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Improved Zeta DC – DC with Hybrid Multilevel Converter Topology for Single –Phase Induction Motor Control

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Abstract

This paper presents an improved Zeta DC-DC converter integrated with a hybrid multilevel converter topology for efficient single-phase induction motor (SPIM) control. The proposed system aims to enhance power quality, reduce total harmonic distortion (THD), and improve the dynamic performance of the motor drive. The improved Zeta converter provides a stable and regulated DC link voltage with reduced ripple, ensuring efficient power conversion and better motor control. The hybrid multilevel inverter configuration minimizes switching losses and enhances output voltage quality by generating stepped waveforms with lower harmonic content. This combination enables smooth speed control and high efficiency operation of the SPIM, making it suitable for low-power industrial and residential applications. Simulation results validate the effectiveness of the proposal topology in terms of the reduced harmonics, improved voltage regulation, and enhanced motor performance compared to conventional converter-inverter topologies.

Keywords: Inverter, single-phase, induction motor, zeta converter

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Introduction

The demand for efficient and reliable control of single-phase induction motors (IM) has encouraged innovations in power electronics. Induction motors are widely utilized in domestic, agricultural and industrial applications due to their cost-effectiveness and performance quality in power supply and control strategies [1]. The efficient control of single-phase induction motors (IM) is a crucial area in power electronics research due to the motors widespread use in various applications, such as household appliances, agricultural tools, renewable energy systems, electric vehicles in transportation and industrial equipment [2, 3]. The reliability and efficiency of IM operations strongly depend on the quality of the power supply and the control mechanisms employed [4]. In this regard, DC-DC converters and hybrid multilevel inverters have become vital elements for enhancing energy efficiency, minimizing losses, and enabling high-performance motor control [5]. Hybrid multilevel inverters and DC-DC converters offers favorable avenues to improve the efficiency of motor control [6].

Unlike traditional inverters, multilevel inverters achieve smoother voltage steps, which are crucial for driving induction motors efficiently [7, 8]. Research by [9] highlights the effectiveness of multilevel inverters in reducing total harmonic distortion (THD) and ensuring precise control of output voltage and power flow which enhances motor performance. Improvements in control algorithms for hybrid inverters have played key role in enhancing their overall performance. As a result, hybrid inverters now offer greater efficiency, stability and reliability, making them highly suitable for applications such as motor control, renewable energy systems, and industrial power electronics [10]. The hybrid multilevel inverter, on the other hand generates quality output voltage with reduced harmonic distortion which improves motor performance [11, 12]. Among various converter topologies, the Zeta converter has gained significant attention for its ability to perform both step-up and step-down operations with continuous input current, reduced component stress [13, 14] and making it suitable for single-phase applications [15]. The Studies by some researchers [16, 17] highlighted the effectiveness of Zeta converters in renewable energy and motor drive applications, where stable voltage regulation is necessary.

Furthermore, the Zeta topology's ability to minimize input ripple makes it ideal for applications requiring high power quality, as noted by some scholars [18, 19]. In motor control applications, Zeta converters offer the advantage of isolating the input from the output, thereby enhancing system reliability and also have the capability in achieving high power conversion efficiency for single-phase systems [20, 21]. The Zeta converter and hybrid multilevel inverter have been extensively studied independently but their combined use in single-phase induction motor control remains a relatively unexplored area. Their integrated systems promise to leverage the Zeta converter's voltage regulation capabilities and the hybrid inverter's harmonic reduction benefits [9]. The combined effect between these components can address challenges such as electromagnetic interference, power losses, and reduced motor torque. Recent research by Aravind *et al.* proposes combining DC-DC converters with multilevel inverters for enhanced renewable energy systems, though application in motor control was not extensively studied [22]. Other works done by some researchers [23, 24] demonstrated the potential of hybrid power electronics systems in improving system efficiency and power quality. In addition, the computational approaches for optimizing hybrid power electronics systems are detailed by Mohd *et al.* [25] while highlighting the importance of effective control strategies for achieving system stability and efficiency. In this work, the simulation and modeling of Zeta DC-DC Converter combined with a Hybrid Multilevel Inverter are necessary for enhancing the performance of single-phase induction motor control. MATLAB/Simulink is used to develop detailed models that represent the dynamic behavior of the Zeta converter's voltage regulation and the hybrid inverter's harmonic reduction abilities [26 -27]. These simulations evaluate system responses such as Total Harmonic Distortion, developed motor torque and motor stability under varying load torque conditions and the block diagram is depicted in Fig. 1. By integrating real-time control algorithms and power electronic components in MATLAB/Simulink, the system's effectiveness can be optimized, ensuring reliable motor control for industrial and renewable energy applications.

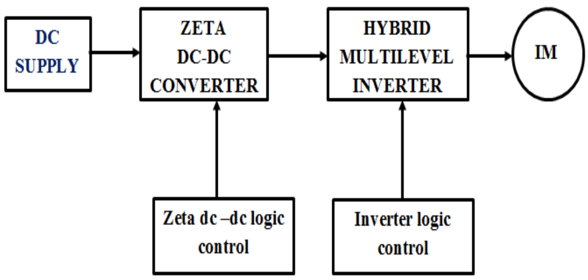

Figure 1: Block diagram of improved zeta topology with hybrid multilevel inverter

The paper is organized as follows: Section II describes the materials and methods used for modeling. Section III presents results and discussion based on motor speed, voltage regulation and total harmonic distortion of the proposed system. Finally, Section IV summarizes this paper conclusion.

Materials and Methods

This research work used the following materials: DC voltage supply, dc – dc converter, Hybrid multilevel inverter, single-phase induction motor, MATLAB software and adopted the method of circuit analysis and pulse width modulation schemes as shown in the subsections of the work.

Improved zeta dc – dc converter

Figure 2 depicts the circuit diagram of the proposed Zeta-based SC dc-dc Converter by [28] (Vosoughi *et al.*, 2019): The topology contains one (1) dc voltage source, two (2) magnetic inductors, five (5) capacitors, nine (9) bidirectional power electronic switches and one (1) high frequency diode. The circuit modes of operation are well detailed by [28], also, the voltage conversion ratio is given by equation (1)

$$G = \frac{V_o}{V_S} = \frac{D}{1-D}(1+(n-1)D) \qquad (1)$$

Where, n is the number of coupling capacitors and D is the duty cycle. The voltage gain depends on the aforementioned parameters.

The coupling inductors L_{z1} and L_{z2} can be designed respectively using equations (2) and (3) as depicted by

$$L_{z1} = \frac{DV_s}{f_s \Delta i_{Lz1}} \qquad (2)$$

Where fs is the switching frequency and Δi_{Lz1} is the change in input inductor current

$$L_{z2} = \frac{D+(n-2)D^2-(n-1)D^3}{(1-D)f_s \Delta i_{Lz2}} V_s \qquad (3)$$

and Δi_{Lz2} is the change in output inductor current. The coupling capacitors can be designed using equation (4) as

$$C_{zn} = \frac{D^2+(n-1)D^3}{(1-D)f_s \Delta V_{Czn} R_{Load}} \qquad (4)$$

Where ΔV_{Czn} is the change in capacitor voltage and R_{load} is the load resistance. Also, the size of output capacitor, C_z can be computed by equation (5)

$$C_z = \frac{D+(n-2)D^2-(n-1)D^3}{8(1-D){f_s}^2 \Delta V_{Cz} L_{z2}} V_s \qquad (5)$$

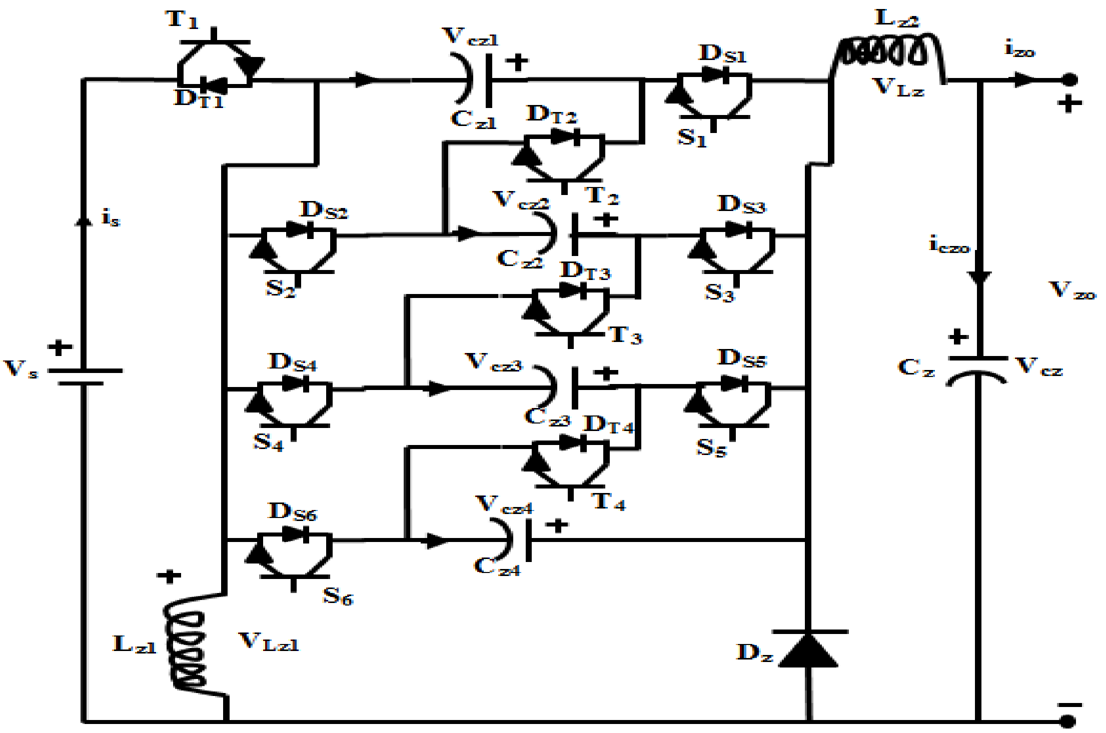

Figure 2: An improved zeta dc – dc converter

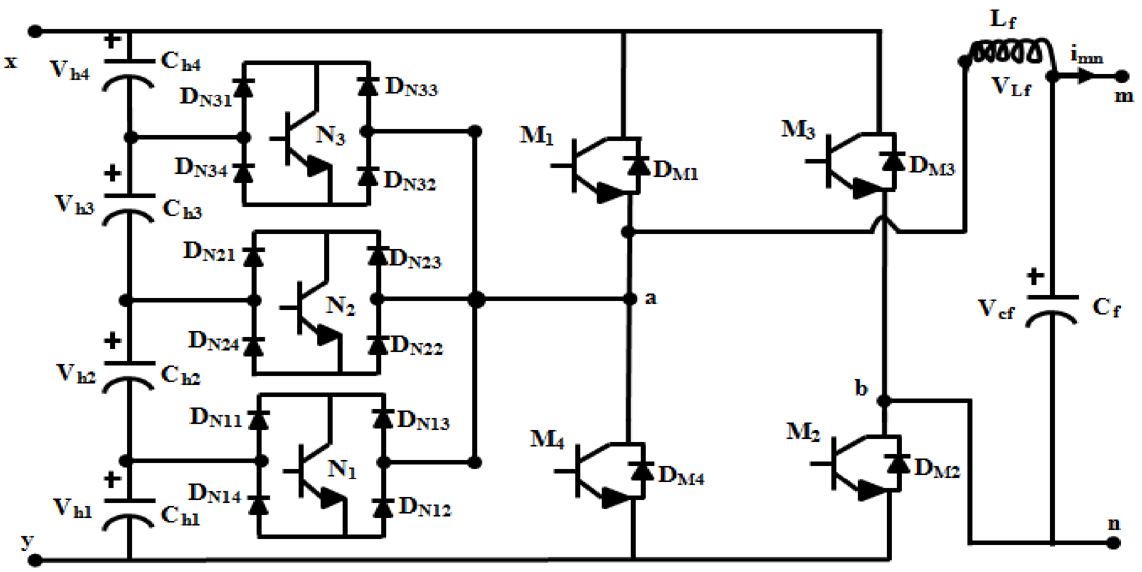

Figure 3: Single-phase hybrid multilevel inverter topology

Hybrid multilevel inverter

Figure 3 shows the power inverter topology based on hybrid multilevel configuration. The circuit contains a convectional H-bridge inverter which contains four diode clamped power switches (M_1 – M_4) and three bidirectional switches (N_1 – N_3) which is modified as proposed by [29]. The output zeta voltage is fed to the inverter circuit, where the supply voltage is divided equally among the coupling capacitors. Capacitors blocking voltage is one fourth of the inverter input voltage, V_{xy}.

$$V_{xy} = \frac{DV_S}{1-D}(1+(n-1)D) = V_o \qquad (6)$$

The power circuit contains output inductive-capacitive (L_f – C_f) filter components. The output voltage switching pattern is as depicted in Table 1 which shows ten (10) different modes of operation. The inverter output voltage is fed to single phase induction motor [30].

Table 1: Output voltage switching pattern for the power inverter

Mode	M_1	M_2	M_3	M_4	N_1	N_2	N_3	V_a	V_b	V_{ab}
1	1	1	0	0	0	0	0	V_{xy}	0	V_{xy}
2	0	1	0	0	1	0	0	$\frac{3V_{xy}}{4}$	0	$\frac{3V_{xy}}{4}$
3	0	1	0	0	0	1	0	$\frac{V_{xy}}{2}$	0	$\frac{V_{xy}}{2}$
4	0	1	0	0	0	0	1	$\frac{V_{xy}}{4}$	0	$\frac{V_{xy}}{4}$
5	0	1	0	1	0	0	0	0	0	0
6	1	0	1	0	0	0	0	V_{xy}	V_{xy}	0
7	0	0	1	0	0	0	1	$\frac{3V_{xy}}{4}$	V_{xy}	$\frac{-V_{xy}}{4}$
8	0	0	1	0	0	1	0	$\frac{V_{xy}}{2}$	V_{xy}	$\frac{-V_{xy}}{2}$
9	0	0	1	0	1	0	0	$\frac{V_{xy}}{4}$	V_{xy}	$\frac{-3V_{xy}}{4}$
10	0	0	1	1	0	0	0	0	V_{xy}	$-V_{xy}$

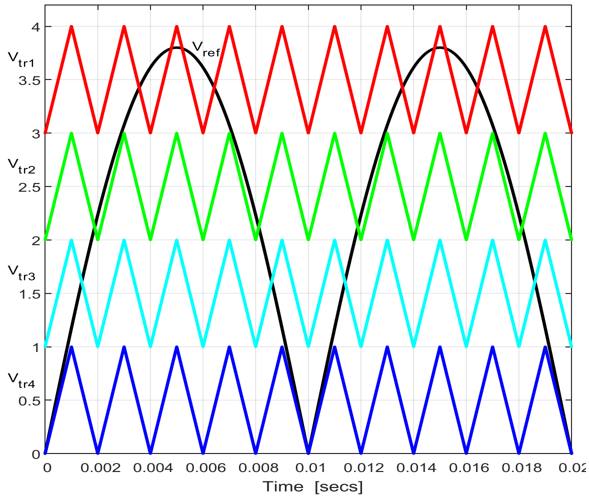

Figure 6: Carriers and reference signals for hybrid multilevel inverter

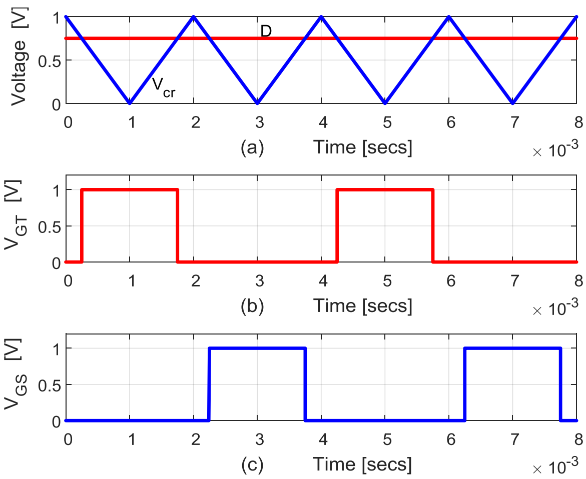

Figure 5: Firing signals for zeta power switches

Logic control for power switches

The gating signal for the Zeta power circuit is generated by comparing a high frequency triangular carrier waveform (V_{cr}) with a variable dc voltage (D) as depicted in Fig. 5(a). Their respective power switches are controlled by Fig. 5(a & b).

In Fig. 6, a rectified sine wave (V_{ref}) is compared with four (4) high frequency triangular carrier signals, V_{tri1}, V_{tri2}, V_{tri3} and $V_{tri4}$to generate the power inverter switches firing signals as shown in Fig. 7. The carrier signals are in phase disposition and each biased at a value of 1 V. The signals are developed using comparators and logic function such as OR and AND-gates.

$$A = Msin(2\pi ft) \quad (12)$$

$$V_{ref} = abs(A) \quad (13)$$

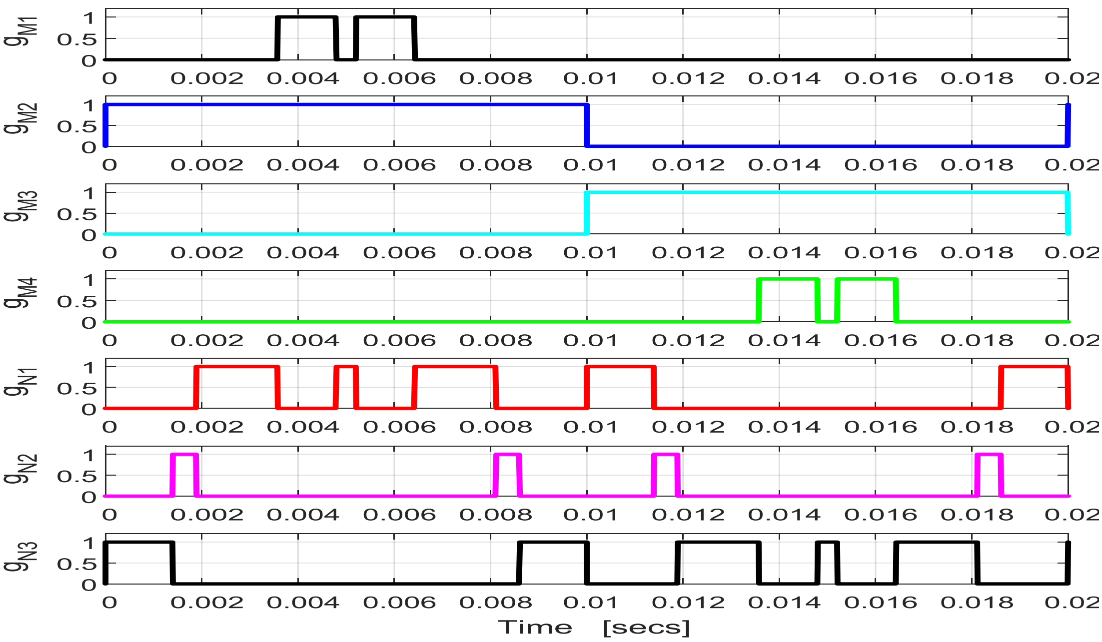

Figure 7: Firing pulses for hybrid multilevel inverter

$$\left.\begin{array}{c} if(A>0);\ g_{M2}: ON\ else\ OFF \\ if(A<0);\ g_{M3}: ON\ else\ OFF \\ if(\{V_{ref}>V_{tri1} AND\ g_{M2}\} OR \{V_{tri4}>V_{ref} AND\ g_{M3}\});\ g_{M1}: ON\ else\ OFF \\ if(\{V_{ref}>V_{tri1} AND\ g_{M3}\} OR \{V_{tri4}>V_{ref} AND\ g_{M2}\});\ g_{M4}: ON\ else\ OFF \\ if\begin{pmatrix}\{V_{ref}>V_{tri2} AND V_{ref}<V_{tri1} AND\ g_{M3}\} OR \\ \{V_{ref}>V_{tri4} AND V_{ref}<V_{tri3} AND\ g_{M2}\}\end{pmatrix};\ g_{N1}: ON\ else\ OFF \\ if\begin{pmatrix}\{V_{ref}>V_{tri3} AND V_{ref}<V_{tri2} AND\ g_{M3}\} OR \\ \{V_{ref}>V_{tri3} AND V_{ref}<V_{tri2} AND\ g_{M2}\}\end{pmatrix};\ g_{N2}: ON\ else\ OFF \\ if\begin{pmatrix}\{V_{ref}>V_{tri2} AND V_{ref}<V_{tri1} AND\ g_{M2}\} OR \\ \{V_{ref}>V_{tri4} AND V_{ref}<V_{tri3} AND\ g_{M3}\}\end{pmatrix};\ g_{N3}: ON\ else\ OFF \end{array}\right\} \quad (14)$$

Simulation Results and Discussion

In order to verify the effectiveness of the proposed induction motor drive system, MATLAB/Simulink simulation tests have been performed on the proposed dc-dc converter and hybrid inverter topologies based on the adopted control technique as depicted in Figs 5 and 6. At the load torque of 2 Nm, under variable duty cycles, Fig. 8 shows the output dc voltages of the converter at various duty cycles. The Figure depicts that increase in duty ratio increases the output dc voltage. Fig. 9 depicts inverter ac output voltages with respect to variation in duty cycles. The performance parameter of the induction motor depends on motor speed and developed electromagnetic torque as displayed in Figs 10 and 11, respectively. At 0.65 duty ratio, the motor speed delayed about 0.8 s before attaining a steady state of 1400 rpm as shown in Fig. 10. Also, at duty cycle of 0.75 the steady state of the motor is attained after 0.14 s with little fluctuations while at 0.85 duty ratio, the settling time is achieved within 0.1 s with high-speed variation. The developed electromagnetic torques are displayed in Fig. 11, a maximum torque of 12.5 Nm is obtained at 0.38 s under 0.65 duty cycle as depicted in Fig. 11(a), while a maximum torque of 65 Nm occurred at 0.1 s for 0.75 duty ratio as depicted in Fig. 11(b), and at 0.85 duty cycle as shown in Fig. 11 (c), the motor experiences high torque fluctuation which may cause mechanical vibration and noise. Fig. 12 displays the speed – torque waveforms under different duty ratio. At 0.85 duty ratio, the maximum torque of 130 Nm occurred at a speed of 1185 rpm and run at 1500 rpm at 2 Nm torque load. Also, at 0.75 duty ratio, the maximum torque of 65 Nm occurred at a speed of 1200 rpm and run at 1500 rpm at 2 Nm torque load. At 0.65 duty ratio, the maximum torque of 12.5 Nm occurred at a speed of 1100 rpm and run at 1400 rpm at 2 Nm torque load. Under this load torque condition, the voltage THD against load torque is plotted as depicted in Fig. 13.

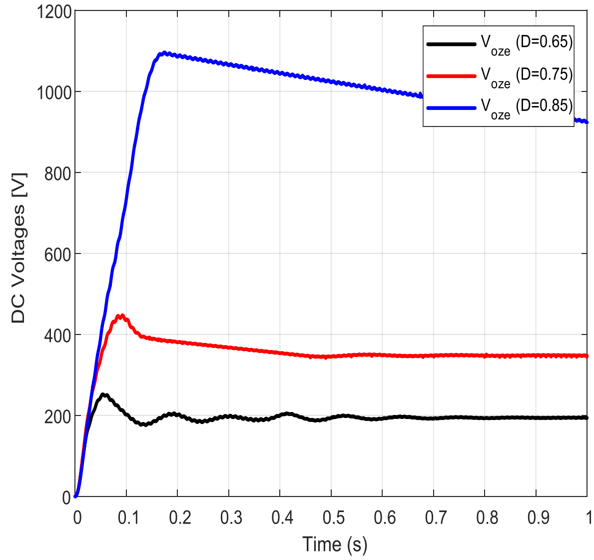

Figure 8: DC output voltages at different values of duty cycle

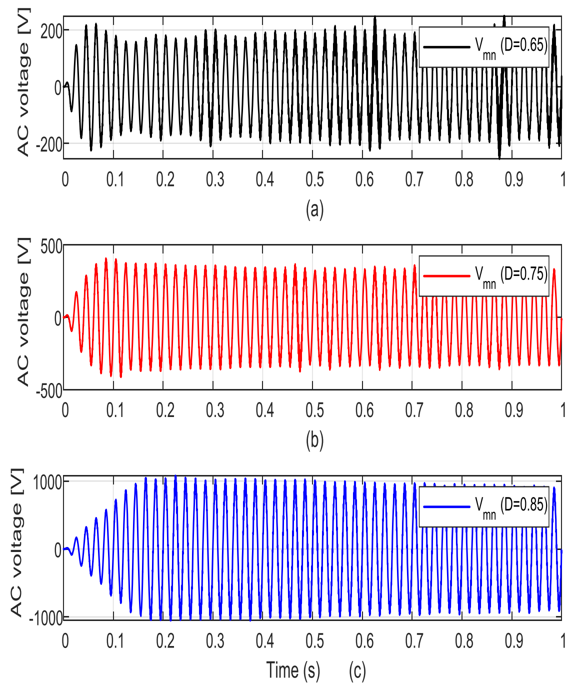

Figure 9: Inverter output voltages (a) at 0.65 (b) at 0.75 (c) at 0.85 duty ratios

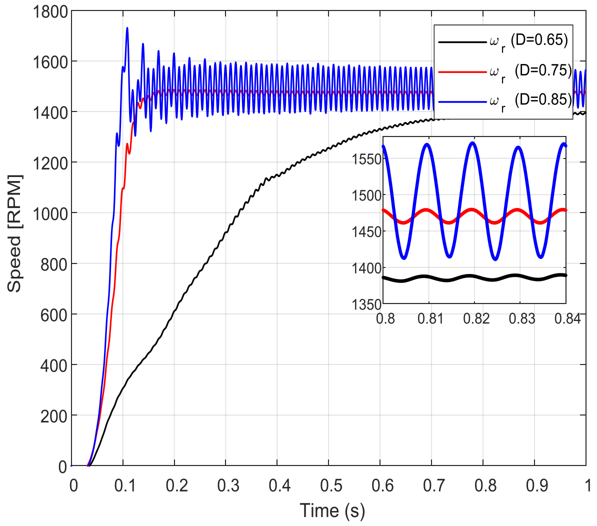

Figure 10: The machine rotor speed waveform

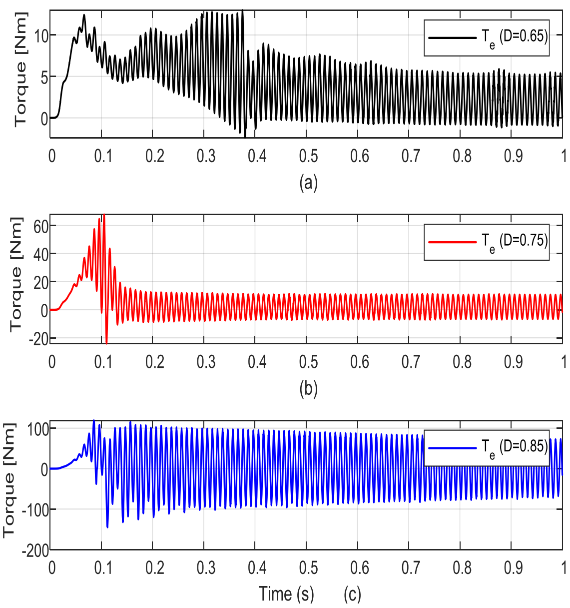

Figure 11: The machine developed torque

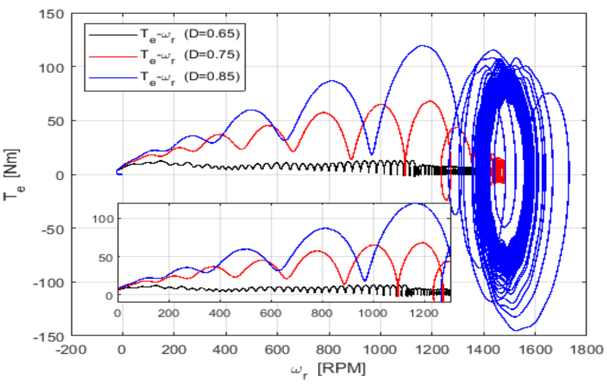

Figure 12: Motor torque – speed plot at different duty ratios

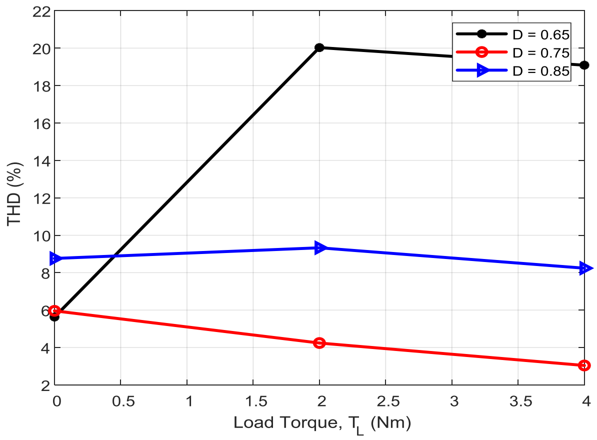

Figure 13: Total harmonic distortion plot against load torque

Table 2 System parameters

Parameters	Value
DC source voltage, V_s	36 V
Inductance, L_{z1}	400 µH
Inductance, L_{z2}	4 mH
Capacitances, C_{z1}, C_{z2}, C_{z3} and C_{z4}	9.8 µF
Capacitance, C_z	10 µF
Capacitances, C_{h1}, C_{h2}, C_{h3} and C_{h4}	47000 µF
Filter inductance, L_f	4.06 µH
Filter capacitance, C_f	6.23 µF
Capacitor start induction motor, Power, freq., Volt.	0.25 Hp, 50 Hz, 220 V
Load torque, T_L	0 Nm, 2 Nm, 4 Nm
Amplitude modulation Index, M_a	0.95
Frequency modulation Index, M_f	200
Inverter and DC converter switching frequencies	3 kHz and 10 kHz

The total harmonic distortion (THD) versus load torque is presented in Fig. 13, these plots provide valuable insights into the harmonic behaviour of an induction machine based on the variation of duty cycle. While THD value is high at low loads due to magnetizing current dominance as observed at duty cycle of 0.75, it typically reduces at moderate load of 2 Nm. At 4 Nm load torque, saturation effects can again influence the harmonics. This study helps in designing efficient and reliable inverter fed induction machine system. The system parameters are presented in Table 2.

Conclusion

The proposed Improved Zeta D-DC Converter with hybrid multilevel converter (HMC) Topology presents a highly efficient effective solution for single-phase induction motor (SPIM) control. By integrating the Zeta converter with a multilevel inverter, the system achieves enhanced voltage regulation, reduced harmonic distortion, and improved dynamic performance of the motor. Furthermore, the proposed system proves to be a superior topology for single-phase induction drives, offering a balance between power quality, efficiency, and motor performance while addressing the challenges of conventional converter-inverter combination. Future work could explore further optimization of switching strategies and integration with renewable energy sources for sustainable motor control applications.

Conflict of interest: 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.

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