INFOKUM
Volume 13, Number 05, 2025, DOI 10.58471/infokum.v13i05
ESSN 2722-4635 (Online)
https://infor.seaninstitute.org/index.php/infokum

Analysis of Frequency and Voltage Stabilization Control in Low-Inertia Power Systems Using a Boost Converter

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Article Info

Keywords:
Boost Converter,
low inertia,
frequency stability,
and electric power system.

ABSTRACT

Low-inertia power systems, especially those based on renewable energy sources such as solar and wind, face major challenges in maintaining frequency and voltage stability. The absence of mechanical inertia in these systems, which is usually available in synchronous generators, makes the system more vulnerable to load changes or network disturbances. Therefore, an effective control method is needed to maintain such stability. This study analysed the frequency and voltage stability control of low-inertia power systems using a Boost Converter. A Boost Converter is used to regulate and stabilize the output voltage of a fluctuating power source, such as a solar panel, by increasing the unstable input voltage. Meanwhile, a frequency control method such as is implemented to imitate mechanical inertia, thus maintaining the frequency at a desired value. The results show that the use of a Boost Converter effectively improves voltage stability, while a VSG-based frequency control strategy successfully imitates the inertia response of a synchronous generator, maintaining a stable frequency despite the system having low inertia. Thus, the combination of these two methods can improve the reliability of low-inertia power systems, especially in applications utilizing renewable energy sources.

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INTRODUCTION

Traditional power systems generally use synchronous generators that have high mechanical inertia. This inertia acts as an absorber of sudden disturbances in the system, such as load changes or other disturbances, thereby helping to maintain the stability of the frequency and voltage of the network. However, with the increasing use of renewable energy sources such as solar and wind, which do not have mechanical inertia, the power system is starting to shift to a low-inertia configuration. These renewable energy sources produce power that is intermittent and tends to experience significant fluctuations, making the power system more susceptible to frequency and voltage instability.

The absence of inertia in low-inertia power systems causes frequency changes to be faster and more difficult to control than conventional systems. This is a serious problem, especially when there is a change in load or disturbance that affects the energy supply. Therefore, a control technique is needed that can imitate the function of mechanical inertia to maintain frequency stability that functions to imitate the dynamic behavior of synchronous generators.

In addition, voltage also requires optimal stability, especially when there are fluctuations in energy sources. Boost Converter is one of the important components in renewable energy systems, especially in systems with low or fluctuating input voltages. With Boost Converter, voltage can be increased and stabilized to suit the needs of the electrical load.

Therefore, this study aims to analyze the frequency and voltage stability control in low-inertia power systems using a combination of Boost Converter and Virtual Synchronous Generator-based frequency control methods. The results of this study are expected to provide solutions to the challenges faced by renewable energy-based electric power systems in maintaining their operational reliability and stability.

In today's modern era, renewable energy such as solar and wind power has become the main alternative in providing electrical energy. However, the use of renewable energy has a major weakness, namely the absence of mechanical inertia, which is very necessary to maintain the stability of the electric power system. Unlike conventional synchronous generators that have natural inertia that helps dampen frequency changes due to disturbances or changes in load, renewable energy sources such as solar panels and wind turbines do not have an inertial component. This causes the frequency in a renewable energy-based power system to fluctuate more easily and be susceptible to disturbances.

Unstable frequency fluctuations can cause serious problems, including equipment failures and even widespread blackouts. Therefore, frequency control in low-inertia power systems is an important challenge to overcome. One of the emerging approaches to overcome this problem is the application of Virtual Synchronous Generators (VSGs), which function to mimic the inertial properties of conventional synchronous generators.

In addition to frequency issues, voltage stability is also a challenge. Frequent voltage fluctuations in renewable energy sources can damage equipment and disrupt the quality of power supplied. This is where the role of the Boost Converter becomes important, where this tool functions to increase and stabilize the voltage from an unstable energy source.

By looking at these problems, this research is very relevant in the effort to create a stable, reliable, and efficient electric power system, especially in renewable energy-based systems. The control system proposed in this study is expected to provide an important contribution to the development of low-inertia power systems in the future, as well as increasing the reliability of electricity supply from renewable energy sources that are increasingly used throughout the world.

Literature Review

Electric Power System

Electric Power System An electric power system is a system consisting of several components in the form of generation, transmission, distribution and loads that are interconnected and work together to serve the electricity needs of customers according to their needs. In general, the electric power system can be described with a scheme such as in Figure 1 below Electricity:

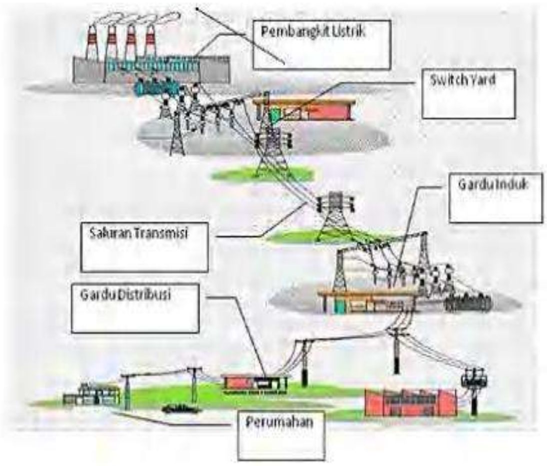

Figure 1. Electric Power System

The function of each component in general is as follows:

1. Transmission is a component that functions to distribute power or energy from the generation center to the load center.
2. Distribution is a component that functions to distribute electrical energy to the locations of electrical energy consumers.
3. Load is electrical equipment at the consumer's location that utilizes electrical energy from the system.

In an electric power system, the voltage used in each component can vary according to its importance. In other words, each component in the electric power system has a different voltage level. The division of voltage levels can be seen in Figure 2 below.

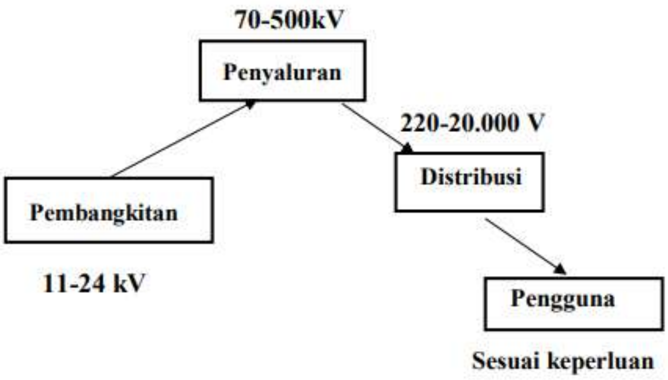

Figure 2. Division of Electrical Voltage Levels

In the generation system, the voltage level is adjusted to the specifications of the generator used, for generators with larger capacities usually use a higher voltage level. This is done so that the current flowing is not too large because for a certain power capacity, the amount of current flowing is inversely proportional to its voltage. The voltage level in the generator is usually not high, because the higher the generator voltage level, the number of generator turns must be even greater. More turns make the generator larger and heavier so that it is considered inefficient. In the transmission line system, a higher voltage level is usually used.

Distribution networks usually use lower voltages than transmission line voltages. This is because the power distributed by each distribution network is usually relatively small compared to the power distributed by the transmission line, and also adjusts to the voltage of customers or users of electrical energy. There are two types of distribution network voltage levels that are often used, namely 20 kV for medium voltage networks (JTM) and 380V for low voltage networks (JTR).

Thus, a substation containing a step-down transformer is required to reduce the voltage from the transmission line to the 20 kV distribution voltage. A distribution transformer is also required to reduce the voltage from 20 kV to 380 V according to the customer voltage. The customer load voltage level is adjusted to the type of load, for example, industrial loads that usually require relatively large power usually use a medium voltage of 20 kV, while household loads with relatively small power usually use a low voltage of 380 V.

Stability of the Electric Power System.

Reliability is "the ability of a system to continuously distribute power or energy". Quality is "the ability of an electric power system to produce standard quantities set for voltage and frequency". A Stability system is "the ability of a system to return to normal operation after experiencing a disturbance". applies and must immediately return to normal if the system is disturbed. For a very complex network where several generators are interconnected with each other, the electrical power output in the form of quantities such as voltage and frequency must be considered so that no generator is overloaded and other generators have small loads. The electric power system has a very dynamic load variation where every second it will change, with this change the supply of electric power remains and must be supplied with the appropriate power amount, if at a certain time there is an unexpected spike or decrease in load then this change can be categorized as a disturbance in the electric power system, namely an unbalanced condition between the supply of electricity and the demand for electrical energy due to disturbances either in the generator or in the transmission system, resulting in the work of other generators becoming heavier.

Today's power system is much wider, plus the interconnection between complex systems and involving hundreds of machines that dynamically influence each other through extra high voltage network intermediaries, these machines have related amplification systems. The range of problems analyzed mostly involves large disturbances and no longer allows using linear processes. Transitional stability problems can be further divided into "First swing stability" and "multi swing". First swing stability is based on a fairly simple generator model without including its control system, usually the time period investigated is the first second after the disturbance occurs in the system. A possible classification of power system stability into three parts, namely rotor angle stability, frequency stability, and voltage stability which can be seen in Figure 3.

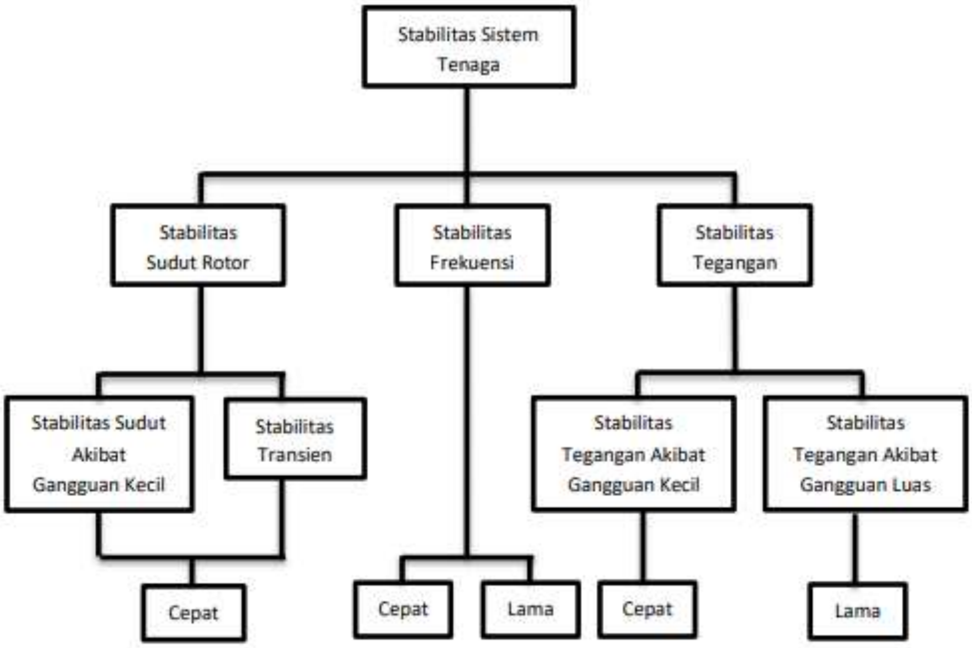

Figure 3. Classification of Electric Power System Stability

If in the system, the machine is found to remain in a synchronous state before the end of the first second, this is categorized as a stable system. The stability of the electric power system is classified based on several things below (Saadat, 1999):

1. The nature of the resulting instability is related to the main system parameters where the instability can be observed.
2. The disturbance size is considered to indicate the most appropriate method of calculating and predicting instability.
3. Devices, processes, and time spans that must be taken into consideration in determining stability.

Virtual Synchronous Generator

The principle of Virtual Synchronous Generator (VSG)is based on the integration of dynamic converter technology from static and dynamic operation on electromechanical characteristics. This can be represented by the concept of VSG as shown in Figure 4. The three different components of VSG are PEC (which consists of two stages of power conversion, namely DC to DC stage and DC to AC stage), an energy storage device (battery, supercapacitor, flywheel, etc.) and a control scheme that controls the power exchange between the energy storage and the power system. This power exchange supports the system power by preventing frequency fluctuations similar to the rotational inertia SG . VSG is usually placed between the Distributed Generator (or DC source) and the grid. The DC source that goes to the VSG algorithm performs the Synchronous Generator (SG) function by providing inertia and damping that supports the grid system by looking at the concept of VSG and its application to the three-phase inverter connected to its control can be seen in Figure 4 (a) and (b) as follows:

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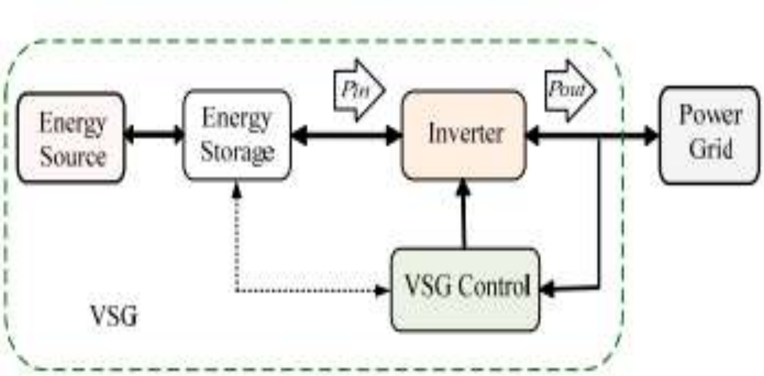

Figure 4. VSG Concept [1]

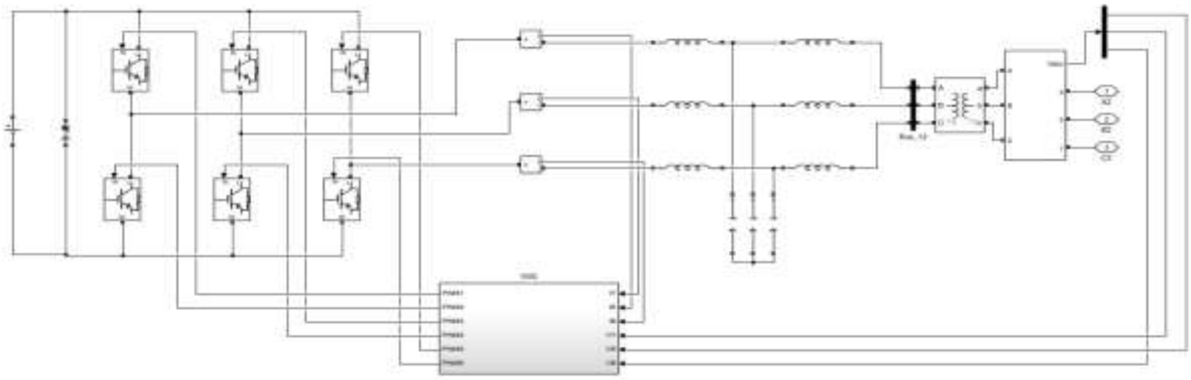

Figure 5. Three Phase Inverter with VSG Control

Figure 4 and 5 explain the concept of VSG, namely a combination of control algorithms of power electronic components that function to imitate the inertial power response of Renewable Energy Sources (RES) and increase the stability of the system frequency. The basic concept of VSG is to change the nature of renewable power plants based on power electronics to be similar to synchronous generators on the network.

Renewable power plants operate with different conditions and outputs, requiring a converter that results in reduced inertia in the system. The use of VSG uses feedback from voltage and current to manipulate the properties of intermittent-based renewable power plants. In this study, VSG is used to restore the nominal frequency value. VSG can help the system by showing the amount of inertia and damping properties of conventional synchronous generators. The VSG concept can maintain most of the RES in the future power system without sacrificing the stability of the power system by adding inverters, buck boost converters and thyristors (power electronics) to the VSG which are made in parallel.

In an electric power system, frequency is an indicator of the balance between the power generated and the total system load. The system frequency will drop if there is a lack of generation or overload. A large decrease in frequency can result in successive failures of generating units which cause total system failure. Automatic partial load shedding using a frequency relay (under frequency relay) can prevent frequency reduction and return it to normal frequency conditions, with the increasing development of the electric power system and with the presence of new generators entering the interconnection system, the adjustment of the frequency relay needs to be reviewed. One of the characteristics of an electric power system that is very important to maintain its stability is frequency.

Electric Power System

In general, the purpose of an electricity company is to maintain continuity of electricity service, so that the power distributed can reach customers continuously without interruption. The electric power system starts from the generation, transmission, and distribution systems. As shown in Figure 6.

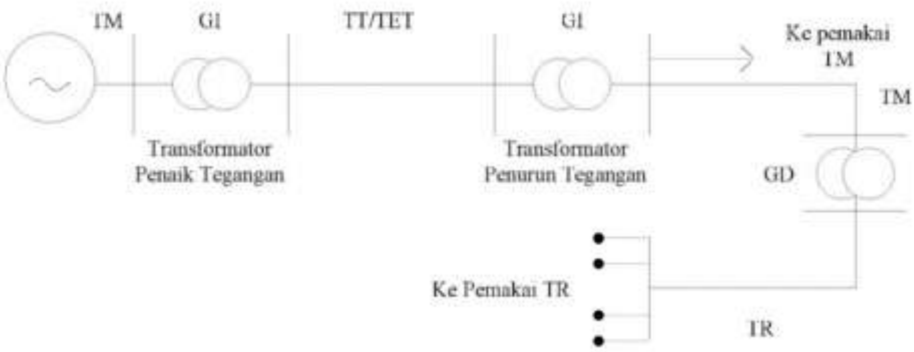

Figure 6. Single line diagram of electric power system

Description:
P : Generator
TM : Medium Voltage
TT : High Voltage
TET : Extra High Voltage
GI : Main Substation
GD: Distribution Substation

However, on the one hand, the electrical equipment in the generation, transmission, and distribution systems will experience basic problems such as disturbances, maintenance, and aging that result in equipment replacement. Although maintenance has the same impact as disturbances and aging resulting in electrical equipment stopping working, maintenance aims to improve the reliability of electrical equipment. Therefore, well-scheduled maintenance is highly expected.

Transformers are important components in the electric power system. Disturbances in power transformers result in the interruption of power flow distributed by the power transformer, decreased reliability of the power transformer, and the most noticeable impact is economic losses to the electricity company. Power transformer disturbances are divided into 2, external disturbances and internal disturbances.

Power transformers are equipped with several protection relays that work together with PMT (Circuit Breaker). Protection relays function to protect power transformers from external and internal disturbances. So the performance of the protection relay works very well, so that no damage occurs to the power transformer.

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METHOD OF RESEARCH

This study employs a modelbased simulation approach to analyze the performance of frequ ency and voltage stabilization control in lowinertia power systems integrated with a boost c onverter. The primary objective is to design and evaluate a control system capable of maintai ning frequency and voltage stability in power systems with reduced inertia, as typically foun d in modern grids with high renewable energy penetration.

This is an applied research study utilizing a quantitative and simulationbased approac h. The research is conducted numerically using computer simulations with MATLAB/Simulin k software to model the power system, the boost converter, and the control algorithms.

The research consists of several key stages:

The initial phase involves collecting and reviewing literature on the following topics:

1. Characteristics of low-inertia power systems
2. Impact of inertia on frequency and voltage stability
3. Operating principles of boost converters in DC-DC power systems
4. Modern control techniques such as PID, PI, and model-based control (e.g., Model Predictive Control)
5. Application of converters in mitigating voltage and frequency disturbances

References include international journals, technical books, and IEEE standards.

The lowinertia power system is mathematically modeled, considering the main characteristics of inverter-based generators (e.g., solar power or battery storage) that lack mechanical inertia. Key parameters such as terminal voltage, system frequency, and dynamic loads are included in the model.

The boost converter is designed based on basic DC-DC converter equations, including:

a. Input-output voltage relationship
b. Duty cycle as the control variable
c. Current and voltage response on the load side

At this stage, a dual-control system is designed:

a. Frequency Control: Implemented using PI controllers or other control strategies to stab ilize frequency during load changes.
b. Voltage Control: Regulates the boost converter's duty cycle to maintain stable output voltage under varying input or load conditions.

The control design employs loop tuning techniques and model-based design. Control parameters are determined through simulation of system responses to disturbances or load variations. The complete model of the lowinertia power system, boost converter, and control system is implemented in MATLAB/Simulink. Simulations are carried out for various scenarios, including:

a. Sudden load steps
b. Voltage disturbances on the input side
c. Voltage fluctuations from renewable sources

Observed parameters include:

a. Frequency deviation
b. Output voltage deviation

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c. System recovery time (settling time)
d. Overshoot and steady-state error

Simulation results are analyzed to evaluate the control system's performance. Quantitative analysis is conducted using standard control performance metrics such as:

a. ISE (Integral of Squared Error) to assess accuracy
b. Rise Time and Settling Time to assess response speed
c. System stability, observed via time-domain response graphs and frequency analysis

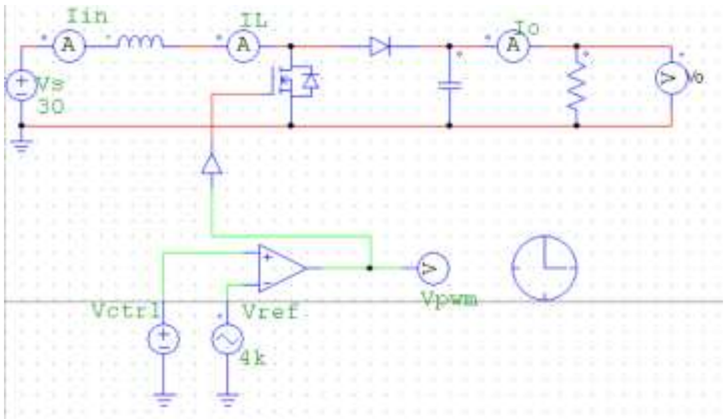

Figure 7. Simulation Design

Comparisons are also made between systems with and without the boost converter, as well as with and without control.Validation is performed by comparing the simulation results with reference data from the literature or previous studies. Where available, the model may also be validated using experimental data from small-scale laboratory setups or prototypes.

RESULT

In this paper contains the analysis of the test results that have been carried out. The purpose of this test is to find out whether each part of the system and the system as a whole has worked according to plan.

Boost Converter Calculation Results and Simulation

The following is the calculation result data for the boost converter as specification data for the boost converter.

Vin max = 30 volts
Vin min = 12 volts
Vo = 320 volts
Io = 10 A
f = 4 kHz

$$R = \frac{V_o}{I_o} = \frac{320\ V}{10A} = 32\ \Omega$$

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Table 1. Boost converter calculation results.

Vin min	12 Volt
Vin max	30 Volt
Vout	≥ 320 Volt
Iout	10 A
Freq	4 kHz
R	32Ω
Duty cycle	0.9625 / 96.25%
Inductor (L)	54.1405 μH
Capacitor (C)	3632.07 uF

From the calculation data, a trial was then carried out using simulation on the boost converter circuit

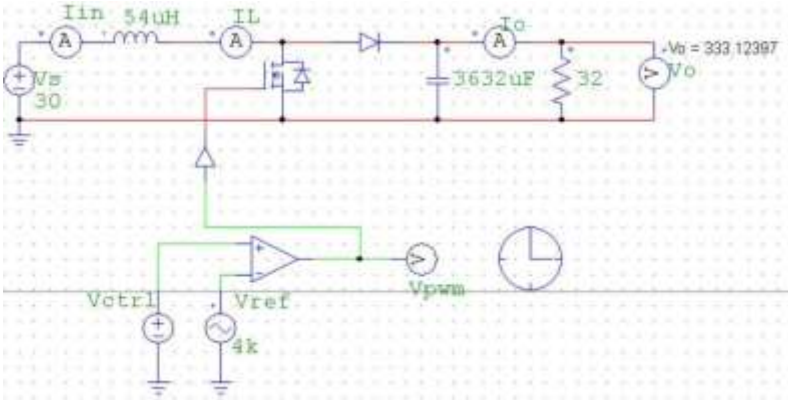

Figure 8. Simulation Circuit

In Figure 8 from the boost converter circuit, enter the inductor value of 54uH, capacitor of 3632uF, resistor value of 32Ω. With a duty cycle of 96.25% as a switching regulator, the boost circuit uses a MOSFET with specifications capable of withstanding high voltage because the switching process is very fast. By carrying out this simulation, the following output results were obtained:

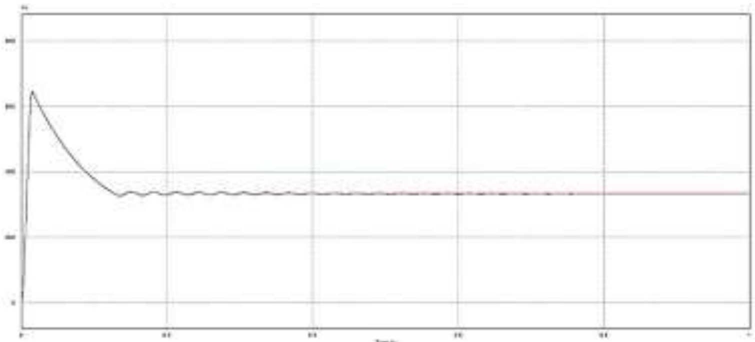

Figure 9. Boost Simulation

In the simulation results, an output of 333 volts DC was obtained, with a duty cycle value of 96.25%.

Boost Converter Test Results.

In the Boost Converter test, the NE555 IC is used as a PWM switching regulator. This test aims to determine whether the circuit can work and produce an output greater than its input.

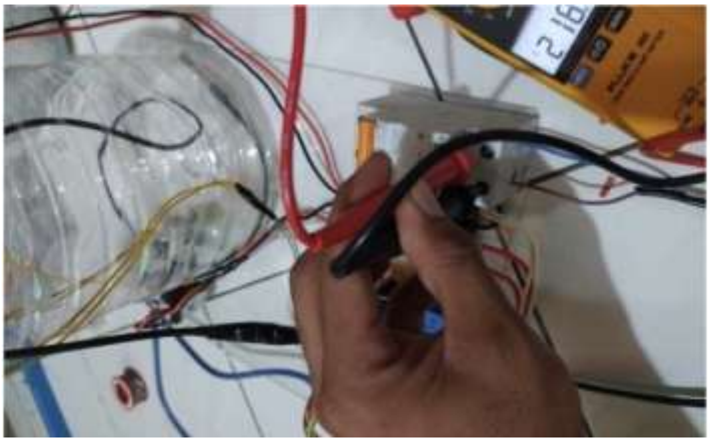

Figure 10. Boost converter test results

This test aims to determine the work of the DC - DC converter used as a voltage stabilizer while increasing the voltage from the summing output. This test is carried out by providing input voltage variations of 7.5, 9 and 11 Volt DC on this boost converter circuit. With a switching frequency variation value of 1kHz to 5kHz and a DC converter duty cycle used as a voltage stabilizer, the test results are shown in table 2 as follows.

Table 2. Boost Converter Test Results

No.	VoltageInput (V)	frequency (kHz)	Voltage on Inductor (V)	Voltage on Capacitor (V)	VoltageOutput (V)
1	7.5	1	7.49	18.52	18.52
2	7.5	2	7.49	18.55	18.55
3	7.5	3	7.49	18.55	18.55
4	7.5	4	7.49	18.55	18.55
5	7.5	5	7.49	18.54	18.54
6	9	1	8.99	22.35	22.35
7	9	2	8.99	22.39	22.39
8	9	3	8.99	22.39	22.39
9	9	4	8.99	22.38	22.38
10	9	5	8.99	22.38	22.38
11	11	1	10.99	27.48	27.48
12	11	2	10.99	27.53	27.53
13	11	3	10.99	27.53	27.53
14	11	4	10.99	27.53	27.53
15	11	5	10.99	27.53	27.53

From the results of the boost converter test in table 2, it is processed into a graph to show the voltage response in the boost converter circuit.

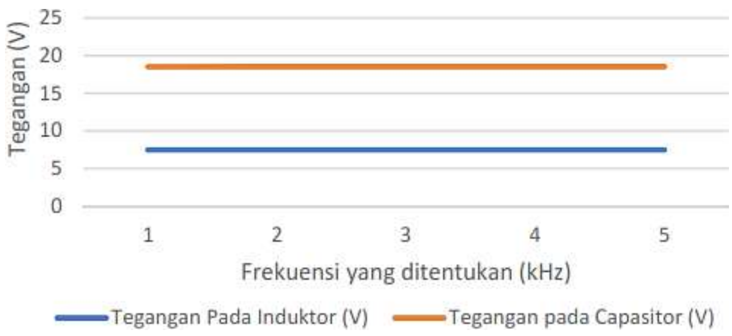

Figure 11. Voltage graph on the inductor and capacitor

In Figure 11 the inductor voltage value is 8.99 volts and the capacitor voltage value is ±22.3 volts with a frequency variation of 1kHz to 5kHz. And the output value is ±22.3 Volts DC.

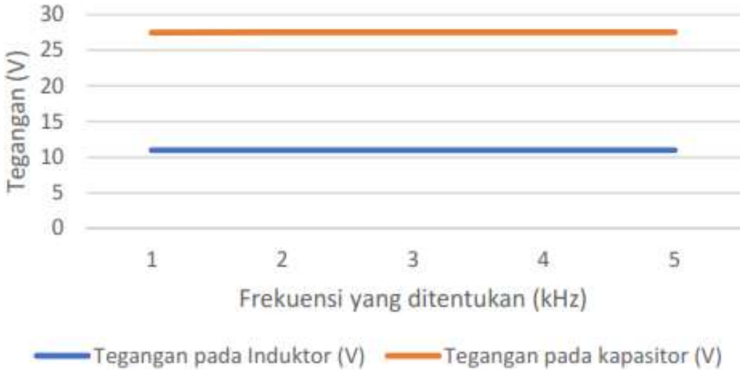

Figure 12. Graph with 11 Volt input.

The voltage value obtained after measuring the boost converter test, the inductor voltage value is 10.99 and the capacitor voltage value is ±27.5 with a frequency variation of 1kHz - 5kHz.

CONCLUSION

This study has analyzed the performance of frequency and voltage stabilization control in lowinertia power systems integrated with a boost converter using a simulationbased approach. The key findings are as follows: Power systems with reduced mechanical inertia, such as thoe dominated by inverterbased renewable energy sources, are more susceptible to frequency and voltage instability during load disturbances or source fluctuations.This study has analyzed the performance of frequency and voltage stabilization control in lowinertia power systems integrated with a boost converter using a simulationbased approach. The key findings are as follows: Power systems with reduced mechanical inertia, such as the dominated by inverterbased renewable energy sources, are more susceptible to frequency and voltage instability during load disturbances or source fluctuations. The integration of a boost converter allows for dynamic voltage regulation, especially under input or load variation scenarios. The converter effectively maintains output voltage levels by adjusting its duty cycle in real time. The proposed control strategy, combining a frequency PI controller with voltage regulation via the boost converter, demonstrates a significant improvement in system response. Simulation results show reductions in overshoot, shorter settling times, and smaller steady-state errors compared to uncontrolled or non-optimized systems. These results suggest that even in the absence of traditional mechanical inertia, controlbased solutions using power electronic converters can provide virtual inertialike response characteristics, ensuring reliable operation of modern grid systems.

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