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A Fuel Cell based Seven Level Hybrid Cascaded H-bridge Multilevel Inverter

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***Abstract*—The poor quality of voltage and current of a Pulse width modulation (PWM) inverter fed induction machine can be due to the presence of harmonics which results in significant level of energy losses. The Multilevel inverter is used to reduce the harmonics. Cascaded H-bridge multilevel inverter can be implemented using only a single power source and capacitor. Without transformers, the scheme proposed here allows the use of a single power source with the remaining $'n-1'$ sources being capacitors which is referred to as hybrid cascaded H-bridge multilevel inverter (HCMLI). HCMLI provides high-quality output power due to its high number of output levels, and results in high conversion efficiency and low thermal stress as it uses a fundamental frequency switching scheme. By replacing capacitive source with Fuel Cell (FC) and with necessary modification this topology can be implemented in Hybrid Electric Vehicles (HEV).**

***Index Terms*—Hybrid Cascade Multilevel Inverter (HCMLI), Cascaded Multilevel Inverter, Fundamental Frequency Modulation, Pulse width modulation (PWM), Switching loss reduction,Total harmonic distortion (THD), Fast Fourier Transform (FFT).**

I. Introduction

In recent years, industry has begun to demand higher power equipments, which now reaches the megawatt level. Controlled drives in the megawatt range are usually connected to the medium voltage network. Today, it is hard to connect a single power semiconductor switch directly to medium voltage grids (2.3, 3.3, 4.16, 6.9 kV). For these reasons, a new family of Multi Level Inverters (MLI) has emerged as the solution for working with higher voltage levels. Multilevel inverters include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms [1].

One of the biggest problems in Power Quality (PQ) aspects is the harmonic contents in the electrical system. Generally, harmonics may be divided into two types: 1) voltage harmonics, and 2) current harmonics. Current harmonics is usually generated by harmonics contained in voltage supply and depends on the type of load such as resistive, capacitive or inductive load. Both harmonics can be generated either by the source or the load [2]. Harmonics generated by load are caused by nonlinear operation of devices, including power converters, arc-furnaces, gas discharge lighting devices, etc. Load harmonics can cause overheating of the magnetic cores of transformer and motors. On the other hand, source harmonics are mainly generated by power supply with non-sinusoidal voltage waveform. Voltage and current source harmonics imply power losses, Electromagnetic Interference (EMI) and pulsating torque in Alternate Current (AC) motor drives. Thus the reduction of harmonics become one of the major issue in these electrical and electronic systems. Thus the concept of using multilevel inverters were introduced in to various fields after its evolution [3].

The multilevel Voltage Source Inverter (VSI) has many industrial applications such as in power supplies, static VAR compensators, drive systems, etc. One of the significant advantages of multilevel configuration is the harmonic reduction in the output waveform without increasing switching frequency or decreasing the inverter power output. The output voltage waveform of a MLI depends on the number of levels of voltages, typically obtained from capacitor voltage sources.

The so called multilevel starts from three levels. As the number of levels reach infinity, the output THD approaches zero. The number of the achievable voltage levels, however, is limited by voltage unbalance problems, voltage clamping requirement, circuit layout, and packaging constraints. Three capacitor voltage synthesis-based MLI's are introduced, i.e. Diode-Clamped Multilevel Inverter, Flying-Capacitor Multilevel Inverter and Cascaded-Inverters with Separated Direct Current (DC) Sources [4].

Unlike the diode clamp or flying capacitors inverter, the cascaded inverter does not require any voltage clamping diodes or voltage balancing capacitors. This configuration is useful for constant frequency applications such as active frontend rectifiers, active power filters, and reactive power compensation. Choosing appropriate conducting angles for the H bridges a specific harmonic in the output waveform can eliminated [5].

The structure of the HCMLI is not only simple and modular but also requires the least number of components compared to other types of MLI's. This in turn, provides the flexibility in extending the HCMLI to higher number of levels without increase in circuit complexity as well as facilitates packaging.

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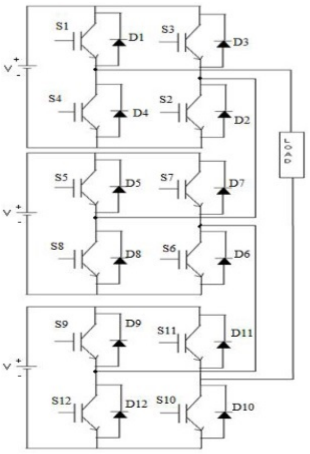

Fig. 1. Seven Level cascaded MLI.

By replacing capacitive sources with FC's this topology can be easily extended to future Hybrid Electric Vehicle applications with less pollution.

II. Cascaded Multilevel Inverter Scheme

The seven-level MLI is obtained by cascading three full bridge inverter circuits. The three full bridge inverters are connected in series and a single phase output is taken. Each full bridge is fed from separate DC source. The number of output levels 'm' in each phase is related to number of full bridge inverter units 'n' by, 'm=2n+1'. Here number of levels is seven, hence number of inverter circuits connected in series is three. The single phase seven level topology of cascaded H-bridge multilevel inverter is shown in Fig. 1. Each H-bridge is fed with the same value of DC voltage hence it can be called as symmetrical cascaded multilevel inverter. Each full bridge inverter can generate three different voltage outputs: $+V_{dc}$, 0, and $-V_{dc}$. The output phase voltage is synthesized by sum of three inverter outputs.

III. Simulation Circuit of Single Phase Cascaded Multilevel Inverter

Simulation circuit consists 3 H-bridges, having a total of 12 switches and 3 seperate sources. Each source having a voltage of V_{dc}.The simulation circuit is represented in Fig. 2. And the output waveform is shown in Fig. 3. Using selective harmonic elimination method it is possible to reduce harmonic level compared to the previous multilevel inverter topologies. From the simulation circuit of single phase cascaded MLI, we found that THD obtained is 18. By implementing HCMLI topology the number of switches,DC sources,and THD can be reduced further more. By replacing FC in the place of sources the HCMLI can be extended for future applications.

IV. Working Principle Of Seven Level HCLMI

A 7-level hybrid cascaded H-bridge MLI has two H-bridges for each phase, one H-bridge is connected to a DC source, another H-bridge is connected to a capacitor as shown in Fig. 4 [6].

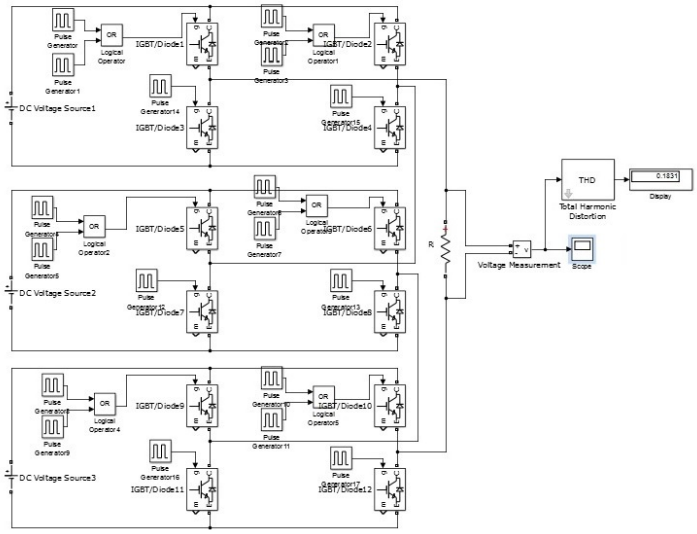

Fig. 2. Simulation circuit of single phase cascaded MLI.

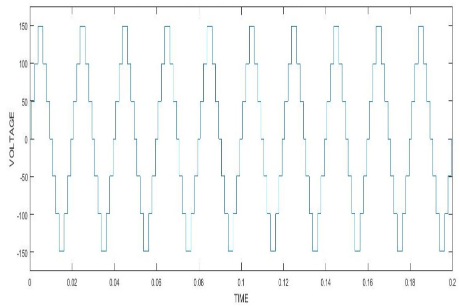

Fig. 3. Seven level waveform of cascaded MLI.

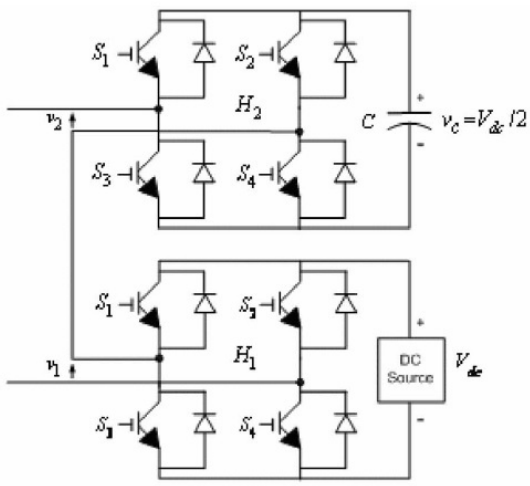

Fig. 4. Single phase structure of a Multilevel cascaded H-bridge inverter

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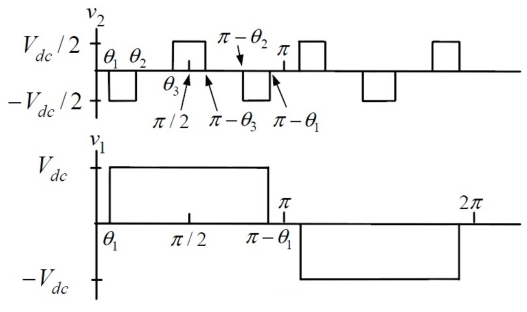

Fig. 5. H-Bridge which achieve the same output voltage

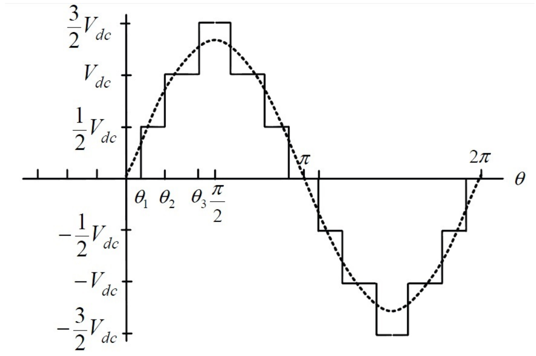

Fig. 6. Output Waveform of an 7-Level HCMLI.

θ	v_1	v_2	$v = v_1 + v_2$
$0 \leq \theta \leq \theta_1$	0	0	0
$\theta_1 \leq \theta \leq \theta_2$	0	$V_{dc}/2$	$V_{dc}/2$
$\theta_1 \leq \theta \leq \theta_2$	V_{dc}	$-V_{dc}/2$	$V_{dc}/2$
$\theta_2 \leq \theta \leq \theta_3$	V_{dc}	0	V_{dc}
$\theta_3 \leq \theta \leq \pi/2$	V_{dc}	$V_{dc}/2$	$3V_{dc}/2$

TABLE I
OUTPUT VOLTAGES FOR A 7-LEVEL INVERTER.

The DC source for the first H-bridge (H_1) could be a battery or FC 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 MLI is $v(t) = v_1(t) + v_2(t)$.

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 . To regulate the capacitors voltages to ensure the output. The 7-level fundamental switching scheme has been proposed. This switching scheme uses a possible cycle to output -(V_{dc}+V_c), -V_{dc}, -(V_{dc}-V_c), 0, (V_{dc}-V_c), V_{dc}, (V_{dc}+V_c) voltage [7]. If capacitor voltage is V_c and the inverter current is i, then if V_c<$V_{dc/2}$ and $i > 0$ the capacitor is being charged. In other case if V_c>$V_{dc/2}$ and $i < 0$ the capacitor is discharged. Then the capacitors voltage (V_c) can be regulated by charging and discharging. When V_c=$V_{dc/2}$ is chosen, the output voltage waveform is a 7-level waveform.

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 -$V_{dc/2}$, 0, or $V_{dc/2}$. For example if the switch S_2 from the bridge H_1 and the switches S_2, S_3 from bridge H_2 are ON then the output voltage will be $V_{dc/2}$. Thus,by controlling the switching periods of both the bridges H_1 and H_2 it is possible to generate -3$V_{dc/2}$, -V_{dc}, -$V_{dc/2}$, 0, $V_{dc/2}$, V_{dc}, 3$V_{dc/2}$, the seven output voltage levels. Thus different output seven level voltage can also be achieved by adding v_1 and v_2 in two different ways [8].The output seven level voltage waveform obtained by adding the two voltage level is represented in Fig. 6.

Fig. 5. shows H_1 and H_2 bridge voltages. By combining these two voltage levels in different time intervels output seven level waveform shown in Fig. 6. is generated. Let θ be the angular range for the operation of H-bridges. For $\theta_1 \leq \theta <$ θ_2, v_1 = V_{dc} and v_2= $V_{dc/2}$ are chosen. The fact that the output-voltage level $V_{dc/2}$ can be achieved in two different ways is exploited to keep the capacitor voltage regulated [9]-[10], which is explained in the Fig. 5.

For obtaining 7 level in this HCMLI capacitive source should have a value half to the DC input supply selected. Capacitance value is decided based on the following factors.

1)The capacitance value is chosen large enough so that the variation of its voltage around its nominal value is small (generally speaking, one can choose the capacitive load time constant to be 10 times than that of the fundamental period).

2) The capacitor charging energy is greater than or equal to the capacitor discharge energy in a cycle.

V. SIMULATION ANALYSIS

The simulation results for single phase HCMLI fed Induction Motor (IM) and three phase HCMLI fed IM circuit is given. The HCMLI for single phase circuit is given in Fig. 7. The single phase circuit consist of two H-bridges. Each bridge consist of four IGBTs. The two bridges are connected together, also a load resistor is connected across the bridges. The output is taken across the load resistor [11]. The two bridges consists of seperate input DC sources. Proper switching sequence is selected for producing the seven levels at the output by opening and closing the switches of the two H-bridges. Here pulse width and phase delay of different switches are controlled. And the desired switching sequence for seven level is generated. OR gates are used to combine different pulses in the simulation circuit. A seven level waveform is obtained as the output of the given circuit.

For extending a HCMLI single phase circuit in to three phase circuit, three single phase circuits are connected together through one end terminal. And through the other end they are connected to a three phase star connected load. The voltage across the three phases are measured . For obtaining the three phase circuit output we have to maintain 120° phase shift across the three single phase circuits. Thus seven level output voltage waveforms which are phase shifted by 120° is obtained in the three phases as output [12].

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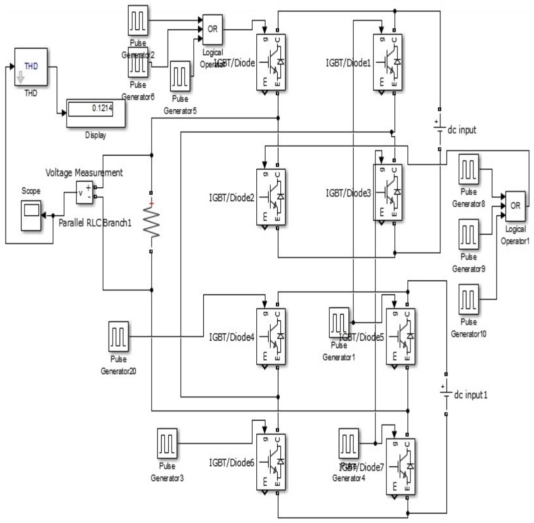

Fig. 7. Seven Level HCMLI for single phase IM.

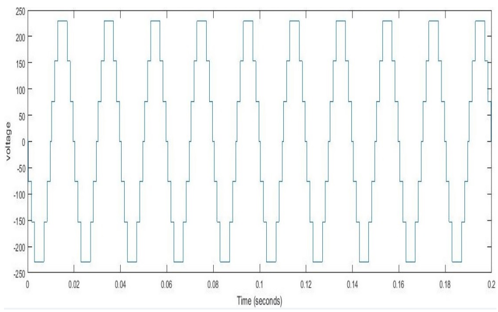

Fig. 8. Output Waveforms for single phase seven level circuit.

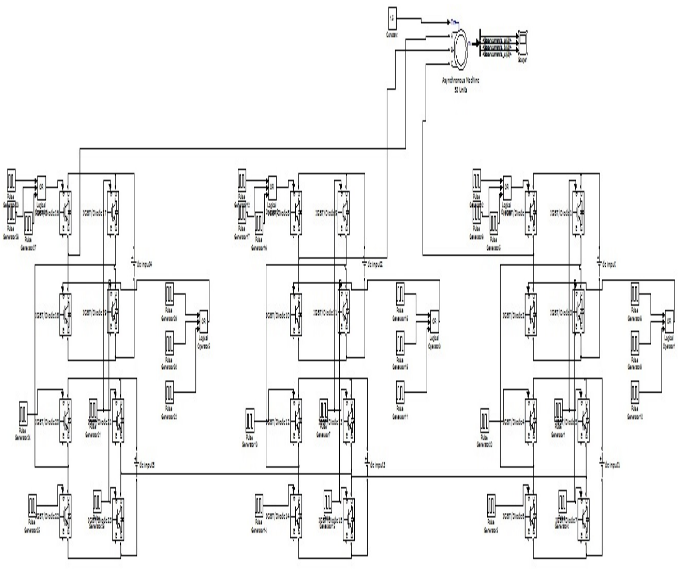

Fig. 9. HCMLI three phase circuit connected to an IM.

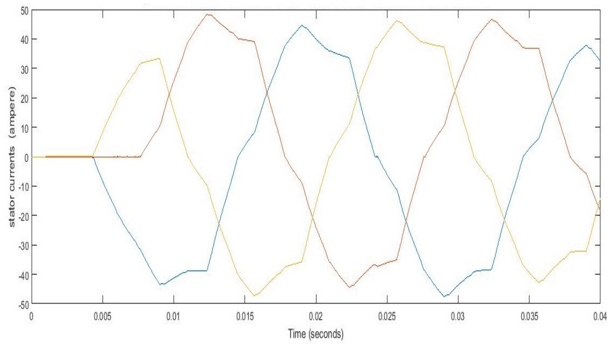

Fig. 10. Output Stator Current waveforms for a three phase circuit connected to an IM.

The HCMLI three phase circuit connected to an asynchronous machine model is simulated and is represented in Fig. 9. A constant torque and the outputs from three single phase circuits are fed as an input to the asynchronous machine. The various parameters of stator, rotor, also mechanical parameter can be included in the measurement by selecting parameters using the bus selector. Here stator currents through three phases are measured. Their phase shifted output waveform obtained can also be represented. The three phase HCMLI connected to an induction machine is represented as Fig. 9. And their stator current output waveforms are represented by using Fig. 10. Here measurement is taken on 5.4HP, 400V, 50Hz, 1430RPM asynchronous machine and its stator parameters are plotted by using this method. In all these circuits pulse width and phase delays are adjusted using pulse generators.

The stator currents represented in Fig. 11, are displaced by 120° to each other. The hardware circuit of the prototype is divided into two parts: the microcontroller based control circuit and power circuit. The power circuit consists of two H-bridges, each H-bridge consisting of four MOSFET named IRF830. Also the section consists of a single DC source for the H_1 bridge and capacitive source for the H_2 bridge. The control circuit section consisting of an easily programmable and erasable 89C51 microcontroller and four fan IC's (IC7392). The assembly language program burned in to the microcontroller determines the duration of gate pulses of each MOSFETs, thus the switching of H-bridge. FAN IC 7392 is a high speed power MOSFET and IGBT gate driver and fan IC's acts as an interface between the H-bridge and 89C51 microcontroller.

VI. Fuel Cell-based HCMLI

By replacing the capacitive source with a FC the HCMLI can be modified. The large capacitive source can be replaced by a more ecofriendly FC [13]. Different types of FC's are available nowadays. Here alkaline FC's are suggested. The only requirement of this FC is Hydrogen and Oxygen from atmosphere. The product after reaction is water, which is also ecofriendly and can be reused or recycled [14]. Because of these advantages we can use FC employed HCMLI in HEV's in future. It has a great scope,due to the renewable nature of FC product. Alkaline FC's can be used up to a temperature of 220° without changing its property. The electrolyte used in this

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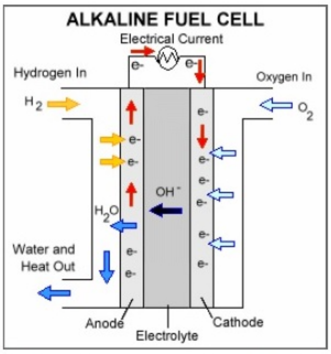

Anode Reaction: $2H_2 + 4OH^- \gg 4H_2O + 4e^-$
Cathode Reaction: $O2 + 2H_2O + 4e^- \gg 4OH^-$

Fig. 11. Working principle of Alkaline FC.

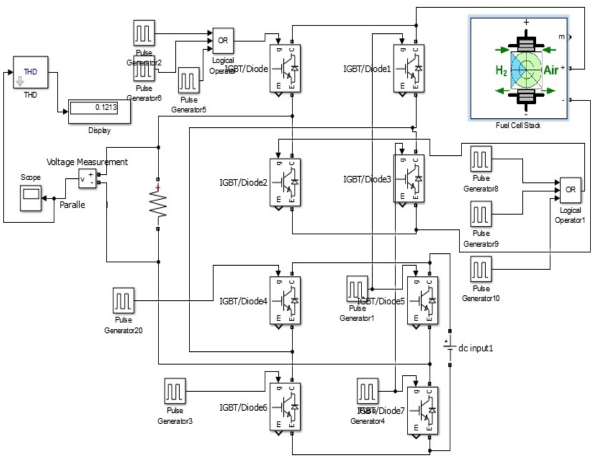

Fig. 12. FC based 7 Level HCMLI.

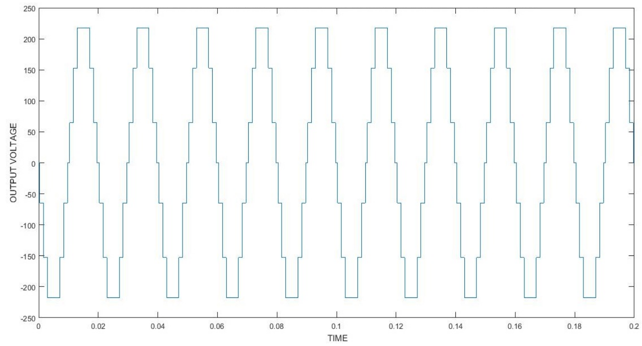

Fig. 13. Output waveform of FC based 7 Level HCMLI.

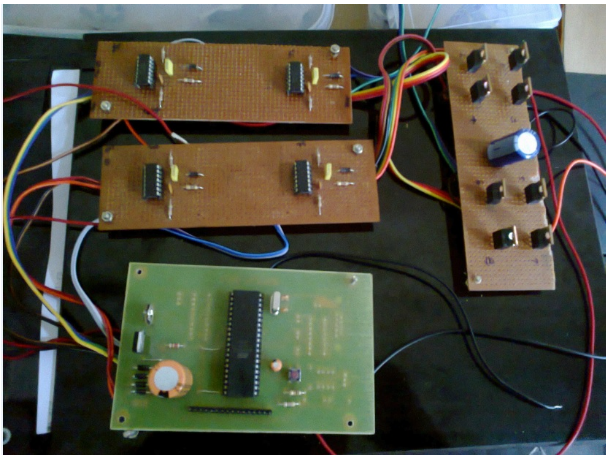

Fig. 14. 7 Level HCMLI.

cell is 40 percentage aqueous 'KOH'. Due to these advantages FC's are also employed by NASA in space applications [15].

FC's generates electricity through an electrochemical process. Electric energy stored in a FC is directly converted in to DC. Electrical energy is generated here without combusting fuel. So they are extremely attractive from an environmental stand point. Chemicals constantly flows in to cell, hence compared to battery it never goes dead. It can be used in high temperature conditions without any change compared to the capacitive sources. An alkaline FC having 2.4 KW and 48V DC is used in place of a capacitive source in HCMLI.

Alkaline fuel cell employed HCMLI is simulated using MATLAB Simulink R2016a. One of the capacitive source of HCMLI is replaced with FC in this topology. Simulation done with FC is represented in Fig. 12. And the output seven level waveform is shown in Fig. 13. By increasing the number of FC's and combining single phase circuits with appropriate switching phase sequence this topology can be extended to three phase systems also [16].

The FFT analysis of conventional cascaded MLI and HCMLI is represented in Fig. 15. and Fig. 16. From the FFT analysis of HCMLI it is found that the third order harmonics and its multiples are removed. And other low order odd harmonics are also reduced. And as a whole sum the THD of FC implemented circuit is reduced.

VII. Conclusion

In HCMLI output is obtained by cascading the output voltages of two H-bridges. Output waveform is produced with reduced number of switches and DC input sources with reduced harmonics. By changing the ratings of switches used, capacitor value, and small changes in the microcontroller

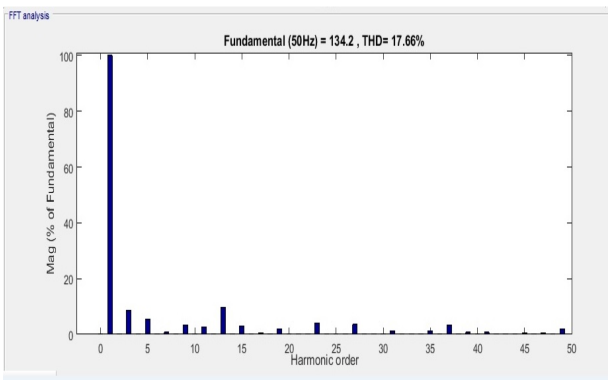

Fig. 15. FFT analysis of conventional MLI.

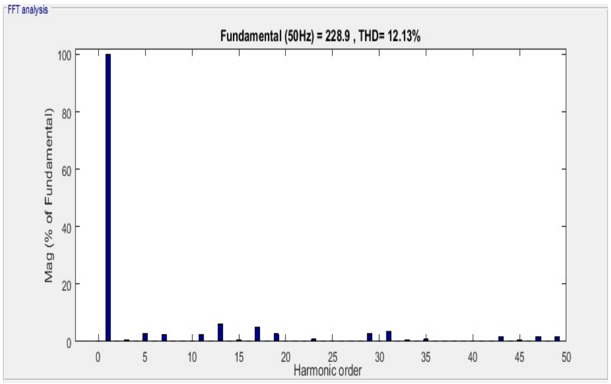

Fig. 16. FFT analysis of HCMLI.

program this low power rated prototype can be extended to high power single phase and three phase circuits. By replacing the large capacitive sources with FC (capacitors which are not suitable for high temperature operating conditions) this circuit can be extended for Hybrid Electric Vehicles, with lesser emission of materials. Corossion produced weight and volume will be less compared to the earlier topologies.The simulative results of HCMLI shows that the lower order odd harmonics are considerably reduced, especially the third order harmonics which are almost fully removed compared to the conventional MLI scheme. Despite of these advantages, present high cost of FC's compared to capacitive or DC sources is the challenge that we wanted to overcome for popularising this technology. The FC HCMLI produces a seven level waveform with THD reduced from '17.66' to '12.13'. By increasing the number of cells,the fuel stack can be used for high power applications.

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