Fuel Cell Based Power Generation with Multilevel DC-AC Conversion

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Abstract: **Fuel cell based power generation is attracting lot of attention as fuel cells are efficient, silent and 'green' energy sources. Since dc power is generated from a fuel cell, it has to be 'inverted' to connect it to an ac load or grid. Though multilevel inverters are capable of synthesizing waveforms with better harmonic profile and overcome the limited voltage and current ratings of semiconductor switches, still for higher level outputs the device count becomes high. This paper proposes a new topology for multilevel inverters which is capable of synthesizing an output waveform which contains all possible additive and subtractive combinations of the input dc levels and thus improving the output waveform quality from a fuel cell based power generation system. The device count remains minimal as compared to the classical topologies of multilevel inverters. Reducing the device count inevitably leads to increased reliability of the inverter and simplicity, apart from compactness. The proposed concept is validated through simulation study of a twenty-three level inverter based on proposed topology. It produces almost sinusoidal voltage as output and the THD of the load current is less than 0.5%.**

Index Terms-- **Fuel cells, distributed generation (DG), multilevel converter/inverter, harmonics, Total Harmonic Distortion (THD).**

I.INTRODUCTION

GROWTH of a society is determined by energy and past few decades have seen huge growth in demand of various types of energy. Estimations show that as of now the current population on the planet consumes 15 terawatts of power [1]. As per the World Coal Institute [2], at the current rate of consumption, fairly recoverable coal reserves will be exhausted in 130 years, natural gas in 60 years and oil in 42 years. Of all the forms of energy, electricity is considered most flexible and hence it has been abused substantially leading to further exhaustion of precious fuels used to generate electricity. Moreover, the demand for electricity continues to grow very rapidly. Forecasts show total worldwide electricity consumption rising from 12 trillion kilowatt-hours in 1996 to almost 22 trillion kilowatt-hours in 2020. Also by 2020, developing nations are expected to account for 43 percent of the world's total energy consumption as compared to only 28 percent in 1996. Solutions are being sought out to secure long term viability of our future.

This endeavor has led to the concept of Distributed Generation (DG) of electricity. Conventionally, electricity has been generated with what is called 'Centralized Generation' where chief sources have been fossil fuels to generate electricity. There have been many issues with such kind of approach. Apart from major concerns like limited supply of fossil fuels and pollution and subsequent climate changes, there are other important issues like fluctuations in fuel prices, insecurity, high transmission losses and large gestation periods [3].
Distributed Generation (DG) can be defined as an electric power source connected directly to the distribution network or even on the customer side of the meter [4-5]. These are often (but not necessarily) small-scale renewable energy sources, such as photovoltaic panels, biomass or wind turbines. The localization of the DGs can be used beneficially for both the consumer and the producer. Distributed generation also gives benefits like emergency back-up, improved system performance, increased reliability, potential utility capacity deferrals, ancillary service power, improved security and economics [3]. Hence, distributed generation has received a lot of attention from engineers and researchers. The most popular distributed generators include microturbines, fuel cells, biomass, diesel, small wind plants and photovoltaic (PV) generators [6].Power generation from sources like wind turbines and PV cells are intermittent in nature and depend on wind and solar radiations. They are significantly affected by the changes in climate. As for the diesel generators, they emit polluting gases leading to climate changes. Among different types of DG technologies, fuel cells are very appealing because of their high efficiency, high power quality, very less pollution (if any) and continuous power generation capability [7]. There are types of fuel cells which can generate electrical power ranging from milliwatts to megawatts [8].

This paper focuses on how available fuel modules can be connected to the load/grid through a novel multilevel inversion scheme which improves the output ac waveform by synthesizing all possible additive and subtractive combinations of the dc levels obtained from the sources. Multilevel inverter topologies have the advantage that they overcome voltage limit capability of the available semiconductors devices. They are capable of synthesizing output waveforms with better harmonic profile, low switching losses, high voltage capability and low dV/dt [9-11]. These features make multilevel converters attractive for high-power applications.

The classical multilevel converter topologies viz. neutral point clamped (NPC) converters [12], flying capacitors (FC) converters [13] and classic cascaded H-bridge (CHB) converters [14] are commercially available. However, for increased number of voltage levels (i.e. beyond three and five), the number of switching devices, diodes and capacitors increases immensely thereby increasing the overall cost and complexity in implementation . Newer topologies are being reported to reduce the overall count of active and passive devices in the multilevel converter topology [15-20].
In this work, a new topology is devised and its concept is explained in section II. The generalized multilevel inverter topology based on aforesaid concept is also presented in this. Working of the topology is explained with the help of a nine-level inverter. Section III describes how various fuel cell modules can be arranged so as to obtain the desired number of output levels using the proposed topology. Section IV describes the proposed twenty-three level inverter. In section V, the simulation results for the proposed inverter are presented and conclusions are given in section VI.

II.PROPOSED CONCEPT AND TOPOLOGY

The concept adapted for the topology is that the inverter should be capable of synthesizing all possible additive and subtractive combinations of the dc levels obtained from fuel cell modules. Some examples of such combinations are explained below:

(a) With single dc source

If a single dc source of voltage V1 is present, the possible combinations are: +V1, 0 and -V1. The resultant inverter can be a three/two level inverter.

(b) With two dc sources

If two dc sources with voltages V1 and V2 are present, the possible combinations are:

(i) Taking one level at a time: +V1, +V2, -V1 and –V2.
(ii) Taking two levels at a time: +V1+V2 , +V1 –V2 , +V2 – V1 and -V1 – V2
(iii) Zero level: one

Thus for two dc sources, there are nine possible combinations that can be obtained in the output waveform.

(c) With three dc sources

If three dc sources with voltages V1, V2 and V3 are present, the possible combinations are:

(i) Taking one level at a time: +V1, +V2, +V3, -V1 , –V2, -V3
(ii) Taking two levels at a time: +V1+V2 , +V1 –V2 , +V2 – V1 , -V1 – V2, +V2+V3 , +V2 –V3 , +V3 – V2 , -V2 – V3, +V1+V3 , +V1 –V3 , +V3 – V1 and -V1 – V3.
(iii) Taking three levels at a time: +V1 +V2 +V3, +V1 +V2 -V3, +V1 -V2 +V3, +V1 -V2 -V3, -V1 +V2 +V3, -V1 +V2 -V3, -V1 -V2 +V3 and -V1 -V2 -V3.
(iv) Zero level: one

Therefore, for three dc sources, there are twenty seven additive and subtractive combinations.

(d) With 'n' number of dc sources:

If 'n' number of dc sources with voltages V1 , V2, V3,…., Vn are present then total number of possible combinations can be as:

$$\text{Total number of levels} = \left(\sum_{m=1}^{n} \frac{n!}{m!\,(n-m)!}\,2^m\right) + 1 \qquad \dots(1)$$

The generalized structure of the proposed topology is shown in **figure 1** [21]. The arrangement of switches and dc sources is in such a manner that it is possible to obtain all possible combinations in the output. Moreover, if 'n' number of sources are present, then '4n' switches are required to synthesize all possible combinations. Therefore,

$$\textbf{Total number of switches required} = 4n, \qquad \dots(2)$$

where n = number of dc sources.

For example, **figure 2** shows the proposed structure for two dc sources (obtained through two fuel cell modules of different voltages) capable of producing a nine level output. **Figure 3** shows how various combinations of switches can be used to obtain these nine levels.

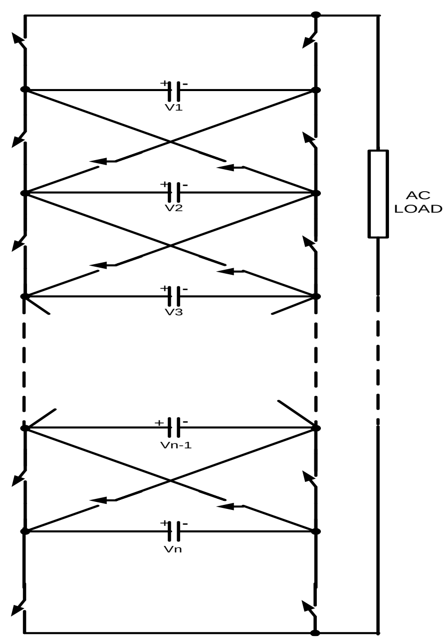

Figure 1 Proposed multilevel topology with 'n' sources

III. FUEL CELL MODULE ARRANGEMENTS

Acting as separate dc sources (SDCS's), the fuel cell modules can be configured so as to attain the desired number of levels in the output waveform [22]. Various possible arrangements for the fuel cell modules based on the dc level a module provides can be:

(i) 'unary' arrangement will result if all the dc levels are equal, i.e.

$$V_1 = V_2 = V_3 = \ldots = V_n \qquad \textbf{...(3)}$$

(ii) 'binary' arrangement will result if the dc levels make a geometric progression with a factor of '1/2' i.e.

$$\frac{V_1}{V_2} = \frac{V_2}{V_3} = \cdots = \frac{V_{n-1}}{V_n} = 2 \qquad \textbf{...(4)}$$

(iii) 'trinary' arrangement will result if the dc sources make a geometric progression with a factor of '1/3' i.e.

$$\frac{V_1}{V_2} = \frac{V_2}{V_3} = \cdots = \frac{V_{n-1}}{V_n} = 3 \qquad \textbf{...(5)}$$

For above three arrangements, the number of actual levels in the output waveform can be obtained using equation (1) and the results are summarized in **Table 1**. It is seen that for two or more than two dc sources (i.e. for n>1), trinary arrangement results in most number of levels as compared to other two arrangements .

TABLE 1 FUEL CELL MODULES ARRANGEMENT AND OUTPUT LEVELS

Sr. No.	**Arrangement of dc sources**	**Number of levels in the output waveform**
1	Unary	2n + 1
2	Binary	$2^{(n+1)} - 1$
3	Trinary	3^n

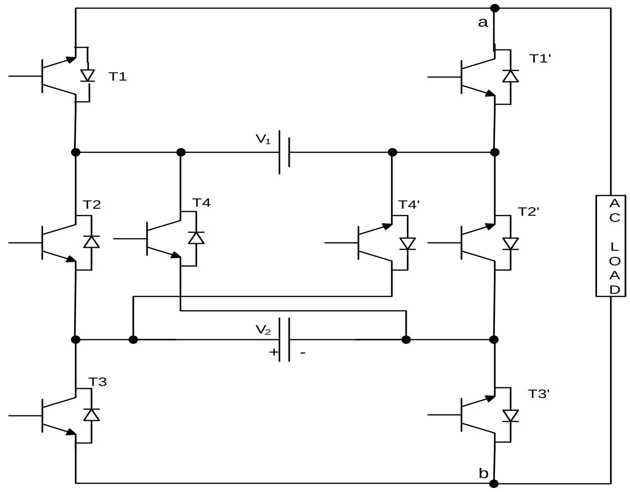

Figure 2 Proposed structure for nine level single phase output

IV. PROPOSED INVERTER WITH THREE SOURCES

As described in the previous section, for three dc sources, the proposed topology is capable of synthesizing twenty seven levels. In **figure 4**, such a topology with three sources is shown and **Table 2** summarizes various levels obtained for different switching conditions. For a switch, '0' and '1' indicate OFF and ON conditions respectively. In the aforesaid table, redundant states are not shown for the sake of brevity.

A multicarrier pulse-width modulation (PWM) scheme is used along with the look-up table of **Table 2** in order to feed switching signals to the switches

V. SIMULATION STUDY OF PROPOSED TOPOLOGY WITH THREE INPUT DC VOLTAGES

Multilcarrier PWM control has been used to simulate the proposed topology for single-phase operation with three dc input voltages, using MATLAB/Simulink. The dc voltages V1, V2 and V3 are taken to be 700V, 300V and 100V respectively. The inverter is operated in open loop mode and the load is taken to be an RL load with R = 2 ohms and L = 5 mH. The frequency of the reference sinusoidal wave is taken as 50 Hz and that of the carrier waveforms as 800 Hz as shown in **figure 6.**

As explained in the previous section, with three dc input voltages, the possible number of combinations is twenty seven. However, with the present selection of three voltages to be 700V, 300V and 100V, the number of unique voltage levels comes out to be twenty-three. These are 0 to 1100V and 0 to -1100V, with successive difference of 100V. Thus the resultant inverter is a twenty-three level inverter.

Figure 7(a) shows the output voltage of the simulated inverter and **figure 7(b)** shows its harmonic spectrum. As can be seen, the voltage waveform is a close imitation of a sine wave and the total harmonic distortion is 5.66% without any filter. Moreover, the prominent harmonics are 13th, 15th and 17th, i.e. harmonics are shifted to higher order side. **Figure 8(a)** and **(b)** show the load current and its harmonic spectrum. Here also the THD is very low, only 0.34%.

VI. Conclusions

A novel multilevel topology is proposed with a view to attain all the possible additive and subtractive combinations of the input dc voltage levels. Such a concept can be used to obtain high-quality output waveform from a fuel cell based power generation system which is a promising technology for standalone as well distributed generation systems. Working states of the proposed topology is explained with a nine-level topology and simulation study of a twenty-three level inverter is presented. Simulation validates the proposed concept and high quality voltage and load current waveforms are obtained.

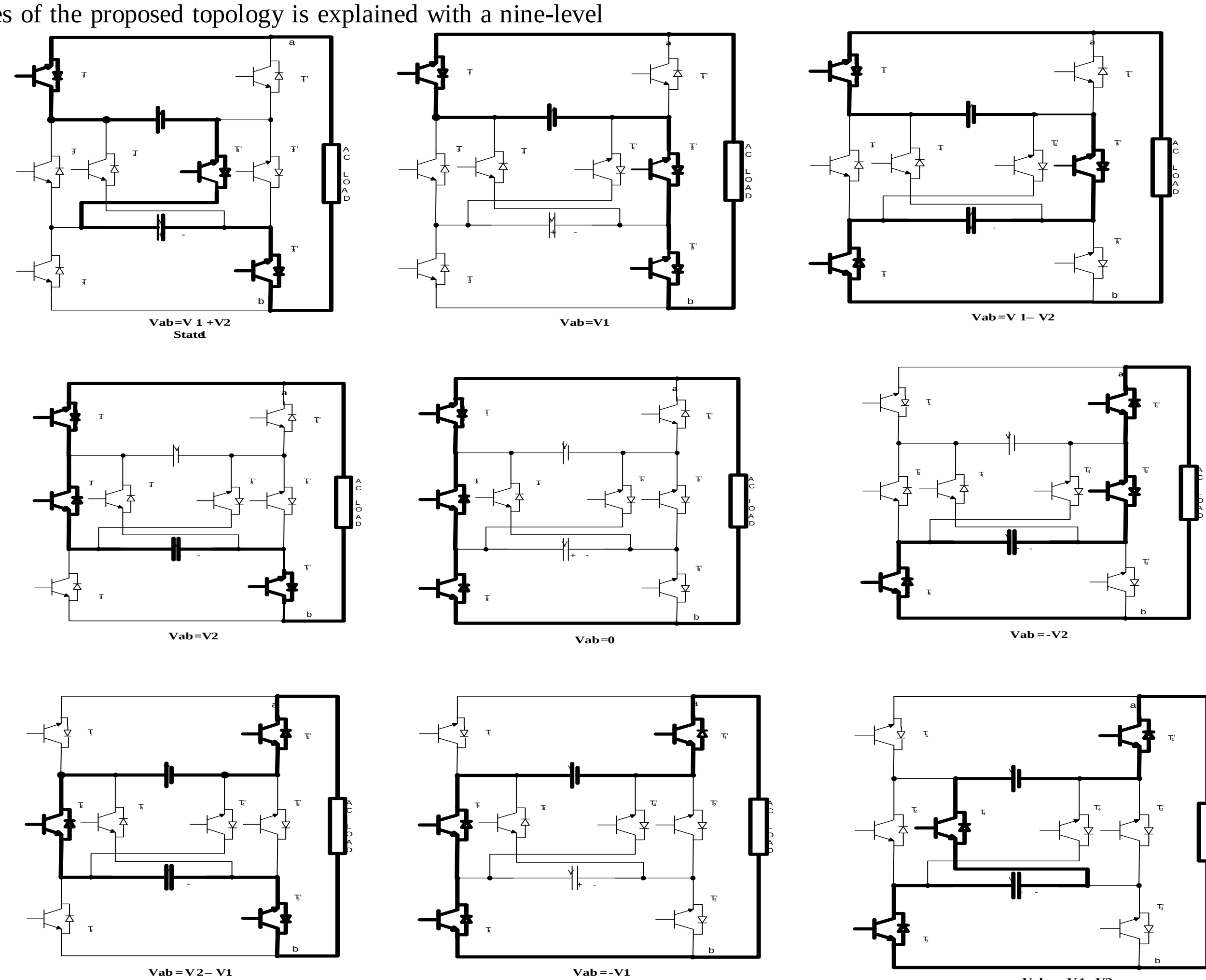

Figure 3 Switching combinations to obtain nine level output through the proposed topology

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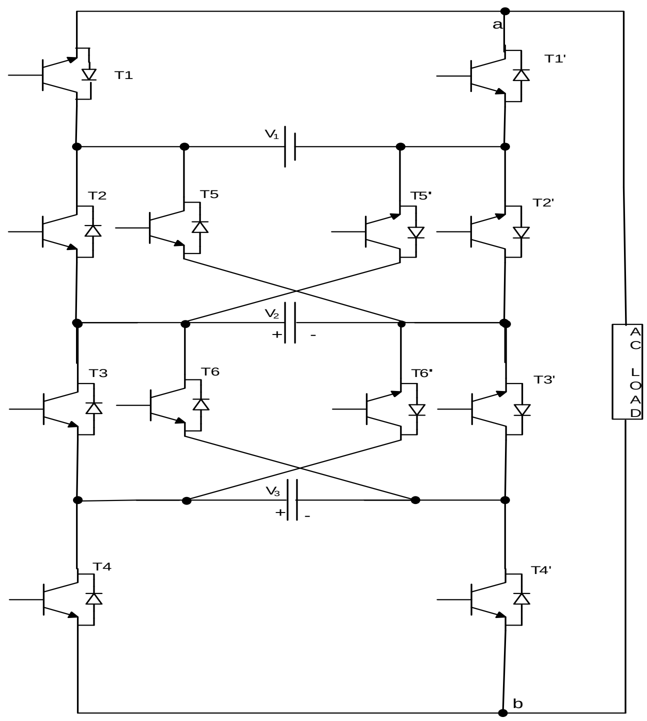

Figure 4 Proposed topology with three sources and twenty-seven possible levels

TABL

S.N.	Output Voltage Level (V_{ab})	T_1	T_2	T_3	T_4	T_5	T_6	T_1’	T_2’	T_3’	T_4’	T_5’	T_6’
1	0	1	1	1	1	0	0	0	0	0	0	0	0
2	$+V_1$	1	0	0	0	0	0	0	1	1	1	0	0
3	$+V_2$	1	1	0	0	0	0	0	0	1	1	0	0
4	$+V_3$	1	1	1	0	0	0	0	0	0	1	0	0
5	$-V_1$	0	1	1	1	0	0	1	0	0	0	0	0
6	$–V_2$	0	0	1	1	0	0	1	1	0	0	0	0
7	$-V_3$	0	0	0	1	0	0	1	1	1	0	0	0
8	$+V_1+V_2$	1	0	0	0	0	0	0	0	1	1	1	0
9	$+V_1 –V_2$	1	0	1	1	0	0	0	1	0	0	0	0
10	$+V_2 – V_1$	0	1	0	0	0	0	1	0	1	1	0	0
11	$-V_1 – V_2$	0	0	1	1	1	0	1	0	0	0	0	0
12	$+V_2+V_3$	1	1	0	0	0	0	0	0	0	1	0	1
13	$+V_2 –V_3$	1	1	0	1	0	0	0	0	1	0	0	0
14	$+V_3 – V_2$	0	0	1	0	0	0	1	1	0	1	0	0
15	$-V_2 – V_3$	0	0	0	1	0	1	1	1	0	0	0	0
16	$+V_1+V_3$	1	0	1	0	0	0	0	0	0	1	1	0
17	$+V_1 –V_3$	1	0	0	1	0	0	0	1	1	0	0	0
18	$+V_3 – V_1$	0	1	1	0	0	0	1	0	0	1	0	0

19	$-V_1 - V_3$	0	0	0	1	1	0	1	0	1	0	0	0
20	$+V_1 + V_2 + V_3$	1	0	0	0	0	0	0	0	0	1	1	1
21	$+V_1 + V_2 - V_3$	1	0	0	1	0	0	0	0	1	0	1	0
22	$+V_1 - V_2 + V_3$	1	0	1	0	0	0	0	1	0	1	0	0
23	$+V_1 - V_2 - V_3$	1	0	0	1	0	1	0	1	0	0	0	0
24	$-V_1 + V_2 + V_3$	0	1	0	0	0	0	1	0	0	1	0	1
25	$-V_1 + V_2 - V_3$	0	1	0	1	0	0	1	0	1	0	0	0
26	$-V_1 - V_2 + V_3$	0	0	1	0	1	0	1	0	0	1	0	0
27	$-V_1 - V_2 - V_3$	0	0	0	1	1	1	1	0	0	0	0	0

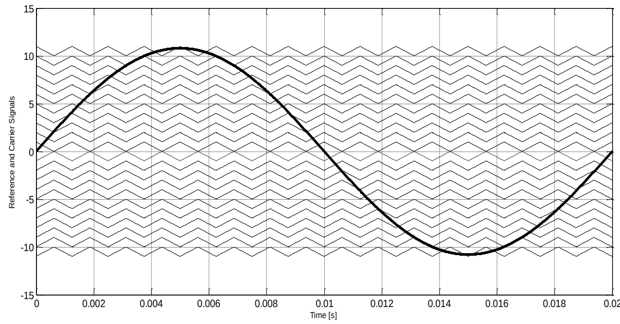

Figure 6 Reference and carrier waveforms for twenty-three level inverter

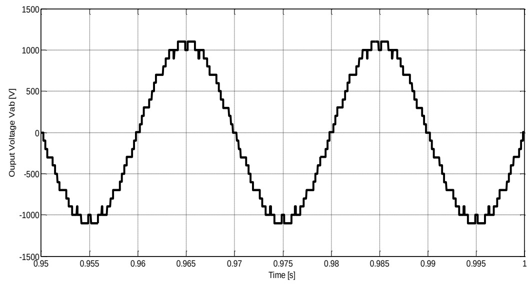

Figure 7(a) Output waveform for proposed twenty-three level inverter

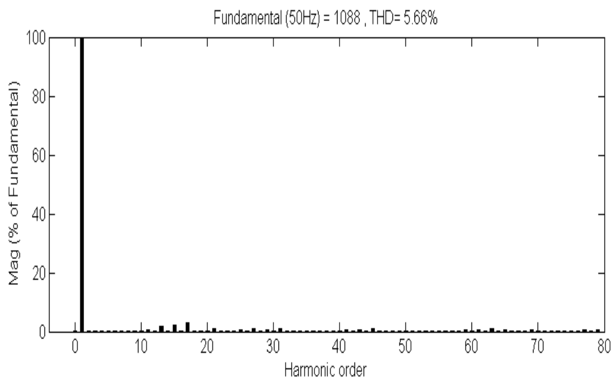

Figure 7(b) Harmonic spectrum of voltage waveform in 7(a)

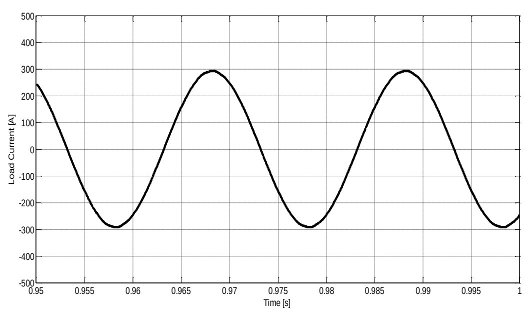

Figure 8(a) Load current waveform for twenty-three level inverter

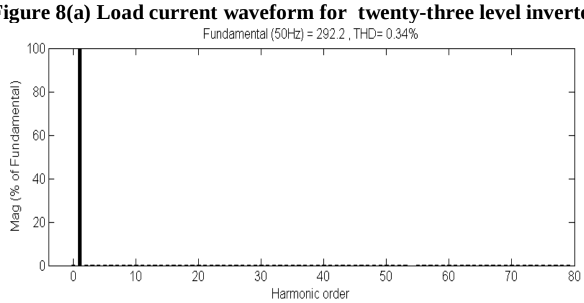

Figure 8(b) Harmonic spectrum of current waveform in 8(a)

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