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Design and Harmonic Elimination of sinusoidal pulse width modulation (SPWM) Based Five Level Cascaded H-Bridge Multilevel Inverter for Photovoltaic System for Educational Purposes

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ABSTRACT

In this modern era, the electrical power system faces a shortage of fossil fuel-based energy sources. To overcome this problem, people more focus on giving towards renewable energy sources like solar energy, wind energy, and nuclear energy sources. This also can be used to overcome global warming and reduce pollution by fossil fuels . This study used a photovoltaic (PV) array to give supply to the Multilevel Inverter (MLI) with different irradiance values , which can be used for educational purposes . The sinusoidal pulse width modulation (SPWM) method is used here to control the converter . SPWM technique is the easiest technique than the other types of pulse width modulation (PWM) technique. In this technique the switching loss is very low, therefore efficiency is high. After the simulation , the output waveforms are similar to the sinusoidal waveform for the resistive load . In this topology , after simulation , the total harmonic distortion (THD) contents were found to be less by using an LC filter. The model is simulated in MATLAB/Simulink. The analysis of output voltage waveforms is discussed with the reduced THD.

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1. INTRODUCTION

In this modern era, the electrical power system faces a shortage of fossil fuel-based energy sources. To overcome this problem, people more focus on giving towards renewable energy sources like solar energy, wind energy, and nuclear energy sources. There is also another reason to use renewable energy sources to overcome global warming and to reduce pollution by fossil fuels. The major concern in the power sector is the increase of power demand day by day due to the unavailable of enough resources to meet the power demand by renewable energy sources. Demand has increased for renewable energy sources to be utilized along with the conventional source of energy systems to meet the energy demand. The use of fossil fuels has caused the fossil fuels to be decreased and affected the environment by greenhouse gas emissions and causing global warming.

Solar energy is easily available. Solar energy can be able to operate an independent generating unit or a grid that can be connected generating unit depending upon the nearby grid. Thus, it is used to power remote sensing areas where there is unavailable electrical power and where the cost of the distribution of power will be expensive. Another advantage of solar energy is reliability. We can operate it whenever and wherever we want to operate it. To deal with the present energy crisis we have to develop the best way in which power can be drawn from solar radiation. The power conversion mechanisms are becoming less in size in the last few years. The development in engineering mainly in power electronics and material science can help engineers to design efficiently to decrease the high-power demand (Lai *et al*., 1996). By using the multi-input converter and various power electronics devices we can get more power and it will reduce the voltage fluctuation as well as harmonics in the system. But due to the more expensive and less efficient of this type of system, they are not competitive in markets as the leader of power generation sources. One of the methods is to use different types of converters to combine the micro-sources, ESD, and different kinds of load into a common DC bus (see **Figure 1**) (Franquelo *et al*., 2008).

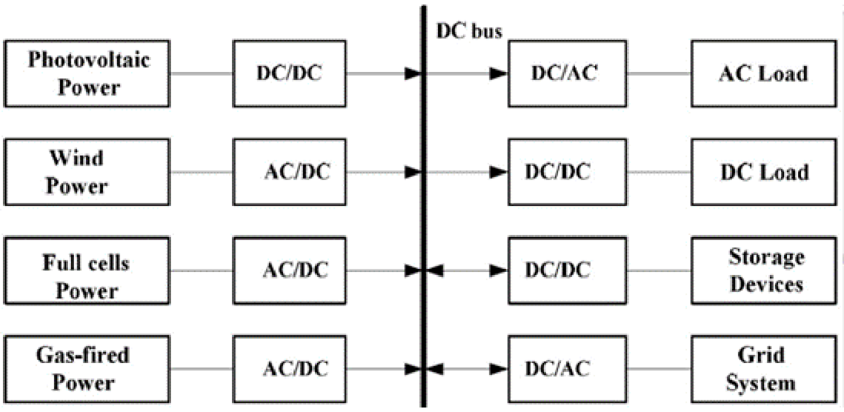

Figure 1. Inter-connection of the grid, sources, converters, loads.

Following problems linked with this type of system are given below:

(i) There are more PE converters in this system therefore harmonic content will be high. So here harmonic filter will be used which is very expensive and size is very high.

(ii) The efficiency will get reduced due to the losses of power of the different PE converters used in the system.

(iii) This type of system is very complex in design because different types of converters are used.

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This research uses a photovoltaic (PV) circuit to provide supply to a Multilevel Inverter (MLI) with different radiation values , which can be used for educational purposes . To overcome this problem , a PE technology called MLI is proposed . This is a suitable method for combining different RES proposed. The objective of MLI is to get the AC voltage from the various levels of DC voltage . The number of levels of any MLI will be chosen haphazardly . Thus, the output voltage of the MLI can have a high level without the use of any transformer . Due to the step characteristic of the MLI, the output voltage is approximately sinusoidal so that filter size will get reduced . Here the multilevel inverter is discussed . There are three types of MLI topologies used : Diode clamped MLI , Flying capacitor MLI , and Cascaded H bridge MLI.

Among those topologies, the CHBMLI is the most appropriate topology and it is mostly used. **Figure 2** is the CHBMLI topology with RES. The number of inverters used in every single type of RES can be better.

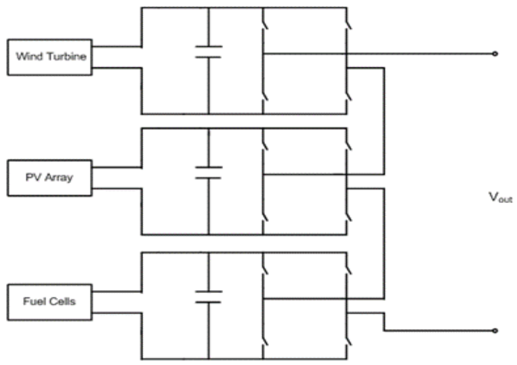

Figure 2. CHBMLI with RES.

The advantages of the CHBMLI are given:
(i) Used for HV application.
(ii) Efficiency is high.
(iii) PQ can be enhanced by this system.
(iv) Low switching stress.
(v) It needs a smaller number of components than the others.
(vi) The cost is less and also the weight of this type of MLI is less.

2. METHOD

We analyzed data from models that can be used for educational purposes. In this model, the SPWM method is used to give a pulse to the inverter. It is an easy way to get a pulse among all the PWM methods.

3. RESULTS AND DISCUSSION

3.1. Solar Cell Modelling

A solar cell is a p-n junction diode. N region is highly doped and thin. In the n region, light passes easily. Doping of the P region is less in which most of the depletion region is present on the P side. A solar cell is an important element of a solar panel in which more cells are connected. A photovoltaic module can be designed by connecting more cells in parallel and series connection (Gonzalez *et al*., 2008). Electron hole pairs (EHPs) are mostly generated in the depletion layer. Due to the electric field and built-in voltage, electrons progress toward the N region and holes toward the P region. When a load is given, the electrons Passover load recombine with holes. Detailed information is in **Figure 3** (Tolbert *et al*., 1999).

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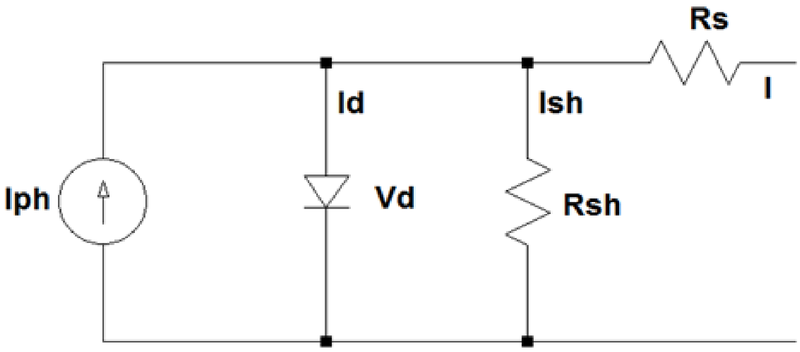

Figure 3. Single diode model.

Taking only one model of the solar cell; this will be designed by taking two resistors, one current source, and a diode. Above solar cell model can be called a single-diode model. The characteristic equation (1) of the following PV cell is given in the following:

$$I = I_{lg} - Ios\left[\exp\left\{q \times \frac{V+I\times Rs}{A\times K\times T}\right\} - 1\right] - \frac{V+I\times Rs}{Rsh} \quad (1)$$

where the explanation in equations (2) and (3):

$$Ios = Ior \times (\frac{T}{Tr})^3 \times [\exp\left\{q \times Ego \times \frac{\frac{1}{Tr}-\frac{1}{T}}{A\times K}\right\}] \quad (2)$$

$$I_{lg} = \{I_{scr} + K_i \times (T-25)\}\times lambda \quad (3)$$

The characteristic equation depends upon the connection of the solar module. That is the total number of cells connected in series and parallel. Current variation in the solar module due to shunt resistance is less and due to the series resistance is more (see equation (4):

$$I = Np + Ilg \times Ios \times \left[\exp\left\{q \times \frac{\frac{V}{Ns}+I\times\frac{Rs}{Np}}{A\times K\times T}\right\} - 1\right] - \frac{V\times\frac{Np}{Ns}+I\times Rs}{Rsh} \quad (4)$$

In **Figures 4 and 5**, the I-V and P-V curves are given. From this, it was observed that the cell works as constant CS for small operating voltages. It also works as constant VS for a small operating current.

When the photon of light drops on a solar cell, it delivers the free electrons from the upper layer of the cell. By applying the formula of threshold energy, we can get the appropriate intensity of light.

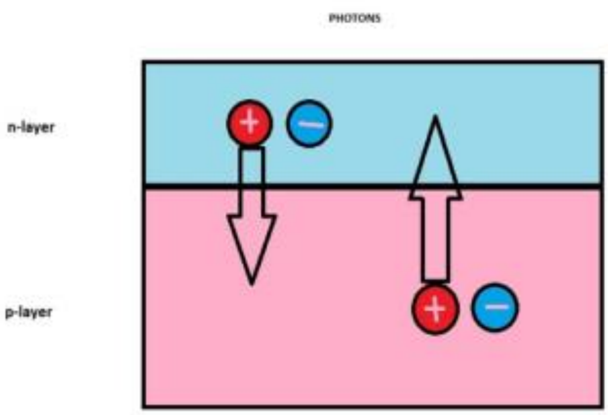

Figure 4. PV cell.

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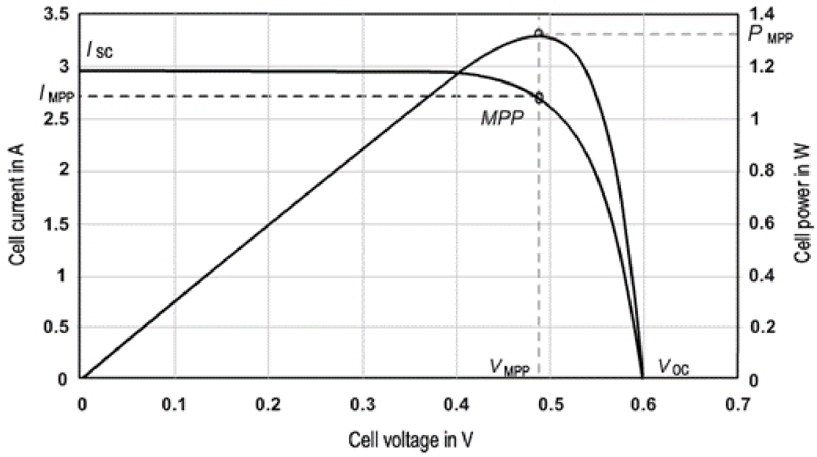

Figure 5. P-V and I-V curves.

3.2. Effect due to Solar Irradiation

In a solar cell, the P-V and I-V curves are highly dependent upon solar irradiance values. The solar irradiance value fluctuates as the environmental condition changes such as in the rainy season and the summer season. The control mechanisms are there in the system that can be known for any change. It can change the operation of the solar cell to get load demands. When there is more solar irradiance then we get more input to the solar cell. Then the power magnitude will be more for the same voltage. When the solar irradiance value rises, then the OC voltage also rises. It increases when sunlight drops on solar cells. Electrons are having more excitation energy. Therefore, electron mobility increases and large power is produced. Detailed information is in **Figures 6 and 7**.

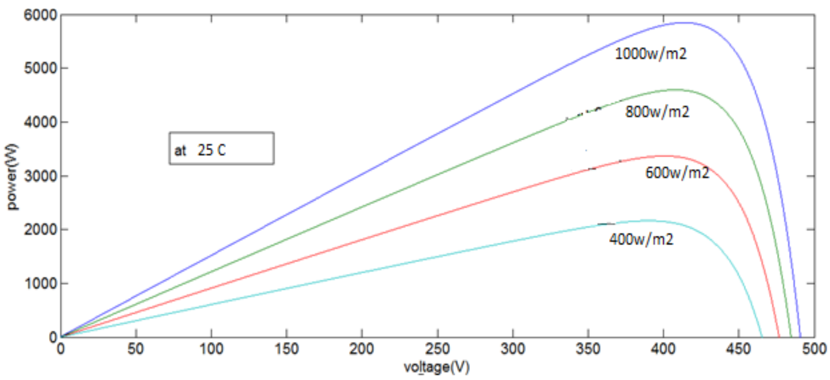

Figure 6. P-V curve having different irradiance.

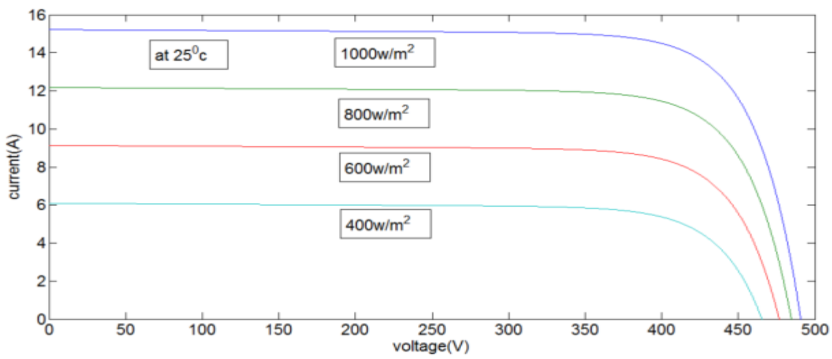

Figure 7. I-V curve having different irradiance.

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3.3. Effect due to Temperature

When temperature increases besides solar cells then power generation capacity will get reduced. So, this has a negative impact on the operation of solar cells. The OC voltage value decreases when the temperature around the solar cell gets increased. The band gap increases of the material as the increases in temperature. Thus, high energy is needed to cross the barrier. So here the efficiency of solar cells will get decrease. Detailed information is in **Figures 8 and 9**.

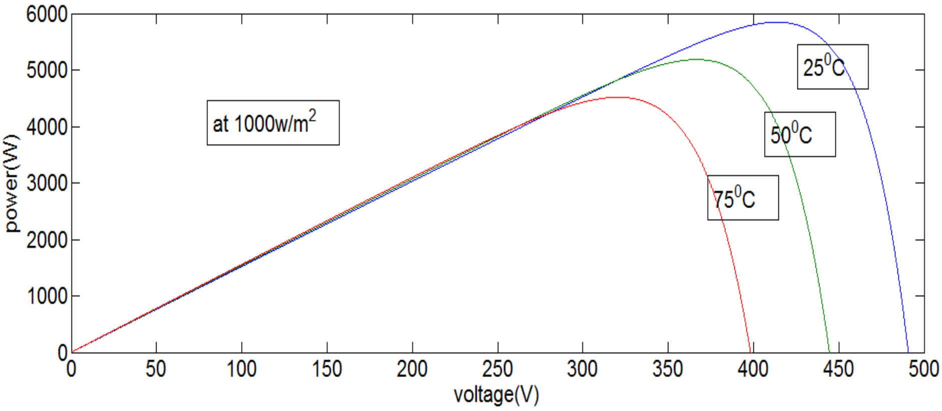

Figure 8. P-V curve having different temperatures.

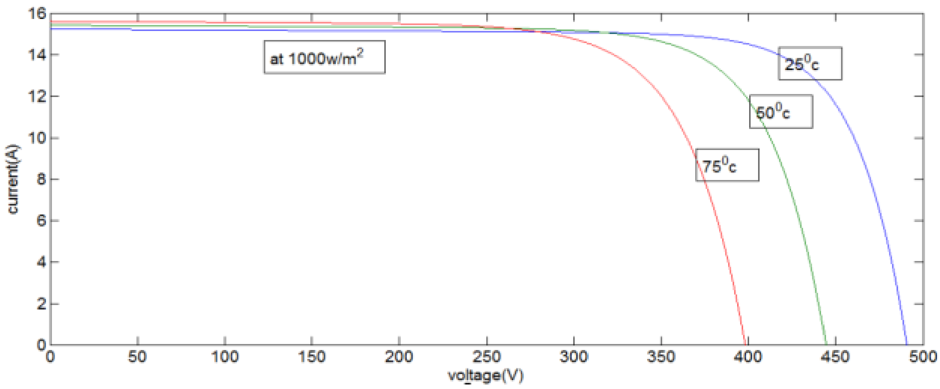

Figure 9. I-V curve having different temperatures.

3.4. Multilevel Inverter

It is an electrical device in which it converts direct current (DC) to alternate current (AC). Here the inverter can't produce power. Power is supplied by the DC source. There are two types of inverters concerning the connection in a single phase. One is a half-bridge inverter and another is a full-bridge inverter. The output voltage of a half-bridge inverter is half of the supply voltage. And the output voltage of the full bridge inverter is the same as the supply voltage. It is also used for emergencies as backup power when there is no supply in the home. It is also used in aircraft systems to convert a part of the aircraft's DC to AC power. An inverter can generate a square wave, sine wave, modified sine wave, pulsed sine wave, or pulse width modulated wave. The major inverter generates square waves and quasi-square waves.

The basic inverter circuit consists of an oscillator, a controlling circuit, switching circuits, drive circuits of power devices, and a transformer to step up the voltage. The output voltage of the inverters shows harmonic distortion. This is shown due to the application of power electronics devices and using of nonlinear loads in the system. Here the output waveform is distorted. So, to overcome this problem multilevel inverter comes into action.

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3.5. Basics of MLI

Nowadays with increasing in technology, many industrial applications have required high power to meet the demand. Some devices in industries may require medium and low power for their operation. Using a high-power source may give benefits to some motors which require high power. But it can damage other loads. Some medium-voltage motor drives and utility applications require medium voltage. The MLI is used in industrial applications to get pure sinusoidal waveform. By using MLI the THD is less as compared to normal inverter. Here efficiency is also more. There are many topologies of MLI available. The only difference is the process of switching and the source of input voltage to the MLI (Rodriguez *et al*., 2002).

There are 3 MLI topologies that are commonly used: Diode clamped MLI, Flying capacitor MLI, and Cascaded H bridge MLI.

Here more details about CHBMLI and its modulation systems are given. Here sinusoidal PWM method is used.

3.6. Diode Clamped MLI

The main aim of this type of MLI is to use diodes and capacitors. **Figure 10** is a three-level diode-clamped MLI (Ozdemir *et al*., 2008). The output voltage is given as Van where n is the neutral point in the circuit. This series-connecting huge capacitors C_1 and C_2 can divide the DC bus voltage Vdc into three levels.

It gives several voltage levels across, unlike phases of bulk capacitors. These capacitors are connected in series. The diode transfers less voltage. Therefore, stress on other electrical appliances will reduce. The output voltage is half of the input DC voltage. Detailed information is in **Figure 11**.

This is the disadvantage of diode-clamped MLI. By enhancing many switches, diodes, and capacitors it can crack. This type of MLI is limited up to three levels because of the capacitor balancing issues. This type of MLI gives high efficiency due to all switches using fundamental frequency. This is an easy system of B2B power transmission systems.

The switching state of various outputs of **Figure 10** is shown in the following:

(i) When Van = $\frac{Vdc}{2}$, two switches (S_1, S_2) are closed.

(ii) When Van = 0, switches (S_2, S_2') are closed.

When Van = $\frac{-Vdc}{2}$ then the two switches S_1' and S_2' are closed.

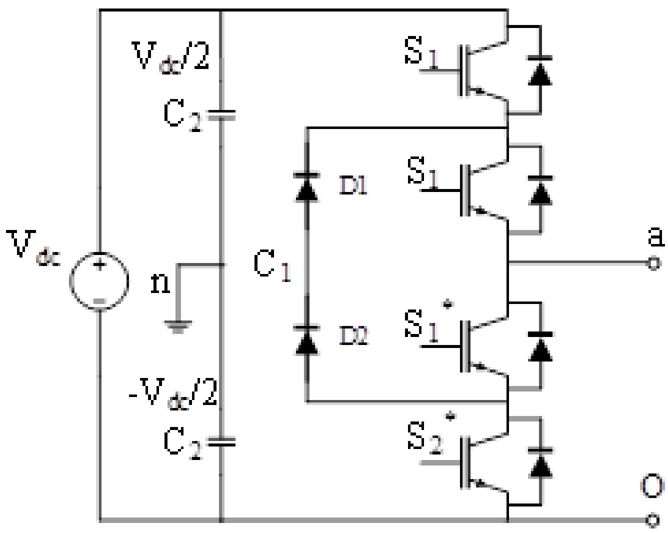

Figure 10. Three-level diode clamped MLI.

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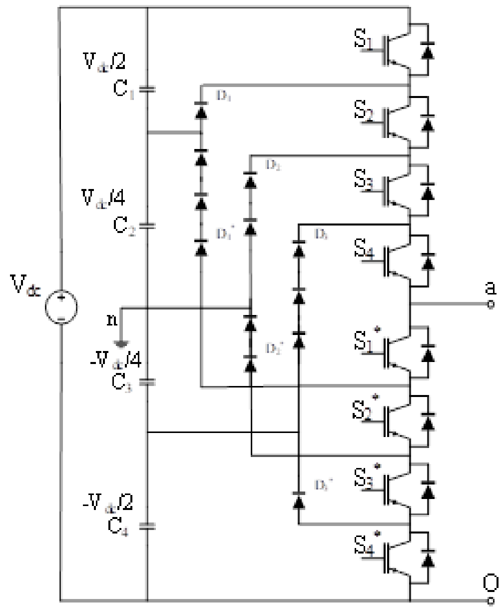

Figure 11. 5-level diode clamped MLI.

In **Figure 11**, a five-level diode-clamped MLI is plotted. Here DC link voltage V_{dc} is shared with four bulk capacitors named C_1, C_2, C_3, and C_4. Consider the level of the MLI is L. The voltage rating of the clamping diode is equal to the voltage rating of the active switching device (Vdc/4 for the five-level diode clamped MLI), then the number of clamping diodes can be found by $[(L - 1) \times (L - 2)]$. Here the number of clamping diodes will increase quadratic with the level L. When the level of this type of MLI is very large, the number of diodes essential in this circuit becomes more. This makes the total system impractical to implement.

There are some applications of this type of MLI, including Static VAR compensation, Variable speed motor drives, HV system interconnection, and HVDC and AC transmission lines.

3.7. Flying Capacitor MLI (Capacitor Clamped MLI)

The main aim of this type of MLI is to use capacitors. The capacitor-clamped switching cells are connected in series. Here the capacitors transfer a small amount of voltage to electrical appliances. In this type of MLI, switching states are the same as the switching states of diode-clamped MLI. In this type of MLI, there is not any use of clamping diodes. Here the output is also half of the input DC voltage and this is the disadvantage of this type of MLI. This type of MLI can control both the active and reactive power flow. Here switching losses will be there because of high-frequency switching. Here only switches and bulk capacitors are used.

The three-level and five-level capacitor-clamped MLI are shown in **Figures 12 and 13**. The advantage of this type of MLI is that it gives redundancies for some output voltage. The number of redundancies will be more with the increase in the level of output voltage.

With this redundancy, the balancing of capacitor voltages will be very simple. It can be balanced with the help of some modulation methods and control strategies. It is also possible to select which capacitor is going to charge or which capacitor is going to discharge. Flying capacitor MLI has an identical problem as the diode clamped MLI when the level of the MLI is very high.

Applications of flying capacitor MLI are Static VAR generation, used in both rectifier and inverter, Sinusoidal current rectifiers, and Used in the converter for harmonic distortion capability (Rodriguez *et al*., 2005).

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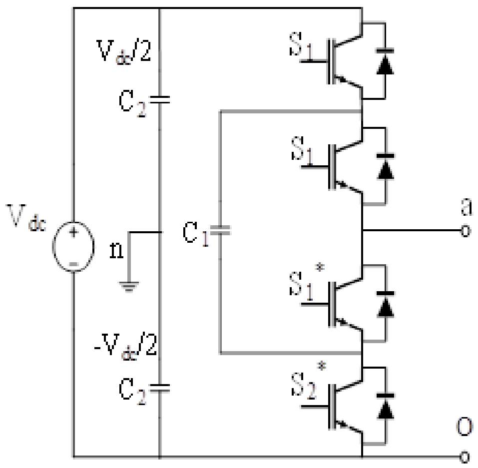

Figure 12. Three-level capacitor clamped MLI.

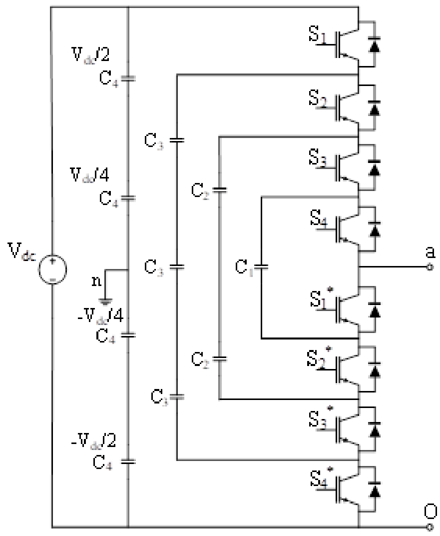

Figure 13. Five-level capacitor clamped MLI.

3.8. Cascaded H-Bridge MLI

In cascaded H-bridge MLI, only capacitors and switches are used. But it requires a smaller number of components for each level (Cecati *et al*., 2003). This topology mainly contains power conversion cells in series. Here scaling of power is very much easy. An H-bridge is a combination of some capacitors and switches. It provides separate input DC voltage to each of the H-bridge. This type of MLI consists of H-bridge cells. Each cell may give three different voltage levels. These levels are zero, positive DC voltage, and negative DC voltage. One advantage of this type of MLI is that it needs a smaller number of components compared with diode-clamped MLI and flying capacitor MLI. Here the price of the MLI is less. The weight of this type of MLI is also less than the other two types of MLI. Soft-switching can be possible by using new switching methods.

The advantage of using multilevel cascade inverters is to remove the big transformer used in the normal multiphase inverters. Clamping diodes are required in the case of diode-clamped MLI and flying capacitors are required in the case of flying capacitor MLI. But this type of MLI requires a large number of isolated voltages to supply each cell in the MLI. The topology of cascaded H-bridge MLI is shown in **Figure 14**.

The output voltage is combined by adding voltage which is generated by the different modules. If different DC sources have equal voltage levels (Vdc), then the resultant phase

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voltage is going to be in the range from –nVdc to +nVdc and the level will be 2n+1. Here n is the total number of modules or it can be called many separate DC sources. If the number of DC sources will increase then the level of the output voltage will be more. So, there will be sinusoidal output voltage produced without filtering. The cascaded H-bridge MLI topology has more advantages, so it is used in medium and high-power applications (Rodriguez *et al*., 2002).

One advantage is its modularity. Here every DC source supply to separate full bridge inverter. Therefore, it's easy to fill different DC sources even not changing the shape and size of the system. The CHBMLI mainly comprises many single-phase full-bridge inverter circuits (Kjaer *et al*., 2005). Here each bridge is supplied by different DC sources which may be batteries, PV cells, or any type of DC supply. Detailed information is in **Figure 15**.

The output of each bridge will be added to get an approximately sinusoidal output voltage waveform. For getting the nth level of cascaded H-bridge MLI in every full bridge inverter unit consisting of different DC sources and four semiconductors switches (Alonso *et al*., 2003). It will able to get three dissimilar voltage levels. These levels are $+V_{dc}$, 0, and $-V_{dc}$ which depend upon switching states. Every switching state conducts for 180^0 or half cycles irrespective of the pulse width of the quasi-square wave. Here **Figure 16** shows a nth level cascaded H-bridge MLI. Each H-bridge will be started at a fixed time at a different start-up angle. Considering each bridge supplied by a different DC source then the output of every bridge which appears in the CHBMLI output is the sum of different DC sources for three phases nth level MLI. The following output equations (5), (6), and (7) are:

$$V_{an} = V_{a1} + V_{a2} + V_{a3} + \cdots \ldots \ldots \ldots V_{an} \quad (5)$$
$$V_{bn} = V_{b1} + V_{b2} + V_{b3} + \cdots \ldots \ldots \ldots V_{bn} \quad (6)$$
$$V_{cn} = V_{c1} + V_{c2} + V_{c3} + \cdots \ldots \ldots \ldots V_{cn} \quad (7)$$

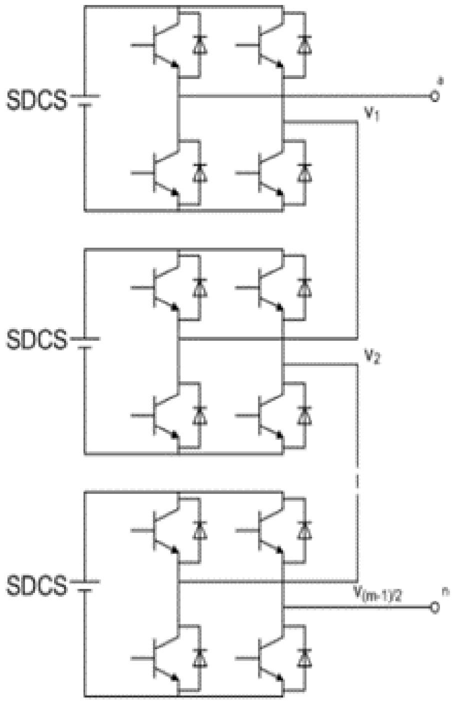

Figure 14. Cascaded H-bridge MLI.

Equation 1 shows that the output voltage of CHBMLI is equivalent to the addition of different DC sources of MLI.

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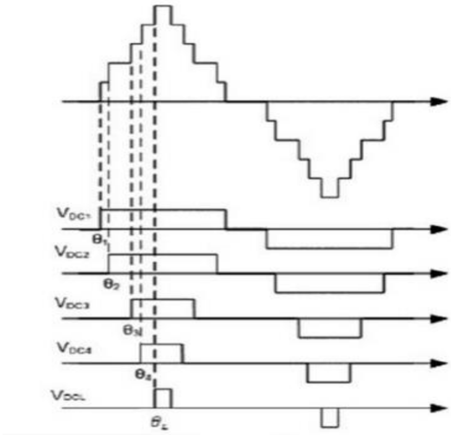

Figure 15. Staircase waveform of voltage of single phase MLI.

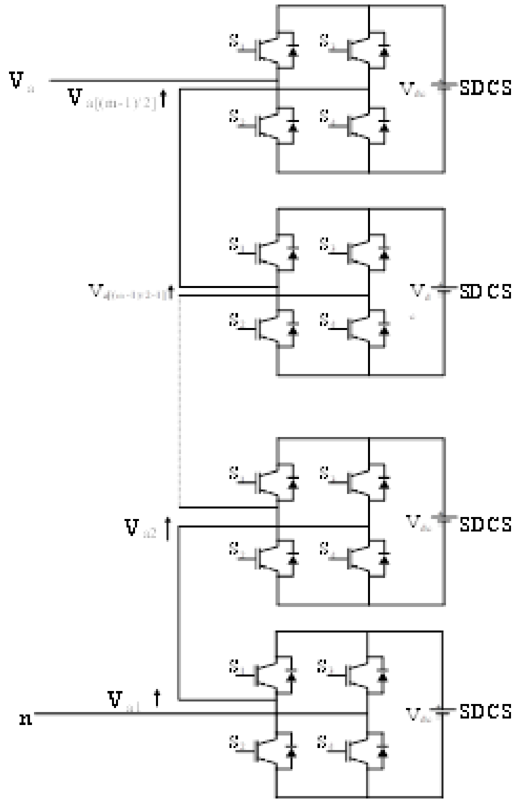

Figure 16. Single phase diagram of CHBMLI.

The Fourier series of the voltage waveform of CHBMLI of **Figure 16** expanded in equation (8):

$$Vout(wt) = \sum_{n=1,3,5\ldots}^{\infty} b_n Sin(nwt) \quad (8)$$

where b_n is given by $b_n = \sum_{n=1,3,5\ldots}^{2N-1} V_{dc1}Cos(na_1) + V_{dc2}Cos(na_2) + \ldots + V_{dcL}Cos(na_{L-1}) + V_{dcL}Cos(na_L)$, L is the number of DC sources of each full bridge, and *N* is the number of switching angles

3.9. Sinusoidal PWM (SPWM) Technique

These days PWM inverters are becoming more popular among the other types of inverters in some industries. PWM methods are designed as equal amplitude pulses. The size of the pulses is modified. Thus, the output voltage can be generated with less THD. Some of the

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PWM techniques are single pulse, multiple pulse, and sinusoidal pulse modulation. For the turn-off process of switches forced commutation is done.

In Sinusoidal PWM (SPWM) usage of more pulses for a half cycle is there. In this SPWM pulse width is the SINE function of the angular position of the pulse for any cycle. The triangular carrier wave of large frequency (V_c) is matched with the sinusoidal reference wave (V_r) of any preferred frequency. From V_c and V_r switching action can be obtained. **Figure 17** shows how the duty cycle or the pulse is given to the inverter . **Figure 18** shows the sinusoidal PWM method. Here the sinusoidal reference wave and triangular carrier wave are shown concerning the pulses. Here six pulses per half cycle are given in equation (9):

$$N = \frac{f_c}{2f} \quad (9)$$

where *N* is the number of pulses, f_c is the frequency of the carrier wave, and *f* is the frequency of the reference wave (see equation (10)).

$$M = \frac{V_r}{V_c} \quad (10)$$

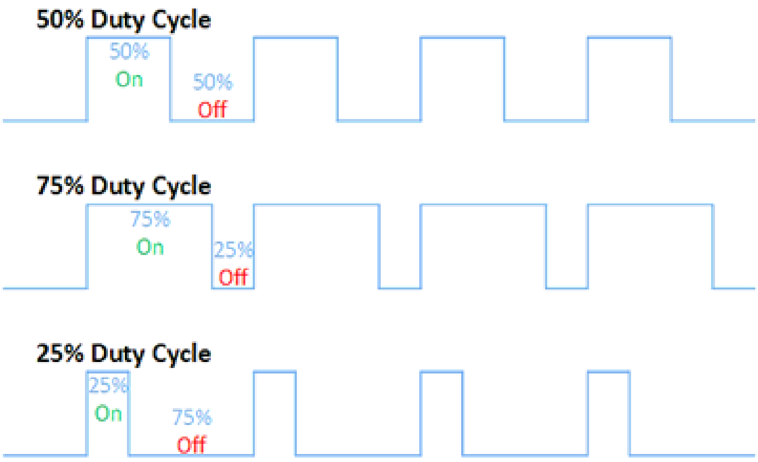

Figure 17. Types of Duty cycle.

Here *M* is named the modulation index. It gives control of harmonic content present in the output voltage waveform. The output voltage can have a particular value by changing the MI. When the MI value will be large, then it will be called over-modulation. In over-modulation, the waveform of the output voltage will be non-linear. When N is increased, then the harmonic content is reduced so the filters used for this will be less. But when there will be more value of N, then the switching frequency will be more. So, the switching losses will be more and the efficiency will decrease.

There are many advantages to using the SPWM method, including a higher modulation index, the easiest method than the others with less cost, less switching loss, and giving the best control of circuits (see **Figure 19**).

In the LC filter, both the Inductor filter and Capacitor filter are combined to filter the AC components. RF of the Inductor filter varies directly with the load. It varies inversely with the load in the capacitor filter. So, when combined, then RF is independent of load.

The choke gives more resistance to AC components. A choke allows DC components. It connects in series with the load. Here the capacitor which is connected parallel with the load filters the AC component. Indeed, the ripples are filtered and a pure DC component is produced.

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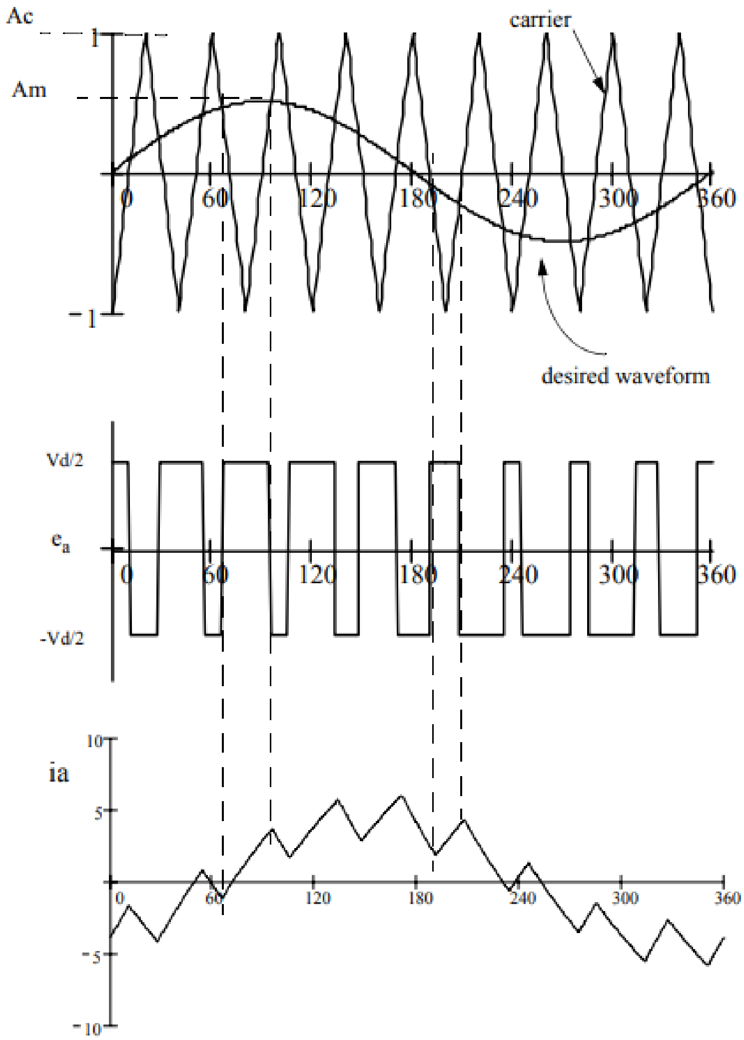

Figure 18. Sinusoidal PWM

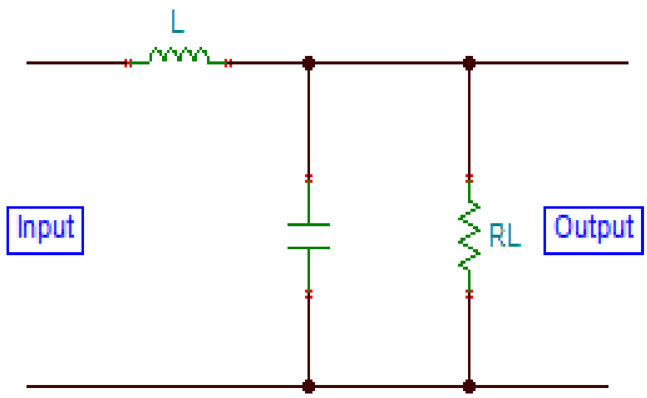

Figure 19. LC filter.

3.10. Simulation Results

The model MLI was constructed and simulated in MATLAB/SIMULINK (see **Figure 20**). In this model a sinusoidal PWM (SPWM) based MLI is designed. It is a three-phase MLI. **Figure 20** shows that the model is without using any filter. Here the load connected to the MLI is resistive. Solar PV array is considered as the source here.

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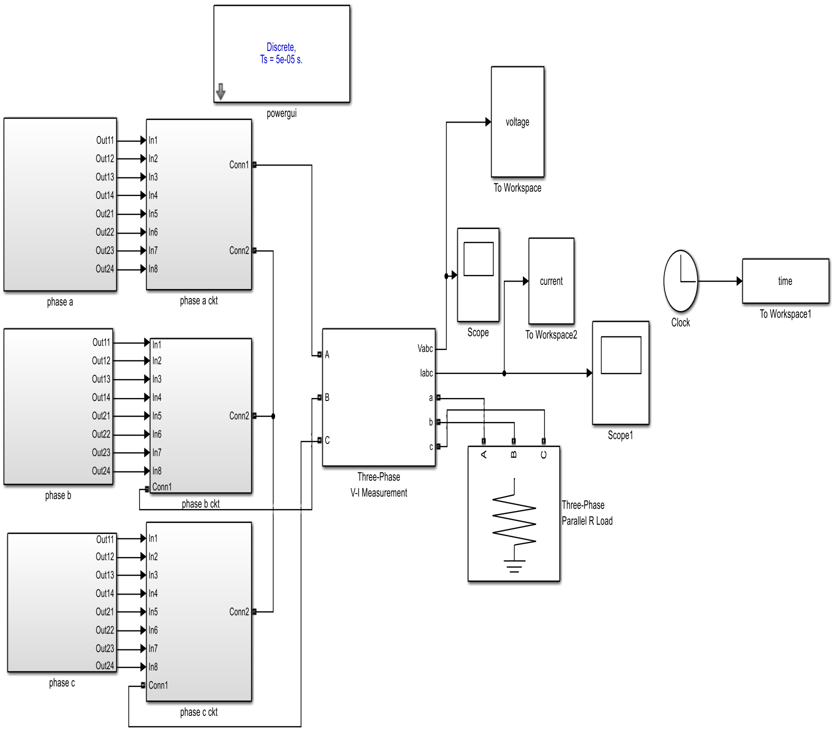

Figure 20. Simulation of MLI without filter.

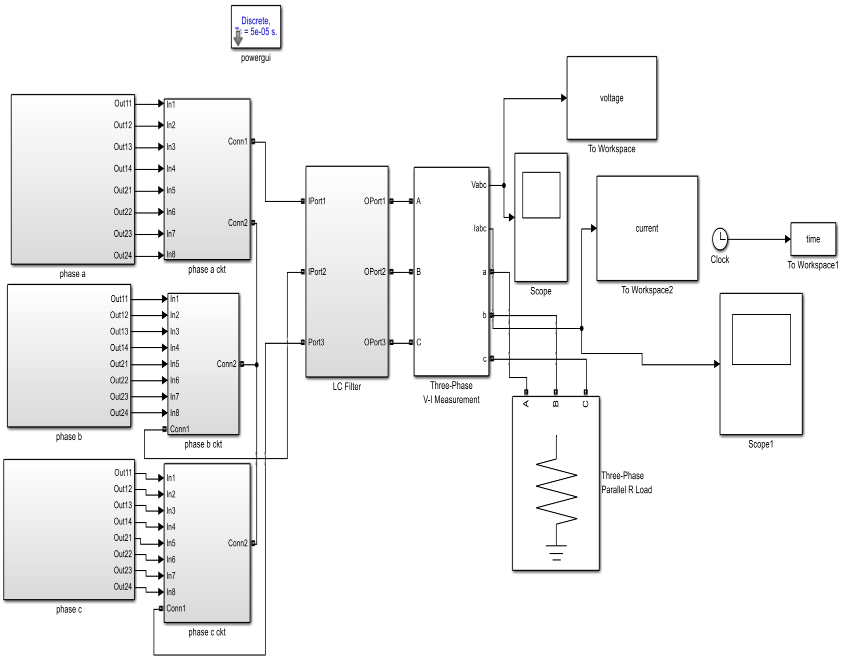

Figure 21. Simulation of MLI with LC filter.

Figure 21 shows the model by using an LC filter. By using a filter, the THD reduces. **Figure 22** shows the LC filter used in the model . The simulation time which is taken here is 50 seconds.

Simulation results are achieved using MATLAB. Output voltage and current waveform are plotted. Voltage, current, power, and irradiance of the PV array are also plotted here. Also, the THD values before and after the LC filters are plotted. Simulation parameters are given in **Table 1**.

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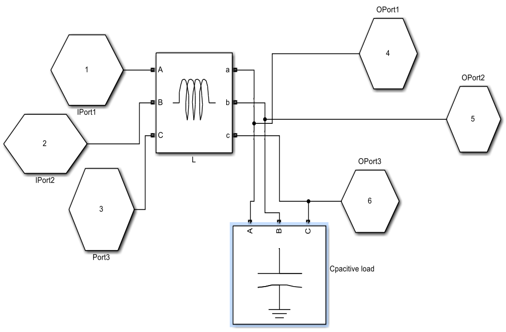
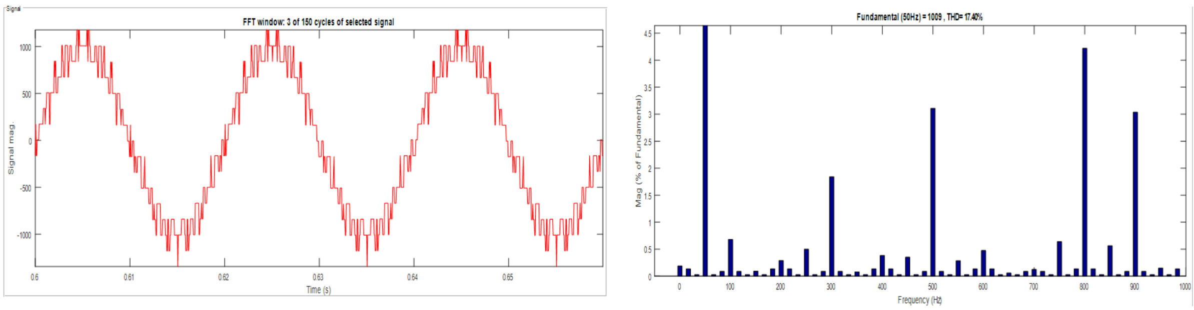


Figure 22. LC filter.

Table 1. Simulation parameters.

Parameters	Value
L of filter	0.4 mH
Capacitive load of filter	2 KVAR
Active power of the load	1 KW
Irradiance of PV	250 and 750 (W/m^2)
Temperature of PV	25°C
Capacitance across PV array	1 mF

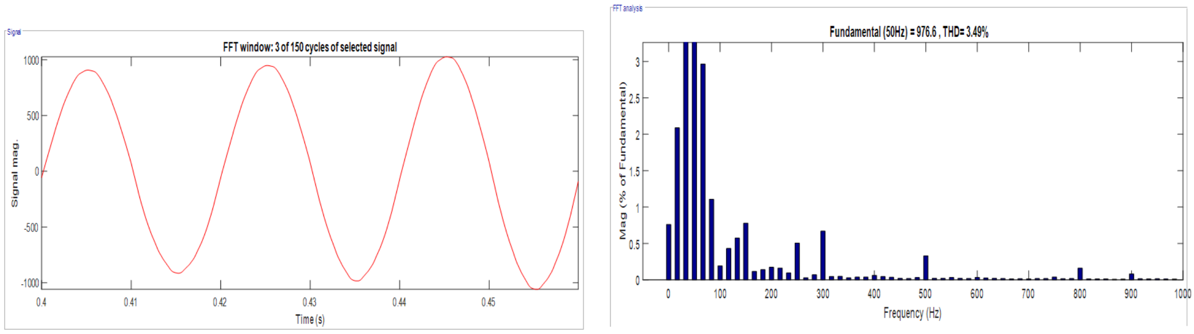
The THD analysis is shown in **Figures 23 and 24**. The signal magnitude and THD% without using any filter are shown in **Figure 23**.



(a) (b)

Figure 23. Without using filter (a) signal magnitude (b) THD%

The signal magnitude and THD% by using the LC filter are shown in **Figure 23**. Here the THD reduces to an ales value when we use the LC filter.



(a) (b)

Figure 24. Data obtained using LC filter (a) signal magnitude (b) THD%.

Figure 25 shows output voltage waveform of MLI. Here output voltage waveform is similar to the sinusoidal waveform.

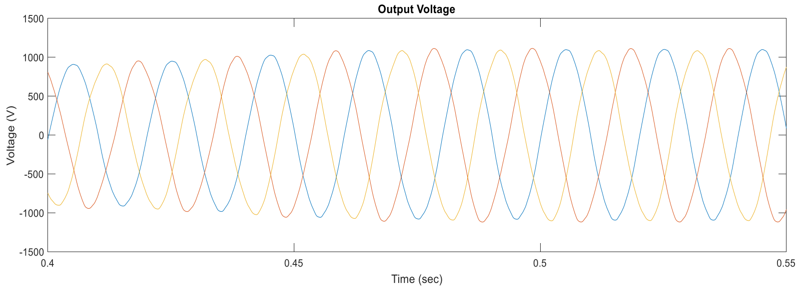


Figure 25. Waveform of output voltage.

Figure 26 shows the output voltage waveform of MLI. Here output voltage waveform is similar to the sinusoidal waveform.

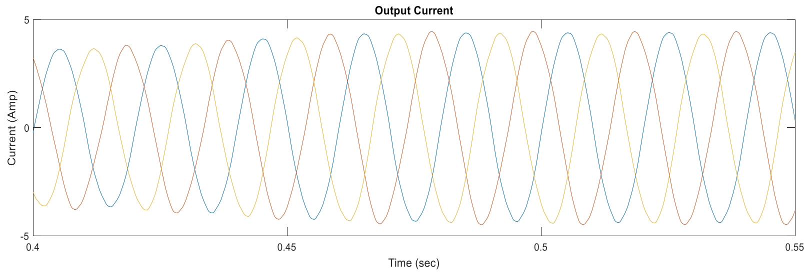


Figure 26. Waveform of output current.

Figure 27 shows the waveform of PV voltage. Here how the voltage is varying concerning time is shown.

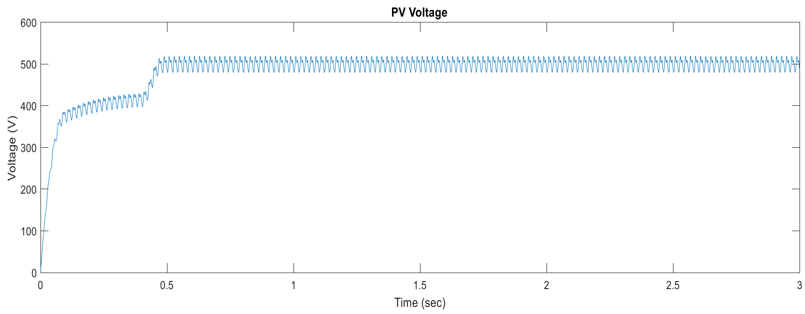


Figure 27. PV Voltage.

PV current is shown in **Figure 28**. Here how the current is varying concerning time is shown.

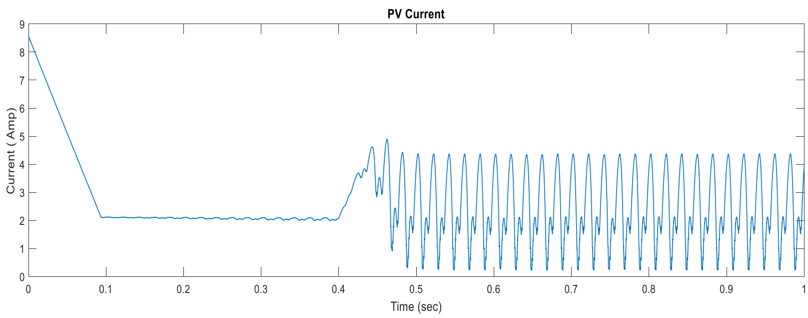


Figure 28. PV Current.

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PV power is shown in **Figure 29**. Here how the power is varying concerning time is shown.

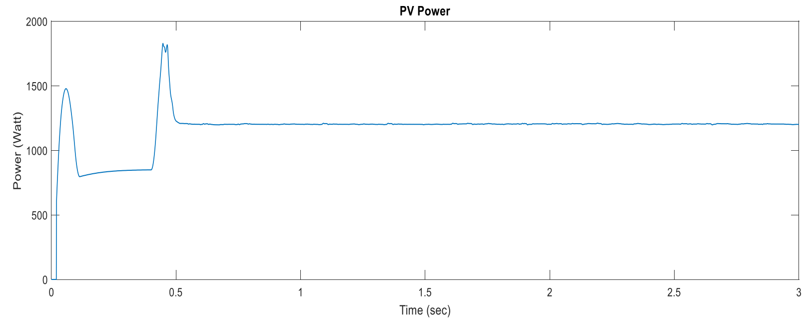

Figure 29. PV Power.

Solar irradiance is shown in **Figure 30**. Here how the irradiance is varying concerning time is shown.

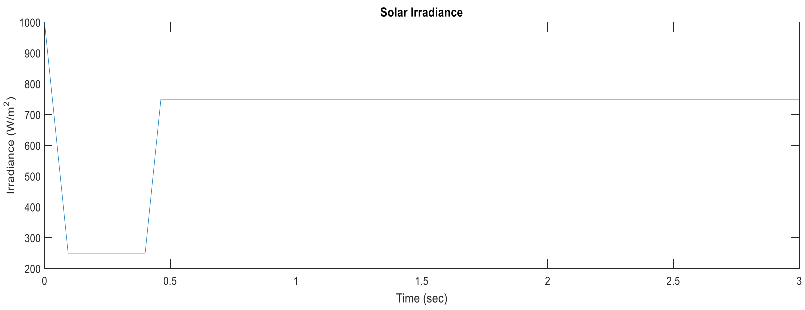

Figure 30. Solar irradiance variation.

4. CONCLUSION

In this report, a description of MLI is provided, which can be used for educational purposes. The pulse given to the switches of the converter is based on the Sinusoidal PWM method. It is a very easy method among the other types of PWM methods. Here a PV array is used as the source given to the converter. Here the different values of irradiance and temperature are taken into consideration. Here the THD of the output voltage waveform remains at 17.40 %. When the LC filter is used then the THD reduces to 3.49 %. Here the output voltage and current waveform are similar to the sinusoidal waveform. Fourier analysis is done to analyze the THD. Line voltages, phase voltages, and different cell voltages are plotted here. Also, the THD values are plotted. The voltage, current, power, and irradiance waveform of the PV cell is also plotted and analyzed. This model is simulated in MATLAB/SIMULINK.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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