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Design and Implementation of a Transformer Winding Machine with Buck-Boost Converter-Based DC Motor Drive

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Abstract

This research presents the design and implementation of a high-frequency transformer winding machine driven by a DC motor with a Buck-Boost converter to produce transformers accurately and efficiently. The system integrates a DC motor controlled by a Buck-Boost converter, which regulates the voltage to the motor, ensuring stable performance during the winding process. The winding machine design includes a stable mechanical platform, a V-belt mechanism for power transmission, and optocoupler sensors for real-time monitoring of winding turns. The Buck-Boost converter stabilizes voltage fluctuations, allowing smooth motor operation under various input conditions, thereby improving machine efficiency and reliability. Experimental tests on the rectifier, Buck-Boost converter, and DC motor demonstrate high efficiency and stable performance, with minimal deviation between calculated and experimental results. Test results show that this machine can perform precise winding across different duty cycles, with optimal speed control and stable operation. Compared to existing transformer winding machines using induction motors or stepper motors, this system offers better control, faster winding speeds, and greater adaptability to different production conditions. The developed machine significantly contributes to industries such as transformer manufacturing and power electronics, with increased productivity, reduced production costs, and improved transformer quality, especially in high-frequency applications such as renewable energy systems and electric vehicle charging.

Keywords: Buck-Boost Converter, DC Motor Drive, Mechanical Design, Transformer Winding Machine

Abstrak

Penelitian ini menyajikan desain dan implementasi mesin penggulungan transformator frekuensi tinggi yang digerakkan oleh motor DC dengan konverter Buck-Boost untuk menghasilkan transformator secara tepat dan efisien. Sistem ini mengintegrasikan motor DC yang dikendalikan oleh konverter Buck-Boost, yang mengatur tegangan ke motor, memastikan kinerja yang stabil selama proses penggulungan. Desain mesin penggulungan mencakup platform mekanik yang stabil, mekanisme V-belt untuk transmisi daya, dan sensor optokopler untuk pemantauan jumlah lilitan secara real-time. Konverter Buck-Boost menstabilkan fluktuasi tegangan, memungkinkan operasi motor yang lancar pada berbagai kondisi input, sehingga meningkatkan efisiensi dan keandalan mesin. Uji eksperimen pada rectifier, konverter Buck-Boost, dan motor DC menunjukkan efisiensi tinggi dan kinerja stabil, dengan deviasi minimal antara hasil perhitungan dan eksperimen. Hasil uji menunjukkan bahwa mesin ini dapat melakukan penggulungan yang tepat pada berbagai duty cycle, dengan menghasilkan kecepatan yang optimal dan operasi yang stabil. Dibandingkan dengan mesin penggulungan transformator yang ada yang menggunakan motor induksi atau motor stepper, sistem ini menawarkan kontrol yang lebih baik, kecepatan penggulungan yang lebih cepat, dan adaptabilitas yang lebih tinggi terhadap berbagai kondisi produksi. Mesin yang dikembangkan ini memberikan kontribusi signifikan bagi industri seperti manufaktur transformator dan elektronik daya, dengan peningkatan produktivitas, pengurangan biaya produksi, dan peningkatan kualitas transformator, terutama pada aplikasi frekuensi tinggi seperti sistem energi terbarukan dan pengisian daya kendaraan listrik.

Kata kunci: Konverter Buck-Boost, Penggerak Motor DC, Desain Mekanis, Mesin Penggulung Transformator

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INTRODUCTION

High-frequency transformer winding machines are crucial for ensuring precise and efficient production of electrical transformers, especially in the modern technological era. High-frequency transformers are vital components in power electronic transformers used in various applications, including medium voltage DC distribution, renewable energy, electric vehicle battery charging, and energy storage systems (Cao et al., 2023; Li et al., 2023; Wang et al., 2023). Advancements in electronic control technology combined with power electronics have enabled a more efficient winding process, enhancing transformers' overall performance and reliability.

DC motors have become the primary choice in various applications due to their ability to easily control speed and torque (Kim, 2017; Triyani, 2018). Their wide control range allows for precise adjustments in position and speed by varying armature voltage, making them ideal for such tasks. However, controlling DC motors presents challenges, particularly regarding sudden voltage and current fluctuations, which can disrupt the process. To mitigate these issues, DC/DC power converters like Buck-Boost converters are employed. These converters provide smoother starts, stabilize voltage with minimal current ripple, and are capable of handling a wide input voltage range, making them an excellent choice for DC motor drives. (Antritter et al., 2006; Forouzesh et al., 2017; García-Rodríguez et al., 2018; Hernandez-Marquez et al., 2016; Hossain et al., 2018; Jung et al., 2018; Kurniawan et al., 2020; Pamuji et al., 2024; Veerachary & Khuntia, 2022).

Research on Buck-Boost converters for DC motors has explored various aspects, such as modifying converters to step up low input voltage (Bhuvaneswari et al., 2023), using AC-DC converters with PWM control as motor driver (Ahmed, 2005), and focusing on the application of fuzzy logic controllers to maintain motor speed constant despite load variations, with results showing improved stability and efficiency (Pamuji et al., 2024). Some studies also develop control models based on the state-space average method and frequency approach (Zhou & He, 2014), as well as the use of trajectory tracking and active disturbance rejection approaches to address changes in torque and angular velocity without direct measurement (Jesus Linares-Flores et al., 2006; Jesús Linares-Flores et al., 2012). However, while these studies have successfully improved motor control in various applications, there is limited research examining the efficiency of Buck-Boost converters when applied specifically to transformer winding machines.

The development of automatic transformer winding machines has involved diverse approaches in motor selection and control strategies to enhance winding precision and efficiency. Induction motors have been commonly employed, such as in low-frequency transformer winding machine, which used a single-phase induction motor controlled via a relay and Arduino microcontroller (Mardiansyah et al., 2025). Similar configurations were adopted by Mulik & RajkumarKamble and Nur Rohmat et al., who utilized induction motors with relay-based control systems (Mulik & RajkumarKamble, 2015; Nur Rohmat et al., 2022). While these systems are reliable, they face limitations in dynamic speed regulation due to the on/off nature of relay control. To achieve finer control, stepper motors have been explored in several designs. For example, Irfan et al. and Ahyar & Irdam implemented stepper motors driven by L298N motor drivers with Arduino microcontrollers (Ahyar & Irdam, 2019; Irfan et al., 2021), while Bahar & Fikri advanced this approach by employing an A4988 driver for enhanced precision (Bahar & Fikri, 2023). However, stepper motors often struggle in high-torque applications, where continuous rotation and variable load handling are critical. Alternatively, DC motors have been investigated for their ability to balance controllability and power output, as demonstrated by Hasyim Asy'ari et al. and Aziz et al., who integrated DC motors with relay-based and L298N driver systems, respectively, using ESP8266 microcontrollers (Aziz et al., 2025; Hasyim Asy'ari et al., 2024). Despite these advancements, existing designs still rely on basic control methods (e.g., relays or fixed-voltage drivers like the L298N), which lack adaptive voltage regulation and energy efficiency. This gap in control optimization is addressed in this study through the implementation of an STM32-controlled Buck-Boost converter, which offers dynamic voltage regulation for improved DC motor drive performance.

The objective of this research is to design and implement a high-frequency transformer winding machine that uses a DC motor driven by a Buck-Boost converter. This machine aims to ensure precise and efficient production of electrical transformers by leveraging the DC motor's ease of speed and torque control. The Buck-Boost converter in this study will address fluctuations in current and voltage, facilitating a smoother and more stable winding process and ultimately improving the overall performance and reliability of the transformers.

METHOD

This chapter outlines the methodology used in the design and implementation of a transformer winding machine with a DC motor driven by a Buck-Boost converter. The methods employed in this research are divided into two main sections. First, the design of the transformer winding machine system is explained, with a focus on the implementation of the mechanical structure and the components within it. Second, the integration of the Buck-Boost converter into the DC motor is discussed, including the modeling of the converter circuit design and its role in regulating motor speed for optimal winding performance.

A. Transformer Winding Machine System Design

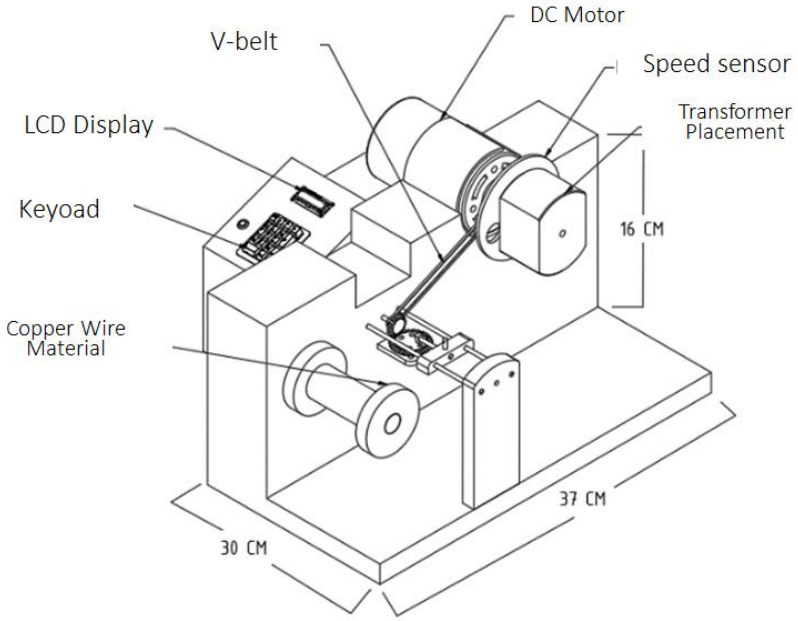


Figure 1. Transformer winding machine design

The design of the Transformer Winding Machine System consists of two main aspects: the mechanical structure of the machine and the electronic control system that drives its operation. In the mechanical layout, as shown in Figure 1, the winding machine is designed to accommodate the transformer core and the copper wire used in the winding process. The machine is built on a stable platform with dimensions of 30 cm x 37 cm, providing ample space for precise operation. A DC motor, securely mounted at the rear, drives the rotation of the transformer using a V-belt mechanism, which is crucial for transferring power from the motor to the winding spindle. The system is also equipped with an optocoupler sensor to ensure real-time monitoring of the winding count to maintain accuracy in the winding process. User interaction is facilitated through an LCD and keypad, allowing the operator to input winding parameters and monitor the operation status.

Figure 2 illustrates the electronic control system for the winding machine, starting from the AC power source converted to DC via a rectifier. The DC power is then regulated by the Buck-Boost converter, which adjusts the voltage supplied to the DC motor, ensuring smooth and controlled winding speed. The control circuit comprises several components, including a microcontroller (STM32), which serves as the central processing unit. This microcontroller communicates with various subsystems such as the LCD & keypad, optocoupler sensors for counting the number of turns, and PWM gate drivers to control the Buck-Boost converter.

In the Buck-Boost converter, the isolation, amplification, and gate driver circuits play critical roles in safely and efficiently controlling the PWM signal. The isolation circuit protects the control circuit from high-voltage disturbances on the power side, ensuring that the PWM signal remains safe and galvanically isolated. The amplification circuit boosts the low PWM signal to drive power components like MOSFETs with adequate voltage and current (Rachwanto et al., 2022). The gate driver then ensures that these switching devices operate quickly and accurately, enabling optimal voltage conversion regulation in the Buck-Boost converter.

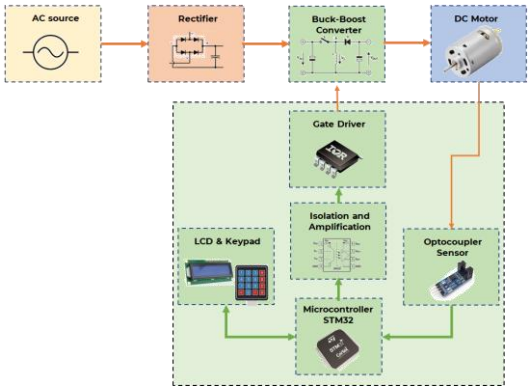


Figure 2. Block diagram electrical system for transformer winding machine

B. Buck-Boost Converter-Based DC Motor Drives

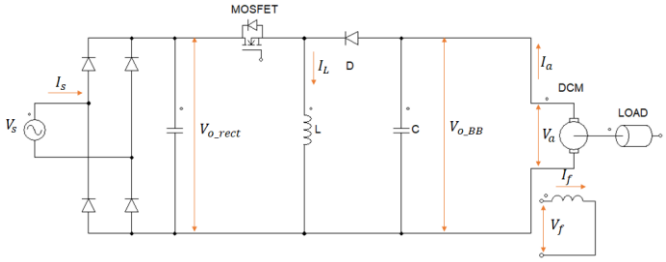


Figure 2. A complete circuit of buck-boost converter-based DC motor drives with an AC voltage source

To perform a steady-state transfer function analysis of the AC source topology, rectifier, Buck-Boost converter, and DC motor that produces speed, each stage can be analyzed step-by-step, and the transfer function of each component can be derived to obtain the overall transfer function that links the DC motor speed to the AC source.

The sinusoidal AC voltage is converted into DC voltage through the rectifier. The rectifier used is a full-wave rectifier for a more stable DC output. The sinusoidal AC voltage at the source is expressed in Eq. (1), while the output voltage equation of the rectifier can be seen in Eq. (2).

$$V_s = V_m \sin(\omega t) \tag{1}$$

$$V_{o_{rect}}(s) = \frac{2V_m}{\pi} \tag{2}$$

The Buck-Boost Converter transforms the DC voltage produced by the rectifier into a DC voltage that can be either higher or lower, depending on the duty cycle. The formula for the output voltage of the Buck-Boost converter, given the input voltage from the rectifier, is shown in Eq. (3). Therefore, the transfer function from the input voltage (V_{o_rect}) to the output voltage (V_{o_BB}) in the Laplace domain can be formulated in Eq. (4), where D represents the duty cycle value (Ahmed, 2005).

$$V_{o_BB}(s) = \frac{D}{1-D} V_{o_rect}(s) \tag{3}$$

$$\frac{V_{o_BB}(s)}{V_{o_rect}(s)} = \frac{D}{1-D} \tag{4}$$

For the DC motor model, the electrical equation can be seen in Eq. (5) and the mechanical equation can be seen in Eq. (6). From Eq. (6), the expression for $I_a(s)$ can be derived as shown in Eq. (7). When Eq. (7) is substituted into Eq. (5), the transfer function of the DC motor is obtained as in Eq. (8). Under steady-state conditions, the transfer function from Eq. (8) becomes as shown in Eq. (9)

$$V_a(s) = (R_a + sL_a) I_a(s) + k_e \omega_m(s) \tag{5}$$

$$K_T I_a(s) = (Js+B) \omega_m(s) \tag{6}$$

$$I_a(s) = \frac{(Js+B)\omega_m(s)}{K_T} \tag{7}$$

$$\frac{\omega_m(s)}{V_a(s)} = \frac{K_T}{L_a J s^2 + (L_a B + R_a J) s + (R_a B + K_e K_T)} \tag{8}$$

$$\frac{\omega_m(s)}{V_a(s)} = \frac{K_T}{R_aB+K_eK_T} \quad (9)$$

The steady-state transfer function of the entire system topology (from AC source to DC via rectifier, then to Buck-Boost converter, and finally to DC motor) can be seen in Eq. (10)

$$\frac{\omega_m(s)}{V_s} = \frac{DK_T}{(R_aB+K_eK_T)(1-D)} \quad (10)$$

The implementation of the electrical system in this work, summarized in Figure 2, is presented in Table 1.

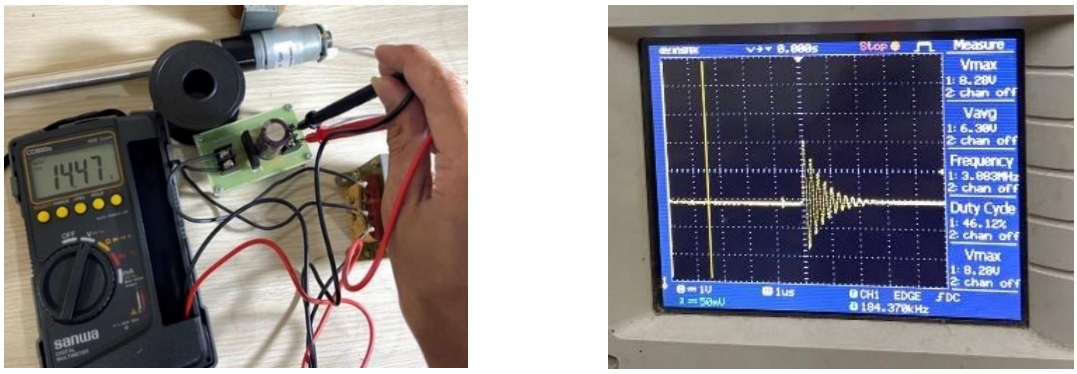
Table 1. Overall detailed parameters of the complete circuit of buck-boost converter-based DC motor drives for transformer winding machine

Components	Type	Value
Rectifier bridge diode	KBL610	-
Rectifier Capacitor	Polarity	500 µF
Buck-boost MOSFET	IRFP150N	-
Buck-boost inductor	-	84 µF
Buck-boost capacitor	Polarity	2.7 µF
Buck-boost diode	MUR1560	-

RESULTS AND DISCUSSION

The design and implementation of the transformer winding machine, driven by a DC motor with a Buck-Boost converter, have undergone a series of comprehensive tests to evaluate its performance. This section discusses the results from both the electrical and mechanical aspects of the system. The results highlight the efficiency and stability of the Buck-Boost converter in managing power delivery to the DC motor, as well as the accuracy and reliability of the winding process.

A. Buck-Boost Converter-Based DC Motor Drives Performance



(a) (b)

Figure 3. Output voltage testing of the rectifier: (a) Measurement with a voltmeter (b) Measurement with an oscilloscope

The Buck-Boost converter plays a crucial role in regulating the voltage supplied to the DC motor that drives the transformer winding machine. This converter is designed to either increase or decrease the input voltage as needed based on the duty cycle input.

Table 2. Results of the rectifier testing

Vac_input (V)	Vo_DC Experiment (V)	Vo_DC Calculation (V)	Error Vo (%)
6	7.21	7.63	5.5
12	14.47	15.27	5.23
15	18.48	19.09	3.19
20	24.56	25.45	3.49

The input voltage to the Buck-Boost converter is obtained from the output of the rectifier. The testing of the rectifier output voltage is shown in Figure 3. (a), while the oscilloscope measures of the voltage are displayed in Figure 3. (b). The overall data from the rectifier testing is presented in Table 2. The table shows that the comparison between calculated and experimental values results in an error range of 3.19% to 5.5%. These error values fall within a relatively acceptable range for most practical applications, indicating that the rectifier is performing within expected tolerances. Specifically, an error percentage of 5.5% at the lower input voltage of 6V may still be considered within a reasonable margin for most systems where precise voltage regulation is not critical. However, as the error decreases at higher input voltages, with values approaching 3.19% at 15V and 3.49% at 20V, the performance of the rectifier and overall system improves, resulting in better alignment between experimental and calculated results. In terms of system performance, these error values suggest that while there is some deviation between the expected and actual output voltages, the overall impact on the performance of the Buck-Boost converter and the transformer winding machine may be minimal. Overall, the errors are manageable, and the system can still operate efficiently with minimal consequences on the performance of the winding machine.

The subsequent testing aimed to obtain functional data for the Buck-Boost converter at each duty cycle. The tests were conducted using a 15W 24V DC motor load. The input voltage for the Buck-Boost converter was 6V, with duty cycles ranging from 10% to 90%. Figure 4 shows the Buck-Boost converter testing process. The output voltage measurements of the Buck-Boost converter are presented in Figure 4. (a), while the oscilloscope readings of the voltage are displayed in Figure 4. (b). The overall data from the Buck-Boost converter testing is presented in Table 3.



(a) (b)

Figure 4. Output voltage testing of the Buck-Boost converter: (a) Measurement with a voltmeter (b) Measurement with an oscilloscope

Table 3. Results of the Buck-Boost converter testing

Duty Cycle (%)	Vin (V)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	Efficiency (%)
10	6	0.005	0.03	-0.264	0.08	0.021	70.4
20	6	0.02	0.12	-0.967	0.11	0.106	88.641
30	6	0.04	0.24	-2.036	0.11	0.223	93.316
40	6	0.08	0.48	-3.473	0.13	0.451	94.060
50	6	0.13	0.78	-5.52	0.13	0.717	92
60	6	0.23	1.38	-8.61	0.15	1.291	93.586
70	6	0.43	2.58	-13.67	0.17	2.32	90.073
80	6	1.09	6.54	-23.32	0.23	5.363	82.012
90	6	3.11	18.66	-36.55	0.4	14.62	78.349

In this testing, increasing the duty cycle resulted in a significant rise in current and input power, while the output voltage remained negative at all duty cycle levels. At low duty cycles (10-40%), efficiency improved

with increasing duty cycle, peaking at 40% with an efficiency of 94.06%. However, at higher duty cycles (50-90%), efficiency tended to decrease, with the lowest value of 78.349% at a 90% duty cycle. Although the output power (Pout) increased with the duty cycle, the decrease in efficiency at higher duty cycles indicates an optimal performance limit for this converter.

In the testing of the Buck-Boost converter, the output voltage showed negative values at each duty cycle variation. However, this does not affect the performance of the transformer winding machine, as the negative voltage merely indicates the direction of motor rotation in the machine. In the context of operating the transformer winding machine, the crucial aspect is the power provided by the converter, not the voltage polarity. Therefore, even though the output voltage is negative, the performance and efficiency of the winding system remain optimal and unaffected.

The final test was the DC motor characterization test on the transformer winding machine, aimed at understanding the relationship between voltage, speed, and current to ensure optimal performance in transformer winding applications. The test setup is shown in Figure 5. By studying how the motor reacts to voltage changes, this test provides valuable insights into the motor's ability to operate at various speeds, which is essential for adjusting winding speed according to the size and type of wire used. In the DC motor characterization test for the transformer winding machine, data showed that the motor speed increased with rising voltage, as presented in Table 4. This data indicates a linear relationship between voltage and motor speed, making it suitable for transformer winding applications that require variable speed and precise control.



Figure 5. Characteristics testing of the DC motor used for the transformer winding machine

Table 4. Results of the DC motor characterization testing

Motor Voltage (V)	Motor Current (A)	Motor Speed (rpm)
5	0.17	47
6	0.2	51
8	0.21	70
10	0.21	89
12	0.22	103
15	0.26	132
24	0.43	214

B. Transformer Winding Machine Performance

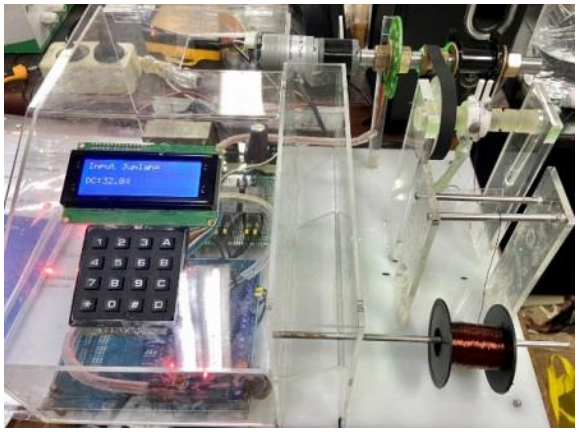


Figure 6. Testing of the transformer winding machine

Table 5. Results of the transformer winding machine testing

Number of Turn Input	Duty cycle (%)	Number of Turn Result	Time duration (s)	Motor voltage (V)	Motor current (A)	Winding speed (rpm)
30	36	30	58	-3.21	0.18	41
60	36	60	116	-3.24	0.17	41
90	36	90	174	-3.25	0.18	41
30	57	30	34	-5.40	0.22	68
60	57	60	70	-5.35	0.21	67
90	57	90	103	-5.41	0.22	68

In the testing of the transformer winding machine using a PQ5050 high-frequency transformer for power electronics as shown in Figure 6, the experimental results presented in Table 5 indicate that the machine is capable of producing precise winding counts according to the set input values, namely 30, 60, and 90 turns, with even winding distribution due to the integrated winding alignment mechanism. When compared to previous research or similar machines, these results demonstrate competitive performance. Some earlier transformer winding machines used induction or stepper motors with simpler controls, but they were often limited in terms of speed control and winding time. In contrast, the machine tested in this study shows the ability to operate stably across various duty cycles and optimize the winding time according to the adjusted voltage and current conditions. At a duty cycle of 36%, the motor speed remained stable at 41 RPM, while at 57% duty cycle, the motor speed increased to 68 RPM, significantly accelerating the winding process.

The contribution of this machine design to the industry, particularly in transformer manufacturing and power electronics applications, is crucial. This machine offers increased efficiency in the transformer winding process, with the ability to produce more accurate and uniform windings. The flexible control system, which adjusts the motor voltage and current, allows this machine to adapt to diverse production needs, providing faster cycle times without compromising quality. As the demand for high-frequency transformers, such as those used in renewable energy and electric vehicles, rises, this machine has great potential to enhance industrial competitiveness, reduce production costs, and improve the reliability and efficiency of transformer products.

CONCLUSIONS

the design and implementation of the high-frequency transformer winding machine with a DC motor driven by a Buck-Boost converter have proven to be highly effective in improving transformer winding precision and efficiency. The integration of the Buck-Boost converter ensures smooth and stable voltage regulation, which enhances the DC motor's performance, enabling more accurate and uniform windings across various duty cycles. The machine's ability to adjust voltage and current dynamically provides significant advantages in terms of

speed control and winding time optimization. The experimental results highlight its competitive performance compared to traditional transformer winding systems, especially in terms of its efficiency, accuracy, and flexibility in adapting to different production requirements. This development offers a substantial contribution to industries involved in transformer manufacturing and power electronics, offering increased productivity, reduced costs, and improved transformer reliability and performance, particularly in emerging applications such as renewable energy and electric vehicles.

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