Indian Journal of Science and Technology, *Vol 8(35), DOI: 10.17485/ijst/2015/v8i35/80548, December 2015*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Implementation of Grid Connected PV array using Quadratic DC-DC Converter and Single Phase Multi Level Inverter

R. Mahalakshmi[1*] and K. C. Sindhu Thampatty[2]

[1]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Bengaluru - 76, Karnataka, India; deivamaha@gmail.com
[2]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Ettimadai, Coimbatore – 641112, Tamil Nadu, India; t_sindhu@cb.amrita.edu

Abstract

Electrical energy generation from solar and wind is increasing day by day and the extraction of good quality electrical energy effectively as well as efficiently is really challenging. This paper focuses on the extraction of electrical energy from solar cells and interconnecting it to the single phase grid through a Quadratic Buck-Boost Converter (QBBC) and Multi Level Inverter (MLI). MLI uses three DC sources, one of which is derived from the solar array through QBBC with Maximum Power Point Tracking (MPPT) controller. In this paper, a new converter topology which accepts wide variations in input voltage has been designed to produce minimum distortion in MLI output with reduced number of switches. The proposed system is designed and implemented in the laboratory and the output is analyzed in different operating conditions

Keywords: Grid Connected PV Array, DC-DC Converter, Multi Level Inverter, MPPT Controller, Quadratic Buck Boost Converter

1. Introduction

Day by day depletion of coal, fossil fuels (non-renewable sources) and increase in electricity demand by the consumers makes the world to think about electricity generation from the solar energy. Also nowadays many researchers concentrate on interconnection of solar energy into the grid using many power converter topologies. Though the grid interconnection with solar energy has more advantageous, there are many technical complexities involved in it. The interconnection is done through the DC-DC converter and inverter. The DC voltage which is obtained from the solar energy is not constant DC. In order to connect it to the grid, variable DC voltage obtained from the solar array has to be converted into the constant DC and it has to be intern connected to the grid through the inverter. Conventional inverter outputs AC two level square wave with more harmonics which cannot be connected directly connected to the grid. To reduce the harmonics present in the output of the inverter, different MLI topologies are proposed in different literatures. The work proposes the Quadratic Buck-Boost DC-DC Converter (QBBC) and Multi Level Inverter (MLI) topology for the grid integration of PV array. The conversion efficiency of QBBC is more compared to conventional DC-DC converters such as buck, boost and buck-boost converters. The conventional converters have the limitation on the switching frequency of operation of MOSFET switch of the converter and also they suffer from low duty ratio limitation. The QBBC can allow the operation of switching frequency in the range of MHz. The disadvantages of conventional converters are eliminated by QBBC[1] and they have a voltage ratio of $-D^2/(1-D)$ which is quadratic dependence. They are mainly used for the conversion of wide range of input voltage variations and high switching frequency operations[1]. This paper proposes the six level (quarter cycle) H-bridge MLI topology which utilizes three

**Author for correspondence*

DC sources. One of the DC sources is replaced by solar array with QBBC. MLI uses several DC voltage sources and power semiconductor devices to synthesize a staircase waveform[2]. The Multi Level stepped waveform has improved harmonic profile as compared to the two level waveform obtained from the conventional inverters[3] Further advantages of MLI's are higher efficiency, reduced dv/dt stresses on the load, lower acoustic noise and Electromagnetic Interference (EMI). Total Harmonic Distortion (THD) of the multi-level alternating waveform reduces as number of levels in the output increases. It inadvertently leads to necessity of a large number of power semiconductor devices and accompanying gate driver circuits. Hence, the overall system is rendered complex and expensive[4,5]. Therefore, practical implementation demands reduction in number of switches and gate driver circuits[6]. By using different DC input voltage sources at the input of MLI, the number of levels in the output waveform can be increased (i.e. two or more input DC sources are unequal)[7]. As the number of DC voltage input sources increases, producing an output with more number of levels, therefore results in sine wave with less harmonic distortion[10]. Thus, the size and requirement of output filter at the MLI output is reduced. Many new configurations on DC-DC converters, MLI and PWM techniques have been designed[11-20]. Output of the MLI is further connected to the single phase grid for injecting a power during high sunshine hours. Thereby, reducing the demand of non-renewable energy sources.

This paper is organized as follows; section 2 deals with overall system description. Section 3 describes the circuit operation of quadratic buck –boost converter; Section 4 explains the operation of MLI topology. Section 5 and 6 deal with simulation and hardware results of the proposed system.

2. System Description

The overall block diagram of the proposed system is shown in Figure 1. The aim of this work is to inject an electric energy generated from the renewable energy sources such as solar and wind etc into the single phase grid. The proposed grid connected system has two stages of conversion.

Stage 1: Solar electricity converted into constant DC using QBBC with MPPT controller.

Stage 2: DC voltage obtained from QBBC is converted into the multi stepped alternating wave through H-bridge MLI. Second stage of conversion makes constant DC into

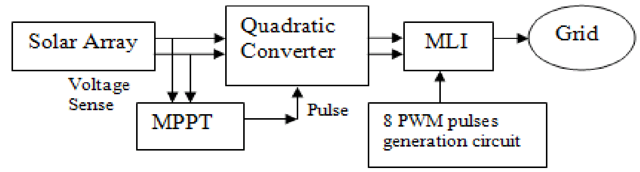


Figure 1. Block diagram of proposed system.

multi stepped AC. The conventional single phase inverter output contains more harmonics which cannot be directly used by commercial AC loads and it cannot be directly fed into the grid. The second stage of conversion in the system uses MLI in order to generate less harmonic sine wave to interface with the grid or load. Proposed MLI outputs six level (quarter cycle) alternating waveform using three DC voltage sources. One of the DC sources is replaced by solar array with QBBC. Thus results in solar array connected into the grid through DC-DC converter and MLI.

3. Circuit Description

3.1 Quadratic Buck Boost Converter

Figure 2 shows the QBBC which is used for converting variable solar array output voltage into constant DC voltage and it is utilized as one of the input voltage sources of the MLI.

The voltage conversion ratio of QBBC = = $\frac{-D^2}{1-D}$ (1)

where D is duty ratio = $T_{on}/(T_{on}+T_{off})$.

T_{on} is the ON time of the switch.

T_{off} is OFF period.

This type of converters are obtained by combining two fundamental conventional converters such as buck and buck-boost converter and a circuit reduction is done to result as cascaded DC-DC converter with only one active switch. Operation and advantages of QBBC is well explained by Maksimovic D et al. Figure 3(a) and (3b) show the two modes of operation of QBBC.

3.1.1 OFF State operation of QBBC

In this period the inductor current is made to freewheel through diode and thus charging the capacitor as shown in Figure 3(a). The output voltage held by filter capacitor C_2 freewheels current through inductor and diode thus exhibits a freewheeling action. In this mode, the diodes D_2, D_3 are forward biased thus allowing current to pass through and charging the capacitors. The capacitor C_2 maintains voltage across the load resistors.

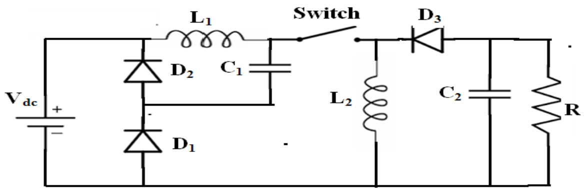
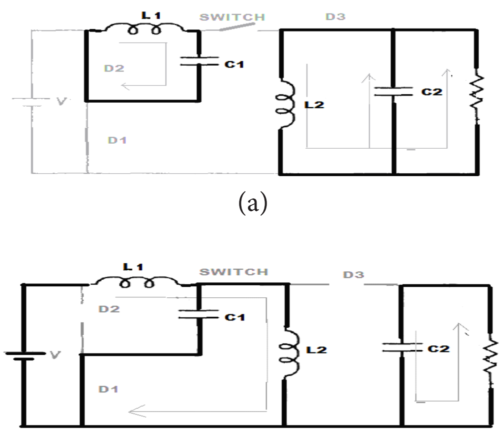


Figure 2. Quadratic Buck-Boost converter.



(a)

(b)

Figure 3 **(a)** Mode 1 operation of QBBC (OFF). **(b)** Mode 2 operation of QBBC (ON)).

3.1.2 ON State Operation of QBBC

During this period, L_1 is charged with the DC source as shown in Figure (3b). The voltage across L_2 includes DC source voltage as well as voltage from C_1 and is shown in Figure (3b). The diodes D_2 and D_3 are reverse biased and the capacitor C_2 maintains the constant output voltage across the load. The ripples in the capacitor voltages and inductor currents are assumed to be zero. When the MOSFET is turned ON, the diode D_1 is ON and the current flowing through the diode D_1 is given by equation 1.

$$I_{D1} = I_{L2} - I_{L1} \tag{2}$$

The MOSFET average current $I_{MOSFET} = D^{*}I_{L2}$

$$I_{D1} = (1-D) \times I_{L2} \tag{3}$$

Where I_{L1} and I_{L2} are current flowing through inductor L_1 and L_2.

(Eq-3) confirms that diode D_1 is indeed ON. During the MOSFET ON time, D_2 and D_3 are OFF.

3.1.3 Design Equations for QBBC

For the design of inductors and capacitors the following set of equations are used which are provided in[1]

$$K_1 = k_1 = \frac{2L_1 f_s}{R} \tag{4}$$

$$K_2 = k_2 = \frac{2L_2 f_s}{R} \tag{5}$$

Where
L_1 is inductance of inductor L_1.
L_2 is inductance of inductor L_2.
f_s is the switching frequency.
R is a load resistance.

K_1 and K_2 are constants which describes the minimum values of the inductors to operate the Converter.

$$k_2 > \frac{(1-D)^2}{D^2} \tag{6}$$

$$k_2 > (1-D)^2 \tag{7}$$

The values of the K_1 and K_2 are determined using the equations (4) and (5). The inductors L_1 and L_2 are calculated further using the conditions from the equations (6) and (7). Capacitors C_1 and C_2 are designed depending on the time constant of the circuit (□) and the value of the inductors. The proposed QBBC is designed to obtain constant DC voltage of 60V from variable input voltage ranging from 28V to 32V.

3.1.4 MPPT Controller

The objective of the MPPT controller is to change the duty cycle of the switching pulse which is provided to the MOSFET. The controller senses the output voltage of the solar array which is varying from 28V to 32V and changes the duty cycle accordingly to adjust the output DC voltage for 60V. Figure 4 shows the simulink model of first stage of conversion (PV array cascaded with the QBBC) of grid connected solar system with MPPT controller.

4. Grid Tied Multi Level Inverter

MLI (H-bridge topology) uses, three DC sources such as V_{dc} (30V), 2 V_{dc} (60V), 2 V_{dc} (60V). A single-phase module of the proposed topology is shown in Figure 5. It has three electrically isolated input DC sources viz. V_{dc1}, V_{dc2} and V_{dc3} .V_{dc2} and V_{dc3} are selected such that $V_{dc2} = V_{dc3} = 2V_{dc1}$. V_{dc2} is derived from solar panel through quadratic buck-boost converter. In the proposed topology, the input DC sources are so connected in such a way that the higher potential terminal of source V_{dc1} is connected to the lower potential terminal of source V_{dc2} and vice-versa via power

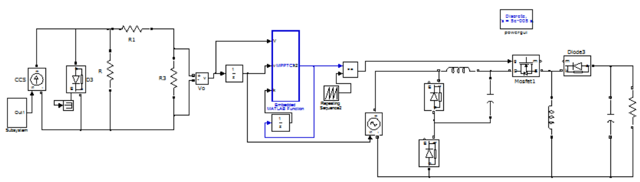


Figure 4. Matlab Simulink diagram of PV array cascaded with QBBC.

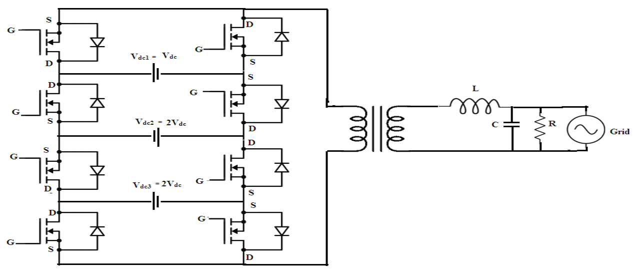


Figure 5. Gird tied MLI.

switches. Thus, the switched sources form a series connection through the power switches. In the structure shown in Figure 5, 8 switches are used (S_j and S_{jB} where j = 1,2,3,4). The switching sequence of the MLI operation is presented in the table 1. Switching pulses for S_{1B}, S_{2B}, S_{3B} and S_{4B} are compliment of S_1, S_2, S_3 and S_4. It has been observed that four switches must conduct simultaneously to obtain a given voltage level. For example, to synthesize output voltage, $V_o(t) = 3\ V_{dc}$, switches S_1, S_3 S_{2B} and S_4 will conduct while the rest of the switches are blocked. The modes of operation of the MLI are described in[10]. It is also important to mention that for all the positive voltage levels and a zero level (states 1 to 6), switch S_{2B} always conduct while for all the negative voltage levels (states 8 to 12), switch S_2 always conduct. Therefore, it is possible to operate these two switches at fundamental frequency to obtain all eleven levels in full cycle (Six levels in the quarter cycle). The output levels of MLI are 0,+V_{dc},2V_{dc},+3V_{dc},+4V_{dc} and +5V_{dc}. Therefore maximum value of the voltage is 150V since the V_{dc} is 30V.

Pulses are applied to the switches of MLI using simple PWM technique. Four pulses for the switches S_j where j = 1,2,3,4 are obtained by comparing ramp signal of 50Hz and DC signal as shown in Figure 6. The compliment of pulses to S_1 through S_4 is fed to the complementary switches S_{1B} to S_{2B} respectively. THD of the MLI's output is analyzed and the output is connected to the grid 220V, 50Hz through the LC filter. In order to connect the output of MLI (+150V peak) to grid, step up transformer is used

Table 1. Switching states of MLI

Output Voltage	S_1	S_2	S_3	S_4	S_{1B}	S_{2B}	S_{3B}	S_{4B}
+150V	1	0	1	0	0	1	0	1
+120V	0	0	1	0	1	1	0	1
+90V	1	0	1	1	0	1	0	0
+60V	0	0	1	1	1	1	0	0
+ 30V	1	0	0	0	0	1	1	1
0	0	0	0	0	1	1	1	1
- 30V	0	1	1	1	1	0	1	1
- 60V	1	1	0	0	0	0	1	1
- 90V	0	1	0	0	1	0	1	1
-120V	1	1	0	1	0	0	1	0
-150V	0	1	0	1	1	0	1	0
0	1	1	1	1	0	0	0	0

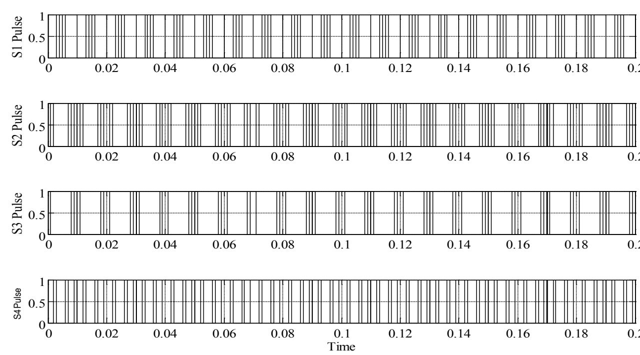


Figure 6. Switching Pulses to the switches using simple PWM techniques.

to obtain 220V (rms) and is connected to the single phase grid through the filter.

THD of the waveform is analyzed using the following equation[21,22]

$$\text{THD} = \text{THD} = \frac{\sqrt{v_{rms}^2 - v_1^2}}{v_1} \quad (6)$$

In order to reduce the harmonics present in the MLI output LC filter is used and designed using the equation (7).

$$L \geq L \geq \frac{R_{L_{max}}}{3w} \text{ for single phase. C is selected as } \mu F^{22}. \quad (7)$$

Where L is the filter inductance.

R_{Lmax} is the maximum load resistance.

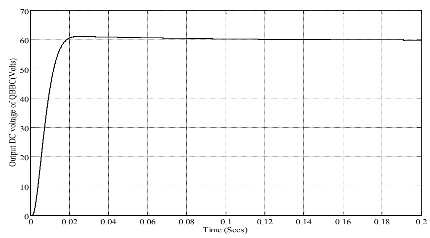


Figure 7. Output of the QBBC.

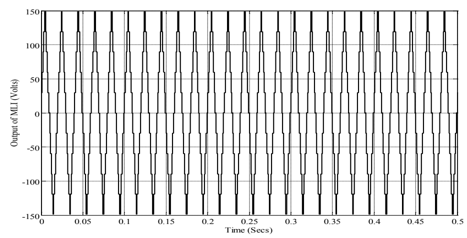


Figure 8. Output of MLI.

5. Simulation Results

The solar array produces the varying output voltage ranging from 28V to 32V and is fed to the QBBC to produce the constant DC voltage of 60V as shown in Figure 7. This is used as one of the input sources to the MLI. Figure 8 shows the output of the MLI with six levels in it. The six levels in quarter cycle are 0V,30V,60V,90V,120V and 150V.Total Harmonic Distortion (THD) of the MLI output is analysed without addition of output filter. The THD of the MLI output which is shown in Figure 8 is equal to 16.71% as shown Figure 9. In order to reduce the harmonics, LC filter is included at the secondary of the transformer and the observed THD is shown in Figure 10. After the inclusion of LC filter the THD of the MLI output voltage is reduced from 16.71% to 11.71%. The output voltage from MLI is stepped up to 220V rms and is connected to the single phase grid of 220V. Figure 11 shows the voltage across the stepup transformer and is equal to 220V rms. Figure 12 shows the grid voltage after interconnecting to the PV array using proposed system.

6. Hardware Design and Results

The topology of six level inverter with reduced number of switches is implemented in hardware and the hardware setup is shown in Figure13 and switching pulses are generated using digital circuits. From the detailed analysis of simulation results, the ratings of the switches are decided.

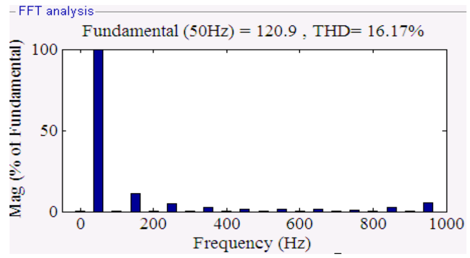


Figure 9. THD of MLI output without filter.

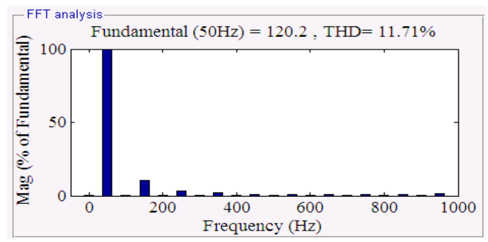


Figure 10. Output of the MLI with filter.

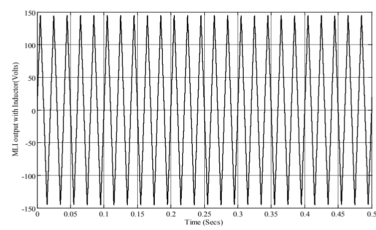


Figure 11. THD of the wave with LC filter.

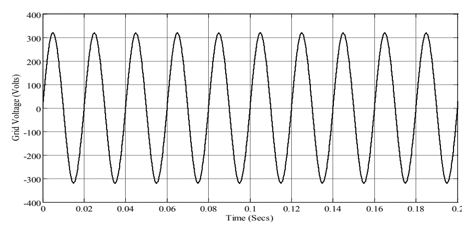


Figure 12. Grid voltage.

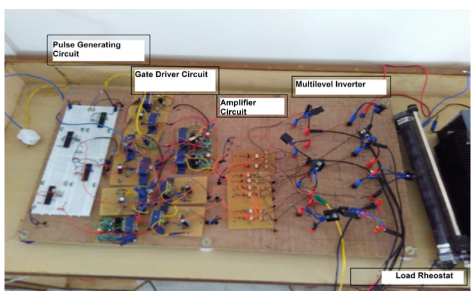


Figure 13. Hardware implementation of the multilevel.

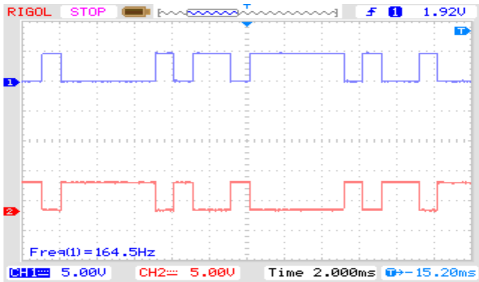


Figure 14. Pulses generated from the PIC16F877A through Simple PWM method for switch S_1 and $S_{1B.}$

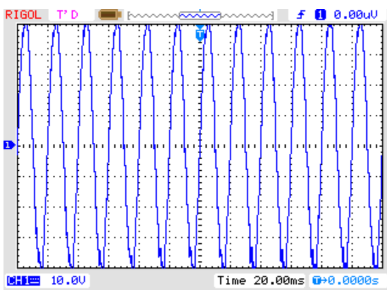


Figure 15. Output of the MLI.

The requirements for implementing MLI are three regulated DC supplies (8V, 16V and 16V), eight MOSFET IRF840 switches, and driver circuits for each MOSFETs, etc. DC power supplies are obtained through step down transformer, rectifier and regulator Integrated Chip (IC). The output of this circuit is used as DC supply source for the TLP250 IC which is the driver IC.

The pulses produced by the gate control circuit may not be able to turn on the switches if their amplitudes are less than a threshold value. So the pulses must be amplified and isolated before they are applied to the switches. The pulses generated through the pic16F877A through simple PWM technique are shown in Figure 14.The hardware implementation of the MLI with the resistive load of 100Ω, 1.7Amps is done. The output voltage across the load is observed and is shown in Figure 15.

7. Conclusion

Thus the development and design of quadratic buck-boost converter and six level Multi level inverter is proposed for the grid integration of solar array when there is high sunshine period. This system can be well utilized for grid connected hybrid renewable energy sources. Thereby demand of non-renewable energy sources can be reduced. The performance characteristics of QBBC with MPPT controller is found to be efficient compared to conventional DC-DC converters and can be installed where there is a wide variation in solar radiation.

8. References

1. Maksimovic D, Cuk S. Switching Converters with Wide DC Conversion Range. IEEE Transactions on Power Electronics. 1991; 6(1):151–57.
2. Franquelo LG, Rodriguez JL, Leon J, Kouro S, Portillo R, Prats MA. The age of multilevel converters arrives. IEEE Industrial Electronics Magazine. 2008; 2(2):28–39.
3. Rodriguez J, Lai JS, Peng FZ. Multilevel inverters: A survey of topologies, controls, and applications. IEEE Transactions on Industrial Electronics. 2002; 49(4):724–38.
4. De S, Banerjee D, Siva Kumar K, Gopakumar K, Ramchand R, Patel C. Multilevel inverters for Low-power application. IET Power Electronics. 2011; 4(4):384–92.
5. Malinowski M, Gopakumar K, Rodriguez J, Perez MA. A Survey on Cascaded Multilevel Inverters. IEEE Transactions on Industrial Electronics. 2010; 57(7):2197–206.
6. Cheng Y, Qian C, Crow ML, Pekarek S, Atcitty S. A comparison of diode-clamped and cascaded multilevel converters for a STATCOM with energy storage. IEEE Transactions on Industrial Electronics. 2006; 53(5):1512–21.
7. Ahmad RA, Mekhilef S, Ping HW. New Multilevel Inverter with reduced number of switches. Proceedings of the 14th International Middle East Power Systems Conference, MEPCON' 10, University of Malaya, Kuala Lampur: Malaysia.
8. Kavitha M, Arunkumar A, Gokulnath N, Arun S. New Cascaded H-Bridge Multilevel Inverter Topology with Reduced Number of Switches and Sources. IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE). 2012; 2(6):26–36.
9. Dogga S, Sumanth Kumar AV. A new nine level symmetrical inverter from seven level inverter. 2014 International Conference on Advances in Electrical Engineering, Vellore, TN, India, 2014. p. 1–8.
10. Nair R, Mahalakshmi R, Thampatty KCS**.** Performance of three phase 11-level inverter with reduced number of switches using different PWM techniques. 2015 International Conference on Advancement in Power and Energy (TAP energy); Kollam, Kerala, India. 2015. p. 375–80.
11. Gupta KK, Kumar L, Jain S. A new seven level hybrid inverter. 2012 International Conference on Computation of Power Electronics, Drives and Energy Systems (PEDES); Bengaluru, India. 2012. p. 45–58.

12. Laali S, Abbaszadeh K, Lesani H. Development of Multi-Carrier PWM for Multilevel Inverters. 2010 International Conference on Electrical Machines and Systems (ICEMS); Incheon. 2010. p. 77–81.
13. Tolbert LM, Peng FZ, Habetler TG. Multilevel PWM methods at low modulation indices. IEEE Transactions on Power Electronics. 2000;15(4):719–25.
14. Sedghi S, Dastfan A, Ahmadyfard A. A new multilevel carrier based pulse width modulation method for modular multilevel inverter. 2011 IEEE 8th International Conference on Power Electronics - ECCE; Asia, Jeju. 2011. p. 1432–39.
15. McGrath BP, Holmes DG. Multicarrier PWM strategies for multilevel inverters. IEEE Transactions on Industrial Electronics. 2002; 49 (4):858–67.
16. Tolbert LM, Habetler TG. Novel multilevel inverter carrier-based PWM method. IEEE Transactions on Industry Applications. 1999; 35(5):1098–107.
17. Nandurkar MSR, Rajeev MM, Lesani H. Design and simulation of three phase inverter for grid connected photovoltic systems. Proceedings of Third Biennial National Conference, NCNTE; 2012. p. 80–3.
18. Kim H, Sul SK. Analysis on Output LC Filters for PWM Inverters. IEEE 6th International Power Electronics and Motion Control Conference IPEMC '09; Wuhun, China. 2009. p. 384–9.
19. Jayaprakash S, Ramakrishnan V. A New Single-stage Solar Based Controlled Full-bridge DC-DC Converter. Indian Journal of Science and Technology. 2014; 7(9).
20. Mahalakshmi R, Manjunath HV, Thampatty KCS. Design and implementation of quadratic buck-boost converter for PV array. International Journal of Applied Engineering Research. 2015; 10:1023–34.
21. Rashid MH. Power Electronics - Circuits, Devices and Applications. 3rd ed. Prentice-Hall Inc.; 2003.
22. Umanand L. Power Electronics Essentials and Applications. 1st ed. Wiley India Pvt Ltd; 2009.