Analysis of Voltage Stabilization in Wind Power Plants Using a Boost Converter

Tanwirul Muttaqin, Zuraida Tharo

Abstract

The main issue in Wind Power Plant (WPP) systems is the instability of the output voltage caused by fluctuations in wind speed. This unstable voltage complicates the battery charging process and can damage electronic equipment. This research aims to analyze the performance of a Boost Converter in stabilizing the output voltage of a WPP system. The Boost Converter circuit was designed with PWM signal control using an Arduino Nano microcontroller, supported by a TLP250 driver to regulate the switching duty cycle. Tests were carried out at various turbine rotational speeds (RPM), and the results show that the Boost Converter is capable of increasing and stabilizing the output voltage close to the reference value of 14 volts. The average output voltage obtained was 14.81 volts, with minimal deviation despite input fluctuations. In addition, an Internet of Things (IoT)-based monitoring system using the Blynk application successfully monitored the voltage in real time with a reading difference of about 0.2 volts compared to direct measurements. The findings indicate that the Boost Converter is effective for stabilizing voltage in small-scale WPP systems and supports the development of renewable energy in remote areas.

Keywords: Wind Power Plant (WPP), Boost Converter, DC Voltage, Arduino, PWM, IoT.

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Introduction

Energy is a fundamental necessity in modern human life, and its demand continues to increase along with population growth and technological advancement. Electrical energy, as one of the primary forms of energy, plays an essential role in daily activities across industrial, transportation, and household sectors. However, the high dependence on fossil energy sources such as coal, petroleum, and natural gas has led to serious issues, one of which is the environmental crisis marked by rising greenhouse gas emissions that contribute to global warming (IPCC, 2021). With the decreasing availability of fossil fuels and growing awareness of the importance of environmental conservation, the transition toward the use of new and renewable energy sources has become imperative. Wind energy is one form of renewable energy that originates from nature and has great potential for development, particularly in coastal and highland areas that have relatively high wind speeds (Kumar & Reddy, 2020).

A Wind Power Plant (WPP) is a system that utilizes the kinetic energy of wind to generate electrical energy. The system operates by capturing wind that rotates a turbine or windmill. The mechanical rotation of the turbine is transferred to the generator shaft to convert mechanical energy into electrical energy (Ackermann & Soder, 2002). However, one of the major challenges in WPP systems is the fluctuation of output voltage caused by variable wind speeds. This unstable voltage affects the performance of energy storage systems, such as batteries, as well as the electrical loads being powered. To address this issue, a Boost Converter is used a type of DC-DC converter designed to step up the input DC voltage to a higher output voltage level. The working principle of a boost converter involves storing energy in an inductor and then releasing it through a diode and capacitor to the load, with the timing regulated by a switching component such as a MOSFET (Erickson & Maksimovic, 2001). By using a boost converter, the fluctuating output voltage from the wind generator can be stabilized before being supplied to the energy storage system (battery) or the load.

The use of a boost converter in WPP systems can enhance overall system efficiency, ensure that the output voltage remains within the desired operating range, and extend the lifespan of other electronic components that are sensitive to voltage spikes or drops. Previous studies have also shown that implementing boost converters in renewable energy systems such as WPP and photovoltaic systems can improve voltage stability and the efficiency of delivered power (Chauhan & Saini, 2014). Moreover, the use of PWM (Pulse Width Modulation)-based controllers in boost converters helps regulate the output voltage precisely by adjusting the duty cycle of the PWM signal. This control implementation is crucial for maintaining stable output voltage amid varying wind speeds and fluctuating loads.

Literature Review

1. Wind Energy and Wind Power Plants (WPP)

Wind energy is a form of renewable energy derived from the movement of air caused by differences in atmospheric pressure. A Wind Power Plant (WPP) converts the kinetic energy of wind into electrical energy through the mechanism of wind turbines and generators. This technology has continued to develop along with the increasing demand for clean energy and concerns about the environmental impacts of fossil fuels (Ackermann & Söder, 2002). According to Manwell et al. (2009), WPPs have high efficiency in areas with consistent wind speeds. However, their implementation in developing countries remains limited due to inadequate infrastructure and instability in the electrical output generated. Research by Kumar and Reddy (2020) emphasizes that WPPs can be integrated with energy storage systems to enhance reliability, but additional technologies are required to maintain voltage stability.

2. Voltage Instability Issues in Wind Power Plants (WPP)

A key characteristic of WPPs is their dependence on wind speed, which varies over time. These fluctuations cause the generator's output voltage to become unstable, affecting energy storage systems such as batteries as well as the connected electronic equipment. This issue is further supported by the findings of Raza et al. (2019), who revealed that the voltage produced by wind generators often falls outside the safe operating range for DC link systems or inverters. According to Chauhan and Saini (2014), voltage stability is crucial in renewable energy systems, particularly in hybrid systems that combine multiple energy sources. Voltage instability not only reduces system efficiency but can also shorten the lifespan of electronic components.

3. Boost Converter as a Voltage Stabilization Solution

A Boost Converter is a type of DC-DC converter used to increase the DC input voltage to a higher level. The working principle of a boost converter, as explained by Erickson and Maksimovic (2001), involves storing energy in an inductor and regulating the switching signal to produce a stable output. In the context of Wind Power Plants (WPP), a Boost Converter can be used to stabilize the generator's output voltage before it enters the battery or inverter system. A study by Kutkut (2000) showed that using a Boost Converter in a wind-based battery charging system can increase charging efficiency by up to 15% and reduce battery cell degradation. Further research by Nguyen et al. (2016) also implemented a boost converter in a small-scale WPP system and demonstrated improved voltage stability within ±2% of the reference value.

Research Method

This system design was developed to address the output voltage instability of Wind Power Plants (WPP), which occurs due to fluctuations in wind speed. The system is designed to boost and stabilize the DC voltage from the wind generator using an automatically controlled Boost Converter.

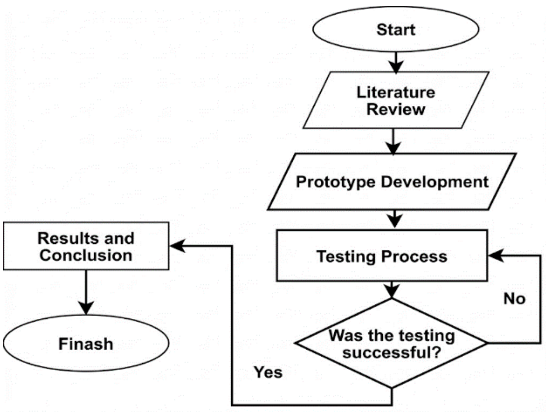

Figure 1. Research Flowchart

Explanation of the Research Flowchart

1. Start
   The initial phase of the research begins, marking the start of the analysis and design process for the Wind Power Plant (WPP) system.
2. Problem Identification
   Identifying the main issue, namely the voltage fluctuations at the output of the wind generator, which cause instability in the WPP electrical system.
3. Literature Review
   Collecting information and theories from journals, books, and scientific references related to WPP, voltage characteristics, and Boost Converters.
4. Design of the WPP and Boost Converter System
   Designing the energy conversion system of the WPP, including:
   a. Wind turbine
   b. Generator
   c. Boost converter circuit

   d. Control system (e.g., microcontroller or PWM control)
5. System Simulation (e.g., MATLAB/Simulink or Proteus)
   Conducting simulations of the WPP integrated with the boost converter.
   The simulation aims to observe the behavior of input and output voltages as well as the converter's performance.
6. Output Voltage Testing
   Measuring the output voltage produced by the boost converter. The data is compared between:
   a. Input voltage from the wind generator
   b. Output voltage after being conditioned by the boost converter
7. Analysis of Test Results
   Analyzing data from simulations and measurements to determine whether the boost converter successfully stabilizes the voltage.
   Indicators used include:
   a. Voltage increase
   b. Output voltage stability
   c. Power conversion efficiency
8. Conclusion and Recommendations
   Drawing conclusions based on the analysis regarding the effectiveness of using a boost converter in WPP systems and providing suggestions for future system improvements.
9. End
   Marking the completion of the research and documentation process.

Results

1. Buck-Boost Converter

A Buck-Boost Converter is a power electronics circuit that can be used to either increase (boost) or decrease (buck) the output voltage. The output voltage of this converter can be regulated by adjusting the duty cycle in the control system. A distinctive characteristic of the buck-boost converter is that its output voltage can be higher or lower than the input voltage and has an opposite polarity to the input voltage (Juarsah et al., 2015).

A buck-boost converter generally consists of several main components, including:

1. Inductor (L): Functions as an energy storage component that will release energy to the load.
2. Capacitor (C): Stabilizes the output voltage by filtering ripple.
3. MOSFET (Switch): Serves as the switching element to control the flow of energy.
4. Diode and resistor: Supporting components for rectification and current control.

In its working principle, when the MOSFET is active (ON), energy is stored in the inductor. When the MOSFET is inactive (OFF), the stored energy is released to the capacitor and the load. This process is repeated at high speed according to the predefined switching frequency. An interesting aspect of the buck-boost method is that the output voltage has an opposite (inverted) polarity to the input voltage. This allows the buck-boost converter to be used in applications requiring voltage inversion without the need for a transformer.

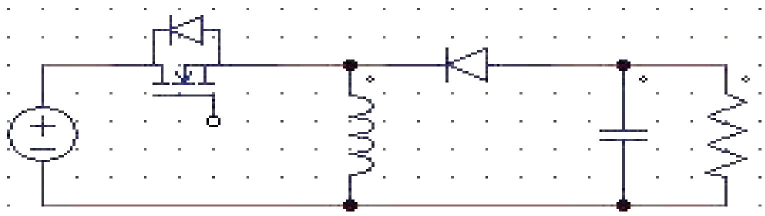

Figure 2. Buck Boost Converter Circuit.

In designing a buck-boost converter, the choice of component values significantly influences the operating modes, namely Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM):

1. Capacitor Selection (C)
   a. If the converter operates in CCM mode, the capacitor value is designed to be greater than the minimum value (C > Cmin).
   b. If the converter operates in DCM mode, the capacitor value is designed to be smaller than the minimum value (C < Cmin).

The basic equation for determining the minimum capacitor is as follows:

$$C_{min} = \frac{I_{out} \cdot D}{f \cdot V_{ripple}}$$

Where:

a. Iout = output current,
b. D = duty cycle,
c. f = switching frequency,
d. Vripple = output voltage ripple tolerance.

Inductor Selection (L)

a. For CCM mode, the inductor is designed to be larger than the limit value (L > Lb).
b. For DCM mode, the inductor value is made smaller than the limit (L < Lb).

Equation for the inductor value limit:

$$L_b = \frac{(1 - D) \cdot R}{2f}$$

Where:

a. D = duty cycle,
b. R = resistive load,
c. f = switching frequency.

Despite its relatively simple and flexible circuit, the buck-boost converter has several drawbacks, including:

a. Lack of isolation between the input and output sides (non-isolated converter),
b. High ripple levels in the output voltage and current,
c. Negative output voltage, which can limit its use in systems requiring positive direct voltage.

Nevertheless, buck-boost converters remain widely used in various applications such as portable power supplies, battery systems, and electronic devices that require flexible voltage regulation.

2. Cuk Converter

A CUK converter is a type of DC-DC converter that functions to increase (boost) or decrease (buck) the voltage from a DC source. Unlike conventional buck-boost converters, a CUK converter produces an output voltage opposite in polarity to the input voltage, but with a circuit that has the advantage of reducing ripple current on both the input and output sides. The CUK converter circuit consists of two capacitors (C1 and C2) and two inductors (L1 and L2), located on the input and output sides, respectively, as well as a switching element such as a MOSFET and a diode (Triandini et al., 2015). This topology is known to perform better in producing continuous current than a buck-boost converter.

Basic Structure of a CUK Converter:

1. Inductor L1: Located on the input side, it filters current fluctuations from the source.
2. Inductor L2: Located on the output side, it supplies continuous current to the load.
3. Capacitor C1: The primary energy coupling capacitor, which transfers energy from the input side to the output side.
4. Capacitor C2: filters the output voltage ripple.

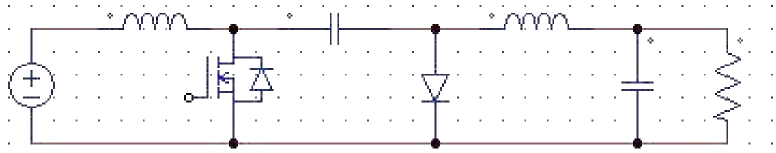

Figure 3. Cuk Converter Curcuit

1. Inductor Selection (L1 and L2)

The inductor value is chosen so that the current change (ΔI) does not exceed 5% of the average inductor current. An inductor that is too small will produce high current ripple, while an inductor that is too large will slow down the system's dynamic response. The basic equation for calculating the inductor value is:

$$L = \frac{V \cdot D \cdot T}{\Delta I}$$

Where:

a. L = inductor value (H),
b. V = input or output voltage depending on the inductor position,
c. D = duty cycle,
d. T = switching period (T = 1/f),
e. ΔI = current change tolerance (usually 5% of I_avg).

2. Capacitor Selection (C1 and C2)

Capacitor selection is based on the voltage ripple tolerance limit. For capacitor C1 (coupling capacitor), the average voltage across it is the sum of the input and output voltages:

$$V_{C1} = V_{in} + |V_{out}|$$

The maximum allowable voltage ripple is usually set at 5% of the average voltage value:

$$\Delta V_{C1} = 5\% \times V_{C1}$$

Capacitor C2 functions to filter the output voltage to ensure stability and freedom from noise or sharp fluctuations due to switching.

3. Voltage Conversion System Test Results

The design of this system begins with the utilization of wind energy through a wind turbine coupled with a DC generator. The output from the generator is a fluctuating DC voltage, which is then conditioned using two types of converters, namely the Buck-Boost Converter and the Cuk Converter. The goal is to stabilize the output voltage close to the reference value of 14 V. To regulate the output voltage value, PWM (Pulse Width Modulation) control is used which is generated by the Arduino Nano microcontroller. The PWM duty cycle value is adjusted dynamically depending on the input voltage from the generator. The PWM signal from the Arduino is amplified using the TLP250 driver, before being forwarded to the Buck-Boost and Cuk Converter power switching circuits.

4. Voltage Measurement Results

Testing was conducted at various turbine rotational speeds (RPM), with the measured input voltage (Vin), Buck-Boost Converter output voltage (Vout BB), and Cuk Converter output voltage (Vout Cuk) as shown in the following table:

Table 1. Buck-Boost and Cuk Converter Output Voltages

No	RPM	V In (V)	V Buck-Boost (V)	V Cuk (V)
1	856	26.00	14.8	14.5
2	583	19.39	14.7	14.5
3	458	14.32	15.1	14.6
4	434	14.52	14.9	14.3
5	346	11.57	14.9	14.5
6	289	9.59	14.5	14.4
7	191	6.76	14.8	14.4
8	687	22.87	14.4	14.3
9	392	13.36	14.9	14.5
10	666	18.60	14.9	14.5
11	637	21.48	14.9	14.5
12	528	17.53	14.5	14.1
13	490	16.30	15.3	14.4
14	462	15.40	15.1	14.2
15	564	18.25	14.5	13.9
Average			14.813	14.373

This study aims to analyze the effectiveness of using a Boost Converter in stabilizing the output voltage of a Wind Power Plant (PLTB). As is known, a PLTB system produces DC voltage from a generator that is highly dependent on wind speed. Because wind fluctuates, the generator's output voltage is also unstable. This instability presents a challenge in directly using wind energy to charge batteries or power DC loads.

To address this issue, a Boost Converter circuit controlled by a PWM-based microcontroller was designed and tested. With an appropriate duty cycle setting, the Boost Converter can increase and stabilize the input voltage to approach the reference voltage, namely 14 volts. Test results show that although the generator's input voltage fluctuates depending on the turbine's RPM, the Boost Converter's output voltage remains relatively constant at around 14.8 volts.

Based on the test data, it was found that the Boost Converter is capable of:

1. Converting a low input voltage (e.g., 6.76 V at 191 RPM) to a voltage close to the reference value (approximately 14.8 V).
2. Stabilizes the output voltage at various input voltage levels, with small deviations from the target (±0.3 V).
3. Compensates for input power drops without significantly affecting output voltage stability, as long as it remains within the system's current and power tolerances.

This conversion effectiveness demonstrates that the Boost Converter is highly suitable for application in small-scale wind power plants (PLTB) or off-grid systems that require a constant output voltage for storage systems or electronic loads. Furthermore, the use of the TLP250 driver to amplify the PWM signal from the microcontroller has been shown to help maintain switching stability in the power transistors, thus supporting the efficiency and stability of the voltage conversion.

Testing also included Internet of Things (IoT)-based monitoring using the Blynk application. The results showed that the system could be accessed and monitored in real time via an Android device, although there was a deviation in the voltage reading of approximately 0.2 volts compared to direct measurements. This is within tolerance limits and does not significantly impact decision-making. Overall, the Boost Converter in this system successfully mitigates voltage fluctuations from the wind power plant and provides a more stable output voltage suitable for practical applications. Compared with other conversion methods such as Buck-Boost or Cuk Converter, Boost Converter shows higher output stability, especially under low voltage input conditions.

5. Conclusion

Based on the results of the design, testing, and analysis that have been carried out, it can be concluded that the use of a Boost Converter in a Wind Power Plant (PLTB) system is effective in stabilizing the output voltage of the generator which is fluctuating due to variations in wind speed. The Boost Converter is able to increase the low input voltage to an output voltage close to the reference value of 14 volts, with an average measurement result of 14.81 volts. This shows that the converter works well in maintaining voltage stability even though the input voltage value changes according to the turbine rotation. In addition, the system integration with PWM control based on the Arduino Nano microcontroller and the use of the TLP250 driver also proved to play an important role in producing stable and precise switching signals. Monitoring through the Blynk IoT platform successfully provides real-time voltage readings, with a small difference of ±0.2 volts from direct measurements, which is still within the tolerance limit. Overall, the Boost Converter can be recommended as an effective solution for stabilizing voltage in wind-based renewable energy systems, especially for small-scale applications or off-grid systems.

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