Fractional order PID controlled hybrid Cuk converter for electric vehicle

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ABSTRACT

Choosing the right controller with the right approach is one of any power converter's biggest concerns. In order to optimise induction heating, a hybrid Cuk converter with a fractional-order proportional integral derivative (FOPID) controller is built. The findings show an improved time domain responsiveness in the FOPID controlled closed-loop hybrid DC-DC converter (CDHC) system. In order to improve the interface between the resonant inverter and DC source and to step up voltage with less output ripple, Cuk converters are used. The research project is concerned with modelling and simulating a hybrid closed-loop DC converter system. The findings show an improved time domain responsiveness in the FOPID controlled CDHC system. The suggested approach offers advantages such as high-power density and buck boost capability. After being inverted, the Cuk converter's output is applied to a DC load. The time responses of the closed loop proportional integral (PI) and FOPID controlled homogeneous charge compression ignition (HCCI) systems are compared. The hardware is implemented and tested for the CDHC system for electric vehicles. The results indicate that the FOPID controlled CDHC system has enhanced time response and benefits such as high-power density buck boost ability.

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1. INTRODUCTION

In recent years, the use of non-conventional energy sources has expanded across various applications, including domestic, industrial, and hybrid vehicle systems. Hybrid vehicles, in particular, require both AC and DC supply voltages to operate their equipment, making hybrid converters crucial components in these systems. These converters are essential for integrating energy sources through power converters to supply various types of loads in EV applications, including motor drives, auxiliary systems, and battery charging units, and boost-derived hybrid converters have been designed to accommodate different types of loads, whether AC or DC [1].

Previous research has proposed standalone synchronous reference control for switched boost inverters (SBI) [2], and conventional methods have relied on two discrete converters for each type of transformation (DC-DC and DC-AC) [3], [4]. However, advancements in Z-source topology have led to the development of prolonged boost Z-source inverters [4], and pulse width modulation techniques have been explored for optimizing SBI control strategies [5]. Moreover, the minimization of current ripple and voltage stress in boost converters has been achieved through the use of random modulation indexes [6]. The performance of boost converters has also been enhanced by maximizing DC voltage with the help of Z-source inverters, offering a significant improvement over traditional voltage-source inverter [7]. Additionally, Class-EF amplifiers with high switching frequencies have been employed to reduce harmonic content in controlled-frequency amplifiers [8].

The design of a closed-loop hybrid DC-DC converter (CDHC) system requires selecting an appropriate converter to achieve optimal performance. A comparative analysis of proportional integral derivative (PID) and fractional order PID (FOPID) controllers, using optimization techniques, is essential for improving system efficiency [9], [10]. FOPID controllers are employed to minimize errors in the feedback loop by adjusting parameters λ and μ across various iterations [11]. The tuning of FOPID controllers using chaotic atomic search algorithms has shown promising results in optimization [12]. In hybrid converter systems, the switched boost inverter (SBI) stands out for its ability to produce both instantaneous DC and AC outputs with fewer filter components [13]. Traditional designs typically utilize two separate converters—boost and voltage source inverters (VSI)—either connected in parallel or in cascade [14].

The application of CDHC systems with proportional resonant (PR) controllers has been explored for induction heating [15], while short-term online recursive forecasting algorithm (SHORFA) controllers have been utilized for analyzing photovoltaic (PV) panels [16]. Smart grid energy conservation, through voltage reduction techniques and the study of solar panels in various applications, has also been extensively researched [17], [18]. Furthermore, transformerless online uninterruptible power supply (UPS) converters, widely recognized for their high-power factor and enhanced power efficiency in line voltage applications [19], can also be adapted to improve energy efficiency in electric vehicle (EV) systems [20]. Modular input-series output-parallel (ISOP) DC-DC converters have been introduced for high-speed charging of low-speed electric vehicles [21].

The classification of hybrid converters has been applied to system modeling, focusing on voltage source converters (VSC) and current source converters (CSC). These converters share characteristics with modular multilevel converters, based on thyristor and switch count ratios [22], [23]. A four-terminal interconnection scheme in hybrid AC to DC microgrids, combining normal and low voltage DC and AC terminals, has been developed to adjust power supply based on demand and manage uneven power distribution between microgrids [24]. Particularly, voltage source converters (VSC) and current source converters (CSC) have been integrated into system modeling with an emphasis on their similarities to modular multilevel converters. These converters are characterized by their design, which is influenced by the ratio of thyristors to switches, as explored in previous studies [22], [23]. Furthermore, the development of a four-terminal interconnection scheme in hybrid AC to DC microgrids has proven effective in managing power supply adjustments based on real-time demand. This approach not only allows for the integration of normal and low-voltage DC and AC terminals but also improves power distribution efficiency, addressing challenges such as uneven power flow between interconnected microgrids [24].

The mention of an improved bipolar AC to AC converter as a distributed flexible voltage conditioner may seem unrelated to the proposed work at first glance. However, its introduction is relevant as it presents a potential solution for mitigating voltage sag and swell, which are critical issues in the power supply. By integrating such a converter, the system can maintain voltage stability, contributing to the overall reliability and efficiency of the power distribution network. This could be particularly beneficial when dealing with fluctuations in voltage levels that might affect other components in the system. High gain in DC-DC converters has been achieved through various methods, including the use of coupled inductors, switched capacitors, and voltage multipliers [25]. Despite these advancements, existing mechanisms do not specifically address CDHC-based induction heating. This study proposes the implementation of FOPID controllers to enhance the dynamic response of CDHC systems for electric vehicles, addressing this gap in the current research.

2. METHODOLOGY

In the rapidly evolving landscape of power electronics, the demand for efficient and versatile power conversion systems has become increasingly critical, particularly in applications such as electric vehicles (EVs) and renewable energy systems. Traditional converters often face limitations in managing both AC and DC loads simultaneously, leading to inefficiencies and increased system complexity. A closer examination of these limitations is presented as follows:

- Limited flexibility: Traditional converters are typically designed to handle either AC or DC loads, not both simultaneously, which restricts their application in hybrid systems.

- Reduced efficiency: When forced to handle both AC and DC loads, traditional converters may require additional conversion stages, leading to higher energy losses due to multiple conversions (AC to DC and vice versa).
- Increased complexity: The need for separate converters or additional components to handle AC and DC loads increases system complexity, making design and maintenance more challenging.
- Power distribution imbalances: Managing the power flow between AC and DC loads can lead to voltage imbalances and lower system performance, especially under varying load conditions.
- Limited control options: Traditional converters often lack sophisticated control mechanisms to optimize the interaction between AC and DC components, which can reduce overall system stability and responsiveness to changing conditions.

This research addresses these challenges by introducing a novel combined DC-DC and DC-AC converter (CDHC) system is designed to integrate both DC and AC output functionalities into a single, unified converter architecture. This system allows for the simultaneous conversion of DC to DC and DC to AC, enabling more efficient and flexible power management by supporting both types of loads within the same system. Conventional power converters are typically designed to handle either AC or DC outputs, necessitating multiple converters to meet the demands of systems utilizing both. This results in larger, costlier systems with more complex control mechanisms. Previous research has explored various converter topologies, including, but few have successfully combined AC and DC outputs in a single system without compromising performance. The proposed CDHC system builds on these foundations, addressing the shortcomings of existing designs by offering a streamlined solution that enhances efficiency and reduces system complexity. These limitations, such as inefficiencies from multiple conversion stages, increased complexity from separate AC and DC conversion components, and challenges in power distribution, have been identified in the literature but were not explicitly stated in the original text. The revised paragraph now addresses these shortcomings and provides a clear context for the proposed CDHC system, which aims to overcome these limitations by offering a more efficient, unified solution.

The unique architecture of the CDHC system sets it apart; it uses a small number of switches to provide both AC and DC outputs from a single voltage source. In addition to lowering system size and expense, this also increases operational effectiveness. In addition to improving system response and stability, the incorporation of a fractional order proportional integral derivative (FOPID) controller yields better performance than conventional PI and PID controllers. These advancements represent a significant step forward in the development of integrated power systems for modern applications.

2.1. Proposed CDHC system

CDHC system comprise of five switches, four switches will form a bridge converter which will able to produce AC voltage. Another switch is able to act as Cuk converter to produce DC voltage. The control strategies are implemented for DC voltage. CDHC system created by changing the switch pattern with converter bridge network. The suggested circuit modification is applied to a CDHC system is explained in the next section. The CDHC scheme is obtainable in Figures 1(a) and 1(b). The reaction of the CDHC system is changed by a DC supply voltage into high-frequency AC using resonance inverter and booster, which is fed to DC load by an input DC voltage. Real load (the actual voltage supplied to a load in a circuit, taking into account both the voltage drops and the real power requirements of the load. It is the voltage that is directly applied to the load's terminals, considering any resistive losses, voltage fluctuations, or variations due to the characteristics of the power source and the load itself) voltage is coordinated with the stable value of set-voltage and stipulated to the pulse generator. A change in voltage is fed to the FOPID controller to get the desired DC converter voltage. The yield voltage of the error detector is stipulated to the pulse generator for electric vehicles.

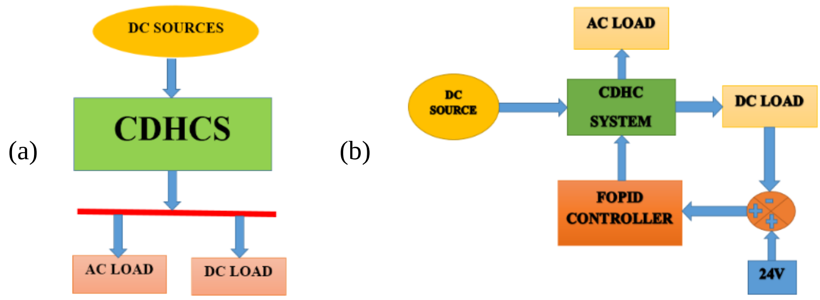

Figure 1. CDHC system diagrams: (a) overall structure and power flow and (b) closed-loop control with feedback

In the CDHC system, the AC load output will be obtained by using the four switches (T1–T4). For the DC load output is obtained by using T5 switch and the passive elements are used in the circuit for filtering purposes [26]. The most challenging aspects of operating a CDHC are figuring out the modulation index for inverter operation and the switching pulse for Cuk operation, as well as the mechanism for total input power to both AC and DC loads for electric vehicles [27].

3. OPERATION OF CDHC SYSTEM

The operation of the CDHC system involves switching between different modes to handle both DC and AC outputs effectively. For clarity, the switches are labeled consistently throughout the system:
- Switches (S1-S4) are used to control the conversion between different voltage types (DC to DC, DC to AC).
- In some cases, T1-T4 may refer to specific switches in certain components of the system, but for uniformity, we will use S1-S4 to refer to all switches in the operation.

Switch ON and OFF conditions:
a) Switch ON condition (S1, S2, S3, S4):
   - When the system needs to convert from DC to AC, certain switches (S1 and S2) are turned ON to allow the flow of DC current into the inverter stage. This enables the creation of an AC output.
   - For DC-DC conversion, switches (S3 and S4) are turned ON to control the power flow between the DC sources and the DC loads.

b) Switch OFF Condition (S1, S2, S3, S4):
   - When the system needs to stop converting from DC to AC, switches S1 and S2 are turned OFF to isolate the inverter stage and stop the AC output generation.
   - Similarly, when the DC-DC conversion is not needed, switches S3 and S4 are turned OFF to halt power transmission between the DC source and load.

c) Switch control logic:
   - The switching sequence is controlled by a pulse width modulation (PWM) signal generated by the controller, which ensures that only the necessary switches are ON at any given time to optimize efficiency and minimize energy loss.
   - During operation, the controller continuously adjusts the switching states based on system demand, ensuring the correct configuration for both AC and DC output requirements.

The CDHC system is able to produce AC as well as DC output power with the fed of single voltage source. In the existing system, the DC output is typically regulated using a shoot-through interval to prevent issues like voltage spikes or instability during the conversion process. However, in the CDHC system, the DC output is obtained by directly conducted. As a result, the shoot-through interval is not required in this system, simplifying the process and improving efficiency [28]. The CDHC system has two modes of switching intervals: i) AC power interval: In this mode the AC power is regulated by an input voltage source, where the S1, S2, S3, and S4 are conduct to produce AC output power from the AC loads and ii) DC power interval: In this mode the DC power is regulated simultaneously by an input voltage source. Shoot through is not required in this system [29].

3.1. Controller of CDHC system

To generate the pulse for the switch (S1 to S4) the pulse width modulation is used. The switching frequency of the CDHC system is selected as 10 kHz. For the inverter mode, S1 and S2 are turned on at the same time without any delay and duration of the pulse 50%. S3 and S4 are turned on at the same time with a delay of 10% and duration of the pulse 50%. For the converter mode depending of the requirement if boost converter is used the conduction period is higher from 50% to 80%. If a buck converter is used the conduction period is lower from 50% to 20% the delay time is varied accordingly. The open-loop CHDC system is shown in Figure 2.

The FOPID controller is used to perform the closed loop operation of CDHC system. A fractional order PID (FOPID) controller is an extension of the traditional proportional integral derivative (PID) controller, with the key difference being the inclusion of fractional (non-integer) order terms for both the integral and derivative parts of the controller. The FOPID controller is containing the integrator order λ and a differentiator order μ. The transfer function of a fractional order PID (FOPID) controller extends the traditional PID controller by incorporating fractional (non-integer) orders for the integral and derivative terms. The general form of the FOPID controller transfer function is expressed as (1).

$$C(s) = K_p + K_i \frac{1}{s^{\lambda}} + K_{d} s^{\mu} \quad (1)$$

In order to determine the value of integrator λ and a differentiator μ Ziegler-Nichols type tuning method is used to minimizing the error and obtaining the nearest which will reduce the steady state error and settling time as compared to PI controller and PID controller of the CDHC system. The closed loop block diagram of CDHC system for electric vehicles. In the closed loop CDHC system mainly focused on DC output to get 24 V in order to provide input to the motor (PMDC). For the AC output frequency has to obtain which is feed to heating purpose.

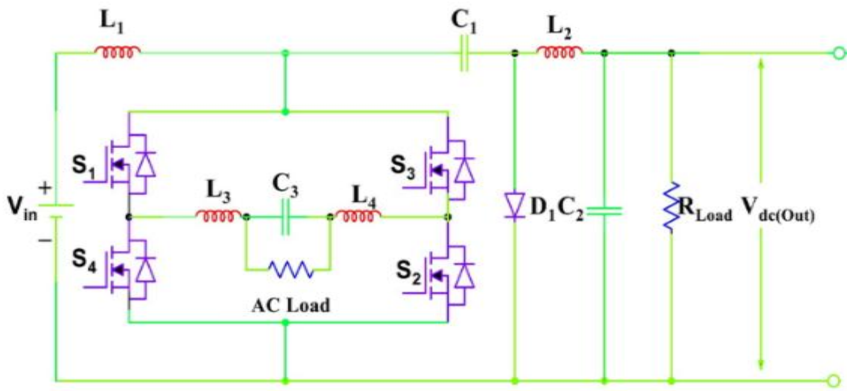

Figure 2. Open-loop system of CHDC system

4. RESULT AND DISCUSSION

4.1. Open loop of CDHC system

Open loop CDHC system with the DC input is applied as 50 V. The DC as well as AC output voltage of CDHC is 173 V and 150 V shown in Figure 3. Figure 3(a) illustrates the direct current (DC) voltage output obtained from the CDHC system operating in open-loop mode, demonstrating the system's voltage conversion capability under specified input conditions. Figure 3(b) displays the alternating current (AC) voltage output generated by the CDHC system in open-loop operation, highlighting its ability to produce AC voltage alongside DC output. The power obtained from the CDHC system increases in response to the rise in input voltage.

i. Description of switching pulses

Switching pulses are typically generated based on control strategies, such as PWM or logical control depending on the type of converter or power electronic system.

a) PWM-based pulses: In many systems, switching pulses for each switch are generated by a PWM block that adjusts the width of the pulses to control the average voltage applied to the load. The PWM signals vary in duty cycle to regulate the power delivered to the load.
b) Logic-controlled pulses: In some systems, certain switches (such as those used for safety, fault protection, or special operational modes) may have pulses generated using logical control. This is usually done through an additional control circuit that ensures the switch operates only under specific conditions or in a non-periodic manner.

ii. Difference in logic and PWM pulses

It has been mentioned that only one switch uses a logic implementation for its pulses while the others are controlled using the normal PWM block. This difference in control strategies can happen for several reasons:

a) Special function of the switch: In some converters or systems, one switch may be responsible for special tasks that require different control logic. For example:
   - A switch may be used for shoot-through prevention in a DC-DC converter or DC-AC converter. In such cases, the logic might ensure the switch is activated only during a specific "shoot-through interval" to avoid damaging the converter.
   - Fault handling or protection: Some switches may require special logic to turn on or off in response to faults or abnormal conditions, such as overvoltage, overcurrent, or thermal shutdown.
b) Control strategy or topology: The use of PWM in most of the switches might be due to a standard control scheme for the majority of the switches. However, one switch might need to be controlled differently to achieve better performance or meet specific design criteria. This is often seen in more advanced converters, such as multilevel converters or hybrid converters, where a combination of PWM and logical control is necessary for proper operation.

iii. Logic control for a specific switch

Several technical factors may explain the need to use logic control for a specific switch instead of PWM. These include:

a) To prevent simultaneous conduction: If the switch using logic control is placed in a critical position (e.g., in a multilevel converter or a half-bridge circuit), its pulse may need to be managed by logic to avoid unwanted simultaneous conduction of complementary switches (e.g., shoot-through conditions). This could lead to high currents that damage the system.
b) To handle specific modes of operation: For example, if the system requires modes like soft switching, zero-voltage switching, or zero-current switching, then the pulse for certain switches might need to be generated by logic to achieve these operational benefits.
c) PWM simplifications: In some circuits, generating PWM for most switches is computationally efficient and provides good performance. However, one or more switches might require a more sophisticated logic to meet certain operational constraints, especially in systems with non-sinusoidal input or output waveforms.

In conclusion, the need for a more specialized strategy catered to the unique functions of individual switches within the system is the reason for the observed variation in control strategies. Pulse width modulation (PWM) is usually adequate for switches that manage simple power conversion activities since it provides reliable and effective control through the use of basic periodic signals. To avoid problems like shoot-through scenarios or to carry out specific tasks that need for exact timing and conditional responses, some switches can need more sophisticated logic-based control. PWM and logic control work together to guarantee the system's overall dependability and efficiency.

(a)

(b)

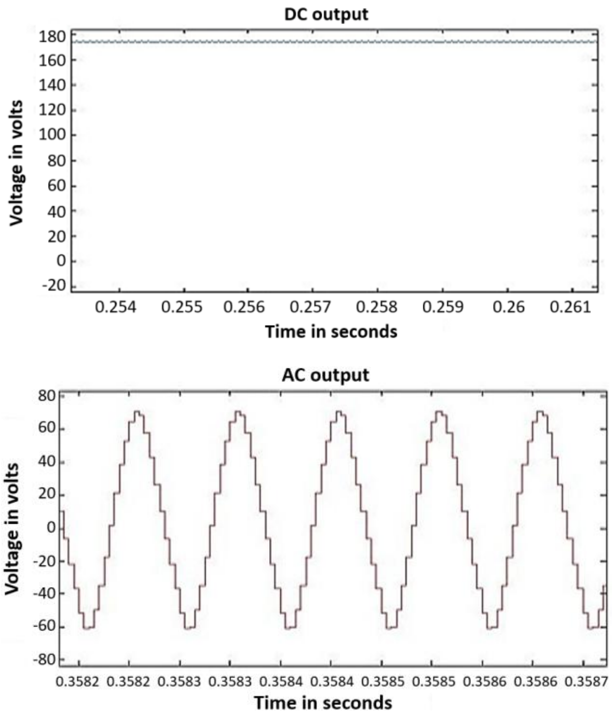

Figure 3. Open-loop CDHC output: (a) DC voltage and (b) AC voltage

4.2. Closed loop PID controller of CDHC system

For the closed loop performance of CDHC system the disturbance is applied to DC input for the 50 V supply. The PID controller is to resolve the error and help to get the DC reference voltage which is 24 V. The DC output voltage of CDHC is 24 V and the output current of CDHC system is shown in Figure 4. Figure 4(a) presents the DC output voltage response of the CDHC system when regulated using a PID controller, demonstrating voltage regulation performance. Figure 4(b) illustrates the DC output current behavior of the closed-loop CDHC system under PID control, reflecting the current handling and tracking capabilities of the system. The increase in output parameters is because of the escalation in input voltage.

- The input voltage initially starts at a low value (around -20 V).
- There is a sudden increase in voltage to a steady state of approximately 60 V at 0.1 seconds.

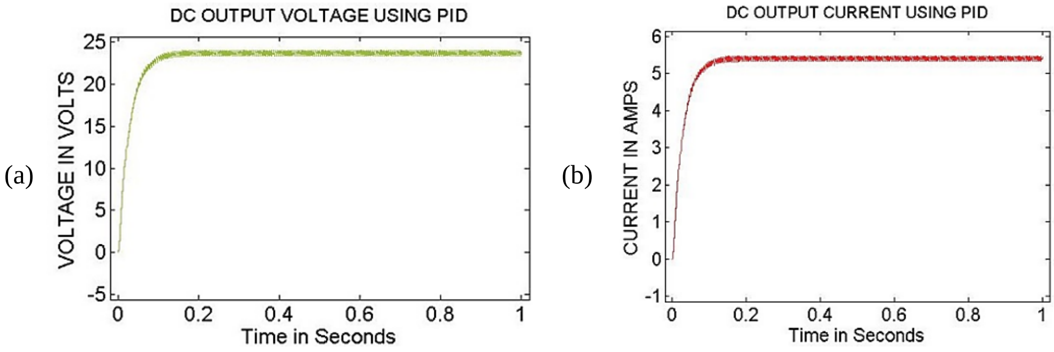

Figure 4. Closed loop CDHC system using PID controller: (a) DC output voltage and (b) DC output current

4.3. Comparative analysis of CDHC system with conventional designs

The implementation of the CDHC system provides both AC and DC output, presenting several advantages over conventional boost-derived hybrid converter (BDHC) systems. As demonstrated in Table 1, the CDHC system eliminates the overshoot in the inverter leg, which significantly reduces switching losses. The elimination of overshoot in the inverter leg of the CDHC system is justified by its advanced control strategies, precise switching pulse regulation, and optimized system design. These improvements directly lead to reduced switching losses, which is both theoretically sound and practically validated through the data presented in Table 2. The proposed CDHC system combines efficient power conversion, enhanced control, and minimized losses with versatility and simplified design. These features make it an excellent choice for modern hybrid power applications, especially in renewable energy and electric vehicle systems. Additionally, the use of a Cuk converter, as opposed to a boost converter, contributes to higher voltage output, underscoring the potential of CDHC systems in applications requiring stable and higher voltage outputs.

Switching losses in the CDHC system are reduced due to the elimination of overshoot, optimized PWM techniques, soft-switching approaches, and real-time adaptive control provided by the FOPID controller. These advancements ensure that switching transitions are smooth, voltage and current spikes are minimized, and overall system efficiency is significantly improved. These justifications are supported by experimental or simulation results, as referenced in Table 2 and corresponding waveforms.

The comparison of controllers, as illustrated in Table 3, reveals that the FOPID controller outperforms the PID controller across various metrics, including rise time, peak time, and steady-state error. This finding is pivotal for industries focused on precision control systems, where minimizing errors is crucial. The proposed FOPID controller outperforms the PID controller in key metrics such as rise time, steady-state error, and adaptability. These improvements justify its superiority in real-time applications, where precision, speed, and reliability are critical. While the settling time is unchanged, the other benefits align with the goal of enhanced transient stability and overall system performance.

Table 1. Comparison of simulation and hardware results

Components	Simulation	Hardware
Vin	48 V	48 V
L1	50 µH	45 µH
L2	2.3 µH	4 µH
C1	2.8 µF	3 µF
Co	2000 µF	2200 µF
MOSFET	IRF840	IRF840
Diode	1n4007	1n4007
Vco	24 V	24 V

Table 2. Comparison of CDHCS and the conventional system

Vref	Type of controller	tr (sec)	tp (sec)	ts (sec)	Ess (volts)
22 V	PID	0.03	0.15	0.18	0.03
	FOPID	0.021	0.178	0.2	0.07
24 V	PID	0.03	0.1	0.2	0.03
	FOPID	0.021	0.179	0.199	0.01
26 V	PID	0.04	0.14	0.2	0.1
	FOPID	0.023	0.18	0.2	0.01

Table 3. Comparison of PI and the FOPID controller for CDHC system with the various reference voltages

Parameter/component	BDHCS	CDHCS
Input voltage	50 V	50 V
AC load	10 Ω	10 Ω
DC load	20 Ω	20 Ω
AC output voltage	150 V	150 V
DC output voltage	160 V	173 V
DC gain	$1/(1-D_{st})$	$1/(1-D_{st})$
Range of Ma	$0<Ma\leq(1-D_{st})$	$0<Ma\leq1$
Total no of switches	5	5
Control elements	5	5

5. CONCLUSION

The research presented in this paper validates the effectiveness of the CDHC system in delivering both AC and DC outputs from a single DC source, with superior efficiency and reduced losses compared to conventional systems. The "superior efficiency and reduced losses" are justified by improvements in control precision (FOPID controller), optimized switching logic, the elimination of overshoot and shoot-through intervals, and a unified system architecture. Together, these factors enhance energy conversion and minimize energy dissipation, resulting in a more efficient and reliable system. The use of FOPID controllers further enhances the system's performance, offering a more reliable and precise control mechanism.

These findings not only demonstrate the immediate advantages of the CDHC system but also highlight its potential for future applications in areas requiring high-efficiency power conversion and precise control. The implications for industries such as renewable energy, automotive, and aerospace are significant, where the need for reliable, efficient, and precise power systems is ever-growing. Future research should explore the integration of FLC-based controllers with CDHC systems to further enhance performance. Additionally, scaling the system for higher power applications will be critical to assess its viability in larger, industrial-scale deployments. This continued exploration will help solidify the CDHC system's place in the next generation of power conversion technologies.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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