VIRTUAL AND HARDWARE PROTOTYPING OF A MODULAR MULTILEVEL INVERTER FOR PHOTOVOLTAICS

by

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Abstract

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This thesis details the idea of virtual and hardware prototyping of a distributed controlled multilevel inverter used as a grid-tie interface for photovoltaic. The system framework consists of multilevel inverters composed of solar panel array connected in series with the inverter module, enabling the use of renewable energy resources. The inverter module is built of buck-boost converter and a cascaded h-bridge inverter, which converts the obtained independent DC voltage source from each of the solar array to AC. With the increasing convenience of using a small photovoltaic grid for residential purposes, this system can be used to facilitate various DC appliances that require medium voltage and high power configurations. Moreover, the ability of multilevel inverter to operate at the switching frequencies higher as well as lower than the fundamental switching frequencies helps the user to control the total harmonic distortions by extracting the maximum power from each h-bridge inverter. A control algorithm allows the system to regulate at different output dc voltages obtained from the buck-boost converter and determine the switching times for the h-bridges in the grid-tie. The distributed inverter was evaluated by designing three to dozen inverter modules in the PLECS software. Further, for developing the hardware prototype, the buck – boost converter has been

tested using the perfboards and the breadboard. The framework, consisting of multilevel inverters, suggested that the total harmonic distortions can be reduced using this structure and therefore, we can integrate the solar arrays for electricity generation.

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Chapter 1

Introduction

The recent advances in the photovoltaic cells, its power electronics and its integration for the residential power plants or connecting it directly to the grid, the photovoltaic inverters must evolve as well. They must sustain the high power and high voltage ratings. A modular multilevel inverter that gives improved power conversion, reliability, modularity, scalability and smart grid functionality has been discussed in this thesis. The following chapter overlooks the motivation behind the thesis topic and explores the grid technology, inverter developments and also the challenges that led to these developments.

1.1 Motivation for Designing Modular Multilevel Inverter

Rising global energy consumption, demand for more energy, higher pollutants in the atmosphere and steady depletion of the natural resources have forced the researchers to find alternative, clean and cheap sources of energy. This has lead to re-designing and advancing the present technologies without compromising its efficiency and made to reduce the carbon footprints. Keeping that in mind, the grid technology has undergone significant changes. The conventional grid can now be controlled through a central location which is known as a smart grid. The smart grid, further, has seen developments in the form of micro grid. A typical micro grid in other words is an individual user's electricity grid by which he can generate his own energy.

These micro grids can support about 10KW of energy. A micro grid usually uses the renewable sources of energy such as solar energy, wind energy or fuel cells for the generation of electricity. These components are then integrated with an inverter module to convert the DC to AC. These residential micro grids can be used as standalone systems or can be connected to the PV grid.

The newer trends in the grid technologies are focusing on integration the renewable sources as energy sources. Also, in order to make the system more economical the DC side of these PV systems is operated at medium voltages for high voltage and high power configurations [25]. These trends require that the inverter design also change for providing the higher voltages and power. Multilevel inverters, that allows the use of IGBTs and diodes with less switching frequency and lower breakdown voltages thus are used. Such multilevel inverter is being used for this thesis.

1.2 Challenges in Designing Modular Multilevel Inverter

The inverter modules connecting the photovoltaic (PV) modules to the single phase or three phase grid and in the residential micro-grid configurations are known as the PV inverters. These PV inverters are functioned to extract maximum power from the connected PV modules, and if connected to the grid, they inject sinusoidal currents to the grid. The power inverters are classified into different inverter topologies depending on the number of power stages, position of the link capacitors and if they use a transformer or not. These considerations provided a basis for further developments in the PV inverter configurations and designs.

1.2.1 PV Inverter Configuration

The PV inverters have been classified on the number of power stages in the inverter module. There has been considerable evolution in the inverter configurations to enable the PV module to function at the maximum power point (MPP). The initial inverter configurations consisted of single stage inverters which are future developed as the two stage inverters.

1.2.1.1 Single Stage Inverters

The past technology of the inverter systems included a centralized single stage inverter [6], [7] which is as shown in Figure 1-1(a). An overview of the evolution of these PV inverters is been discussed in [7].

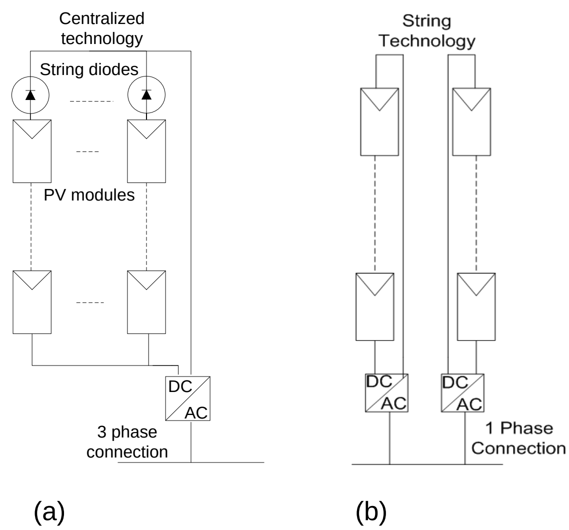


Figure 1-1 Single Stage Inverters (a) Centralized Inverter and (b) String Inverter [7]

The centralized inverters consisted of the PV modules in series connections for generating high voltages. For extracting high power levels, string diodes were used to connect these series PV modules in parallel. This configuration had considerable disadvantages of using high voltage connecting cables which limited the design expansion. The system had considerable MPPT losses, PV module mismatch losses and string diode losses. Also, the presence of higher current harmonics reduced the power quality.

The reduced centralized single stage inverter [6], [7] also known as string inverter was developed which is as shown in Figure 1-1(b) was thus later developed to increase the power quality of the system. In this configuration, each of the series connected PV modules was connected to the inverter by a string. These inverters had higher energy harvesting than the centralized inverters and also easier to configure. However, for obtaining a higher output voltage at normal operation, large number of PV modules needed to be connected in series. This increased the overall cost of the complete configuration.

1.2.1.2 Two Stage Inverters

In order to have a much better flexibility than that of the single stage inverter and the ability to enlarge the grid system, more developments in the inverter module have been carried out. This resulted in the development of two stage inverter [6], [7] configurations which are as shown in Figure 1-2.

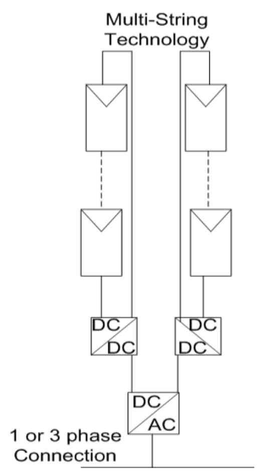


Figure 1-2 Two Stage Inverters [7]

Two stage inverters use fewer PV modules in series and also a DC/DC converter in between the PV modules and the inverter. The converter controls the MPPT and amplifies the PV module output voltage if it has a low DC output voltage. This configuration enables each PV module to have separate MPPT and has fewer losses as no string diodes are connected in the string. Therefore, the overall efficiency of the system is increased and the production cost is reduced.

Therefore, a two stage PV inverter configuration is considered in this thesis. The thesis framework includes a DC/DC converter connected in series with the PV module and each of such string is connected to the DC/AC inverter. The DC/DC converter handles the MPPT of the PV module and amplifies the voltage. The DC/AC inverter switches at the grid frequency and unfolds the sinusoidal wave to the grid.

1.2.2 PV Plant Design

A typical photovoltaic plant consists of the photovoltaic modules connected in series by a string and then connected to the inverter which are then connected to the grid or any other utility system through a transformer. This can be a single stage or a two stage inverter configuration.

The DC/AC PV inverter converts the input DC into output AC. Then the connected transformers are used to increase or decrease the obtained AC values.

The recent advancements in the PV plant suggest using a transformer-less system owing to the increased magnetic and ohmic losses of the transformer, their increased weight and size. The benefits of a transformer-less design are higher efficiency, lower weight and easier installation. They enable the connection of inverters in series or parallel thus, increasing the power output of the system. The ability to use other external control devices for controlling the plant ensures greater stability.

Therefore, a transformer-less PV inverter module has been used in this thesis. Several solar panels are connected in series with DC/DC converters and then with a cascaded H-bridge inverter for better controllability and efficiency of the system which are then connected directly to the grid or to other utility systems. The control techniques regulate the system at the desired output DC or AC voltage.

1.3 Description of Modular Multilevel Inverter

DC/AC inverters are required to switch at the desired switching frequency and then unfold the sinusoidal input DC voltage to the grid or the connected utility system. They are being used in several industrial applications. With the development of the GTO, SCR, triac, IGBT, BJT, MOSFET and other switching devices, the inverters were developed according these switches. Such configurations improved the output voltage ranges of the system with a lower THD. The most recent inverter techniques are the PWM technique and the multilevel inverter technique [3].

1.3.1 Multilevel Inverter

Multilevel inverter [24] is one of the most extensively used DC/AC inversion techniques in the photovoltaic grid applications. It is the development after the PWM inverters that use horizontal chopping of the reference waveform to achieve a similar output waveform. The advantages of the multilevel inverter are:

- Low switching frequency
- Low pulse height, therefore, low dv/dt
- Less harmonics
- Smooth switching, therefore, low switching losses
- Economical due to the simple control circuitry

Therefore, several types of multilevel inverters have been developed. One of the multilevel inverter types – cascaded multilevel inverter is used in this thesis. The ability of this type of inverter to function at medium voltage for high power applications makes our modular multilevel inverter system more efficient. This is because, our system voltage is around 155V, a medium voltage and we are configuring it for about 1.5KW.

1.3.2 Modular Multilevel Inverter

The thesis work explores the modular multilevel inverter [1] and is designed in PLECS following the work mentioned in [1]. Modular multilevel inverters have N individual inverter modules connected together in series and they communicate with each other for appropriate switching at particular frequency, phase and voltage. The inverter module consists of a DC input voltage source consisting of solar panels, a buck-boost converter which regulates the solar panel's output voltage and cascaded H-bridges. This configuration together creates a (2N+1) level modular multilevel inverter. The DC/DC converter enables to extract MPPT from each of the individual PV panel to improve the energy harvesting along with the voltage amplification. The output of this converter is then unfolded by the DC/AC inverter which switches at the grid frequency.

The control algorithm determines the voltage, from the converter output voltage, at which the system should work. It is dependent on the reference voltage of the system and also the number of the solar panels connected in series in the system. This algorithm also determines the switching frequencies at which the user must regulate the switches of the H-bridge inverter which is again dependent on the converter output voltage.

1.4 Research Contribution

1.4.1 Virtual Prototyping

In the proposed system we have designed a two stage modular multilevel inverter using PLECS. The two stage modular multilevel inverter includes an inverter module consisting of a solar panel connected in series with the buck-boost converter. The DC output of the solar panel is the input voltage to the buck-boost converter. For switching the MOSFET of the converter, we are using a closed loop design which uses a PID controller and a PWM. The pulse signals obtained from the PWM switch the MOSFET gates of the converter.

The DC/DC conversion is carried out using the non-inverting buck-boost converter and the DC/AC conversion is carried out by the cascaded H-bridge multilevel inverter. The switching of the H-bridge gate terminals, the IGBT's, is verified using three different switching techniques. The easier one – by using the combinatorial logic toolbox is used for the complete research work. Also, a particular switching frequency is used to trigger all the IGBT's such that the complete system always works in the conduction mode. The feasibility of selecting a switching frequency for each of the cascaded H-bridge inverter in a multi-level inverter at a frequency lesser or greater than the fundamental frequency enables a more convenient use for the user to control the total harmonic distortions observed in the system.

The system architecture is analyzed when it is connected to the grid as well as to the residential DC loads. When a micro-grid is connected to the residential DC loads, all the DC loads draws the required power from the energy sources, here, solar panels connected in series. Therefore, it is required that we can extract a maximum power from each of the solar panel modules, buck-boost converter and also from the cascaded H-bridge inverter. Considering this concept, we have also defined parameter values for each of the individual component in such a way that we get maximum power output from the modular multilevel inverter. The advantage of connecting the complete framework to the grid is that, in case of power fluctuations, power can be borrowed or made available for other users on the grid.

A multi-panel modular multilevel inverter system is being discussed which works efficiently in the boost mode, buck mode and the buck boost mode. The selection of the mode of the multilevel inverter depends on the output voltage of the buck-boost converter controlled by a control algorithm.

1.4.2 Experimental Testbed

For building the hardware prototype, experiments with the open loop buck-boost converter prototype have been carried out. For the experimental testbed, we have generated the gate input signal of 5V for switching the MOSFET using the microcontroller Arduino. The input signal of 18V is given through the regulated DC power supply.

1.5 Thesis Organization

In Chapter 1 we have discussed the motivation behind the thesis topic of deigning a modular multilevel inverter. It mentions the recent developments in the grid technology, converter configuration developments and the inverter developments. It explores the challenges for designing the modular multilevel inverter and sums up the system design going over the simulations and experimental overview of the entire thesis work.

The high level system design, description and modeling of all the parameters are discussed in Chapter 2. The functioning of the inverter module components like – buck-boost converter, H-bridge inverter and the cascaded H-bridge multilevel inverter and also the selection of the different parameters used for the virtual simulations and later for the hardware prototyping is discussed. This chapter also includes the time delay pattern and selection for the H-bridge switching.

Chapter 3 talks extensively about the complete system's virtual prototyping. The working of the proposed buck-boost mode multilevel inverter in boost mode and buck mode is explained in the system framework description. The different switching methods for the H-bridge inverter of the inverter module are mentioned. Once the inverter module components are designed, the multi-panel framework consisting of N inverter modules connected to the n solar panels in series is overviewed.

Chapter 4 covers the virtual prototyping results and discusses the hardware prototype implementation and some of the errors observed. The inverter module is simulated as a standalone system working in boost mode, buck mode and buck-boost mode. It is also tested for working in boost mode when it is simulated for a grid connected PV system. The hardware prototype for the buck-boost converter has also been discussed in this chapter.

Conclusions and the future work of the project are detailed in Chapter 5 which is concluded by a list of references.

Chapter 2

System Description & Modeling

The two stage inverter of the system discussed in the thesis includes a non-inverting buck-boost converter connected in series with each of the PV panel. It is used for the DC/DC conversion and a regulated output voltage is obtained which is then unfolded by the DC/AC inverter used in the circuit. A cascaded h-bridge inverter is used which is switched at the grid frequency. The framework is as seen in Figure 2-. These cascaded h-bridge inverters have been used as multilevel inverters. [11] – [18] has described various configurations of multilevel inverters.

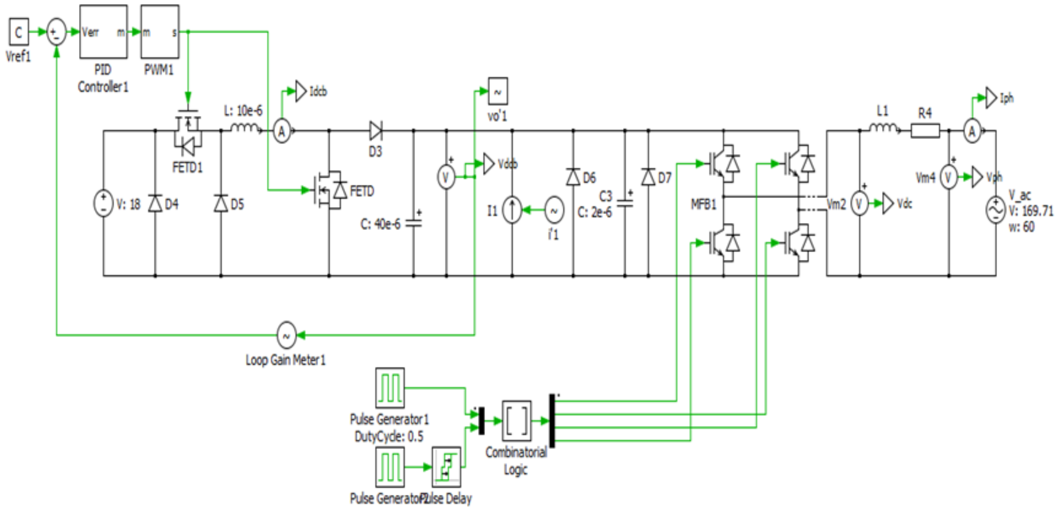


Figure 2-1 System Framework

The complete architecture is discussed by virtual prototyping [19]. The virtual prototype has been analyzed for the stand alone and the grid connected systems. A stand alone PV system's power capacity is sufficient for the working of the home which is about 10KW. The energy is generated using all the natural resources and the DC loads are run on it. The loads must be power rated for the connection to the system. Battery can be used to store the excessive amount of energy generated through this technique.

The designed framework is also checked by connecting it to the PV grid. Connection to the utility grid makes the micro grid available to other users as well. Also, if required, the user can obtain the energy from the grid as well.

The inverter module components are – solar panels, buck –boost converter and h-bridge inverter.

2.1 Buck-Boost Converter

A buck-boost converter is a type of a switched mode power supply that combines the principles of a Buck converter and a boost converter. These types of converters facilitate the user to use them for wide range of the voltages. It can be an inverting or a non-inverting converter. If, for an application, a positive output voltage is required, a non-inverting converter is used. An inverting gives the same output voltage as that of the non-inverting converter, but, with a negative polarity. The converter operates in three modes

Buck mode – if input voltage is higher than the reference voltage,

Boost mode – if input voltage is less than the reference voltage,

Buck-boost mode – if input voltage is similar to the reference voltage.

For our project we are using a non-inverting buck-boost converter with a same reference voltage for the both MOSFETs. These MOSFETs are high switching components which are controlled using a closed loop PID, PWM controller.

The converter can work in a continuous conduction mode or a discontinuous conduction mode. When the input voltage V1 is nearly equal to output voltage V2 the converter will be operated in the buck boost operation mode. The non-inverting buck-boost converter used in this thesis is as shown in Figure 2-2.

During the buck operation mode, the switch S2 is continuously open and so the diode D2.

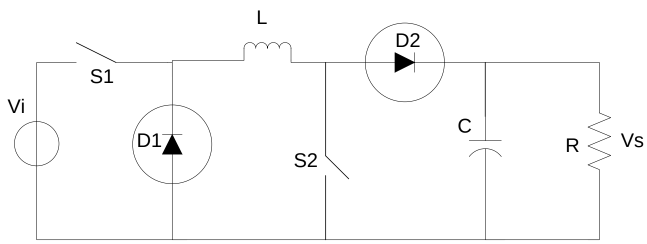


Figure 2-2 Non-Inverting Buck-Boost Converter [3]

During the boost operation mode, the switch S1 is continuously turned on and the diode D1 is constantly blocked.

During the buck-boost operation mode, both the switches S1 and S2 are on and off simultaneously [3]. When the switches are on, the inductor current increases by,

$$\Delta i_L = \frac{V_1}{L} kT.$$

When the switches are off, the inductor current decreases by,

$$\Delta i_L = \frac{V_2}{L}(1-k)T.$$

By the equating the equations forΔi_L, we get the output voltage by,

$$V_2 = \frac{k}{1-k} V_1.$$

When this converter works in buck operation mode and boost operation mode, its input current is discontinuous and hence the converter operates in discontinuous mode.

The input average power is,

$$P_{in} = \frac{I_{max}+I_{min}}{2} kV_1, \text{ and,}$$

the output power is,

$$P_o = \frac{V_2^2}{R}.$$

Other parameters are listed below,

$$I_{max} + I_{min} = \frac{2kV_1}{R(1-k)^2},$$

$$I_{min} = \frac{kV_1}{R(1-k)^2} - \frac{V_1}{2L}kT \text{ and}$$

$$I_{max} = \frac{kV_1}{R(1-k)^2} + \frac{V_1}{2L}kT.$$

Solving the above equations, the buck boost converter parameter values are found by the following equations as given in [3] are,

$$R = \frac{{V_2}^2}{100*n},$$

$$L_{min} = \frac{(1-k)^2}{2}t*R \text{ and}$$

$$C = \frac{2*t}{R}.$$

The ripple voltage Δv_c across the capacitor C is,

$$\Delta v_c = \frac{\Delta Q}{C} = \frac{kTI_2}{C} = \frac{kTV_2}{C} = \frac{k^2TV_1}{(1-k)RC}.$$

2.1.1 State Space Averaging

The modeling of the buck-boost converter can be done using the state space averaging technique [8]. This method enables the user to design the converter for a variety of inputs such as step, ramp or impulse function in which all the initial functions are also included. The switches are driven by a pulse sequence with a constant switching frequency.

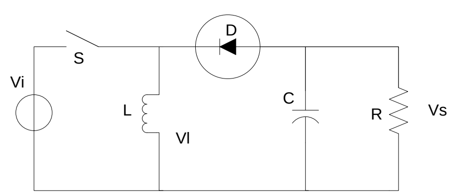


Figure 2-3 Buck-Boost Converter

A buck boost converter circuit is shown in Figure 2-3 and as explained in [8], the state vector for the buck-boost converter is defined as,

$$x(t) = \begin{bmatrix} I_L(t) \\ V_c(t) \end{bmatrix}, \text{ where,}$$

I_L = current through an inductor and

V_c = voltage across the capacitor.

For a given duty cycle, the state space equations in a continuous time domain are,

$$\dot{x}(t) = Ax(t) + BV_s(t) \text{ and}$$

$$y(t) = Cx(t) + DV_s(t), \text{ where,}$$

x is a state vector, V_s is a source vector, A, B, C, D is the state co-efficient matrices.

State model of the converter can be found out using its two operation modes as mentioned below,

Mode 1,

$$\dot{x}(t) = A_1x(t) + B_1V_s(t) \text{ and,}$$

Mode 2,

$$\dot{x}(t) = A_2x(t) + B_2V_s(t), \text{ where,}$$

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \text{ and } B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

The values of the state co-efficient matrices A and B can be found by using,

$$A = dA_1 + (1-d)\,A_2 \text{ and}$$

$$B = dB_1 + (1-d)\,B_2.$$

Therefore, the values of A and B are,

$$A = \begin{bmatrix} 0 & \frac{d-1}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} and\ B = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix}.$$

The state space model is of the following form,

$$\dot{x}(t) = \begin{bmatrix} 0 & \frac{d-1}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} [x] + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} [u] \text{ and}$$

$$Y = \begin{bmatrix} 0 & 1 \end{bmatrix} [x] + [0]\,[u].$$

2.1.2 Transfer Functions

The transfer functions of the buck-boost converter in CCM mode as mentioned in [8] are as given below,

Line-to-output transfer function is,

$$G_{vg}(s) = G_{g0} \frac{1}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)} \text{ and}$$

Control-to-output transfer function is,

$$G_{vd}(s) = G_{d0} \frac{\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)}, \text{ where,}$$

$$G_{g0} = -\frac{D}{1-D}, G_{d0} = \frac{V}{D(1-D)^2}, \omega_0 = \frac{1-D}{\sqrt{LC}}, Q = (1-D)R\sqrt{\frac{C}{L}}\, and\ \omega_z = \frac{(1-D)^2 R}{DL}$$

These plant transfer functions are then compared with the controller transfer functions to find the corresponding gain parameters.

2.1.3 Closed Loop Design

A typical closed loop of a plant is shown in Figure 2-4.

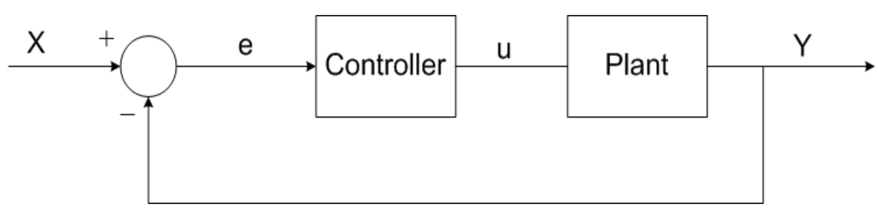


Figure 2-4 Buck-Boost Converter Closed Loop Block Diagram

For designing the closed loop buck-boost converter, the transfer function of the buck boost converter are compared with the control equation,

$$G(s) = K_d \, \frac{s^2 + \frac{K_p}{K_d} s + \frac{K_i}{K_d}}{s}.$$

Then, these two equations are solved for finding the gain parameters of the system. Specific gain values of the converter are selected as given in Table 2-1.

Table 2-1 PID Gain Parameters [9-10]

Parameter	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Kp	Decrease	Increase	Small Increase	Decrease	Degrade
Ki	Small Decrease	Increase	Increase	Large Decrease	Degrade
Kd	Small Decrease	Decrease	Decrease	Minor Change	Improve

2.2 H-Bridge Inverter

H-bridge inverter is used for the DC/AC conversions. It finds variety of applications in the DC/AC and AC/AC conversions. The inverter does not produce any power; the power is supplied by the DC source [3]. The further operation of the h-bridge inverter is explained in [20].

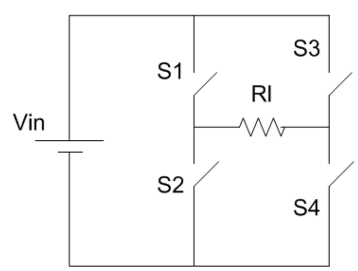


Figure 2-5 H-Bridge Inverter

Figure 2-5 shows a typical H-bridge inverter. It consists of four slow switching switches usually IGBT's. No two adjacent switches are allowed to switch at the same time. If occurred, this will create a short circuit in the system and a condition called as shoot through would be produced. The device would conduct when the switches S1 and

S4 are closed and S1 and S2 are open and vice-versa. However, if S1 and S2 or S3 and S4 are closed at the same time, a short circuit condition would occur.

2.2.1 Switching of the H-Bridge Inverter

The switching of the h-bridge inverter is controlled by turning on two switches at a time. The two signals 0 and 1, off and on, respectively are applied to the inverter. The truth table for the switching levels of the H-bridge inverter is shown in Table 2-2.

Table 2-2 H-Bridge Inverter Switching Levels

S1	S2	S3	S4	Level
1	0	0	1	1
0	1	1	0	-1
1	0	1	0	0
0	1	0	1	0

When the signal is 1, the inverter operates in a positive output condition (S1 and S4 are closed, S2 and S3 are open). When the signal is -1, the inverter operates in a reverse direction, negative output condition (S1 and S4 are open, S2 and S3 are closed). When the control signal is 0, the inverter operates in a bypass mode. This 0 signal mode can be a 0+ or a 0- condition, which again bypasses the inverter.

2.2.2 Dead-Time

During the turning on and turning off of the H-bridge inverter IGBTs, all of the transistors are conducting, that create a low resistance path for the current to flow to the ground. This induces harmonics, current and voltage spikes which might be destructive for the device. In order to avoid the shoot through occurrences in the H-bridge inverters, a delay is introduced in the rising edge of the signal which controls the IGBTs. This delay is known as the dead-time. The dead-time is dependent on the switching states of the inverter.

We have introduced the dead-time in the H-bridge inverter, by calculating the on and off times of the transistors by using the formula,

$$t = \frac{T^{ac}}{2\pi} \sin^{-1}\left(\frac{1}{N+1}\right),$$

where, T^{ac} is the grid period, N is the number of inverter modules and t is the delay time. The result of using the dead time in the H-bridge inverter is as shown in Figure 2-6. The lower waveform shows the desired delay in rise of the control signal.

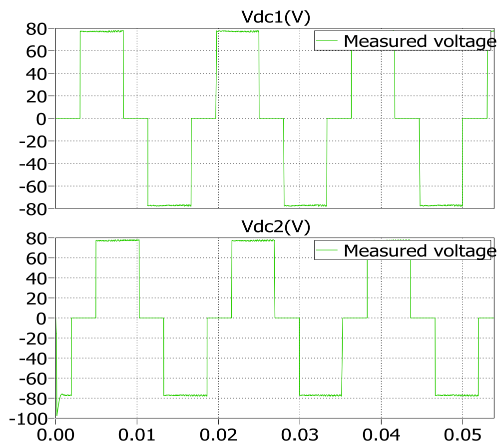


Figure 2-6 Time Delay

2.3 Cascaded H-Bridge Multilevel Inverter

One of the multilevel inverter types – cascaded multilevel inverter is used in this thesis. The ability of this type of inverter to function at medium voltage for high power applications makes our modular multilevel inverter system more efficient. This is because, our system voltage is around 155V, a medium voltage and we are configuring it for about 1.5KW.

The cascaded multilevel inverters are based on the connection of the H-bridges. Figure 2-7 shows a multilevel inverter with N number of H-bridges in phase. Each of the inverter is connected to an individual DC voltage source. The total system output voltage is given by the addition of each of the individual inverter voltages. When these individual voltages are same, the multilevel inverter is known as a cascaded H-bridge inverter.

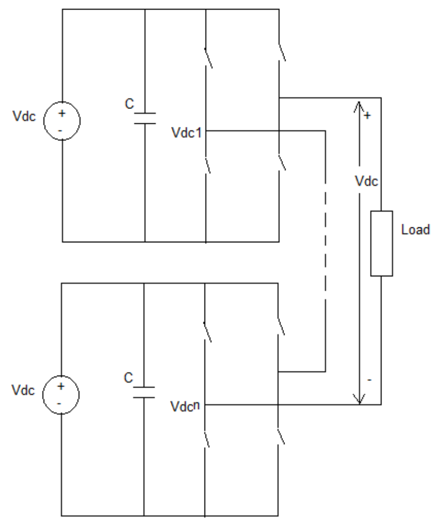


Figure 2-7 Cascaded H-Bridge Multilevel Inverter

The output voltage levels of the multilevel inverter is therefore given by the equation,

$$m = 2n + 1.$$

It is observed that only odd harmonic components are present in these configurations. Switching techniques of these inverters is same as that of the H-bridge inverter.

2.4 Selection of parameters

Selection of proper parameters improves the efficiency of the complete system. Some of the parameters taken into consideration for designing the prototype are mentioned in Table 2-3.

Table 2-3 Summary of Parameters Used in Simulations [1]

Parameter Name	Value
Buck-Boost Input Voltage	18V
Desired Buck-Boost Output Voltage	Vrms/n
Actual Buck-Boost Output Voltage	varies
Grid Period	0.0167s
Grid Frequency	60Hz
Desired Grid Voltage	120 Vrms
Actual Array Voltage	varies

While designing this virtual prototype, any particular MPPT scheme for the solar panels was not considered. Also, the issues like non uniform irradiance, common-mode voltage, floating panels, large leakage currents, and efficiency comparisons were not discussed. The solar panel configurations were used according to the Grape Solar Star solar panel rated for 100W. Its voltage and current at maximum power point is 18V and 5.56A respectively.

The solar panel is then connected in series with the buck boost converter. Therefore, the input voltage to the buck boost converter is same that of the solar panel output voltage of 18V. Desired buck-boost converter output voltage is Vrms/n, however, its actual output voltage is found to vary. Therefore, we have designed the buck-boost converter for 200V and 2A, considering the peak voltages. The voltage flowing through the system is about 155V. So, we are using the MOSFET switches to be rated at 200V and 20A. The power diodes used as protection as rated at 200V and 5A. The DC/DC converter enables us to use the switches with higher switching frequencies, so, we have using a high switching frequency of 100 KHz for the MOSFET. These switches are then protected using the schottky diodes.

The desired output voltage (Vref) of the buck boost converter is given by the Vrms/N. Vrms = Vp*√2 [1]. Therefore,

$$V_2 = \frac{110*\sqrt{2}}{n}.$$

Also, the duty cycle (k) of the buck-boost converter is (Vref/Vref+Vin) which is given by [1],

$$k = \frac{110*\sqrt{2}}{110*\sqrt{2}+ 18*n}.$$

The inverter is connected to the converter through a capacitor, called as a link capacitor. Selection of this link capacitance is of utmost importance while designing the PV system. As detailed in [4] and [5], the value of the link capacitor can be found out using the following equations,

$$C_{DC} = \frac{100*n}{2*\omega*V_{DC}*\Delta V_{DC}},$$

where, ΔV_{DC} is the ripple voltage of the system and is given by,

$$\Delta V_{DC} = \pm 10\% \ of \ V_{DC}.$$

The link capacitor is used as a buffer for the input-output power flow fluctuation. When the system is connected to the grid, ac currents are transmitted to the grid through the inverter. On the DC side, the PV array will change the output DC voltage. The link capacitor has to balance such current fluctuations and maintain the peak current values. If the fluctuations are more, the size of the capacitor is required to be increased, but, this would make the system more bulky and costly. Therefore, economical sizing of the link capacitor is required.

The DC/AC inverter has four IGBT switches. These are rated for high power about 1.5KW (same as the required module output voltage). The multilevel inverter enables the use of low switching devices such as IGBTs. Therefore, we have less breakdown voltage at the output. The load is also rated for high power ratings.

Chapter 3

Virtual Prototyping

This chapter covers the research work done in this thesis regarding the complete system's virtual prototyping. The working of the proposed buck-boost mode multilevel inverter in boost mode and buck mode and different switching methods for the H-bridge inverter is explained. The system architecture for multiple solar panels as individual energy source is also discussed.

3.1 System Framework

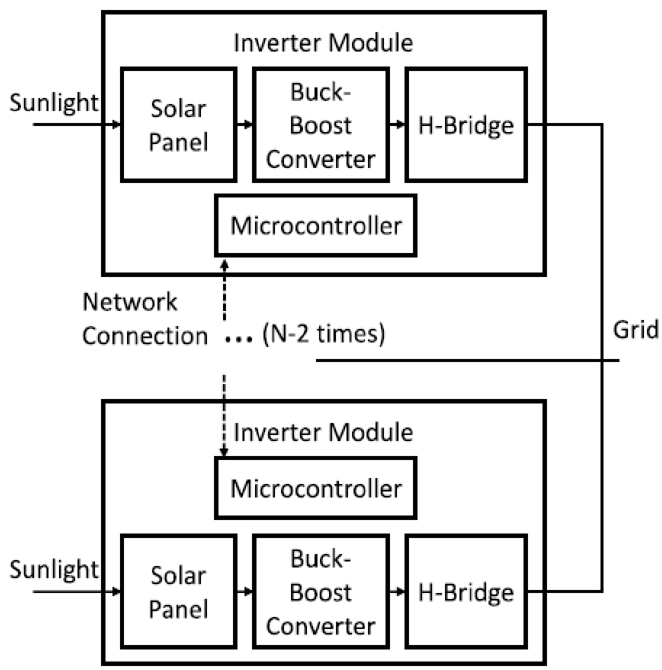


Figure 3-1 Modular Multilevel Inverter [1]

With the extensive research in the multilevel inverter modeling techniques, [1] mentions a modular multilevel inverter as shown in Figure 3-1. The inverter module consists of solar panels connected in series with the buck-boost converter which are then connected to the h-bridge inverter. This inverter module is connected to the grid and is also used as a standalone system for the residential systems. The inverter components are controlled and communicate with each other through the microcontrollers connected to each of the module.

Elaborate modular multilevel inverter architecture has been explained in [1] and its schematic is as shown in Figure 3-2.

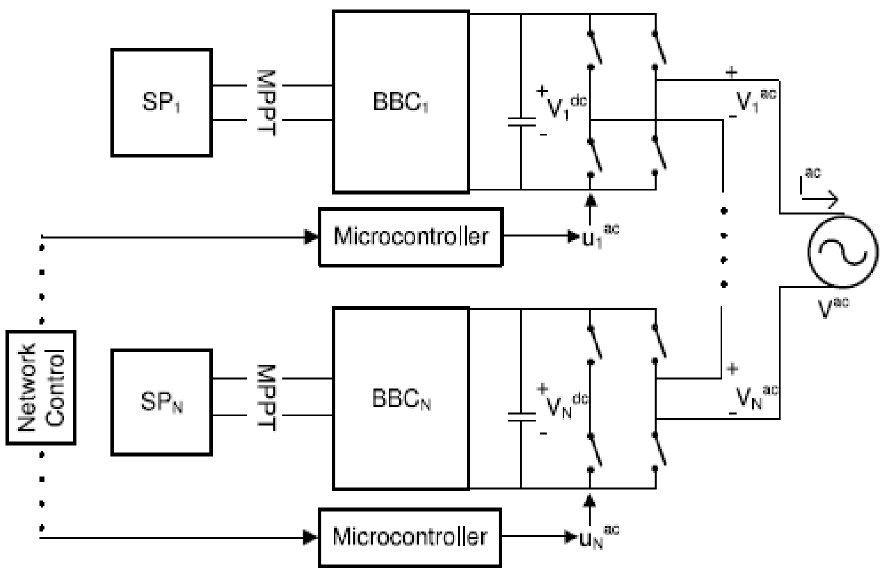


Figure 3-2 Elaborate Schematic of the Modular Multilevel Inverter [1]

According to this framework, the output voltage from the solar panel is given as an input to the buck boost converter. The output voltage of the converter is the DC voltage that is maintained in the link is the input voltage to the h-bridge inverter. The h-bridge switches are triggered at particular switching frequencies and give the corresponding AC output voltage. The network information about the number of panels being used is given by the network control via microcontroller.

The prototype has been designed using the software PLECS. PLECS gives the ability to the user to draw the exact schematics, the results of which can be analyzed using the scope. The scope gives the mean, min, max, THD values of the output waveform and also FFT waveforms are easily available on the scope. Moreover, it gives faster simulation results.

The modular multilevel inverter schematic designed using PLECS is shown in Figure 3-3.

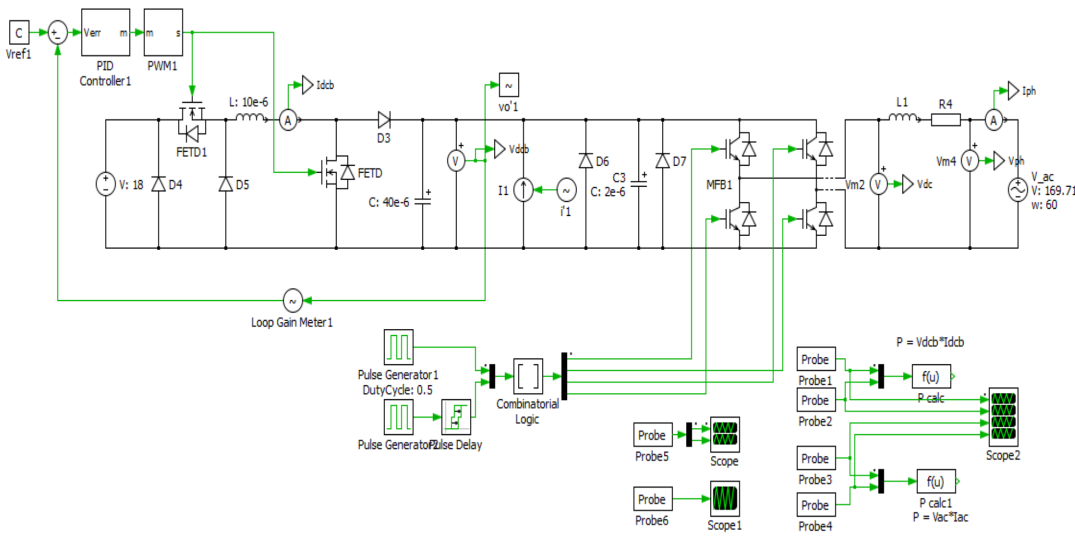


Figure 3-3 Modular Multilevel Inverter Schematic Using PLECS

This is a two stage inverter module circuit where the non-inverting buck-boost converter is used for DC/DC conversion and the H-Bridge inverter is used for the DC/AC conversion. The input voltage for the complete framework is set at 18V, which is the Grape Solar Star solar panel's maximum power point voltage. The input power for one panel configuration is 100W, same as the power rating of the solar panel. When we connect multiple solar panels (say n = number of solar panels) in series, the input power for the framework would be 100*n W.

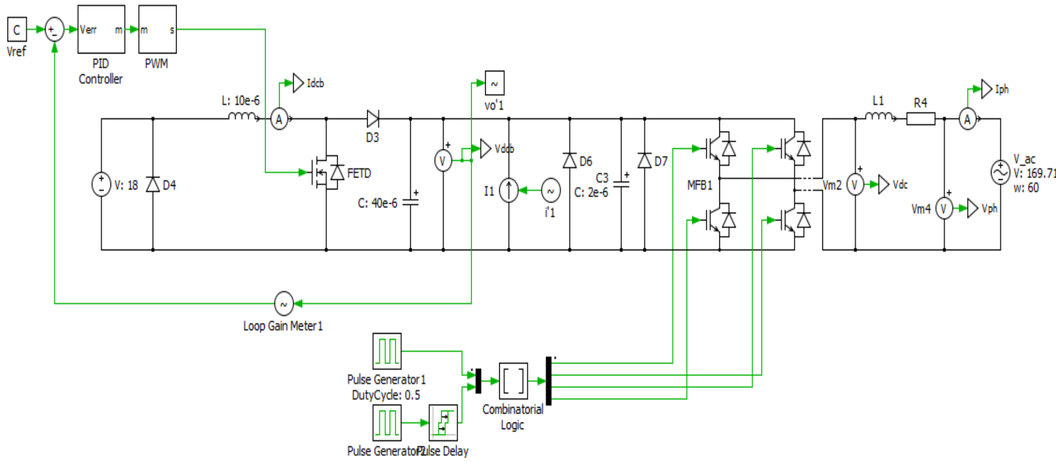
The output voltage of the solar panel is given as the input voltage (Vdc) to the non-inverting buck-boost converter. The converter is rated for 110V and the actual output voltage of the buck-boost converter varies. The obtained output voltage of the converter is given by Vref = Vp/N and Vp = Vrms*√2. For the closed loop modeling of the converter, the input voltage of the framework is compared with the reference voltage or the output voltage of the buck-boost converter. In this process, the reference signal is controlled using the PID controller. Using PWM, this controlled signal is used to generate pulse signals which are then compared to the input signal of the architecture. Whenever the input signal is less than the PWM signal, the system works in the boost mode, when it is greater than the PWM signal, it works in the buck mode and whenever both the signals are similar, i.e. the error signal is negligible; the system works in a buck-boost mode.

For DC/AC conversion, the output voltage from the buck-boost converter is given as the input voltage to the h-bridge inverter. With proper switching frequencies to the h-bridge inverter gate terminals, the DC signals are converted to AC.

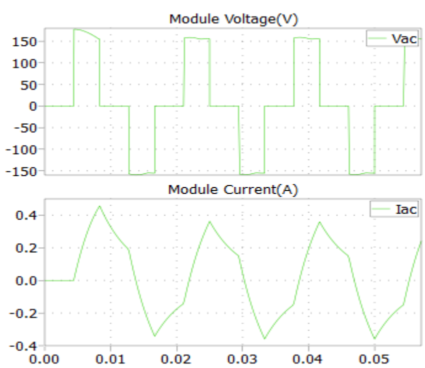
3.1.1 Boost Mode Modular Multilevel Inverter

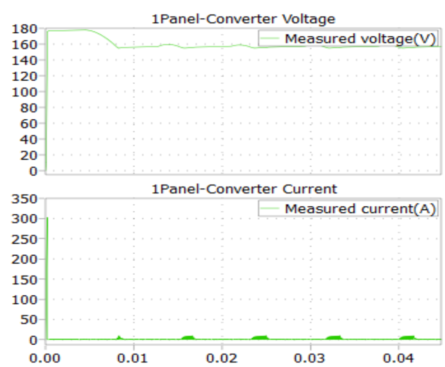
Using a non-inverting buck-boost converter enables a user to run the system in one particular mode and get the desired output voltage levels. Figure 3-4(a) shows the boost mode multilevel inverter. In this mode, the boost parameter conduct and the voltage is boosted to the desired output voltage.

Figure 3-4(b) shows the complete module output levels for the boost mode multilevel inverter and Figure 3-4(c) shows the output of the boost converter.



(a)



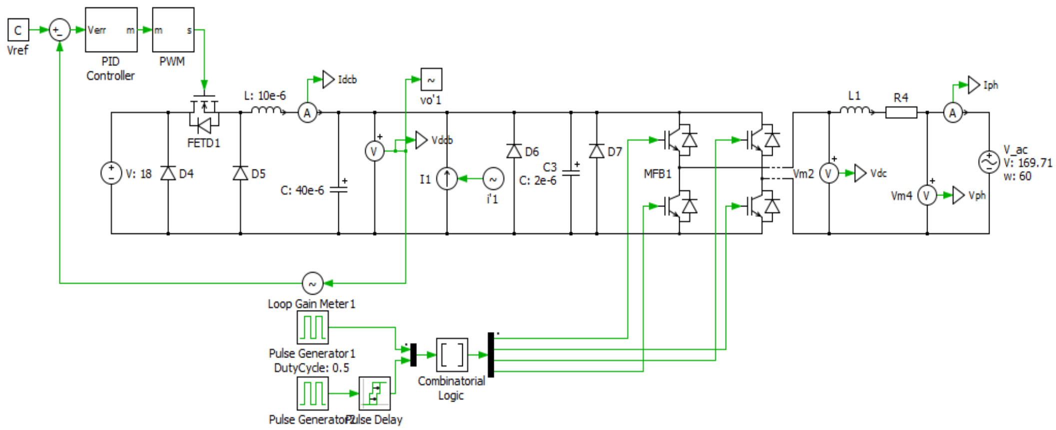


(b) (c)

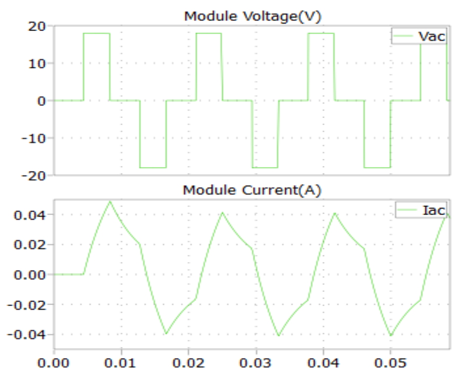
Figure 3-4 Boost Mode Schematics of (a) Modular Multilevel Inverter (b) Module Output and (c) Converter Output

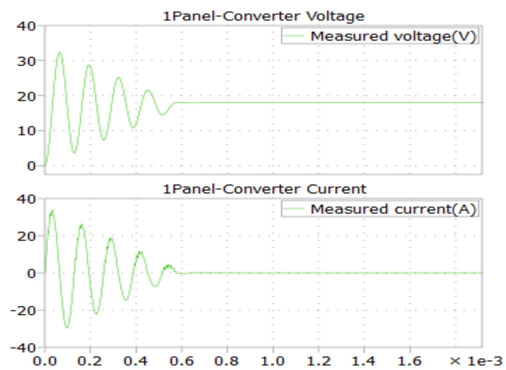
3.1.2 Buck Mode Modular Multilevel Inverter

The system architecture is also tested to work in the buck mode. Figure 3-5(a) shows its architecture. Here, the boost parameters are switched off and as the reference signal is less than the input signal, the converter output voltage is less than the reference voltage. The module output voltage levels for this configuration is shown in Figure 3-5(b) and Figure 3-5(c) shows the buck converter output voltage and current characteristics.



(a)





(b) (c)

Figure 3-5 Buck Mode Schematics of (a) Modular Multilevel Inverter (b) Module Output and (c) Converter Output

3.2 H-Bridge switching

The IGBT's of the cascaded h-bridge inverter are triggered in a particular sequence such that there is no short circuit or shoot through condition in the circuit. The inverter conducts for three levels (-1, 0 and +1). Following this flowchart, the switching times for the switches Sw1, Sw4, Sw2, Sw3 would be [1 1 0 0; 0 0 1 1; 1 0 1 0; 0 1 0 1].

Three gate signal triggering mechanisms are studied for the given framework.

3.2.1 Individual Switching Signals

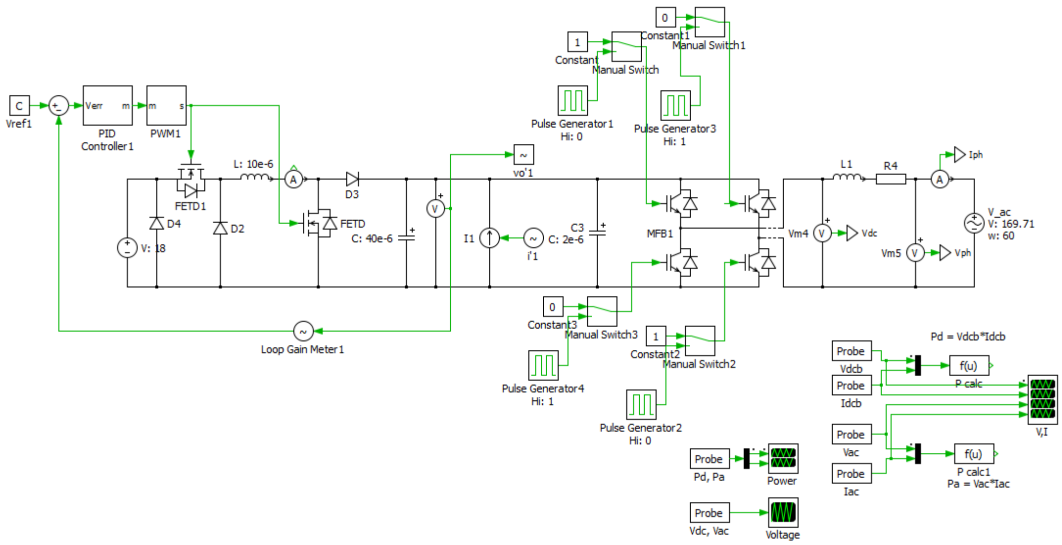
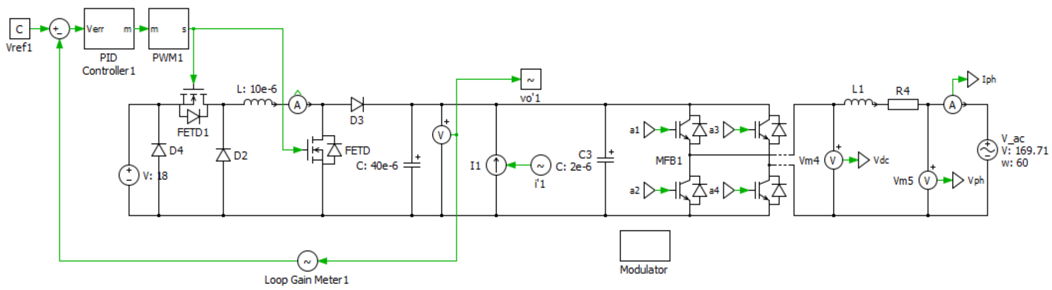


Figure 3-6 H-Bridge Inverter Switching with Individual Switching Signals

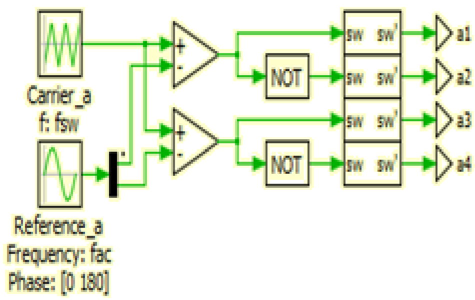
In the individual input signal triggering, each gate is given one signal at a time from each individual pulse generators. Therefore, there would four such input signal generators with a specific pulse signal voltage value and frequency as shown in Figure 3-6. The benefit of using this scheme is ease of its use and implementation avoiding use of any complex logic circuits.

3.2.2 Modulator

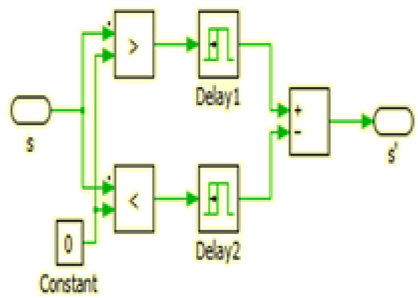
The second H-Bridge triggering mechanism uses a modular as shown in Figure 3-7(a), where there is separate logic gate schematic for each of the four input terminals. There are two input signals for each of the gate terminal with some phase difference. These two input signals are compared for polarity and then with a specific time delay are fed to the gate terminals of the inverter. The mechanism is further explained in Figure 3-7(b) and Figure 3-7(c).



(a)



(b)



(c)

Figure 3-7 H-Bridge Inverter Switching Schematic showing (a) Modulator (b) Modulator Inputs and (c) Time Delay

3.2.3 Combinatorial Logic

The third method of H-Bridge triggering used is by using the combinatorial logic as shown in Figure 3-8.

PLECS facilitates the use of the combinatorial logic toolbox by using the binary input signals to select one row from the truth table as explained in [2]. The output truth table would be [1 1 0 0; 0 0 1 1; 1 0 1 0; 0 1 0 1] where the outputs of the combinatorial block are [1 1 0 0] [0 0 1 1] [1 0 1 0] [0 1 0 1]. These signals are then given as input to all the four gate terminals Sw1, Sw4, Sw2 and Sw3 one at a time in a continuous pattern. The phase delay in the generator signal makes it possible for the system to generate the different voltage levels.

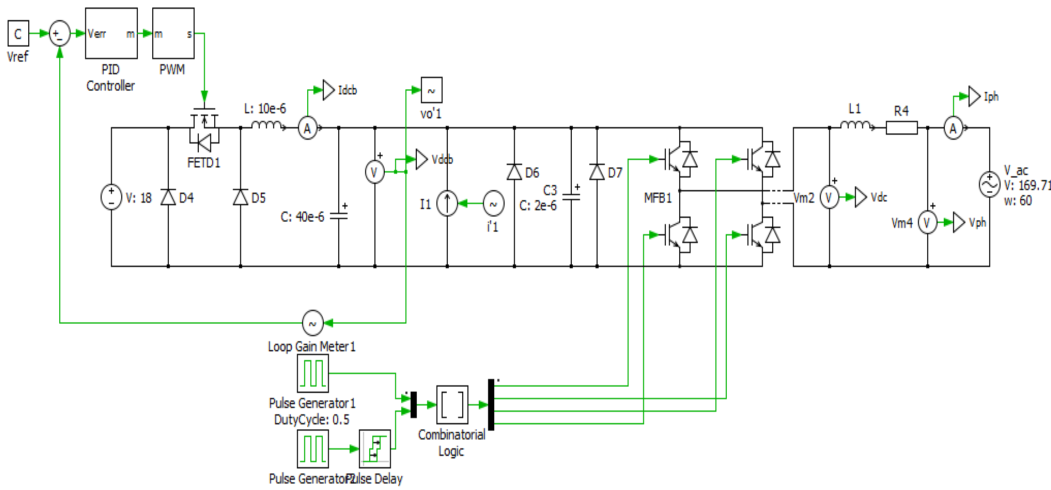


Figure 3-8 H-Bridge Inverter Switching Using Combinatorial Logic

3.3 Multi-panel framework

The complete modular inverter is now tested for the multilevel inverter. In this multilevel inverter scheme each of the solar panel and the inverter module communicate with each other via the network signals and the microcontrollers. Figure 3-9 below shows a two panel modular multilevel inverter. Similarly, higher panel multilevel inverters are designed and tested. It is observed that the output voltage across each of the individual modules equals the total system output voltage. While switching these multi-panel inverters, the adjacent gate signals are not given the same input signals. In other words, each of the H-bridge inverter is triggered in the same way the one panel was triggered. It takes care of the short circuit or the shoot through conditions of the H-bridge inverter.

In these configurations, the output voltage of each of the buck-boost converter becomes Vp/n, therefore, the reference voltage across each converter panel would be Vref/n. The complete module output voltage levels follow the scheme of (2N+1) where N is the number of cascaded H-bridge inverters in the framework.

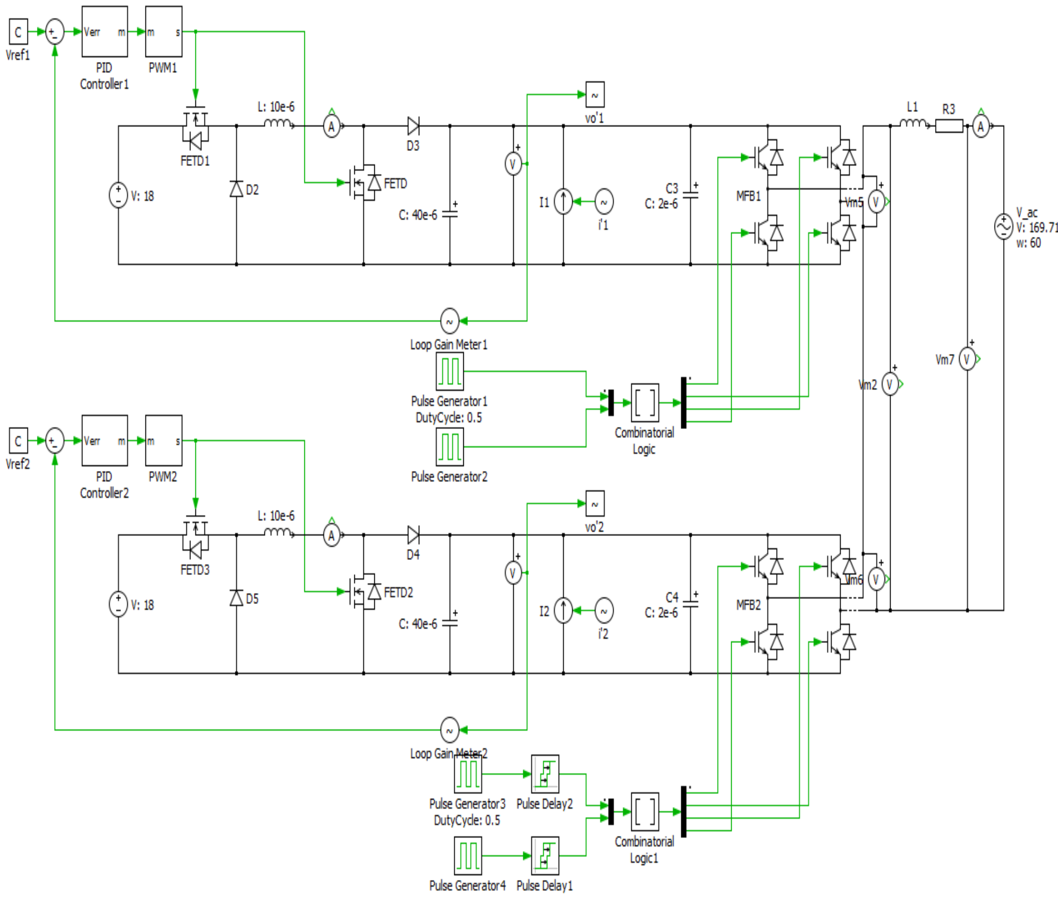


Figure 3-9 Two Panel Modular Multilevel Inverter

Chapter 4

Simulation Results & Hardware Prototyping

In this thesis we have designed a modular multilevel inverter using the power electronics design software, PLECS. The proposed inverter module has been tested for multiple solar panel configurations by using the multilevel inverter concept, thus, called modular multilevel inverter. The inverter module has been tested as a standalone system for the residential PV system and also by connecting it to the grid. These simulation results are tabulated in the following chapter. This chapter also explains some of the hardware prototype testing results.

4.1 PV Inverter Module as a Standalone System

The modular multilevel inverter structure was tested for the PV inverter system as a standalone system for residential applications. In this scheme, for less wattage configuration, generally less than 10KW, the residential PV system is sufficient enough to run the household loads. In order to extract most of the power from the connected components, they were designed taking into consideration all the design and energy harvesting parameters.

The typical residential stand alone power system consisting of the DC loads directly connected to the PV inverter module has been analyzed using the Figure 4-1.

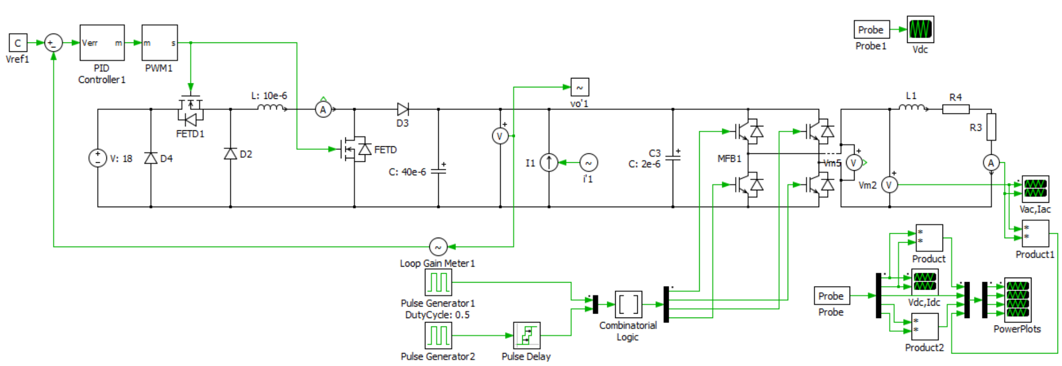


Figure 4-1 PV Inverter Module Connected to the DC Load

The output of this system is shown in the Figure 4-2. Upper section of this plot shows the output voltage of the complete inverter module. The output voltage has 3 levels (2n+1), as given by the output levels of the multilevel inverter. Here, n = 1. The output voltage of the complete configuration is found to be same as that of the desired output voltage. The lower section of this plot shows the current values for this configuration. For obtaining, high power outputs, this single panel framework has been connected with more such panel frameworks in series. This system has same voltages across each of the individual panels. This will increase the voltage and the power rating of each of the panel configurations. Also, the advantage of such series connections enables the use of renewable energy sources in the framework. Depending on the output voltage range, the framework regulates in either of the boost, buck-boost or buck mode.

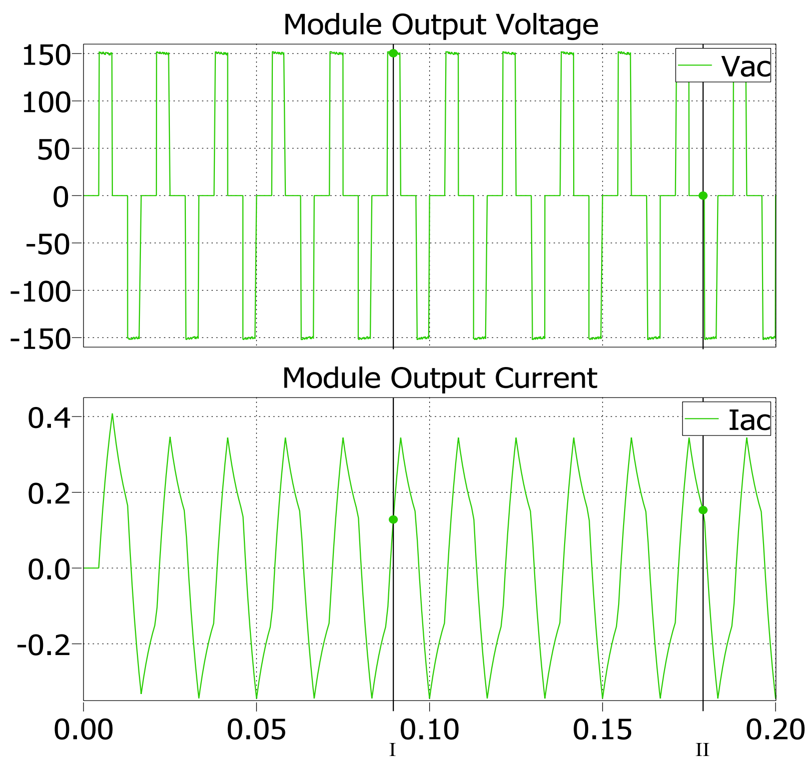


Figure 4-2 Modular Multilevel Inverter with 3 Output Levels

4.1.1 Module in Boost Mode

This framework is then connected in series with other solar panels in order to test the working of the multilevel inverters. The values of solar panels (n) have been varied to get the necessary output voltage levels. For a 5 level output voltage multilevel inverter, two solar panels are connected in series (n =2). Figure 4-3(a) shows this result. It is also found that the total output voltage of the multilevel inverter framework is the sum of the individual voltages found across each of the solar panel module. Figure 4-3(b) shows that the total system voltage is the sum of the individual voltages across each of the panel.

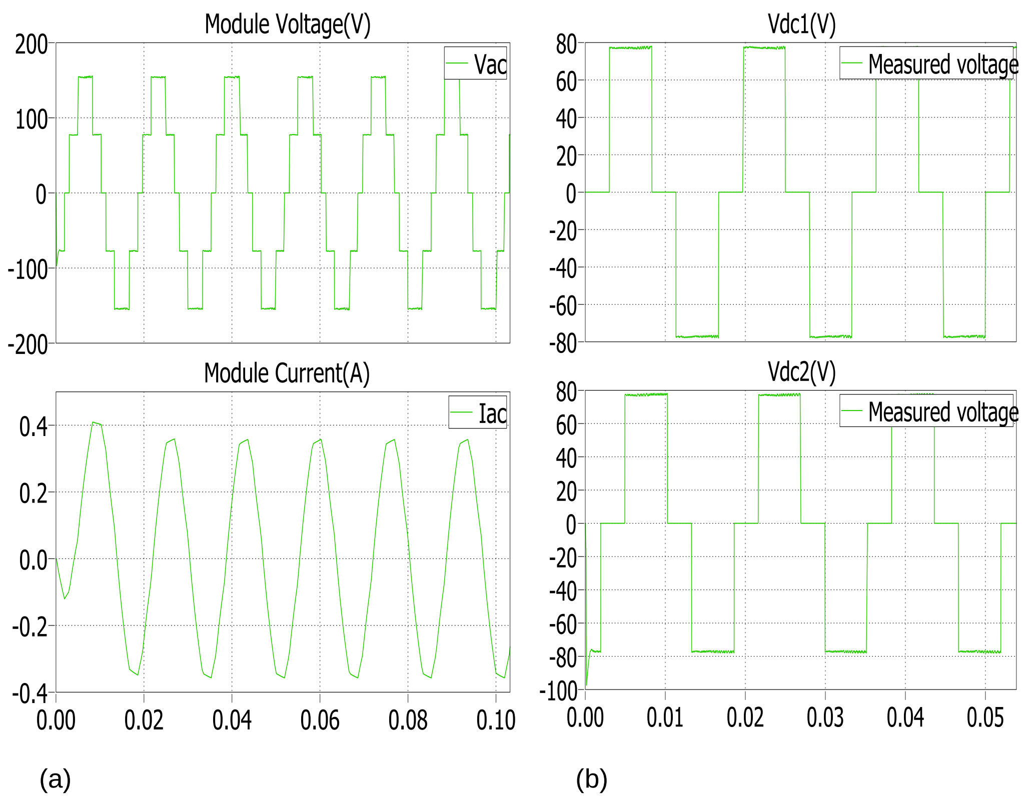


Figure 4-3 (a) Modular Multilevel Inverter with 5 Output Levels and (b) Individual Panel Voltages for a 5 Level Modular Multilevel Inverter

Similarly, when three solar panels are connected in series (n = 3), we get the results as shown in Figure 4-4. Figure 4-4(a) show the total output voltage levels for a 7 level multilevel inverter and Figure 4-4(b) shows the individual output voltages across each of the solar panel.

As long as the reference voltage remains greater than the input voltage, the complete system works in the boost mode. Here, we are considering the input voltage to be 18V and the reference voltage is the output voltage of the buck-boost converter (155.56/n). Therefore, whenever, the reference voltage is greater than 18V, the system works in boost mode, and, when the reference voltage becomes less than the input voltage, the framework works in the buck mode. It works in buck-boost mode when the reference voltage is similar to the input voltage.

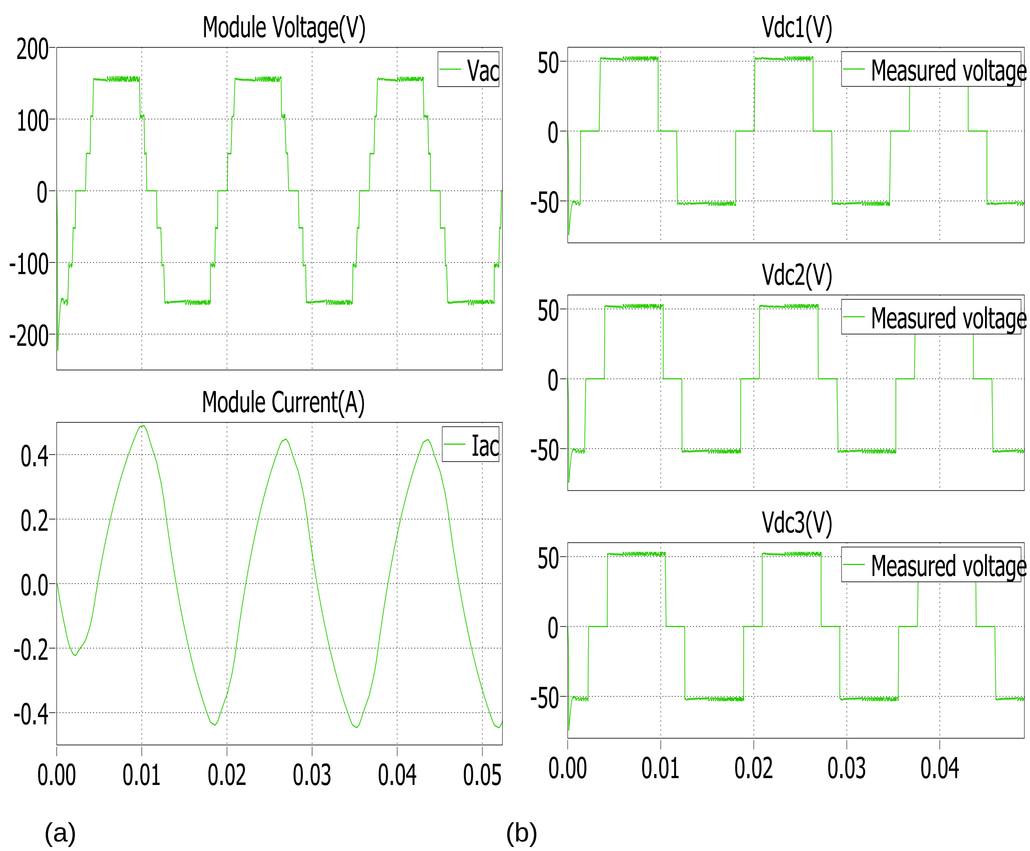


Figure 4-4 (a) Modular Multilevel Inverter with 7 Output Levels and (b) Individual Panel Voltages for a 7 Level Modular Multilevel Inverter

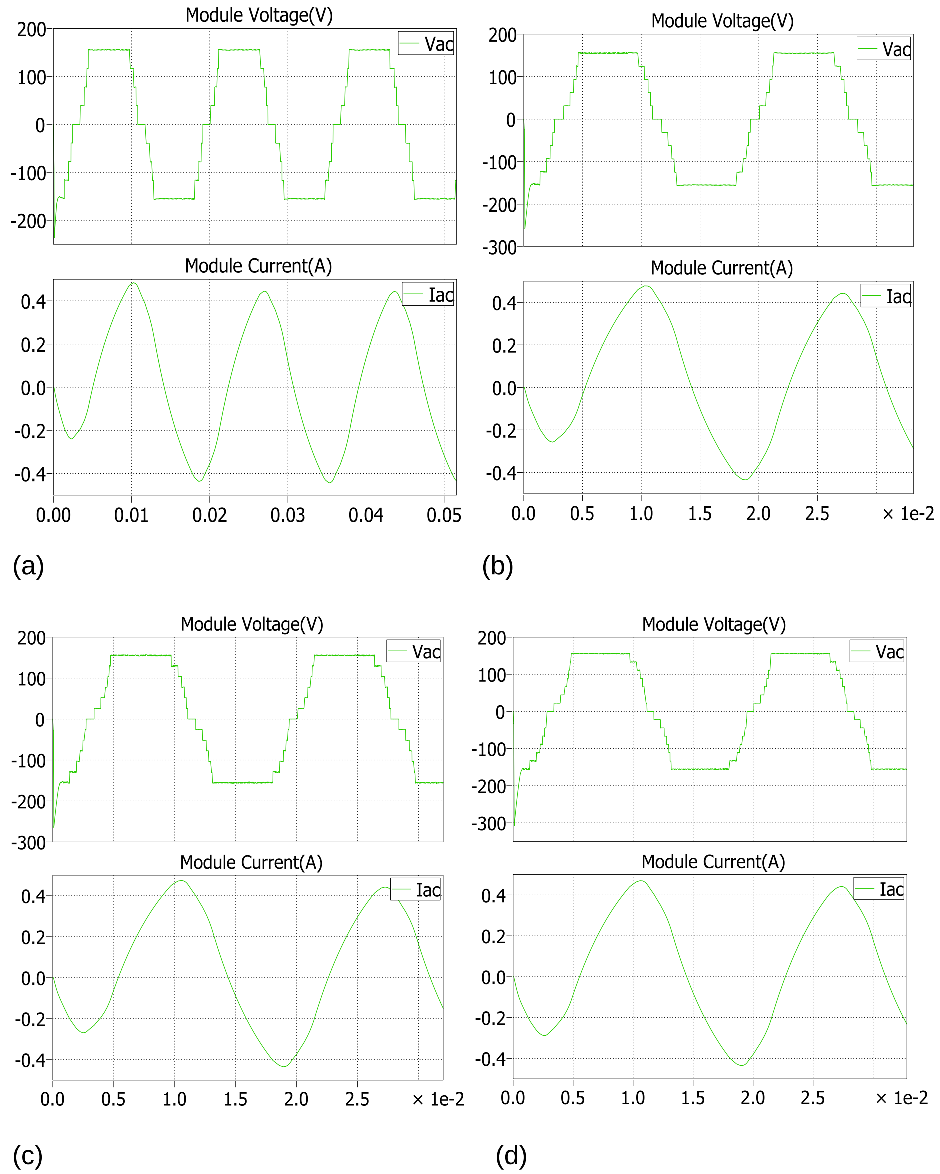


Figure 4-5 Modular Multilevel Inverter with (a) 9 Output Levels (b) 11 Output Levels (c) 13 Output Levels and (d) 13 Output Levels

For n = 1 to 7, the system works in boost mode. It is seen that the output voltage divided equally among all the individual panels. Figure 4-5 shows the output voltages of the architecture in the boost mode. These output levels in Figure 4-5 (a), (b), (c) and (d) depict the configuration for 9, 11, 13 and 15 levels respectively.

4.1.2 Module in Buck-Boost Mode

As soon as the reference voltage is same as that of the input voltage, the inverter system behaves in the buck-boost mode. Here, when the eight or nine solar panels are connected in series, the reference voltage is similar to that of the input voltage. Figure 4-6 shoes the output levels of a 17 level multilevel inverter. It behaves in the buck-boost mode.

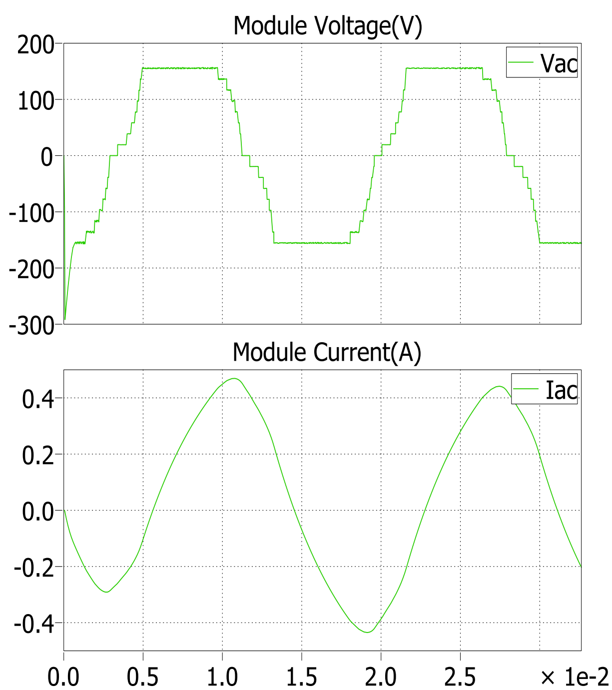
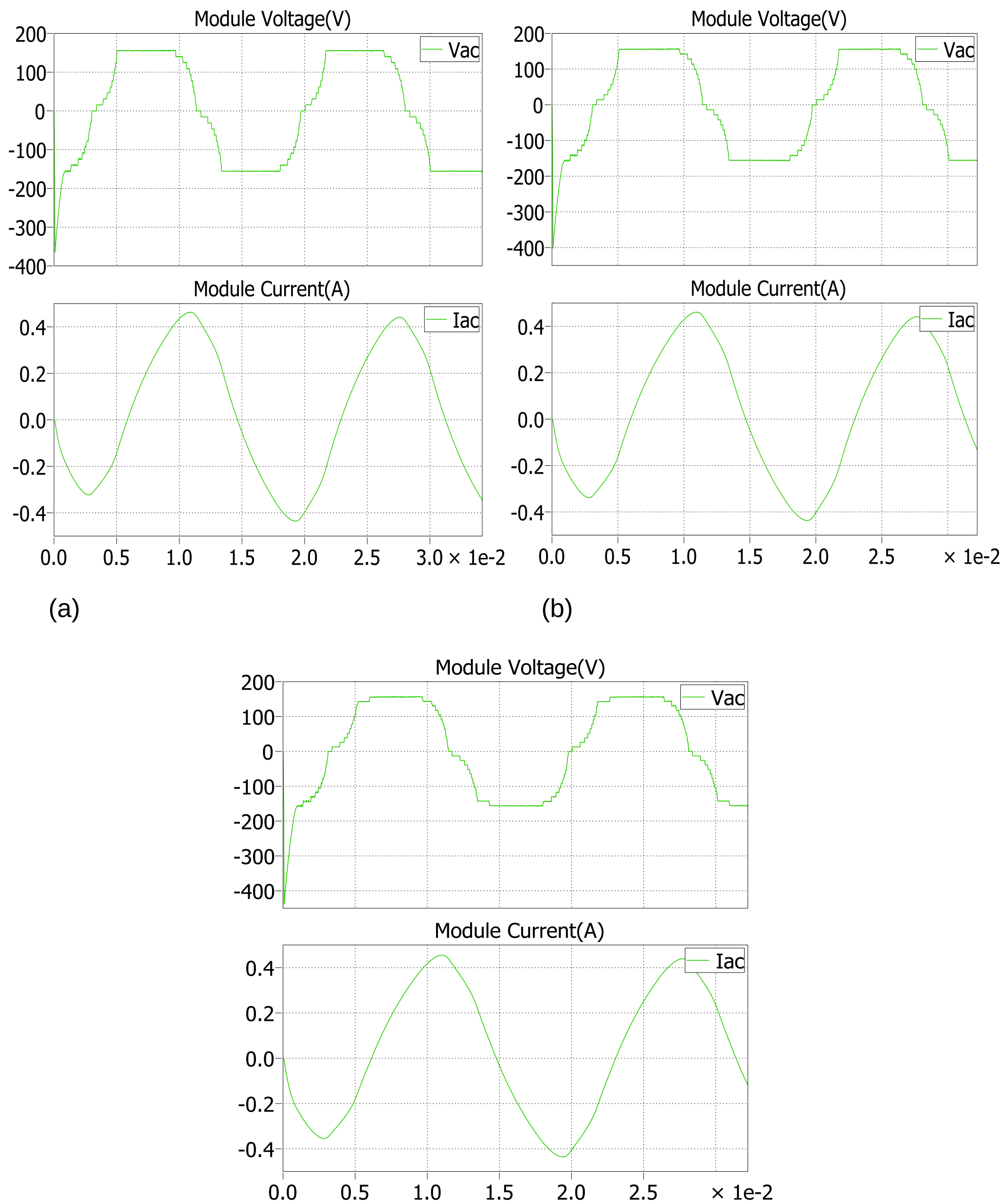


Figure 4-6 Modular Multilevel Inverter with 17 Output Levels

4.1.3 Module in Buck Mode

The modeled prototype was also tested for its working in the buck mode. Whenever we use ten or more solar panels in series, the reference voltage is less than that of the input voltage; it works in the buck mode. Figure 4-7 show output voltage levels of the buck mode modular multilevel inverter. It is also seen that the individual voltage sources sum up to the output voltage of the system.



(a) (b)

(c)

Figure 4-7 Modular Multilevel Inverter with (a) 21 Output Levels (b) 23 Output Levels and (c) 25 Output Levels

4.2 PV Inverter Module Connected to the Grid

The modular multilevel inverter structure was also tested for the PV inverter system connected to the grid. In this scheme, for higher wattage configuration, generally more than 10KW, the residential PV system connected to the grid facilitates the transfer of energy. If the required wattage is less than that of the generation, energy from the grid can be utilized. Similarly, if more energy is generated in the system, it can be transferred to the grid and made available for other consumers.

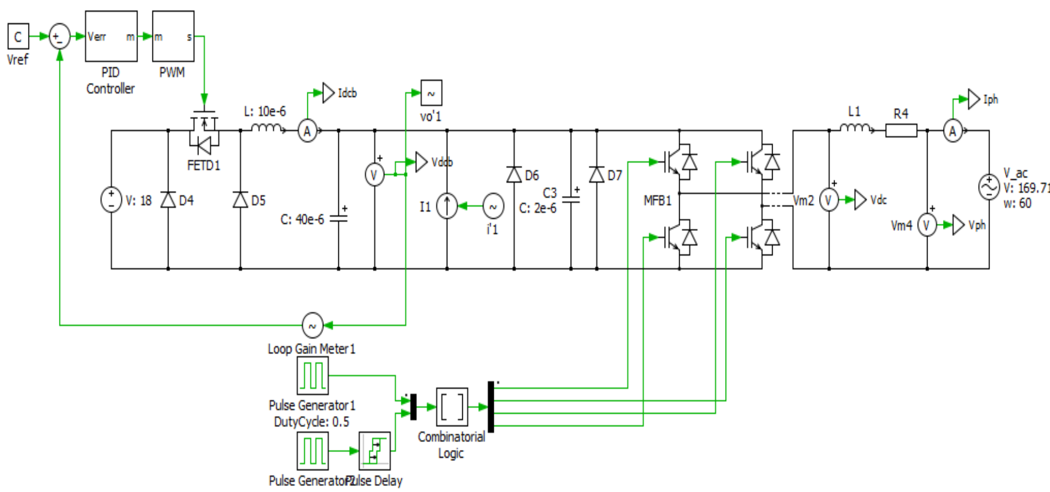


Figure 4-8 PV Inverter Module Connected to the Grid

A typical residential PV system connected to the grid is shown in Figure 4-8. The modular multilevel inverter scheme was tested for the multi-panel configurations as well. The complete module output, individual panel output was analyzed according to the output levels of a typical multilevel inverter values. The three level output voltage of the multilevel is shown in Figure 4-9. This one panel configuration's DC voltage level as well as the AC voltage is seen to be in sync with each other as expected.

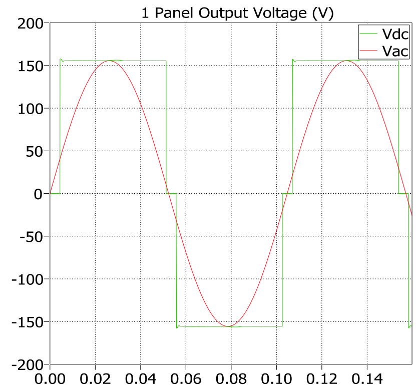
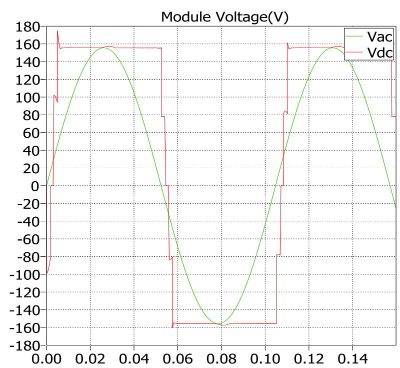
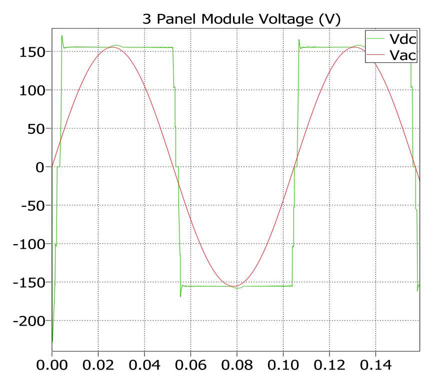


Figure 4-9 Modular Multilevel Inverter Connected to Grid with 3 Output Levels

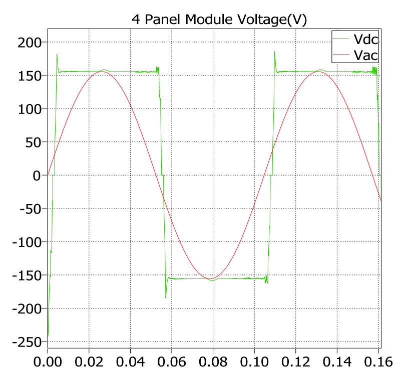
4.2.1 Module in Boost Mode



(a)



(b)



(c)

Figure 4-10 Boost Mode Modular Multilevel Inverter Connected to Grid with (a) 5 Output Levels (b) 7 Output Levels and (c) 9 Output Levels

Again, the complete multi-panel multilevel inverter architecture was analyzed for boost mode, buck-boost mode and buck mode. Figure 4-9 show the results of the multi-panel multilevel inverter configuration results. These modules work in the boost mode with the corresponding output voltage levels. However, in these results; as the system is connected to the grid, some harmonic distortions some seen in the system.

4.3 Hardware Prototyping

After extensive virtual prototyping, hardware prototyping of the converters is being carried out to check the parameter values. This section explains about the hardware implementation of the system and the steps involved for the testing of the framework.

4.3.1 Generation of Input Signal

An unregulated DC power supply's voltage output changes directly with the change in the input AC voltage. Also, the output voltage changes with the change in load. Moreover, presence of AC components due to direct connection to the AC power source induces pulsations in the output waveform. Hence, using an unregulated DC power supply has its limitations. Therefore, a regulated DC power supply, which maintains a constant output voltage irrespective of the change in the AC input signals or load variations, is used in this experiment. The input of 18V is supplied through the regulated DC source and the complete setup output is obtained on the oscilloscope.

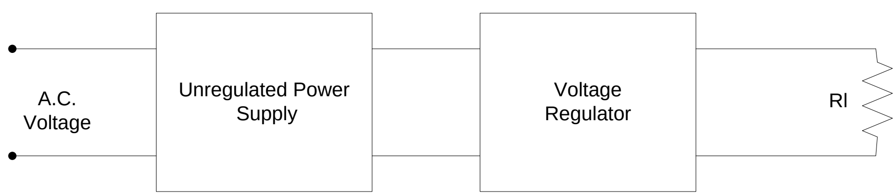
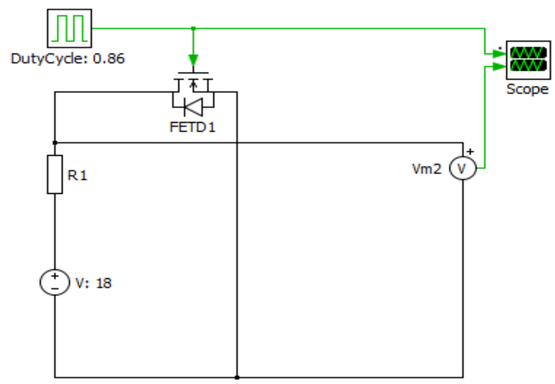


Figure 4-11 Block Diagram of Regulated Power Supply

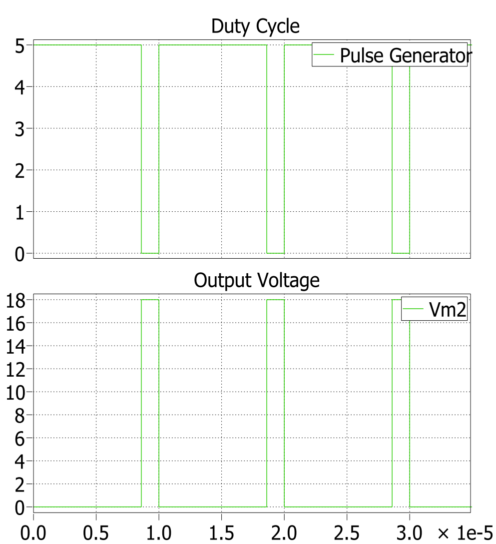
A regulated power supply is shown in the Figure 4-11. It consists of an ordinary power supply, the output of which is fed to the connected voltage regulating device.

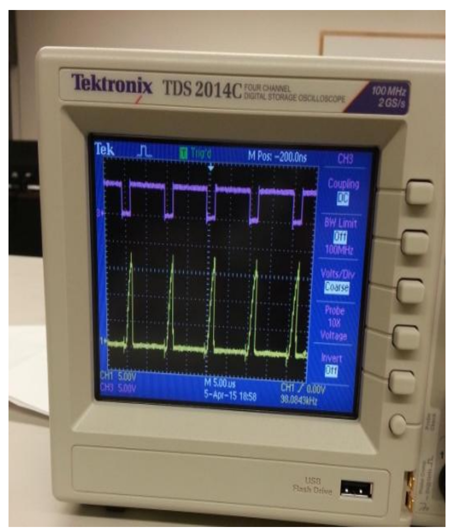
Practically, the internal resistance of an unregulated power supply is large which affects the load current drawn from the supply. These DC variations are regulated by the voltage regulator that gives a final constant output voltage. Thus, using a regulated DC power supply reduces the erratic operation of the electronic circuit.

4.3.2 Generation of Duty Cycle



(a)





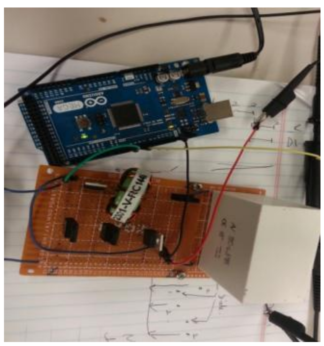
(b) (c)

Figure 4-12 Models of (a) MOSFET Schematic (b) MOSFET Schematic Simulation Output and (c) MOSFET Hardware Output

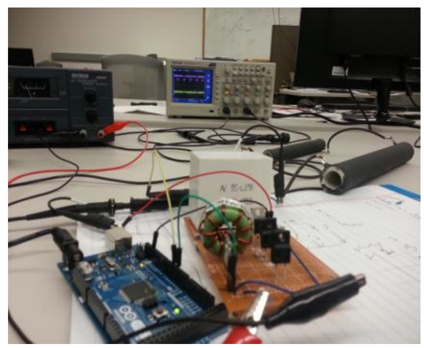
The generation of the duty cycle for the MOSFET has been carried out using the schematic shown in Figure 4-12(a). An output graph similar to the simulation output graph as shown in Figure 4-12(b) is obtained that is shown in Figure 4-12(c). From these graphs we observed that the duty cycle (purple waveform) and the system input voltage (yellow waveform) are same as the simulation results.

The MOSFET has been rated for the output voltages and currents flowing through the buck-boost converter circuit having a rating of 200V and 2A. The duty cycle input of 5V (purple waveform) is given through the microcontroller; setting it at 86% with the switching of 100KHz. Output is obtained through Arduino's Port E (pins 2-7).

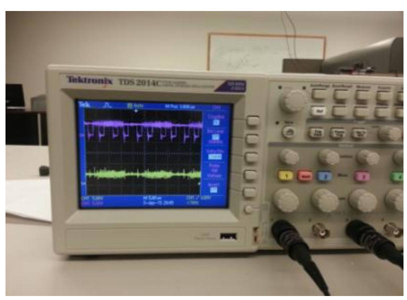
4.3.3 Testing of Non-Inverting Buck-Boost Converter



(a)



(b)



(c)

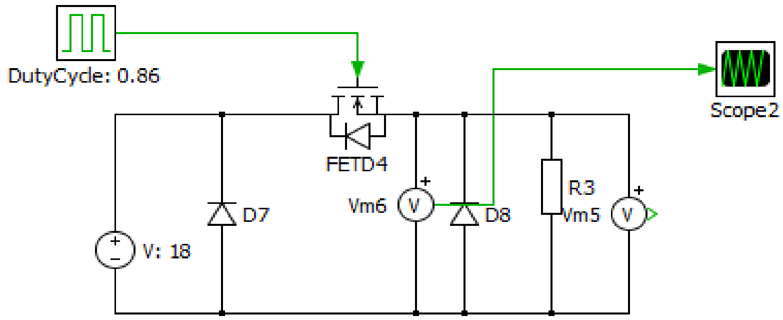
Figure 4-13 Snapshots of (a) Non-Inverting Buck-Boost Converter and Arduino (b) Buck – Boost Converter Hardware Prototype (c) Converter Output Waveforms

Thereafter, the non-inverting buck-boost converter was tested. The input voltage from the microcontroller was given to the gate signals of both the MOSFETs. Three load resistors with sufficient power rating have been used. Figure 4-13(a) shows the non-inverting buck-boost converter hardware schematic along with the Arduino used for generating the duty cycle input signal while Figure 4-13(b) shows the complete setup of the prototype.

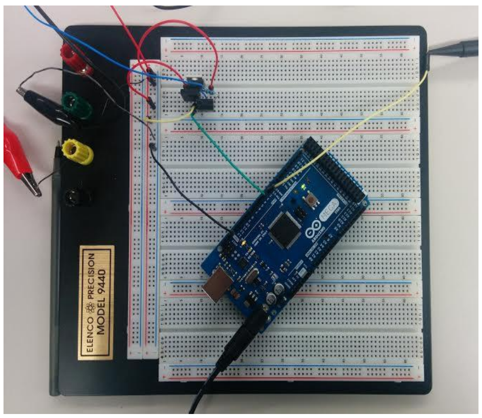
From the output waveform Figure 4-13(c), it is observed that even though the MOSFETs have been triggered properly (purple waveform), the converter is not working as expected. The desired waveform is around 155V (complete system voltage), but, we can see spikes in the obtained output voltage waveform (yellow waveform) and it is not set at the required output voltage obtained from the simulations.

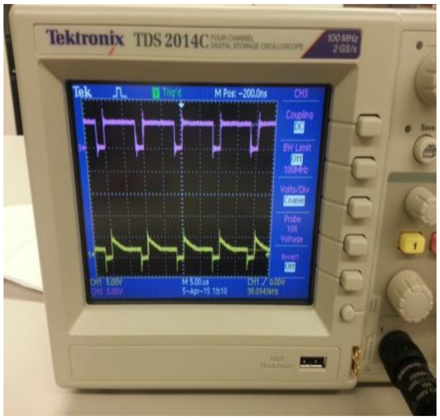
4.3.4 Testing of MOSFET

From the hardware testing of the buck-boost converter, a discrepancy is observed in the output voltage waveforms from the simulations and the hardware setup. The MOSFET is found to conduct in an unexpected behavior. This unexpected behavior of the MOSFET can be due to the faulty operation of one of the MOSFET's due to over-currents. The MOSFET is again tested for any discrepancy using the Figure 4-14(a). Figure 4-14(b) shows its hardware schematic and the output waveforms are shown in Figure 4-14 (c). Output waveforms depict that even though the MOSFET has been triggered properly, it is not working as expected when connected to the circuit. The output voltage is held constant at 5 V, which is not expected. It concludes that heat sinks and other triggering method should be used.



(a)



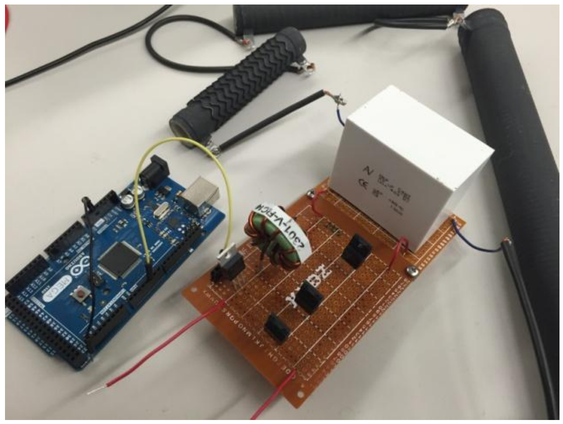


(b) (c)

Figure 4-14 Schematics of (a) MOSFET Testing (b) MOSFET Testing Hardware (c) MOSFET Testing Output

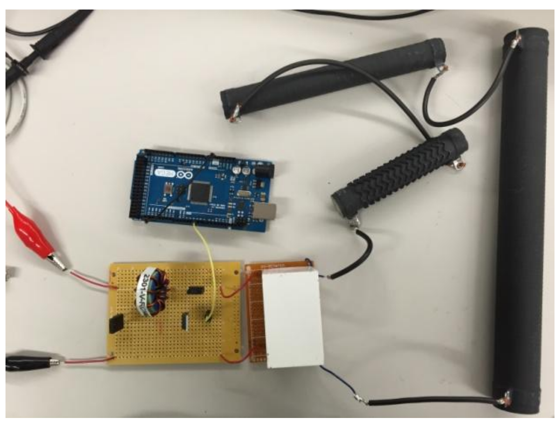
4.3.5 Testing of Buck Converter

The next step of the hardware prototyping involved testing of the individual converters. A hardware model for the buck converter was built as shown in Figure 4-15 with one input of 18V from the regulated DC source and other input from the Arduino. The setup was tested for the output voltage and the duty cycle was found out using the 18V input voltage. The multimeter reading of the output voltage of the buck converter was found out to be 9.08V. Then, the duty cycle was calculated as 0.51, nearly 50% duty cycle. It means that the converter conducts for half time in the complete duty cycle.



4-15 Schematic of Buck Converter

4.3.6 Testing of Boost Converter

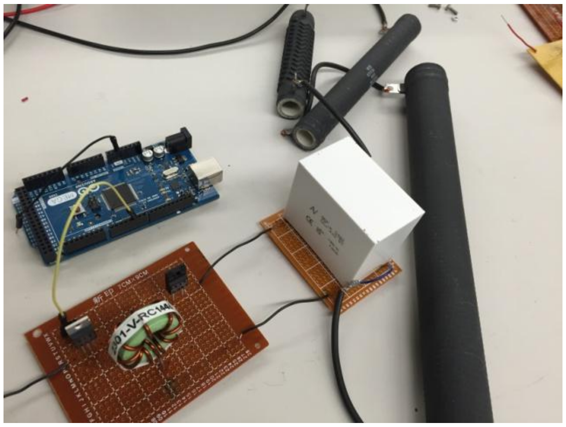


4-16 Schematic of Boost Converter

The boost converter as shown in Figure 4-16 was built and was tested for the parameter verification. The input voltage of 18V was given from the regulated DC source and the gate input signal to the MOSFET was given through the Arduino. However, as soon as this hardware prototype was powered on, the regulated DC supply went into the current limited mode.

4.3.7 Testing of Inverting Buck-Boost Converter

The inverting buck-boost converter was also tested. Figure 4-17 shows its schematic. The input voltage is of 18 V and the gate signal for the MOSFET is through the Arduino. It was observed that, this converter went into the current limited mode as well.



4-17 Schematic of Inverting Buck-Boost Converter

Practically, any device is to be designed under the current limits. Once any device goes into the current limiting mode, it is no longer able to protect the device from the over-currents flowing through the system. Also, the voltage regulation loss, which means that the voltage falls off from that current limit, is also observed. Therefore, current limit adjusting technique must be implemented to make sure that the system does not undergo breakdown.

Chapter 5

Conclusion & Future Work

The proposed development of the distributed controlled multilevel inverter has been extensively tested using various simulations. The conclusions of these results are mentioned in this chapter. However, significant changes can be made in the proposed structure to make it more efficient. Such improvements are also mentioned in this chapter.

5.1 Conclusion

In this thesis we introduced the idea of virtual and hardware prototyping of a distributed controlled multilevel inverter used as a grid-tie interface for photovoltaic. The system framework consisted of multilevel inverters composed of solar panel array connected in series with the inverter module. The inverter module built of buck-boost converter and a cascaded h-bridge inverter was designed using the software PLECS. Further, for developing the hardware prototype, the buck – boost converter has been tested using the perfboards and the breadboard. The framework, consisting of multilevel inverters, suggested that the total harmonic distortions can be reduced using this structure and therefore, we can integrate the solar arrays for electricity generation.

Modular multilevel inverter architecture components have been modeled tested and analyzed individually and then with the complete framework for stand alone as well as grid connected residential pv systems. Modeling parameters for the buck-boost converter have been found out using the closed loop analysis and by using the state space equations of the system. Further, the system parameters have been checked for the stability by finding the loop gains such as, Kp, Kd, and Ki.

Different techniques for generating switching signals for the H-Bridge inverter have been tested. Firstly, individual signal generators with specific pulse value and the switching frequency have been used as the input signals for each of the four IGBT's of the inverter. In-order to reduce the number of inputs, we have designed two architectures for the input signal switching using two input signals. One method uses a combinatorial block while the other method uses logic gates.

The designed framework has been tested for about a dozen of panels. The modular multilevel inverter output follows the multilevel output levels (2n+1). When we connect up to 7 panels in series, the complete architecture works in a boost mode; if 8 or 9 panels are connected in series, the system works in a buck-boost mode and when 10 or more than 10 panels are connected in series, the complete architecture works in the buck mode.

The complete system has also been tested as a photovoltaic system connected to the grid and as a standalone. The stand alone system is sufficient for the residential home applications where the loads are connected directly to the system. The benefit of using these systems is that it takes the load off the conventional grid. Also, this complete framework can be connected directly to the grid. This facilitates the user to take the energy from the grid and transfer it to the grid again, if necessary.

Even though the complete architecture works either in the boost, buck-boost or buck mode, it gives the same output voltage required by the system. This converter operation flexibility facilitates the user to use this system for lower voltages as well as higher voltages. Also, the use of cascaded multilevel h-bridge inverter is useful at the switching frequencies less than or greater than the fundamental frequencies.

5.2 Future Work

During the hardware testing, we came across some MOSFET functioning discrepancies which must be looked after. It is observed that while building up the open loop buck-boost converter, it failed to function properly. The reference voltage of 5V from the duty cycle is less than the input voltage of 18V; therefore, the configuration must work in buck mode. The system parameters can be directly checked for the buck mode instead of the complete buck-boost converter hardware setup.

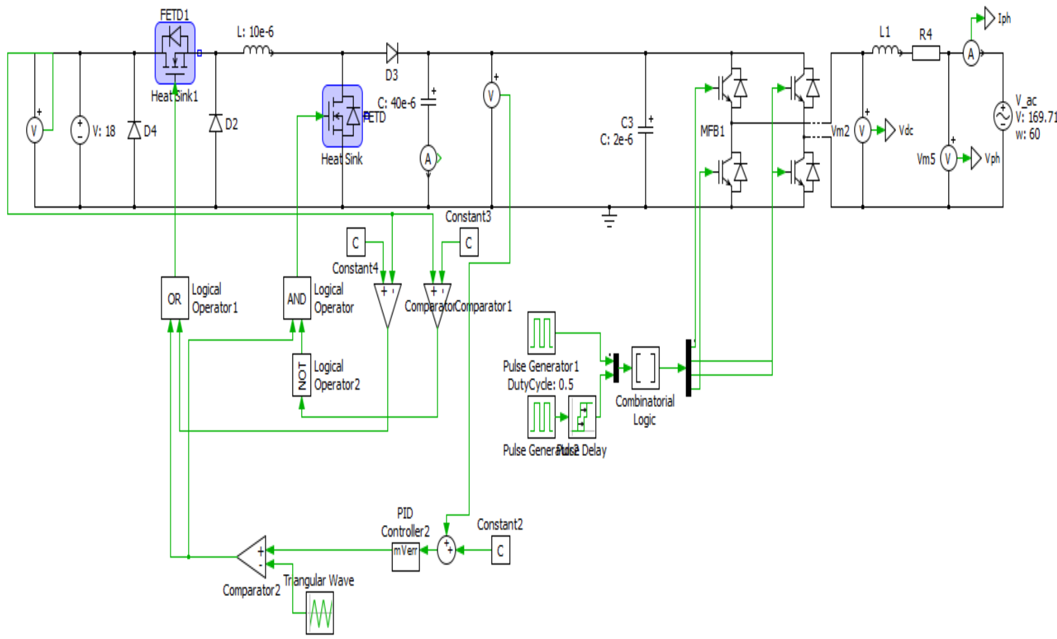


Figure 5-1 MOSFET Triggering

An alternative closed loop MOSFET triggering mechanism as shown in Figure 5-1 can be implemented for the buck-boost converter. The inputs for each buck mode, boost mode and buck-boost mode can be implemented using the logic gates which can be compared with the reference voltages and the output voltage of the converter.

There can be some developments carried out on the virtual prototype. While designing the virtual prototype, no particular MPPT scheme was considered and in the future work, it can be one of the areas that can be worked on. Also, factors such as non uniform irradiance, common mode voltage, floating panels, large leakage currents, and efficiency comparisons are not discussed; which can be looked at. Others improvements like distributed control and fault tolerances can be introduced in the updated architecture.

Building on the virtual implementation of the modular multilevel inverter, the complete hardware architecture can be implemented and tested using the DS1103 PPC Controller Board [21]. It is a single board system having comprehensive I/O and real time processing unit that can be used for rapid control prototyping. The block diagram for this hardware setup is as shown in Figure 5-2.

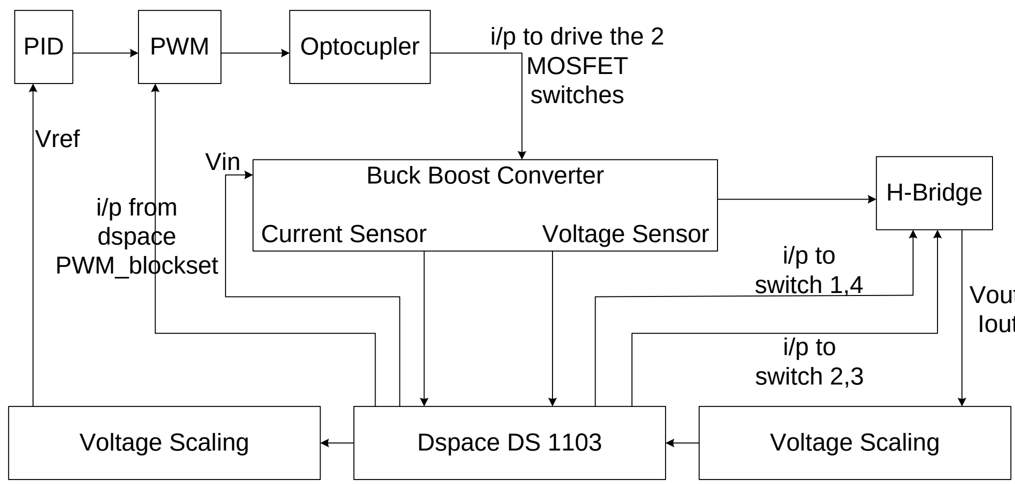


Figure 5-2 Block Diagram for Hardware Setup

[22]–[23] mention some of the applications of the DS1103 controller box. In addition to these this controller can be used in the fields of robotics or motor control. Once this connection is established we test the complete system by connecting it with the GW Grape solar panel. This model can be further extended for larger systems like – solar panels connected in series.

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Biological Information

Shweta Hardas grew up in Nagpur, India and has resided in India for the majority of her life. She earned her B.E. in Electrical Engineering from Nagpur University in June 2012, India and M.S. in Electrical Engineering from University of Texas at Arlington, USA in May 2015. During her stay at the University of Texas at Arlington, Shweta has been involved with several projects, where gained an insight for the meaningful additions to the recent technologies. Her main concern is reducing the carbon footprints therefore reducing the energy wastage by designing energy efficient systems. Shweta's research interests include control systems, power electronics and robotics for building enhanced system architectures.