Solar Photovoltaic Power Conversion Using Modular Multilevel Converter

Rajasekar S., *Student Member IEEE* and Rajesh Gupta, *Senior Member IEEE*

Abstract— **This paper makes an attempt to develop grid connected solar photovoltaic array power conversion using modular multilevel converter. The proposed system makes use of single stage power conversion with maximum power point tracking and modular multilevel converter (MMC) as interfacing unit into the grid. Here perturb & observe method of maximum power point algorithm is used to regulate the DC link voltage of the MMC and to synchronize the grid utility voltage with the current for attaining near unity power factor operation under varying environmental conditions. The simulation results presented in this paper verifies the operation of proposed MMC topology such that the AC output is free from the higher order harmonics and grid voltage and current are in phase. The simulation studies are carried out under power system computer aided design PSCAD/EMTDC 4.2 environment.**

Index Terms— **Grid, modular multilevel converter (MMC), photovoltaic (PV) array, total harmonic distortion (THD).**

I. Introduction

RECENTLY renewable energy power supplied into the utility grid has been paid much attention due to increase in fossil fuel prices, environmental pollution and energy demand boom. Among various renewable energy resources such as solar, wind, tidal, geothermal, biomass etc., the solar photovoltaic system being more attractive and promising green resource because of its abundant availability, safe resource, cost free and eco-friendly [1]. The solar photovoltaic (PV) modules directly converts the light energy into the electrical energy, but energy obtained from the PV module acts as low voltage DC source and has relatively low conversion efficiency. In order to improve the efficiency and convert low voltage DC source into usable AC source, the power electronics converters are used to transform DC into AC. Conventional inverter topologies such as voltage source inverter (VSI) and the current source inverter (CSI) are being utilized to convert solar power generated electrical power into the utility grid. Whereas these topologies require additional DC/DC converter stage resulting in a two stage power conversion and also require interfacing transformer to inject power into the grid. These topologies not only increase the circuit complexity but also increase the cost and space requirements.

The single stage solar power conversion will satisfy all the control objectives like maximum power point tracking (MPPT), synchronization with grid voltage, and lower harmonic content in the output current. At present scenarios several solutions for a grid connected PV system with conventional two-level and multilevel inverter has been reported in the literature [2]. In case of two-level inverter, it inject maximum PV power into the grid with a unity power factor, however the system fails to be free from higher order harmonics, high voltage stress across the semiconductor power switch and high power losses due to high switching frequency [6]. In order to overcome the above mentioned problems, multilevel inverter came into picture and attracted more attention because of their significant properties. They offer lower total harmonic distortion (THD), low dv/dt device switch voltage stress, lowering the switch voltage and power rating etc. The multilevel inverter is well suited for high power medium voltage applications and in particular dominated by cascaded multilevel inverter and neutral point clamped multilevel inverter. In these medium voltage applications cascaded multilevel inverter and neutral point clamped multilevel inverter requires transformer to obtain electrical isolation between active DC sources of the H-bridge or NPC converter cells. This condition introduces losses, increases converter footprint, making converter costly, bulky and complex. The main drawback of the cascaded multilevel converter coupled with the transformer makes circulation current between phase during unbalanced network conditions and it may cause asymmetrical phase voltages.

The modular multilevel inverter has strong potential to replace cascaded multilevel converter in medium voltage applications [10]. This paper, presents the design of a solar photovoltaic power conversion system with single stage modular multilevel converter. Currently intensive research is going on in MMC and it has high potential for medium power applications. Modular multilevel converters have several advantages over conventional multilevel topologies. Those significant are as follows.

- Generate low harmonic output voltage, this eliminates filtering requirements.
- For medium voltage application, it allows to avoid interfacing transformer.
- Modular structure allows to extend higher number of levels easily.
- Capacitor voltage balancing is attainable independent of the load.

Although MMC are investigated with many applications, but it has not been reported in the literature with single stage solar PV power conversion system. This paper demonstrates the effective implementation of the photovoltaic supported MMC for grid interface which satisfy all the control objectives like maximum power transferring under varying environmental conditions, synchronizing grid utility voltage with output current for unity power factor operation and low total harmonic distortion. Ssection II gives introduction about

Authors are with the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Allahabad-211004, India (e-mail: rajasekarsmvec@gmail.com, rajeshgupta310@rediffmail.com)

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basic characteristics of the photovoltaic module which is followed by section III that describes MMC topology with the proposed single stage power conversion of solar energy. Section IV discusses about perturb & observe maximum power transfer algorithm and role of maximum power point tracking in MMC topology. Section V and VI explains about simulation results and effectiveness of the proposed topologies over conventional inverter topologies.

II. OVERVIEW OF A PHOTOVOLTAIC (PV) MODULE

To understand the PV module characteristics it is necessary to study about PV cell at first. A PV cell is the basic structural unit of the PV module that generates current carriers when sunlight falls on it. The power generated by these PV cell is very small. To increase the output power the PV cells are connected in series or parallel to form PV module. The electrical equivalent circuit of the PV cell is shown in Fig. 1.

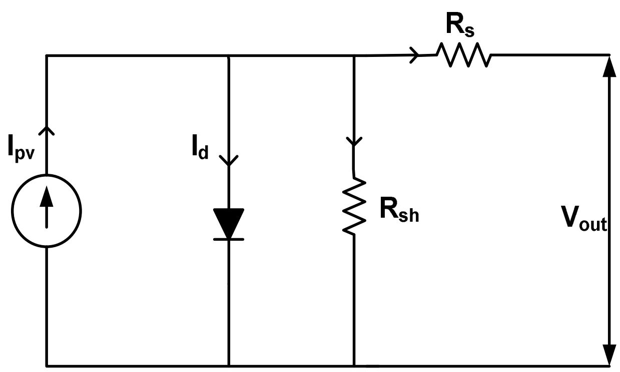

Fig.1. Electrical equivalent circuit of PV cell.

The main characteristics equation of the PV module is given by [2]

$$I = I_{pv} - I_o\left[\exp\left(\frac{q(V + IR_s)}{\alpha KT}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{\alpha K}\right]\left(\frac{1}{T_n} - \frac{1}{T}\right) \qquad (2)$$

$$I_{pv} = [I_{sc} + K_i(T - T_n)]\frac{G}{G_n} \qquad (3)$$

Where,

I and V	cell output current and voltage;
I_o	cell reverse saturation current;
T	cell temperature in Celsius;
K	Boltzmann's constant;
q	electronic charge;
Ki	short circuit current/temperature coefficient;
G	solar radiation in W/m2;
G_n	nominal solar radiation in W/m2;
E_g	energy gap of silicon;
$I_{o,n}$	nominal saturation current;
T_n	nominal temperature in Celsius;
R_s	series resistance;
R_{sh}	shunt resistance;
α	ideality factor between 1.0 to 1.5;
I_{pv}	light generated current;

The I-V characteristic of a PV module is highly non-linear in nature. This characterisitcs drastically changes with resepct to changes in the solar radiation and cell temperature..Whereas the solar radiation mainly affects the output current, the temperature affects the terminal voltage. Fig.2 shows the I-V characterisitcs of the PV module under varying solar radiations at contant cell temperature (T = 25 ºC).

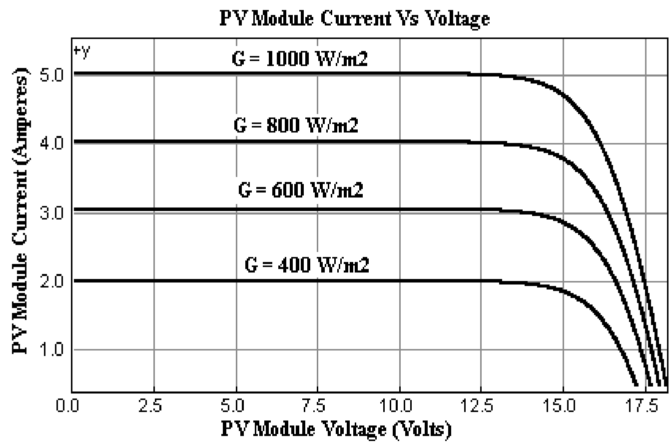

Fig.2. Current versus voltage at constant cell temperature T = 25 ºC.

Fig.3 shows the I-V characterisitcs of the PV module under varying cell temperature at contant solar radiation (1000 W/m^2).

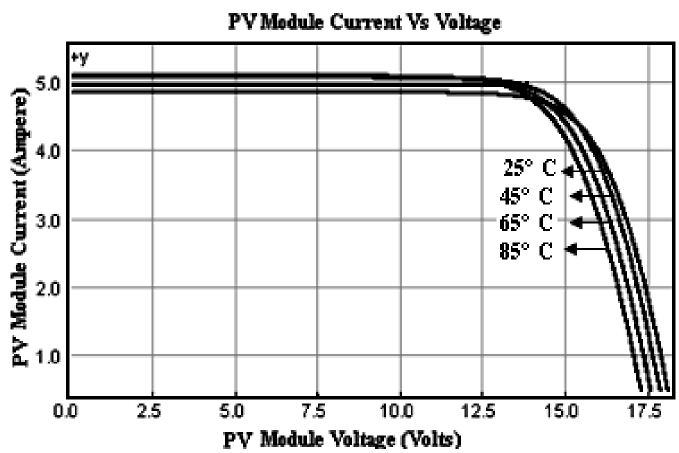

Fig. 3. Current versus voltage at constant solar radiation G = 1000 W/m^2.

III. MODULAR MULTILEVEL CONVERTER

Modular multilevel converter is new topology suitable for medium voltage applications. Marquardt and Lesnicar designed modular multilevel converter (MMC) in 2002. The basic component of the MMC is called a submodule. It is a half bridge with capacitor as shown in Fig.4. Each submodule consist of two insulated-gate bipolar transistor (IGBT)/diode switches (S1, S2, D1 and D2). The switches within the submodule are switched in complementary fashion. The submodule has two switches, the main switch S1 and auxillary switch S2. When S1 is on and S2 is off, the output voltage V_o is equal to ½ V_{dc} and no charging take place at the capacitor. When S1 is off and S2 is on, the output voltage V_o is equal to zero and capacitor is charging. Table.1 gives the switching states of the submodule.

TABLE.1
SWITCHING STATES OF A SUB-MODULE

Main Switch (S1)	*Auxillary Switch (S2)*	*Output Voltage(V_o)*	*Capacitor state*
ON	OFF	½ V_{dc}	Not Charging
OFF	ON	0	Charging

Fig.5 shows the three level configuration of the MMC, where two sub modules are connected in series on the upper arm and two sub modules are connected on the lower arm. Inductance Ul_a and Ll_a are used to take over the difference between the current of the upper and lower arm. Whereas R_L and L_L are load resistance and load inductance of the MMC converter. Depending upon the voltage requirement the sub modules are inserted on the upper and lower arm.

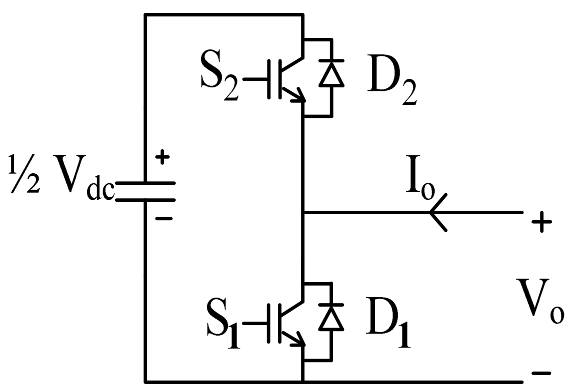

Fig. 4. Structure of one sub-module.

The number of voltage levels for the MMC can be identified using the formula

$$N_V = n/2 + 1 \quad (4)$$

Where, N_V – number of voltage levels
n – Total number of sub-modules

In this paper three level output voltage is obtained using ramp comparison current control technique with the modular multilevel converter [11]. The control function v_{error} is compared with the carrier v_{tri} of switching frequency f_{sw} and amplitude V_{tri}. The three level output voltage is obtained by following unipolar PWM of the control function.

$$v_{error} - v_{tri} > 0, \text{ then S1 is on and } V_o = ½\, V_{dc} \quad (5)$$

$$v_{error} - v_{tri} < 0, \text{ then S2 is on and } V_o = -½\, V_{dc} \quad (6)$$

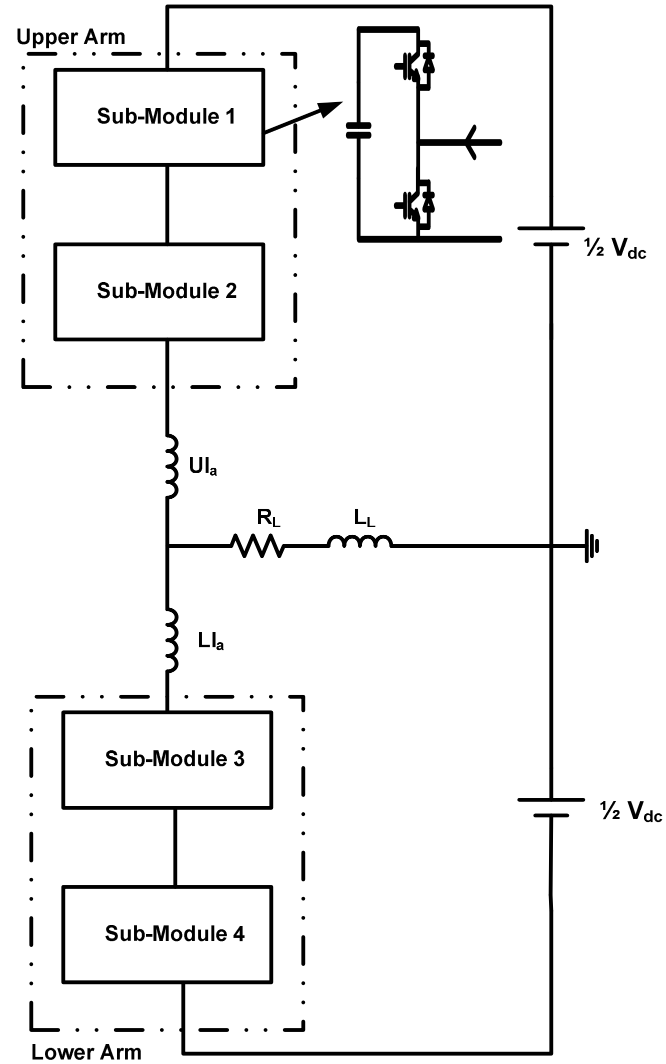

Fig. 5. Single phase of three level modular multilevel converter.

IV. PROPOSED SYSTEM AND ITS CONTROLLER

In this section, the proposed topology of the photovoltaic supported modular multilevel converter and its controller design with maximum power point tracking technique are described. The MMC proposed for a grid connected photovoltaic system is based on the single stage solar power conversion system. Fig.6 shows the photovoltaic supported modular multilevel converter single phase grid connected system. The photovoltaic module is nonlinear in nature, because it is greatly affected by its environmental condition like change in solar radiation and cell temperature. During day time sunshine won't be constant, cloud may pass over so panel may be not be getting constant radiations. Therefore it is necessary to track the maximum power all over the day. The maximum power point tracker works on the fact that derivation of the output power with respect to the panel voltage is equal to zero at maximum power point. Fig.7 depicts the P-V characteristics of the PV module.

$$\frac{\partial p}{\partial v} = 0 \text{ , } V = V_{max} \quad (7)$$

$$\frac{\partial p}{\partial v} > 0 \text{ , V < V}_{max} \tag{8}$$

$$\frac{\partial p}{\partial v} < 0 \text{ , V > V}_{max} \tag{9}$$

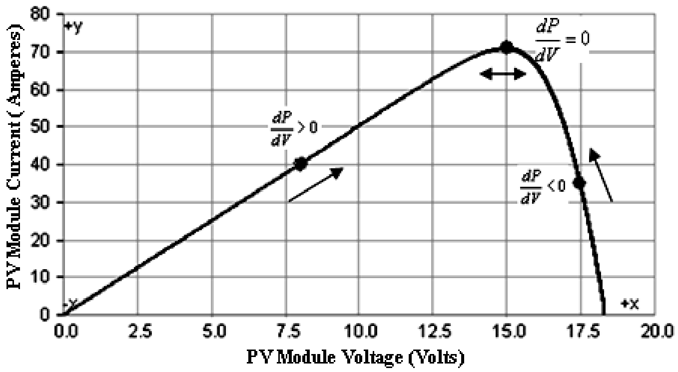

Fig.7. P-V characterisitcs of the module.

The most popular and simple MPPT algorithm is the perturb & observe which is also called as hill-climbing algorithm. This technique employs simple feed back arrangement with the comparison of present and previous measured values.

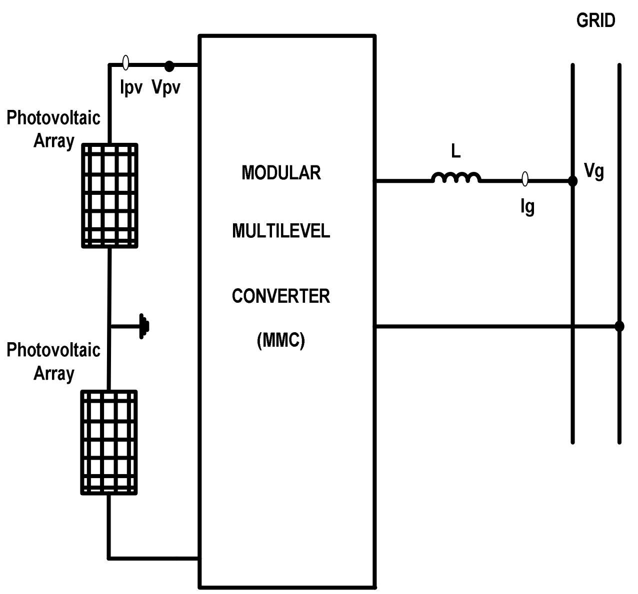

Fig. 6. Photovoltaic Supported Three Level Modular Multilevel Converter.

The proposed MMC is controlled by two control loops. The inner current control loop and the outer voltage control loop. The inner current control loop is designed to control the grid current to be sinusoidal and synchronized with the grid voltage. In outer voltage control loop, the reference DC link voltage is generated by the MPPT algorithm; it sensed I_{PV} and V_{PV} and then generate V_{max}. This V_{max} is DC link voltage required to be regulated across the MMC. The error resulting from the DC voltage control loop is passed through the proportional plus integral (PI) controller. A sinusoidal signal in phase with the utility grid is multiplied by the current reference to form the input reference current for the inner control loop.

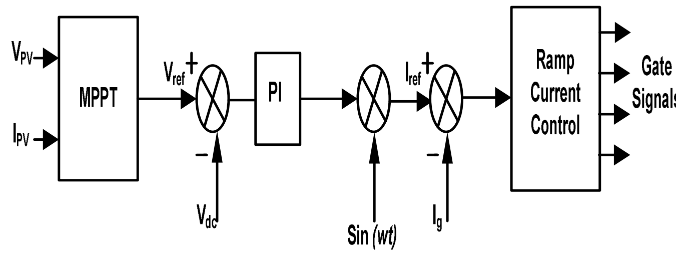

Fig. 8. Block diagram of outer and inner control loop.

V. Simulation Results and Discussions

The proposed modular multilevel converter for grid connected PV system with single stage power conversion is simulated with PSCAD/EMTDC (4.2 version) environment. The photovoltaic array is composed of 108 number of cells connected in series to form a module and 14 modules connected is series to generate voltage of 1200 V. The circuit parameters are shown in the Table.II.

Table.II
System parameter

Item	Value
PV array rated voltage	1.2 kV
Standard Environmental Condition Solar radiation, G Cell temperature, T	 1000 W/m2 25 ^{0}C
System Frequency	50 Hz
Switching frequency,f_{sw}	2 kHz
Sub-Module capacitor, C	500 µF
Ac line inductance, L	1 mH
Grid voltage, V_g	350 V
Number of cell in each arm	2
DC link Voltage	600 V
Arm inductance, Ula,Lla	0.1 mH

The capacitor voltage across lower and upper arm of Modular Multilevel converter depicts in Fig.9. We can observe that converter voltage across the capacitor are balanced and maintains less voltage ripple. This increases PV lifetime, also desirable feature of MMC for grid connected PV system.

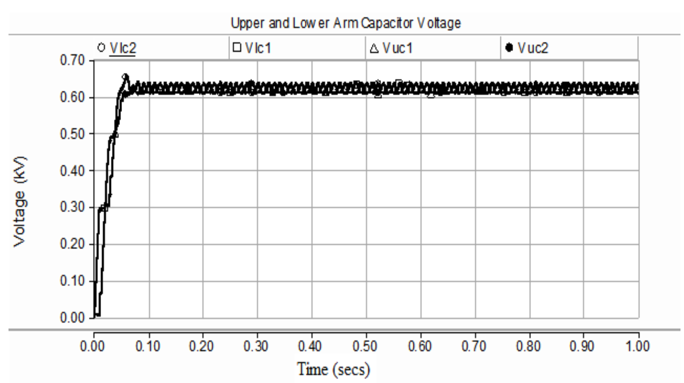

Fig.9 Capacitor voltage across lower and upper arm.

Fig.10 demonstrates the effectiveness of the proposed system controller such that the injected grid current is accurately tracks the reference current. This tracking makes the grid current sinusoidal and free from harmonics.

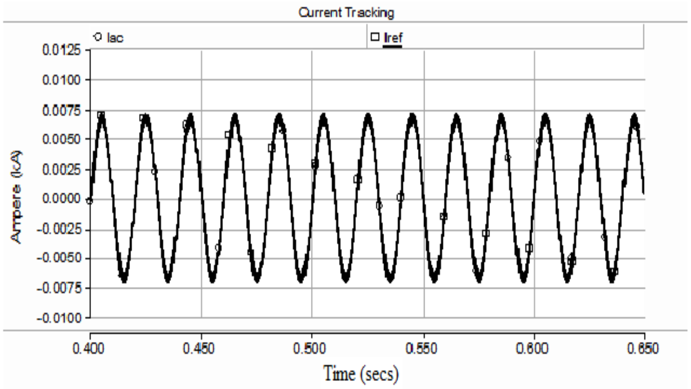

Fig.10 Current tracking of grid current.

The three-level MMC output voltage is shown in the Fig.11. The proposed controller has the better efficiency and performs almost at unity power factor condition such that the grid voltage and injected current are in-phase. This is clearly visible in Fig.12. Effectiveness of the ramp current control technique is shown in the Fig.13, where triangular carrier of 2 kHz is compared with the error signal in order to produce gating signal for switches of the MMC. Fig.14 shows the AC side grid voltage with the output voltage of the proposed MMC. Fig.15 shows the grid current, lower arm current and upper arm current.

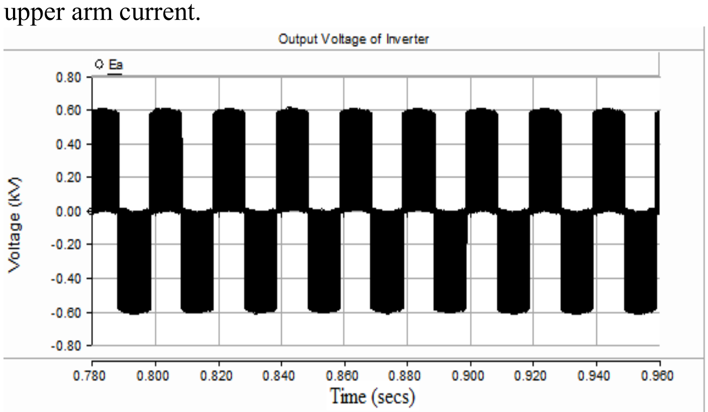

Fig.11 Output voltage of modular multilevel converter.

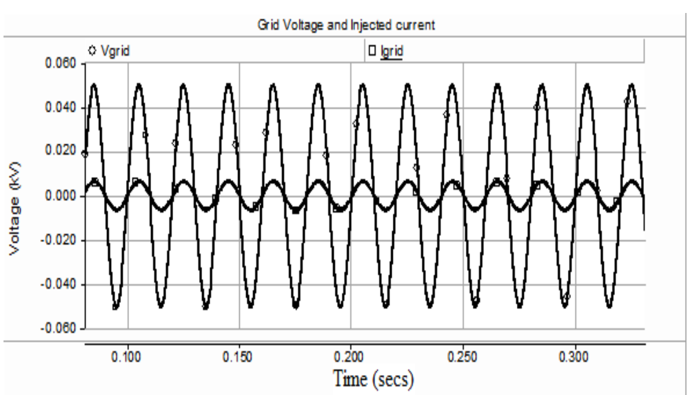

Fig.12 Grid voltage and injected current.

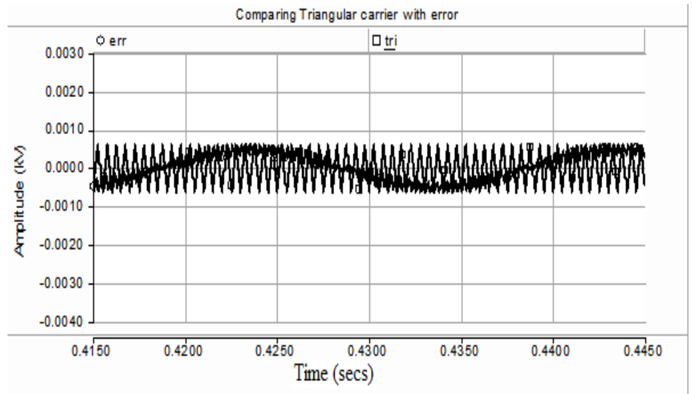

Fig.13 Triangular carrier comparison with the error signal.

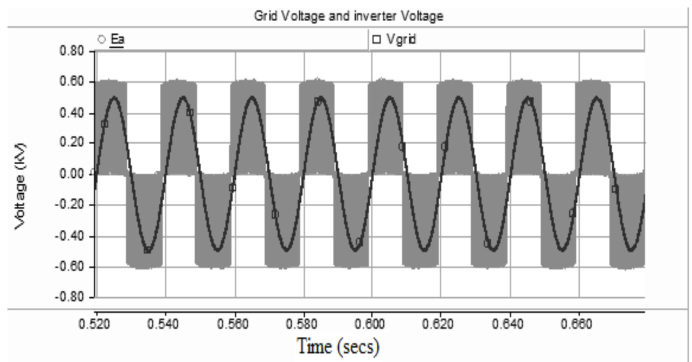

Fig.14 Grid voltage and MMC output voltage.

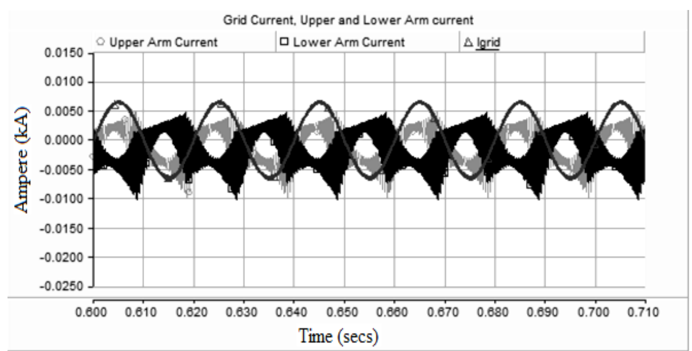

Fig.15 Grid current, lower arm current and upper arm current..

VI. CONCLUSION

In this paper, a single stage MMC based grid connected photovoltaic system is proposed. The modular concept allows the application to be extended for wide power range. This study makes an attempt and verifies that the MMC system is capable of injecting power into the grid with low total harmonic distortion, unity power factor and high efficiency. Conventional multilevel converter requires interfacing transformer for grid connected system applications, whereas MMC topology requires filter to connect inverter into the grid. Low switching frequency of the switches in the MMC leads to low power loss. The effectiveness of the proposed grid connected MMC single stage power converter is demonstrated through simulation studies.

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