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Implementation of Single-Phase Two-Switch Midpoint Unidirectional Multilevel Converter System

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Abstract:
This paper deals with implementation of a single-phase three level converter system under low voltage condition. The frequency of the switches is made constant and involves change in t_{on} and t_{off} duration. For this condition the pulse width modulation control scheme for a single phase three level rectifier is developed to improve the power quality. The hysteresis current control technique is adopted to bring forth three-level PWM on the dc side of the bridge rectifier and to achieve high power factor and low harmonic distortion. Based on the proposed control scheme, the line current is driven to follow the sinusoidal current command which is in phase with the supply voltage. By using three-level voltage pattern the blocking voltage of each power device is clamped to half of the dc link voltage. The simulation and experimental results of 20W converter under low input voltage condition are shown to verify the circuit performance. Open loop simulation and hardware tests are implemented by applying a low voltage of 15 V(rms) on the input side.

Keywords: Arduino due, hysteresis current control, pulse width modulation, power factor correction, total harmonic distortion, voltage unbalance

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1 Introduction

Conversion of single-phase or three-phase ac to dc by means of converter finds it application in various areas of power electronics such as telecom power supplies, battery systems, electric drives etc. Conventionally, the thyristor bridge or diode bridge are most popularly used ac-dc power converters [1] for obtaining dc power from the ac grid. The advantages of these topologies include size, reliability, control, structure and cost. However, these topologies have disadvantage that they inject unwanted current harmonics into the grid. This results in the distortion of the grid voltage which causes poor power quality in the loads connected to the grid. To overcome the above problems, switch-mode rectifiers (SMR) [2] or power factor corrected (PFC) rectifiers [3] are used. They are utilized to replace the conventional rectifiers as the front-end converter for many power equipment. Basically, a SMR is formed by inserting a dc-dc converter between diode rectifier and capacitive output filter.

For high voltage and high power applications multilevel converters [4] play a major role for the improvement of output signals quality of the converter. In recent times, it is problematic to connect only one power semiconductor switch directly to the grid due to high voltage range. To overcome this difficulty, use of high speed switching components are needed, and avoiding the problem of linking them directly to the grid. Multilevel converters [5–7] have ability to attain higher voltages with a lower maximum device rating. Several multilevel topologies have been developed in the last few years, among them diode clamped (Neutral clamped) topology [8] is the best suited for this circuit configuration. The main reason for the selection of diode clamped topology is because of its advantages. It has high efficiency for fundamental switching frequency and all the output capacitors share the common dc link.

Power factor is also an important performance parameter [3]. Improving power factor helps us in better and economic performance of the system. When the ratio between the voltage and current is a constant, then the input will be resistive hence the power factor will be 1.0. When the ratio between voltage and current is other than one due to the presence of non-linear loads, the input will contain phase displacement, harmonic distortion

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and thus, the power factor gets degraded. The main objective of the paper is to obtain unity power factor at input side of the circuit. The hysteresis current control technique is used to obtain it. IEEE standard 519 describes the requirements and practises which improve the system performance by reducing current harmonics and to make the power factor almost unity [6].

Arduino microcontrollers are easy to handle, low cost, more precise and can read analog values and provide switching signals to the power switches. MATLAB-Arduino interface can be used to generate gating signals which makes it a standalone device which receives inputs to it and generates outputs. Arduino due is a microcontroller based on the 32-bit processor of Atmel SAM3X8E ARM Cortex-M3 MCU. Arduino DUE offers 54 digital input/output pins (of which 16 can be used as PWM outputs) 12 analog inputs with 12 bits of resolution, 4 UART's (hardware serial ports) two DAC (digital to analog converter) outputs, an 84 MHz crystal oscillator, two USB connections, a power jack, an ICSP header, a JTAG header, and a reset button. A Simulink support package for Arduino Due for communicating with MATLAB is installed in the software. A library of Arduino package is installed in the Simulink which allows access to Arduino I/O pins.

2 Circuit description

The circuit configuration of the ac-dc converter consists of a single phase diode bridge rectifier [1, 4, 9], two power switches, one boost inductor, two fast recovery diodes and two bulk capacitors is shown in Figure 1. The capacitors not only filter the rectified voltage but also store some energy in case of line failure. The boost inductor is connected in series with the bridge rectifier to boost the voltage at the output side. A hysteresis current control, voltage controller is employed in the control scheme to increase the power quality of the circuit. A hysteresis current control is adopted to increase the dynamic response of the rectifier [10]. By using PWM scheme, voltage unbalance problem can be eliminated from the circuit. A voltage controller is used to reduce the ripple content on the capacitors and to regulate dc bus voltage.

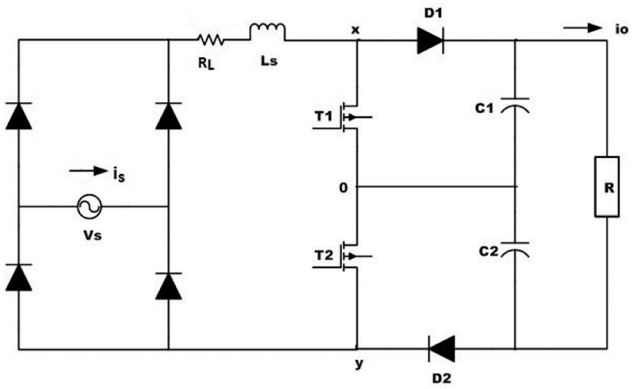

Figure 1: Single phase multilevel converter circuit.

3 Modes of operation

The main objective of the control scheme of the single phase three level ac-dc converter is to reduce harmonic content in supply side and to increase the power factor to unity. There are two power switches and two fast recovery diodes in the circuit. Two power switches are controlled based on the output of the look-up table. According to the switching states of two power switches the single phase ac-dc converter can be divided into four modes of operation. In mode-1 as shown in Figure 2(a), both power switches T_1 and T_2 are turned on where as the two diodes D_1 and D_2 are turned off. This mode is used to increase the inductor current.

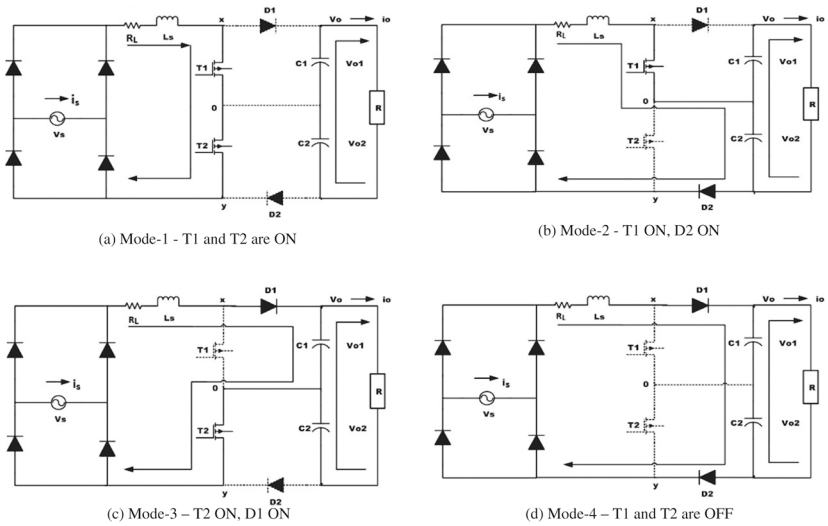

Figure 2: Modes of operation. (a) Mode-1 - T1 and T2 are ON, (b) Mode-2 - T1 ON, D2 ON, (c) Mode-3 – T2 ON, D1 ON, (d) Mode-4 – T1 and T2 are OFF.

In mode-2, the power switches T_1 and diode D_2 is turned on. Power switches T_2 and diode D_1 is turned off. Diode D_1 is reverse biased and D_2 is conducting. This mode is used to compensate capacitor C_2 voltage and is shown in Figure 2(b). In mode-3 as explained in Figure 2(c), the power switches T_2 and diode D_1 is turned on. Power switch T_1 and diode D_2 are turned off. Diode D_2 is reverse biased and D_1 is conducting. This mode is used to compensate capacitor C_1 voltage. In mode-4, both power switches T_1 and T_2 are turned off whereas the two diodes D_1 and D_2 are turned on and is given in Figure 2(d). This mode is used to charge the capacitors and it leads to the decrease in inductor current.

4 Operating regions

The aim of the multilevel converter which is employed is to produce multilevel PWM pattern on the dc side. To achieve this, the rectifier should be operated in particular region. According to the modes of operation the rectifier will operate in particular region. To achieve three level pattern on dc side there are two operating regions which is shown in the Figure 3.

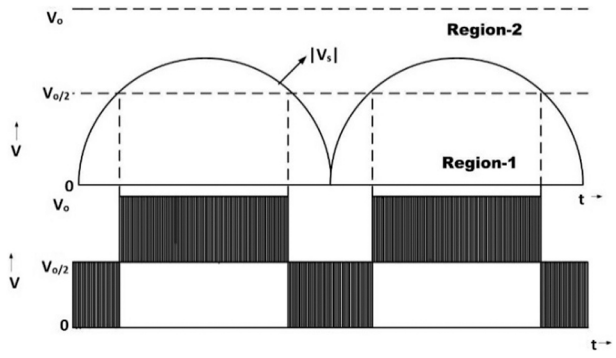

Figure 3: Operating regions of the converter.

Using these two operating regions it can generate three level PWM pattern on dc side. According to the proposed control scheme it is necessary that the output voltage must be greater than the supply voltage and smaller than two times of the peak line voltage ($V_{s,peak} < V_0 < 2V_{s,peak}$). The change in the inductor current is expressed as in eq. (1)

$$\frac{di_L}{dt} = \frac{|V_s(t)| - v_{xy}}{L_s} \tag{1}$$

If the inductor current variation and the rectified line voltage are known, then the dc bus voltage v_{xy} can be decided by selecting the specific mode of operation to turn on the power switches.

Region-1($0 < V_s < v_0/2$): In this region inductor current is decreased to charge the output capacitors. Each output capacitor voltage on the dc side is greater than the rectified line voltage. To charge the output capacitors the possible operating modes are mode 2 and 3. If the operating mode 2 is selected then the inductor current charges the output capacitor C_2. To charge the output capacitor $C_{1,}$ mode 3 is selected. The voltage on the boost inductor is $|V_s|$ and mode 1 is used to increase the inductor current. The PWM waveform is switched between 0 and $v_0/2$. Three operating modes (mode 1, 2 and 3) are used in this region to increase or decrease the inductor current and charge the output capacitors for voltage balance.

Region-2 ($v_0/2<V_s<v_0$): In this region the PWM waveform is switched between $v_0/2$ and v_0 as shown in Figure 3. Each capacitor voltage is less than rectified line voltage. Mode 2 and 3 are selected to charge the output capacitors and decrease the inductor current. Mode 4 is employed to decrease the inductor current to make rectified line voltage greater than the output capacitor voltages. Three operating modes (mode 2, 3 and 4) are used in this region to increase or decrease the inductor current and charge the output capacitors for voltage balance.

5 Design procedure

To design a multilevel ac-dc boost converter, the rectified voltage of the bridge rectifier has to be calculated which in turn is fed to the boost converter [11]. Assume the input voltage as 15 volts ($V_s = 15V_{rms}$) and load is purely resistive.

The peak to peak voltage of the bridge rectifier is given as in eq. (2)

$$V_{p-p} = V_s * \sqrt{2} \tag{2}$$

The average voltage of the bridge rectifier is given as in eq. (3)

$$V_{dc} = \frac{2V_{p-p}}{\pi} \tag{3}$$

The input and output voltages of the multilevel boost converter were fixed as 13.5V and 27V. The duty ratio of the converter is fixed as 0.5. Here, an Arduino Due is used to generate gating signals for the switches T_1 and T_2 with switching frequencies 10 kHz and 20 kHz.

The output voltage of the multilevel boost converter after neglecting the voltage drop across the switches and diodes is given as in eq. (4)

$$V_o = \frac{V_{dc}}{1-D} \tag{4}$$

The average power in the boost inductor can be determined by finding the average power supplied by the source and the average power absorbed by the resistive load. Output power is in eq. (5)

$$P_o = \frac{V_o^2}{R} = V_o I_o \tag{5}$$

The average current in the boost inductor is given as in eq. (6)

$$I_L = \frac{2V}{(1-D)\,R} \tag{6}$$

The maximum value of the boost inductor L can be calculated as in eq. (7)

$$L = \frac{V_o D(1-D)^2}{2I_o f} \tag{7}$$

In practice, a normal capacitance will result in s. The peak-to-peak output voltage ripple can be calculated from the capacitor current waveform. The change in capacitor charge can be calculated from eq. (8)

$$|\Delta Q| = \frac{V_o DT}{R} = C\Delta V_0 \tag{8}$$

An expression for ripple voltage is then in eq. (9)

$$\Delta V_o = \frac{V_o DT}{RC} = \frac{V_o D}{RCf} \tag{9}$$

Where f is the switching frequency. Alternatively, expressing capacitance in terms of output voltage ripple yields in eq. (10)

$$C = \frac{D}{R(\Delta V_{o/V_o)f}} \tag{10}$$

The parameters of the converter are designed using above design procedure and the critical designed values are presented in the Table 1.

Table 1: System Parameters.

Sl no.	Name of the parameter	Value
1.	Source voltage	15V (rms), 50Hz
2.	Rectified voltage	13.5V
3.	Boost inductor	5mH
4.	Capacitors (C1 & C2)	4700µF
5.	Output voltage	27V
6.	Voltage ripple	5.8V
7.	Current ripple	0.56A

Assuming the capacitance value as very large because of the two switches, the capacitance of the capacitors considered is 4700µF. In order to get three level patterns on the dc side, the switching frequencies of the switches T_1 is 10 kHz and T_2 is 20 kHz and the value of the inductor also changes accordingly. So, that maximum value of the inductor is taken into consideration.

The above design constraints are done for a input voltage of 15V(rms), which are used in simulation and laboratory prototype under open loop condition. The procedure for implementation of the circuit in open loop condition is explained below.

5.1 Generating pulses for switches using Arduino Due

The Arduino board should be interfaced to MATLAB/SIMULINK software through programming port of Arduino. The required installation files of Arduino package have to be installed in the MATLAB/SIMULINK software. After successful installation of the Arduino based Simulink package, the Arduino based Simulink files can be seen in MATLAB/SIMULINK library. Now, the analog I/O blocks, digital I/O blocks, PWM blocks can be accessed from MATLAB/SIMULINK software library.

To generate gating pulses for switches the desired switching frequency for the switch is declared in the pulse generator block. The output of the pulse generator block is given to digital output pin which is directly linked to Arduino due board. The pulses produced from the digital output pin of Arduino due are given to driver IC (MC34151-P) which will generate pulses for switches T_1 and T_2. To eliminate the grounding issue in the circuit, an optocoupler (MC2TE) is used. The optocoupler is directly connected to the driver IC which helps in generating pulses without any grounding issue. The switch T1 ground in the circuit is floating while the switch T_2 ground is grounded to the circuit ground. To eliminate this grounding issue MC2TE optocoupler is used. The basic block diagram of the circuit is shown in Figure 4

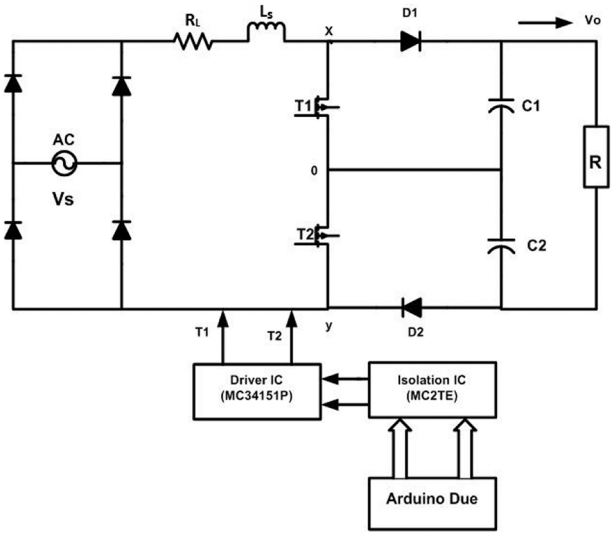

Figure 4: Pulse generator using Arduino due board and driver circuit.

5.2 Simulation and experimentation considerations

For experimental setup the source voltage provided to the circuit is controlled using auto transformer. The source voltage is applied to the bridge rectifier (KBPC5010). The rectified voltage from bridge rectifier (KBPC5010) is given to the multilevel boost converter. The boost inductor considered is 5mH which is made up of ferrite core. The power switches are implemented by IRF540N MOSFET. The power diodes used in this circuit are MUR820 and the current sensor (LA55-P) is used to sense the inductor current and input current. The experimental setup of single phase multilevel ac-dc boost converter is shown in Figure 5.

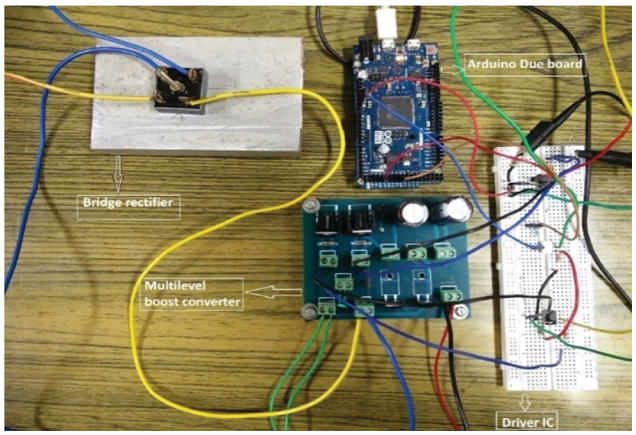

Figure 5: Hardware setup of the multilevel converter.

6 Control scheme

The power switches T1 and T2 can be controlled to generate a three level PWM pattern on dc side and a hysteresis current controller is used to force the line current to be sinusoidal with low current harmonics. The hysteresis current controller is implemented by taking inductor current as actual current and a reference current is generated using a sine wave generator which is in phase with rectified line voltage. The inductor current command is controlled within a preset band h, which makes it to follow the current command with limited current distortion. The voltage unbalance problem which is inherent on the output capacitors is considered and the measured capacitor voltages are fed into the control algorithm to compensate appropriate capacitor voltage. This control algorithm is also used to control the dc bus voltage during load transients. It reduces the losses on output side and reduces ripples on the dc bus voltage. In order to generate a three level waveform, the three digital control signals used are defined as in eqs. (11), (12), (13).

$$k1 = \begin{cases} 1, & |V_s| > \min(v_{01}, v_{02}) \\ 0, & |V_s| < \min(v_{01}, v_{02}) \end{cases} \tag{11}$$

$$k2 = \begin{cases} 1, & v_{01} > v_{02} \\ 0, & v_{01} < v_{02} \end{cases} \tag{12}$$

$$k3 = \begin{cases} 1, & |i_L^*| - i_L > h \\ 0, & |i_L^*| - i_L < h \end{cases} \tag{13}$$

The three digital signals k1 - k3 are implemented using NAND gates to produce a three level staircase waveform and to make the power factor unity. The signal k1 is the signal of the region detection which will detect the appropriate region and generates the control logic. The signal k2 is the signal of the compensated capacitor which compensates the capacitor voltages and generates control logic according to it. The signal k3 is hysteresis current comparator which is adjusted in between a preset band h. The relations between these three control logic generates control signals to the power switches. The relations between the control logic are shown in Table 2.

Table 2: Relation between switching signals (T1, T2) and control signals (k1, k2, k3) for three level PWM rectifier.

k1	k2	k3	T1	T2	Mode	v_{xy}
0	0	0	0	1	3	$v_0/2$
0	0	1	1	1	1	0
0	1	0	1	0	2	$v_0/2$
0	1	1	1	1	1	0
1	0	0	0	0	4	v_0
1	0	1	0	1	3	$v_0/2$
1	1	0	0	0	4	v_0
1	1	1	1	0	2	$v_0/2$

The following eqs. (14) and (15) can be derived from the relation between the switching signals and control signals using karnaugh maps which will drive the two power switches.

$$\mathrm{T1} = \overline{k1}\,k2 + \overline{k1}\,k3 + k2k3 \tag{14}$$

$$\mathrm{T2} = \overline{k1}\,\overline{k2} + \overline{k1}k3 + \overline{k2}k3 \tag{15}$$

NAND gates are used to implement the eqs. (14) and (15). If two capacitor voltages v_{01} and v_{02} are equal, then there are three level PWM pattern on the waveform of v_{xy}. The control algorithm which is discussed above is shown in Figure 6

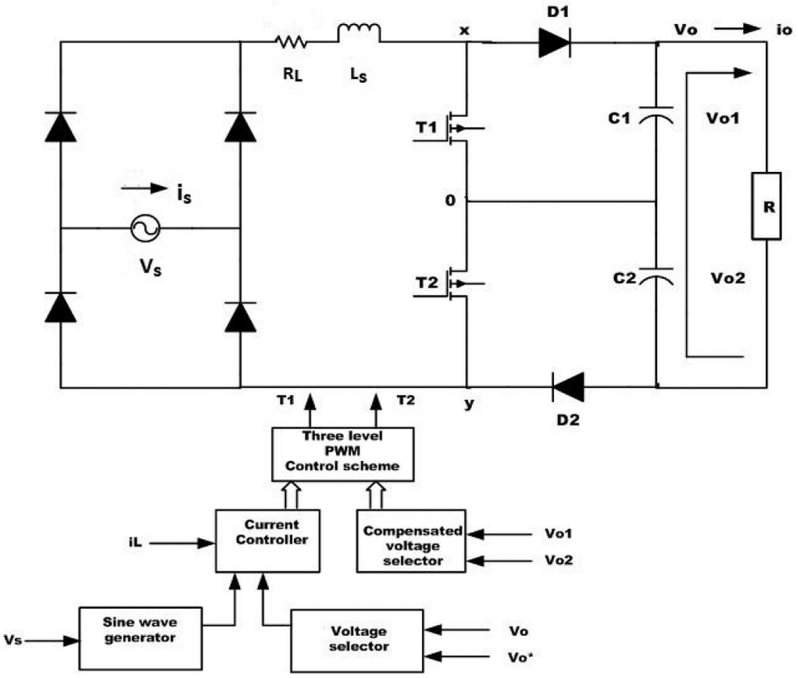

Figure 6: Control scheme block diagram.

Hysteresis current controller (HCC) is used to control the inductor current (i_L). The rectified phase locked loop circuit output from the sine wave generator block is multiplied by the error voltage to form an inductor current command. The current controller continuously tracks the command current and the inductor current is controlled within the hysteresis band. This will help in achieving a less distorted inductor current (i_L).

7 Results & discussions

The results of both simulation and hardware are presented and detailed analysis of each waveform is discussed here. The results of the hardware setup are observed in the digital oscilloscope which is connected to the different ground. The difference between simulation and hardware results sometimes occur because of that grounding issue.

The Figure 7 refers to switching signals which are given to switches T1 and T2 of the circuit in hardware and simulation respectively. The switching frequency of the switch T2 is double the frequency of the switch T1 according to the modes of operation of the circuit.

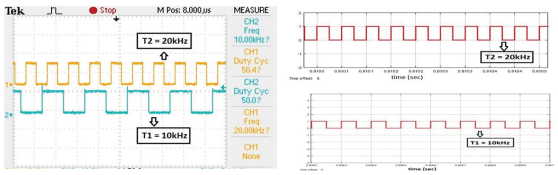

Figure 7: Hardware and Simulated switching pulses.

The supply voltage considered in the simulation and hardware setup is 15V (rms) while the peak to peak supply voltage is 21.2V. To sense the voltage in hardware setup a step down transformer of 230V/15V is used.**Figure 8**depicts switching stress of both the switches. The waveforms related to studied converter with simulation and experiemnts are shown in Figure 9. To get the exact peak voltage of 21.2V, the obtained maximum voltage has to be converted in hardware setup using scaling factor. In hardware setup, to give supply to the circuit an autotransformer is used. It is connected directly to the mains and it will eliminate the inrush current at the start.

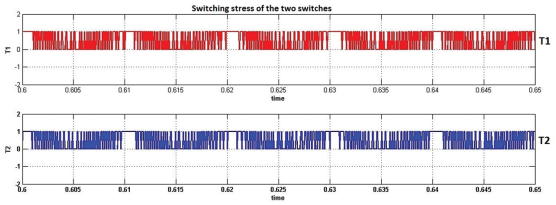

Figure 8: Switching stress of the two switches.

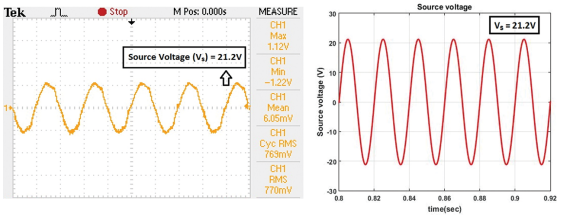

Figure 9: Hardware and simulated test source voltage of the converter.

Figure 10 refers to the input current of the circuit in hardware and simulation respectively. Input current is also sensed using current sensor and obtained values are converted into current using scaling factor. It can be clearly observed that the input current is not purely sinusoidal which means the current harmonics are present in the input side. To eliminate current harmonics a closed loop control should be implemented for the circuit.

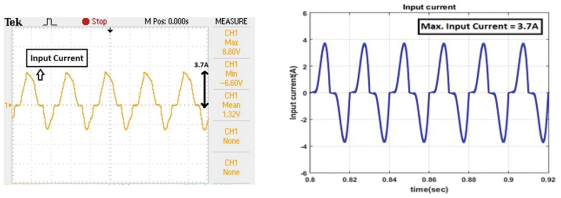

Figure 10: Hardware and simulated input current of the converter.

Figure 11 which is shown below refers to the output voltage waveform of the circuit in hardware and simulation respectively. From the figure, it is observed that the output voltage is boosted to 27V from 13.5V. The output voltage across the load is gradually charged from zero to 27V. The output voltage in hardware setup is free of transients because of the presence of the auto transformer. The auto transformer eliminates the inrush current so the outputs in hardware setup are free of transients. In simulation, the sudden supply is directly given to the circuit and because of this the circuit keeps on charging and reaches the steady state. So, in hardware implementation the inrush flow of current cannot be observed. To eliminate inrush current in simulation an external inrush circuit has to be used [12]. **Figure 12** shows the transient response of output voltage with 27 V.

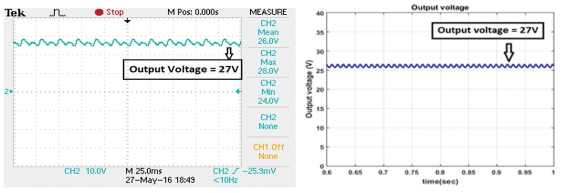

Figure 11: Hardware and simulated output voltage of the current.

Figure 13 which is shown below refers to the transient and steady state response of the capacitor voltages of the two capacitors. The addition of the two capacitor voltages gives the total output voltage across the load.

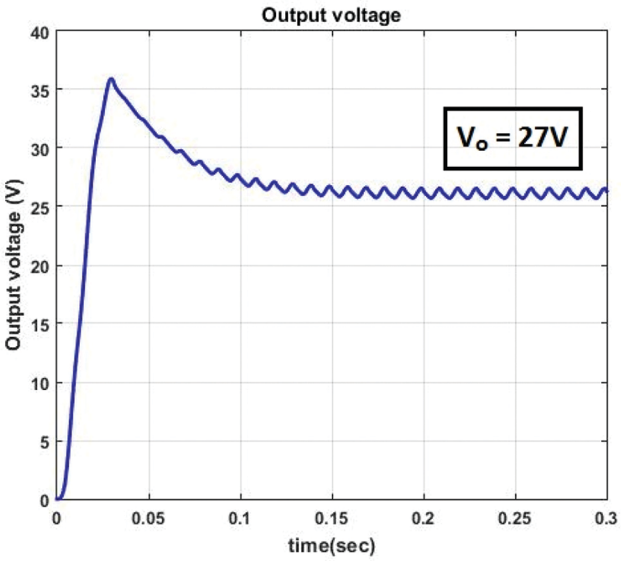

Figure 12: Transient response of the output voltage.

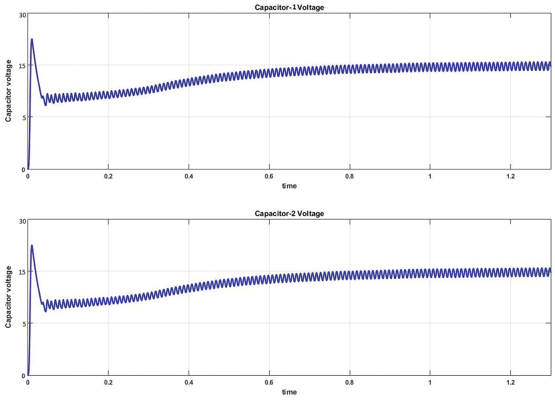

Figure 13: Transient and steady state response of the two capacitors respectively.

Figure 14 which is shown below refers to the response of the inductor current and also comparison between source voltage and inductor current. Inductor current which is shown is obtained after converting ac to dc so there is no negative cycle for it.

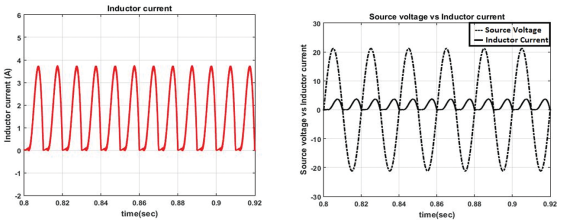

Figure 14: Simulation results of transient response of inductor current.

Figure 15 refers to the input current with respect to source voltage. Input current is in phase with the source voltage and with harmonics.

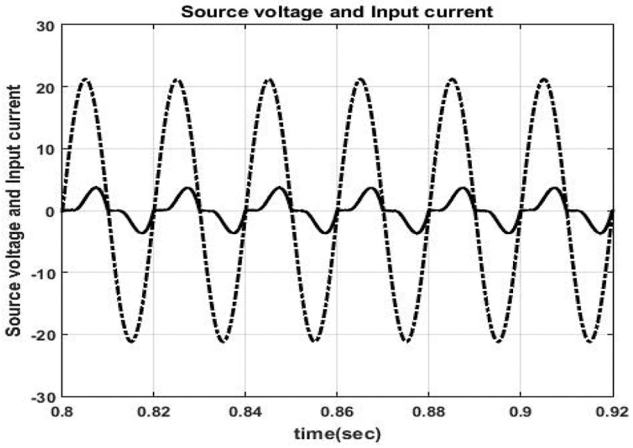

Figure 15: Source voltage and input current of the converter.

Figure 16 refers to the THD analysis of the circuit. The THD% of the input current is 38.77 % so that there are more current harmonics in the circuit. To remove the current harmonics and make it unity power factor a control scheme has to be implemented.

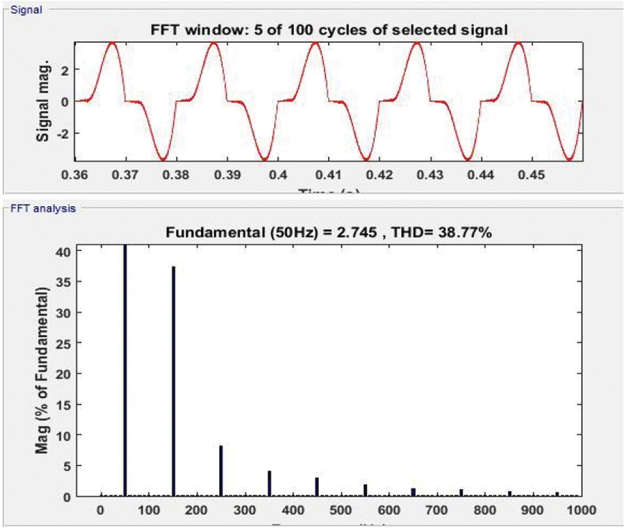

Figure 16: THD analysis of the input current.

8 Conclusions

Implementation of control scheme for single-phase three level converter system under low voltage condition is analysed in the paper. The control scheme is based on the control logic given to the switches. For low voltage applications Arduino is used to generate the switching pulses to the power switches. A driver IC (MC34151) and optocoupler (MC2TE) is used for driving the switches and eliminating the grounding issue between the switches respectively. The output voltage of the converter is boosted two times the rectified voltage according to the theoretical calculations. The comparison between simulation and experimental results under low voltage condition are observed from the results. The experimental results are in agreement with the simulation results. A three level pulse width modulation technique is used to generate a three level staircase waveform on dc side. The voltage unbalance in the dc bus side is reduced using the control scheme.

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