

PERFORMANCE AND ANALYSIS OF HYBRID CASCADED MULTILEVEL INVERTER APPLIED TO INDUCTION MACHINE

K.Sai Saritha¹, R.G.S.Lakshmi², J.A.Ganeswari³

^{1,2,3}Sai Ganapathi Engineering College.EEE Dept., Visakhapatnam, (India)

ABSTRACT

This paper proposes a hybrid cascaded multilevel inverter to get a desired ac voltage from several dc voltages. These multilevel inverters are used for high power applications. These inverters give less total harmonic distortion (THD), and also can reduce the power switches when compared with conventional cascaded multilevel inverters. It is a five level inverter with single DC source which is used to generate a five level output with two bridges and six switches and performance of three phase induction motor is analyzed when connected to fuel cell. In general the output of an inverter is controlled with the help of various controlling techniques. In this proposed work these multi level inverters are controlled with modified SPWM scheme to reduce the switching losses. The objective of this paper is to evaluate the performance of an induction motor with hybrid cascaded multilevel inverter with DC source and further the DC source is replaced by a renewable energy source such as solar panels, fuel cell etc and to control the speed of the induction motor. The method can be easily extended to a m-level inverter. MATLAB/SIMULINK platform is chosen to simulate the proposed model and control technique.

Keywords: *Cascaded Multilevel Inverter (CMI), Hybrid Multilevel Inverter (HMI), Modified SPWM scheme, fuel cell, Dc- Dc boost converter, THD.*

I. INTRODUCTION

Multilevel Inverters are extensively used in a variety of industrial applications such as in ac drive system, VAR compensators and power supplies and to handle high power ratings [1]-[2]. Some sort of connections (series-series, series-parallel, parallel-parallel, parallel-series) are necessary to overcome the troubles of the narrow voltage and current ratings of power electronic devices. Multilevel inverters have the ability to synthesize waveforms with a better harmonic spectrum, therefore suitable to attain higher voltages. They are applied in many industrial applications such as, AC power supplies, static VAR compensators and drive systems etc. Different converters Topologies have proposed [3] for nonconventional energy sources to control power flow effectively in both grid-connected as well as in stand-alone applications. Generally, three different major multilevel converter structures have been reported in the literature: cascaded H-bridge converters with separate dc sources (SDCS), diode clamped (neutral clamped), flying capacitor (capacitor clamped).

In this paper cascaded H-bridges converter is used with a separate dc sources (Photovoltaic and Fuel cell) for getting higher the output voltages. However, this topology contains huge number of switches and this number

will be depended upon output voltage levels. Numerous modulation and control strategies are developed in order to eliminate the selective harmonics such as Pulse width modulation (PWM), Sinusoidal PWM, Space Vector PWM, Selective harmonic elimination. In this paper a modified PWM technique is proposed in order to effectively eliminate the order of harmonics.

Hybrid cascaded multilevel inverter is modeled through a conventional cascaded multilevel inverter [4]-[5]. The proposed model has been shown in Fig.1. Hybrid multilevel inverter composed of IGCT H-Bridge and an IGBT H-Bridge inverter. The advantage of IGCT inverter is, it can be operate at higher volt ampere ratings when compared to IGBT inverter and the advantage of IGBT inverter is it can perform operation at higher switching frequency when compared to IGCT inverter. Therefore the hybrid inverter can perform the advantages of both IGCT and IGBT I.e. it can operate at higher VA rating with lower switching losses and has less number of power switches as conventional cascaded multilevel inverter (CMI) [6]. Hybrid multilevel inverter (HMI) with a single SDCS is suitable for the applications in electrical vehicle applications. There are mainly two types of HMI's: a three phase inverter with six switches and a single phase inverter with four switches. The objective of HMI is, to combine this model with the renewable energy systems for a high power application. Both IGBT and IGCT inverter switching pattern is developed with low switching losses.

II. PROPOSED FUEL CELL FED HMI

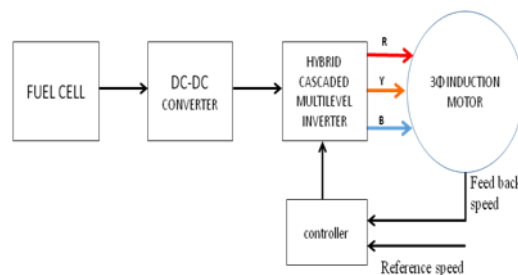


Fig.1. fuel cell fed hybrid multilevel inverter

2.1 Fuel Cells

The concept of fuel cell is known in 1839 after Sir William Grove. Recently, the fuel cell has been revived and shows tremendous promise in the transportation and utility sectors [7]. Fuel cells will convert chemical energy into electrical energy therefore these devices are called electrochemical devices. Fuel cell is analogous to a battery because it also consists of two electrodes and an electrolyte [8]. The fuel is oxidized at the anode and produces positive ions that flow through the electrolyte. The electrons are directed outside creating current through the external circuit and then back to the cathode. Oxygen (air) is supplied at the cathode and reduced, consuming the electrons from the external circuit, and the only resultant byproduct is H₂O (water). Fuel cells are pollution free, renewable energy source therefore it has wide range of applications and are perfectly suitable in electrical vehicles and in distribution generation.

The V-I characteristics

There are three main regions in V-I curve characteristics of the fuel cell, ohmic region is the normal operating area of the fuel cell as shown in Fig.2. Fuel cells are often stacked together in series to get high voltage. But the reliability will reduced if the fuel cells are connected in series, since failure of one cell led to stops entire functioning.

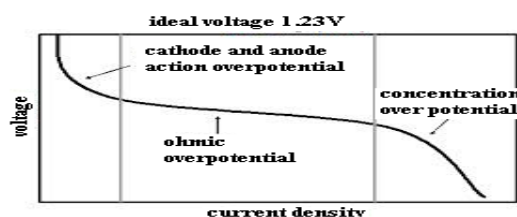


Fig.2. single cell polarization curve

The efficiency of a fuel cell is another advantage over internal combustion engines, which are limited by the Carnot cycle efficiency. The efficiency of a fuel cell is limited to 40-50% range due to the direct conversion from chemical to electrical energy. Power gets lost in the form of heat, which can be get back relatively easily and put to use. A big advantage with PEMFCs is Co-generation.

2.2 DC-DC Boost Converter

A converter which converts low level DC voltage into high level DC voltage called DC- DC Boost. In this paper a fuel cell is used as a DC source, in general the output of fuel cell is small. In order to maximize or to enhance the fuel cell output a boost converter is used [9]. It normally operates either in continuous conduction mode [10] or in discontinuous conduction mode. In this paper boost converter operates in Continuous Conduction Mode (CCM) as shown in Fig.3.

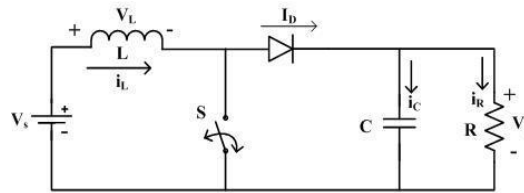


Fig.3. DC-DC Boost Converter Circuit Diagram

CCM involves two step processes to get power transferred from source to load. Inductor stores the energy when the switch 'S' is turned ON, and its equivalent circuit is shown in Fig.4 (a). Stored energy gets transferred to load through diode when the switch 'S' is turned OFF and its equivalent circuit is shown in Fig.4 (b). Also equivalent waveforms of voltage across an inductor, current through diode, current through inductor, and capacitor current are shown in Fig.5.

The relation between input voltage and load voltage for an ideal DC-DC Boost Converter, is given by

$$V_o = \frac{V_s}{(1-D)} \quad (1)$$

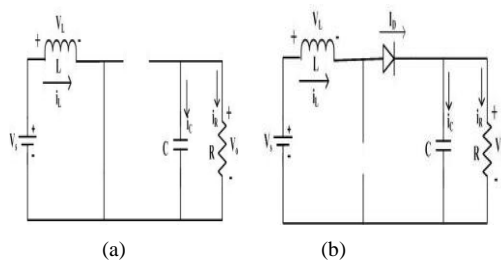


Fig.4. DC-DC Boost converter with on (a) and off (b) state circuit Diagrams

To obtain desired regulated output voltage from the dc-dc boost converter which feeds to inverter, double lead integral controller is designed to achieve minimum closed loop stability margins[11].

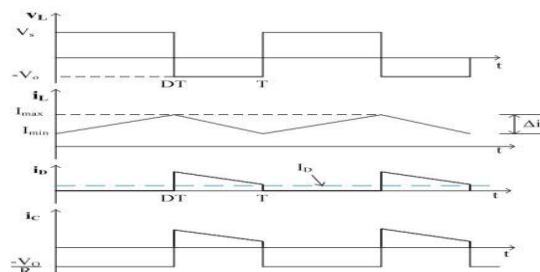


Fig.5. Current and voltage waveforms of DC-DC Boost Converter

The boost converter operates in CCM for $L > L_b$ where

$$(2)$$

For $D=0.8$, $R=10\Omega$ and $f=100$ KHz, the boundary value of inductance is $L_b=0.055$ mH.

The current supplied to the output RC circuit is discontinuous [12]. Thus a large filter capacitor is required to limit the output voltage ripple. The filter capacitor must provide the output DC current to the load when the diode D is off. The minimum value of the filter capacitor that results in the voltage ripple V_r is given by

$$(3)$$

At $D=0.8$, $V_r/V_o=2\%$, $R=10\Omega$ and $f=100\text{KHz}$ the minimum capacitance for the boost converter is $C_{\min}=0.0159\text{mF}$.

2.3 Hybrid multilevel inverter

Hybrid multilevel inverter (HMI) with a single SDCS is suitable for the applications in electrical vehicle applications. The main objective of HMI is, to combine this model with the renewable energy systems for a high power application [13]. Both IGBT and IGCT inverter switching pattern is developed with low switching losses.

The proposed hybrid multilevel inverter has the less number of switches compared to a conventional cascaded multilevel inverter. The hybrid multilevel inverter consists of two types of inverters, a conventional three phase six switches inverter and a single phase four switches H-bridge inverter. There upon, two SDCS is used to supply both the inverters.

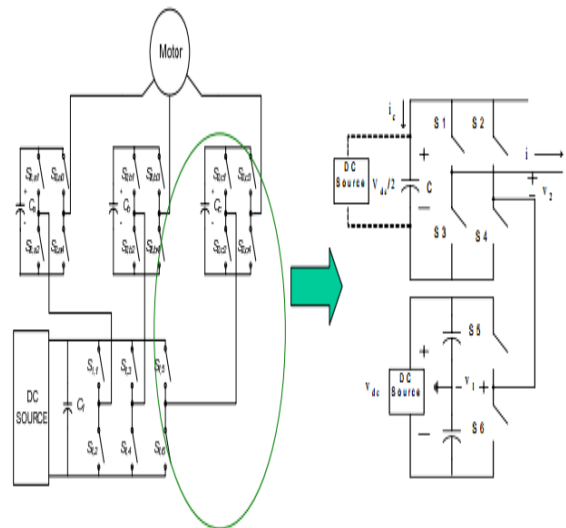


Fig.6. Topology of the hybrid multilevel inverter

The topology of the proposed hybrid multilevel inverter is shown in the Fig.6, which includes a complete and a simplified single-phase topology. The bottom is one leg of a standard 3- leg inverter with a dc power source. The top is an H-bridge in series with each standard inverter leg. The H-bridge can use a capacitor, battery or other dc power source. The output voltage v_1 of this leg (with respect to the ground) is either $+V_{dc}/2$ (S_5 closed) or $-V_{dc}/2$ (S_6 closed). This leg is connected in series with a full H-bridge, which in turn is supplied by a capacitor voltage. If the capacitor is used and kept charged to $V_{dc}/2$, then the output voltage of the H-bridge can take on the values $+V_{dc}/2$ (S_1, S_4 closed), 0 (S_1, S_2 closed or S_3, S_4 closed), or $-V_{dc}/2$ (S_2, S_3 closed). The capacitor's voltage regulation control method consists of monitoring the output current and the capacitor voltage so that during periods of zero voltage output, either the switches S_1, S_4 , and S_6 are closed or the switches S_2, S_3, S_5 are closed depending on whether it is necessary to charge or discharge the capacitor.

2.4 PWM Scheme

From the above discussion it should be noticed that the main inverter has three legs, six-switches and working on square wave mode where as the auxiliary or H-bridge inverter has four-switches and working on PWM mode. In general PWM signals are generated with a single chip having only one carrier signal accompanied six PWM channels but in this proposal HMI involves 12 PWM channels, because of main and auxiliary inverters. Thereafter the reference signal of SPWM used for auxiliary inverter is modified by using equations (4)-(7).

$$f(t) \quad (4)$$

$$\frac{\tau_p}{\tau_c} = \begin{cases} 2 \left(f(t) - \frac{1}{2} \right); \frac{1}{2} \leq f(t) \leq 1 \\ 2 \left(\frac{1}{2} - f(t) \right); 0 \leq f(t) \leq \frac{1}{2} \end{cases} \quad (5)$$

$$A_1 \quad (6)$$

$$A_2 \quad (7)$$

Where $f(t)$ is a reference signal
 M_a is modulation index
 T_p/T_c is pulse width of PWM
 A_1 multiplexing signal
 A_2 multiplexing signal

The proposed PWM paradigm is shown in Fig.7. Where (a) is output phase voltage which is the sum of both auxiliary and main inverters output voltage. (b) is auxiliary inverter (conventional three phase six switch inverter) and main inverter (single phase four switch H-bridge inverter) output voltages, (c) is modulation signals of both main and auxiliary inverters.

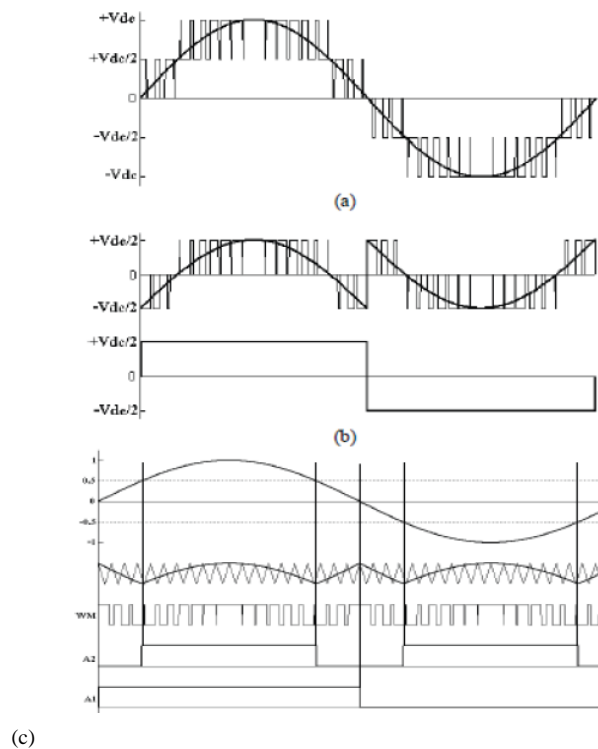


Fig.7. Proposed PWM paradigm: (a) output phase voltage, (b) auxiliary and main inverter output voltages and (c) modulation signals of both main and auxiliary inverter.

III. INDUCTION MOTOR

In the recent years the control of high performance induction motor drives for general industry applications and production automation has received widespread research interests. Induction machine modeling has continuously attracted the attention of researches not only because such machines are made and used in largest numbers but also due to their varied modes of operation both under steady and dynamic states. Traditionally, DC motors were the work houses for the adjustable speed drives (ASDs) due to their excellent speed and torque response. But, they have the inherent disadvantage of commutator and mechanical brushes, which undergo wear and tear with the passage of time. In most cases, AC motors are preferred to DC motors, in particular, an induction motor due to its low cost, low maintenance, lower weight, higher efficiency, improved ruggedness and reliability. All these features make the use of induction motors a mandatory in many areas of industrial applications. The advancement in power electronics and semiconductor devices in order to achieve a smooth, continuous and low total harmonic distortion (THD).

Three phase induction motors are commonly used in many industries and they have three phase stator and rotor winding. The stator windings are supplied with balanced three phase ac voltages, which produce induced voltage in rotor windings due to transformer action. It is possible to arrange the distribution of stator windings so that there is an effect of multiple poles, producing several cycles of magnetomotive force (mmf) around the air gap. In this paper three phase induction motor as a load. The equivalent circuit for one phase of the rotor is shown in Fig.8.

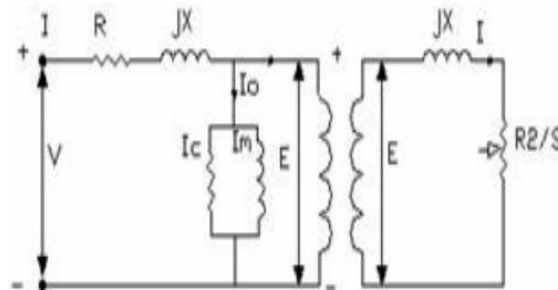


Fig8: Steady state equivalent circuit of an induction motor

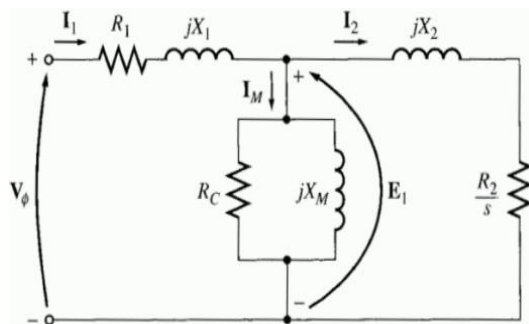


Fig9: Equivalent circuit refer to stator

The complete circuit model with all parameters referred to the stator is in Fig.9. Where R_s and X_s are the per phase resistance and leakage reactance of the stator winding. X_m represents the magnetic reactance. There will be stator core loss, when the supply is connected and the rotor core loss depends on the slip.

3.1 Simulation and Results

Case 1: Proposed PWM scheme:

Simulation result of proposed PWM scheme is shown in Fig.10.

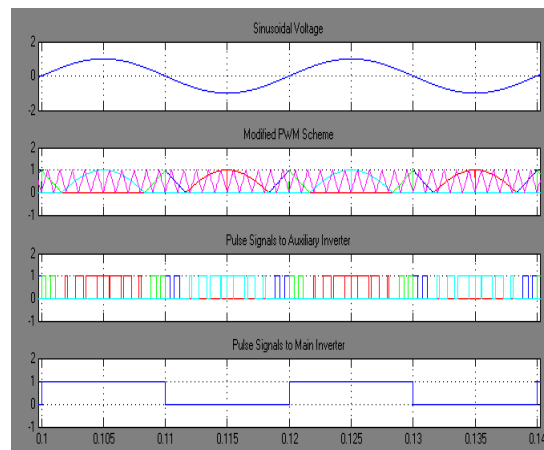


Fig10: Proposed PWM scheme

Case2: Three phase hybrid cascaded multilevel inverter:

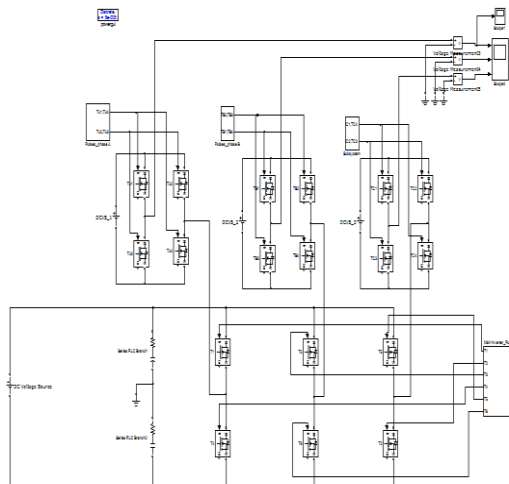


Fig11: Matlab/Simulink model of three phase hybrid cascaded multilevel inverter.

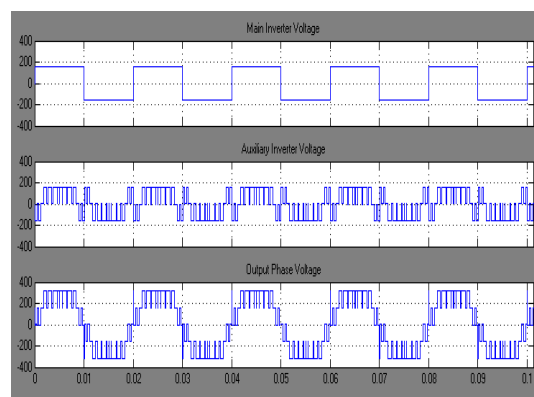


Fig12: main inverter, auxiliary inverter and output phase voltage

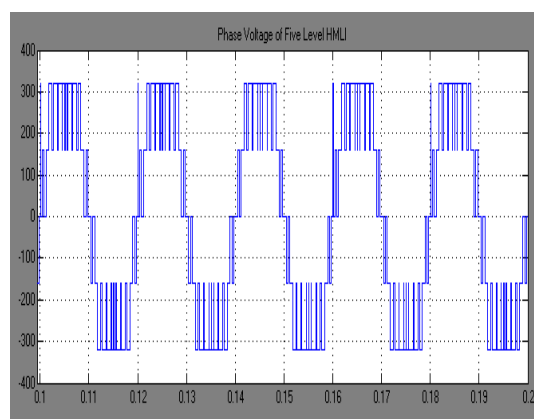


Fig13: five level output phase voltage of hybrid multilevel inverter

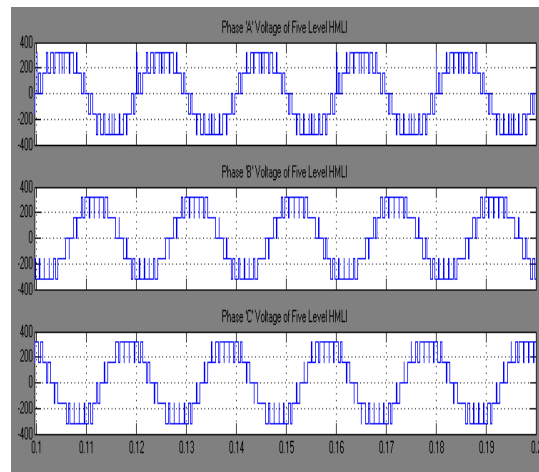


Fig14: Three phase five level voltages of hybrid multilevel inverter.

The Matlab/Simulink model of three phase hybrid cascaded multilevel inverter is shown in Fig.11. and main inverter, auxiliary inverter and output phase voltage waveform and five level output phase voltage waveform of hybrid cascaded multilevel inverter and three phase five level output voltage waveform of hybrid cascaded multilevel inverter is shown in Fig. 12, 13 and 14 respectively

Case3: fuel cell powered DC to DC boost converter:

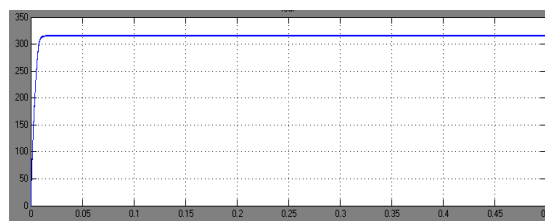


Fig15: output voltage of boost converter

The output voltage of boost converter by using fuel cell as DC source is shown in Fig.15.

Case4: Three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source (open loop):

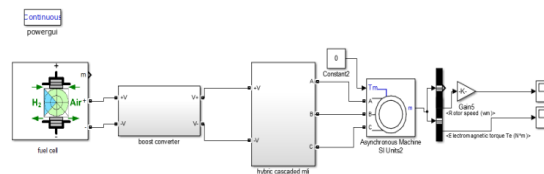


Fig16: Matlab/Simulink model of three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source (open loop).

Matlab/Simulink model of the three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source in open loop is shown in Fig.16 for evaluating motor characteristics.

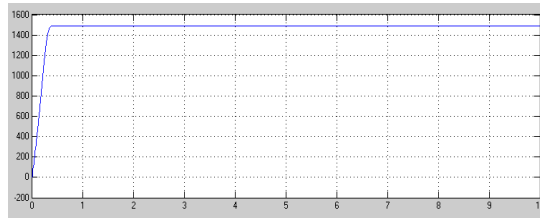


Fig17: speed of induction motor drive

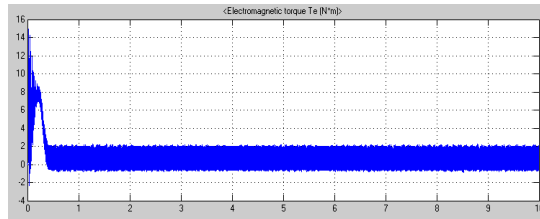


Fig18: electromagnetic torque of induction motor drive.

The speed, electromagnetic torque, of the three phase hybrid cascaded multilevel inverter applied to induction motor is shown in Fig.17 and 18 respectively.

Case 5: Three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source (closed loop):

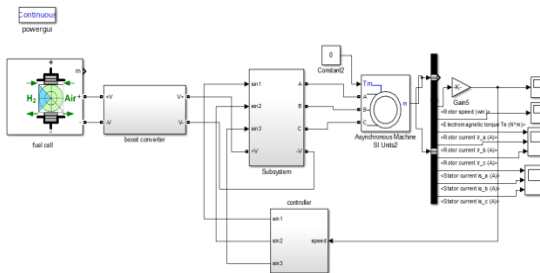


Fig19: Matlab/Simulink model of three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source (closed loop).

Matlab/Simulink model of the three phase hybrid cascaded multilevel inverter applied to induction motor by using fuel cell as dc source in closed loop is shown in Fig.19 for evaluating speed of the machine.

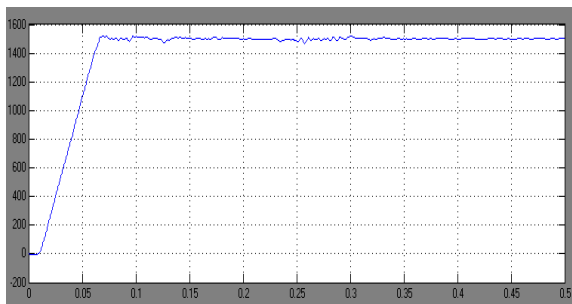
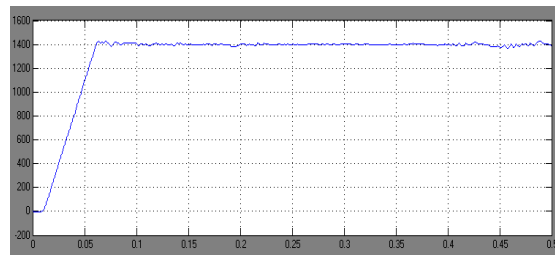


Fig 21: speed of induction motor drive (at 1400rpm)

Fig 20: speed of induction motor drive (at 1500rpm)



The speed of induction motor at 1500 and 1400 rpm is shown in Fig.20,21 respectively.

Case 6: THD analysis for cascaded and hybrid cascaded mli:

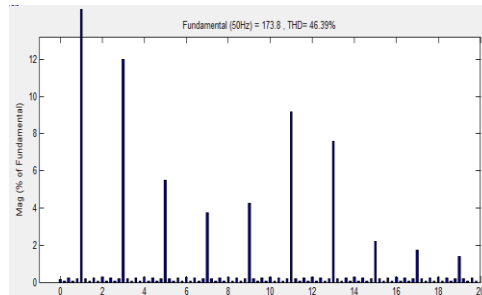


Fig22: THD analysis for cascaded MLI

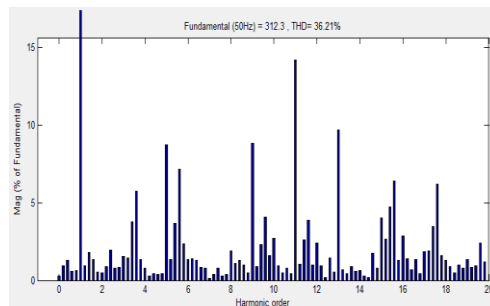


Fig23: THD analysis for hybrid cascaded MLI

THD analysis for cascaded and hybrid cascaded mli is shown in Fig.22 and 23 respectively. The proposed hybrid cascaded multilevel inverter has less THD value when compared to conventional cascaded multilevel inverter.

Comparison of THD for CMI and HMI:

%THD for different values of m_f , m_a for CMI and HMI are shown in Table 1 and 2 respectively.

% THD for CMI			
$m_f \backslash m_a$	0.8	0.9	1.0
21	46.38	41.07	35.12
18	46.84	40.76	34.57
15	45.26	40.15	33.73
12	45.94	39.54	33.02
9	44.18	37.95	32.16

Table1. % THD for CMI

The proposed HMI for $m_f=21$ and $m_a=1$ the % THD is found to be 33.47 in table 2 which is comparatively less than the value of CMI i.e., 35.12 in table 1.

% THD for HMI			
$m_f \backslash m_a$	0.8	0.9	1.0
21	37.54	35.21	33.47
18	36.94	34.44	32.86
15	36.07	33.46	31.56
12	35.23	32.65	29.29
9	34.95	31.52	27.55

Table2. % THD for HMI

IV. CONCLUSION




This paper presented a three phase five level cascaded H-bridge inverter, which uses single DC source and fuel cell as DC source and connected to three phase induction motor is used as a load to observe the performance characteristics of motor and speed of the induction motor is controlled. The modified PWM technique has also been developed to reduce the switching losses. Also, the proposed topology can reduce the number of required power switches and THD value when compared to conventional cascaded multilevel inverter. Simulation results have been performed. The switching losses of the hybrid multilevel inverter are less than the conventional cascaded multilevel inverter; consequently system efficiency would be improved. The result shows that this alternative hybrid cascaded multilevel inverter can be applied for high power applications and can be used to interface with renewable energy sources.

REFERENCES

- (1) M. D. Manjrekar, P. Steimer and T. A. Lipo, "Hybrid Multilevel Power Conversion System: A Competitive Solution for High Power Applications," *IEEE Trans. On Industry Applications*, Vol. 36, No. 3, pp. 834-841, May/June 2000.
- (2) H. Liu, L. M. Tolbert, B. Ozpineci, Z. Du, "Comparison of Fundamental Frequency and PWM Methods Applied on a Hybrid Cascaded Multilevel Inverter," *IEEE Industrial Electronics Society Annual Conference*, Orlando, Florida, November 10-13, 2008, pp. 3233-3237
- (3) S.khomfoi, l.m.tolbert, "multilevel power converters" power electronics handbook, 2nd edition Elsevier, 2007, ISBN 978-0-12-088479-7, chapter 17, pp.451-482.
- (4) Lezana, P.; Rodriguez, J.; Oyarzun, D.A. "Cascaded Multilevel Inverter with Regeneration Capability and Reduced Number of Switches", *Industrial Electronics, IEEE Transactions on* vol.55, no.3, pp.1 059, I 066, March 2008.
- (5) K Sivakumar Anandarup Das Rijil Ramchand Chintan Patel K Gopakumar "A Hybrid Multilevel Inverter Topology for an Open-End Winding Induction-Motor Drive Using Two-Level Inverters in Series With a Capacitor-Fed H-Bridge Cell", *IEEE Transactions on Industrial Electronics* Vol. 57, NO. 11, November 2010.
- (6) Donald Grahame Holmes, Brendan P. McGrath "Opportunities for Harmonic Cancellation with Carrier-Based PWM for Two-Level and Multilevel Cascaded Inverters", *Industry Applications, IEEE Transactions on* Vol. 37, No. 2, March/April 2001.
- (7) Yongping, H., Y. Zhihua, and W. Gang. 2010. "An improved dynamic voltage model of PEM fuel cell stack ". *International Journal of Hydrogen Energy*, vol. 35, n. 20, p. 11154- 11160.
- (8) Zandi, M., A. Payman, J-P. Martin, S. Pierfederici, B. Davat, and F. Meibody-Tabar. 2011. " Energy Management of a Fuel Cell/Supercapacitor/Battery Power Source for Electric Vehicular Applications ". *IEEE Transactions on Vehicular Technology*, vol. 60, n. 2, p. 433-443.
- (9) F. Hulehel and S. Ben-Yaakov, "Low-frequency sampled-data models of switched mode dc-dc converters power electronics," *IEEE Trans. Power Electronics*, vol. 6, no. 1, pp. 55-61, Jan. 1991
- (10) M. Ferdowsi, "An estimative current mode controller for dc-dc converters operating in continuous conduction mode," in *Proc. Applied Power Electronics Conference*, Mar. 2006, pp. 19-23

- (11) C. C. Fang and E. H. Abed, "Sampled-data modeling and analysis of closed-loop PWM dc-dc converters." in Proc. IEEE Int. Symp. Circuits and Systems, May 30- Jun. 2, 1999, pp. 110-115.
- (12) Power electronics circuits, devices and applications, third edition by Muhammad H. Rashid.
- (13) "Performance and analysis of hybrid multilevel inverter fed induction motor drive", in international journal of modern engineering research, vol. 2, issue. 2, mar-apr 2012, pp-346-353.

BIOGRAPHY

	Ms.R.G.S.Lakshmi is graduated her M.tech in power and industrial drives from vignan's institute of information technology and B.Tech in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, Vizianagaram. She is presently working as an Assistant professor in Sai Ganapathi Engineering College, Visakhapatnam, AP. Her research areas include Power Systems, power electronics, Photo-Voltaics, PWM techniques and Multi level Inverters.
	Mrs.K.Sai Saritha is graduated her M.tech in power systems from Pydah Engineering college and B.Tech in Electrical and Electronics Engineering from SISTAM College, Srikakulam. She is presently working as an Assistant professor, HOD in Sai Ganapathi Engineering College, Visakhapatnam, AP. She is having teaching experience of last 9 years. Her research areas include Power Systems, power electronics, PWM techniques, electrical machines.
	Mrs.J.A.Ganeswari is graduated her M.tech in power Electronic Drives and Controls from Andhra University, Visakhapatnam and B.Tech in Electrical and Electronics Engineering from Regional Engineering College(NIT) Warangal. She is presently working as an Assistant professor in Sai Ganapathi Engineering College, Visakhapatnam, AP. She is having teaching experience of last 8 years. Her research areas include Power electronics and drives, power systems, power quality issues.