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ORIGINAL RESEARCH
PAPER



Hybrid bidirectional multilevel inverter structures for induction motor drive

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ABSTRACT

Multilevel inverters performance enhancement is a major topic, which has attracted the attention of most of the researchers, to evolve with newer topologies and modulation strategies. In this manuscript, two novel hybrid bidirectional multilevel inverter structures, which are suitable for bidirectional loads, are proposed. An enhancement in the voltage levels and reduction of the component count are achieved for these newly introduced structures. Modular expansion and series cascading are suggested systems for extension of the voltage levels. The prime requirement in most of the industrial drives is a controlled output. VSI fed induction motor drive satisfies this requirement. The Multi-carrier PWM technique has been applied to the basic bidirectional seven level models and nine level model and its performance with induction motor as load has been analyzed for various modulation indices. The simulated results of the proposed structures are verified using MATLAB/SIMULINK platform. The characteristics such as stator current, rotor current speed and torque plots achieved as above model affirm that its performance is good. By then, the tracking time of the proposed work during reference speed change, load change and constant reference change is 0.185, 1.094 and 1.5 s. The tracking time of the VSI during reference speed change, load change and constant reference change is 0.5 s, 3.8 and 3.5 s. The tracking time of the MLI during reference speed change, load change and constant reference change is 0.2 s, 1.8 and 2 s.

KEYWORDS

hybrid bidirectional multilevel inverter, cascading, modular expansion, phase disposition multicarrier pulse width modulation (PDMPWM), total harmonic distortion (THD), induction motor drive

1. INTRODUCTION

The future era of power electronics is focused on energy conservation so as to attain a pollution free environment by adopting energy efficient power modulators for power conversion. Multilevel inverters have become an integral component of the power electronic system. Multilevel inverter has been used in a variety of applications which include high speed adjustable drives, FACTS devices for reactive power compensation, battery powered vehicles and for grid integration [1–8]. FACTS devices means power electronic components used for Flexible AC transmission. Because of its ever increasing applications, the performance improvement of multilevel inverter had been most essential criterion and it attracted many researchers towards introducing newer topologies and control techniques [9–11].

In conventional inverters losses and the output voltage harmonic content were found to be too high so multilevel inverter has emerged as an alternative to address this issue and also to attain high voltage levels. The role of MLI is to synthesize a stepped waveform output voltage with better quality and lesser THD. As the number of stages maximizes, the harmonic content decreases significantly in output voltage step waveform [12].

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The three major classical topologies of MLI are clamped diode [13, 14], flying capacitor [15, 16], and cascade type [17, 18]. The requirement of a large number of diodes at neutral point and neutral point voltage balance problems are the drawbacks and in flying capacitor the need of many storage capacitors and capacitor voltage balancing issue were the demerits. In case of cascaded H-bridge, the requirement of many isolated sources has been a major drawback. In spite of its disadvantage it is more widely used owing to its modularity and its structure is devoid of passive energy storing devices.

Increased switch count and its related gate driver circuits and protection circuit were the main disadvantages of multilevel inverters. To overcome these issues many researchers have suggested newer topologies with innovative ideas [19–22]. Many derived structures like artificial neutral point clamped derived from NPC converter and packed U cell converter derived from FC with component reduction have been introduced [23].

Several hybrid topologies which combine two topologies have emerged. Cascaded multilevel inverter with sub multilevel inverters and modular multilevel converter were among the emerging structures which have been recently introduced [24]. Hybrid inverters mainly consist of two sub-circuits. One basic circuit generates the required positive levels and the other circuit functions as a polarity reversal circuit which is an H-bridge circuit [25–29].

A space-vector-modulated pulse width-modulation (PWM) scheme has been suggested for the power circuit topology proposed. With this PWM scheme, a total of 64 space-vector combinations are possible, distributed over 19 space-vector locations. A further improvisation is suggested, in which two two-level inverters with unequal dc-link voltages (which are in the ratio 2:1), feed an open-end winding induction motor. It has been shown that this configuration is capable of achieving four-level inversion. The total number of space-vector locations produced in this scheme is enhanced to 37. A reduction in the switching ripple is achieved with this scheme, compared to the former, as the number of constituent sectors is enhanced to 54,

compared to 24 with the former. Mohammad Rezaei et al., [30] have illustrated a new cascaded switched-capacitor multilevel inverters (CSCMLIs) using two modules containing asymmetric DC sources to generate 13 levels. Dyanamina and Kakodia [31] have performed to improve the speed response; a compensating voltage component is supplemented by an amending integrator.

The rest of the paper is organized as follows: Section 2 shows the operation of the basic topology. Section 3

Table 1. Switching sequence of basic 7L BMLI

S1	S2	S3	S4	S5	S6/S7	S8	Load Voltage $V_{AB}(t)$
1	1	0	0	0	0	0	0
1	0	1	0	1	0	0	vdc
1	0	1	0	0	1	0	2Vdc
1	0	1	0	0	0	1	3Vdc
0	0	1	1	0	0	0	0
0	1	0	1	1	0	0	-Vdc
0	1	0	1	0	1	0	-2Vdc
0	1	0	1	0	0	1	-3Vdc

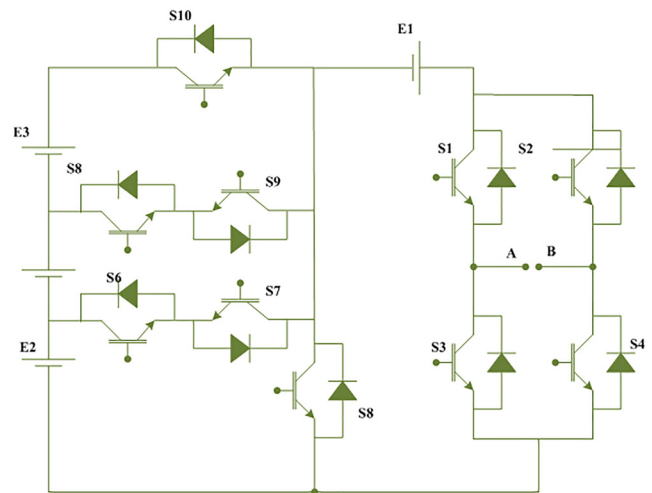


Fig. 2. Nine level bidirectional MLI

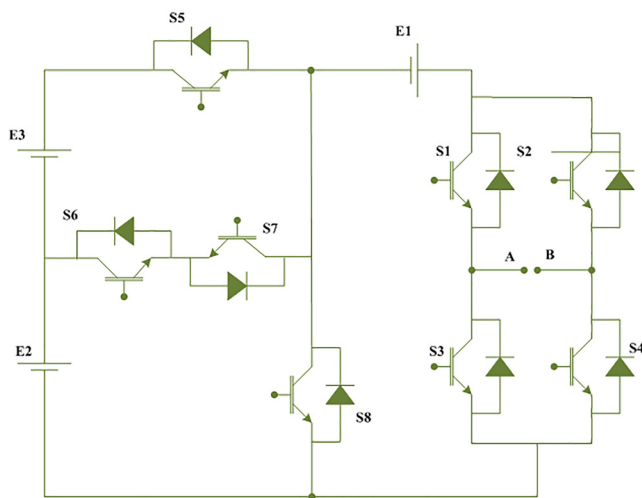


Fig. 1. Seven Level bidirectional MLI

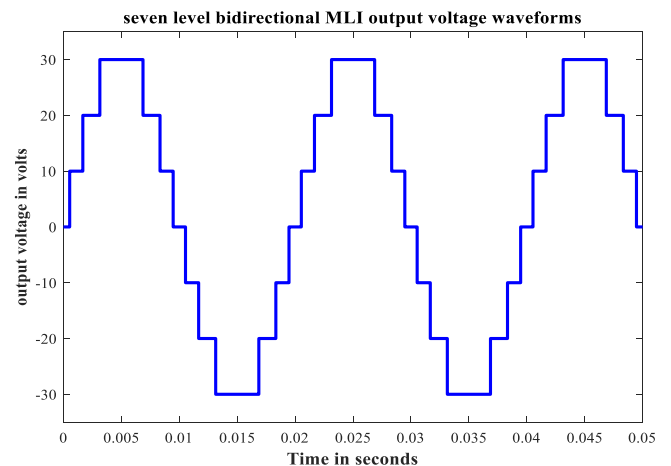


Fig. 3. Output voltage waveform of 7L BMLI



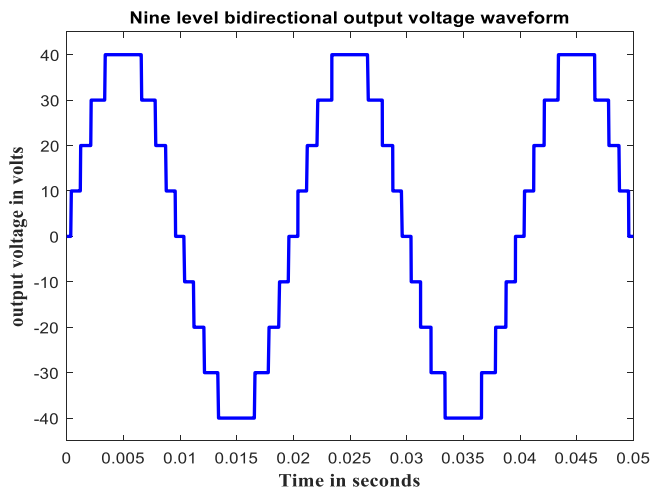


Fig. 4. Output voltage waveform of 9L BMLI

Table 2. Modular expansion method

S. No	No of unidirectional switches	No of bidirectional switches	No of levels (N) $V_0 = 2 * M + 1$	No of Sources (M)
1	6	1	7	3
2	6	2	9	4
3	6	3	11	5
4	6	4	13	6

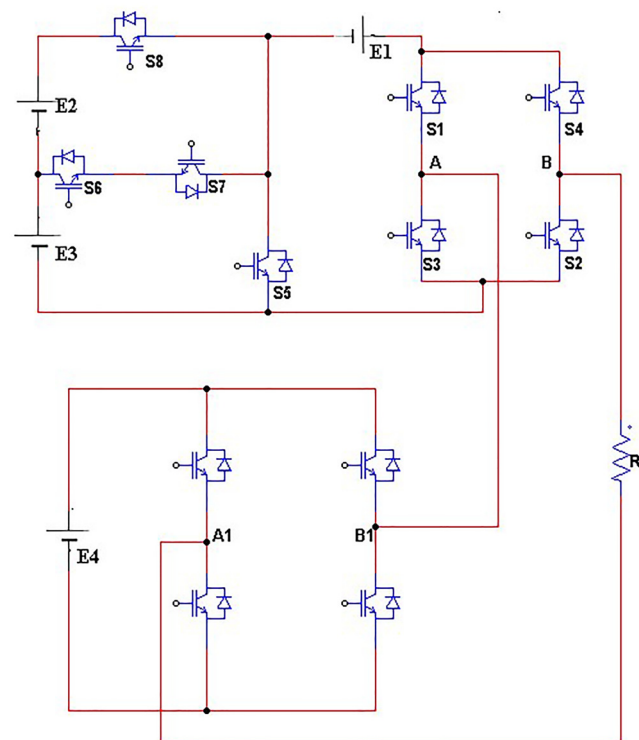


Fig. 5. Proposed hybrid structure 1 (7L basic unit cascaded with H-bridge circuit)

describes the simulation and experimental results and analysis for the hybrid structures. Section 4 provides the conclusion of the research paper.

2. OPERATION OF THE BASIC TOPOLOGY

The basic unit which is a seven level bidirectional MLI model as referred by Samsami et al is demonstrated [9, 32–35] in Fig. 1.

This structure is capable of supplying inductive loads with bidirectional current. The basic circuit comprises of seven IGBT switches. Out of these six switches are unidirectional and one switch is bidirectional. The operation of this circuit is described by a switching table as indicated in Table 1 for symmetrical voltage selection. When S5 is on and S6/S7 and S8 are off it produces level 1 with E1 as output voltage. When S6 is on and S5 and S8 are off then it produces E1 + E2 as output voltage. When S8 is on and S5 and S6/S7 are off it produces E1 + E2 + E3 as the output voltage [36–40]. An output voltage waveform for seven level circuits is shown in Fig. 1. With asymmetrical voltage selection by

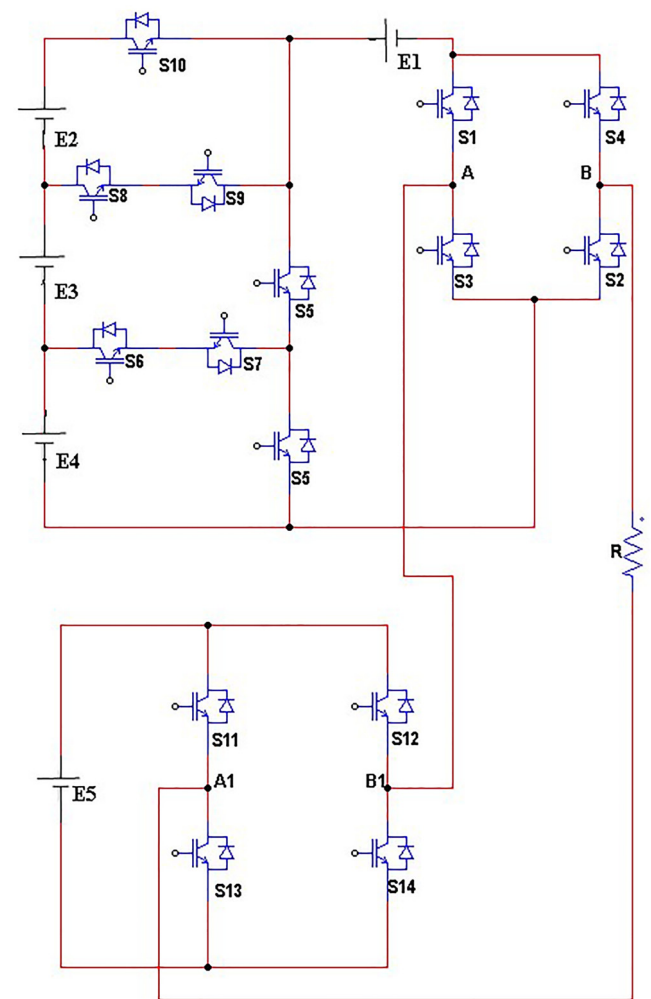


Fig. 6. Proposed hybrid structure 2 (9L basic unit cascaded with H-bridge circuit)



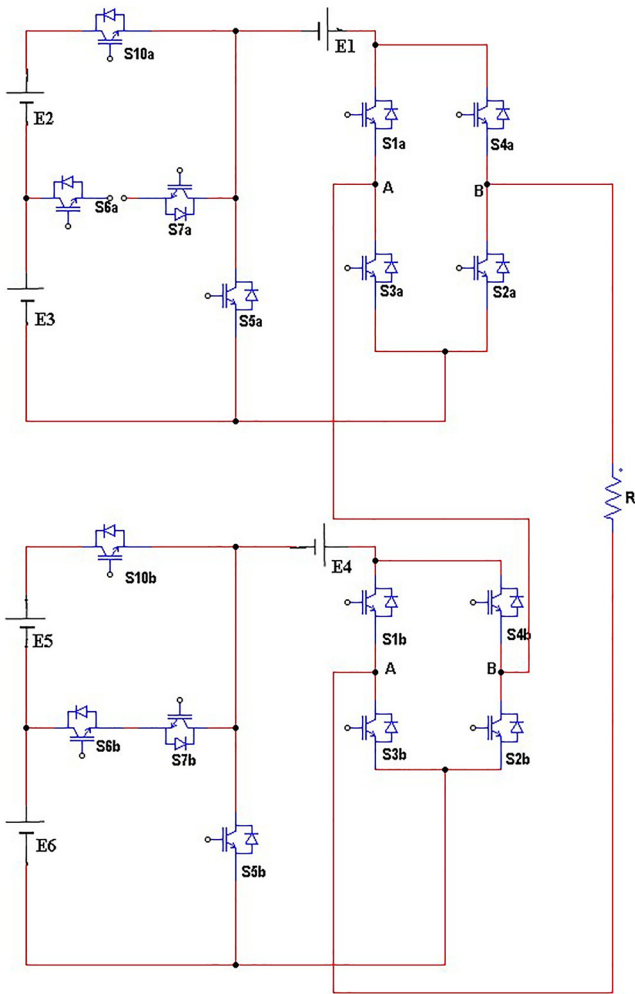


Fig. 7. Proposed hybrid structure by cascading basic units with dc sources ratio (1:7)

suitable relationship of voltages the number of output stages could be extended to nine. The nine level models can also be obtained by modular expansion method by including one more voltage source and a bidirectional switch, as indicated in Fig. 2 [41-44] and their output voltage waveform is demonstrated in Figs 3 and 4.

2.1. Level extension methods

Modular expansion, normal and staircase layer are processes of increasing the output levels. Table 2 shows the component requirement and source requirement for specific levels using modular expansion.

Table 4. Component comparison of the 49L HBMLI with CHB symmetrical MLI

Parameters	CHB symmetrical	Proposed bidirectional topology
No of H-bridges	24	0 (instead it needs another basic unit in series)
No of Dc sources	24	6
No of switches	96	16
No of output levels	49	49

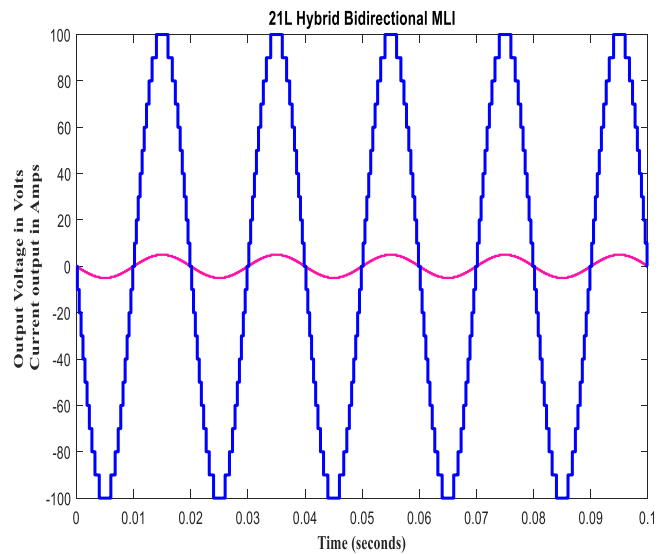


Fig. 8. 21Level hybrid BMLI output voltage

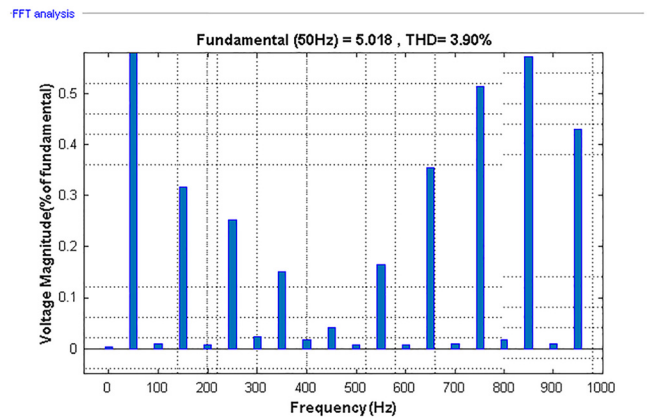


Fig. 9. Voltage harmonic spectrum of 21L hybrid BMLI current waveform

Table 3. Extension of levels by cascading basic circuit

S. No	Various cascading methods using symmetric structures	DC sources ratio	No of unidirectional switches	No of bidirectional switches	No of level (N)	No of sources (M)
1	Basic unit and one H-bridge	01:07	10	1	21	4
2	Basic unit and two H-bridges	01:07:07	14	1	35	5
3	Basic unit 1 and basic unit 2	01:07	12	2	49	6



2.2. Cascading basic units with H-bridge circuit

By cascading the basic 7L unit with H-bridge circuit with $E1 = E2 = E3 = 1 \text{ Vdc}$ and $E4$ voltage as 7vdc as illustrated in Fig. 5, it is able to produce 21 level output. If a nine level circuit is cascaded with H-bridge circuit with $E1 = E2 = E3 = 1\text{Vdc}$ and $E4$ voltage as 9Vdc , it is able to produce 27 level output voltage as depicted in Fig. 6.

2.3. Cascading of basic unit with another basic unit

When 7L basic unit is cascaded with another unit, both have voltages as symmetric with $E1 = E2 = E3 = \text{Vdc}$ it produces thirteen level output. If asymmetric method is chosen still more increase in levels is achieved. When the first 7L basic unit is having $E1 = E2 = E3 = \text{Vdc}$ and the cascading unit is having $E4 = E5 = E6 = 7\text{Vdc}$ as illustrated in Fig. 7, it is probable to create 49Level output waveform. As the voltage levels increase, the harmonic

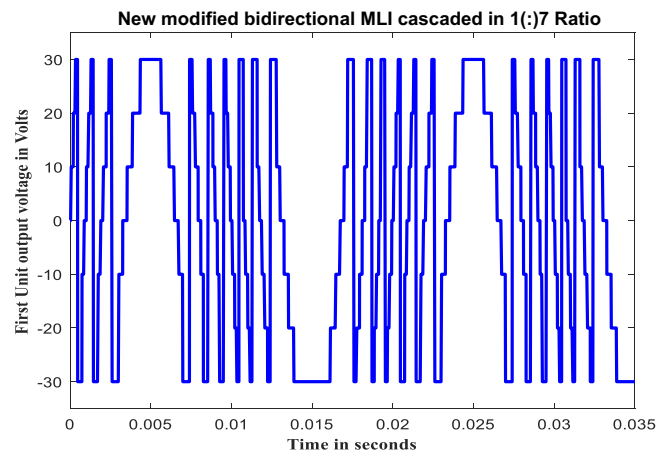


Fig. 12. Output voltage waveform of basic unit 1

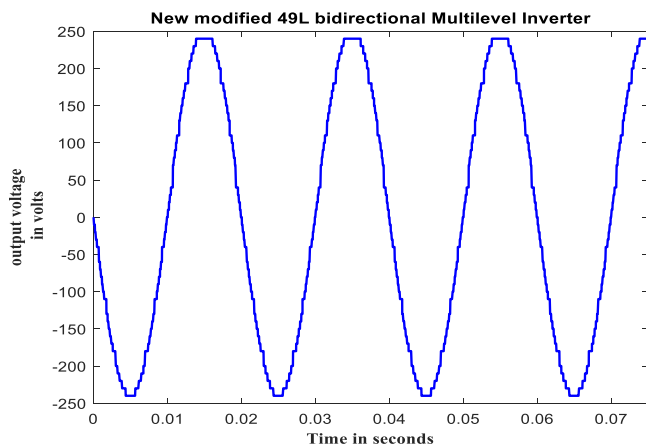


Fig. 10. Output voltage waveform of 49L HBMI

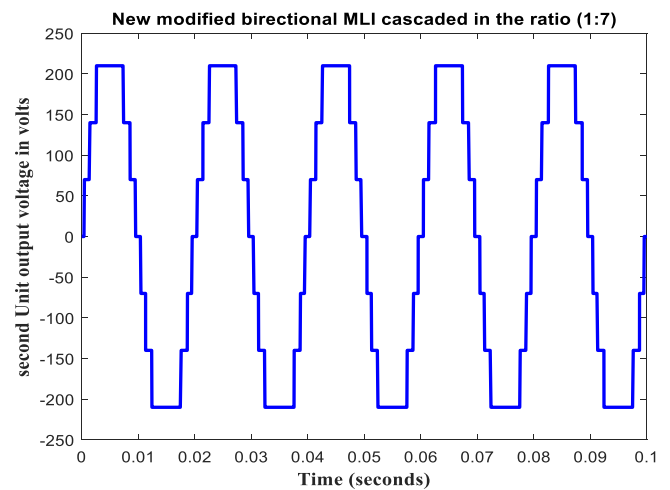


Fig. 13. Output voltage waveform of basic unit 2

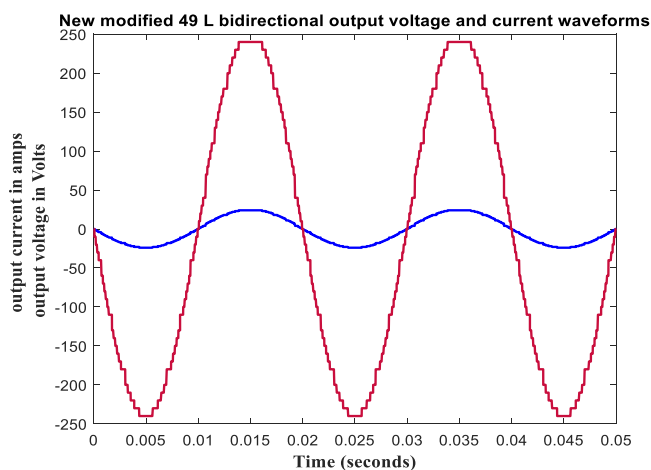


Fig. 11. Output current waveform of 49L HBMLI

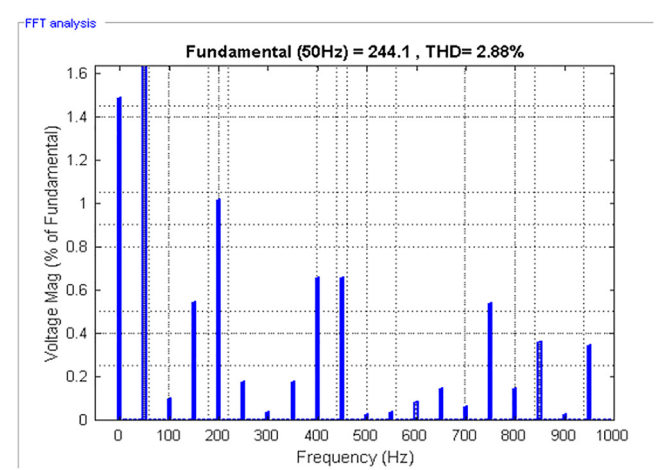
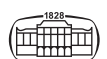


Fig. 14. Voltage harmonic spectrum of 49L HBMI



content in output voltage waveform is reduced. Some of the ways to cascade with the base circuit for maximizing the number of stages is represented in Table 3 and component comparison with CHB MLI is suggested in Table 4.

3. SIMULATION AND EXPERIMENTAL RESULTS AND ANALYSIS FOR THE HYBRID STRUCTURES

The output voltage waveform for 21L circuit obtained by cascading a single phase 7L basic unit cascaded with

H-bridge circuit with RL load with $R = 100\Omega$ and $L = 50$ mH is indicated in Fig. 8. The THD content on output voltage waveform found to be 3.90 as depicted in Fig. 9.

An output voltage waveform for 49L circuit obtained by cascading a single phase 7L basic unit1 with similar 7L basic unit2 in asymmetric topology with DC voltage distribution ratio of the sources in the ratio 1:7 with R load with RL load are illustrated in Figs 10 and 11. An output obtained from the basic unit and the cascaded units are shown in Figs 12 and 13. The FFT analysis is demonstrated in Fig. 14 and THD content on output voltage waveform is found to be 2.88.

The 21L HBMLI is tested using three phase induction motor model available in MALAB Simulink as the load and

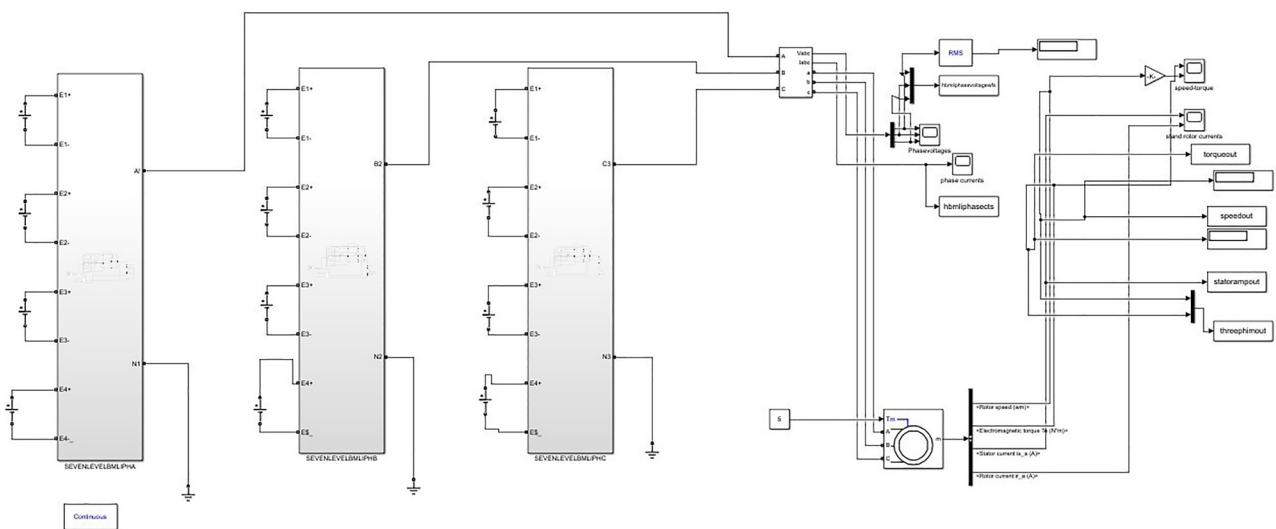


Fig. 15a. Twenty one levels HBMLI fed induction motor drive

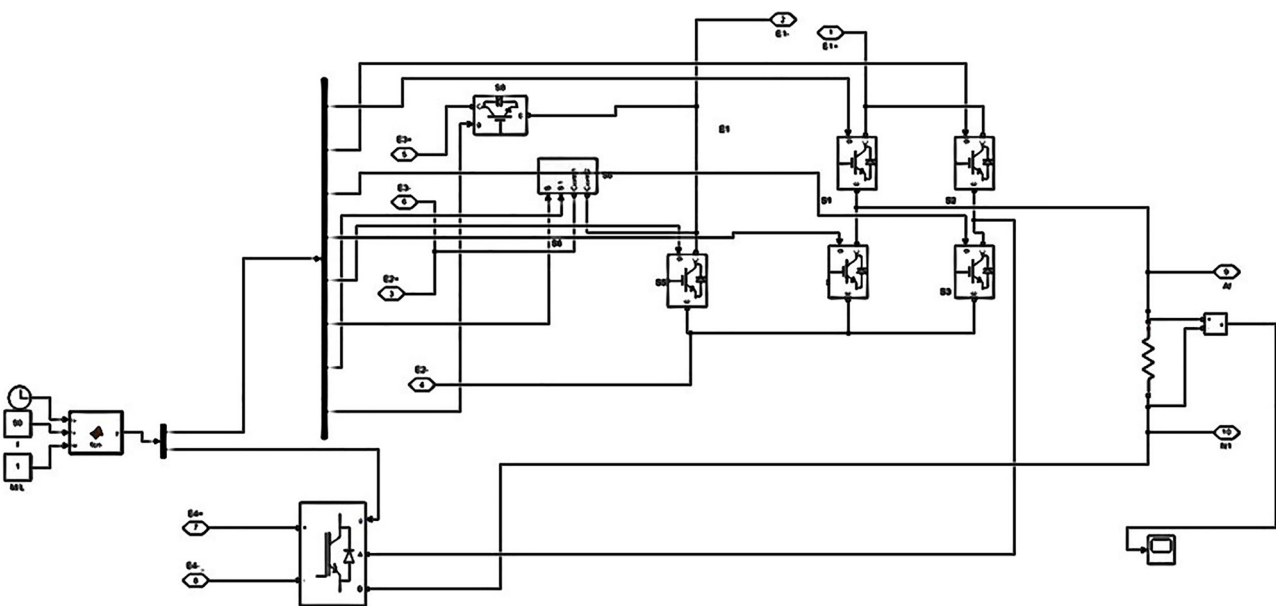


Fig. 15b. Circuit assembly subsystem of seven level BMLI



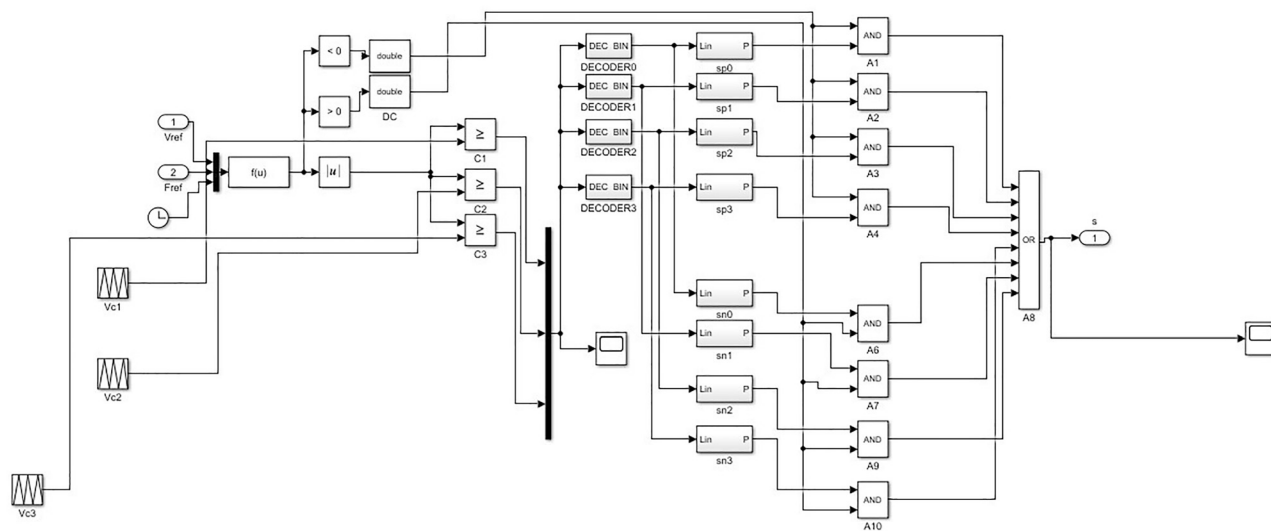


Fig. 15c. PDPWM subsystem

its performance characteristics like stator current, rotor current, speed, torque are analyzed. The twenty-one level three phase bidirectional MLI fed induction motor model diagram using MATLAB/Simulink is illustrated by Fig. 15a. Circuit assembly subsystem of Seven level BMLI is shown in Fig. 15b. PDPWM Subsystem is given in Fig. 15c. The performance characteristics of the 21level HBMLI like speed, stator current, torque, rotor current are presented in Fig. 16, Figs 17 and 19 and the phase voltages are shown in Fig. 18.

Simulink model three phase induction motor (asynchronous motor) of 5.4 H.P, 400 V, 50 Hz and 1430 RPM rated speed has been chosen from Simulink library. PDPWM control technique is applied by selecting modulation index as 1.0 and switching frequency of IGBT is selected 1 kHz and that of modulating wave is 50 Hz respectively. Even though various speed control methods are available for induction motor v/f speed control technique is the mostly preferred one due to its characteristics such as good

transient and dynamic performance. It also provides good speed control range and it is easier to implement.

For authenticating the efficiency of 7L BMLI, the induction motor is worked in the range with a standard V/F mode ($0 < m_i < 1$) with varying modulation indexes and its readings are tabulated in Table 5.

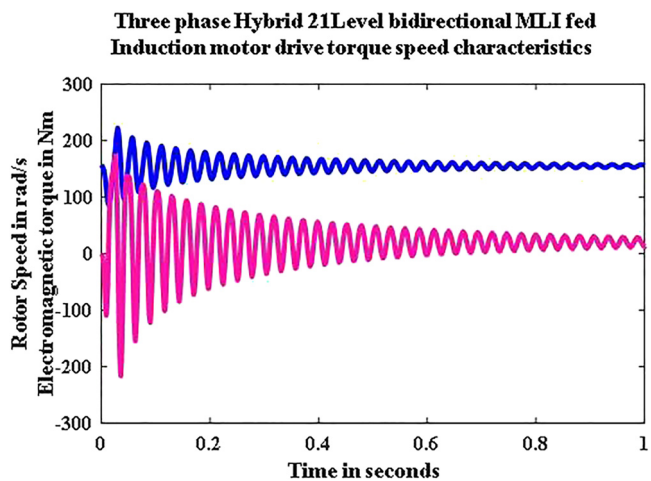


Fig. 16. Speed, torque characteristics of twenty one level HBMLI

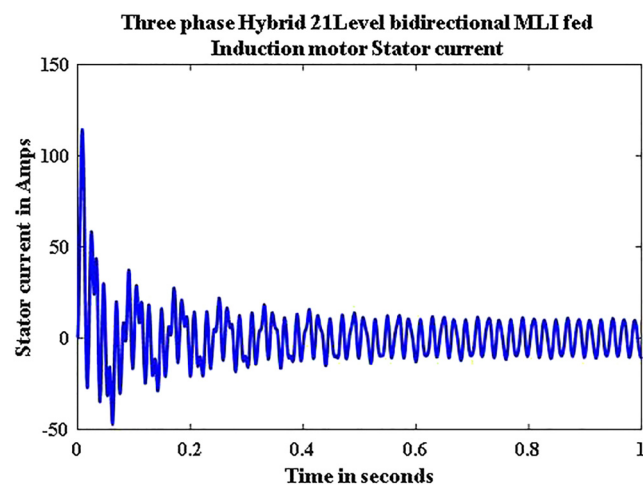


Fig. 17. Stator current characteristics of twenty-one level HBMLI

Table 5. Performance of three phase 9-level BMLI fed induction motor at no load

Modulating wave for PDPWM	M.I	Three phase induction motor fed with 9-level CHBMLI		
		V line in Volts	% THD	V_{AN} in Volts
Sine wave	1	493.3	11.73	285.5
	0.8	396	14,3	229.7
	0.6	301	22.07	174.6
	0.4	208	35.63	121.2



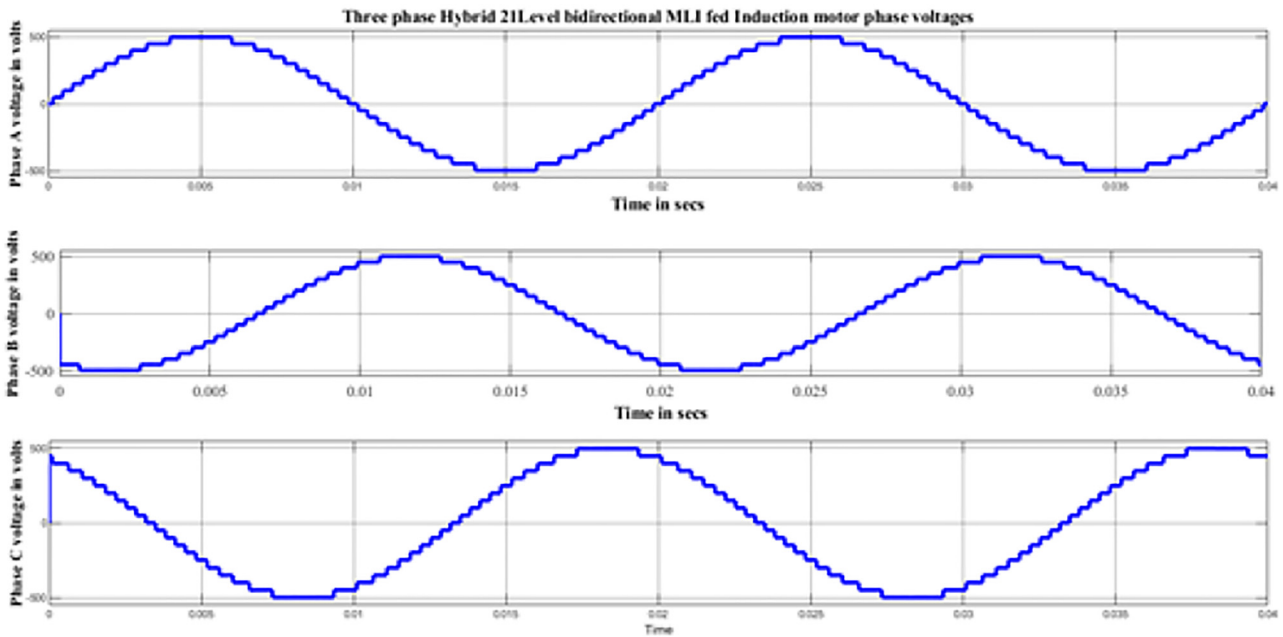


Fig. 18. Twenty-one HBMLI phase voltages

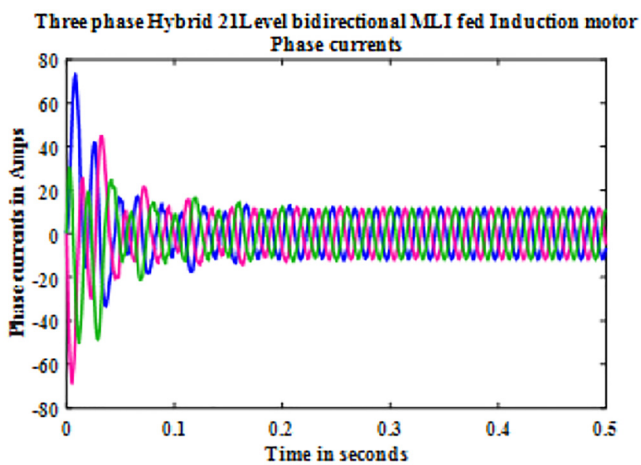


Fig. 19. 21 level three phase HBMLI fed induction motor drive phase currents

Seven level BMLIs in dissimilar modulation codes (0.4, 0.6, 0.8 and 1.0) are recommended on Figs 20–23. The variation of modulation index modifies the number of stages. The stator currents are nearly sinusoidal for all cases of M.I values and the stator current for M.I = is shown in Fig. 24.

The performance of the 9 BMLI has been verified by operating the induction motor by varying the modulation index in the range ($0 < M.I < 1$) with standard V/f mode and its readings are tabulated in Table 6. The line and phase voltage of nine stages BMLI are demonstrated in Figs 25 and 26.

Table 7 explains the efficiency of the conventional and proposed topology. The proposed topology affirms the best result over the conventional topology. The efficiency values of the proposed topology are 99.003% (Table 8). Table 8 shows that the proposed hybrid structure is robust under changing load conditions.

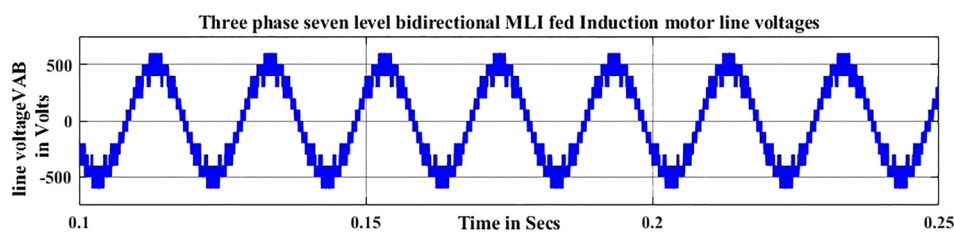


Fig. 20. Line voltage VAB for M.I = 1 using PDPWM at switching frequency as 1 kHz

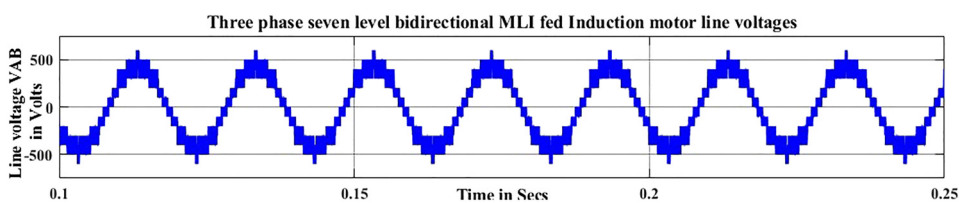


Fig. 21. Line voltage VAB for M.I = 0.8 using PDPWM at switching frequency as 1 kHz



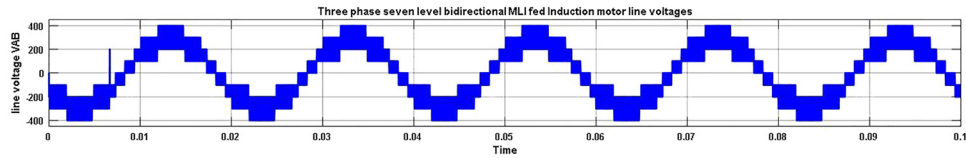


Fig. 22. Line voltage VAB for M.I = 0.6 using PDPWM at switching frequency as 1 kHz

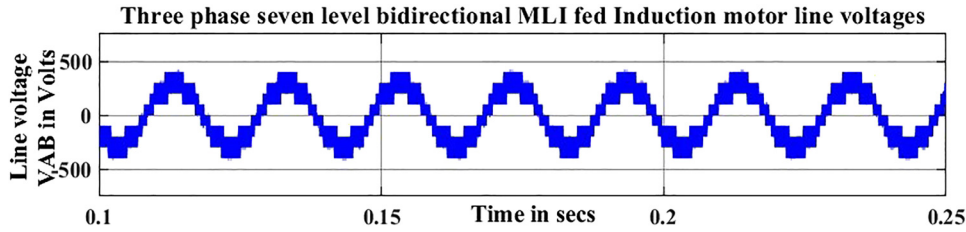


Fig. 23. Line voltage VAB for M.I = 0.6 using PDPWM at switching frequency as 1 kHz

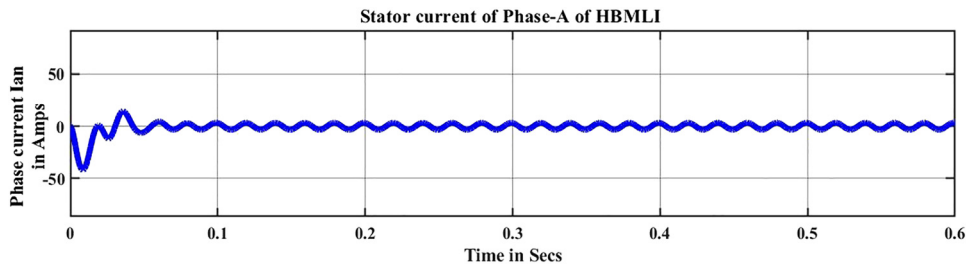


Fig. 24. Stator current of BMLI fed induction motor when M.I = 1

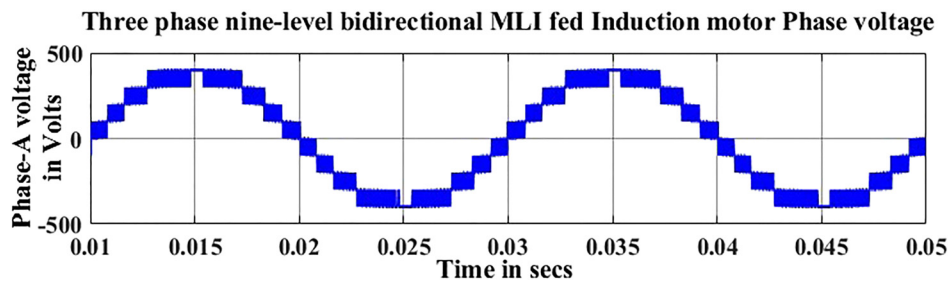


Fig. 25. Phase voltage van with M.I = 1 and switching frequency 1 kHz using PDPWM technique

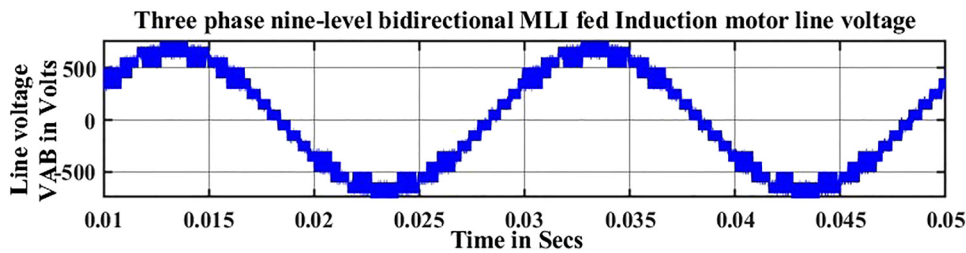


Fig. 26. Line voltage V_{AB} with M.I = 1 and switching frequency 1 kHz using PDPWM technique



Table 6. Performance of three phase 7-level BMLI fed induction motor at no load

Modulating wave for PDPWM	M.I	Three phase induction motor fed with 7-level HBMLI		
		V line in Volts	% THD	V _{AN} in Volts
Sine wave	1	371.8	15.06	215.7
	0.8	301	22.10	174.6
	0.6	230.1	29.9	134.2
	0.4	157.3	38.13	92.87

Table 7. Efficiency for various topologies

Various topologies	Efficiency obtained (%)
Proposed technique	99.003
H-bridge topology	80.343
Flying capacitor topology	75.603
Neutral point clamped (NPC) topology	55.893

Table 8. Tracking time response of IM

Power converter	Reference speed change Tracking time	Load change Tracking time	Constant reference change Tracking time
VSI [45]	0.5 s	3.8 s	3.5 s
MLI [45]	0.2 s	1.8 s	2 s
Hybrid Bidirectional Multilevel Inverter Structure	0.185 s	1.094 s	1.5 s

4. CONCLUSION

In this manuscript two novel hybrid bidirectional MLI configurations are proposed. The simulated results are obtained for 21L and 27L for the proposed structures by series cascading with level doubling network. The simulated results are verified for 49L and 81L output, which are synthesized using series cascading method with two similar basic units. All these hybrid BMLI structures produced output with lesser voltage harmonic content. The simulated results of the three phase 21LHBMLIMATLAB SIMULINK model with induction motor as the load is verified. Certainly, these hybrid BMLI structures with increased output voltage levels and minimized THD would be well suited for medium powered AC drive applications. The efficiency of the NPC topology, flying capacitor, H-bridge topology and proposed topology is 55.893%, 75.603%, 80.343% and 99.003%. Further, this research is prospective to future research in the area of high quality energy transfer using power converters.

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