An Advanced Five Level Cascaded Inverter Based Power Conditioning System for Solar Power Applications

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***Abstract* – Because of their promising nature and ability to overcome the drawbacks of conventional energy systems, most of the countries are looking towards renewable energy systems at present. This paper mainly deals with a power conditioning system which can be used to extract variable DC power from sun and convert it into Ac power to drive the three phase loads using FPGA. It also proposes the utilization of cascaded H-bridge multilevel inverter because of its unique features which are suitable especially for solar applications. The power conditioning system comprises of two stages. In first stage we convert variable DC from sun into fixed DC with boost converter and in second stage, DC is converted to 3-phase AC by cascaded H-bridge inverter. Multicarrier sinusoidal pulse width modulation is used to control the multilevel inverter which drives 3 phase loads efficiently.**

Keywords- Solar PV System, Multilevel Inverters, Boost Converter, Sinusoidal Pulse Width Modulation, Cascaded Inverters, FPGA

I. INTRODUCTION

About 40 percentage of the total primary energy is used in generating electricity. Nearly 70 percentage of the energy used in our homes and offices is in the form of electricity. To meet this demand, most of the developed countries are dependent on conventional power plants like nuclear, thermal and hydro power plants. With rapid consumption of fossil fuels such as coal, oil and gas, energy crisis and environmental pollution is increasing day by day. Because of which all the countries are now emphasizing towards development of new, clean, green, economical, safe and reliable energy sources. The research in renewable energy has become an increasingly important topic in 21st century with the increasing energy crisis.

Solar PV cell is a basic element in solar PV system which converts light energy into electrical energy. Combination of several PV cells together forms Solar PV Module. This will produce variable DC output voltage with the inputs of solar irradiation and temperature. Under normal operating condition, it operates at a unique operating point to produce maximum output power [3]. We can easily obtain maximum efficiency by using Maximum Power Point Tracker (MPPT), which is a part of power conditioning system. Power Conditioning System (PCS) is a part of power electronic system used to manage the electrical energy effectively and to provide high quality maximum power from solar PV modules.

The proposed PV system comprises of 2-stage power conversion system. The first stage converts the variable DC voltage obtained from solar PV module/array into fixed DC using Boost converter. In the second stage of power conversion, the output of the first stage is fed to 3-phase, Cascaded H-Bridge Inverter. Multilevel inverters have drawn tremendous attention in the power industry. The unique features of these inverters have nominated them as significant alternatives for solid state power converting units even at low and medium power range. The fact that multilevel converters require several DC sources in their input side makes them more attractive for PV power applications [2]. They have been developed in such a way so as to overcome the shortcomings of solid-state switching device ratings by using a series connected semiconductor device which blocks the higher voltage levels involved.

Here, a 12V solar PV module is used to feed closed loop DC-DC Boost converter to drive the Cascaded Inverter. Voltage Mode control (VMC) technique is employed to control the Boost Converter. The 2-stage Power conditioning system is controlled with the help of digital controller (FPGA). Simulation of Proposed system with resistive load gives the THD value of 5.93%, which is highly appreciable and acceptable.

II. PROPOSED SYSTEM

The proposed system is the combination of several elements which includes PV cell or module, Power conditioning system, boost converter, FPGA controller, and cascaded inverter and load.

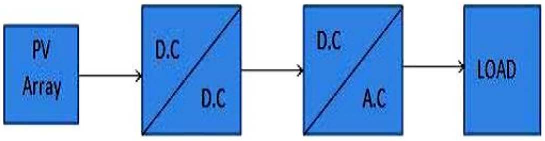

Figure 1: Block diagram of proposed system

Block diagram of the proposed PV system is shown by figure 1. The detailed discussion on every elements of proposed system will be done in further sections. The power conditioning system for proposed system is shown in figure 2.

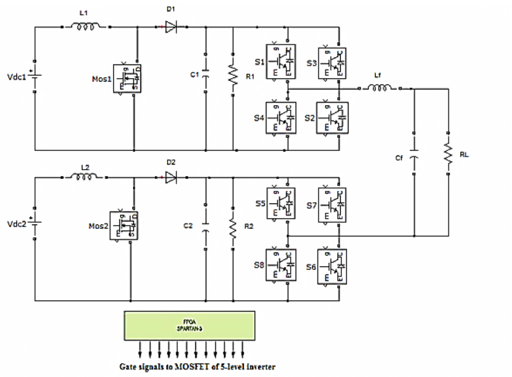

Figure 2: Proposed power conditioning system with FPGA controller

A. *Power Conditioning System:*

As discussed above, power conditioning system is one of the major elements of the proposed PV system.Power Conditioning System is branch of power electronics, which is used to describe the management of electrical energy effectively, track the maximum operating point and provide good quality of desired AC output [5].

A 2- stage power conditioning system is an effective way of generating higher level voltage from the lower level voltage efficiently. The first stage converts the variable DC voltage obtained from solar PV module/array into fixed DC using Boost converter. In the second stage of power conversion, the output of the first stage is fed to 3-phase, Multilevel Cascaded Inverter. Voltage Mode control (VMC) technique has been employed to control the Boost Converter. Sinusoidal Pulse Width Modulation (SPWM) is an open loop control technique, which is employed to drive switches of Multilevel Cascaded Inverter. Here, the 2-stage Power conditioning system is controlled with the help of digital controller (FPGA).

Power conditioning Elements should have modern and sophisticated electronic devices instead of rudimentary electronic devices which normally dissipates excess amount of power in the form of heat [3]. Since PV Systems cost is relatively high as compared to other energy source systems, in order to meet optimised cost of PV system, it is suggested to use high efficiency power conditioning elements.

B. *PV Cell:*

A PV cell is a solar device or a module which converts solar energy directly to electrical energy. The series or parallel connection of many solar cells together forms a PV module. The amount of solar energy obtained is not constant. It is the function of PV array voltage and current set point. Further, the power is also affected by external conditions like solar irradiance and temperature. It is better to build a simulation model for thorough investigation of PV module because of its complex behaviour [4].

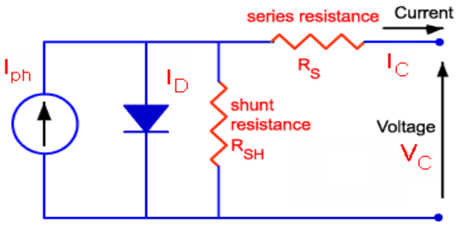

Figure 3: Practical model of PV cell

In general, a solar module is composed of many solar cells connected in series or in parallel. It is made up of rectangular modules (or panels) that measure between 2 to 5 feet on a side. The most common type of PV module has an aluminium frame and a glass cover protecting the collection of polycrystalline PV cells [8]. When exposed to light, each PV cell produces 0.5 volt DC. The best performing commercially available PV cells are roughly 20% efficient at converting solar energy into electricity.

Figure 3 shows an equivalent practical circuit for a PV cell. It contains a light source, diode, series and parallel resistors. The output current of a PV cell can be given as:

$$I = I_{ph} - I_D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

I = Output Current in Amps

I_{ph} = light Current in Amps

I_D = Diode Current in Amps

R_s = Series resistance

R_{sh} = Shunt resistance

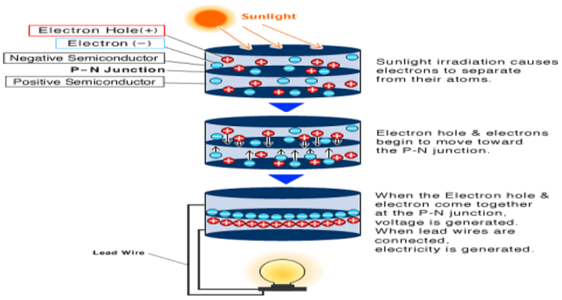

Figure 4: Working of a PV cell

In a PV cell, electrons and holes move across the PN junction same as that of a semiconductor diode. The electron-hole pair combination in return generates energy depending upon the amount of solar irradiance and temperature. Figure 4 shows in detail the working of PV cell.

C. *Boost Converter:*

DC –DC converters are used with the aim of tracking maximum power from the solar panels and step up/down the available DC voltage. A DC-DC Boost Converter is one of the important elements of power conditioning system which converts low level DC voltage to high level DC voltage. This converter operates either in continuous conduction mode or in discontinuous conduction mode. In the power conditioning system proposed in this paper, the boost converter operates in Continuous Conduction Mode (CCM) as shown in figure 5.

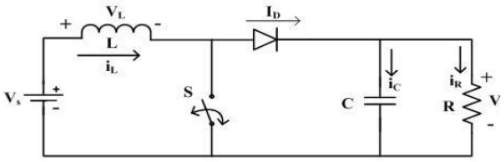

Figure 5: DC-DC Boost converter

In CCM, power can be transferred from source to load using 2 step processes. When the switch 'S' is turned ON, inductor stores the energy, whose equivalent circuit is shown in figure 6. When the switch 'S' is turned OFF, energy stored in the inductor and supply energy is transferred to the load through the diode and it is shown in the figure7.Equivalent waveforms for the various voltages and currents are shown in the figure 8.

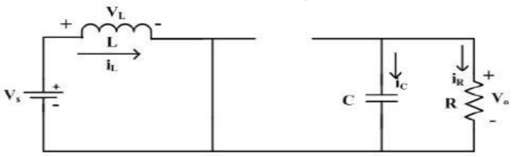

Figure 6: ON State circuit diagram

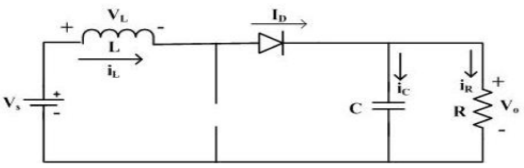

Figure 7: OFF State circuit diagram

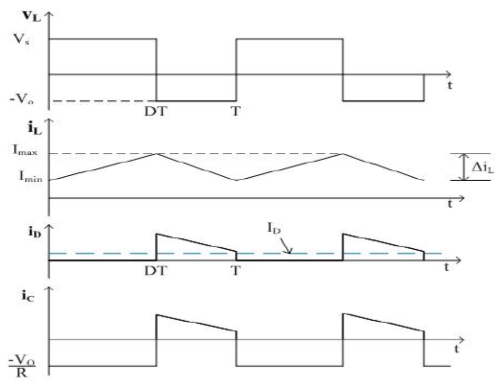

Figure 8: Current and voltage waveforms

For an ideal DC-DC Boost Converter, the relation between input voltage and load voltage is given by:

$V_0 = V_s/ (1\text{-}D)$…………………………….. (2)

Where,

V_0 = Output voltage in volts

V_s= Supply voltage in volts

D= Duty ratio

To obtain the regulated output of desired level with minimum stability margin, we can have closed loop control circuit as shown below:

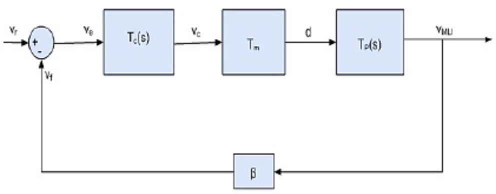

Figure 9: Block diagram of closed loop feedback converter

In the above block diagram, reference voltage V_r is compared with feedback voltage $V_f$to generate error voltage V_e. Error Voltage is then corrected by double lead controller $T_c(s)$ and it produces the control voltage V_c.Pulse width modulator T_m compares the fixed frequency saw-tooth voltage V_{saw} with the control voltage V_c and produces the required duty ratio D.

The DC-DC Boost converter plant $T_p(s)$ gives desired output voltage V_{MLI} corresponding to the corrected duty ratio produced by modulator. The double lead integral controller can be designed and implemented on FPGA spartan-3 XS3C5000.

D. *Cascaded 5-Level Inverter:*

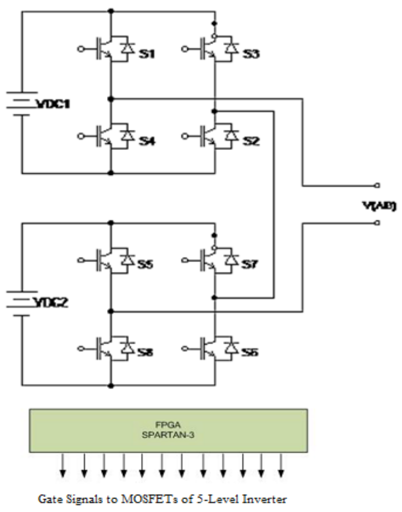

Figure 10: Circuit diagram of 5-Level Cascaded Inverter

5-level cascaded inverter is also one of the important devices in power conditioning system to convert regulated DC voltage into 3-phase AC voltage to drive 3-phase loads. The circuit diagram for the 5-level inverter is shown in figure 10.

This topology generates a high quality output current under any condition specifically in partial shading. Through different combinations of four switches from each cells, each converter can generate three different output voltages namely $+V_{dc}$, 0, $-V_{dc}$. The AC output thus obtained is the sum of individual converter outputs. The number of output phase voltage levels is given by n=2N+1, where N is the number of available DC sources [6]. For example the output of above given inverter topology swings from $-2V_{dc}$ to $+2V_{dc}$ with five levels.

A level shifted sinusoidal pulse width modulation scheme is employed as an open loop control strategy to control the cascaded 5-level inverter. In this scheme, the gate pulses for each phase MOSFETs can be generated by comparing two carrier signals of carrier switching frequency with the reference sinusoidal voltage of line frequency. This control technique is also employed on FPGA to generate the gate pulses.

E. *FPGA (Field Programmable Gate Array):*

A field-programmable gate array (FPGA) is an integrated circuit designed to be configured by a customer or a designer. FPGA configuration is generally specified using a Hardware Description Language (HDL). FPGAs contain a large number of logic gates and RAM blocks to implement complex digital computations. Their designs employ very fast I/Os and bidirectional data buses. They contain programmable logic components called logic blocks which can be reconfigured to perform the complex combinational functions or merely simple logic functions [7]. These blocks also include memory elements which may be flip flops or some complex block of memory. They provide instant manufacturing turnaround and negligible prototype costs which makes them suitable for embedded system design.

We can use, Spartan-3 xc3s5000 FPGA to generate the pulses for both dc-dc boost converter and cascaded 5-level inverter.

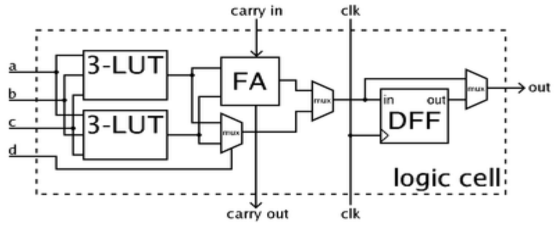

Figure 11: Generalised structure of FPGA

The process to design the process using FPGA can be presented as:

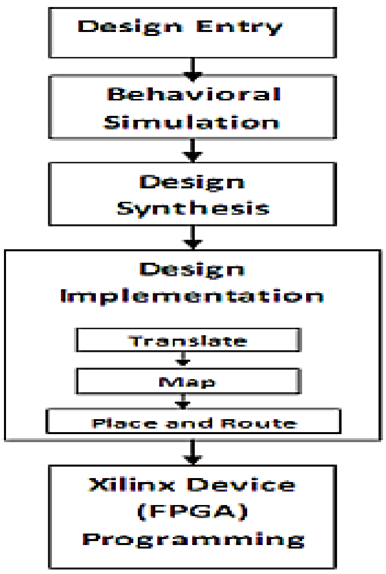

Figure 12: FPGA Design Flow

III. SIMULATION RESULTS

The proposed system is developed in MATLAB simulink environment and the simulation results are shown below.

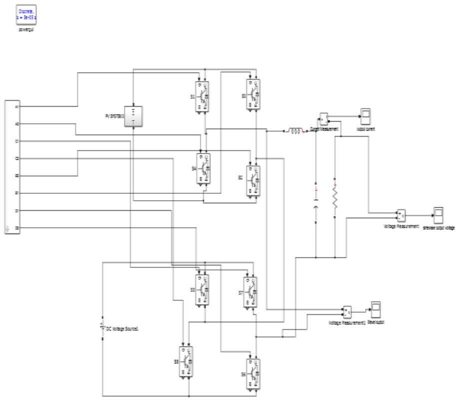

Figure 12: Simulink Model of 5-Level Cascaded Inverter

The above system was simulated with the following system specifications:

For PV System

Temperature of PV system (T) = 297.7K

Irradiance (G) = 1000 W/m^2

For DC-DC Converter

FET resistance (Ron) = 0.1Ω

Internal diode resistance (Rd) = 0.01Ω

Sampling time (Ts) = 5.00e-005S

Input Voltage (Vdc) = 12V

Output voltage (V0) = 26V

Inductance (L) = 12e-3 H

Capacitance (C) = 1500e-3

Diode forward voltage (V_f) = 0.8V

Load resistance (R_L) = 10Ω

Figure 12 shows the complete simulink diagram for DC-DC boost converter fed 5-level cascaded inverter system for solar power applications. Simulation results for PV system are presented in figures 13 and 14. Figure 15 shows the constant DC output of boost converter. Figure number 16-19 shows the voltage and current output waveforms along with THD analysis.

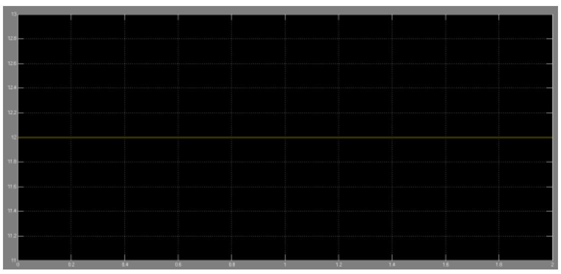

Figure 13: PV cell output voltage waveform

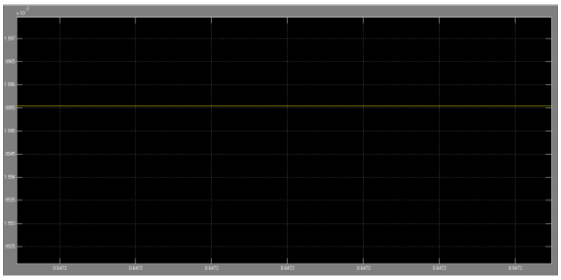

Figure 14: PV cell output current waveform

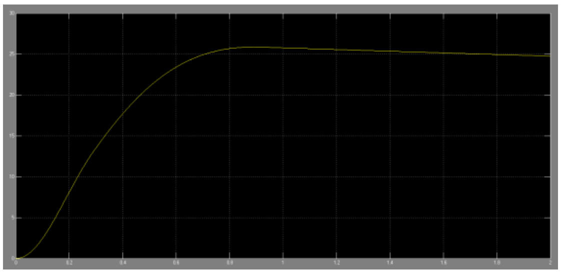

Figure 15: Boost converter output voltage

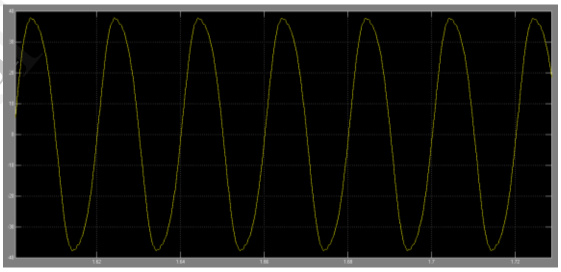

Figure 16: Sine wave output of 5-level inverter

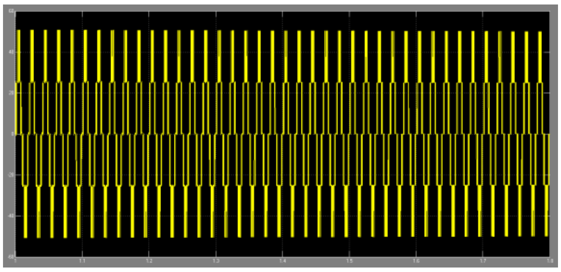

Figure 17: 5-Level output voltage of inverter

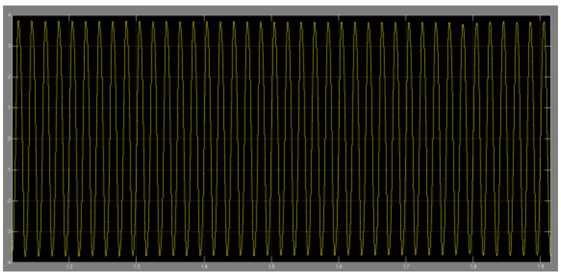

Figure 18: Output current waveform of 5-level cascaded inverter

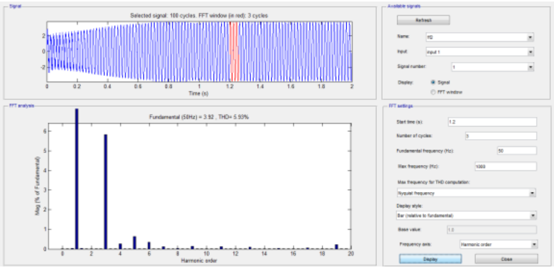

Figure 19: THD analysis of 5-level output current

IV. CONCLUSION AND DISCUSSION

This paper presents the analysis of an advanced power conditioning system with 5-level cascaded inverter for solar applications. THD value of current for 5-level inverter is obtained as 5.93% for resistive load which satisfies the required standard for cascaded inverter. This makes the cascaded inverter system more superior to other inverters and makes it more suitable for renewable energy applications especially for solar power systems. All these results clearly show that cascaded inverter has a very good scope in future for both the domestic as well as industrial applications.

REFERENCES

[1] Jose Rodriguez, J.-S. Lai, and F.Z. Peng (2002), "*Multilevel inverters: A survey of topologies, controls, and applications*," IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[2] S. Ali Khajehoddin, Praveen Jain and AlirezaBakhshai (2007), "*Cascaded Multilevel Converters and Their Applications in Photovoltaic Systems*", 2nd Canadian Solar Buildings Conference Calgary, pp. 1-6, 10-14 June, 2007.

[3] RaveendhraDogga, Gururswamy K P, Padhmanabh Thakur (2013); "*FPGA based 2-stage power conditioning system for PV power generation*," 2013 International Conference on Power, Energy and Control (ICPEC), pp.44-50.

[4] Yuncong Jiang, Jaber A. Abu Qahouq and Mohamed Orabi (2011), "*Matlab/Pspice Hybrid Simulation Modelling of Solar PV Cell/Module*", pp. 1244-1250, IEEE transaction 2011.

[5] Raveendhra, Dogga.; Pathak, M.K.; Panda (2012), A.; "Power conditioning system for solar power applications: Closed loop DC-DC convertor fed FPGA controlled diode clamped multilevel inverter," *Electrical, Electronics and Computer Science (SCEECS), 2012 IEEE Students' Conference on* , vol., no., pp.1-4, 1-2 March 2012.

[6] Vinayaka B.C, S. Nagendra Prasad (2014)"*Modeling and Design of Five Level Cascaded H-Bridge Multilevel Inverter with DC/DC Boost Converter*", International Journal of Engineering Research and Applications, vol.4, issue 6 (version 5), pp. 50-55, June 2014.