A Novel PWM Hybrid Multilevel Inverter for Fuel Cell Applications

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ABSTRACT

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy and it is a clean energy source. Among the several types of fuel cell, Proton Exchange Membrane Fuel Cell (PEMFC) is a suitable choice for distributed energy sources. In this paper, modeling of PEM fuel cell has been carried out and simulated using MATLAB. A single phase Hybrid Multilevel Inverter (HMLI) with reduced number of switches interfaced with PEMFC has been designed and analyzed. A novel hybrid Pulse Width Modulation (PWM) technique which employs multiple reference signals and a single inverted sine carrier wave has been proposed for HMLI. The inverter circuit topology and its control scheme have been described in detail and their performance has been verified based on Total Harmonic Distortion using MATLAB/SIMULINK.

General Terms

Analyze, verification

Keywords

Proton Exchange Membrane Fuel Cell (PEMFC), Hybrid Multilevel Inverter (HMLI), Multiple References Pulse Width-Modulated (PWM), Total Harmonic Distortion (THD).

1. INTRODUCTION

Fuel cell is a high quality green energy source and it is gaining much attention because of its light weight, compact size, low maintenance, high efficiency and reliability. Compared with the other types of fuel cells, PEMFC shows promising results with its advantages such as low temperature, high power density, fast response, and zero emission if it is run with pure hydrogen, and it is suitable for use in portable power supply, vehicles, residential and distributed power. This paper presents a single phase hybrid multilevel inverter (HMLI) interfaced with proton exchange membrane fuel cell (PEMFC).

There are several types of multilevel inverters has been proposed but the one Considered in this work is the hybrid cascade multilevel inverter. In this paper, a seven-level HMLI is used instead of conventional three-level inverter because it offer grater advantages, such as improved output waveform, smaller filter size, lower EMI and lower total harmonic distortion(THD).The new inverter topology offers an important improvement in terms of less component count and reduced complexity when compared with the other conventional inverters [1].

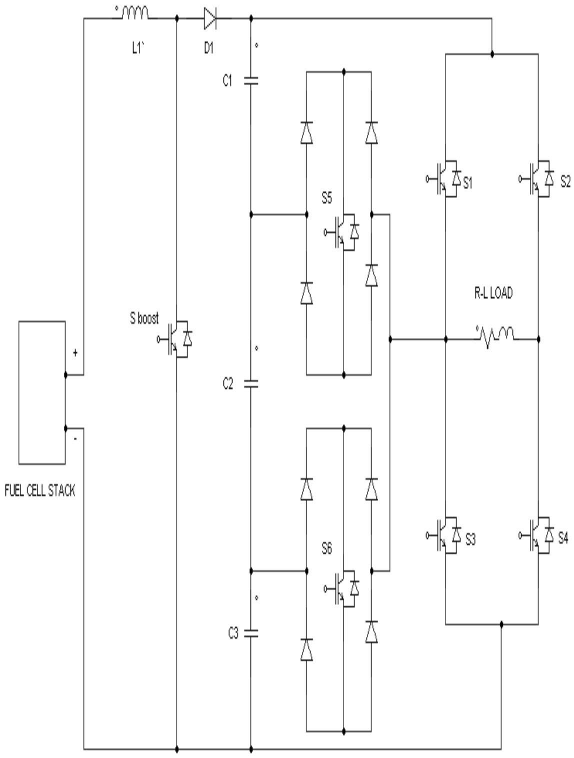


Figure 1: Hybrid multilevel inverter for fuel cell system

A seven-level HMLI topology [2-4] is interfaced with PEMFC via dc-dc boost converter, as shown in Fig. 1. An auxiliary circuit comprising for diodes and a switch is configured together with a conventional full-bridge inverter to form this topology. A novel PWM modulation technique is used to generate switching signals for the switches and to generate seven output–voltage levels: 0, +Vdc/3, +2Vdc/3, +Vdc, -Vdc/3, -2Vdc/3,-Vdc. Simulation results are presented to validate the proposed inverter configuration.

2. HYBRID SEVEN-LEVEL INVERTER

The proposed single-phase seven-level inverter consist of single-phase conventional H-bridge inverter, two bidirectional switches and a capacitor voltage divider formed by C_1, C_2 ,and C_3, as shown in Fig. 2. The modified H-bridge topology is significantly advantageous over other topologies, i.e., less power switch, power diodes, and less capacitor for inverters of the same number of levels.

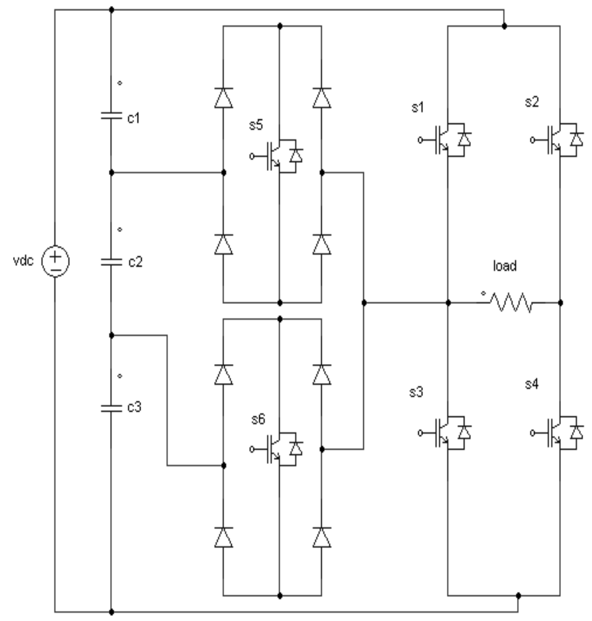


Figure 2: Proposed seven-level inverter topology

Proper switching of the inverter can produce seven output-voltage levels (0, $+V_{dc/3}$, $+2V_{dc/3}$, $+V_{dc}$, $-V_{dc/3}$, $-2V_{dc/3}$, $-V_{dc)}$.The proposed inverter operation can be divided into seven switching states, as shown in the Table 1.

Table 1. Conduction Table For Hmli

Vo	S1	S2	S3	S4	S5	s6
Vdc	On	Off	Off	On	Off	Off
2 Vdc/3	Off	Off	Off	On	On	Off
Vdc/3	Off	Off	Off	On	Off	On
0	On	On	On	On	Off	Off
-Vdc	Off	On	Off	Off	On	Off
-2 Vdc/3	Off	On	Off	Off	Off	On
-Vdc/3	Off	On	On	Off	Off	Off

1) To obtain + V_{dc} : S_1 is ON and S_4 is ON. All other controlled switches are OFF, the voltage applied to the load terminals is + V_{dc}.

2) To obtain + $2V_{dc}/3$: The bidirectional switch S_5 is ON and S_4 is ON .All other controlled switches are OFF, the voltage applied to the load terminals is + $2V_{dc}/3$.

3) To obtain + $V_{dc}/3$: The bidirectional switch S_6 is ON and S_4 is ON. All other controlled switches are OFF, the voltage applied to the load terminals is + $V_{dc}/3$.

4) To obtain Zero output: This level can be produced by two switching combinations; switches S_3 and S_4 are ON, or $S_1$and S_2 are ON, and all other controlled switches are OFF, the voltage applied to the load terminals are zero.

5) To obtain - $V_{dc}/3$: The bidirectional switch S_5 is ON and S_2 is ON. All other controlled switches are OFF, the voltage applied to the load terminals is - $V_{dc}/3$.

6) To obtain -$2V_{dc}/3$: The bidirectional switch S_6 is ON and S_2 is ON. All other controlled switches are OFF, the voltage applied to the load terminals is - $2V_{dc}/3$.

7) To obtain – V_{dc}: S_2 is ON and S_3 is ON. All other controlled switches are OFF, the voltage applied to the load terminals is - V_{dc}.

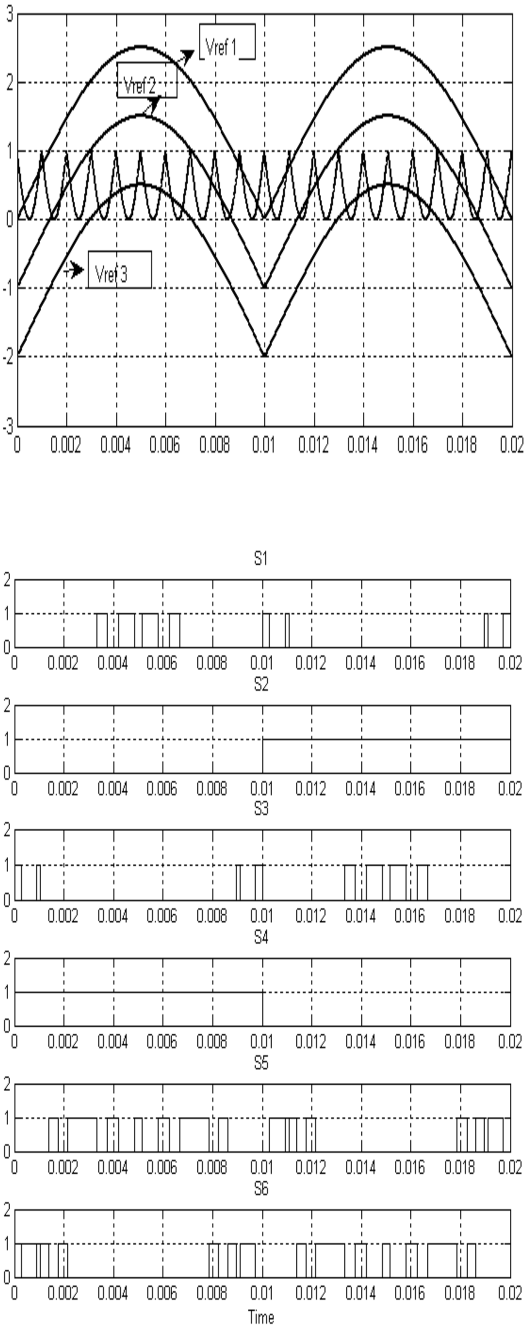


Figure 3: Multiple reference PWM technique and switching pattern for HMLI

3. MODULATION STRATERGY FOR HYBRID MULTILEVEL INVERTER

In conventional modulation techniques [5-7] single reference signal is compared with multiple carrier signals to generate PWM signal. A novel modulation technique was proposed to generate PWM signals. Multiple reference signals were compared with single inverted sine carrier signal. The multiple reference signals had the same frequency and amplitude and were in phase with a bias value that was equivalent to the amplitude of the carrier signal. The reference signals were each compared with the carrier signal to generate the switching pattern. If V_{ref1} had exceeded the peak amplitude of Vcarrier, V_{ref2} was compared with Vcarrier until it had exceeded the peak amplitude of Vcarrier. Then, onward, V_{ref3} would be compared with Vcarrier until it reached zero. Once V_{ref3} had reached zero, V_{ref2} would be compared until it reached zero. Then, onward, V_{ref1} would be compared with Vcarrier.

Fig. 3 shows the resulting switching pattern. Switches S_1, S_3, S_5, and S_6 would be operated at the rate of the carrier signal frequency, whereas S_2 and S_4 would operate at the rate of reference frequency.

Modulation index ma for seven-level inverter is given as [2]

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

where A_c is the peak-to-peak value of carrier and A_m is the peak value of voltage reference Vref . Because, in this paper, three reference signals that are identical to each other are used, (1) can be expressed in terms of the amplitude of carrier signal Vc by replacing Ac with Vc, and Am = V_{ref1} = V_{ref2} = V_{ref3}= V_{ref}.

4. MODELING OF FUEL CELL

Proton Exchange Membrane Fuel Cell (PEMFC) combines hydrogen and oxygen over a platinum catalyst to produce electrochemical energy with water as the byproduct. Fig. 4. shows the V-I characteristics of a typical single cell operating at room temperature and normal air pressure. The variation of the individual cell voltage is found from the maximum cell voltage and the various voltages drops (losses). The output voltage of a single cell can be defined as

$$\boldsymbol{V_{fc} = E_{nernst} - V_{act} - V_{ohm} - V_{conc}} \qquad (2)$$

Where E_{nerst} represents the reversible voltage; V_{act} is the voltage drop due to the activation of the anode and cathode; V_{ohm} is a measure of ohmic voltage drop associated with the conduction of the protons through the solid electrolyte and electrons through the internal electronic resistances; V_{conc} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases.E_{nerst} represent the no-load voltage, while the sum of all the other terms gives the reduction of the useful voltage achievable at the cell terminals, when a certain load current is required. For n cells connected in series and forming a stack, the voltage (E_{cell}), can be calculated by

$$E_{cell} = n * V_{fc} \qquad (3)$$

Several factors are responsible for the voltage drop in a fuel cell [8-10] and they are referred as polarization. The losses originate from three sources namely activation polarization, ohmic polarization and concentration polarization.

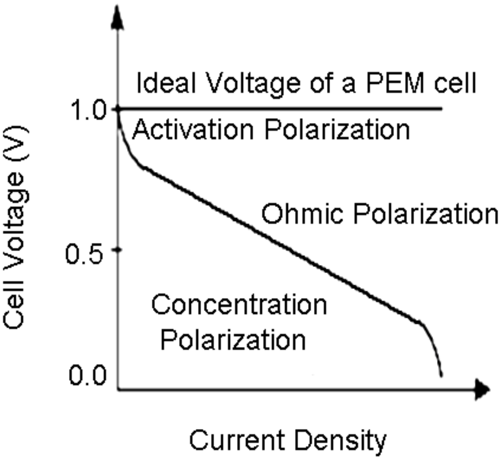


Figure 4: Ideal V-I Characteristics of a Single PEMFC

4.1 Activation polarization

The activation over voltage is the voltage drop due to the activation of anode and cathode .It can be calculated as:

$$V_{act} = -[\varepsilon_1 + \varepsilon_2 * T + \varepsilon_3 * T * \ln(C_{o2}) + \varepsilon_4 * \ln(I_{stack})] \qquad (4)$$

where, I_{stack} is the cell operating current (A), and the ε_i's represent parametric coefficients for each cell model, whose values are defined based on theoretical equations with kinetic, thermodynamic, and electrochemical foundations .C_{o2} is the concentration of oxygen

4.2 Ohmic polarization

This loss occurs due to the electrical resistance of the electrodes, and the resistance to the flow of ions in the electrolyte .It is given by

$$V_{ohm} = I_{stack} * (R_m + R_C) \qquad (5)$$

where R_c represents the resistance to the transfer of protons through the membrane, usually considered constant and R_m is

$$R_m = \rho_m * \frac{l}{A} \qquad (6)$$

ρ_m is the specific resistivity of the membrane for the electron flow (cm), A is the cell active area cm and l is the thickness of the membrane (cm), which serves as the electrolyte of the cell.

4.3 Concentaration polarization

This is due to the change in concentration of reactants at the surface of the electrodes as the fuel is used causing reduction in the partial pressure of reactants, resulting in reduction in voltage given by

$$V_{conc} = -\frac{RT}{n} * F * ln\left[l - \frac{i}{i_1}\right] \qquad (7)$$

In this paper, dynamic model of a PEM fuel cell [11-12] system developed in MATLAB-SIMULINK is presented. A PEM fuel cell system is designed using fuel cell stack. A PEM fuel cell which has values of 6 kW, 45 V DC is used. Maximum power of the fuel cell stack reaches to 8.325 kW by adjusting the fuel flow rate 85 lpm).Table 2 shows the PEMFC specifications.

Table 2. Fuel Cell Specifications

No. of cells	65
R	0.0756 ohms
P_{H2}	1.5 bar
P_{O2}	1 bar
Fuell cell Temp.	338 kelvin
Flow rate of H2	50.06 lpm

5. SIMULATION RESULTS

To obtain the V-I characteristics of the PEM fuel cell, the model is simulated using MATLAB/SIMULINK [13-14] for the following values of input variables: P_{H2} (anode pressure) = 1.5 bar, P_{O2} (cathode pressure) = 1bar, T (temperature of the cell) = 323K. The simulated V-I characteristics of a single PEM fuel cell are shown in Fig.5 which depicts the various polarization losses.

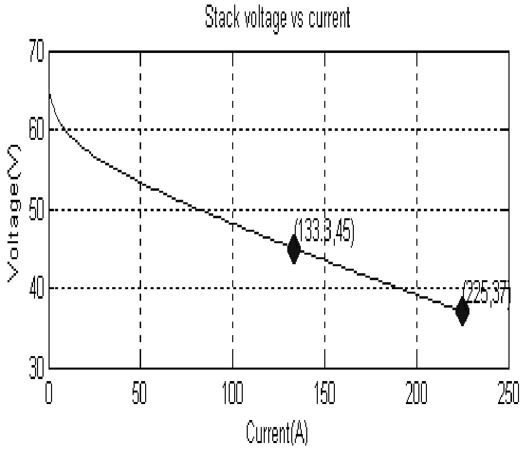


Figure 5: V-I characteristics of PEMFC

The work presents the proposed multiple reference PWM technique for the hybrid seven-level cascaded multilevel inverter is simulated using MATLAB-SIMULINK with the parameters shown in Table 3. The investigation is made in terms of THD.

Table 3. Simulation Parameters

Output fuel cell voltage V_{fc}	65 V
Output Boost Converter voltage V_o	300 V
Output Load voltage V_l	300 V
switching frequency F_s	3150 Hz
R	10 ohms
L	3mH

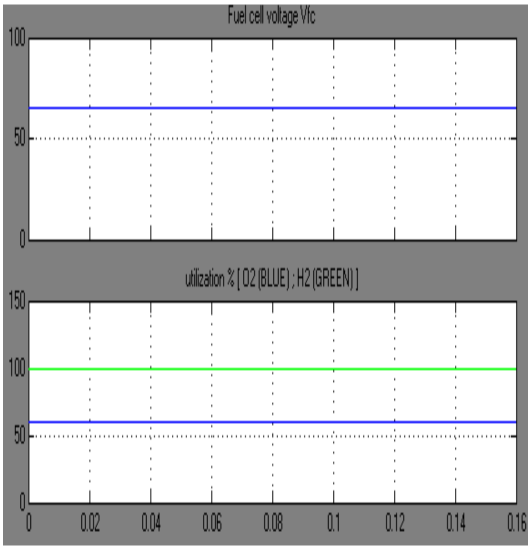


Figure 6: Output voltage and % utilization of fuel waveforms for PEMFC

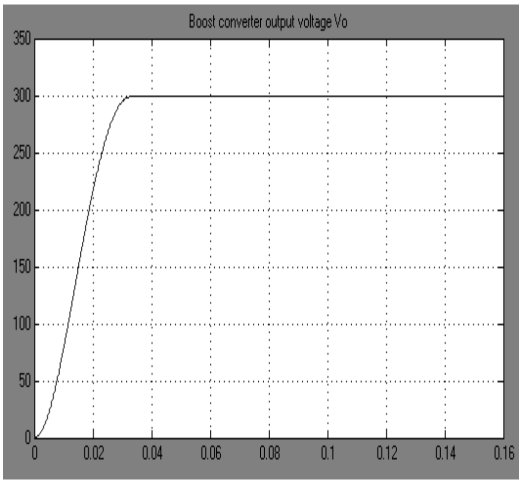


Figure 7: Output voltage waveform for Boost converter

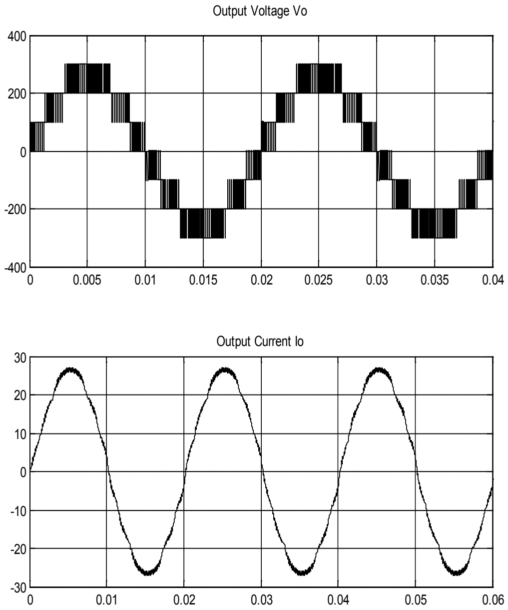
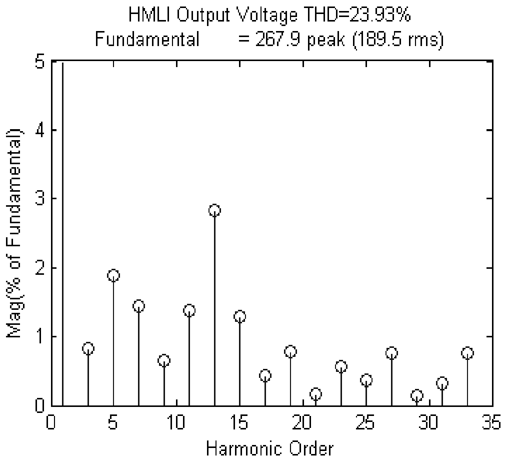


Figure 8: Output voltage and current waveforms for HMLI



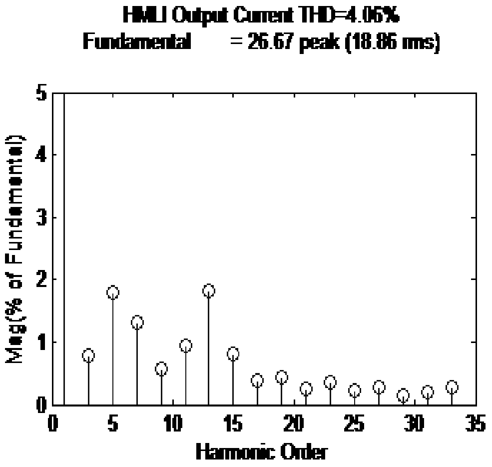


Figure 9: THD results of output voltage and current waveforms for HMLI

The output voltage and current waveforms for HMLI interfaced with the fuel cell Boost Converter are shown in Fig. 5-7. Fig. 8 shows the THD measurements, the seven-level HMLI produced the lowest THD compared with the five and three-level inverter. This proves that, as the level increases, the THD reduces.

5 CONCLUSION

In this paper a single phase HMLI with reduced number of switches interfaced with PEMFC has been designed and analyzed. Also this paper presented a novel PWM switching scheme for the proposed multilevel inverter. It utilizes multiple reference signals and an inverted sine carrier signal to generate PWM switching signals. The proposed seven-level HMLI with reduced number of switches gives a reduced THD compared to the conventional MLI. Therefore, HMLI with multiple reference PWM technique is a suitable topology for fuel cell applications.

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