A HYBRID CASCADED FIVE-LEVEL INVERTER WITH INTERLEAVED TECHNIQUE FOR FUEL CELL APPLICATION

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***Abstract*-This paper proposes a single-phase five level cascaded multilevel inverter (CMLI) for fuel cell system with interleaved technique. High output voltage is regulated by designing the interleaved DC-DC converter. In this four-phase Interleaved Boost DC-DC Converter is interfaced between the Proton Exchange Membrane Fuel Cell (PEMFC) and the CMLI to regulate low input current ripples and also to convert low voltage high current input to high voltage low current output. Multilevel inverter provides less distortions or harmonics at output voltage as compared with interleaved power converter. In this paper, comparison is done between single phase multilevel inverter and interleaved inverter which validate the effectiveness of these inverter. Input current ripple cancellation can be attained by the interleaved DC-DC power conversion technique to minimise the hysteresis energy losses inside the fuel cell stacks and also to meet the demands of battery charging considerations on the high-voltage applications. The operation principles and design considerations of the power converter and multilevel inverter circuit topology are analysed and discussed in detail. Efficiency of PEM fuel cell by ripple cancellation can be increased by using MATLAB/SIMULINK**.

***Keywords:* Proton exchange membrane fuel cell, Ripple cancellation, Cascaded multilevel inverter, Interleaved DC-DC converter**.

I.INTRODUCTION

In recent years the interleaving technique has becoming more popular for high power applications. The best known application is in powering microprocessor and also in fuel cell applications. Comparing with the other types of fuel cells, Proton Exchange Membrane fuel cell shows the charming attraction with its advantages such as clean electricity generation, high energy density, high output voltage capability and high efficiency. As PEM fuel cell presents low voltage output, a distributed energy source consisting of this PEM fuel cell normally requires a high power boost converter for energy management to assist the slow responding fuel cell.

In this work, a five level multilevel inverter is considered instead of three level inverter, because it provides greater advantages such as upgraded output waveform, compact filter size, lower THD, lower EMI .This multilevel inverter topology offers an improvement in terms of less component count.

Reduces complexity when compared with the other inverter. A five level inverter topology is interfaced with PEMFC via 4-phase interleaved boost converter.

In this paper, a four phase interleaved DC-DC converter between the proton exchange membrane fuel cell (PEMFC) and the multilevel inverter has been introduced to regulate high voltage output and also provides ripple free input current. As shown in figure1 step-up DC-DC converter increases the voltage to the post stage DC-AC inverter in high power grid applications. Current fed full bridge DC-DC converter must be concerned with following criteria: large step up ratio, low input current ripple for PEM fuel cell applications. Current fed full bridge DC-DC converter with voltage doubler consist of input choke with high inductance on the low voltage side because high ripple current causes hysteresis losses inside the fuel cell system

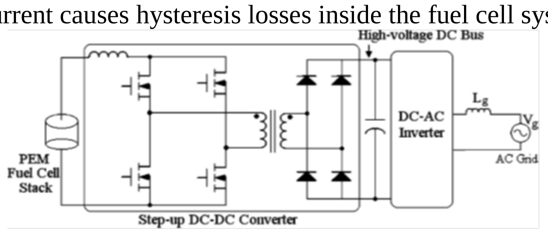

Figure 1 A PEM fuel cell power converter system

Increased power losses on the input choke results in poor conversion efficiency and less power density for the DC-DC converter in high power PEM fuel cell stacks. In order to overcome these drawbacks interleaved DC-DC converter is designed and analysed to achieve low input current ripple and high efficiency performance due to the ripple cancellation at high current side and voltage doubler at high voltage side which is shown in figure 2

A constant voltage (CV) feedback control with a current-limit (CL) protection is constructed to raise the reliability of the studied fuel cell power converter. Four phase parallel connected current fed DC-DC power converter is implemented to present low output voltage ripple that is preferred for the battery charging considerations and also no voltage imbalance problem exist among the output capacitors of DC-DC converter when connected in series. Even in this paper active clamp circuit is also designed to suppress the voltage spike on power switches which is usually a critical issue in practical high power applications.

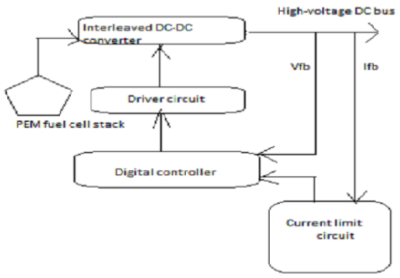

Figure 2 A Digital Controlled Interleaved DC-DC converter

II.PROTON EXCHANGE MEMBRANE FUEL CELL

The PEM fuel cell consists of anode terminal, cathode terminal, electrolyte solution and catalyst. Hence PEM fuel cell construction is shown in figure.3.When the pressurized of hydrogen gas is moved into PEM fuel cell at anode side. Proton (H+) and Electron (e-) are generated by the collision between Hydrogen gas and the catalyst. Electron (e-) flows into the external circuit as a DC current and again flows into the fuel cell at cathode terminal because electron (e-) cannot pass through the electrolyte inside the PEM fuel cell. Proton (H+) flows at cathode terminal through the electrolyte. The chemical response at the anode terminal of the fuel cell is

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

Pressurized oxygen flows into PEM fuel cell at cathode side. The combination of electron (e-), proton (H+) and oxygen (O_2) produces the purified water has to be drained out from fuel cell system as shown in figure 3.The chemical reaction at the cathode terminal of the fuel cell is

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow \text{Water} \quad (2)$$

The chemical response between anode and cathode terminal gives the water

$$H_2 + \frac{1}{2} O_2 \rightarrow \text{Water + Heat + Electrical energy} \quad (3)$$

Thermo-dynamic output voltage (E) of each single cell of PEMFC will be determined by Gibb's Free Energy Change (ΔG) which is 237 KJ/mol. At standard operating temperature 25˚C

$$E = \frac{\Delta G}{nF} = 1.23 \text{ V} \quad (4)$$

Where F is a Faraday's constant (96,485 Coulombs)
n is the number of an electron(here is 2 electron)
Theoretically output voltage of single cell must be 1.23 V. But practically, no load voltage at each cell is about 0.5 to 0.8V due to the voltage drop inside cells of the PEMFC. Therefore, it is always necessary to connect number of cells in series circuit which is called fuel cell stack for various applications in order to provide desired output load voltage.

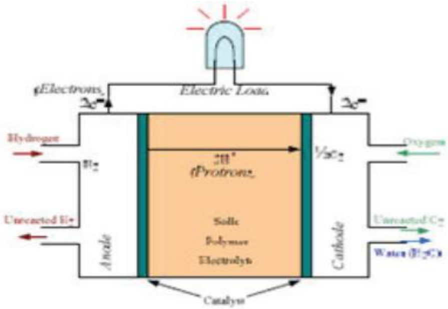

Figure 3 Construction of the PEM Fuel cell

In this paper ,the source or input is taken from the PEM fuel cell which is having less voltage of about 0.5V, this input voltage is not sufficient to provide the voltage to the power converter. Hence, the fuel cells are connected in series according to the requirement in order to increase the voltage. Table-1 shows the PEMFC specifications.

Table-1: PEM Fuel cell specifications.

No. of cells	37V
R	0.0756 ohms
P_{H2}	1.5 bar
P_{O2}	1 bar
Fuel cell temp.	338 Kelvin
Flow rate of H_2	50.06m

III.CURRENT-FED FULL BRIDGE DC-DC POWER CONVERTER WITH VOLTAGE-DOUBLER

As high power fuel cells provides low output voltage, as a result large current flows which bring conduction losses along the path it flows. This kind of power losses is a major efficiency killer in a DC-DC converter design .Hence improvement on conduction losses became the key to achieve higher conversion efficiency. Motivated to select this Current-fed full bridge power converter for PEM fuel cell is due to its high performance in electrical applications and reduction in size and electromagnetic emission along with increase in productivity, transient reaction and reliability are among the most advantages to select this converter.

Figure 4 shows the current fed full bridge DC-DC power converter includes input choke L_{in} , power switches Q_A~Q_D, step up transformer T1 and secondary voltage doubler . The input choke L_{in} pretends as boost inductor to reserve the energy and supplies the energy from fuel cell stack according to the operation of primary switches. Current fed full bridge DC-DC converter raises the voltage spike problem on the power switches. To overcome this problem active clamp circuit is implemented to conquer the voltage spike and increase the system reliability of the power converter. The circuit operation are analysed with the six switching modes of this power converter.

Duty cycle D of power switches should be higher than 50% in order to provide continuous current I_{Lin} to input inductor. Duty cycle is grounded on number of phases, as number of phases rooted on ripple cancellation, as number of phases increases the ripples are reduced. The voltage doubler regulates high voltage output by reducing the voltage stresses on the secondary side rectifier diodes. V_{NP} and V_{NS} represent the primary and secondary voltages respectively. The voltage transfer ratio of the current fed full bridge DC-DC power converter with voltage doubler can be procured as follows.

$$\frac{Vo}{Vin} = \frac{2}{n(1-D)} \qquad (5)$$

Where n represents the transformer turns ratio .The current ripples on the input choke L_{in} can be shown

$$\Delta I = \frac{nVo(1-D)}{2Lin}\,(-0.5 + D)\,T_S \qquad (6)$$

At the boundary mode operating condition, the current transfer ratio can be procured as follows:

$$\frac{Io}{Iin} = \frac{n(1-D)}{2} \qquad (7)$$

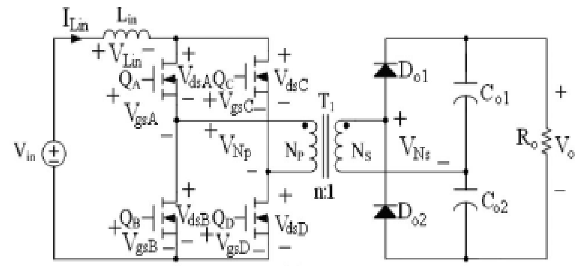

Figure 4 Current fed full bridge DC-DC power converter

IV.INTERLEAVED CURRENT-FED FULL BRIDGE DC-DC CONVERTER

Interleaving technique provides high voltage ratio and also low ripple. In this paper four phases parallel connected current fed DC-DC power converter is analysed i.e. structure of this converter is parallel connected with four voltages - doubler boost converter by interleaving their output voltages to reduce the ripples and increasing the efficiency of the power converter. Interleaving technique lowers the current stresses and inductor in the fuel cell stacks. This interleaving topology is suitable to interface for fuel cell to convert low voltage high current to high voltage low current. This interleaving concept serves many benefits

- RMS current at the input capacitors is reduced which helps to use of less expensive and lesser input capacitors.
- High frequency ripple cancellation can be achieved by interleaving the multi-phase dc/dc converter.
- Peak currents in primary and secondary transformer windings can be reduced which can be achieved by interleaving the 2L forward converter.
- Transient Response is improved which results in reducing the output filter inductance and increases the output ripple frequency.
- Form factor is improved for low profile solutions.
- Interleaving topology separates the heat generating components which helps to reduce the heat sink requirements.
- Electromagnetic interference (EMI) is reduced due to reduction of peak current in power converter.

Figure 5 shows the interleaved current fed full bridge DC-DC converter for the PEM fuel cell application. Ripple cancellation can be accomplished by the interleaving DC-DC converter with a phase shift as provided by the equation

$$\Phi = \frac{360}{m} \qquad (8)$$

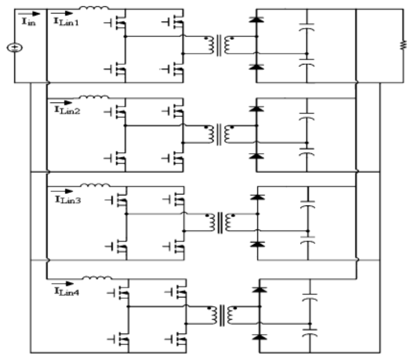

Figure 5: Interleaved current fed full bridge dc-dc converter

Higher efficiency can be achieved by splitting the output current into 'm' paths, which automatically reduces I^2R losses and inductor losses. The gating pulses of the power switches for four phases are shifted by $360^\circ/m$, i.e $360^\circ/4$ for m=4, which is 90 degrees.

V.CASCADED FIVE-LEVEL INVERTER WITH INTERLEAVING TECHNIQUE

The suggested single-phase five- level inverter includes of single-phase cascaded hybrid bridge inverter with two subsystems consist of each two phase interleaved converter which are connected in series having two sets of four bidirectional switches as shown in figure 7 and figure 8 respectively. The H-bridge topology has more advantages than other topologies i.e. less power switches, power diodes, less capacitors for inverters of same number of inverters

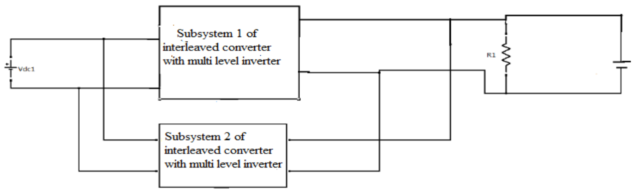

Figure 7 Block diagram of interleaved converter with multi-level inverter

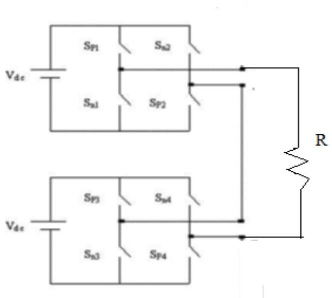

Figure 8 Block diagram of multi-level inverter of subsystem

Five output voltage levels is produced by the proper switching of the inverter.(0,+$V_{dc/2}$,V_{dc},-$V_{dc/2}$,-V_{dc}).Inverter operation is divided into five switching states as shown in Table-2.

1. **To Acquire +V_{dc}:** S_1, S2 and S_5, S_6 are switched ON .All other controlled switches are OFF, hence the voltage applied to the load terminals is +V_{dc}.
2. **To Acquire +$V_{dc/2}$:** The bidirectional switches S_1, **S_2,** S_5 and S_7 are switched ON. All other switches are OFF, hence the voltage applied to the load terminal is +$V_{dc/2}$.
3. **To Acquire Zero output:** This level can be obtained by four switching combinations; switches S_1 S_3 S_5 S_7 and S_2 S_4 S_6 S_8 are switched ON. All other controlled switches are OFF, hence the voltage applied to the load terminal are zero.
4. **To Acquire -$V_{dc/2}$:** The S_3 S_4 and S_6 S_8 switches ON .All other controlled switches are OFF, hence the voltage applied to the load terminals is –$V_{dc/2}$.
5. **To Acquire –V_{dc}:** The switches S_3 S_4 S_7 S_8 are switched ON. All other switches are OFF, hence the voltage applied to the load terminal is -V_{dc} .

Table-2.Conduction modes for hybrid cascaded multilevel inverter converter

V_O	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
0	On	Off	On	Off	On	Off	On	Off
+$V_{dc/2}$	On	On	Off	Off	On	Off	On	Off
+V_{dc}	On	On	Off	Off	On	On	Off	Off
+$V_{dc/2}$	On	On	Off	Off	On	Off	On	Off
0	Off	On	Off	On	Off	On	Off	On
-$V_{dc/2}$	Off	Off	On	On	Off	On	Off	On
-V_{dc}	Off	Off	On	On	Off	Off	On	On
-$V_{dc/2}$	Off	Off	On	On	Off	On	Off	On

A. Design Consideration of Interleaved Power Converter with Multilevel Inverter

The designing of interleaved power converter includes the selection of number of phases, the inductors, output capacitors and power switches. In order to choose these components duty cycle range and peak currents should be known.

1 Choosing the Number of Phases

This paper is designed for four phases because ripples are reduced with the increasing number of phases. So as to increase the efficiency of power converter ripples should be reduced .Hence, the ripples reduces to 12% of that conventional boost converter. Furthermore, as the number of phases increases complexity and cost of the system increases as trade-off between this numbers of phase four is chosen .The chosen number of inductors, switches and diodes are same as the number of phases for all the phases.

2 Preference of Duty Ratio

The selection of duty cycle depends on the number of phases .As the number of phases increases the low ripples can be achieved .Hence the selection of duty cycle plays significant role in achieving the efficiency for the PEM fuel cell stacks. For four phase interleaved boost converter, the ripple is minimum at duty cycle, D=0.125.Hence the duty cycle 0.125 value is chosen for designing this system.

3 Selections of Inductance and Capacitances

Selection of inductances and capacitances can be obtained by using formulae respectively

$L = V_S D/\Delta i_L F$ (9)

Where V_S is source voltage and i_L represents the inductor currents ripple.

$C = V_O DF/ R\, \Delta V_o$ (10)

Where V_O is the output voltage (V), D represents the duty cycle, F is frequency (Hz) which is generally considered of 50 Hz, R represents resistances (Ω) and ΔV_o represents change in output voltage (V).

4 Selections of Power Devices

Power diodes supplies low cut in voltage, higher reverse leakage current, higher frequency. MOSFET's are used switching devices since it is current controlled device which is having low input impedances.

VI. SIMULATION RESULTS

A. Interleaved Current-Fed Full Bridge DC-DC Converter

The work is based on the simulation performance of interleaved current fed full bridge DC-DC power converter, from this multi-level inverter is proposed. In the proposed DC-DC converter, equivalently there are four single phase full bridge converters is simulated using MATLAB-SIMULINK with the parameters as shown in a Table-3 .Four subsystem is developed for each converter in mat lab and output of the fuel cell is observed. It can be observed that ripple cancellation on the fuel cell stack current can be achieved by the interleaved gating signal with 90˚ phase shift. The four phase current fed full bridge dc-dc converter is parallel connected with each subsystem as shown in figure 9

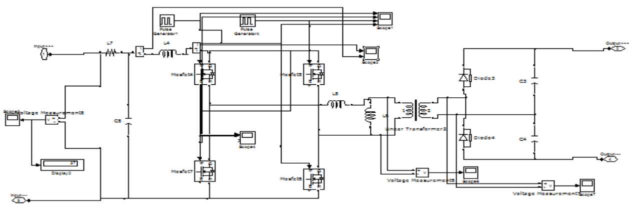

Figure 9 simulation model of each interleaved subsystem.

Table-3 simulation parameters

Output fuel cell voltage V_{fc}	37V
Output boost converter voltage V_O	1799V
Switching Frequency F_S	50Hz
R	1000000
L	1.2 e^{-6}

The input current ripple cancellation, output voltage, output currents are attained with input voltage of 37V when PEMFC is connected with the interleaved boost converter as shown in figure-10, figure-11, and figure-12. In this converter the current is decreased due to the increasing voltage due to the interleaved technique. Due to this technique current ripples are cancelled in order to achieve the efficiency of power converter.

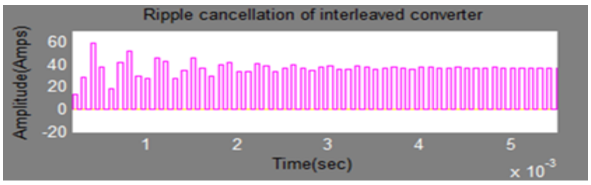

Figure-10 Input current ripple cancellation waveform of four-phase dc-dc converter

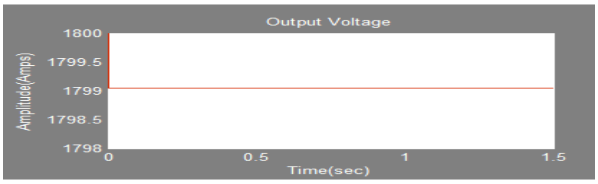

Figure 11 Output voltage of interleaved dc-dc converter

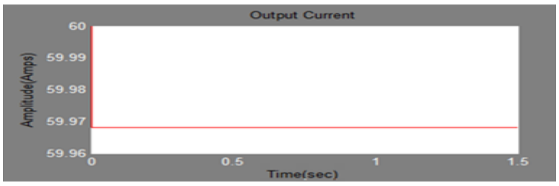

Figure 12 Output current of interleaved dc-dc converter

B. Interleaved Power Converter with the Multi-level Inverter

Multi-level inverter is implemented to the four-phase current fed full bridge converter to provide high voltage to the existing system. In this paper five level multi-level inverter is designed to reduce the ripples at the input current more effectively when compared with the interleaved converter of single phase inverter. In this proposed converter, two subsystem exists which is connected in parallel so as to increase the voltage and also simulated by using the MATLAB/SIMULINK as shown in figure 13 and figure 14

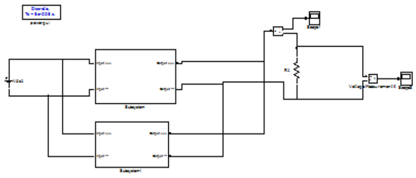

Figure 13 simulation model of interleaved multi-level inverter

The work presents the hybrid five level inverter is implemented to the interleaved power converter. The output voltage and current waveforms of multi-level inverter is shown in figure 15 and figure 16.Figure 17 shows the ripples cancellation on input current of interleaved converter with multi- level inverter

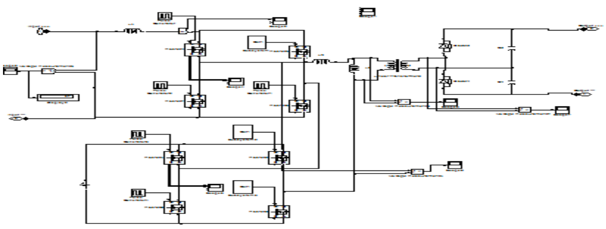

Figure 14 simulation model of each subsystem

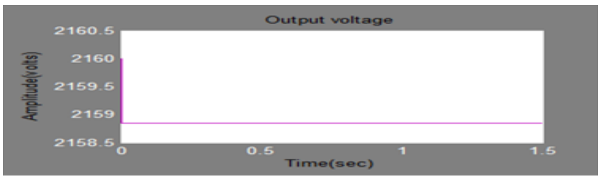

Figure 15 Output voltage of interleaved multi-level inverter

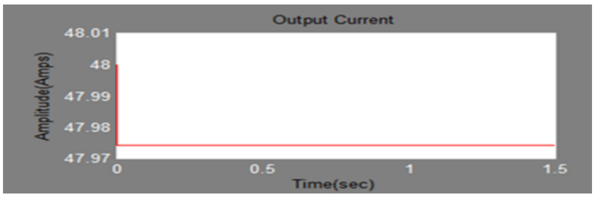

Figure16 Output current of interleaved multi-level inverter

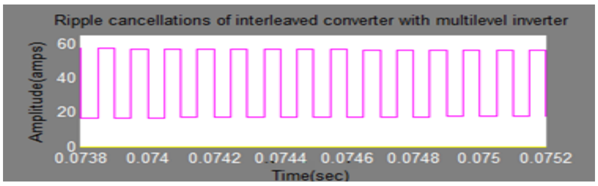

Figure17 Ripple cancellation of interleaved multi-level inverter

Figure18,19,20,21 shows the input voltage ,voltage at primary windings, voltage at secondary winding and output current of subsystems respectively, due to the multi-level inverter, the ripple cancellations are achieved at output current of each subsystem more effectively as it compared with single-phase inverter. Hence ripples free current waveform is observed in figure16.

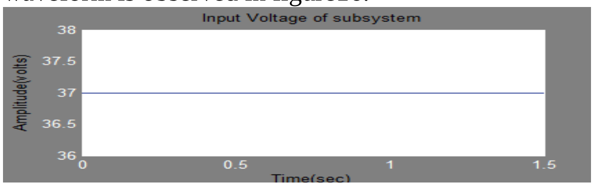

Figure18 Input voltage of subsystem

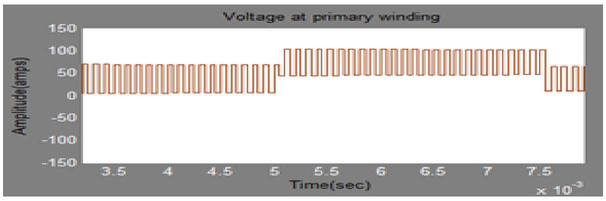

Figure19 voltage at primary winding of subsystem

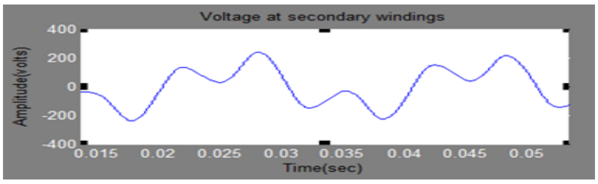

Figure20 Voltage at secondary windings of subsystem

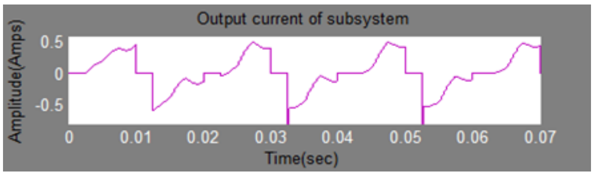

Figure21 Output current of subsystem

The simulation results of interleaved boost converter (IBC) are compared with interleaved converter with multi-level inverter (IMLC) which is shown in Table-4.

Table-4 Comparison of IBC and IMLC

Parameter	IBC	IMLC
Output voltage	1.8KV	2.5 KV
Output current	59.97Amps	47.97Amps
Input Ripples	0.06%	0.04%

VII.CONCULSION

The proposed five-level hybrid cascaded multi-level inverter (HCMLI) gives reduced ripples at the input current than interleaved current-fed full converter. As this work even provides comparison between the multi-level inverter and single-phase inverter to validate the effectiveness of these inverters. High efficiency execution and low input current ripples can be attained by the studied interleaved current-fed full bridge converter with the multi-level inverter. In this paper, survey is done between the PEM fuel cell and HCMLI when current-fed full bridge converter is interleaved in four phases.

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REFERENCES

[1] X. Kong AM. Khambadkone,“ Analysis and Implementation of a High Efficiency Interleaved Current Fed Full Bridge Converter for Fuel Cell System,” *IEEE Trans. Power Electron*,vol.22,no.2,pp.543-550,Mar.2007

[2] DM. Ali,” A Simplified Dynamic Simulation Model (prototype) for a Stand-alone Polymer Electrolyte Membrane (PEM) Fuel Cell Stack,” in Proc.12th Int .*Middle-East Power Syst*.Conf,2008,pp.480-485.

[3] J.M.Kwon, E.H.Kim,B.H.Kwon,K.H.Nam ,”High efficiency fuel cell power conditioning system with input current ripple reduction,” *IEEE Transaction on Industrial Electronics*,vol.56,no.3.826-834,Mar.2009.

[4] W.Lee,B.M.Han,H.Cha, ”Battery Ripple Current Reduction in a Three-phase Interleaved DC-DC Converter for 5kW Battery Charger,”2011 *IEEE Energy Conv .Congress and Exposition*,pp.3535-3540

[5] Y.Bo,Y.Xu,X.Zeng,J.Duan,J.Zhai,D.li, ”Analysis, Design of a High Step-up Current Fed Multi-resonant DC-DC Converter With Low Circuiting Energy and Zero Current Switching for all Active Switches, ”*IEEE Transaction on Industrial Electronics*,Vol.59,Issue:2,pp.964-978,Feb 2012.