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# Grid Tied Solar Panel Interfacing using $2(\sum_{N=1,2,3...} 3^{(N-1)})+1$ Level Inverter with Single Carrier Sinusoidal Modulation; where N is the number of H-bridges

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**Abstract**

This paper presents a Trinary Based Cascaded H Bridge Multi Level Inverter employing Single Carrier Sinusoidal Modulation (SC-SPWM) for Grid Tied Solar Panel Interfacing. Each inverter bridge is connected to a 200W solar panel. This topology uses Trinary logic for input voltage source division which results in significant reduction in the number of H-bridges and hence the number of power switches when compared to the conventional technique. This cascaded multilevel inverter has $2(\sum_{N=1,2,3...} 3^{(N-1)})+1$ levels, where N is the number of H-bridges. Single carrier sinusoidal pulse width modulation (SC-SPWM) is used to produce grid voltage and grid frequency .To assure optimal operation of the inverter when connected to the power grid, simulation results are shown for voltage and current during power transfer mode and THD is measured.

**Index Terms:** Cascaded H Bridge Multi Level Inverter, Solar panel interfacing, Trinary logic, Single carrier sinusoidal modulation (SC-SPWM).

## Introduction

In the current global climate, demand for a renewable energy system has increased due to environmental issues and limited fossil fuels. Along with this demand, Photo voltaic (PV) and wind turbine (WT) systems have become the most common type of grid connected renewable energy systems. However, to connect these systems with the grid, output voltage and frequency adjustments are the challenging issues. In response to the growing demand for medium and high power applications, multi level inverters have been attracting growing consideration in variable speed wind turbine (WT) and Photo voltaic (PV) systems. [1],[2]. Multilevel inverters are mainly used in high power applications where they have proved to be reliable and efficient. [3] They operate with low frequency and present high efficiency. Multilevel inverters enable the output voltage to be increased without increasing the voltage rating of the switching components [4] so that they offer the direct connection of renewable energy systems to grid voltage without using the expensive, bulky and heavy transformers.

## Cascaded multilevel inverters

Among different types of multilevel inverters, Cascaded type of multilevel inverter is commonly used in PV applications due to its modularity and structure. However, the main problem associated with the Cascaded type is the need for isolated DC sources which are not usually available without the use of transformers. In some specific applications such as photovoltaic systems, separate dc sources exist and can be used in the Cascaded type [5],[6]. A diversity of multilevel converter topologies have been used in photovoltaic applications [7], [8], [9] and a comparison of some topologies is presented in [10].

Fig. 1 shows the structure of cascaded multilevel inverter. The full-bridge topology with four switches is used to synthesize a three-level square-wave output voltage waveform. The cascaded multilevel inverter consists of series connections of N full-bridge topology. For N number of full-bridges, the effective number of output voltage steps ($N_{step}$) in symmetric multilevel and the maximum output voltage ($V_m$) of this N cascaded multi-level inverter is given by the following equations:

$$N_{step} = 2N + 1 \tag{1}$$

$$V_m = N\,Vd \tag{2}$$

Cascaded multilevel inverters synthesize a medium voltage output based on a series connection of power cells which use standard low-voltage component configurations.

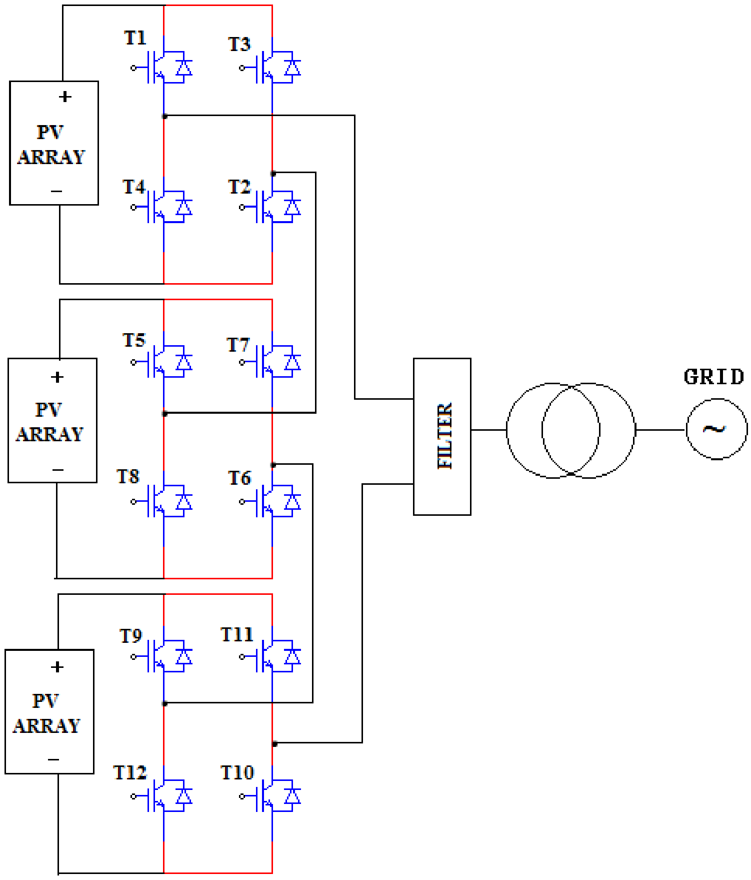


**Figure 1:** Cascaded multilevel inverter.

This characteristic allows one to achieve high-quality output voltages and input currents and also outstanding availability due to their intrinsic component redundancy. Due to these features, the cascaded multilevel inverter has been recognized as an important alternative in the medium-voltage inverter market.

## Modulation Method

Modulation control of a multilevel inverter is quite challenging and much of the reported research is based on somewhat heuristic investigations. Most of the available works on PWM schemes for a multiphase voltage source inverter cover either carrier-based PWM or space vector PWM schemes. When it comes to multilevel voltage source converters, the first notion is that need for a large number of switches that may lead to complex pulse-width modulation (PWM) switching scheme. However, early developments in this area demonstrated the relatively straightforward nature of multilevel PWM. Various PMW techniques applied to the multilevel converters are discussed in [11], [12].

The most popular and simple switching scheme for multilevel voltage source converter is Multi-carrier-PWM (MCPWM) shown in fig.2. For an N-level converter, (N-1) carrier signals with the same frequency fc and peak-to-peak amplitude Ac are placed in such a way, that they occupy continuous bands between the positive and negative DC rail of the inverter[13],[14]. The voltage reference, or modulation, waveform has a peak-to-peak amplitude $A_m$ and frequency $f_m$, and it is centered in the middle of the carrier set. The voltage reference is continuously compared with each of the carrier signals. In multilevel converters, the amplitude modulation index ($m_a$) and the frequency ratio ($m_f$) are defined by equations (3) and (4), respectively.

$$m_a = A_m / A_c(N-1) \tag{3}$$

$$m_f = f_c/f_m \tag{4}$$

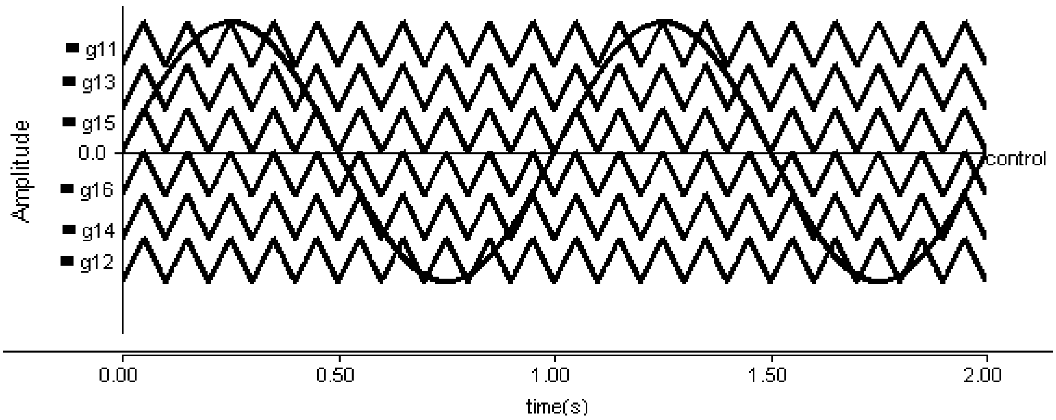


**Figure 2:** Level Shifted Multi Carrier PWM.

There are three schemes for level shift multi-carrier modulation listed as follows:

i. In-phase disposition (IPD), where all carriers are in phase.
ii. Alternative phase opposite disposition (APOD), where all carriers are alternatively in opposite disposition.
iii. Phase opposite disposition (POD), where all carriers above the zero reference are in phase but in opposition with those below the zero reference.

This paper addresses Grid Tied Solar Panel Interfacing Using Trinary Based Cascaded H Bridge Multi Level Inverter employing Single Carrier Sinusoidal Modulation (SC-SPWM). Compared with the existing cascaded multilevel inverters, this topology provides grid voltage and frequency

## PV Interface Module

Synchronization between grid and inverter is made when both have same phase angle, frequency and amplitude. The grid output voltage is used to generate sine wave that is used as the reference signal which will generate the SPWM signals to drive the switches. The power flow to the grid is controlled according to equation (5)

$$P = \frac{V_{in}.V_{grid}}{X}\sin\delta \tag{5}$$

Where $V_{in}$ is the inverter voltage, $V_{grid}$ is the grid voltage, δ is the voltage angle between inverter voltage and grid voltage, X is the connection impedance. Maximum power point tracking algorithm can be used to determine the optimal output power and phase angle variation.

## Multilevel Inverter with DC Sources in Trinary Fashion

The cascaded multilevel inverter shown in fig.1 can have different input voltage source division. Table1 shows the comparison of Cascaded MLI with different possible voltage source division (Equal, Binary and Trinary divided DC sources). Therefore it is obvious that the Trinary multilevel inverter can generate a larger number of levels with the same number of H-bridge cells. For instance, by using three series-connected H bridges inverters with dc voltage sources configured in Trinary fashion ($V_{DC}$, $3V_{DC}$ and $9V_{DC}$) it is possible to generate 27 distinct voltage levels at output phase voltage, while with dc voltage sources configured in the ratio 4: 2:1 it is possible to achieve 15 distinct levels and with equal dc voltage sources it is possible to achieve only 7 distinct levels. Table 2 shows the switching pattern and the output voltage level while with dc voltage sources configured in the ratio 9: 3 :1

**Table 1:** Comparison of Cascaded MLI with different possible voltage source division.

| Cascaded MLI | No. of DC Sources (N) | No. of Switches (4N) | No. of Levels / Phase |
|---|---|---|---|
| Equal DC Sources | 3 | 12 | (2N+1) = 7 |
| Binary DC Sources | 3 | 12 | (2(N+1)-1) = 15 |
| Trinary DC Sources | 3 | 12 | $2(\sum_{N=1,2,3...} 3^{(N-1)})+1=27$ |

**Table 2:** Switching pattern and the output voltage level with dc voltage sources configured in the ratio 9: 3 :1.

| T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | T10 | T11 | T12 | V0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 2 |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 3 |
| 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 4 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 5 |
| 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 6 |
| 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 7 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 8 |
| 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 9 |
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 10 |
| 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 11 |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 12 |
| 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 13 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | -1 |
| 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | -2 |
| 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | -3 |
| 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | -4 |
| 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | -5 |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | -6 |
| 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | -7 |
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | -8 |
| 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | -9 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | -10 |
| 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | -11 |
| 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | -12 |
| 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | -13 |

## Single Carrier Sinusoidal PWM (SC-SPWM)

The basis of selecting the method of controlling the converter output voltage is dependent on the ability to control the THD. In this paper, Single Carrier Sinusoidal PWM (SC-SPWM) is adopted to control the inverter output voltage. Fig 5 shows the Single Carrier Sinusoidal PWM. The main advantage of SC-SPWM is its ability to define the location of the switching transitions that control or eliminate selected harmonics. This PWM technique is aimed at high power voltage source inverter systems in utility applications where the output frequency is fixed to the utility's grid frequency. Moreover many number of carrier signal generation for increased levels in a multilevel inverter are avoided. In SC-SPWM, only one carrier signal train is generated which is compared with the sinusoidal reference signal. Switching pulses are generated by comparing the sinusoidal reference with the triangular carrier signal for the first level. For the next level, the sinusoidal reference signal is level shifted down by one and compared with the triangular carrier signal for switching pulse generation. Thus switching pulse for multiple levels is achieved by comparing the level shifted sinusoidal reference with single triangular carrier signal.

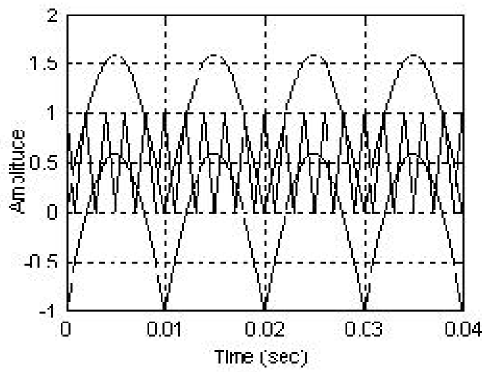


**Figure 5:** Single Carrier Sinusoidal PWM.

The Fig.6 shows the block diagram of generating Single Carrier Sinusoidal PWM (SC-SPWM). The sinusoidal reference is taken from the grid voltage. This sinusoidal reference waveform is given to a zero crossing detector which gives signal to the switch selector to turn on the switches of the H-Bridge. The bi-directional sinusoidal reference waveform is converted to a unidirectional signal and given to a level shifter and level detector. The level detector detects the level of the sinusoidal reference waveform to determine the level to be compared with the carrier and gives signal to the level shifter which shifts the sinusoidal reference waveform downwards by one level. This level shifted sinusoidal reference waveform is compared with high frequency carrier signal to generate PWM pulses. Thus the sinusoidal reference waveform is level shifted downwards and scaled between 0 to 1 and compared with a single triangular carrier train. The signal from level detector and the PWM pulses are given to level selector which separates the PWM pulses corresponding to each level. The switch selector matches the PWM pulses with the switching pattern of Cascaded MLI and turns ON the necessary switches of the corresponding level according to the switching pattern.

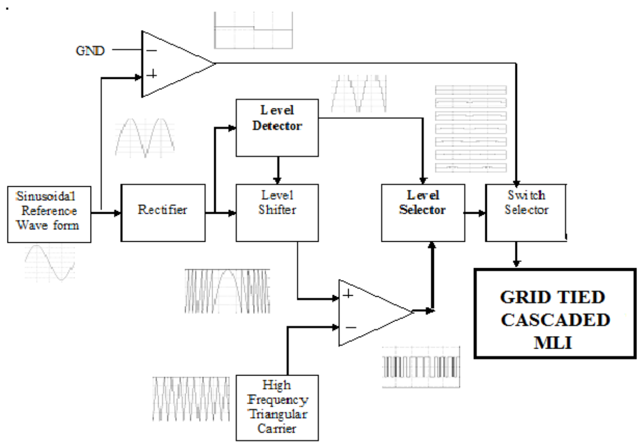


**Figure 6:** Block diagram of Single Carrier Sinusoidal PWM (SC-SPWM) generation.

The connection to the grid is done through a variable transformer to assure that at any time the number of H Bridges used can be controlled, the grid voltage generated by the inverter is met and also to give more flexibility to the experiment since irradiance levels might not be enough. The individual solar panel output power is proportional to solar irradiance variations that occur during the day. The MPPT algorithm can be used which will work sensing the output power.

## Simulation Results

In this paper, the simulation model is developed with MATALB/SIMULINK. The SIMULINK model for the power circuit is shown in Fig 7.

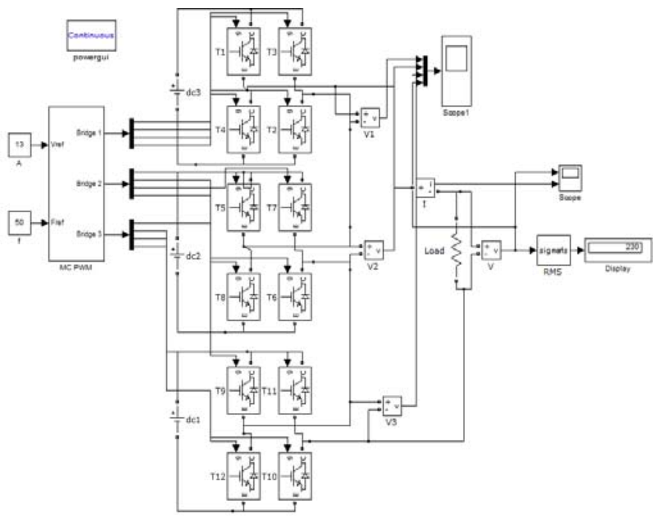


**Figure 7:** Simulation Circuit of Cascaded MLI.

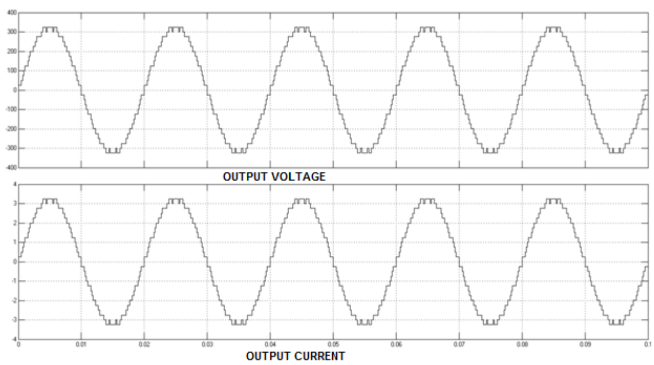


**Figure 8:** Output voltage and Current Waveforms.

(X-axis: 1Unit=0.01s; Y-axis: 1Unit=100V (Voltage Waveform); 1Unit=1A (Voltage Waveform))

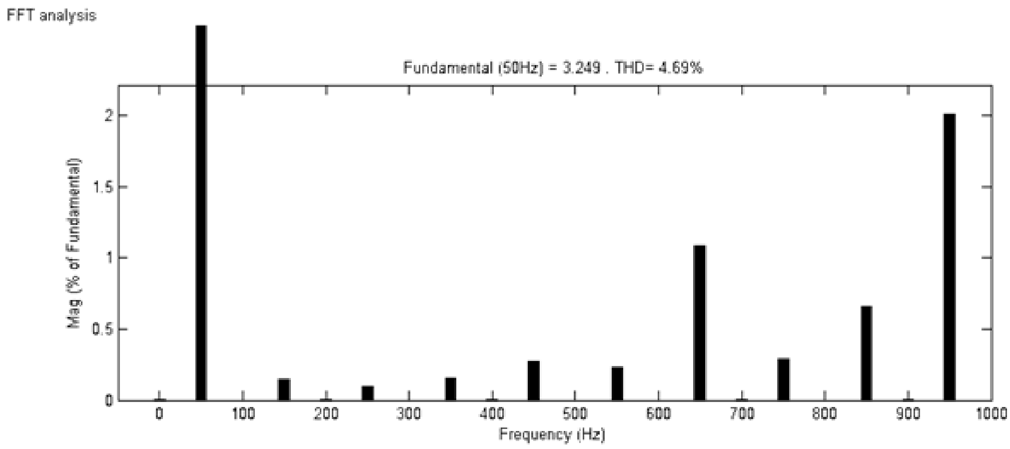


**Figure 9:** THD for Grid Tied Cascaded MLI with Trinary DC sources.

Fig 8 and Fig 9 represents the simulation results of output voltage and current waveforms and current harmonics spectrum respectively. The synthesized output voltage waveform show better output voltage quality. The quality of the output voltage waveforms from SC-SPWM operation is evaluated based on the performance index namely the total harmonic distortion (THD). It is found that the SC-SPWM offers a lower THD of 4.59% .

## Conclusion

There has been a noticeable increase in use of Solar PV based systems for power generation, given its renewable nature. A solar PV based grid tie inverters are used for dc-ac conversion. The conventional line commutated ac-to-dc inverters have square-shaped line current which contains higher-order harmonics. The line current with the high harmonic contents generates EMI and moreover it causes more heating of the core of distribution/power transformers. Alternatively, PWM based inverters using MOSFET/IGBT switches are also used for the same purpose. However, apart from higher switching losses, the power handling capability and reliability of these devices are quite low in comparison to thyristors. A pure sinusoidal line current or waveform with low harmonic contents is the most desirable. In the present work, a Grid Tied Solar Panel Interfacing Using Trinary Based Cascaded H Bridge Multi Level Inverter employing Single Carrier Sinusoidal Modulation (SC-SPWM) is discussed which improves the wave shape and hence reduces the total harmonic distortion (THD) of the line current. Moreover, the performance of the proposed topology is far better than the conventional line-commutated inverter. It reduces THD, losses, switching stress and EMI. The operation and performance of the proposed multilevel inverter is verified through simulation using MATLAB/ SIMULINK. It was also shown to be valid for any number of phases or levels. Analyses and simulations demonstrated the superiority of the proposed system.

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