Buck-Boost AC-AC Converter with Inverting and Noninverting Modes

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Abstract— AC-AC power conversion is the most popular way to generate quality ac power after the introduction of power electronics. Traditionally, an ac voltage converter is made with a transformer tap changer or with an ac-ac converter based on buck topologies or through ac-dc-ac converter. In this paper a new buck-boost ac-ac converter which has both inverting and noninverting configuration is introduced. ie; the same converter can perform the traditional buck and boost operations and also the inversion operation. The converter has got six diode- switch pairs, one inductor and two capacitors. Another advantage of this converter is that it does not posses any shoot through (commutation) problem even when all the switches are in on state. The noninverting mode can be used where normal boost or buck operation has to be performed and the inverting mode can be used for the compensation of sag or swell.

Key words: AC-AC Converter, Buck-Boost Converter, Inverting Mode, Noninverting Mode, DVR Application

I. Introduction

An AC-AC voltage controller is a converter which controls the voltage, current and average power delivered to an AC load from an AC source[1]. They are used in practical circuits like light dimmer circuits, speed controls of induction motors, traction motors control etc. Traditionally, an AC voltage converter is made with a transformer tap changer or with an ac-ac converter based on buck topologies or through AC-DC-AC converter. Developments of different topologies and switching techniques make AC-AC converter more versatile.

There are two major areas where AC–AC power conversion is necessary. One is the popular v-f AC drive where output voltage and output frequency both are required to be variable. The most popular topologies for such application are indirect AC–AC converters with a dc link and matrix converters[2]. However, in another case where only voltage variation or regulation is needed with no change in frequency, direct PWM AC–AC converters are used, and they perform as AC choppers or power line conditioners[3]. They have some advantages like the provision of better power factor, efficiency, low harmonic current in line, ease of control, smaller size and lower cost. Moreover, it is a single-stage conversion with simple topology. However, they have some disadvantages, such as high Total Harmonic Distortion (THD) in the source current, low power factor, and poor power transfer efficiency. Moreover, they do not boost the input voltage without using transformer in the circuit. There are many other converters that boost the voltage, step down and the one can perform inversion. But all these converters posses a common commutation problem[4]-[5].

A family of single-phase PWM AC–AC power converters are there to overcome these disadvantages[6]. The basic PWM AC-AC converter topologies are the buck converter, boost converter, buck–boost converter, and Cuk converter. The step down converter produces a lower average output voltage than the ac input voltage. The average output voltage can be calculated in terms of duty ratio. By varying the duty ratio, the output voltage can be controlled. But it cannot be used to step up the voltage and inversion cannot be performed. The boost converter produces a higher output voltage than the ac input voltage. The main application of this boost converter is in regulated dc power supplies and the regenerative breaking of dc motors. Here also the duty cycle can be adjusted to control the output voltage. It can only boost the voltage and no inversion is performed. A buck boost converter can be obtained by the cascade connection of the two basic classic step up/step down converters. The buck–boost converter is a type of AC -AC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The output voltage is adjustable based on the duty cycle. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. The main application of this buck boost converter is in power supplies, where a negative polarity output may be desired with respect to the input voltage, and the output voltage can be either higher/lower than the input voltage based on the duty ratio. The problem with this converter is that the phase angle is reversed at the output. Also, higher voltage stress across switches. Cuk converter is similar to that of the buck boost converter. It provides a negative polarity regulated output voltage with respect to the input voltage. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. Cuk topology can both step up and step down the input voltage; however, the phase angle is reversed. Moreover, this topology have disadvantage of higher voltage stress across switches. The Cuk topology can overcome the currents discontinuity but at the cost of additional passive components, increasing the size and cost of converter and decreasing the efficiency.

The AC-AC converters based on the impedance source network also called ZS AC-AC converters, can both buck and boost the input voltage, but the step-down operation always results in reversing of phase angle. Moreover, they use more passive components and have higher current flowing through active switches during shoot through, which make their use less attractive. In buck-type multilevel AC-AC converters based on the concept of flying capacitors are proposed, which can reduce the voltage stress of switches and improve the quality of output voltage. However, they need RLC booster to be connected in parallel to load, in order to reduce the voltage imbalance problem of flying capacitors.

The organisation of the report is as follows: Chapter 2 presents the working and operating principle of buck boost AC-AC converter. Chapter 3 provides the design considerations of the Buck-Boost converter topology. Chapter 4 describes the simulation study of the proposed converter with inverting and non inverting topology.

Chapter 5 explains the hardware analysis of the proposed converter. Finally, Chapter 6 explains the conclusion.

II. BUCK-BOOST AC-AC CONVERTER WITH INVERTING AND NONINVERTING MODES

The topologies discussed above are not suitable to perform all the inverting and noninverting operations. Hence, a new converter in buck-boost configuration is developed to operate in both inverting and noninverting modes. The AC-AC converter consists of six unidirectional current flowing bi- directional voltage blocking switches S1 to S6 , six diodes, one inductor L, and filter capacitors Cin and C0. The switches can be realized by series combination of power MOSFETs with external fast recovery diodes. The circuit is as shown in Fig. 1.

In this figure, body diodes of MOSFETs are not shown as they never conduct, and thus, their poor reverse recovery problem is eliminated. For high power applications, it can either use six reverse blocking IGBTs or six IGBTs with external fast recovery diodes in series. The converter can operate as traditional noninverting buck and boost converters with voltage gain of D and 1/(1-D) respectively, and also as inverting buck-boost converter with voltage gain of D/(1-D).

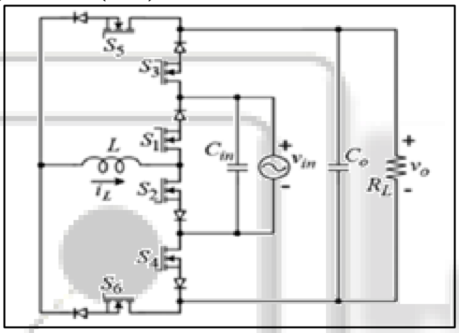


Fig. 1: Buck Boost AC-AC converter with inverting and non inverting modes

Therefore, it can be used as noninverting buck-boost converter to replace the traditional inverting buck–boost converter in various AC-AC conversion applications. For its application as DVR, the noninverting buck-boost mode can be used to compensate voltage sags, and inverting buck-boost mode for voltage swells.

A. *Noninverting Buck Mode Operation*

The PWM switching sequence during noninverting buck mode and key waveforms are shown in Fig. 2.

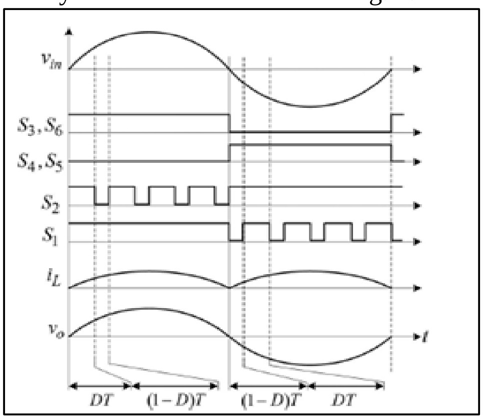


Fig. 2: Operation and key waveforms of noninverting buck mode

For positive half of input ac voltage, switches S_1,S_3,S_6 are always turn on and S_4, S_5 are always turn off, while switch S_2 is switched at high frequency. Fig. 3 shows the equivalent circuits of the proposed converter for $V_{in} > 0$.

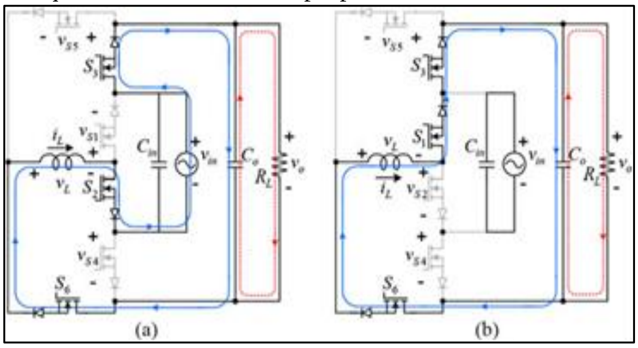


Fig. 3: Buck operation during positive cycle. (a) during DT interval (b) during 1-D interval

During DT interval when switch S_2 is turned on, the inductor stores the energy and by applying KVL,

$$V_L = V_{in} - V_0 \quad (1)$$

During (1-D)T interval, switch S_2 is turned off , the energy stored in L is released to load any by applying KVL,

$$V_L = -V_0 \quad (2)$$

For $V_{in} < 0$, switches S_2, S_4, S_5 are always turn on while switches S_3, S_6 are always turn off, and S_1 becomes high frequency switch. The operation for $V_{in} < 0$ is same as explained for $V_{in} > 0$, with only difference is that now the switch S_1 performs same as S_2 and vice versa. The equivalent circuits during this negative half-cycle are shown in Fig. 4.

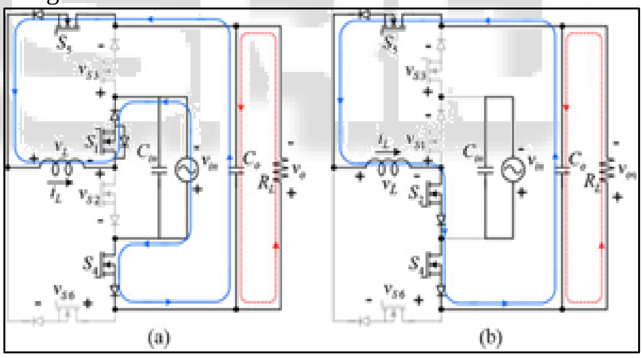


Fig. 4: Buck operation during negative cycle. (a) during DT interval (b) during 1-D interval

By applying volt–second balance condition on inductor L from (1) and (2), the gain in this buck mode is given by,

$$\frac{V_0}{V_{in}} = D \quad (3)$$

From above equation, it can be concluded that the voltage gain of the new AC-AC converter in this operation mode is the same as that of non-inverting buck AC-AC converter.

B. *Noninverting Boost Mode Operation*

The switching sequence of the converter during non-inverting boost mode and key waveforms are shown in Fig.5

For Vin > 0, switches S2, S3, S6 are always turn on and S1, S4 are always turn off, while switch S5 is switched at high frequency.

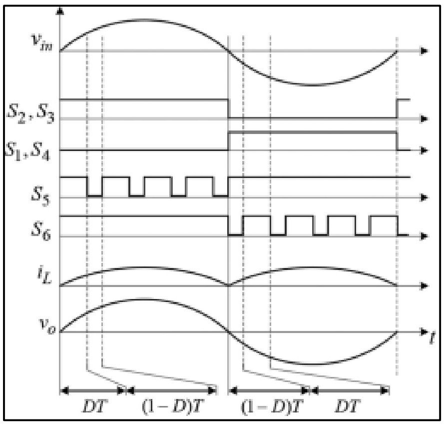


Fig. 5: Operation and key waveforms of noninverting boost mode

Fig. 6 shows the equivalent circuits of the proposed converter for Vin > 0. During DT the switch S5 is turned on and the input energy is stored in inductor L. During (1-D)T interval, switch S5 is turned off and the energy stored in inductor is released to load. Applying KVL yields,

$$V_L = V_{in} - V_0 \quad (4)$$

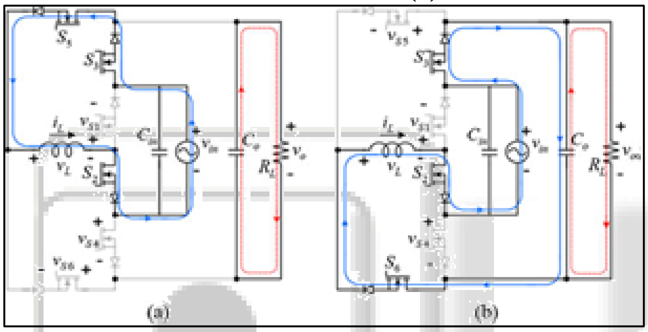


Fig. 6: Boost operation during positive cycle. (a) during DT interval (b) during 1-D interval

For Vin < 0, switches S1, S4 , S5 are always turn on while switches S2, S3 are always turn off, and S6 becomes high frequency switch. The operation for Vin < 0 is the same as explained for Vin > 0, with only difference is that now the operation of switch S6 is same as that of S5 and vice versa. The equivalent circuits during this half-cycle are shown in Fig. 7. The voltage gain in this boost mode is given by,

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \quad (5)$$

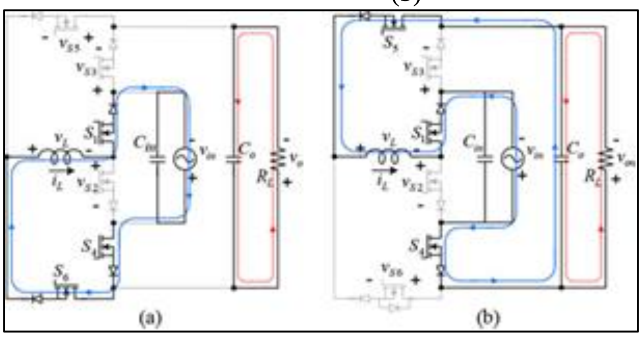


Fig. 7: Boost operation during negative cycle. (a) during DT interval (b) during 1-D interval

From above equation, it can be concluded that the voltage gain of the new AC-AC converter in this operation mode is the same as that of non-inverting boost AC-AC converter.

C. Inverting Buck Boost Mode Operation

The switching sequence of the converter during inverting buck–boost mode and key waveforms are shown in Fig. 12. For Vin > 0, switches S2, S4, S5 are always turn on and S1, S6 are always turn off, while switch S3 is switched at high frequency. Fig. 8 shows the equivalent circuits of the proposed converter for Vin > 0. During DT interval, switch S3 is turned on and the input energy is stored in inductor, L. Applying KVL, we get

$$V_L = V_{in} \quad (6)$$

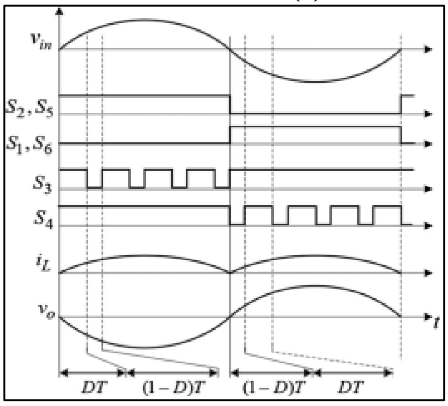


Fig. 8: Operation and key waveforms of inverting buck boost mode

During (1-D)T interval, switch S_3 is turned off and energy stored in inductor is released to load. Applying KVL yields,

$$V_L = -V_0 \quad (7)$$

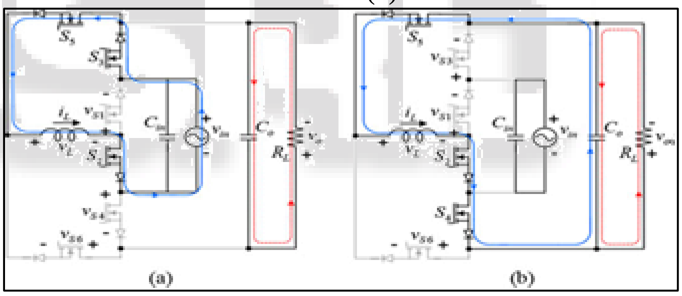


Fig. 9: Buck Boost operation during positive cycle. (a) during DT interval (b) during 1-D interval

For $V_{in} < 0$, switches S_1, S_3, S_6 are always turn on while switches S_2, S_5 are always turn off, and S_4 becomes high frequency switch. The operation for $V_{in} < 0$ is the same as explained for $V_{in} > 0$, with only difference is that now the switch S_4 acts the same as S_3 and vice versa. The equivalent circuits during this half-cycle are shown in Fig. 10.

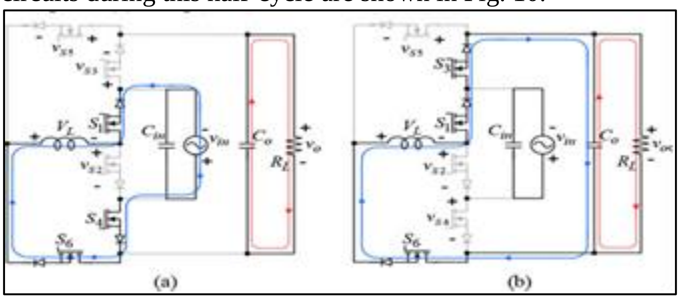


Fig. 10: Buck Boost operation during negative cycle. (a) during DT interval (b) during 1-D interval

The voltage gain in this buck–boost mode is given by,

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \quad (8)$$

From the above equation, it can be concluded that the voltage gain of the AC-AC converter in this operation mode is the same as that of inverting buck-boost AC-AC converter.

D. Commutation Free Buck Boost Converter

Another major advantage of buck boost converter is that it is free from commutation problem. Consider if all of the six gating signals of switches in the converter are high, offering many closed paths for current to flow. Three of them named as loops 'a', 'b', and 'c' in Fig. 11 can actually cause shoot-through of voltage source/capacitors, only if the current could flow through them.

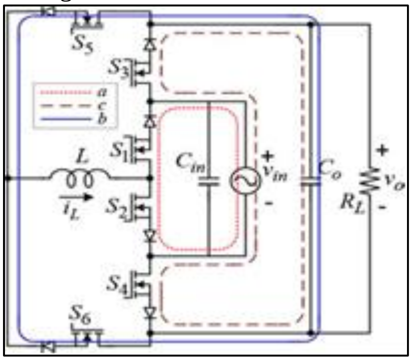


Fig. 11: Possible shoot through paths when all gating signals are high

The flow of current through these loops could cause short-circuit of input voltage, output voltage and direct parallel connection of input voltage and output voltage respectively, each of which can results in excessive current flow through switching devices which may damage them. All of these three paths contain two unidirectional switches with their series diodes connected in opposite direction. Therefore, a closed loop cannot be formed for current flow as one of the series diodes would always become reverse biased, which eliminates the shoot-through. This immunity from shoot-through increases the reliability of the converter as it has no commutation problem, the PWM dead-times in gating signals are not needed, which increase quality of output voltage.

III. DESIGN CONSIDERATIONS

The design parameters of inductor and switches will be determined based on maximum values of their stresses for inverting buck–boost operation. The value of inductor L depend on its maximum current handling capability and allowable current ripple. For a fixed output power P_0 , the maximum current I_L flows through inductor during boost operation when input voltage has lowest value V_{inmin}.

$$P_0 = \frac{V_0}{I_0} \qquad (9)$$

$$C = \frac{DTV_0}{\Delta RV_0} \qquad (10)$$

For Buck mode, the ratio of the converter is a function of the duty ratio.

$$\frac{V_0}{V_{in}} = D \qquad (11)$$

For Boost mode, the ratio of the converter is a function of the duty ratio.

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \qquad (12)$$

The inductor for the boost mode can be found using the formula,

$$L = \frac{D(1-D)TV_{inmin}V_0}{xP_0} \qquad (13)$$

For Buck-Boost mode, the ratio of the converter is a function of the duty ratio.

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \qquad (14)$$

The inductor buck-boost mode can be found using the formula,

$$L = \frac{(1-D)V_0TV_{inmin}V_0}{yP_0(V_0+V_{inmin})} \qquad (15)$$

IV. SIMULATION STUDIES

This section presents the simulation studies of buck boost converter with inverting and noninverting modes in MATLAB/SIMULINK environment. Output voltage, Output Current of an open loop buck boost converter in noninverting buck and boost mode is analysed here. Design of various components of buck boost converter has been done to produce 750 watt output power by boosting a 180V input voltage to a 230V output voltage for a time period and there after step down a 280 V input voltage to a 230 V output voltage at a switching frequency of 25 kHz. The designed values used are as shown in table I.

Parameters	Values
Input voltage(buck)	280V
Input voltage(boost)	180V
Output voltage	230V
Output frequency	50Hz
Switching frequency	25kHz
Inductance	800µH
Capacitance	22µF
Load resistance	70Ω

Table 1: Design Parameters

The input voltage, gating signals for six switches, output voltage and output current waveforms are shown in Fig. 12 to Fig. 14. And the simulation results are shown in table II.

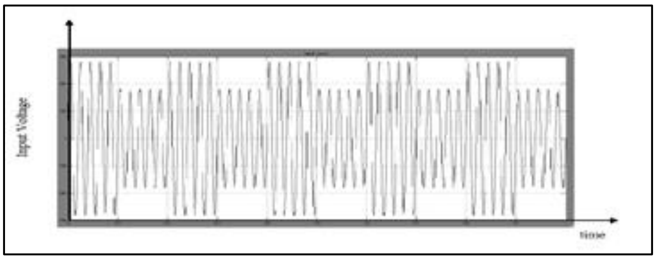


Fig. 12: Input voltage waveform of the Buck-Boost AC-AC Converter

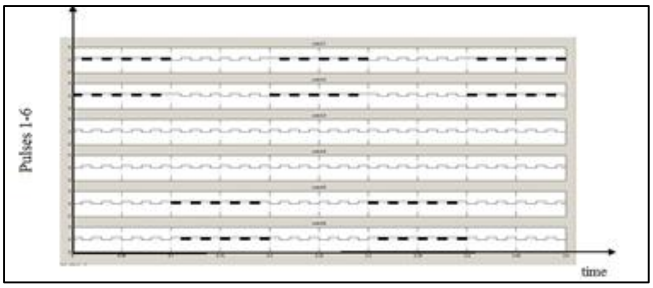
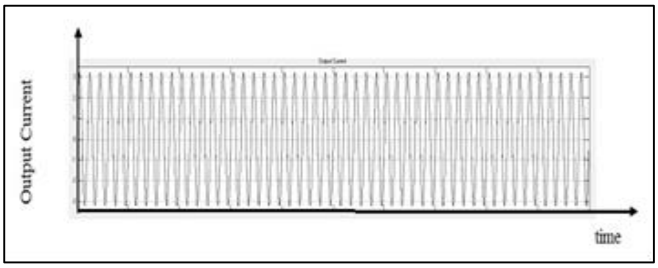
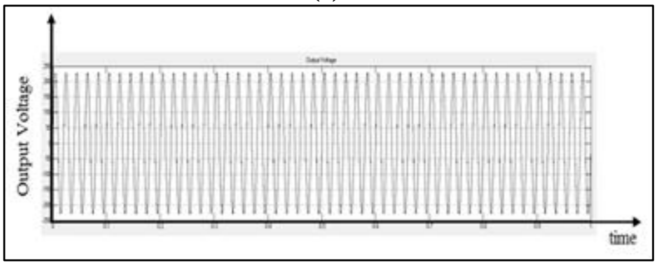


Fig. 13: Gating pulses for switches from S_1 to S_6 of the Buck-Boost AC-AC Converter



(a)



(b)

Fig. 14: Output current (a) and output voltage (b) waveforms of Buck-Boost AC-AC Converter

Parameters	Values
Output frequency	50Hz
Switching Frequency	25kHz
Inductor	800µH
Output filter Capacitor	22 µF
Load resistance	70Ω
Output Power	750W
Output voltage	230V
Output Current	3.2A
THD	5.58%

Table 2: Simulation Results

The total harmonic distortion of the output voltage and current waveforms are analysed. And this is done using the powergui block in the simulink library. Provision for FFT analysis is there in the powergui block. The circuit is simulated and loaded to the FFT block and it is found that the output voltage has a total harmonic(THD) of 5.58%. And also it can be seen that the output current has the same characteristics of the output voltage. The THD of output voltage is as shown in Fig. 15.

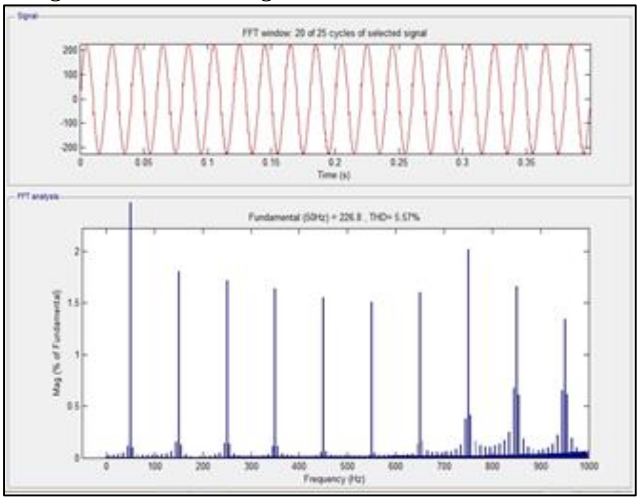


Fig. 15: THD of output voltage waveform

V. Experimental Studies

After performing simulation studies of buck boost converter in MATLAB/simulink environment, a prototype model of the converter is being made to validate its use in real time applications. This section involves the description of the prototype model. For the prototype, a single mode(boost) is considered. The prototype model is designed for feeding a 50W load from 24V input and to provide a 72 V boosted output. It consist of Power Circuit of Buck-Boost AC to AC converter, Gate Driver Circuit for the switches S1 to S6 and PIC Microcontroller. The completed laboratory set-up of buck-boost converter is as shown in Fig. 16. The switches IRFZ44N, diodes with 3A rating were used for implementation. In order to generate the gating pulses, a program is written in mikroC and is burned to PIC16F877A. A 58V is obtained at the output with an input of 24V. The output current is noted to be 1.2A and the obtained efficiency of the converter is 81.67%.

VI. Conclusion

A single-phase PWM AC-AC converter with noninverting buck and boost modes and inverting buck-boost converter mode is combined in one topology. The converter uses six unidirectional current flowing bidirectional voltage blocking switches, filter capacitors and one inductor. The converter has no shoot-through problem even when all switches are turned on simultaneously and therefore, PWM dead-times are eliminated to produce high quality output voltage. And thus the converter can solve commutation problem without using bulky and lossy RC snubbers or dedicated soft commutation techniques. Only two switches are switched at high frequency during each half-cycle, which reduces the switching losses. Use of power MOSFETs results in low switching loss, fast switching speed, etc. In its application as DVR, the inverting buck-boost mode of the proposed converter can also be utilized along with non-inverting buck and boost modes, to compensate both voltage sags and swells.

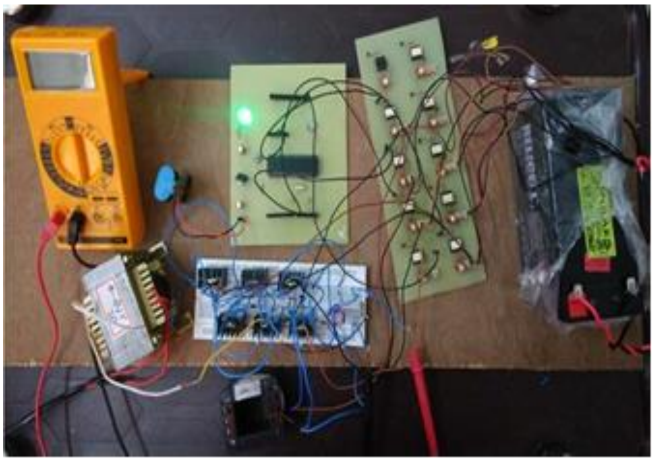


Fig. 16: Experimental setup of AC-AC Buck Boost Converter

References

[1] F. Z. Peng, L. Chen, and F. Zhang, “Simple topologies of PWM ac-ac converters,” IEEE Power Electron. Lett., vol. 1, no. 1, pp. 10–13, Mar. 2003.

[2] B. Metidji, N. Taib, L. Baghli, T. Rekioua, and S. Bacha, “Novel single current sensor topology for venturini controlled direct matrix converters,” IEEE Trans. Power Electron., vol. 28, no. 7, pp. 3509–3516, Jul. 2013.
[3] X. P. Fang, Z. M. Qian, and F. Z. Peng, “Single-phase Z-source PWM ac-ac converters,” IEEE Power Electron. Lett., vol. 3, no. 4, pp. 121–124, Dec. 2005.
[4] Y. Tang, S. Xie, and C. Zhang, “Z-source ac-ac converters solving commutation problem,” IEEE Trans. Power Electron., vol. 22, no. 6, pp. 2146–2154, Nov. 2007.
[5] L. He, S. Duan, and F. Z. Peng, “Safe-commutation strategy for the novel family of quasi-Z-source ac-ac converter,” IEEE Trans. Ind. Informat., vol. 9, no. 3, pp. 1538–1547, Aug. 2013.
[6] M. K. Nguyen, Y. G. Jung, and Y. C. Lim, “Single-phase ac–ac converter based on quasi-Z-source topology,” IEEE Trans. Power Electron., vol. 25, no. 8, pp. 2200–2210, Aug. 2010.
[7] M. K. Nguyen,Y. G. Jung, andY.C. Lim, “Voltage swell/sag compensation with single-phase Z-source AC/AC converter,” in Proc. 13th Eur. Conf. Power Electron. Appl., 2009, pp. 1–8.
[8] B. Sahu and G. A. R. Mora, “A low voltage, dynamic, noninverting, synchronous buck-boost converter for portable applications,” IEEE Trans. Power Electron., vol. 19, no. 2, pp. 443–452, Mar. 2004.