FUZZY LOGIC CONTROL FOR SINGLE PHASE MULTILEVEL INVERTER

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Abstract : *A single phase cascaded inverter consisting of two full bridges creates a five level AC output voltage. Due to switch combination redundancies, there are certain degrees of freedom to generate the five level AC output voltage. A single phase Pulse Width Modulation (PWM) Multil Level Inverter (MLI) produces AC output voltage of desired magnitude and frequency. The purpose of voltage controller for the inverter is to produce regulated output voltage with low distortion under all loading conditions. A Fuzzy Logic Controller (FLC) isdeveloped using Matlab-Simulink for the chosen inverter having application in Uninterruptible Power Supplies (UPSs). For comparison purposes, a PI controller is also developed. The results are presented and evaluated. FLC is found to have better performance.*

Key words: *MLI, PWM, PI control, fuzzy logic control.*

1. Introduction

The general requirement of inverter system for high power AC power supply application is to maintain high quality output voltage with Total Harmonic Distortion (THD) typically specified to be less than 5% at a fixed frequency regardless of the loading condition [1]. Multilevel inverter has drawn tremendous interest in high power applications because it has many advantages: it can realize high voltage and high power output through the use of semiconductor switches without use of transformer and without dynamic voltage balance circuits. When the number of output levels increases, harmonics of the output voltage and current as well as Electro Magnetic Interference (EMI) decrease. The main feature of a MLI is its ability to reduce the voltage stress on each power device due to utilisation of multiple levels on the DC bus. In [1] and [2], Fuzzy Proportional Integral Control (FPIC) is proposed to replace the conventional linear PI controller employed in the on line optimal PWM control scheme presented in [3]-[5]. Development of a DSP-based fuzzy PI controller for an optimal PWM control scheme for MLI is presented in [6]. Three PWM methods with different vertical and horizontal offset combinations are investigated in [7]-[9] leading to the quantification of their output harmonics. Multilevel PWM methods based on control degrees of freedom combination and their theoretical analysis are discussed in [10].

Since above survey of literature reports little work on intelligent control for MLIs, an attempt is made in this work to develop fuzzy controllers for the chosen inverter. The simulation results are presented and analysed with PI controller developed.

2. Multilevel Inverter

Multilevel inverters are being considered for an increasing number of applications due to their high power capability associated with lower output harmonics and lower commutation losses. There are several types of multilevel inverters but the one considered in this work is the Modular Structured Multilevel Inverter (MSMI). Multilevel inverters have become an effective and practical solution for increasing power and reducing harmonics of AC load. Fig.1 shows a single phase five level configuration of the MSMI. The MSMI is unique when compared to other types of multilevel inverters in the sense that it consists of several modules that require separate DC sources. Compared to other types of multilevel inverters, the MSMI requires less number of components with no extra clamping diodes or voltage balancing capacitors that only further complicate the overall inverter operation. As can be seen from Fig. 1, each module of the MSMI has the same structure whereby it is represented by a single phase full-bridge inverter. This simple modular structure not only allows practically unlimited number of levels for the MSMI by stacking up the modules but also facilitates its packaging.

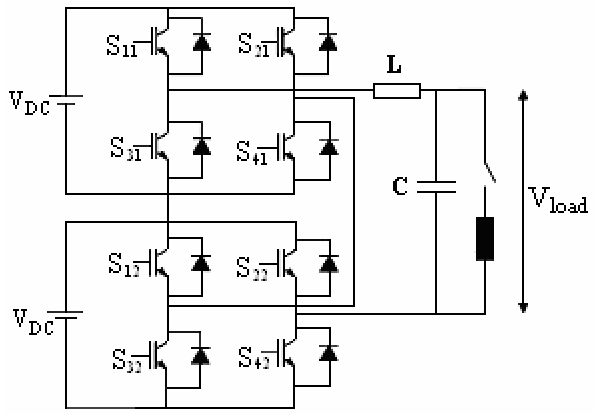

Fig.1 Five Level MSMI.

The operation of the MSMI can be easily understood whereby the load voltage is equal to the summation of the output voltage of the respective modules that are connected in series. The number of modules (M) which is equal to the number of DC sources required depends on the total number of positive, negative and zero levels (m) of the MSMI. It is usually assumed that m is odd as this would give an integer valued M which would simplify further analysis. In this work, load voltage consists of five levels which include $+2V_{DC}$, $+V_{DC}$, 0, $-V_{DC}$ and $-2V_{DC}$ and the number of modules needed is 2. The following equation gives the relationship between M and m:

$$M=(m-1)/2$$

3. Modulation Strategies for Multilevel Inverter

A number of modulation strategies are used in multilevel power conversion applications. They can generally be classified into three categories:

- Multistep, staircase or fundamental frequency switching strategies
- Space Vector PWM strategies
- Carrier based PWM strategies

Of all the PWM methods for cascaded multilevel inverter, carrier based PWM methods and space vector methods are often used but when the number of output levels is more than five, the space vector method will be very complicated with the increase of switching states. So the carrier based PWM method is preferred under this condition in multilevel inverters. This paper focuses on carrier based PWM techniques which have been extended for use in multilevel inverter topologies by using multiple carriers.

Multilevel carrier based PWM methods have more than one carrier that can be triangular waves or sawtooth waves and so on. The modulating/ reference wave of multilevel carrier based PWM method can be sinusoidal or trapezoidal. This paper presents the Carrier Overlapping PWM (COPWM) method that utilizes the vertical offsets among carriers.

3.1. COPWM Strategy

For an m-level inverter using carrier overlapping technique, m-1 carriers with the same frequency f_c and same peak-to-peak amplitude A_c are disposed such that the bands they occupy overlap each other; the overlapping vertical distance between each carrier is $A_c/2$. The reference waveform has amplitude of A_m and frequency of f_m and it is centered in the middle of the carrier signals. The reference wave is continuously compared with each of the carrier signals. If the reference wave is more than a carrier signal, then the active devices corresponding to that carrier are switched on. Otherwise, the devices switch off. The amplitude modulation index m_a and the frequency ratio m_f are defined in the carrier overlapping method as follows:

$$m_a = A_m/((m/4)*A_c)$$

$$m_f = f_c / f_m$$

The vertical offset of carriers for five level inverter with COPWM method is illustrated in Fig.2. Table 1 provides details about chosen inverter.

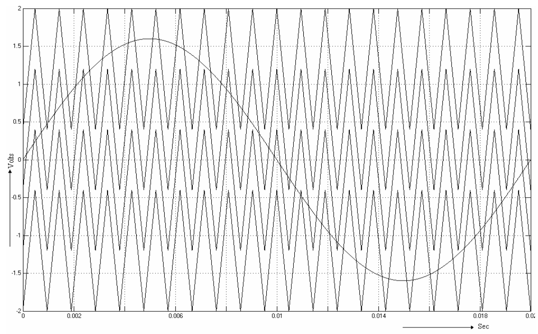

Fig. 2. Carrier arrangement for COPWM strategy.

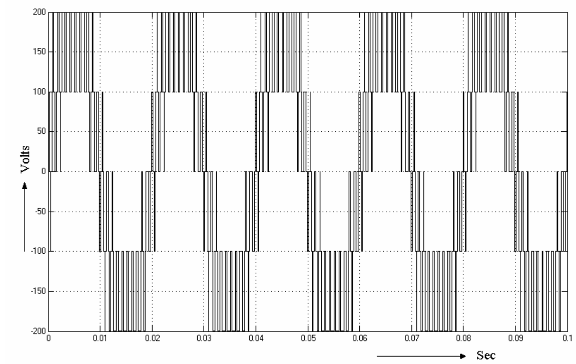

Fig. 3. Five level output voltage generated by COPWM strategy.

The gate signals for chosen five level cascaded inverter are developed using MATLAB-SIMULINK. The gate signal generator model developed is tested for various values of modulation index. The results of the open loop simulation study are obtained in this work in the form of the PWM outputs of the chosen multilevel inverter and Fig.3 shows a sample output for only one value of m_a=0.8.

The %THD and Vrms are evaluated for five level output using COPWM strategy and presented as in Table 2. A non-overlapping Sub-Harmonic PWM (SHPWM) strategy is also presented in this work for comparison purposes (Table 2).

Table 1 Inverter parameters

Parameter	Value	Unit
Switching frequency, f_s	2	KHz
DC source voltage, V_{dc}	100	V
Rated output voltage	300	V_{p-p}
Rated output frequency	50	Hz
Rated output current	30	A_{p-p}
Rated load (linear)	10	Ω
Filter inductor, L_f	1	mH
Filter capacitor, C_f	2.2	mF

Table 2 %THD and V_{rms} for different modulation indices

m_a	SHPWM		COPWM	
	%THD	Vrms (V)	%THD	Vrms (V)
1.0	7.7	141.4	12.9	150.16
0.9	7.35	127.3	10.39	141.7
0.8	8.5	113.1	7.84	131.2
0.7	9.7	98.98	5.72	119.8
0.6	11	84.84	4.28	106.9
0.5	--	--	3.79	88.36
0.4	--	--	5.10	75.1
0.3	--	--	6.74	53.1

The closed loop control is performed (as presented in the next two sections) using the COPWM switching strategy because it gives the minimum THD for low and medium modulation indices (Table 2).

4. PI Control

Today different controllers are used in industry and in many other fields. They are divided into two main groups: i) conventional controllers ii) non-conventional controllers. PI controllers belong to the former category whereas fuzzy controller belong to latter. Inverter control refers to specifying the desired nominal operating point and then regulating the inverter so that it stays close to the nominal operating point in the presence of disturbances and noise. PI controller settings Kp and Ki are designed in this work using Ziegler – Nichols tuning technique. The designed values of Kp and Ki are 0.0125 and 1 sc $^{-1}$ respectively.

5. Fuzzy Logic Control

Fuzzy logic control uses non-mathematical decision based algorithms that use operators' experiences. This type of control strategy is well suited for non-linear systems. Fuzzy logic control is developed in this work to obtain desired output voltage of the chosen inverter. In order to obtain the fuzzy control surface for non-linear, time-varying and complex dynamic systems, there are a number of steps to be followed as discussed below. The block diagram of fuzzy logic control scheme developed for the chosen single phase PWM inverter is shown in Fig.4. The FLC is divided into five modules: fuzzifier, database, rule base, decision maker and defuzzifier. The computational structure of fuzzy logic control scheme is composed of the following:

5.1. Identification of Inputs and Output

The inputs to the FLC are the error $e = V_{ref} - V_o$ and the change in error $ce = e_n - e_{n-1}$ where V_o is the actual output voltage of the MLI, V_{ref} is the desired output voltage and subscript n denotes sampling instances. δm_n is the change of modulation index inferred by the FLC at the n^{th} sampling instant. Using δm_n, the updated modulated signal m_s is obtained and fed to the SPWM generator which provides appropriate PWM signals m_n.

5.2. Fuzzification of Inputs

The crisp input values of e and ce are to be fuzzified and sevent riangular membership functions (Fig.5) are chosen in this work for simplicity.

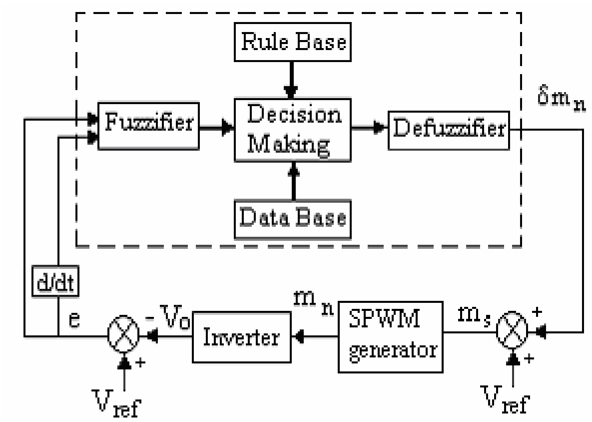

Fig. 4. Fuzzy logic control scheme for chosen single phase PWM inverter.

5.3. Rule Table and Inference Mechanism

The fuzzy rules are in the form

R_i : If e is A_i and ce is B_i then δm_n is C_i

where A_i, B_i and C_i are fuzzy subsets in their universe of discourse. Each universe of discourse is divided into seven fuzzy subsets namely PB (Positive Big), PM (Positive Medium), PS (Positive Small), ZE (Zero), NS (Negative Small), NM (Negative Medium) and NB (Negative Big) as shown in Figs.5 and 6. The values of e and ce are normalised to [-1, 1] as in Fig.5 and values of δm_n have the range [-1, 1] as in Fig.6. For any combination of e and ce, a maximum of four rules are adopted.

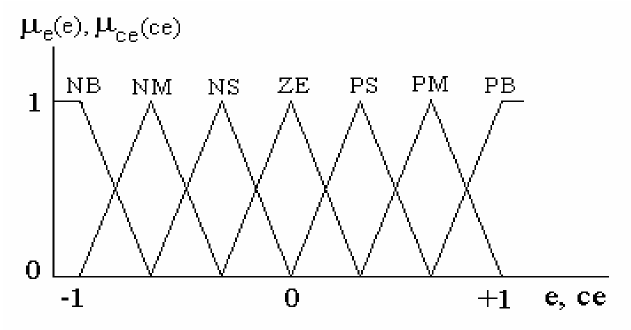

Fig.5. Membership functions for e and ce.

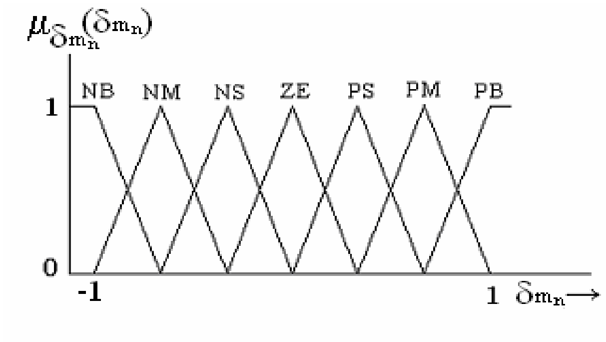

Fig.6. Membership functions for change in modulation Index.

The derivation of fuzzy control rules for chosen inverter is heuristic in nature and is based on the following criteria:

i. When the output of the inverter deviates far from the reference, the change of modulation index must be large so as to bring the output to the reference quickly.
ii. When the output of the inverter is approaching the reference, a small change of modulation index is necessary.
iii. When the output of the inverter is near the reference and is approaching it rapidly, the modulation index must be kept constant so as to prevent further deviation.
iv. When the reference is reached and the output is still changing, the modulation index must be changed a little bit to prevent the output from moving away.
v. When the reference is reached and the output is steady, the modulation index remains unchanged.
vi. When the output is larger than the reference, the sign of the change of modulation index must be negative and vice versa.

According to these criteria, a rule base is derived as in Table 3.

Table 3 Rule base

e\ce	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The inference result of each rule consists of two parts, the weighting factor w_i of the individual rule and the degree of change of modulation index C_i according to the rule and it is written as

$$z_i = min\ \{\mu_e(e)\ ,\ \mu_{ce}(ce)\ \}.\ C_i$$
$$= w_i C_i$$

where z_i denotes the change in modulation index inferred by the i^{th} rule and C_i is looked up from the rule table which shows the mapping from the product space of e and ce to C_i.

5.4. Defuzzification

The defuzzification is carried out in this work using the bisector of area method.

6. Simulation Results

The cascaded five level inverter is modelled in SIMULINK using Power system block set. Switching signals for cascaded multilevel inverter using SHPWM and COPWM techniques are simulated using the gate signal generator model developed. Open loop simulations are performed for different values of m_a ranging from 0.3 – 1.0 and the corresponding %THD and V_{rms} are evaluated using the FFT block and their values are shown in Table 2. SHPWM produces three level output only when m_a is less than 0.

Fig.7 shows the simulated closed loop dynamic responses of load voltage and load current of PI controlled inverter when the load changes from full load (10) to no load (10k) suddenly at t=0. 45secs. Fig.8 shows the corresponding simulated dynamic responses with fuzzy controller. Figs. 9 and 10 display the simulated dynamic responses of load voltage and load current of chosen inverter when the load changes from noload (10 k) to full load (10) suddenly at t=0.345secs with PI and fuzzy controllers. The next two figures display the corresponding steady-state responses for a resistive load. Table 4 and Figs. 13 to 18 provide the comparison of % THD for the PI and fuzzy controllers for the chosen inverter.

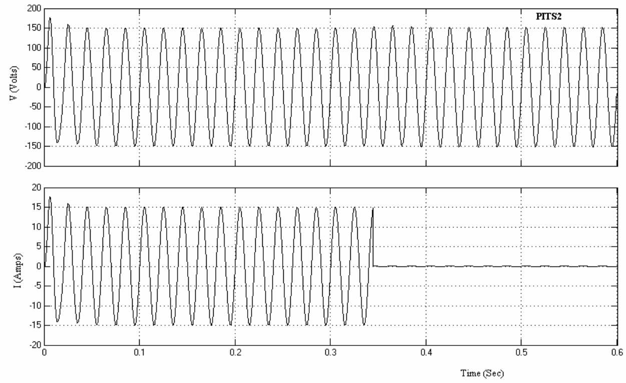

Fig.7 Transient responses of the MLI with PI control.

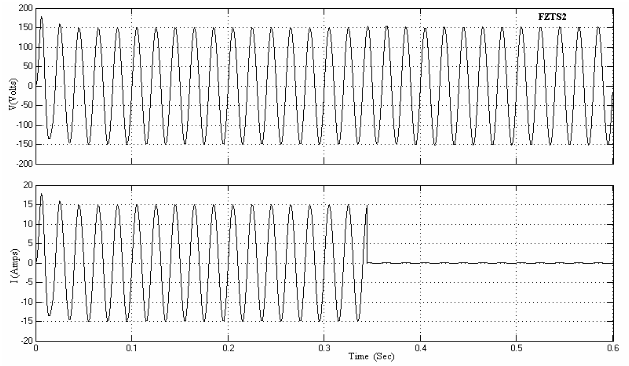

Fig.8 Transient responses of MLI with fuzzy control.

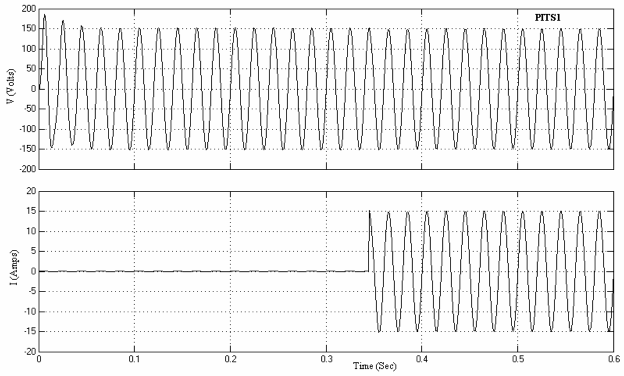

Fig.9 Transient responses of the MLI with PI control.

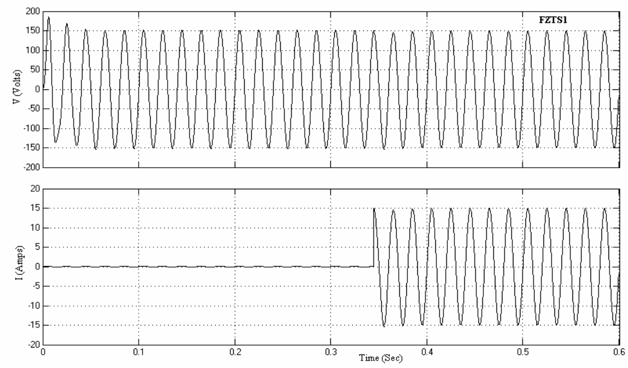

Fig.10. Transient responses of the MLI with fuzzy control.

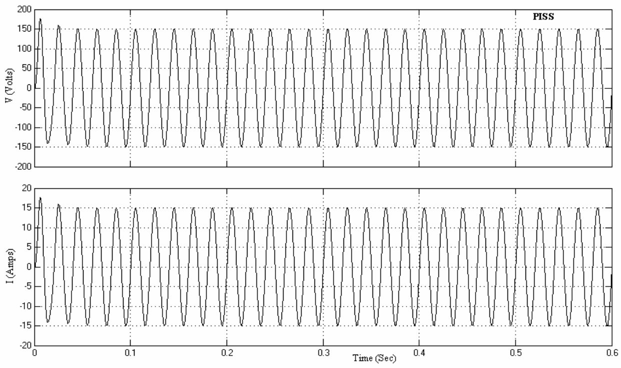

Fig.11. Steady-state responses of the MLI with PI Control.

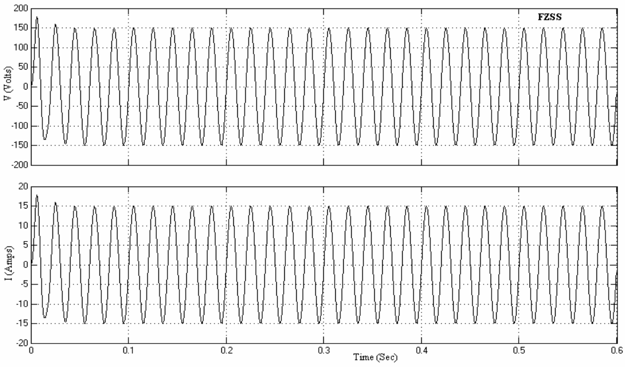

Fig.12. Steady-state responses of the MLI with fuzzy control.

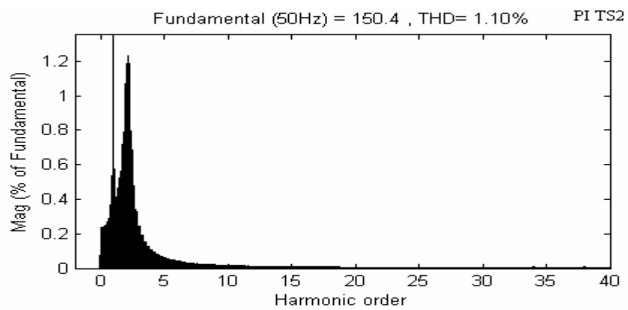

Fig. 13. FFT Plot for PI control - load voltage – sudden load change(10 -10k).

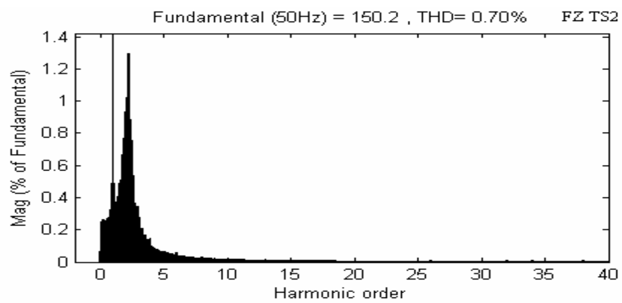

Fig.14. FFT Plot for fuzzy control - load voltage – sudden load change(10 -10k).

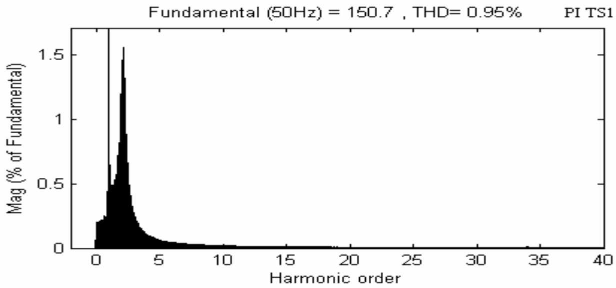

Fig. 15. FFT Plot for PI control - load voltage – sudden load change(10k -10).

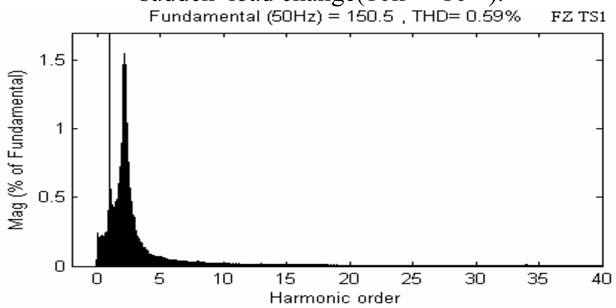

Fig. 16. FFT Plot for fuzzy control - load voltage – sudden load change(10 k -10).

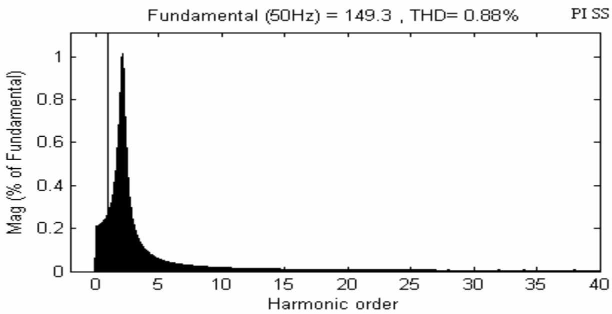

Fig. 17. FFT Plot for PI control - load voltage –10 load.

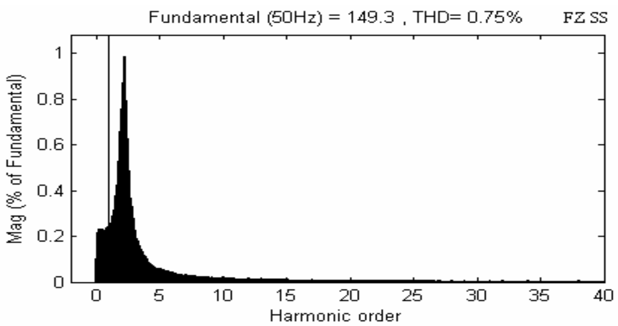

Fig. 18.FFT Plot for fuzzy control -load voltage –10 load.

7. Conclusion

The PI and fuzzy controllers developed have been tested through simulation for regulating output voltage and minimising the harmonics of the chosen cascaded five level inverter. The closed loop responses of the inverter have been obtained under different loading conditions such as sudden change from no load to full load and vice versa. The simulation results (Table 4) show that the inverter with fuzzy control has minimum amount of harmonics.

Table 4 Comparison of %THD for different loading conditions

Load	PI Control	Fuzzy Control
Steady State R=10Ω	0.88	0.75
Transient State R=10kΩ to 10Ω	0.95	0.59
Transient State R= 10Ω to 10kΩ	1.1	0.7

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