FPGA based Fuzzy Logic Control for Single Phase Multilevel Inverter

Shanthi B.
Associate Professor
Centralised Instrumentation and Service Laboratory
Annamalai University, Annamalainagar – 608 002
Tamil Nadu, India

Natarajan S.P
Professor and Head
Department of Instrumentation Engineering
Annamalai University, Annamalainagar – 608 002
Tamil Nadu, India

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. In this paper, the objective of reducing the THD of output of the chosen five level cascaded inverter under steady-state as well as set point tracking with fast transient response are approached from control point of view. A Fuzzy Logic Controller (FLC) is developed using Matlab-Simulink and implemented using Field Programmable Gate Array (FPGA) for the chosen inverter. For comparison purposes, a PI controller is also developed and implemented. The results are presented and analysed.

Keywords
MLI, MSMI, PWM, PI control, fuzzy logic control, FPGA.

1. INTRODUCTION
Multilevel power conversion has gained much attention due to its properties regarding high voltage capability and high power quality. Reduction of THD can be considered from three different perspectives, namely: by considering new switching strategies, by designing alternative circuit topological structures and by proposing appropriate control techniques. The third perspective, i.e. proposition of appropriate control technique is an alternate solution for THD reduction is discussed in this paper. In view of the inherent advantages, the SHPWM switching strategy and cascaded inverter structure are employed in this work. The most commonly used controller is the PI controller. This controller is frequently applied to regulate the AC output voltage because it can reduce the steady-state error to zero. A fuzzy logic control scheme is also used to improve the transient response for both loading and unloading conditions as well as to regulate the output voltage with zero steady-state error under disturbances with minimum THD. The simulations have been carried out for both linear and non-linear loads. The above control strategies are implemented in real time using FPGA for linear and non-linear loads. The waveforms of output voltage and current along with the harmonic spectra of output voltage are presented and evaluated.

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].

2. CASCADED FIVE LEVEL INVERTER
There are several types of multilevel inverters but the one considered in this work is the Modular Structured Multilevel Inverter (MSMI) is also called as cascade MLI. 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.

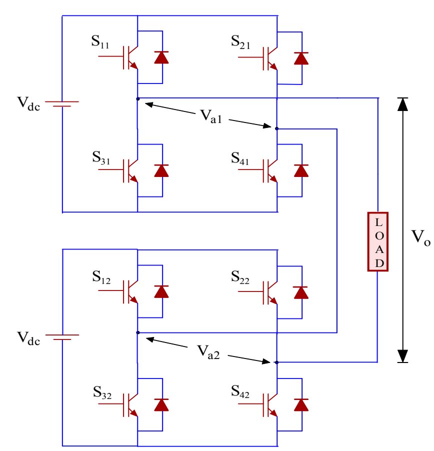

Figure 1. Five level MSMI

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.

3. PI CONTROL
PI control is developed using the control system toolbox. The gate signals are generated using SHPWM strategy. The five level output of the cascaded inverter is fed to the load through LC filter

to produce sinusoidal output (V_o) which is compared with the reference voltage (V_{ref}) to generate the error signal (e). The input to the PI controller is e. The output of the PI controller i.e the compensating signal (C_s) is added with the reference signal to yield the required modulating signal (m_s) which used to generate the gating pulses. Thus a voltage feedback loop is established to realize the required sinusoidal output voltage. Fig.2 shows the block diagram of MLI with PI control. PI controller settings Kp and Ki are designed in this work using Ziegler – Nichols tuning technique. The designed values of Kp and Ki are 0.1 and 0.01 sec^{-1} respectively.

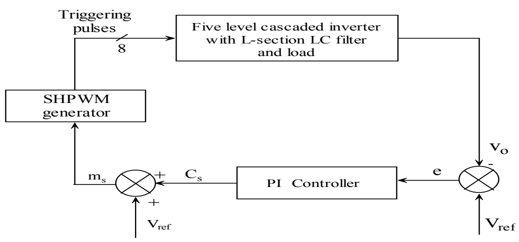

Figure 2. Block diagram for MLI with PI control

4. FUZZY LOGIC CONTROL

Fuzzy logic control employs knowledge 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 and minimize the harmonics of the chosen inverter. The control action is determined in a FLC through the evaluation of a set of simple linguistic rules. The development of the rules requires a thorough understanding of the process to be controlled.

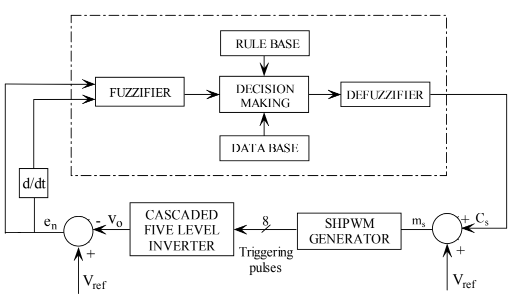

Figure 3. Fuzzy logic control scheme for chosen single phase PWM inverter

The block diagram of fuzzy logic control scheme developed for the chosen single phase PWM inverter is shown in Fig.3. 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:

4.1 Identification of Inputs and Output

The inputs to the FLC are the present error $e_n = V_{ref} - V_o$ and the change in error $ce = e_n - e_{n-1}$ where V_o is the actual output voltage of the inverter, V_{ref} is the desired output voltage and e_{n-1} is the previous error. C_s is the compensating signal inferred by the FLC. Using C_s the updated modulating signal m_s is obtained and fed to the SHPWM generator which provides appropriate PWM/triggering signals.

4.2 Fuzzification of Inputs and Output

The inputs and output of the controller are not quantized in the classical sense that each input or output is assigned a "membership grade" μ to each fuzzy set. The universe of discourse (range) of inputs is divided into several fuzzy sets of desired shapes. Output is also mapped into several fuzzy regions of desired shapes (for Mamdani type fuzzy systems) In this work, seven triangular fuzzy sets are chosen as shown in Fig.4 and Fig. 5 and are defined by the following library of fuzzy membership functions for the error e, change in error ce and for the compensating signal C_s.

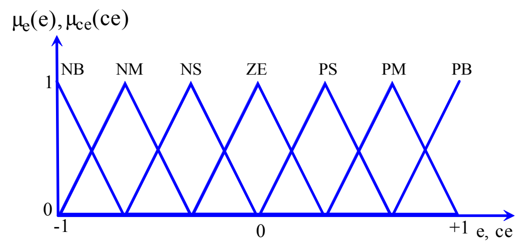

Figure 4. Membership functions for e and ce

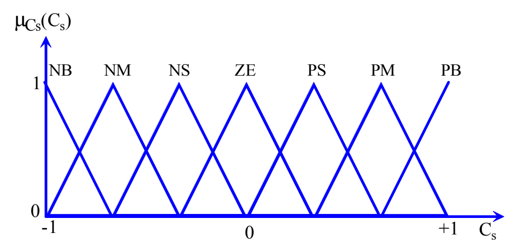

Figure 5. Membership functions for change in modulating signal (C_s)

4.3 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 C_s is C_i

where A_i, B_i and C_i are fuzzy subsets in their universe of discourse.

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 compensating signal/change of modulating signal 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 modulating signal is necessary.
iii. When the output of the inverter is near the reference and is approaching it rapidly, the modulating signal must be kept constant so as to prevent further deviation.
iv. When the reference is reached and the output is still changing, the modulating signal 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 modulating signal remains unchanged.
vi. When the output is larger than the reference, the amplitude of modulating signal must be decreased and vice versa.

According to these criteria, a rule base is derived as in Table 1

Table 1. Rule base of FLC developed for cascaded MLI

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

Since every e and ce belongs to almost two fuzzy sets, a maximum of four rules are considered at any sample to process any combination of input variables (e, ce). The inferred degree of membership for the rest of the rules is zero. 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 modulating signal C_i according to the rule and it is written as

$$Z_i = \min\{\mu_e(e) \cdot \mu_{ce}(ce)\} \cdot C_i$$

$$Z_i = W_i \cdot C_i$$

where Z_i denotes the change in modulating signal 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. Since the inferred output is a linguistic result, a defuzzification operation is performed to obtain a crisp result.

4.4 Defuzzification

The resulting fuzzy set is defuzzified into a crisp control signal. A crisp value for the change in modulating signal is calculated in this work using the bisector of area method.[1]

5. SIMULATION RESULTS

Figs. 6-17 show the steady-state as well as transient responses of the chosen MLI with PI and fuzzy controllers for both linear and non-linear loads. The %THD values of output voltage are measured using FFT block of SIMULINK and tabulated for different loads in Table 2.

Figs. 6-11 display the results of PI controller. Fig.6 shows the steady-state load voltage and current for 40Ω load. Figs.7 and 8 show the transient responses of load voltage and current of chosen inverter when the load changes from rated resistive load (40Ω) to no load suddenly at t=0.085sec and vice versa. Fig.9 shows the steady-state load voltage and current for rectifier load (40Ω, 2200μF). Figs.10 and 11 show the transient responses of load voltage and current of chosen inverter when the load changes from rated rectifier load (40Ω, 2200μF) to no load suddenly at t=0.085sec and vice versa. Figs 12 – 17 show the similar outputs generated using fuzzy logic control. The following parameter values are used for simulation V_{dc}=100V, V_{ref}=300V (peak to peak), L=36mH, C=9μF, f_c=1050Hz and rated load R= 40Ω and rated rectifier load RC=40Ω, 2200μF.

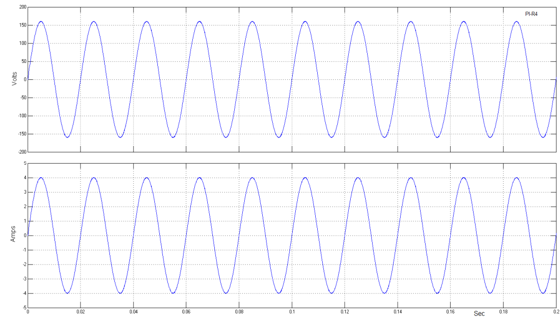

Figure 6. Steady-state load voltage and current for rated resistive load with PI control

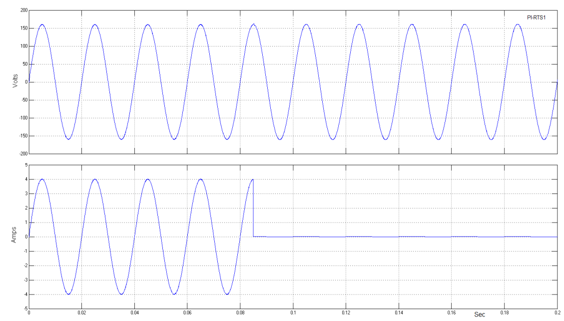

Figure 7. Transients in output voltage and current for sudden load change from rated load (40Ω) to no load with PI control

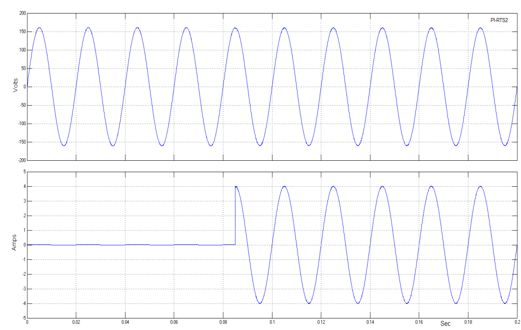

Figure 8. Transients in output voltage and current for sudden load change from no load to rated load (40Ω) with PI control

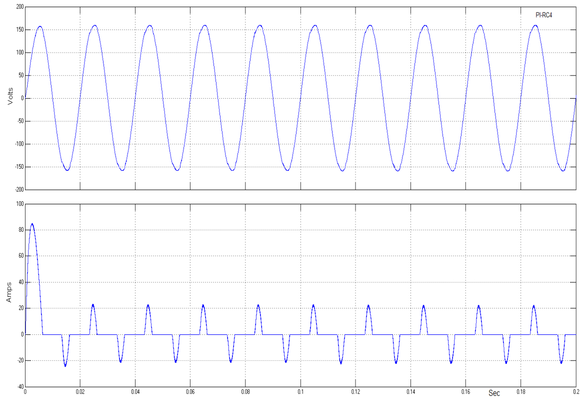

Figure 9. Simulated steady-state load voltage and current for rectifier load (40Ω, 2200µF) with PI control

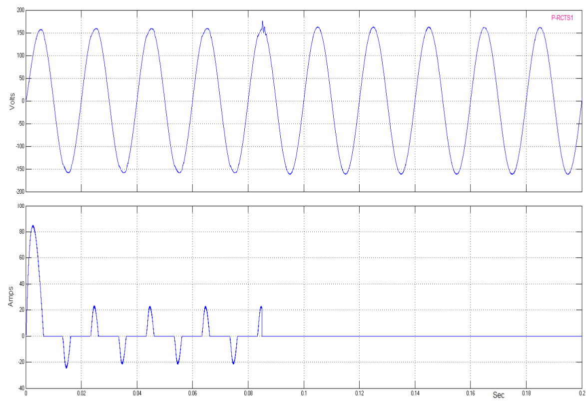

Figure 10. Simulated transients in output voltage and current for sudden load change from rated rectifier load (40Ω, 2200µF) to no load with PI control

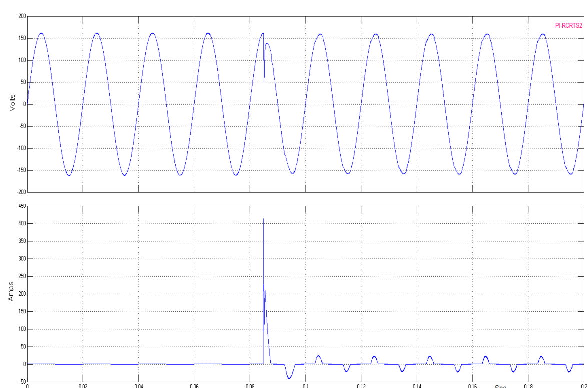

Figure.11 Simulated transients in output voltage and current for sudden load change from no load to rated rectifier load (40Ω, 2200µF) with PI control

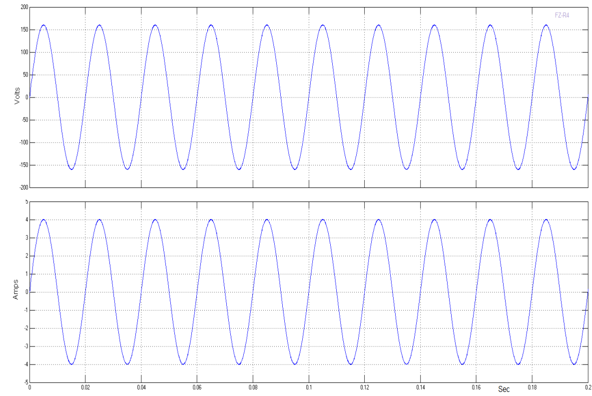

Figure 12. Simulated steady-state load voltage and current for resistive load (40Ω) with fuzzy control

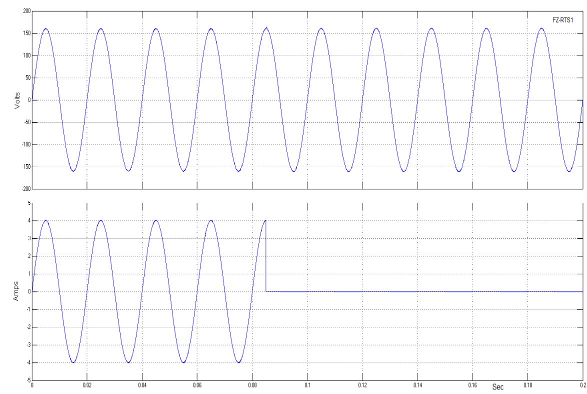

Figure 13. Simulated transients in output voltage and current for sudden load change from rated load (40Ω) to no load with fuzzy control

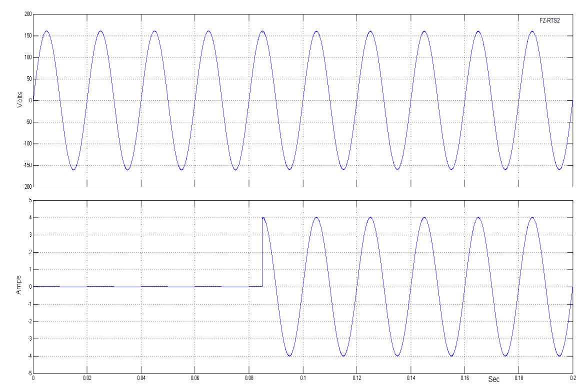

Figure.14. Simulated transients in output voltage and current for sudden load change from no load to rated load (40Ω) with fuzzy control

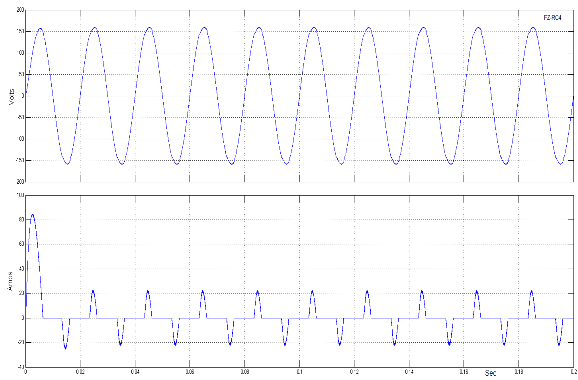

Figure 15. Simulated steady-state load voltage and current for rectifier load (40Ω, 2200µF) with fuzzy control

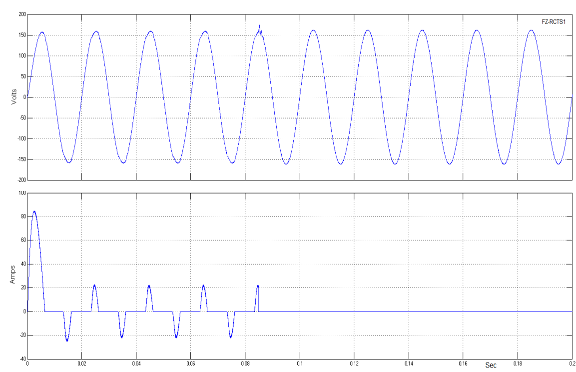

Figure 16. Simulated transients in output voltage and current for sudden load change from rated rectifier load (40Ω, 2200µF) to no load with fuzzy control

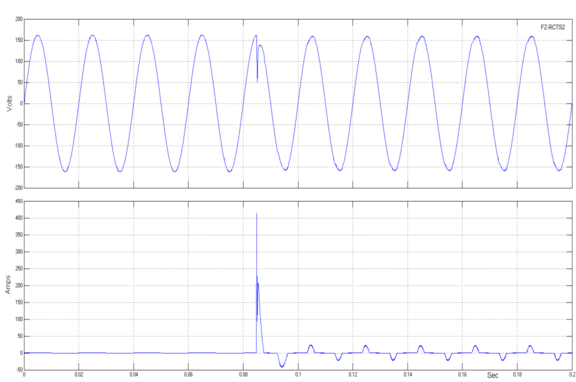

Figure 17. Simulated transients in output voltage and current for sudden load change from no load to rated rectifier load (40Ω, 2200µF) with fuzzy control

Table 2. % THD of output voltage of cascaded MLI for different loads (By simulation)

Load	% THD	
	PI	Fuzzy
RC1 (100Ω, 2200µF)	0.78	0.83
RC2 (100Ω, 4400µF)	0.98	0.98
RC3 (40Ω, 4400µF)	1.48	1.48
RC4 (40Ω, 2200µF)	1.31	1.35
R (40Ω)	0.16	0.06

6. FPGA BASED IMPLEMENTATION OF CONTROL STRATEGIES

This section presents the results of experimental work using SPARTAN-3 FPGA system for single phase five level cascaded type inverter. FPGAs usually include on-chip PWM controllers making implementation easy. Hence the real time implementation of PI and fuzzy controllers for chosen inverter using FPGA is carried out in this work. Multicarrier PWM generation and also the control strategies for the chosen inverter are developed using system generator software of Xilinix.

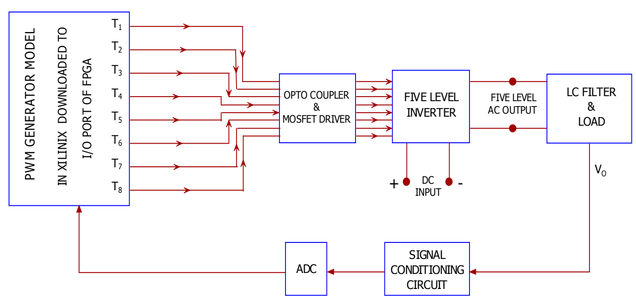

Figure 18. Block diagram of FPGA based closed loop control of five level inverter

The gate signal generator model developed using system generator is compiled and converted into bits and is downloaded into FPGA for execution in real time. The generated switching pulses are fed to pulse amplifiers through the input/output lines of FPGA before being applied to the gates of MOSFETs of the prototype of the chosen inverter. The filtered output (under transient and steady-state conditions) of the five level inverter with sudden load disturbances after appropriate signal conditioning is digitized using off chip ADC and fed to the FPGA through input/output lines. PI control algorithm is implemented in FPGA with K_p=0.1, K_i=0.01 sec^{-1}. Fuzzy control algorithm is developed in xilinix are downloaded to FPGA. The control algorithm generates the compensating signal to provide the required modulating signal for regulating the output voltage of this inverter. Specifications of prototype are V_{dc}=20V, V_{ref}=60V (peak to peak), L=36mH, C=9µF, f_c=1050Hz and rated load R= 40Ω. Fig.18 shows the interfacing of five level inverter with the FPGA based closed loop control strategy.

7. EXPERIMENTAL RESULTS

Figs. 19 (a) and (b) respectively show the steady-state load voltage and current and the corresponding harmonic spectrum of output voltage for rated load (40Ω). Figs.20 and 21 show the transient responses of load voltage and current of chosen inverter when the load changes from rated resistive load (40Ω) to no load and vice versa. Figs. 22 (a) and (b) show respectively the steady-state load voltage and current and the corresponding harmonic spectrum of output voltage for rectifier load (40Ω, 2200µF). Figs.23 and 24 show the transients in load voltage and current for step changes of rated rectifier load (40Ω, 2200µF) to no load and vice versa.

Figs. 25-30 show corresponding results for fuzzy logic control. The % THD is calculated from the FFT spectrum and tabulated for various non-linear loads. Fig.31 shows the Hardware setup.

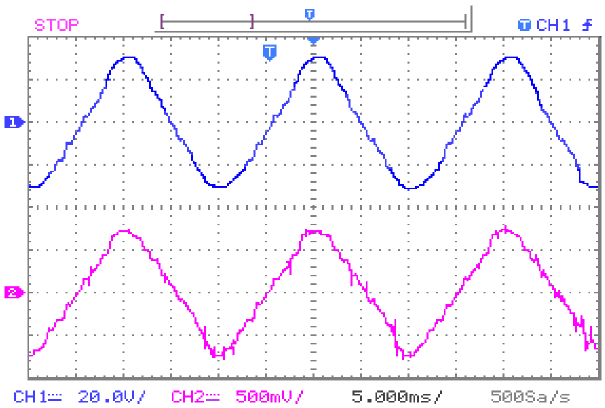

Figure 19 (a): Experimental steady-state load voltage and current for rated resistive load with PI control

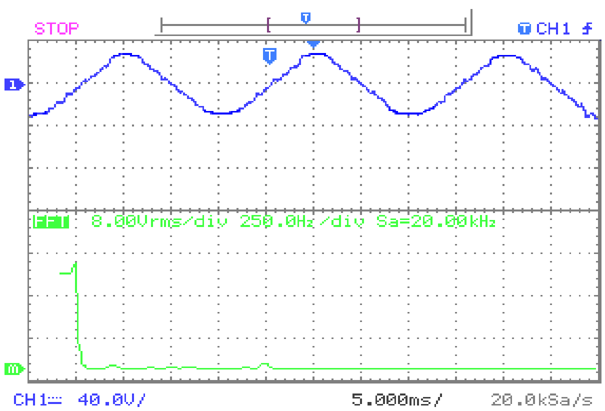

Figure 19 (b): FFT plot of load voltage under steady-state

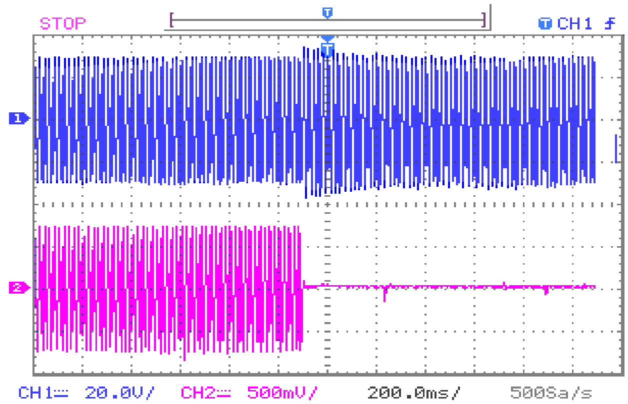

Figure 20. Transients in load voltage and current for sudden load change from rated load to no load with PI control

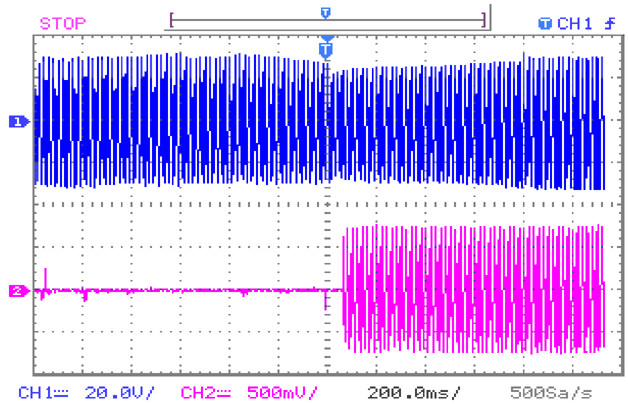

Figure 21. Transients in load voltage and current for sudden load change from no load to rated load with PI control

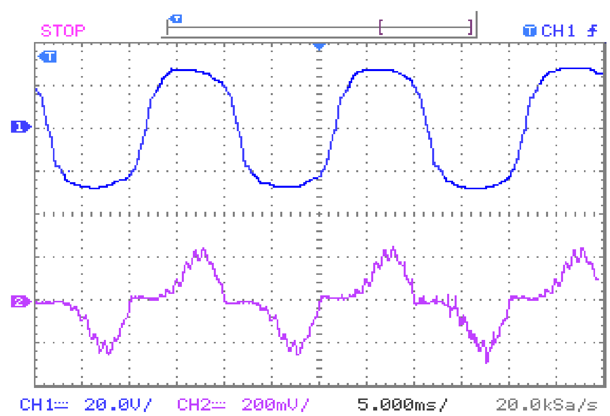

Figure 22 (a). Steady-state load voltage and current for rated rectifier load with PI control

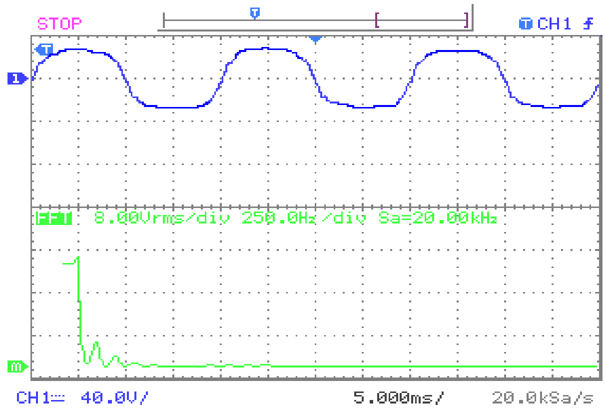

Figure 22 (b). FFT plot of load voltage under steady-state

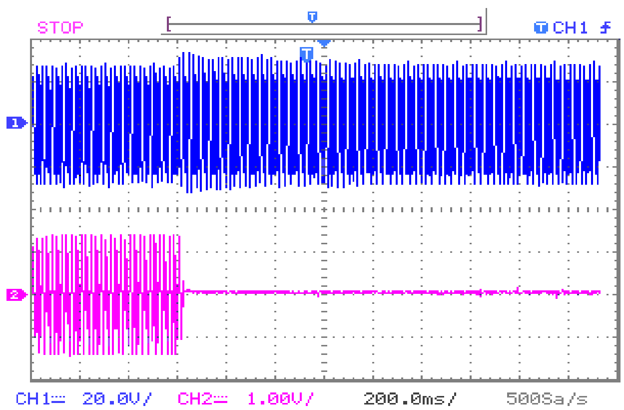

Figure 23. Transients in output voltage and current for sudden load change from rated rectifier load to no load with PI control

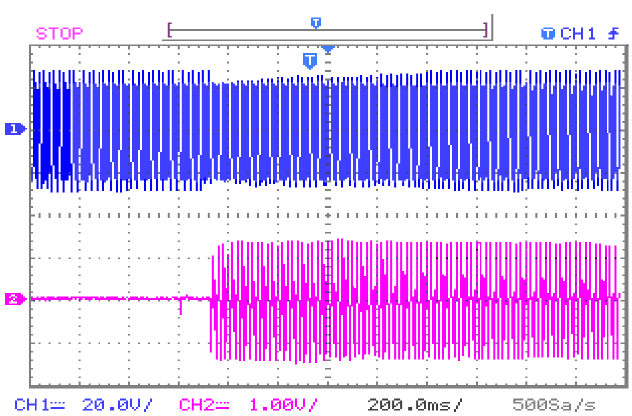

Figure 24. Transients in output voltage and current for sudden load change from no load to rated rectifier load (40Ω, 2200µF) with PI control

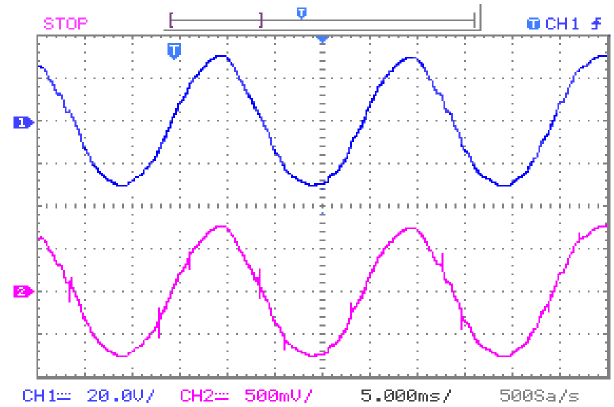

Figure 25 (a). Steady-state load voltage and current for resistive load (40Ω) with fuzzy control

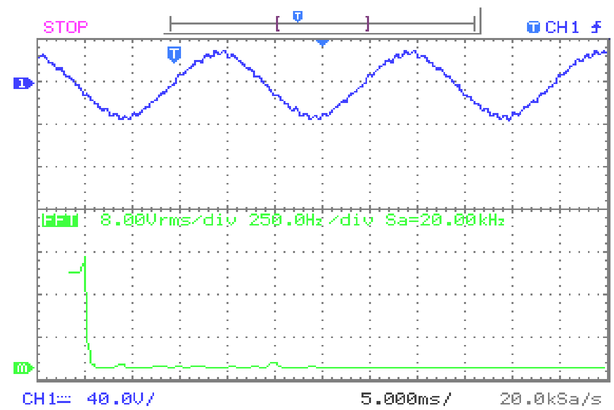

Figure 25 (b). FFT plot of load voltage under steady-state

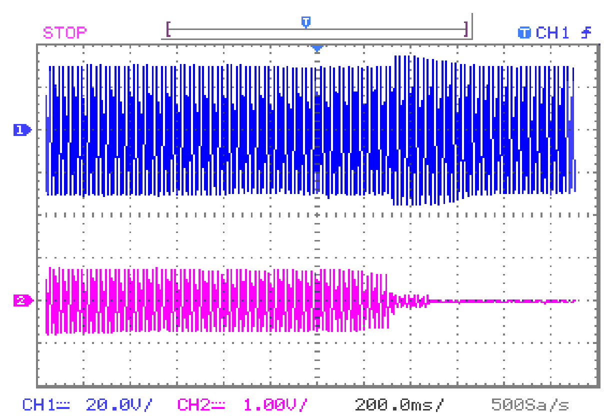

Figure 26. Transients in load voltage and current for sudden load change from no load to rated load (40Ω) with fuzzy control

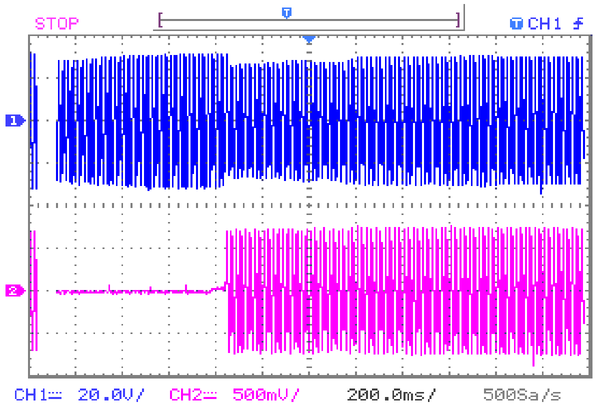

Figure 27. Transients in load voltage and current for sudden load change from rated load (40Ω) to no load with fuzzy control

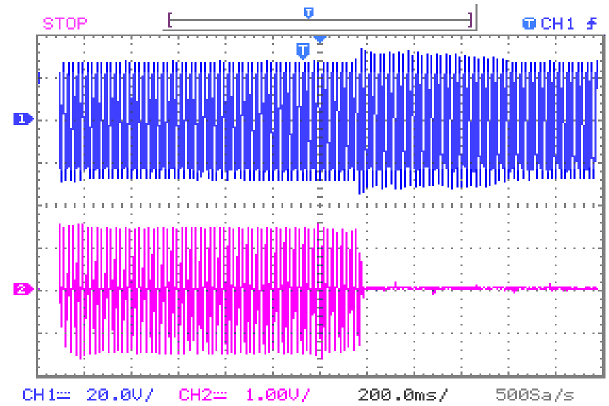

Figure 29. Transients in output voltage and current for sudden load change from rated rectifier load to no load with fuzzy control

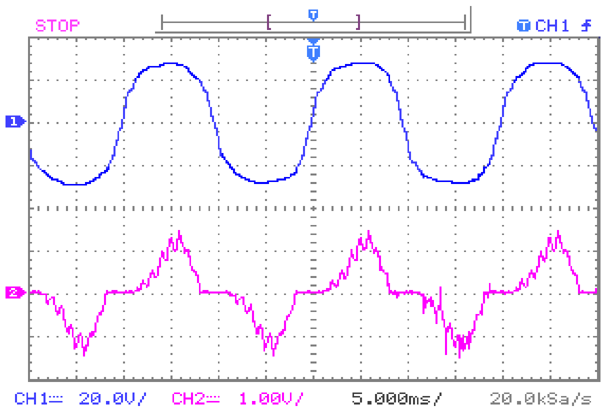

Figure 28 (a). Steady-state load voltage and with fuzzy control (40Ω, 2200µF load)

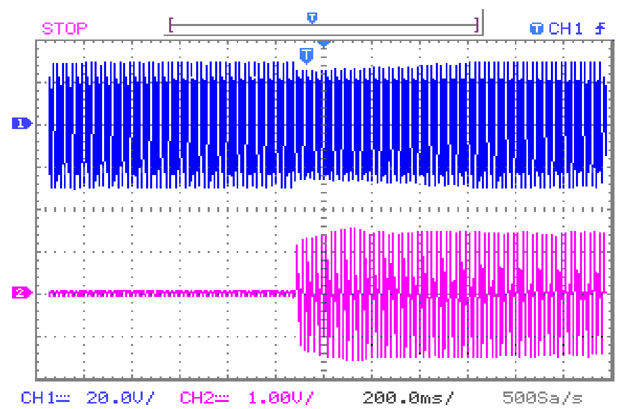

Figure 30. Transients in output voltage and current for sudden load change from no load to rated rectifier load with fuzzy control

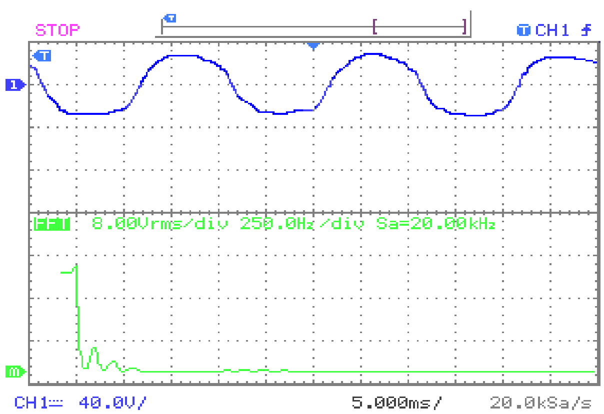

Figure 28 (b). FFT plot of load voltage under steady-state

Table 3. % THD of output voltage of cascaded MLI for different loads (By experiment)

Load	% THD	
	PI	Fuzzy
RC1 (100Ω, 2200µF)	16.79	15.76
RC2 (100Ω, 4400µF)	18.63	17.70
RC3 (40Ω, 4400µF)	17.71	17.17
RC4 (40Ω, 2200µF)	16.60	15.63

Figure 31. Hardware setup for closed loop control of MLI

8. CONCLUSION

The implementation of PI and fuzzy control strategies for single phase PWM inverter has been carried out and the results are presented for both linear and non-linear loads. From simulation results, it is observed that FLC performs better than PI controller in view of harmonic content of the steady-state output voltage with linear loads whereas better output voltage is observed with PI control under loads with less non-linearity. FLC is found to perform better in FPGA based control.

9. REFERENCES

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