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Fuzzy logic based three-level boost converter with Quasi-Z source

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ABSTRACT

For conventional boost converters, switching stress will be more at high gain, in order to alleviate this problem three level boost converters are used. The mismatched voltage levels between the dynamic lower voltage and the required constant higher voltage of the DC link bus of the inverter can be solved using flying-capacitor based three-level boost converter with a quasi-Z source (TLBqZ). The operating principle of wide range voltage-gain for this topology is according to the effective switching states of the converter and the multi-loop energy communication characteristic of the quasi-Z source. The dynamic self-balance principle of the flying capacitor voltage is utilized. An analysis is done on the performance of the converter with PI and fuzzy controller. The fuzzy logic controller is used for switching pulse generation in the converter, as it is more advantageous over PI controller. An H-bridge inverter is fed from the converter that connects to the AC loads. The simulation of the circuit is performed in MATLABR2014a and waveforms are analyzed. An experimental prototype of the converter is implemented using dsPIC30F2010 microcontroller and results are verified.

Keywords: *Fuzzy logic, Quasi-Z source, Three level boost.*

1. INTRODUCTION

The quasi-Z source based converters have become a very attractive choice for renewable and alternative energy applications, where the reliability and reduced number of energy conversion stages could play a vital role [1]. Recent interest in the quasi-Z-source based converters is due to their specific properties of voltage boost and buck functions with a single switching stage.

The conventional boost two-level DC-DC converter is simple in structure, but suffers from disadvantage of limited voltage-gain and high voltage stress across the switches. To reduce the high voltage stress of power semiconductors by half, three-level boost DC-DC converters are used [2]. Three-level converters are a well-adopted solution in applications with high input voltage and high switching frequency. The switches are stressed on half of the total DC bus voltage. But three level boost converters only have the same limited voltage-gain with that of the two-level boost converters. To improve the voltage gain, a new lattice network known as impedance fed power converter (Z-source converter) is introduced. [3]. The Z-source converter consists of a unique impedance network that couples the main circuit to the power source, or another converter. Z-source network is a two-port network that consists of two inductors and two capacitors connected in X-configuration which provides an impedance source connected to the load. The main drawback of Z-source network is that their input and output sides don't share the common ground, which may result in maintenance safety and EMI problems. To overcome these problems, another topology known as quasi Z -source [4] is suggested. Its internal impedance network connects the converter main circuit to the power source or load. The quasi Z-source converter consists of two inductors and two capacitors. The inductor present in the quasi Z-source reduces the source current. The capacitor voltage is lower than in case of Z-source.

There are several conventional and numeric controller types. The controllers can be proportional integral (PI), proportional integral derivative (PID), Fuzzy Logic Controller (FLC) or the combination between them [5]. PID controllers provide robust and reliable performance for most systems if the PID parameters are tuned properly. The derivative term in a PID controller is liable to noise and measurement error of the system, which could result in oscillation of the duty cycle[6]. PI controllers generally give overshoot in output voltage and high initial current when the rise time of response is reduced. Fuzzy logic control uses human-like linguistic terms in the form of If-Then rules to capture the non-linear system dynamics [7]. Fuzzy logic controllers express feedback

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control laws using heuristic knowledge, without knowing parameters of the control plants, for many practical industrial control systems[5]. Fuzzy logic control which does not require a precise mathematical modeling of the system nor complex
computations. This control technique relies on the human capability to understand the behaviour of the system and is based on qualitative control rules[8]. However, since fuzzy control is based on heuristic rules, application of non-linear control laws to face the nonlinear nature of DC-DC converters is easy. The fuzzy control approach is general in the sense that almost the same control rules can be applied to several DC-DC converters. However, some scale factors must be tuned according to converter topology and parameters.

The operation modes and the working of the converter are described in Section 2. Section 3 describes the fuzzy logic control. Simulation results and analysis are discussed in Section 4. In Section 5, the experimental setup and results are presented. Section 6 concludes the paper.

2. THREE LEVEL BOOST CONVERTER WITH QUASI-Z SOURCE FOR AC LOADS

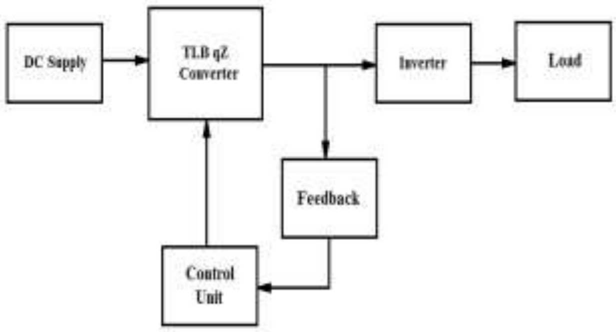

Fig. 1 Block diagram of TLBqZ converter for AC loads

Three level boost converter with the quasi-Z source (TLBqZ) offers a wide range gain utilizing a small amount of duty ratio. The output of renewable energy sources can be taken as the input to the converter. The converter provides a boosting to the input voltage and fuzzy controller is used for better performance to maintain a constant DC output voltage. The output of this converter is fed to an inverter to feed AC loads. The block diagram of the fuzzy logic based three-level boost converter with a quasi-Z source for AC loads is shown in Fig. 1.

A three-level boost DC-DC converter with quasi-Z source can the voltage stress of all semiconductors to half of the output voltage [9]. It also has a common ground for the input and output by using the flying-capacitor three-level structure and operates well with a high voltage-gain, proper duty cycles ($0.5 \leq d < 0.75$), and balancing of the voltage of the flying capacitor without additional hardware. DC-DC three-level boost converter with the quasi-Z source is shown in Fig. 2. The input of the converter is comprised of the voltage source V_{in} and its associated reverse blocking diode D. The three-level DC-DC converter is comprised of a quasi-Z source, two switches, along with flying-capacitor and two diodes(D_2, D_3). The quasi-Z source is utilized to improve the gain, comprises of two inductors L_1, L_2, two capacitors C_1, C_2 and a diode D_1, it allows V_{in} and the DC link bus to have a common ground.

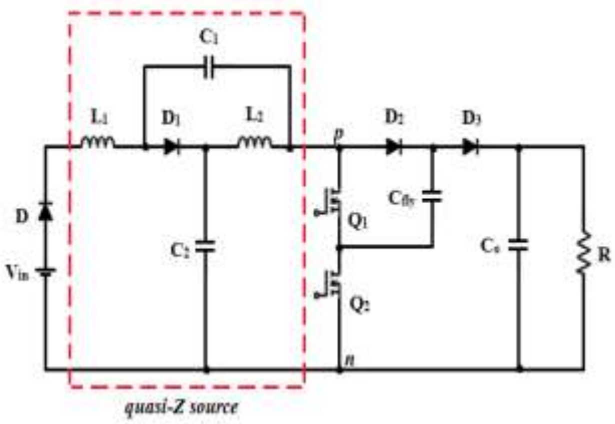

Fig. 2: Schematic of a three-level boost converter with quasi-Z source

2.1 Operating Modes

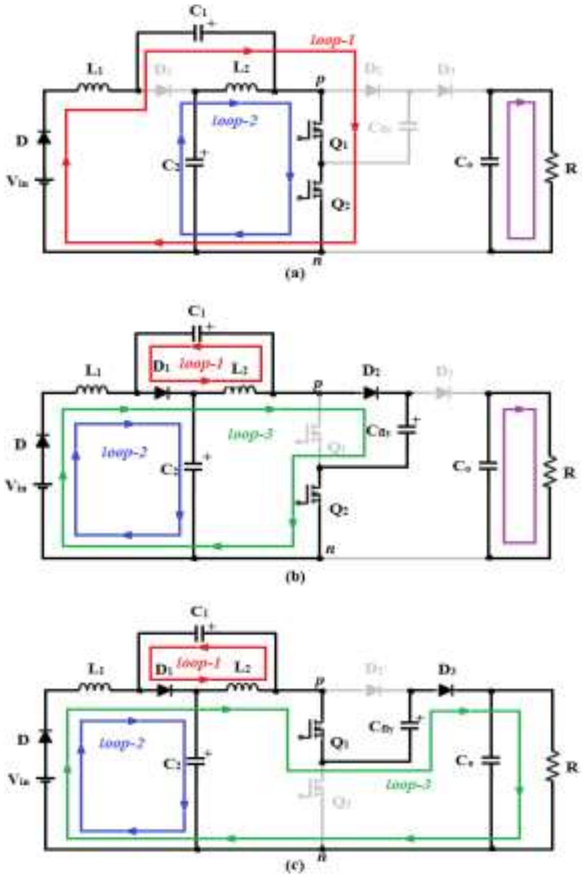

Fig. 3: Energy flow paths in (a) Mode I, III, (b) Mode II, (c) Mode IV

There are four modes of operation for the TLBqZ converter. Mode I & mode III are same in which both the switches are turned on, here L_1 & L_2 are storing energy, while C_1 & C_2 are discharging energy. In mode II & mode IV, only one switch is turned on, L_1 & L_2 discharging energy, whereas C_1 & C_2 are charging. The sequence of the switching states in a switching period is related to the duty cycle ranges of the power switches S_1, S_2.

In mode I and mode III both switches S_1, S_2 are in on state. D_1 is off due to the reverse voltage of L_1. As a result, there is two energy flow paths, as shown in Fig. 3(a) In loop-1, C_1 is discharging, while L_1 is charging through D, S_1 & S_2; similarly, C_2 is transferring energy to L_2 through S_1 & S_2 in loop-2.

$$V_{in} + V_{C1} = V_{L1} \quad (1)$$

$$V_{C2} = V_{L2} \quad (2)$$

There are three energy flow loops in mode II when S_1 is off & S_2 is on as shown in Fig. 3(b). In loop-1, L_2 is discharging, at the same time C_1 is charging through D_1. The inductor current i_{L2} and the capacitor voltage V_{C1} are shown in Fig.4 In loop-2, L_1 and V_{in} in series are discharging, while C_2 is charging through D and D_1. Thus the inductor current i_{L1} and the capacitor voltage V_{C2} can be illustrated in Fig. 4. In loop-3, L_1, L_2, and V_{in} in series are discharging, while the flying-capacitor C_{fly} is charging through D, D_1, D_2, and S_2.

$$V_{L2} = V_{C1} \quad (3)$$
$$V_{in} + V_{L1} = V_{C2} \quad (4)$$
$$V_{in} + V_{L1} + V_{L2} = V_{Cfly} \quad (5)$$

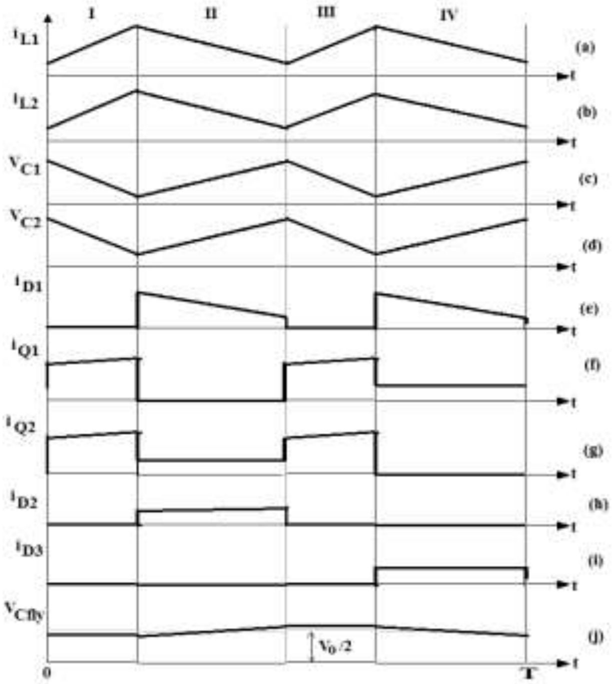

Fig. 4 Waveforms for of TLBqZ converter

From Equations (3), (4), (5)

$$V_{C1} + V_{C2} = V_{Cfly} \quad (6)$$

In mode IV also there is three energy flow paths as shown in Fig. 3(c). It can be seen that the difference between mode II & mode IV is the discharging/charging state of the flying-capacitor C_{fly}, here C_{fly}, V_{in}, L_1, and L_2, are in a series connection and discharge to supply the DC link side through D, D_1, S_1, and D_3. The corresponding voltage and current waveforms are shown in Fig. 4.

$$V_o - (V_{L2} + V_{C2}) = V_{Cfly} \quad (7)$$

From Equations (3), (7)

$$V_o - (V_{C1} + V_{C2}) = V_{Cfly} \quad (8)$$
$$V_{in} + V_{L1} + V_{L2} + V_{Cfly} = V_o \quad (9)$$

2.2 Self-Balance of Flying Capacitor

The voltage across Capacitors C_1 and C_2 is given by [9]

$$V_{C1} = (d - 0.5) \times V_o \quad (10)$$
$$V_{C2} = (1 - d) \times V_o \quad (11)$$

On adding Equations (10) and (11)

$$V_{C1} + V_{C2} = V_o/2 \quad (12)$$

On substituting Equation (12) in (6) and (8), in both cases, we get the voltage across flying capacitor as

$$V_{Cfly} = V_o/2 \quad (13)$$

From the above analysis, it can also be concluded that the flying-capacitor voltage V_{Cfly} is clamped by the sum of V_{C1} and V_{C2} from the quasi-Z source network, and V_{Cfly} can follow half the output voltage V_o by this self-balance characteristic. Therefore, no extra balance controls for the flying-capacitor voltage are required, and the voltage stress of all power semiconductors can still be constant at half the output voltage.

3. FUZZY LOGIC CONTROL

The fuzzy logic controller is a rule-based controller. The fuzzy logic control is designed using the fuzzy inference systems (FIS) with the defined input and output membership functions [7]. The fuzzy sets and rules are designed and accordingly, the duty ratio of the converter can be controlled. The inputs for the fuzzy logic controller are the error (e) and change in error (Δe). The error is calculated with a comparison between the reference value and the output voltage. The fuzzy rule has 7x7 decision table with two input variables and one output variable [7]. The look up table with the input and output rules defined with seven linguistic variables are given in Table 1. Fuzzy logic control does not require a precise mathematical modeling of the system nor complex computations. This control technique is based on qualitative control rules [8].

Table 1. Fuzzy Rule base [7]

e/Δe	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NS	NM	Z	PS	PS	PM	PB
PM	NM	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB

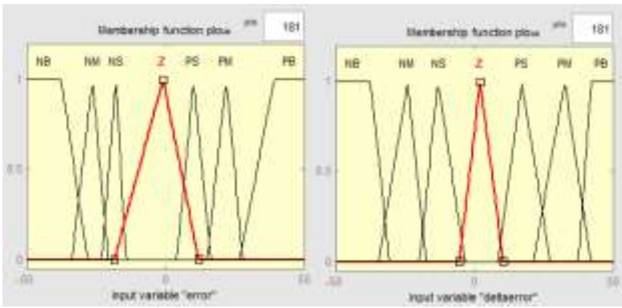

Fig. 5 Input membership functions

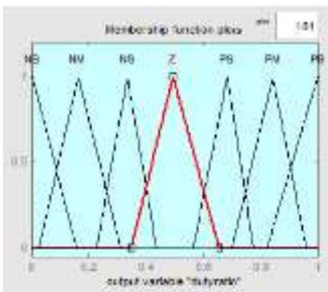

Fig. 6. Output membership function

4. SIMULATION RESULTS AND ANALYSIS

The circuit for Three level boost DC-DC converter with quasi-Z source is simulated in MATLAB R2014a software. The simulation parameters are selected based on the design. The simulation of the converter is performed with an input of 60V DC supply, switching frequency as 10kHz. The inductor values are chosen as 250µH and capacitor values as 50µF. The simulation of the converter is analysed with PI and fuzzy controllers.

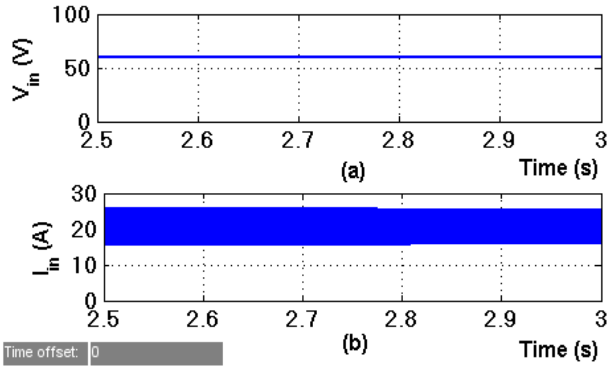

Fig. 7: (a) Input voltage and (b) Input current

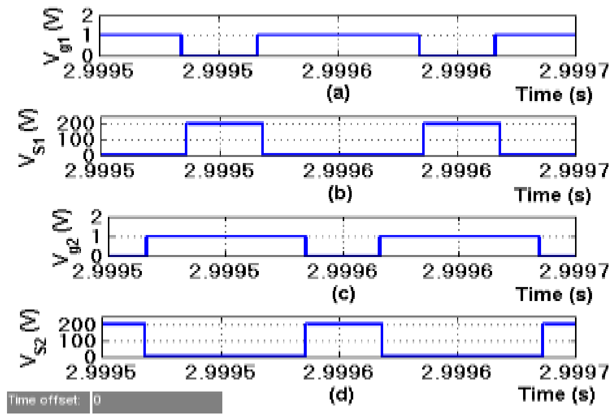

Fig. 8: (a) Gate pulse, (b) Voltage across switch S_1 (c) Gate pulse, (d) Voltage across switch S_2

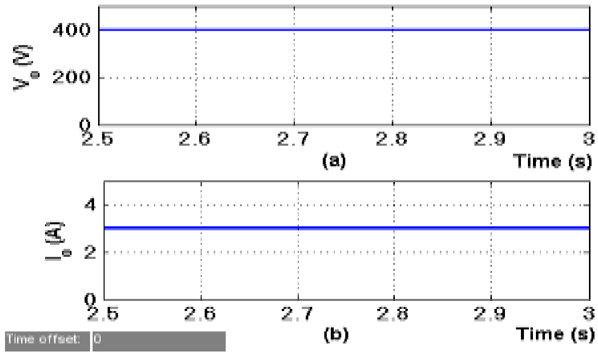

Fig. 9: (a) Output voltage and (b) Output current of converter

Fig. 7 (a) & (b) shows the input voltage and input current of the converter respectively. The input voltage is about 60V and input current is about 21A with a 40% ripple. Gate pulse for the switch S1 is shown in Fig. 8(a). Voltage stress across the switch is about 200V which is about half the output voltage and is shown in Fig. 8(b). Gate pulse for the switch S2 is shown in Fig. 8(c). The pulse for the switch S2 is a shifted version of the pulse for switch S1. Similar to switch S1, switch S2 also has a switching stress of about 200V and is shown in Fig. 8(d). Fig. 9(a) shows the output voltage of the converter and is about 400V. The output current is about 3A and is shown in Fig. 9(b).

4.1 Comparison of Simulation Results with Different Controllers

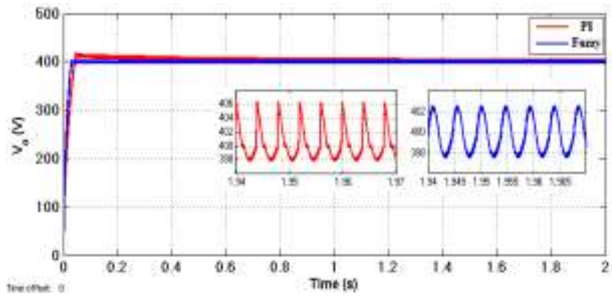

Fig. 10: Output voltage with PI controller and fuzzy controller

Two different control approaches namely, Proportional-integral (PI) control and fuzzy control are used to simulate the TLBqZ converter. PI control is a traditional linear control method, while fuzzy control is a kind of nonlinear control. Comparison between the two controllers are made in the aspect of various time domain specifications. Fig. 8. shows the output voltage of the converter using PI and fuzzy controllers. From these waveforms, it can be verified that the fuzzy logic control can provide a comparatively very smaller settling time, small overshoot, reduced ripples in the output of the converter. A comparison on different time domain specifications of the output voltage using these controllers are shown in Table 2.

Table 2: Comparison on time domain specifications

Controller	**Time Domain Parameters**				
	Rise Time (s)	***Peak Time (s)***	***Settling Time (s)***	***Peak Overshoot (V)***	***Ripple (%)***
PI	0.0326	0.045	0.8	20	2.2
Fuzzy	0.017	0.031	0.031	5	1

Comparison results indicate that the performance of the fuzzy controller is superior to that of PI controllers. The output from the TLBqZ converter with a fuzzy logic controller is fed as the input to the H-bridge inverter. The output voltage and current of the inverter are shown in Fig.11. The peak value of the inverter output voltage is same as that of converter output voltage.

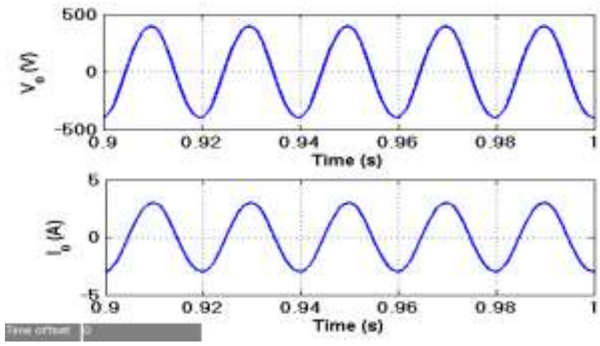

Fig. 11: (a) Output voltage and (b) Output current of the inverter

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5. EXPERIMENTAL SETUP AND RESULTS

A stepped down prototype of the fuzzy-based TLBqZ converter for AC loads is implemented using dsPIC30F2010 microcontroller. The input to the converter is varied in the range of 24-30V DC and the converter output is maintained constant at 156V DC using fuzzy logic control. The converter output is fed as inverter input to produce 110V AC. The power circuit uses the MOSFETs IRF540 and diodes 1N5408. The switching frequency is 20kHz, the inductors used are 3mH and the capacitors are 10µF. The load resistance is about 3kΩ. Fig. 12. shows the hardware setup of the

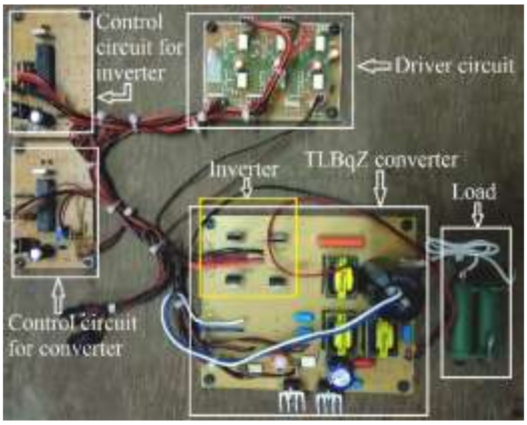

Fig.12: Different hardware sections

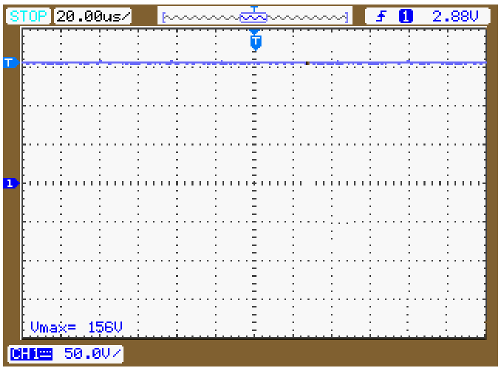

Fig. 13: Converter Output

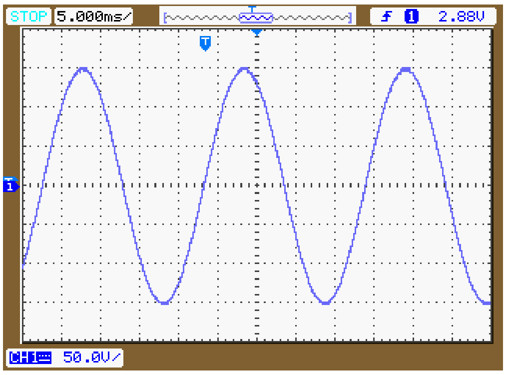

Fig. 14: Inverter Output

fuzzy logic based TLBqZ converter for AC loads. Fig. 13. shows the converter output i.e the inverter input. The filtered output of the H-bridge inverter, 110V AC is shown in Fig.14.

6. CONCLUSION

Fuzzy logic based three level converter with quasi Z-source used to feed AC loads is studied and implemented. It has the advantages of (i) lower voltage stress for the switches, (ii) common ground between the input and output sides, (iii) the wider range of the voltage-gain with modest duty cycles [0.5,0.75) for the switches. In addition, the voltage of the flying-capacitor can be clamped well at half the output voltage by the capacitor voltages of the quasi-Z source net [9]. Simulation of the circuits have been conducted using MATLAB/Simulink to study the features and implement the converter. The control of the setup was established using fuzzy logic. Fuzzy logic control provides small overshoot, better settling time and a reduction in the ripples in the output voltage waveform. A prototype is designed and the hardware is implemented using dsPIC30F2010 microcontroller. The output of the TLBqZ converter is fed to an H-bridge inverter to produce AC voltage. An output of 156V DC is obtained from the converter, which is the peak value of the 110V AC voltage obtained from the inverter.

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