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Application of Single-Phase Controlled Rectifier Full-Wave as a Brushless DC Motor Speed Regulator: An Innovative Approach for Empowering Rural Communities

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ABSTRACT

The utilization of electric bicycles (e-bikes) in Indonesia has seen widespread adoption, primarily driven by the use of Brushless DC (BLDC) motors. This is due to the exceptional stability of speed provided by BLDC motors. However, under load conditions, the speed of the BLDC motor tends to decrease, necessitating the implementation of a controller to maintain optimal performance. This study explores the speed control of BLDC motors through a Six-Step Commutation technique combined with PID control. The BLDC motor is equipped with a Hall-effect sensor, which serves as a rotor position detector. Once the rotor position is detected by the Hall-effect sensor, an inverter circuit is required to supply electrical energy to the motor in a synchronized manner. The Six-Step Commutation circuit effectively converts a DC voltage source into a three-phase AC output. The PID control system stabilizes the motor response, ensuring consistent performance. The system's response time demonstrates an impressive rise time of less than 0.1 seconds, with a settling time under 0.2 seconds. Additionally, the steady-state error ratio and the resulting overshoot are both kept below 1%, indicating a highly efficient and precise control system.

Key Word: *Speed control, Brushless DC Motor (BLDC), Cuk Converter*

I.INTRODUCTION

The Brushless DC Motor (BLDC) is widely regarded as the optimal choice for many daily-life applications, including in homes, industrial settings, and medical equipment, due to its numerous advantages. These benefits include high efficiency, a superior speed-inertial/torsion ratio, a broad speed control range, and low electromagnetic interference (EMI)[1]. These features make BLDC motors particularly suitable for environments where stability and minimal electromagnetic disturbances are critical[2].

The BLDC motor is characterized by its three-phase stator winding and permanent magnets located on the rotor[3]. When operating, the motor's shaft performs the primary function, but to regulate its speed, an inverter is required. Inverters are essential for controlling the speed of conventional BLDC motors, as they facilitate the conversion of DC power into the three-phase AC required for motor operation.

In particular, the use of a Cuk Converter offers a flexible and efficient solution for speed control. This converter is capable of producing an output voltage that can either be higher or lower than the input voltage, with an inverted polarity. Due to the complexity of conventional speed control systems, that the Cuk Converter can effectively control the speed of brushless DC motors[4]. Its ability to operate in different modes and adjust the output voltage up or down makes it an ideal choice for speed regulation in DC motors[5].

This study explores the integration of the Cuk Converter with a PI (Proportional-Integral) control system, which enables precise speed regulation for BLDC motors. By combining these technologies, the control system enhances the motor's performance, ensuring more stable and efficient operation[6][7].

This research is highly relevant to community service and rural empowerment, particularly through the application of advanced motor control technologies in local industries[8]. The ability to regulate motor speeds efficiently using technologies like the Cuk Converter is crucial for developing sustainable, low-cost solutions that improve industrial productivity in rural areas. By integrating this system into local workshops or small-scale industries, rural communities can benefit from increased energy efficiency, reduced operational costs, and enhanced economic opportunities, thereby promoting local development[9][10].

II.METHODOLOGY

1. Literature

A. Brushless DC Motor

Figure 1. BLDC Motors

Brushless DC (BLDC) motors, characterized by their lack of brushes and commutators, present a promising technology with numerous advantages for community-based applications, particularly in rural settings[11]. The absence of brushes leads to improved efficiency and reduced noise during operation, which in turn lowers maintenance costs. These motors can achieve high rotational speeds while minimizing friction, a common issue in traditional brushed motors. However, despite their efficiency and longevity, BLDC motors present challenges in terms of control complexity and higher initial costs due to their intricate design[12].

In a BLDC motor, the stator houses the windings, similar to a permanent magnet synchronous AC motor, while the rotor consists of permanent magnets. Unlike traditional DC motors, BLDC motors operate with a trapezoidal back electromotive force (backEMF), as opposed to the sinusoidal backEMF characteristic of synchronous AC motors. This design enables BLDC motors to have similar electrical characteristics to DC motors, but with greater reliability and efficiency.

The potential of BLDC motors can be maximized through the application of innovative technologies such as the Single-Phase Controlled Rectifier Full-Wave, which serves as an effective speed regulator[13]. This technology can help in the development of cost-effective, efficient, and low-maintenance systems for rural communities, where access to reliable energy and machinery is often limited.

The integration of this technology in rural areas can directly address several key challenges faced by these communities. By providing a reliable and sustainable power solution, this approach can support agricultural processes, small-scale manufacturing, and other community-based initiatives that require motorized systems. Additionally, the reduced operational costs and ease of maintenance make it an ideal solution for rural environments where resources and technical expertise may be limited.

In summary, the application of a Single-Phase Controlled Rectifier Full-Wave as a BLDC motor speed regulator presents an innovative solution with significant potential to empower rural communities. Through improved efficiency, lower maintenance costs, and better energy management, this technology can contribute to sustainable development and socio-economic growth in underserved areas.

- BLDC Modeling

  In this study, a MOOG output BLDC motor from the BN42-53IP-03 series, with a power rating of 874 watts, was utilized. This motor is an essential component in the proposed system for rural community applications, offering both reliability and efficiency in environments where energy resources are often limited.

Table 1. *Motor Parameter*

Parameters	Value
Rated Power	874 Watts
Rated Speed	2810 rpm
Rated Torque	2.9588 Nm
Resistance	0.408 Ohms
Inductance	1.71 mH
Speed Constant (krpm/V)	29.239
Torque Constant (Nm/A)	0,3269
No. Of Polishing	8
Moment Of Inertia	0.4939xKg.
No Load Speed	2920 rpm
No Load Current	0.7 A

B. Commutation Change Detection Methods

In Brushless DC (BLDC) motors, detecting changes in commutation is a critical process for effective motor control. There are two primary methods for detecting commutation changes: sensorless and sensory (sensor-based) methods[14][15]. The sensorless method does not rely on physical sensors to detect rotor position. Instead, it monitors the current activity in each winding, and these current variations are used to determine when commutation changes should occur. One common sensorless technique is the Back Electromotive Force (BackEMF) method. This method detects the motor's neutral point voltage, and through advanced algorithms, the zero-crossing points of the BackEMF are used to signal commutation transitions.

On the other hand, sensor-based methods use physical sensors to track the mechanical motion of the rotor. These sensors provide real-time rotor position data, which are essential for accurately controlling commutation changes[16]. Among these methods, Hall effect sensors are the most widely used due to their simplicity and ease of application. Many machines are manufactured with built-in Hall effect sensors, making them an accessible option for a wide range of systems, including those used in rural community-based applications. Hall effect sensors detect changes in magnetic fields generated by the rotor, allowing for precise tracking of its position. By utilizing this sensor, a 120° phase shift rectifier can be employed to manage the commutation process effectively.

The integration of these commutation detection methods in rural-based motor systems is particularly beneficial. In areas where skilled labor and maintenance resources are scarce, sensor-based commutation detection using Hall effect sensors offers a reliable, cost-effective, and easy-to-implement solution for regulating Brushless DC motors. This is crucial for supporting sustainable development in rural areas where motor-driven systems, such as water pumps, agricultural machinery, and small-scale manufacturing tools, are key to local economic growth and community empowerment.

C. Rectifier

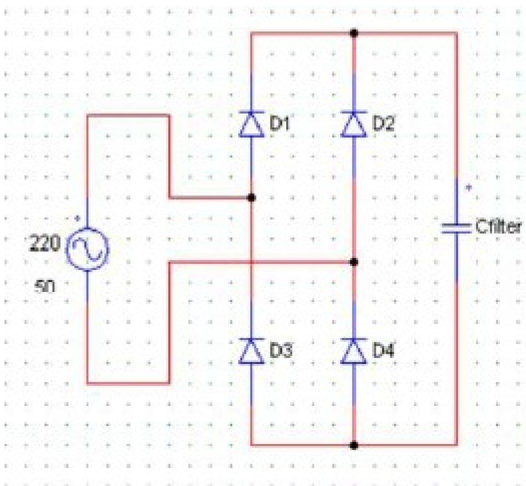

Figure 2. Rectifier Circuit

The voltage rectifier is a crucial component in power circuits, responsible for converting alternating current (AC) into direct current (DC). This conversion is vital for many modern applications, particularly in rural areas where consistent and reliable power is essential for community development. The rectifier typically utilizes diodes as its main components[17]. Diodes are fundamental in this process, as they allow current to flow in only one direction, effectively blocking current from flowing in the opposite direction.

When AC voltage is applied to a diode-based rectifier circuit, it produces a half-wave output. This means that only one half of the AC waveform is passed through, while the other half is blocked, creating an incomplete DC signal. While this basic half-wave rectification is useful in some applications, it is often inefficient for powering sensitive equipment or motors, which require a more stable and continuous DC supply.

In rural settings, where access to reliable electrical infrastructure is often limited, efficient power conversion is essential. By employing advanced rectifier designs, such as the single-phase controlled rectifier full-wave, communities can benefit from smoother, more consistent DC power[17]. This is particularly important for applications such as Brushless DC motors (BLDC) used in agricultural tools, water pumps, and small-scale machinery. A more efficient rectifier design enhances the reliability and performance of these systems, reducing maintenance costs and ensuring that rural communities have access to sustainable energy sources for economic growth.

D. Cuk Converter

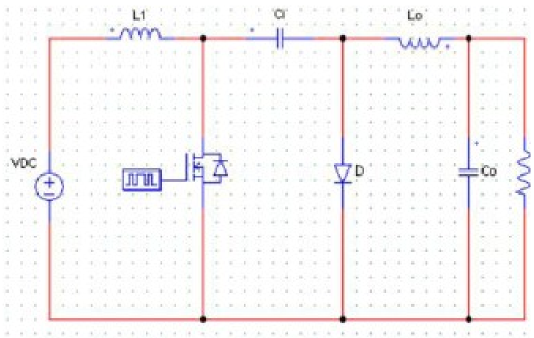

Figure 3. Cuk Converter

The CUK converter is a versatile power conversion circuit, typically employed to enhance the functionality of buck-boost converters. Its primary role is to both step up (boost) and step down (buck) the voltage, providing a flexible solution for varying power requirements[18]. The circuit configuration of the CUK converter consists of several key components, including an input inductor, a switch, a voltage transfer capacitor, a diode, a filter inductor, and a filter capacitor.

In the context of rural communities, the CUK converter offers significant benefits for energy management in small-scale, off-grid applications. By efficiently regulating voltage, this converter ensures that local systems—such as irrigation pumps, renewable energy setups, and other motorized devices—can operate reliably despite fluctuations in the input power supply. Its dual ability to both increase and decrease voltage makes it particularly useful in areas with unstable electrical infrastructure.

Additionally, the CUK converter plays an important role in enhancing the performance of Brushless DC (BLDC) motors, which are widely used for various community-driven activities in rural areas[19]. These motors require stable, consistent power to function optimally, and the CUK converter helps ensure that the voltage supplied is always within the necessary range, contributing to the overall efficiency and longevity of the systems they power.

By implementing such converters in rural settings, we can reduce energy wastage, improve system reliability, and lower maintenance costs for local machinery, ultimately contributing to sustainable economic development and improved livelihoods for rural communities.

- Designing Cuk Converter

Table 2. Rating of Cuk Converter

Input Voltage	**200 V**
Output Voltage	100 V
Output Power	875 V
Frequency	50 KHz
Ripple Input Flow	1%
External Current Rpple	1%
Ripple Voltage	1%
Inductor (L1)	0.01375 mH
Inductor (L2)	0.006875 mH
Capacitors (C1)	0.0000170906 uF
Capacitors (C2)	0.00005 uF
Burden	11,428 Ohms

E. PI Control

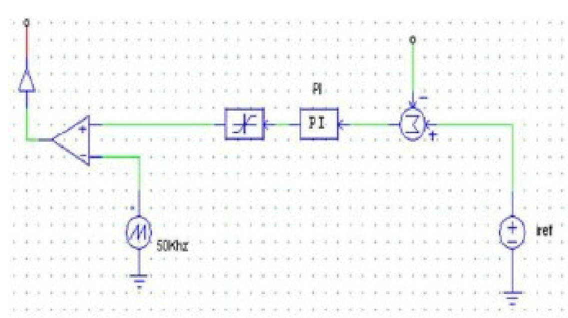

Figure 4. PI Control Circuit

The PI control system is a critical component in regulating the performance of motorized systems, ensuring accuracy in the operation of various devices. The system's effectiveness is determined by its feedback properties, which help minimize errors and improve system stability. The PI controller consists of two main components: Proportional (P) control and Integral (I) control. These two configuration options work together to adjust control variables in order to minimize time-related errors and maintain optimal performance.

In the context of empowering rural communities, the application of PI control in Brushless DC (BLDC) motors is particularly beneficial. Many rural communities rely on motor-driven systems for essential activities such as water pumping, small-scale manufacturing, and agricultural processes[20]. By implementing a PI control system in these applications, the regulation of motor speed and performance becomes more precise, leading to greater efficiency and reduced wear on machinery.

In rural areas, where resources for maintenance and repair may be limited, the ability to ensure accurate and consistent operation of motors without requiring frequent manual adjustments is invaluable. The PI control system helps achieve this by automatically adjusting the control variables, ensuring that motors operate at their optimal speed, regardless of fluctuations in load or power supply. This contributes not only to energy efficiency but also to the sustainability of rural development initiatives.

Furthermore, the integration of such advanced control systems in rural-based technologies supports long-term community development by reducing costs, improving reliability, and enhancing the overall effectiveness of motor-driven systems. This aligns with the goal of empowering rural communities with innovative technological solutions that foster economic growth and social well-being.

F. System Configuration

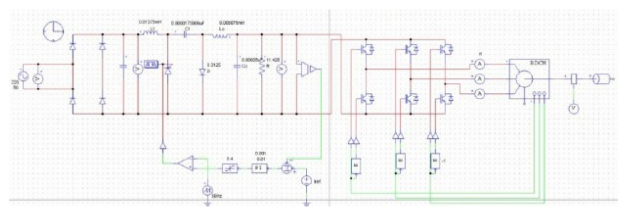

Figure 5. BLDC Control System

In this study, the system model is illustrated in Figure 5, which represents the components of a system designed to regulate the speed of a Brushless DC (BLDC) motor. The system comprises a single-phase AC voltage source, a DC-DC Cuk Converter circuit, and the BLDC motor. The integration of the DC-DC Cuk Converter in place of traditional DC-DC converters is a key innovation aimed at enhancing the control of motor speed for BLDC motor drive systems in rural settings.

This system configuration is crucial for rural applications where stable motor performance is essential for tasks like water pumping, small-scale farming, and other community-driven projects.

Traditionally, speed control systems for BLDC motors have used conventional methods that might not be as efficient or adaptable to varying load conditions. The incorporation of a PI (Proportional-Integral) control circuit within the Cuk converter system optimizes speed regulation, ensuring that the motor runs at a consistent speed despite changes in input voltage or load.

The Cuk converter, placed between the rectifier and inverter, acts as both a current and voltage regulator. This placement helps stabilize the power supplied to the motor, ensuring that the BLDC motor maintains a constant speed. The ability to regulate voltage in this way is particularly valuable for rural communities, where access to stable power sources may be limited. The converter enables a more reliable operation of the BLDC motor, which is critical for reducing downtime and minimizing the need for frequent maintenance.

By implementing such a system, rural communities can achieve more efficient and sustainable use of motor-driven technologies, contributing to economic empowerment and improved quality of life. These technologies, made reliable through advanced speed regulation methods, can enhance productivity in agriculture, water management, and small-scale industry, helping communities thrive with minimal resources.

III.RESULT & DISCUSION

In this study, simulation experiments were conducted using the Power Simulator (PSIM) software to evaluate the performance of the system. The simulation results were carefully analyzed, focusing on key parameters such as motor speed and the comparison between the performance of the Cuk Converter both with and without speed control. Additionally, the system's ability to maintain stable motor speed was assessed under different loading conditions.

The simulations were designed to test the system's behavior under varying loads, ranging from no load to torque values of 0.055 Nm and 0.075 Nm. The input voltage for the simulations was set at 220 V (Vi), representing a typical voltage source, and the output voltage was maintained at 100 V (Vo), which is suitable for the operation of the Brushless DC (BLDC) motor.

This simulation study is particularly relevant for rural communities, where reliable power systems for motor-driven applications are crucial. By evaluating the speed and stability of the BLDC motor under various conditions, the research provides insights into how advanced control methods can ensure consistent motor performance, even with fluctuating power supplies or varying load demands. This is important for rural areas where access to stable energy sources may be inconsistent, and the performance of critical systems such as water pumps, agricultural machines, or small-scale industrial equipment can be significantly impacted by voltage and load variations.

The results of these simulations offer valuable data that can be used to optimize the design and implementation of speed regulation systems in rural energy applications, contributing to sustainable development and improving the quality of life for communities that depend on motor-driven technologies.

1. Analysis

a. Motor with No-Load speed Response

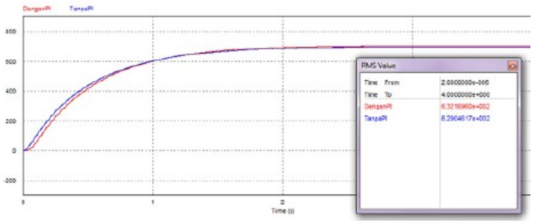

Figure 6. No-Load Speed Graph

As shown in Figure 6, the graph illustrates the performance of the motor circuit under no-load conditions, with a rest time of 4 seconds. In the system with PI speed control, the motor reaches a speed of 703 RPM, demonstrating the effectiveness of the Proportional-Integral (PI) controller in maintaining a stable motor speed. In contrast, the system without PI control shows a slightly lower speed of 695 RPM, highlighting the impact of the control system on improving motor performance.

However, it is important to note that in the uncontrolled motor circuit, the system experiences an overshoot of 6.967 RPM. This overshoot indicates a temporary spike in motor speed, which can lead to instability in motor-driven applications. The inclusion of the PI controller helps mitigate such issues by providing more consistent speed regulation.

For rural communities that rely on motor-driven technologies, such as water pumps, agricultural equipment, and small-scale manufacturing, maintaining stable and reliable motor performance is crucial. The application of PI speed regulation ensures that these systems operate efficiently, even under varying load conditions, reducing the risk of mechanical failure and minimizing the need for frequent repairs. Such improvements in motor control systems can significantly enhance the sustainability and reliability of community-based systems, contributing to economic empowerment and the overall well-being of rural populations.

b. Motor With Load 0.040 Nm speed Response

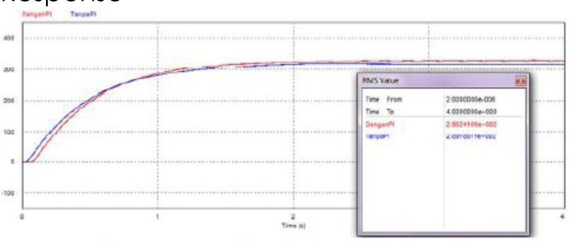

Figure 7. Load Motor Speed 0.040 Nm

From the figure above, it can be concluded that the graph depicting the motor speed under no-load conditions, with a rest time of 4 seconds, shows that the speed of the motor with PI speed control is 328 RPM. In comparison, the motor circuit without PI control results in a slightly lower speed of 318 RPM. This difference emphasizes the contribution of the Proportional-Integral (PI) controller in improving the motor's performance, ensuring more consistent speed regulation.

Additionally, for the uncontrolled motor circuit, an overshoot of 3.205 RPM is observed, indicating a temporary spike in motor speed that could lead to instability, especially under varying load conditions. The inclusion of PI control helps to reduce such overshoot and ensures more stable motor operation.

This improved motor control system is highly relevant to rural communities that rely on motor-driven systems for critical functions such as agricultural machinery, water pumping systems, and small-scale industrial operations. By integrating PI speed control into these systems, it is possible to enhance the efficiency and reliability of rural infrastructure, *providing a sustainable solution to challenges faced by these communities.*

c. Motor With Load 0.055 Nm speed Response

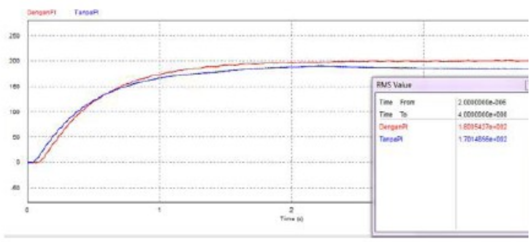

Figure 8. Speed Response of a Load Motor of 0.055 NM

The analysis of the graph presented above reveals that the motor speed in the loadless controlled circuit, with a rest time of 4 seconds, demonstrates a motor speed of 198 RPM when PI speed control is applied. In comparison, the motor circuit without PI control achieves a slightly lower speed of 188 RPM, indicating the contribution of the Proportional-Integral (PI) controller in stabilizing motor performance.

Moreover, in the uncontrolled motor circuit, an overshoot of 1.905 RPM is observed, highlighting a temporary surge in motor speed. Such an overshoot can lead to operational instability, especially in critical applications where consistent motor speed is required for precise operations.

This result is especially relevant to rural communities, where reliable motor performance is essential for various applications, such as pumping systems, agriculture-related equipment, and small-scale energy generation. By implementing PI speed control in these systems, rural communities can benefit from enhanced efficiency, sustainability, and cost-effectiveness.

IV.CONCLUSION

Here are the key conclusions from the design and testing of the CUK converter in this study:

1. Inverse Relationship Between Output and Input Voltage. The output voltage of the CUK converter is inversely proportional to the input voltage, meaning that as the input voltage increases, the output voltage decreases, and vice versa.
2. Operation Mode Based on Duty Cycle. The operation mode of the CUK converter is determined by the duty cycle. When the duty cycle is less than 50%, the converter operates in "buck" mode (stepping down the voltage). When the duty cycle exceeds 50%, the converter operates in "boost" mode (stepping up the voltage).
3. Effect of Load on Motor Speed: There is a direct relationship between the load and motor performance. As the load on the motor increases, the motor speed decreases.
4. Impact of Load on System Performance: The study shows that increasing the load affects the overall system performance, particularly by reducing the motor speed, highlighting the importance of load management in CUK converter applications.

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