LQR uses the quadratic state weighting matrix Q and the quadratic control signal weighting matrix R. The Riccati equation involves matrices Q and R, which influence the solution P used to compute the gain feedback controller matrix called matrix K.

After representing the state space model in Simulink, the next step is to create the LQR program listing in Matlab. The LQR program listing in Matlab requires parameters such as matrix A, matrix B, matrix C, weighting matrix Q, and weighting matrix R. However, LQR is influenced by matrices A, B, Q, and R, and not by matrix C. The reason for this situation is that when controlling something, the system response and reference become crucial factors. Therefore, LQR only requires the parameters that differentiate the system response (matrix A) and the reference input (matrix B). This is intended to minimize the difference between its input and output. Below are the parameter values required for the LQR program listing:

A =

$$\begin{bmatrix} -0.06 & 0.1 & 0 & 0 & -0.1 & 0 & 0 & 0 & 0 \\ 0 & -2 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ -100 & 0 & -5 & 5 & 0 & 0 & 0 & 0 & 0 \\ -0.18 & 0 & 0 & 0 & -0.3 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.125 & -0.1125 & 0.125 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1.6667 & 1.6667 & 0 \\ 0 & 0 & 0 & 0 & 0 & -53.3333 & 0 & -3.333 & 3.333 \\ 0 & 0 & 0 & 0 & 0.3 & -0.27 & 0 & 0 & 0 \end{bmatrix}$$

B =

$$\begin{bmatrix} -0.1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

C =

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Linear Quadratic Regulator (LQR) works by selecting the best values for matrices Q and R, which influence the system response according to desired specifications. Matrix Q is a symmetric real positive semidefinite matrix consisting of 9 columns and 9 rows. This is because matrix Q follows the number of columns and rows in the system matrix A. Matrix Q is often related to the identity matrix, denoted as matrix I, as it assigns equal weight to each state variable in the system. Additionally, matrix R is a symmetric real positive definite matrix consisting of 1 column and 1 row. Positive semidefinite means the matrix does not yield negative numbers but can include zeros. On the other hand, positive definite means the matrix does not yield negative numbers and cannot include zeros. To determine the values of Q and R, the Trial and Error Method (TEM) is employed. Parameters Q and R are adjusted repeatedly until obtaining the optimal gain, represented by matrix K. Matrix K consists of 9 columns and 1 row due to its single-input nature, reflecting the 9 state variables in the system. The result is deemed optimal when the K value, the feedback gain controller, delivers a system frequency response that can reach the setpoint faster and produce undershoot values

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

that can be mitigated by adjusting its Q and R parameters. Below are the weights of Q and R, as well as the values of matrix K obtained:

Q =

$$\begin{bmatrix} 200 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 200 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 200 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 200 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 200 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 200 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 200 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 200 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 200 \end{bmatrix}$$

R = 0.001

K = [-1.0063 0.1686 0.3962 0.2088 -0.5170 -0.0254 -0.0091 0.0009 -0.0057]

The obtained value of K is inputted into Simulink and placed as the gain feedback controller. A gain feedback controller, often referred to as a gain feedback controller, is a type of feedback controller in control systems that regulates the response of a system by adjusting the amplifier or gain in the feedback loop.

In the context of control systems, the gain feedback controller is placed at the output of the system, which is then used as input to regulate the system. The gain feedback controller focuses on adjusting the gain value to achieve specific control objectives. This gain can be a control amplifier or coefficient used to adjust the output or input magnitude within a system.

B. *Study Case 1*

In this case study, the focus is on the behavior of the LFC system when Linear Quadratic Regulator (LQR) control method is not applied, demonstrating how the system responds to load fluctuations and how conventional control can affect frequency stability. Figure 4.1 illustrates the design of the Load Frequency Control (LFC) model in a multi-area system without Linear Quadratic Regulator (LQR).

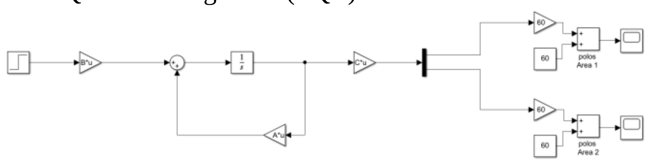

Figure 4.1 Block diagram of Load Frequency Control (LFC) without Linear Quadratic Regulator (LQR)

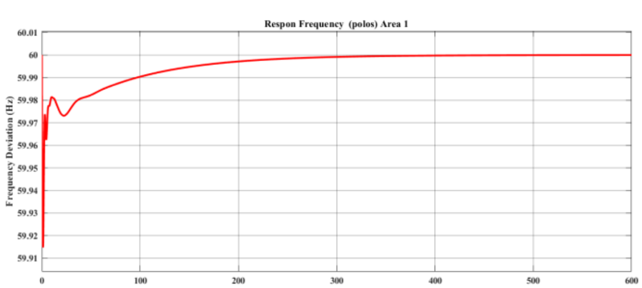

Figure 4.2 Frequency Response of Load Frequency Control (LFC) without Linear Quadratic Regulator (LQR) in Area 1

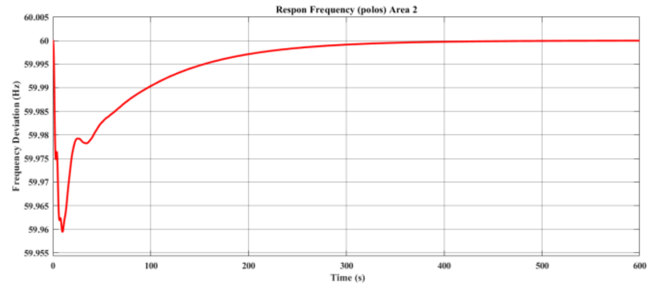

Figure 4.3 Frequency Response of Load Frequency Control (LFC) without Linear Quadratic Regulator (LQR) in Area 2

Table 4.1 Table of Results from Load Frequency Control (LFC) without Linear Quadratic Regulator (LQR)

Parameter	Area 1	Area 2
Rise Time	405 s	450 s
Undershoot	0,086	0,041
Settling Time	450 s	500 s

Based on Figure 4.2 and Figure 4.3, it shows the system response of LFC when not using LQR, indicating how the system reacts to load fluctuations. The undershoot generated is larger in Area 1 compared to Area 2. This is because of disturbances occurring in Area 1 that affect Area 2. Based on the available data, the results of the LFC response without LQR are shown in Table 4.1. In Area 1, a rise time of 405 seconds, an undershoot of 0.086, and a settling time of 450 seconds were obtained. In Area 2, a rise time of 450 seconds, an undershoot of 0.041, and a settling time of 500 seconds were obtained.

Rise time is the time required for the system to reach from 10% to 90% of its final value, which is the settling time. Undershoot is the percentage decrease below the setpoint value before the system reaches the setpoint. Settling time is the time required for the system to reach and remain within the setpoint.

Therefore, based on the data available, Area 1 experiences a larger undershoot, while Area 2 experiences a longer settling time compared to Area 1. This is because the recovery response occurs first in Area 1 due to disturbances, causing Area 2 to take longer to return to its setpoint than Area 1.

C. *Study Case 2*

In this case study, we will elaborate on how the application of the LQR method affects the response to disturbances, highlighting potential improvements in stability and achieved control quality. For this case, the values used are Q = 200 * I and R = 0.001. Here, I is a square matrix with elements of 1 along its main diagonal and elements of 0 elsewhere, indicating an identity matrix of size n×n. Figure 4.2 shows the design of the Load Frequency Control (LFC) model in a multi-area setup with Linear Quadratic Regulator (LQR).

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

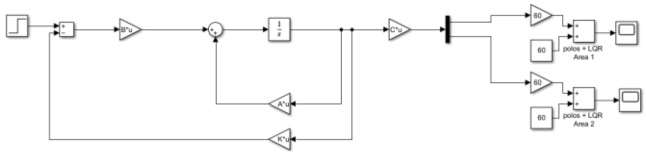

Figure 4.4 Block diagram of Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR)

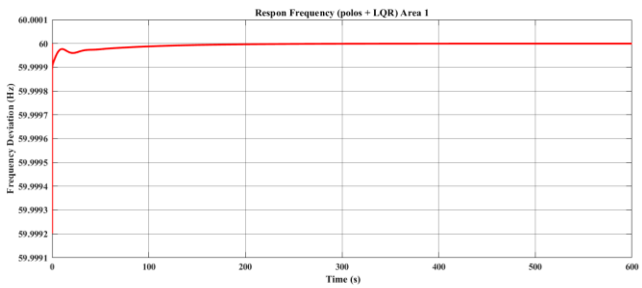

Figure 4.5 Frequency response of Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR) in Area 1

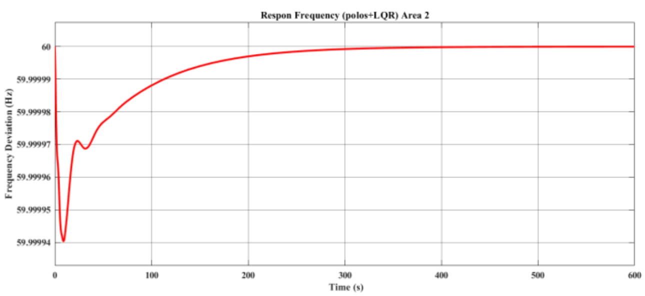

Figure 4.6 Frequency response of Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR) in Area 2

Table 4.2 Results of Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR)

Parameter	Area 1	Area 2
Rise Time	270 s	405 s
Undershoot	0,001	0,001
Settling Time	300 s	450 s

Based on Figures 4.5 and 4.6, it shows the system response of LFC when using LQR, indicating how the system reacts to load fluctuations. According to the available data, the response results from LFC with LQR are obtained as shown in Table 4.2. In Area 1, a rise time of 270 seconds, an undershoot of 0.001, and a settling time of 300 seconds were obtained. In Area 2, a rise time of 405 seconds, an undershoot of 0.001, and a settling time of 450 seconds were obtained.

The effect observed is the reduction in undershoot levels in both Area 1 and Area 2 compared to the LFC system without LQR. This reduction occurs because LQR can mitigate the undershoot levels by providing gain feedback controllers to each state variable in the system. However, Area 2 experiences a longer settling time compared to Area 1 due to the recovery response occurring first in Area 1. This delay in settling time in Area 2 is influenced by the slight effect of LQR on the settling time parameter, which shows a relatively minor difference between Area 1 and Area 2 compared to the undershoot parameter.

Rise time is the time required for the system to reach from 10% to 90% of its final value, i.e., settling time. Undershoot is the percentage drop below the setpoint before the system reaches the setpoint. Settling time is the time required for the system to reach and remain within the setpoint.

D. Study Case 3

In this subsection, the impact of using Renewable Energy Sources (EBT) in the LFC system without the assistance of LQR will be explained, exploring the system dynamics with the integration of renewable energy sources. Figure 4.3 illustrates the Load Frequency Control (LFC) model design in a multi-area system with Renewable Energy Sources (EBT) without Linear Quadratic Regulator (LQR).

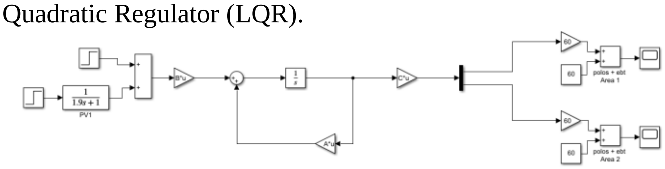

Figure 4.7 Block Diagram of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) without Linear Quadratic Regulator (LQR)

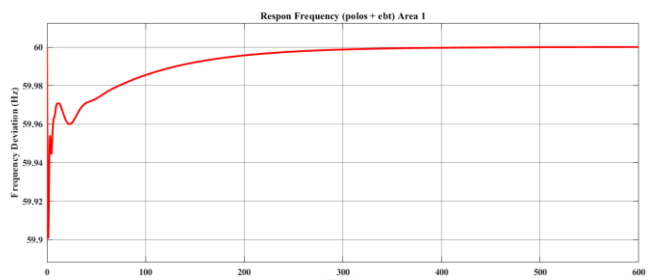

Figure 4.8 Frequency Response of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) without Linear Quadratic Regulator (LQR) in Area 1

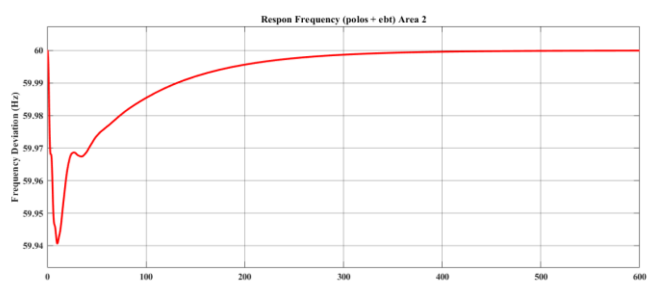

Figure 4.9 Frequency Response of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) without Linear Quadratic Regulator (LQR) in Area 2

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

Tabel 4.3 Results Table of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) without Linear Quadratic Regulator (LQR)

Parameter	Area 1	Area 2
Rise Time	405 s	450 s
Undershoot	0,1	0,06
Settling Time	450 s	500 s

Based on Figure 4.8 and Figure 4.9, it can be seen that the response of the LFC system with Renewable Energy Sources (EBT) without using LQR shows that the system reacts to load fluctuations. Area-1 experiences a greater undershoot compared to Area-2, which is due to disturbances affecting Area-1 and subsequently impacting Area-2. According to the available data, the response results of LFC with EBT without LQR are as shown in Table 4.3. In Area 1, a rise time of 405 seconds, undershoot of 0.1, and settling time of 450 seconds are observed. In Area 2, the rise time is 450 seconds, undershoot is 0.06, and settling time is 500 seconds.

Rise time is the duration for the system to reach from 10% to 90% of its final value, which is settling time. Undershoot represents the percentage decrease below the setpoint before the system reaches the setpoint. Settling time denotes the time required for the system to reach and remain within the setpoint.

Therefore, based on the available data, LFC with EBT without using LQR explains that EBT causes a higher level of undershoot compared to systems without EBT. This is because the low inertia effect in Renewable Energy Sources (EBT) systems can contribute to increased undershoot. Inertia refers to the property of a system that resists change. Conventional generation plants with high inertia, characterized by heavy components like generators and turbines storing substantial kinetic energy, exhibit stable and slow responses to load fluctuations or disturbances in the power system.

On the other hand, certain renewable energy sources such as solar panels and wind turbines have low inertia. This is because EBT often lacks heavy components that store large amounts of kinetic energy like traditional generators and turbines. Consequently, these systems can respond to load changes more quickly but may also be more vulnerable to fluctuations and less stable in some situations.

E. Study Case 4

This subsection will discuss how the combination of EBT and LQR control method affects system response, emphasizing improved performance and stability in LFC systems. In this case, using a Q value of 200 times I and an R value of 0.001. Here, I is a square matrix with elements 1 along its main diagonal and 0 elsewhere. Thus, I is an identity matrix of size n×n. Figure 4.4 illustrates the Load Frequency Control (LFC) model design in multiarea with Renewable Energy Sources (EBT) using Linear Quadratic Regulator (LQR).

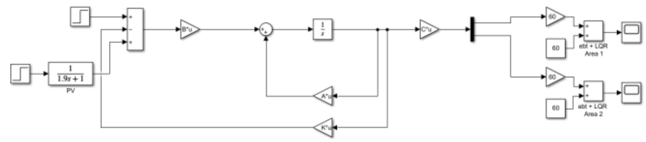

Figure 4.10 Block diagram of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) using Linear Quadratic Regulator (LQR).

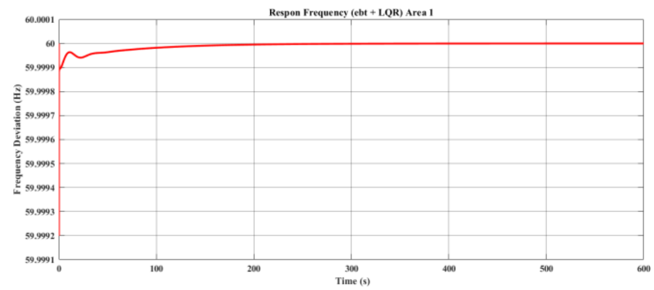

Figure 4.11 Frequency Response of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) using Linear Quadratic Regulator (LQR) in Area 1

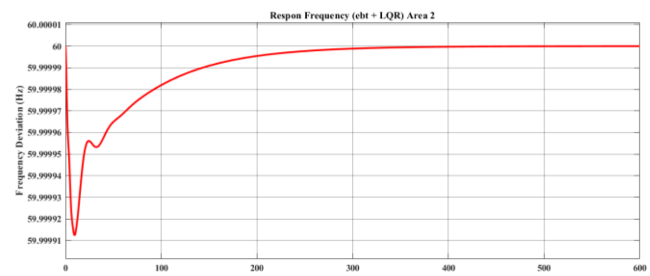

Figure 4.12 Frequency Response of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) using Linear Quadratic Regulator (LQR) in Area 2

Table 4.4 Results Table of Load Frequency Control (LFC) with Renewable Energy Sources (EBT) using Linear Quadratic Regulator (LQR)

Parameter	Area 1	Area 2
Rise Time	270 s	405 s
Undershoot	0,001	0,001
Settling Time	300 s	450 s

Figures 4.11 and 4.12 show the system responses of LFC with EBT when using LQR, indicating how the system reacts to load fluctuations. Based on the data obtained, the response results of LFC with LQR are presented in Table 4.4. In Area 1, a rise time of 270 seconds, undershoot of 0.001, and settling time of 300 seconds were observed. In Area 2, a rise time of 405 seconds, undershoot of 0.001, and settling time of 450 seconds were observed. The effect observed is the ability of LQR to attenuate undershoot levels in Area 1 and Area 2 compared to an LFC system without LQR, despite the presence of EBT. This is

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

because LQR can mitigate undershoot by providing gain feedback to each state variable in the system.

However, Area 2 experiences a longer settling time compared to Area 1, which is due to the recovery response occurring in Area 1 first, leading to disturbances that delay Area 2 in returning to its setpoint value. This discrepancy occurs because LQR has a slight effect on the settling time parameter, resulting in a relatively small difference between Area 1 and Area 2 compared to the undershoot parameter.

Rise time is the duration for the system to reach from 10% to 90% of its final value, which is the settling time. Undershoot is the percentage decrease below the setpoint value before the system reaches the setpoint. Settling time is the time required for the system to reach and remain within the setpoint.

V. Discussion

Based on the results obtained, it is explained that LFC without LQR results in significantly higher undershoot compared to using LQR. This is because LQR can attenuate undershoot levels by providing gain feedback to each state variable in the LFC system. Meanwhile, LFC without LQR tends to be slower in achieving its settling time and rise time compared to LFC with LQR.

Based on the results obtained, it is explained that LFC with EBT without LQR results in higher undershoot levels compared to using LQR. This is because LQR can mitigate undershoot by providing gain feedback to each state variable in the LFC system. Meanwhile, LFC with EBT without LQR tends to be slower in achieving its settling time compared to LFC with EBT using LQR.

Based on the results obtained, it is explained that LFC with EBT results in higher undershoot levels compared to not using EBT. This is due to the lower inertia effect in Renewable Energy Sources (EBT) systems, which can contribute to increased undershoot levels. Meanwhile, LFC with EBT yields the same rise time and settling time parameters as LFC without EBT. This is because the inertia effect does not affect the rise time and settling time parameters; only the undershoot parameter experiences a change between LFC with EBT and LFC without EBT.

Based on the results obtained, it is explained that LFC with LQR, with or without EBT, results in nearly the same undershoot parameter values. Although there is a small difference between them, it is because of using EBT in the system that causes differences in the undershoot parameter, albeit not significantly. However, LFC with LQR, whether with or without EBT, yields the same rise time and settling time values. This is because the inertia effect does not change the rise time and settling time parameters; only the undershoot parameter undergoes variations between LFC with LQR and EBT and LFC with LQR without EBT.

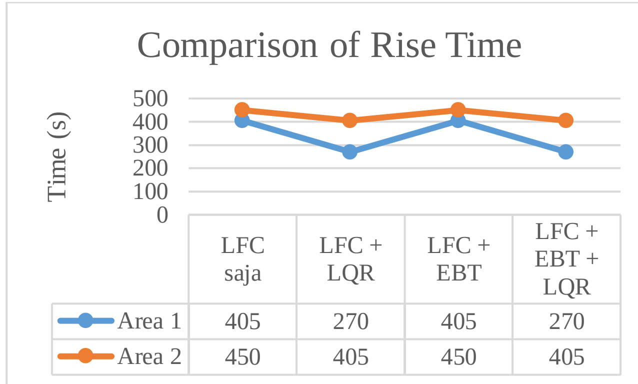

Figure 4.13 Comparison of Rise Time for Each Case Study

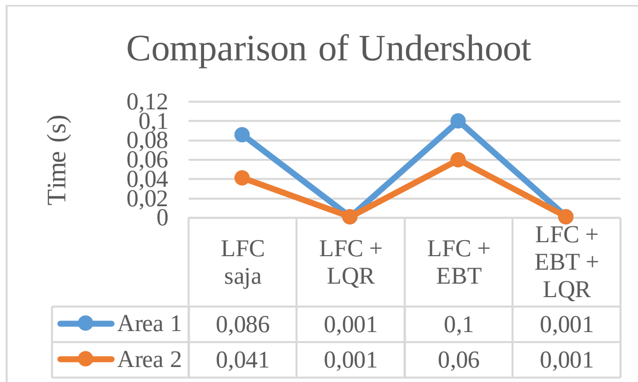

Figure 4.14 Comparison of Undershoot for Each Case Study

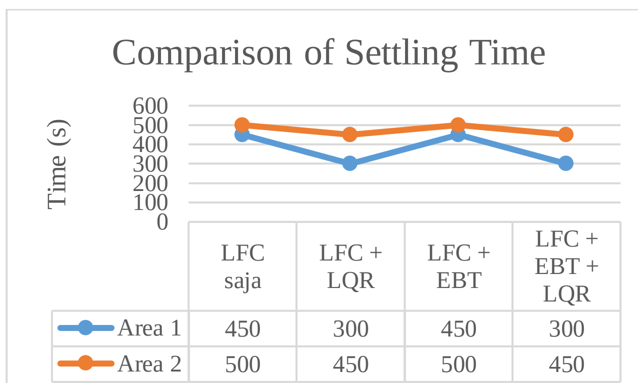

Figure 4.15 Comparison of Settling Time for Each Case Study

VI. Conclusion

Based on the simulation results and discussions conducted, several conclusions can be drawn as follows:

1. Load Frequency Control (LFC) without Linear Quadratic Regulator (LQR) is susceptible to challenges in handling disturbances and provides slower system responses compared to using LQR.
2. In simulation results for study case 1, Area 1 exhibited a rise time of 450 seconds, undershoot of 0.086, and settling time of 450 seconds. In Area 2, a rise time of 500 seconds, undershoot of 0.041, and settling time of 500 seconds were observed.

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

3. In simulation results for study case 2, Area 1 showed a rise time of 300 seconds, undershoot of 0.001, and settling time of 300 seconds. Area 2 exhibited a rise time of 450 seconds, undershoot of 0.001, and settling time of 450 seconds.

4. In simulation results for study case 3, Area 1 had a rise time of 450 seconds, undershoot of 0.1, and settling time of 450 seconds. Area 2 showed a rise time of 500 seconds, undershoot of 0.06, and settling time of 500 seconds.

5. In simulation results for study case 4, Area 1 had a rise time of 300 seconds, undershoot of 0.001, and settling time of 300 seconds. Area 2 exhibited a rise time of 450 seconds, undershoot of 0.001, and settling time of 450 seconds.

6. Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR) significantly enhances system performance with faster responses, attenuated undershoot, improved settling time, and the ability to maintain system frequency at its nominal value.

7. Load Frequency Control (LFC) with Linear Quadratic Regulator (LQR) in Renewable Energy Sources (EBT) provides significant benefits in integrating EBT into the system. However, using EBT in LFC shows changes in system response to unpredictable fluctuations in solar resources. Variability in solar energy production, such as changes in sunlight or weather conditions, affects LFC response. This necessitates modifications in LQR control settings to adapt to inconsistent changes in resource conditions.

8. The presence of Renewable Energy Sources (EBT) results in higher levels of undershoot compared to systems without EBT.

REFERENCES

[1] O. C. Nwankwo and B. O. Njogo, “The Effect of Electricity Supply on Industrial Production Within The Nigerian Economy (1970 – 2010),” J. Energy Technol. Policy, vol. 3, no. 4, pp. 34–42, 2013.
[2] J. T. Elektro, F. Teknik, and U. Hasanuddin, “Sulsel Dengan Memanfaatkan Software,” 2013.
[3] M. Plc, M. Pada, and P. Bintang, “Perancangan Sistem Kontrol Penstabil Tegangan,” J. Tek. Elektro, vol. 3, no. 2, pp. 62–70, 2021.
[4] R. S. Anwar, “Analisis Stabilitas Transien Dan Mekanisme Pelepasan Beban Akibat Penambahan Pembangkit 1x26, 8 MW Pada Sistem kelistrikan PT. Petrokimia Gresik,” 2017.
[5] M. R. Djalal, M. Ali, H. Nurohmah, and D. Ajiatmo, “Aplikasi Algoritma Differential Evolution untuk Desain Optimal Load Frequency Control pada Pembangkit Listrik Tenaga Hibrid Angin dan Diesel,” J. Teknol. Inf. dan Ilmu Komput., vol. 5, no. 5, p. 511, 2018, doi: 10.25126/jtiik.201855430.
[6] M. R. S. Abdilah, I. M. Pujiantara, and M. Yuwono, “Analysis of Transient Stability and Planning Load Shedding Scheme on Electricity System of Projek Chemical Grade Alumina (CGA) PT Indonesia Chemical …,” Core.Ac.Uk.
[7] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. C. Green, “Energy management in autonomous microgrid using stability-constrained droop control of inverters,” IEEE Trans. Power Electron., vol. 23, no. 5, pp. 2346–2352, 2008, doi: 10.1109/TPEL.2008.2001910.
[8] S. R. Bull, “Renewable energy today and tomorrow,” Proc. IEEE, vol. 89, no. 8, pp. 1216–1226, 2001, doi: 10.1109/5.940290.
[9] I. Dincer, “Renewable energy and sustainable development: A crucial review,” Renew. Sustain. energy Rev., vol. 4, no. 2, pp. 157–175, 2000, doi: 10.1016/S1364-0321(99)00011-8.
[10] Z. Yu, W. Liu, L. Chen, S. Eti, H. Dinçer, and S. Yüksel, “The effects of electricity production on industrial development and sustainable economic growth: A VAR analysis for BRICS countries,” Sustain., vol. 11, no. 21, pp. 1–13, 2019, doi: 10.3390/su11215895.
[11] Rahmawati and M. A. Fajri, “Desain Pembangkit Listrik Tenga Pikohidro Menggunkan Program Arduino UNO Pada Penambahan Variasi Aliran Air dan Flywheel,” J. AVoER, vol. 11, pp. 23–24, 2019.
[12] N. Atiqah et al., “Analisis Kestabilan Transien pada Master Plan Sistem Kelistrikan Kalimantan 500 kV Menggunakan Time Domain Simulation,” pp. 262–267, 2023.
[13] M. F. Nur, I. C. Gunadin, and Z. Muslimin, “Studi Optimalisasi Kinerja PLTB Melalui Pemilihan Type Generator Terhadap Stabilitas Sistem Tenaga Listrik (Stabilitas Frekuensi dan Tegangan) Sulbagsel,” J. EKSITASI, vol. 1, no. 1, pp. 7–13, 2022.
[14] P. K. M. P. Teknologi, “Institut teknologi nasional malang 2015,” no. 2, p. 2019, 2015.
[15] S. Kumar Sharma, A. Agarwal, and A. Kulshrestha, “Proposed Method to Control Load Frequency in Single Area Power System,” Int. Res. J. Eng. Technol., vol. 9001, pp. 1592–1595, 2008.
[16] T. Siswanto, D. Hendra Kusuma, and A. Raikhani, “Desain Optimal Load Frequency Control (Lfc) Pada Sistem Pembangkit Listrik Tenaga Mikrohidro (Pltmh) Menggunakan Metode Particle Swarm Optimization (Pso),” Pros. SENTIA – Politek. Negeri Malang , vol. 6, pp. 35–39, 2016.
[17] K. Seleksi, P. Beasiswa, and P. Smk, “VOL . 10 NO . 2 Juni 2017,” vol. 10, no. 2, pp. 49–58, 2017.
[18] B. Mukhlisoti and I. Garniwa M.K, “ANALYSIS OF IMPROVEMENTS TO THE AUTOMATIC GENERATION CONTROL (AGC) FREQUENCY REGULATION SYSTEM IN THE JAVA MADURA BALI SYSTEM FOR INTERMITTENT NEW AND RENEWABLE ENERGY (EBT) INTERCONNECTION,” vol. 2, no. 7, 2023.
[19] “Hadi_Saadat_Power_System_Analysis__1998.pdf.” .
[20] P. System and R. Committee, IEEE Guide for AC Generator Protection, vol. 1995, no. February. 1995.
[21] I. T. Nasional, “Frekuensi Turbin Generator Untuk Pltsampah Kampus Ii Itn Malang.”
[22] M. Rangga Akbar, “Penggunaan Power System Stabilizer Berbasis Recurrent Neural Network Pada Sistem Single Machine Infinite Bus (Studi Kasus Sistem Kelistrikan Lombok) Terhadap Gangguan Kecil,” vol. lim, no. 2009, pp. 1–25, 2002.
[23] I. P. Pawitra, T. Dharma, and F. Zambak, “Optimalisasi Kecepatan Putaran Motor Listrik Sebagai Beban Pada PLTS 5 kWp (Aplikasi : Laboratorium Balai Besar Pengembangan Dan Penjamin Mutu Pendidikan Vokasi Bidang Bangunan Dan Listrik Medan),” RELE (Rekayasa Elektr. dan Energi) J. Tek. Elektro, vol. 5, no. 1, 2022, doi: 10.30596/rele.v5i1.10784.
[24] A. Qazi et al., “Towards Sustainable Energy: A Systematic Review of Renewable Energy Sources, Technologies, and Public Opinions,” IEEE Access, vol. 7, pp. 63837–63851, 2019, doi: 10.1109/ACCESS.2019.2906402.
[25] M. U. Jan, A. Xin, M. A. Abdelbaky, H. U. Rehman, and S. Iqbal, “Adaptive and Fuzzy PI Controllers Design for Frequency Regulation of Isolated Microgrid Integrated with Electric Vehicles,” IEEE Access, vol. 8, no. 1, pp. 87621–87632, 2020, doi: 10.1109/ACCESS.2020.2993178.
[26] M. Fahreza, Hamdani, and Z. Tharo, “Pemodelan dan Pengendalian Frekuensi sistem tenaga listrik pada Simulator Pembangkit Listrik Tenaga Uap,” pp. 233–236, 2019.
[27] T. Sukisno and H. Sunyoto, “Matlab/Simulink Untuk Studi Pengendalian Daya Reaktif Dan Tegangan Pada Sistem Tenaga Listrik Dengan Automatic Voltage Regulator (Avr),” Researchgate.Net, no. May, pp. 1–19, 2020.
[28] T. Susanto and S. Ahdan, “Pengendalian Sikap Lateral Pesawat Flying wing Menggunakan Metode LQR,” PRotek J. Ilm. Tek. Elektro, vol. 7, no. 2, pp. 99–103, 2020, doi: 10.33387/protk.v7i2.2034.
[29] A. B. Zakaria and A. Dharmawan, “Sistem Kendali Penghindar Rintangan Pada Quadrotor Menggunakan Konsep Linear Quadratic,” IJEIS (Indonesian J. Electron. Instrum. Syst., vol. 7, no. 2, p. 219, 2017, doi: 10.22146/ijeis.25503.

Adrian Jonathan Pakpahan is a graduate student from Airlangga University majoring in electrical engineering. He was born and raised in Pekan Baru, Indonesia, and has shown a great interest in understanding technology and science since childhood. During his time at Airlangga University, he was active in various academic and extracurricular activities, including being a member of various student organizations.

Journal of Advanced Technology and Multidiscipline (JATM)
Vol. 03, No. 01, 2024, pp. 26-36
e-ISSN: 2964-6162

Herlambang Setiadi has a Ph.D from The University of Queensland, Brisbane, Australia in 2019. His B. Eng and M.Sc degree are from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia and Liverpool John Moores University, Liverpool, United Kingdom, in 2014 and 2015. Currently, He is investigator at Institute for Systems and Computer Engineering, Technology and Science (INESC TEC) Portugal. In INESC TEC his working on analysing microgrid stability with renewable rich power plant. He is also a lecturer at Faculty of Advanced Technology and Multidiscipline, Universitas Airlangga.
His main area of research interest are small signal stability in power systems, renewable energy integration, dynamic system simulation, control systems and applications of metaheuristic on power and control systems. Based on his research, he published over 75 articles.