A Hybrid Seven- Level Inverter for Fuel Cell Power Conditioning System

R. Seyezhai [1] B.L. Mathur [2]

Abstract –This paper investigates the potentials of a hybrid cascaded seven-level inverter for fuel cell power conditioning systems (PCS). Fuel cell is one of the most important sources of distributed energy because of its high efficiency, high energy density, plus high reliability and long life due to few moving parts. This article proposes a suitable modulation strategy for the hybrid inverter that fulfills the required performance specifications of a fuel cell power system. The main advantage of this topology is that the modulation, control and protection requirements of each bridge are modular and it requires only a single dc source in each phase leg. Among the several modulation strategies proposed for the seven- level inverter, the space vector modulation (SVM) and carrier based PWM are the most popular ones. And this paper focuses on the Phase Disposition (PD) carrier PWM method as it gives less harmonic distortion on the line to line output. The PDPWM is implemented using an FPGA processor so that better resolution is achieved in the control of multilevel inverter output voltage magnitude and it is verified experimentally.

Keywords – Hybrid multilevel inverter, fuel cell, multicarrier PWM, PCS

I. INTRODUCTION

Multilevel inverters are used to synthesize a desired single or three-phase voltage 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. There are several topologies of multilevel inverter but the one considered in this paper is the hybrid cascaded multilevel inverter (HCMLI). This topology has many advantages not only in terms of its simple structure but also allows the use of a single dc source as the first dc source with the remaining (n-1) dc sources being capacitors[1]. The voltage regulation of the capacitor is the key issue and this is achieved by the switching state redundancy of the proposed modulation strategy. This scheme also provides the ability to produce higher voltages at higher speeds with low switching losses and high conversion efficiency. For the cascaded multilevel inverter variety of modulation strategies have been reported, with the most popular being carrier – based and space vector modulation (SVM). Several multi carrier techniques have been developed to reduce the distortion in multilevel inverter, based on the classical SPWM with triangular carriers. Multicarrier PWM methods can be categorized into two groups: Carrier Disposition methods (CD), where the reference waveform is sampled through a number of carrier waveforms displaced by continuous increments of the reference waveform amplitude and phase shifted (PS) PWM methods, through a number of carrier waveforms displaced by continuous increments of the reference waveform amplitude and phase shifted (PS) PWM methods, where multiple carriers are phase shifted accordingly [2]. This paper focuses on the Phase disposition (PD) carrier PWM method as it gives a least THD of 5.2%. Both the HCMLI circuit topology and its control scheme are described in detail and their performance is verified based on simulation and experimental results.

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II. HYBRID CASCADED SEVEN-LEVEL INVERTER

A hybrid seven- level cascaded H-bridge inverter has two H-bridges for each phase. One H-bridge is connected to a dc source and another is connected to a capacitor, as shown in Fig. 1. The dc source for the first H-bridge (H_1) could be a battery or fuel cell with an output voltage of V_{dc}, and the dc source for the second H-bridge (H_2) is the capacitor voltage, to be held at V_c. The output voltage of the first H-bridge is denoted by V_1, and the output of the second H-bridge is denoted by V_2 so that the output voltage of the cascaded multilevel converter is $V(t) = V_1(t) + V_2(t)$.

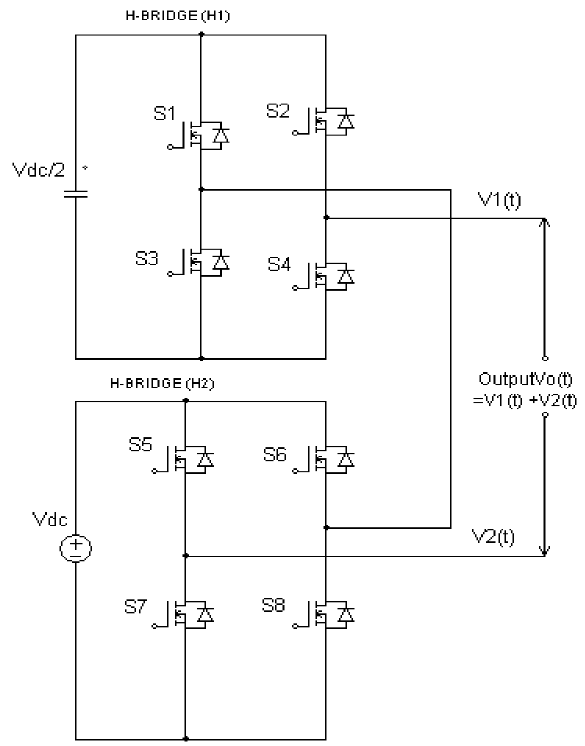

Fig. 1: Hybrid cascaded multilevel inverter

By opening and closing the switches of H_1 appropriately, the output voltage V_1 can be made equal to $-V_{dc}$, 0, or $+V_{dc}$ while the output voltage of H_2 can be made equal to $-V_c$, 0, or V_c.(refer Fig. 2.). Therefore, the output voltage of the converter is a combination of V_{dc} and V_c which can have nine possible values $-(V_{dc}+V_c)$, $-(V_{dc}-V_c)$,$-V_c$, 0, V_c, (V_{dc}-

V_c), V_{dc}, ($V_{dc}+V_c$) and -Vdc. For the nine possible levels used in a cycle, -(V_{dc}-V_c) and (V_{dc}-V_c) can be used to charge the capacitors; -($V_{dc}+V_c$),-V_c, V_c and ($V_{dc}+V_c$) can be used can be used to discharge the capacitors.

The advantages of Hybrid topology are:

- Reduced number of dc sources.
- High speed capability
- Low output switching frequency
- Low switching loss
- High conversion efficiency.
- Flexibility to enhance.

The table I given below shows the comparison of topologies for multilevel inverter. Here the number of switches and number of dc sources required for the different topologies for producing the same seven - level output are compared. The hybrid multilevel inverter topology shows the least number of switches and the least number of dc sources and its output voltage waveform is shown in Fig. 2.

Table I: Comparison of topologies for multilevel inverter

Topology	Primary Devices	DC Buses/ Capacitors	Levels in the Output
Diode Clamped	36	6	7
Flying Capacitor	36	16	7
Conventional H-Bridge	36	9	7
Hybrid H-Bridge	24	6	7

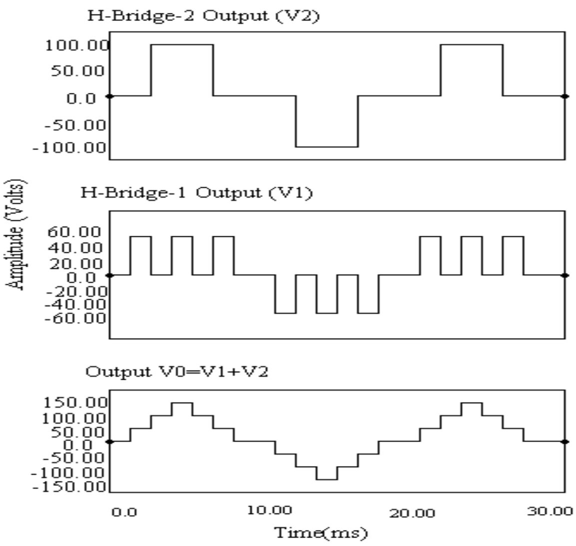

Fig. 2: Output voltage waveform of hybrid cascaded seven level inverter.

III. Proposed Control Scheme for the Hybrid Seven-Level Inverter

There are many control techniques used in multilevel inverters and the most popular being carrier – based and space vector modulation (SVM). Several multi carrier techniques have been developed to reduce the distortion in multilevel inverter, based on the classical SPWM with triangular carriers, Multicarrier PWM methods can be categorized into two groups: Carrier Disposition methods (CD), where the reference waveform is sampled through a number of carrier waveforms displaced by continuous increments of the reference waveform amplitude and phase shifted (PS) PWM methods, where multiple carriers are phase shifted accordingly [3]. The carrier disposition method comprises phase opposition disposition (POD) method, phase disposition (PD) method and Alternative phase opposition disposition (APOD) method. This paper focuses on the Phase disposition (PD) carrier PWM method as it gives a least THD of 5.2%. The PDPWM is implemented using Spartan FPGA processor so that better resolution is achieved.

A. Phase Disposition Modulation Method (PDPWM)

In this method carriers are the same in frequency, amplitude and phases, but they are just different in dc offset to occupy contiguous bands as shown in Fig. 3. For this technique, significant harmonic energy is concentrated at the carrier frequency f_c, but because it is a co-phase component, it does not appear in the line voltage. It should be noted that the other harmonic components are centered on the carrier frequency as sidebands. Among the discussed techniques, PD technique has less harmonic distortion on line voltages [4]. An example of the carriers that is used in a two modular seven- level PWM inverter is shown in Fig.3.There are six distinct carriers, all in phase with one another and with the same magnitudes(A_c), the difference between the carriers is that they are all displaced by dc offset. The reference waveform has peak-to-peak amplitude A_m, a frequency f_m, and its zero is centered in the middle of the carrier set. The reference is continuously compared with each of the carrier signals. If the reference is greater than a carrier signal, then the active device corresponding to that carrier is switched on; and if the reference is less than a carrier signal, then the active device corresponding to that carrier is switched off [5]. With reference to Fig. 1. if we consider the first bridge H_1, the modulation rules are:

If $V_{ref} > V_{triangle\ -1}$, then the switch S_1 – on, S_3- off.

If $V_{ref} < V_{triangle\ -1}$, then the switch S_1 –off, S_3 - on.

The resultant gate control is obtained by comparing each of the carriers to the related part of the sinusoidal reference, which in turn controls a specific gate and the switching pattern for PDPWM is shown in Fig. 4.

In multicarrier PWM, the amplitude modulation index m_a, and the frequency ratio m_f, is defined as

$$m_a = \frac{A_m}{(m-1).A_c} \tag{1}$$

$$m_f = \frac{f_c}{f_m} \tag{2}$$

when applying this method to a multi- modular system the carriers are divided amongst each of the modules. Therefore in the case of obtaining a seven- level output voltage from a two- modular PWM hex bridge inverter, the top module is responsible for producing the bottom of the positive level, and the bottom module is responsible for the top PWM level. The Phase Disposition method has significant harmonic energy and is concentrated at the carrier frequency, which is usually set at a moderate to high value [6].

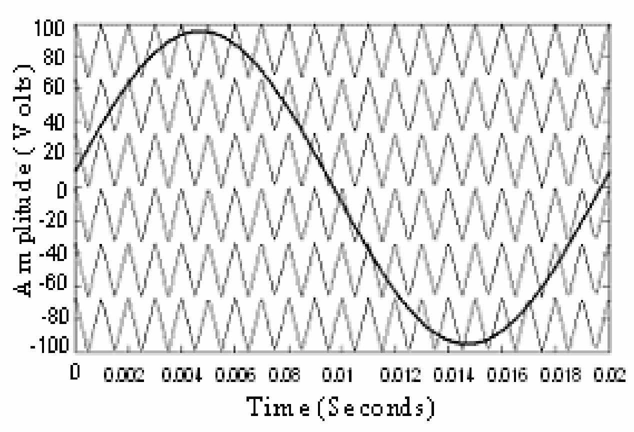

Fig. 3: Modulating and carrier waveforms for PDPWM.

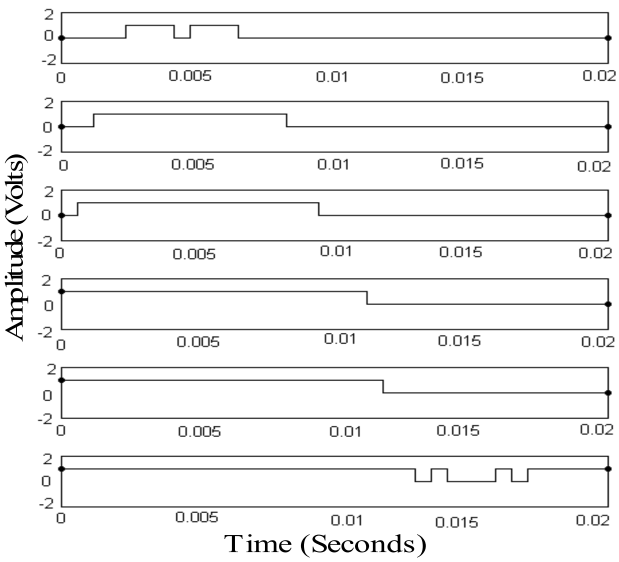

Fig. 4: Switching pattern for PDPWM

For a three-phase system, the value of frequency modulation index (m_f) should be multiples of three and if m_f is odd, the PD-method generates the lowest Total Harmonic Distortion (THD) value. The value of amplitude modulation index (m_a) is 0.95 and the frequency modulation index (m_f) is 21.

IV. Characteristics of a PEM Fuel Cell

The proton exchange membrane fuel cell (PEMFC) has been considered as a promising kind of fuel cell during the last 10 years because of its low working temperature, compactness, and easy and safe operational modes. The proton exchange membrane (PEM) fuel cell is very simple and uses a polymer (membrane) as the solid electrolyte and a platinum catalyst. The hydrogen from a pressurized cylinder enters the anode of the fuel cell and the oxygen (from air) enters the cathode. Protons and electrons are separated from hydrogen on the anode side. In a basic PEM cell, the protons are transported to the cathode side through the polymer and the electrons are conducted through the load outside the electrode. A fuel cell stack is composed of several fuel cells connected in series separated by bipolar plates and provides fairly large power at higher voltage and current levels.

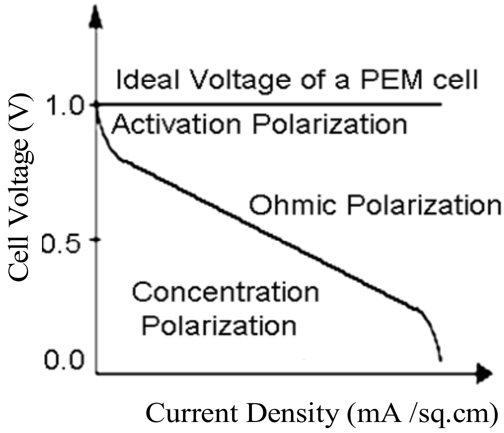

Fig. 5: Ideal VI characteristics of a single PEM fuel cell.

The electrical characteristics of the fuel cell output can be represented by current density versus voltage curve as shown in Fig. 5. The voltage at lower current density drops significantly at higher load current and maximum power occurs in theohmic region. Hence, ohmic region is used as a voltage window for the power conditioner unit input. Since the output voltage generated by each fuel cell is relatively low at full output current, they are stacked in series to produce the required voltage level. In this work a fuel cell unit with an output voltage of 40V is taken and the simulated polarization curve is shown in Fig. 6. And a high efficiency power conversion system is required for better operation. The power conditioning circuits for the fuel cell are inverters and dc/dc converters. In almost every application, ac power is required demanding the utilization of an inverter in the power conditioning system [7].

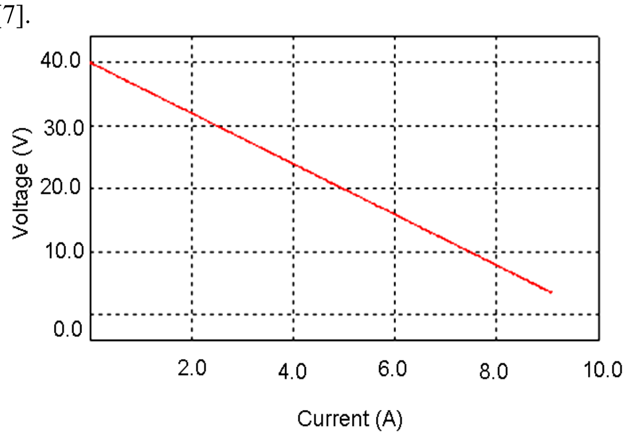

Fig. 6: Polarization curve of a 1kW PEM fuel cell.

And the literature shows multiple types of inverter designs. Also, if more power is required than what is available from the standard size fuel cell, and then modules need to be aggregated. There is more than one approach to aggregate numerous fuel cell modules for high voltage applications. One such approach is the multilevel architecture [8]. In this paper, a hybrid cascaded H-bridge multilevel inverter is proposed for the fuel cell power conditioning system as it not only requires a single dc source in each phase leg but also highly reliable and efficient.

V. Simulation Results

The simulation results for PDPWM based hybrid multilevel inverter for fuel cell power conditioning systems is shown in Fig. 7.

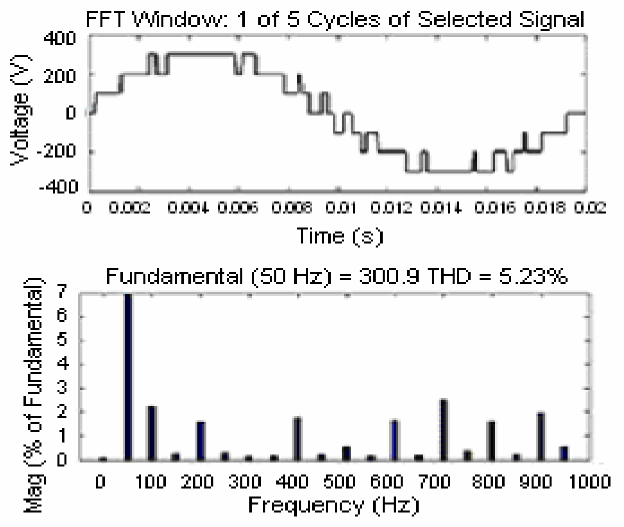

Fig. 7: Simulated output and FFT for PDPWM.

The work presents different pulse width modulation (PWM) control techniques for the hybrid seven-level cascaded multilevel inverter. The investigation is made in terms of Total Harmonic Distortion (THD) and switching frequency [9]. The Fig. 8. gives the harmonic spectra for the multicarrier pwm techniques. It gives a clear picture of the gap between the fundamental and the first significant harmonics for the various multicarrier pwm techniques. While using phase disposition for higher level systems, it is noted that the significant harmonics are locked to the carrier frequency and the gap between the fundamental and the first significant harmonics is decreased even though the amplitude of each harmonic around the carrier frequency is reduced. So, PDPWM seems to be favourable among the disposition techniques.

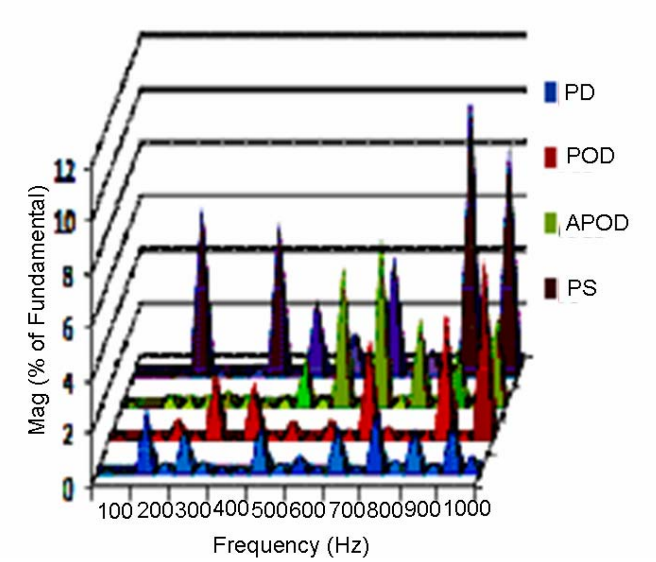

Fig. 8: Spectra for the various multicarrier PWM methods for ma =0. 95

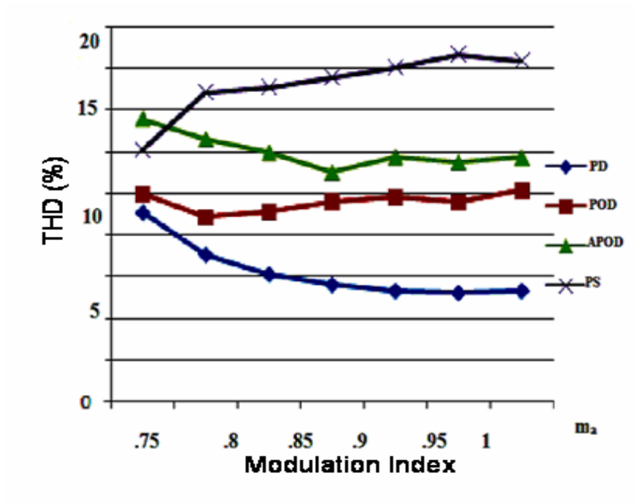

Fig. 9: THD for different multicarrier PWM methods

Fig.9.shows the line voltage THD for the hybrid multilevel inverter based on PD, APOD, POD and PS methods. From the results, it is found that for different amplitude modulation index (m_a) ranging from 0.7 to 1, the PD scheme achieves the lowest line voltage THD compared to other multicarrier PWM techniques. This is due to the fact that the PD method places significant harmonic energy into a carrier component for each phase leg, and relies on common mode cancellation between the inverter phase legs to eliminate this carrier energy from the line-to-line output voltage [10]. Consequently, the harmonic sidebands (which are not fully cancelled between the phases) have less energy. Also, from the simulation study conducted, many distinct features of hybrid MLI using PD scheme for the line voltage can be identified. The line voltage is able to synthesize more levels compared to phase voltage. Besides that, the line voltage yields better spectral performance, hence reducing the need for an output filter. Also, at high modulation index, the PDPWM technique introduces the lowest line voltage THD. PD method shows the lowest THD of about 5.23%. with f_c=1050 *kHz* and m_a= 0.95 as shown in Fig. 9.Hence PDPWM is employed for the hybrid cascade multilevel inverter.

VI. Experimental Results

To experimentally validate the proposed hybrid cascaded H-bridge multilevel inverter as shown in Fig. 1 for the fuel cell power conditioning system [11], a prototype seven - level inverter has been built using IRF450 Power MOSFETS as the switching devices. Only one dc source (fuel cell) was used for the hybrid cascaded MLI and the other source being capacitor (4700uF/100V -2nos in parallel) to generate seven levels. The gating signals were generated using FPGA processor based on phase disposition PWM techniques and the output power level of the inverter is 850W .From the Fig. 13. It is observed that the second level is constant at 20V and it is because of the main dc source. The first and third level requires capacitor voltage where the capacitor voltage is maintained at 10V. The corresponding FFT plot is also shown in Fig. 12. The gating pulses are shown below:

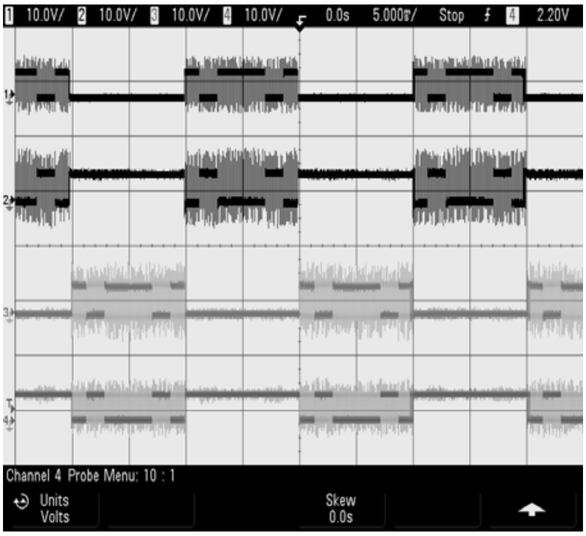

Fig. 10: Pulse pattern for the first bridge

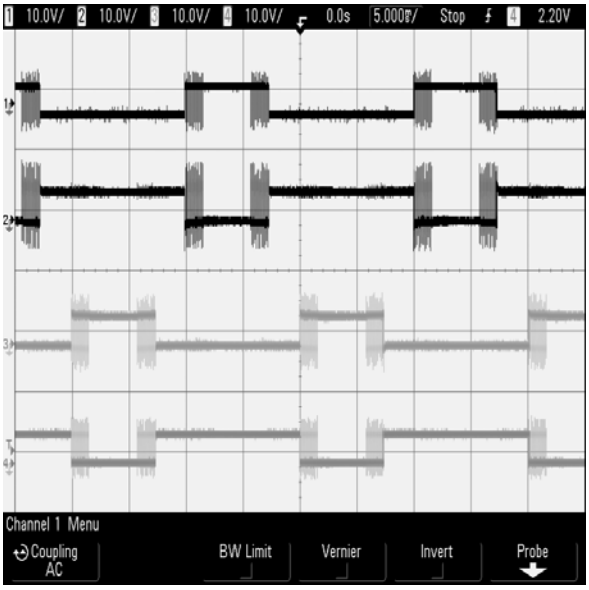

Fig. 11: Pulse pattern for the second bridge.

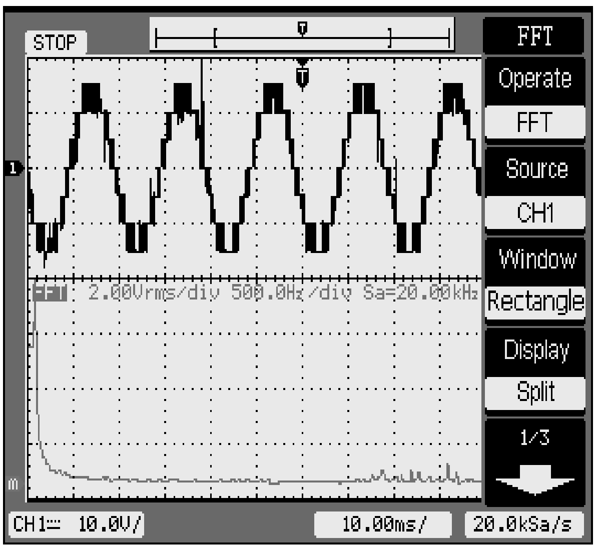

Fig. 12: Experimental output waveform and FFT for the hybrid seven–level inverter.

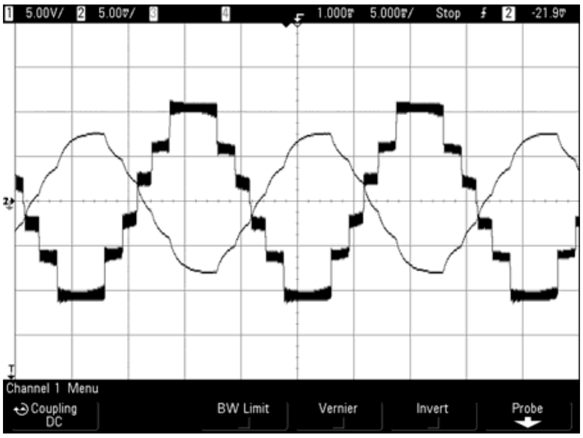

Fig. 13: Experimental equal 7-level output voltage and current waveform for the hybrid inverter with R=50Ω and L=36mH.

VII. Conclusion

In this paper, a hybrid seven level cascaded inverter have been investigated for fuel cell power conditioning system. A single dc power source and two H-bridges for each phase have been used as a good tradeoff between performance and cost. PDPWM technique is recommended as it gives least THD of about 5.23% at a modulation index of 0.95 and carrier frequency of 1050 kHz. This technique of modulation is better when compared with the APOD and PODS ones, as the PD scheme has advantages in three-phase applications due to the cancellation of the main carrier component between phase legs when the line voltages are formed [12]. At high modulation index, the PDPWM technique introduces the lowest line voltage THD. The results of simulation have been verified by experimentation. The proposed hybrid multi level inverter topology is suited for fuel cell electric vehicles motor for drive applications. With this PWM technique of hybrid MLI, it is possible to construct high power drives with high output voltage and low THD.

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BIOGRAPHIES

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