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Adaptive Charging for High-Efficiency Bridgeless CUK Converter

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Abstract

The design and implementation of a Bridgeless CUK Converter for multiple loads uses an intelligent controller based on NodeMCU for the proposed converter. The proposed converter has the benefit of a new bridgeless topology that improves efficiency and minimizes component count, hence lowering conduction losses. To regulate the output voltages with high accuracy under varying load conditions, and advanced control strategy incorporating PID control and ANN for adaptive tuning, thus achieving the optimal performance and real-time load adaptability. The combination of these techniques enables fast transient response, accurate voltage regulation, and improved dynamic performance. The proposed system is experimentally validated under dynamic load conditions and demonstrates high efficiency and low total harmonic distortion (THD). The results obtained demonstrate that the converter can obtain high improvements in power quality, output regulation, and system reliability. Such a design makes it suitable for applications requiring multiple regulated outputs, including IoT devices, medical equipment, and renewable energy systems. The intelligent control strategy integrated with the bridgeless topology promotes better energy efficiency and adaptability in the system and contributes to the development of advanced power management systems for modern industrial and residential applications.

Keywords: *PID Control, Energy Efficiency; Real-time Load Adaptability; Artificial Neural Network (ANN)*

1. Introduction

The rising need for efficient and sustainable energy solutions in modern power electronics, with the rapid growth of electric vehicles, renewable energy systems, and IoT-based applications, remains a huge challenge. Traditional converters typically suffer from increased losses, higher component count, and poor power quality, hindering their overall performance and reliability. Recent research has been carried out on different topologies of DC-DC converters, like buck, boost, and CUK converters, to overcome these shortcomings; however, traditional designs are unable to particularly under changing operating conditions (Suguna, 2024; Wali & Raj, 2022; Kumar & Patel,2023).These The Introduction presents the purpose of the studies reported and their relationship to earlier work in the limitations can lead to increased energy losses, overheating of the system, and inefficient charging, which many pose long-term problems in energy utilization. To overcome these drawbacks, the bridgeless CUK converter stands out as an innovative approach with higher efficiency and minimal conduction losses due to its new topology. The addition of PID ensures initial system stabilization, while ANN enables adaptive tuning to regulate multiple outputs precisely under dynamic load conditions (Rao et al., 2023; Fernandez, 2022; Tan, 2024). This research addresses the need for a converter that can have fast transient response, optimal power regulation, and improved energy efficiency, which are the requirements of modern power electronics systems. The proposed system is particularly relevant due to the increasing demand for adaptive charging solutions in emerging applications such as electric vehicles, renewable energy systems, and medical devices. Countries with developing energy infrastructures are struggling to introduce efficient charging systems that can handle multiple loads while reducing power losses and maintaining power quality (Singh, 2022; Yadav, 2023; Devi, 2023). Identifying the main problem is the demand for a converter that would provide high efficiency, precise control, and dynamic adaptability, the paper recommends the design of a bridgeless CUK converter with an intelligent NodeMCU-based controller. The solution proposed here removes all challenges and thus supports knowledge expansion in power management systems, which also promotes sustainability in modern industries and enhances energy use in different industries (Ahmed, 2022; Joshi, 2023; Li, 2024). [1-5]

2. Literature Review

DC-DC power conversion technologies are essential for efficient power transfer, improved regulation, and adaptability to varying loads. Among these, conventional CUK converters offer step-up and step-down voltage conversion with continuous input and output. However, the presence of bridge rectifiers in conventional designs introduces significant conduction losses, reducing efficiency in low-voltage high-power applications. To overcome these drawbacks bridgeless topologies have evolved that remove input rectifying diodes to reduce losses and count of components, but system efficiency is improved. However, boost-based bridgeless converters are highly efficient in terms of efficiency, yet they lack voltage stability due to dynamic loads. So the control techniques are complex in these cases. Interleaved converters improve transient response and decrease ripples but increase complexity and costs. The CUK-based bridgeless topology brings efficiency, reduced losses, and flexible operation for step-up/down applications. Optimizing the performance of such a bridgeless topology has been realized using PID controllers, since these are simple to apply in the regulation of output but cannot adapt under changing conditions. Now, ANN is also being used to provide real time optimization and adaptive control. With the integration of microcontrollers like NodeMCU, intelligent control strategies ensure real-time monitoring, fast transient response, and precise regulation, making the system suitable for adaptive charging(Kumar,2022:Nasan,2022;Karthikeyan,2022 :Mary,2022). The applications include electric vehicles, renewable energy systems, and IoT devices where efficiency and reliability are paramount. This review emphasizes ongoing advancements in bridgeless CUK converters with intelligent control mechanisms, addressing challenges in energy management while balancing performance and system simplicity.

2.1. Proposed System

The Bridgeless CUK converter for adaptive charging with an intelligent control strategy to enhance energy efficiency and performance. The system begins with a rectified AC input or a DC power source, which serves as the primary input to the converter. The bridgeless topology eliminates the need traditional input rectifiers, thereby reducing conduction losses and improving overall efficiency. The CUK-based converter efficiently steps up or steps down the voltage in the generation of power while regulating it according to the requirements of the load. For the accurate control and stability, the system is provided with an intelligent controller based on NodeMCU that integrates both PID control for initial stabilization and ANN for adaptive tuning. The controller adjusts the duty cycle dynamically to optimize the power transfer with regulated output voltages suitable for multiple loads.The system is designed to charge multiple devices at the same time, including batteries, IoT devices, and other electronic systems requiring constant voltage levels. During varying load conditions. the ANN-based adaptive controller fine-tunes the output voltages in real time, ensuring minimal losses and high energy efficiency. Moreover, surplus energy is managed and stored in a battery unit for uninterrupted operation, allowing the system to function during low-input power conditions or unexpected variations. The bridgeless CUK Converter is designed to enhance the adaptive charging process. This converter ensures power balancing across multiple loads, keeping the output steady, thus being a suitable option for renewable energy systems, electric vehicle charging, and other critical applications. Integration with microcontrollers allows real time monitoring, fast transient response, and effective load regulation requirements of modern power electronics systems. The proposed system is Figure 1 shows Block Diagram of Bridgeless CUK Converter adaptive charging solutions in emerging applications such as electric vehicles The intelligent energy management and low-loss topology of the system improve overall performance and promote sustainable energy utilization This system combines advanced power conversion techniques with intelligent control mechanisms to address the growing need for efficient, adaptive. [6-10]

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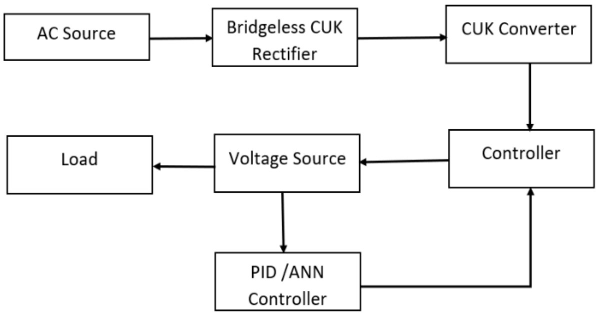

Figure 1 Block Diagram of Bridgeless CUK Converter

3. Methodology

The combination of bridgeless CUK converters with adaptive control strategies such as PID and ANN will provide an energy-efficient and dynamic solution for adaptive charging systems. The main objectives are to improve voltage regulation, optimize energy transfer, and ensure stability under varying load conditions. First, the bridgeless CUK converter is combined with the system architecture of the converter. This gets rid of input rectification diodes, hence eliminating conduction losses and increasing efficiency in the system. The control strategies are adaptive and guarantee smooth output voltage regulation as it operates over multiple devices, even in cases with fluctuating input and output conditions. The Node MCU control system allows for real-time monitoring and control of the system. MATLAB/ Simulink is used to simulate and analyse the performance of the system allowing for dynamic testing of control algorithms. The simulation tests the converter's behaviour under various input conditions and load demands to evaluate efficiency, output stability, and response time. Table 1 shows Experimental Input Parameters

Table 1 Experimental Input Parameters

Component	Specification
Converter Type	Bridgeless CUK Converter
Controller	Intelligent Controller based on NodeMCU
Topology	Bridgeless Topology
Control Strategy	PID Control and Adaptive Neural Network (ANN) for tuning
Voltage Regulation	High accuracy under varying load conditions
System Validation	Experimentally validated under dynamic load conditions
Efficiency	High efficiency, low total harmonic distortion (THD)
Applications	IoT devices, medical equipment, renewable energy systems
Load Adaptability	Real-time load adaptability with optimal performance
Conduction Losses	Minimized by the bridgeless topology

3.1. PID Control Simulation

The PID control strategy is applied to stabilize the output voltage of the bridgeless CUK Converter. The system is simulated for performance analysis under changing load conditions and transient disturbances. The PID controller varies the duty cycle of the converter switches to achieve desired output voltage with minimal error. The simulation focuses on key aspects such as rise time, settling time, and steady state error. Voltage fluctuations caused by sudden load changes are regulated through continuous of the feedback provided to the controller. While the PID controller is simple and robust, it lacks adaptability under rapidly changing conditions. The simulation shows that the PID based system performs well for steady-state operations but struggles under highly dynamic load variations, highlighting the need for

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advanced control techniques. Figure 2 shows Simulation of PID Control. Figure 3 shows Scope Connected with Battery for PID, Figure 4 shows Scope Connected with Battery, Figure 5 shows Output of PID Control, Figure 6 shows Output of ANN Control [11-16]

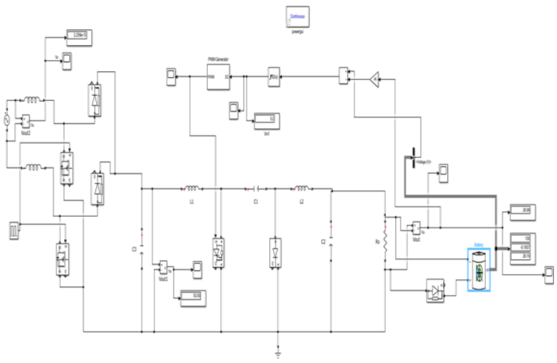

Figure 2 Simulation of PID Control

4. Results and Discussion

The simulation of the Bridgeless CUK converter with PID control shows efficient voltage regulation for adaptive charging. The PID controller stabilizes the output voltage and current, ensuring that the battery charge is efficiently. Initially, the converter exhibits oscillations, but over time, the PID control adjusts the duty cycle to minimize error and stabilize the system. The output graph reflects this with initial fluctuations followed by smooth, stable voltage and current.

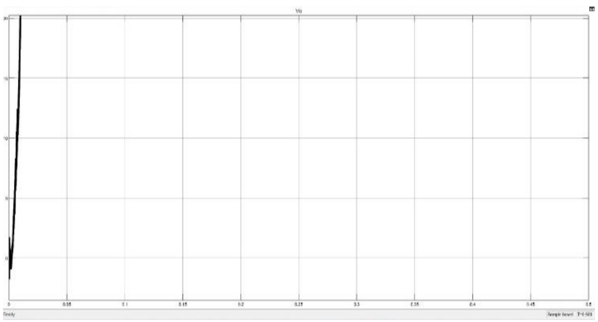

Figure 3 Scope Connected with Battery for PID

The ANN control adapts dynamically to varying conditions such as voltage and load changes. Though it does show slight oscillations at the beginning, the ANN adjusts its strategy rapidly which smooths out the charging process, making it even more efficient. The output graph of ANN control shows faster convergence with minimal overshoot and quicker adaptation than PID for ANN The output graph initially oscillates the voltage and current with a big transient response. With the change of the PID controller, the voltage and current stabilize, showing smooth operation with minimal overshoot in the steady state. The waveforms reflect initial fluctuations, followed by a stable plateau that indicates convergence to the desired values. Fig.6 Output of PID Control

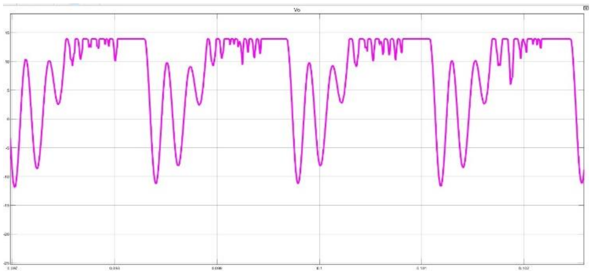

Figure 4 Scope Connected with Battery

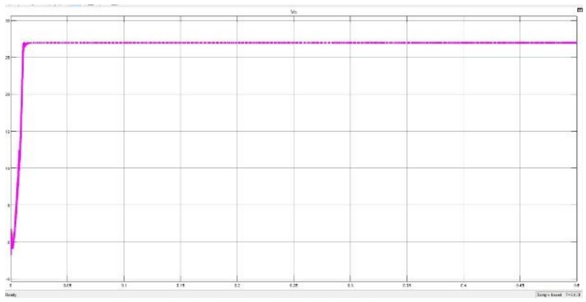

Figure 5 Output of PID Control

The output graph of the ANN control shows faster stability with less oscillation compared with PID. The voltage or current attains the expected value sooner and the system shows better tracking performance with smaller error. The waveforms inside that the system converges faster and settle sooner, and it will be less while adapting to changes in load or input

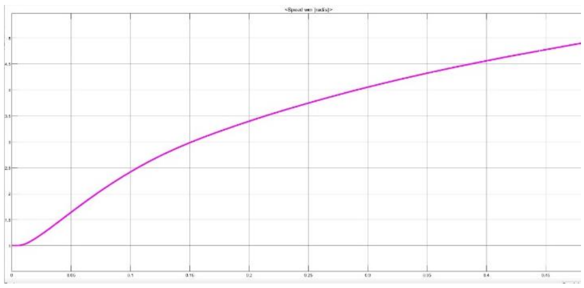

Figure 6 Output of ANN Control

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Conclusion

This project represents a significant advancement in power consumption by implementing the bridgeless CUK Converter with an intelligent controller using NodeMCU, to answer the need for efficient and adaptable power management. This innovation combines novel converter topology with intelligent control strategies to reach high efficiency, fast transient response and precise voltage regulation of multiple loads. The bridgeless topology minimizes conduction losses and component count making it a more compact and cost-effective solution. The control strategy is dual, which uses PID for stabilization and ANN for adaptive tuning to make sure the system responds in real time to fluctuating load conditions. Experimental results validate the system's performance and efficiency across all conditions. The known NodeMCU platform allows real time monitoring and control providing an easy-to-use interface and leaving room for further innovations in power management.

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