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# Design and Development of Hybrid Multilevel Inverter employing Dual Reference Modulation Technique for Fuel Cell Applications

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***Abstract***

*MultiLevel Inverter (MLI) has been recognized as an attractive topology for high voltage DC-AC conversion. This paper focuses on a new dual reference modulation technique for a hybrid multilevel inverter employing Silicon carbide (SiC) switches for fuel cell applications. The proposed modulation technique employs two reference waveforms and a single inverted sine wave as the carrier waveform. This technique is compared with the conventional dual carrier waveform in terms of output voltage spectral quality and switching losses. An experimental five-level hybrid inverter test rig has been built using SiC switches to implement the proposed algorithm. Gating signals are generated using PIC microcontroller. The performance of the inverter has been analyzed and compared with the result obtained from theory and simulation. Simulation study of Proportional Integral (PI) controller for the inverter employing the proposed modulation strategy has been done in MATLAB/SIMULINK.*

***Keywords:*** Multilevel inverter, SiC, dual reference modulation, switching losses, PI

## 1. Introduction

Function of multilevel inverter is to synthesize a desired output voltage from several levels of DC input voltages [1]. As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches the desired waveform. They are of special interest in the distributed energy sources area because several batteries, fuel cell, solar cell and wind turbine can be connected through multilevel inverter to feed a load without voltage balance problems [2]. There are several topologies of multilevel inverter [3], but the one considered in this paper is the hybrid cascaded multilevel inverter employing SiC based switches. The advantages of the proposed topology over the existing ones are reduced number of switches, less number of capacitors and simplified structure and also allow the use of a single dc source.

For the cascaded multilevel inverter variety of modulation strategies have been reported, with the most popular being carrier-based and space vector modulation [4]. Several multi carrier techniques have been developed to reduce the distortion in multilevel inverter, based on the classical SPWM with triangular carriers [5]. But this paper focuses on a dual reference modulation technique with a single inverted sine wave carrier waveform. The advantages of inverted sine wave are enhanced fundamental voltage, reduced Total Harmonic Distortion (THD) and switching losses. The proposed modulation is compared with dual carrier and single reference modulation technique. An inverted sine wave of high switching frequency is taken as a carrier wave and is compared with that of the reference sine wave. The pulses are generated whenever the amplitude of the reference sine wave is greater than that of the inverted sine carrier wave. PIC microcontroller is used to obtain the gating pattern for the individual IGBTS. A detailed study of the proposed modulation technique is carried out through MATLAB/SIMULINK for switching losses and THD. Furthermore, a PI controller is used to control the MLI using the proposed PWM technique. The results were verified experimentally. It was noticed that the proposed modulation strategy results in lower switching losses for a chosen THD as compared to the conventional strategies.

## 2. Hybrid Cascaded Multilevel Inverter

The proposed cascaded multilevel inverter as shown in Fig.1 consists of a full-bridge inverter, capacitor voltage divider, an auxiliary circuit comprising four SiC diodes and a Si IGBT switch [6]. The inverter produces output voltage in five levels: zero, 0.5Vdc, $V_{dc}$, -0.5$V_{dc}$ and -$V_{dc}$. The advantages of the inverter topology are:

- Improved output voltage quality
- Smaller filter size
- Lower EMI
- Lower THD compared with conventional three- level PWM
- Reduced number of switches compared to the conventional 5-level inverter

The circuit operation is explained as follows: The switches $S_1$, $S_2$ and $S_3$ will be switched at the rate of the carrier signal frequency while $S_4$ and $S_5$ will operate at a frequency equal to the fundamental frequency. The operation is divided into four modes. In mode1, switches $S_1$ and $S_5$ conduct and the diodes $D_1$ and $D_4$ are forward biased. The output voltage equals to + 0.5$V_{dc}$. In mode 2, switches $S_2$ and $S_5$ conduct. The output voltage equals to

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$+V_{dc}$. In mode 3, switches $S_1$ and $S_4$ conduct and the diodes $D_2$ and $D_3$ are forward biased. The output voltage equals to $-0.5V_{dc}$. Mode 4 describes the conduction of switches $S_3$ and $S_4$ where the output voltage equals to $-V_{dc}$. The conduction sequence of switches is shown in Table 1 [7].

## 3. Proposed Dual Reference Modulation Technique

Dual reference modulation technique employs two reference signals $V_{ref1}$ and $V_{ref2}$ and a single inverted sine wave carrier for generating PWM pulses for the full bridge inverter and auxiliary circuit as shown in Figure 2. The two reference signals will take turns to be compared with a single carrier at a time. If $Vref_1$ exceeds the peak amplitude of the carrier signal $V_{ref2}$ will be compared with carrier signal until it reaches 0.At this point onwards, $V_{ref2}$ takes over the comparison process until it exceeds the carrier signal.

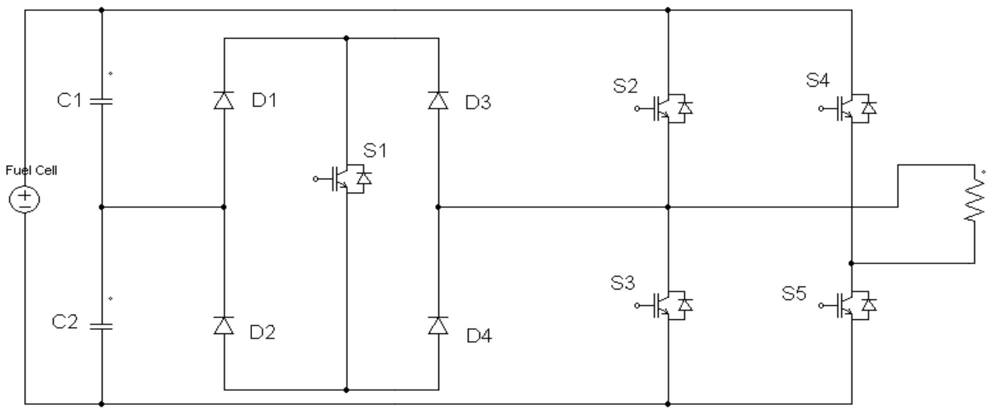


Fig. 1 Circuit Diagram of Hybrid MLI (five-level inverter)

| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $V_{inv}$ |
|---|---|---|---|---|---|
| ON | OFF | OFF | OFF | ON | $+0.5V_{dc}$ |
| OFF | ON | OFF | OFF | ON | $+V_{dc}$ |
| OFF | OFF<br>or<br>(ON) | ON<br>or<br>(OFF) | ON<br>or<br>(OFF) | ON<br>or<br>(OFF) | 0 |
| ON | OFF | OFF | ON | OFF | $-0.5V_{dc}$ |
| OFF | OFF | ON | ON | OFF | $-V_{dc}$ |

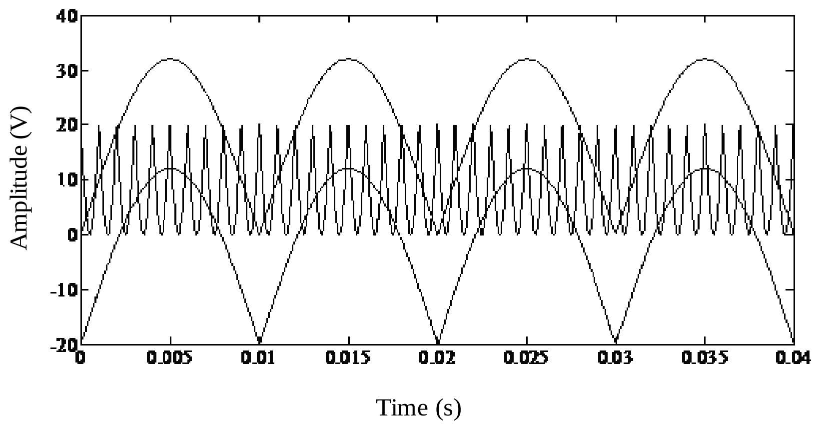


Fig. 2 Dual reference and carrier waveforms for MLI

Normally, (m-1) carriers are needed to produce 'm' level in MLI [8]. But, the proposed modulation technique employs only a single carrier signal leading to simplified pulse generation. The modulation index ($m_a$) for this modulation technique is given by:

$$m_a = \frac{A_m}{2A_c} \quad (1)$$

where $A_m$ represents the peak value of the reference waveform and $A_c$ represents the peak-peal value of the carrier waveform. The pulses generated using the proposed modulation technique is used to trigger the IGBTs in a sequential manner such that the desired output is obtained. The gating pulse obtained in MATLAB/SIMULINK is shown in Fig. 3.

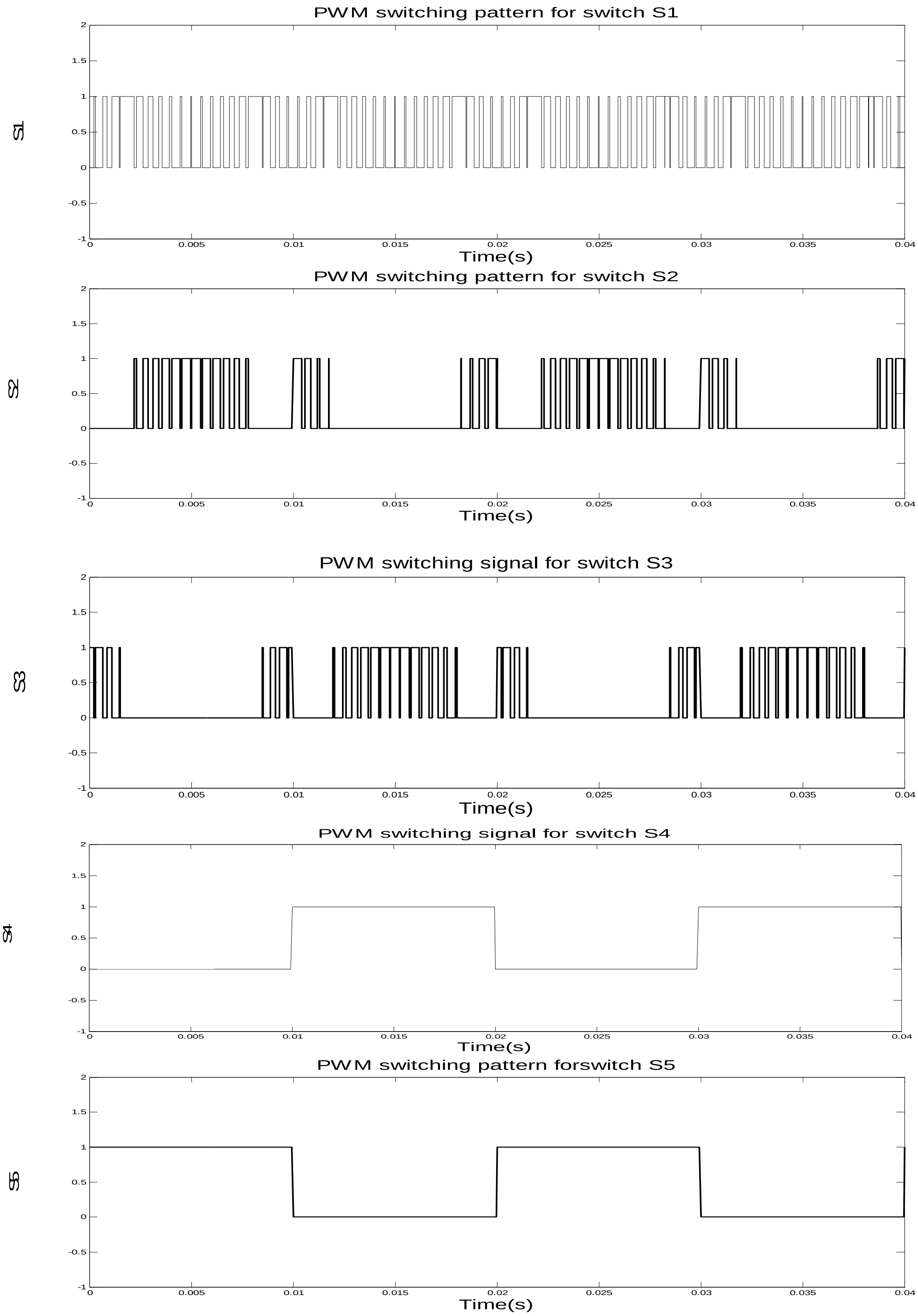


Fig. 3 Gating pattern for MLI using the dual reference modulation technique

The proposed modulation technique is compared with dual inverted sine wave carrier wave as shown in Fig. 4.

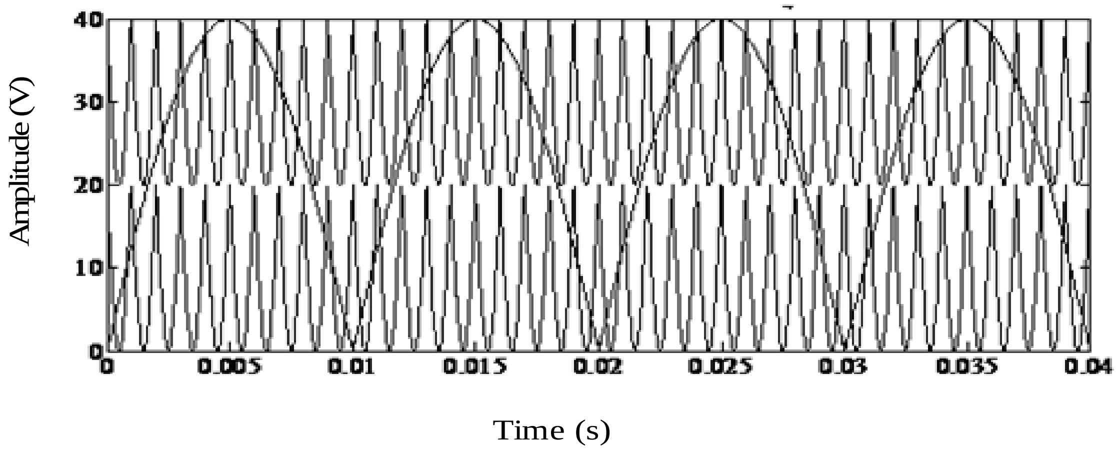


Fig.4. Dual carrier and a single reference waveforms for MLI

**4._Performance Evaluation Of Hybrid Mli Employing Dual Reference Moulation Technique**

The performance evaluation [9] of dual reference modulation technique employing inverted sine wave as carrier for a single-phase five-level inverter has been done using MATLAB and the optimum switching frequency ($f_s$ =12kHz) with minimized total harmonic distortion and switching loss is determined. The simulation result for the load voltage is shown in Fig. 5. The variation of THD with the change in the switching frequency is shown in the Fig. 6. The THD decreases with increase in switching frequency.

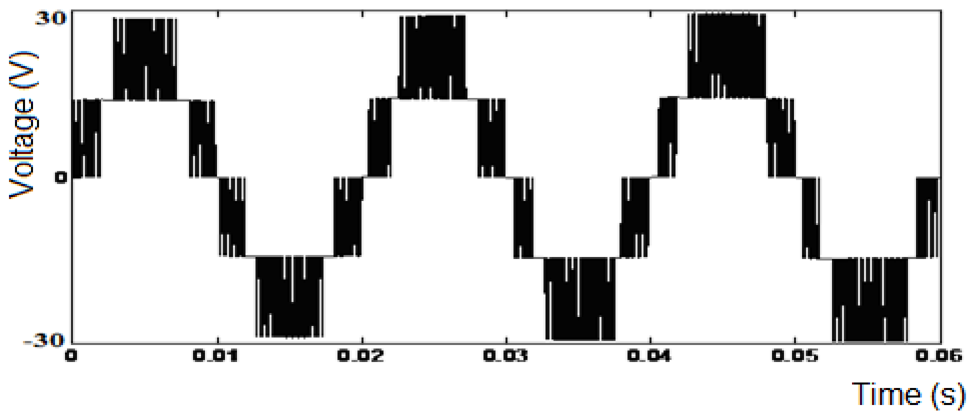


Fig. 5 Simulated five-level output waveform of hybrid MLI

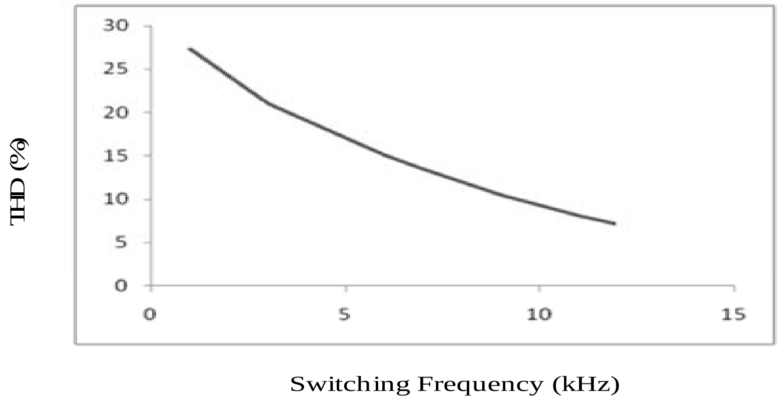


Fig. 6 THD Vs switching frequency

Table 2 shows the comparison of THD for both dual carrier and dual reference modulation techniques for $m_a$=0.75 and $f_s$=12 kHz. It is obvious that the dual reference modulation technique with inverted sine wave has less THD compared to dual carrier modulation technique.

**Table 2 Comparison of Dual Reference & Dual Carrier Modulation Technique**

| Type of Carrier | Dual Reference(THD) | Dual Carrier(THD) |
|---|---|---|
| Inverted sine wave | 6.78 % | 8.55 % |
| Saw Tooth wave | 7.66 % | 9.32 % |

### 4.1. Switching Losses

Switching loss is the power dissipation during turn-on and turn-off switching transitions. In high frequency PWM, switching loss can be substantial and must be considered in the thermal design of the inverter. It is a big drawback that results in a series of problems such as increasing the cost of the inverter and decreasing its efficiency in high voltage and high power applications. Higher the power being processed, the more severe the effect of the switching loss becomes. Switching loss analysis for HCMLI is a complex process due to the wide number of switching states of the inverter [10]. The most accurate method of determining switching losses is to plot the current and voltage waveform in the controllable switch during the switching transition and multiply the waveform point by point to get an instantaneous power waveform. The area under the power curve is the switching energy at turn-on or turn-off. The equations governing the calculation of switching loss for bridge $H_1$ consisting of Si IGBT (FGA25N120) and Si diode (fast recovery diode FR107) are given below and the switching energy is obtained from the area under the power curve. The equations governing the switching loss is given by

$$P_{sw} = f_{sw} E_{sw} \tag{2}$$

where, $P_{sw}$ is the switching loss of IGBT, $f_{sw}$ is the switching frequency, $E_{sw}$ is the switching energy.The switching energy is given by

$$E_{sw} = E_{on} + E_{off} \tag{3}$$

where, $E_{on}$ represents turn-on energy loss, $E_{off}$ represents turnoff energy loss. The expression for $E_{on}$ and $E_{off}$ is given by

$$E_{on} = \int_0^{ton} P(t).dt = \frac{1}{2} V_{CE}\, I_C\, t_{on} \tag{4}$$

$$E_{o_{ff}} = \int_0^{toff} P(t)\, dt = \frac{1}{2} V_{CE}\, I_C\, t_{off} \tag{5}$$

Therefore, the switching energy is given by

$$E_{sw} = \frac{1}{2} V_{CE}\, I_c \left( t_{on} + t_{off} \right) \tag{6}$$

The diode switching loss is given by

$$P_{swD} = \frac{1}{2} V_o\, I_{RM}\, t_{rr}\, f_s \tag{7}$$

where, $P_{swD}$ represents the diode switching loss, $V_o$ represents the voltage, $t_{rr}$ represents the reverse recovery time, $I_{RM}$ represents the peak reverse recovery current, $f_s$ represents the switching frequency. The SiC diode chosen for auxiliary circuit for hybrid MLI has high reverse breakdown voltage, less reverse recovery current, less reverse recovery time and the simulated results are shown in Table 3.

Table 3 Comparison of $I_{rr}$ and $t_{rr}$ for Si and SiC diode

| Parameter | Si Diode | SiC Diode |
|---|---|---|
| Reverse recovery current ($I_{rr}$) | 100A | 20A |
| Reverse recovery time ($t_{rr}$) | 60ns | 20ns |

The switching losses for hybrid MLI using dual reference modulation technique for various switching frequencies are calculated and graph is shown in Fig. 7.

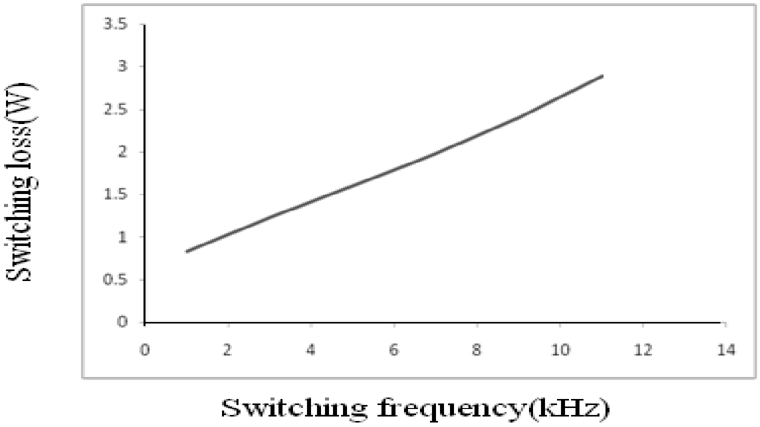


Fig.7 Switching loss Vs Switching frequency

Proportional Integral (PI) controller [11,12] is employed to regulate the load voltage of hybrid MLI and the controller is tuned using Zeigler's Nicols method. The simulation parameter for the closed loop control of hybrid MLI is shown in Table 4.

Table 4. Simulation Parameters for Closed loop Control of MLI

| Parameters | Values |
|---|---|
| Input Voltage ($V_{in}$) | 100 volt |
| Reference Voltage ($V_{out}$) | 80 volt |
| Frequency of the carrier ($f_c$) | 12000 Hz |
| Proportional constant ($K_p$) | 0.6 |
| Integral constant($K_i$) | 1000 |
| For Filter: Inductance (L) | 400mH |
| Capacitance (C) | 2500uF |

The closed loop load voltage and load current waveforms of hybrid MLI is shown in Fig. 8.

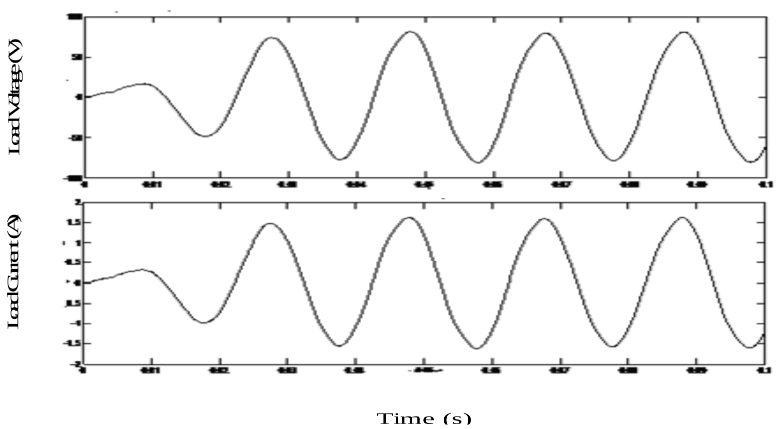


Fig. 8 Closed loop steady-state response of load voltage and load current of hybrid MLI

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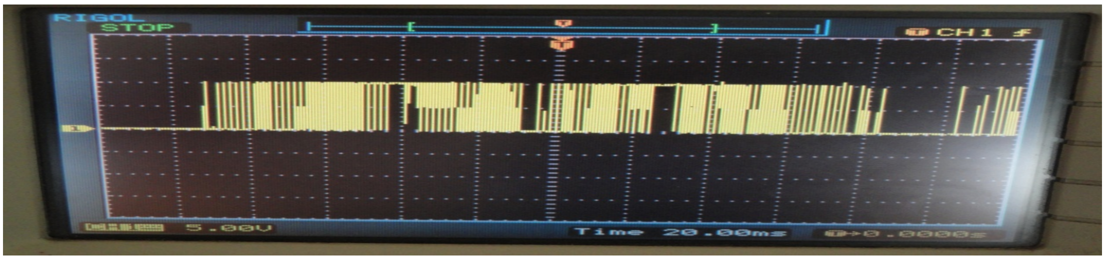
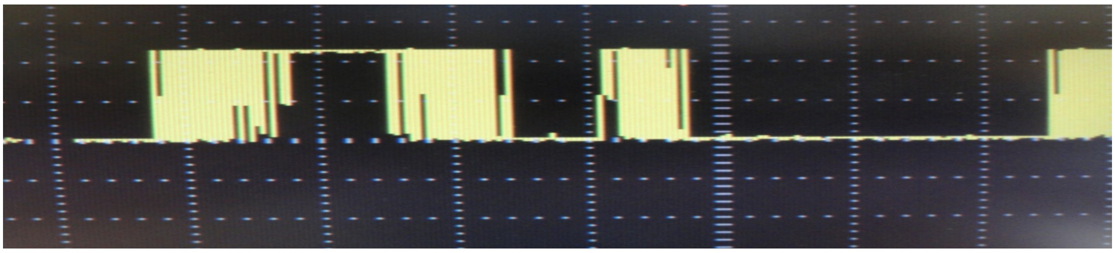
## 5. Experimental Results

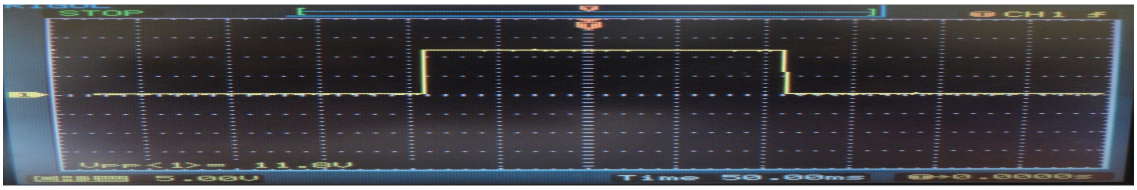
To experimentally validate the hybrid cascaded MLI using the proposed modulation, a prototype five-level inverter has been built using FGA25N120 Si IGBT for the full bridge inverter and CSD100060 SiC diode as the switching devices as shown in Fig.9. The gating signals are generated using PIC18F4550 microcontroller.



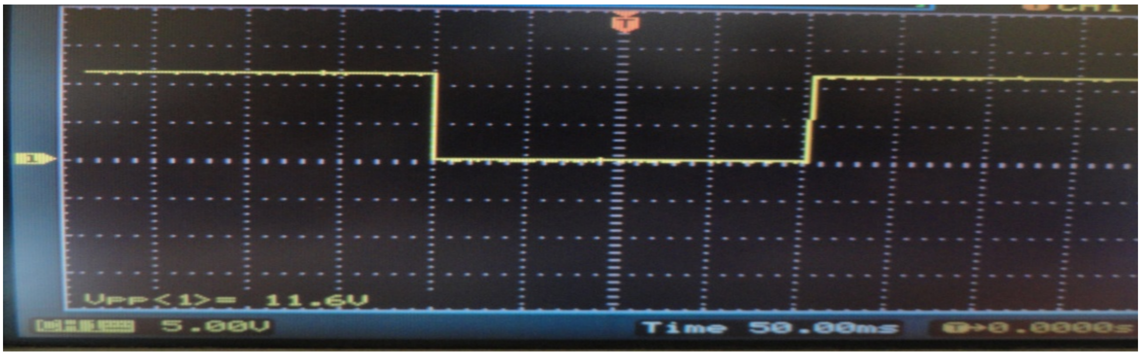
a. Gating pattern for the switch S1 (the switching pattern obtained from portB of PIC18F4550)


b.Gating pattern for the switch $S_2$ (the switching pattern obtained from portB of PIC18F4550)

c. Gating pattern for the switch $S_3$ (the switching pattern obtained from portB of PIC18F4550)



d. Gating pattern for the switch $S_4$ (the switching pattern obtained from portB of PIC18F4550)



e. Gating pattern for the switch $S_5$ (the switching pattern obtained from portB of PIC18F4550)

Fig.9 Gating pattern for the switches in hybrid MLI

The hardware implementation of hybrid MLI is shown in Fig.10.

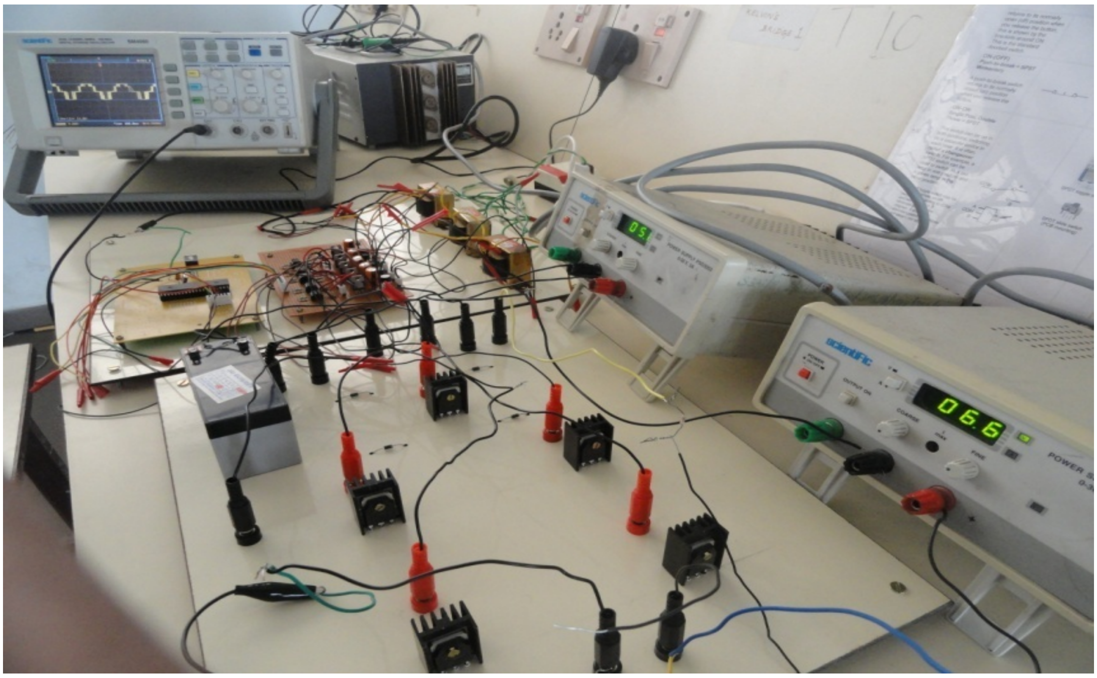


Fig.10 Photograph for hardware implementation of Hybrid MLI

The experimental load voltage of five-level inverter for R-load (R= 30 ohms) is shown in Fig. 11

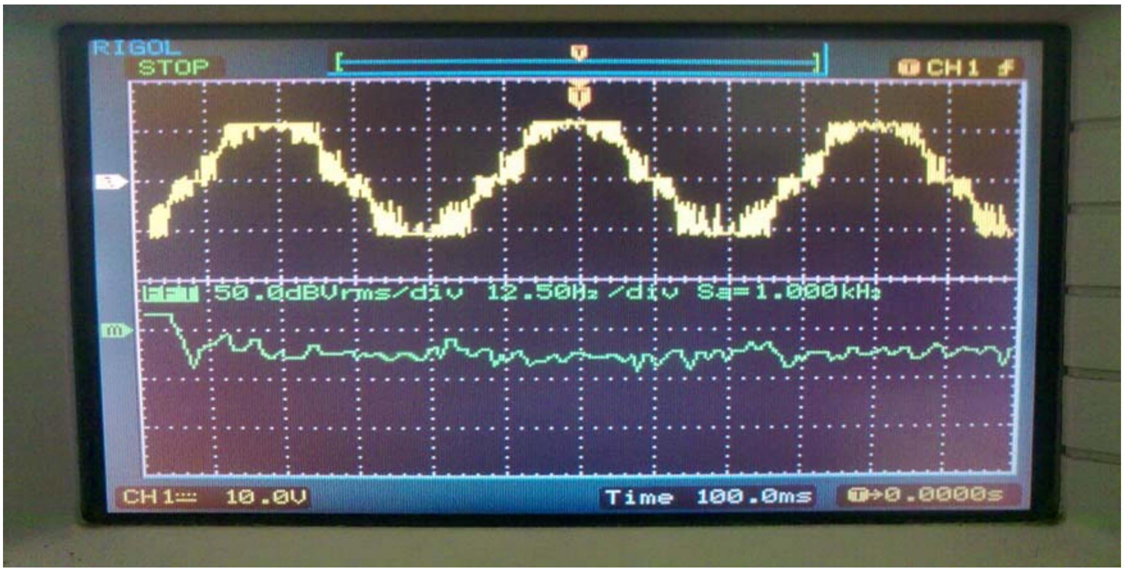



Fig .11 Five-level voltage of hybrid MLI

## 6. Conclusion

This paper has presented a hybrid MLI with SiC diodes for fuel cell applications. A novel dual reference modulation technique employing inverted sinewave carrier has been investigated. The performance parameters of the inverter such as THD and switching losses has been analyzed. It was found that dual reference modulation technique for hybrid MLI resulted in reduced THD of about 6.78% at a modulation index of 0.75 ands witching frequency of 12kHz compared to the conventional single reference and dual carrier technique. A suitable PI controller has been designed to regulate the output voltage of MLI. The results of simulation have been verified by experimentation. The proposed hybrid MLI topology is suited for fuel cell applications. With this dual reference PWM technique of hybrid MLI, it is possible to construct high power drives with high output voltage and low THD.

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## Bibliography of authors

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