A Simple Power Electronic Interface for Grid Connected PV System Using Multilevel Inverter with Hysteresis Current Control

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***Abstract*-A power electronic interface for grid connected photovoltaic (PV) system using boost converter and multilevel inverter (MLI) has been proposed. The variable dc voltage of the PV array ranging from 60V to 80V is fed as input to the boost converter and the duty ratio of the boost converter is adjusted to obtain the required output voltage of 175V. The boosted voltage of the PV array is given to the MLI, which has the advantage of reduced number of switches. The triggering pulses for IGBT switches in the MLI are given by using Hysteresis Current Controller (HCC) technique. This control strategy is effective to make grid current sinusoidal and to achieve unity power factor. The proposed scheme is simulated in MATLAB/Simulink and the results are presented. Experimental model of this scheme is developed and the results are compared. This work uses 5 PV panels of 21V, 5A each in series.**

***Index Terms*- Grid connected Multilevel Inverter, Hysteresis Current Controller, PV array.**

I. INTRODUCTION

Asconventionalsourcesofenergyarerapidlydepletingandthecost of energy isrising, renewable sources of energybecome a promising alternative application, bothforgrid connected systemsandforoff-grid use. For economic reasons the solar energy is not directly interfaced with the utility grid. Hence a power electronic interface is developed to interface the solar PV system to the utility grid [1, 2]. This power electronic interface consists of an inverter and its output is given to a step-up transformer primary. The secondary of the transformer is connected to the grid. The use of transformer introduces losses in the system and also needs more space and leads to noisy operation. Hence a boost converter is introduced between solar system and inverter which eliminates the use of transformer thereby reducing the losses [3].

In recent years, industry has begun to demand higher power equipment, which now reaches the megawatt level. It is not advisable to connect a single power semiconductor switch directly to the highvoltages that is prevalent in many high power industries. Multilevel inverters emerged as the solution for working with higher voltage levels. Multilevel inverters have nearly sinusoidal output voltage waveforms, output current with better harmonic profile, less stressing of electronic components owing to decreased voltages, switching losses that are lower than those of conventional inverters, a smaller filter size, and lower EMI, all of which make them cheaper, lighter,and more compact. However, a very high number of levelsincreases the control complexity and introduces voltage imbalance problems [4].

Various topologies of MLIs have been introduced into the research field over last quarter of a century. Few of the prominent groups of multilevel inverters are [4-6]: Cascaded multi-cell inverter, Neutral point clamped multilevel inverter; Capacitor clamped multilevel inverter and Generalized multilevel inverters.

Generalized multilevel inverters balance each dc voltage levels automatically at any number of levels regardless of active or reactive power conversion and without assistance from other circuits [6].

The performance of an inverter system largely depends on the quality of the control strategy. Different current control techniques for the traditional converters have been considered by several authors [7-9]. The current controlled PWM inverters have some advantages compared to the conventional open-loop voltage source PWM inverters such as; control of instantaneous current waveform with high accuracy, peak current protection,

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and overload rejection and compensation of effects due to load parameter changes.

The proposed scheme consists of a relatively recent topology of MLI, which has the advantages of reduced number of switches [10, 11] fed from a solar PV array through a boost converter. The output from the MLI is fed to the utility grid. The proposed scheme is controlled by a Hysteresis Current Controller. In the existing literatures, authors have controlled the MLI proposed in this work with a dual-reference SPWM which has a complicated control circuitry.

II. Proposed System

The proposed system shown in Fig. 1 consists of the following components: (i) PV array, (ii) Boost Converter, (iii) Multilevel Inverter, and (iv) Hysteresis Current Controller. The input dc voltage of the MLI should be at a greater value than the peak value of the grid. So, a boost converter is used between PV array and MLI to raise the input dc voltage of the inverter to desired levels. In the present case, as the grid voltage is 110V (V_{rms}), this dc link voltage level is fixed at 175V.

The output voltage of the boost converter (V_{dc}) is split into two equal voltages ($V_{dc}/2$) using couple of identical capacitors. The MLI used in the proposed system is capable of giving a 5 level voltage output. It consists of an auxiliary switch and an H-bridge inverter structure. In this paper it is proposed to design and implement an HCC for the MLI. It vastly reduces the complexity of the control circuit of the dual-reference controller employed in the earlier schemes besides providing unity power factor at the grid.

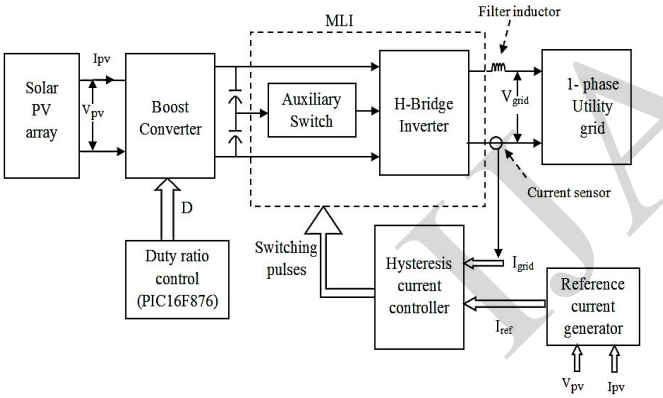


Fig. 1. Block diagram of the proposed system

The duty ratio of the boost converter is controlled by a PIC micro controller (PIC16F876) to fix the dc link voltage at desired level of 175V.A current sensor is used to measure the instantaneous grid current to be used in the hysteresis control. The inverter is connected to the grid through a small value of inductor filter.The HCC transports the power at the input of MLI to the utility grid at unity power factor.

A. Boost Converter

The boost converter shown in Fig. 2 uses an IGBT switch, to pulse width modulate the voltage into an inductor. The output voltage (V_{dc}) of the boost converter is given as the input to the MLI in the proposed scheme.

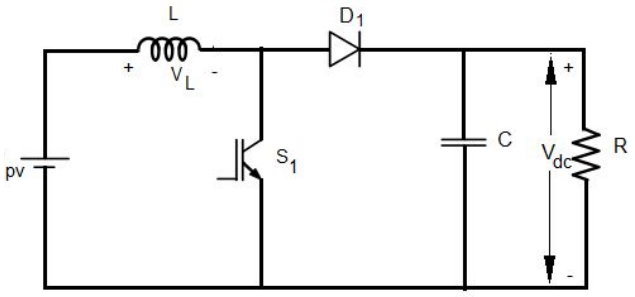


Fig. 2. Schematic diagram of a boost converter

The output voltage of the boost converter is given by equation

$$V_{dc} = \frac{V_{pv}}{(1-D)} \quad (1)$$

where, V_{pv} is the input voltage of boost converter and D is the duty ratio.

The value of inductor is chosen so that the ripple current is greater than twice the minimum load current, as

$$L = \frac{(V_{dc}-V_{pv})(1-D)}{\Delta(I_{load})f_s} \quad (2)$$

where, $\Delta(I_{load})$ is the estimated inductor ripple current and f_s is the switching frequency of the dc-dc converter.

Design of capacitor depends on the maximum allowable output voltage fluctuations:

$$C = \frac{(I_{load})(D)}{\Delta(V)f_s} \quad (3)$$

where, ΔV is the estimated output voltage ripple.

Critical values of inductor and capacitor are obtained as 14.25mH and 112µF respectively, forV_{dc}= 175V, V_{pv}= 80V, D = 0.7 and f_s =10kHz. To make the converter operation in continuous conduction mode, the inductor and capacitor values are chosen as larger than the critical values.

The values of various components used in the boost converter circuit, are furnished in Table 1.

TABLE. 1. Values of Parameters Used In the Boost Converter

Parameters	Values
Inductor, L	20 mH
Capacitor, C	1000 µF
Input dc voltage	60 V - 80 V
Output voltage	175 V

B. Working Principle of the Proposed MLI

The MLI in the proposed scheme consists of an auxiliary switch along with an H-bridge inverter structure. All the switches used are Insulated Gate Bipolar Transistors (IGBT) in parallel with reverse voltage blocking diodes. The schematic diagram of the inverter is shown in Fig 3. The input to the inverter is given between terminal A and terminal C. Voltage between terminals A and B is $V_{dc}/2$ and that between terminals B and C is also $V_{dc}/2$. Working of the MLI over a cycle in open

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loop, to obtain four levels of inverter output voltage can be explained in four modes of operation, each mode existing for 60°, as described below:

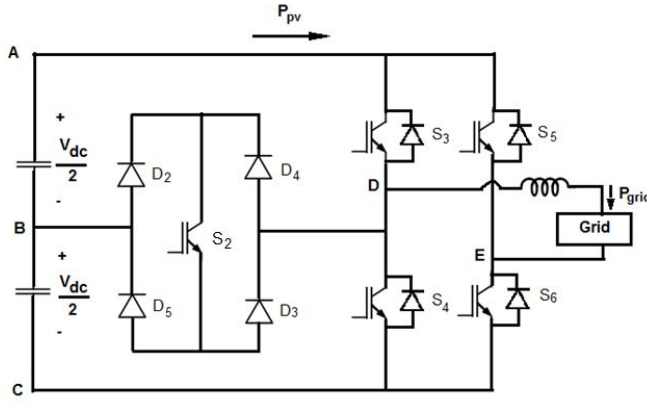


Fig. 3. Schematic diagram of the proposed MLI

Mode I: This mode extends from 0° to 60° and from 120° to 180°. During this period, the switches S_2 and S_6 are triggered and all the other IGBTs are off. The current takes the path B→D_2→S_2→D_3→D→E→S_6→C. The output voltage between terminals D & E is + $V_{dc}/2$ which is fed from the lower half of the dc supply voltage.

Mode II: This mode extends from 60° to 120°. The switches S_3 and S_6 are triggered while all the other IGBTs are in the off state. The current takes the path A→S_3→D→E→S_6→C. The output voltage of the inverter between the terminals D & E is + V_{dc} which is fed from the total voltage across A and C terminal

Mode III: This mode extends from 180° to 240° and 300° to 360°. The switches S_2 and S_5 are triggered and all the other IGBTs are in the off state. The current takes the path A→S_5→E→D→D_4→S_2→D_5→B. The output voltage of the inverter between the terminals D & E is -$V_{dc}/2$ and is fed from the upper half of the dc power supply.

Mode IV: This mode extends from 240° to 300°. The switches S_4 and S_5 are triggered and all the other IGBTs are in the off state. The current takes the path A→S_5→E→D→S_4→C. The output voltage of the inverter between the terminals D & E is -V_{dc} and is fed from the upper half of the dc power supply. Fig. 4 shows the output voltage of the MLI (across the grid) for these 4 modes of operation.

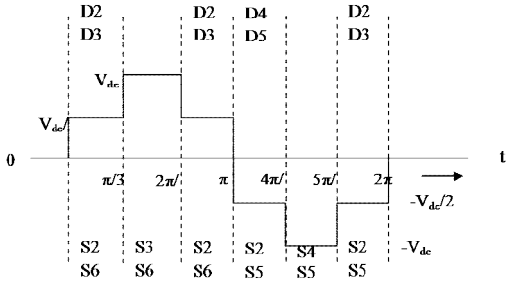


Fig. 4. Output Voltage of the Proposed MLI (Open Loop)

During modes II and IV, only two switches are conducting, impressing the maximum available voltage magnitude at the inverter output.

TABLE. 2. SWITCHING LOGIC OF THE MLI

S_2	S_3	S_4	S_5	S_6	Output voltage
1	0	0	0	1	$+V_{dc}/2$
0	1	0	0	1	$+V_{dc}$
1	0	0	1	0	$-V_{dc}/2$
0	0	1	1	0	$-V_{dc}$

During modes I and III, four devices are conducting impressing half of the maximum available voltage magnitude at the inverter output. Lower number of conducting devices leads to reduction of losses in switches, which justifies the use of this topology of the MLI. The switching logic of the inverter is tabulated in Table 2.

However, due to the presence of multiple voltage levels at the output, need for the harmonic elimination arises. In this work, it is proposed to use a HCC to obtain the desired results.

C. Hysteresis Current Controller

HCC is one type of non- linear current controller based on current error, consists of a comparison between the load current and the tolerance band around the reference current. While the load current is between upper and lower bands, no change is switching action takes place. When the load current crosses to pass the upper limit or lower limit, the switching is done so as to reverse the current direction.

HCC is a relatively simple control strategy and helps in feeding the power to the grid at unity power factor (UPF). The power factor at which the inverter feeds the grid can be controlled by controlling the reference wave used in the scheme.

As shown in the Fig. 5, the switching pulses, to the inverter switches, depends on the error voltage. In Fig. 5, S_3 and S_5 represent the upper switches of the two legs of an H-Bridge inverter while S_4 and S_6 represent the lower switches. In the proposed scheme the working of HCC needs to be slightly modified to utilize the auxiliary switch.

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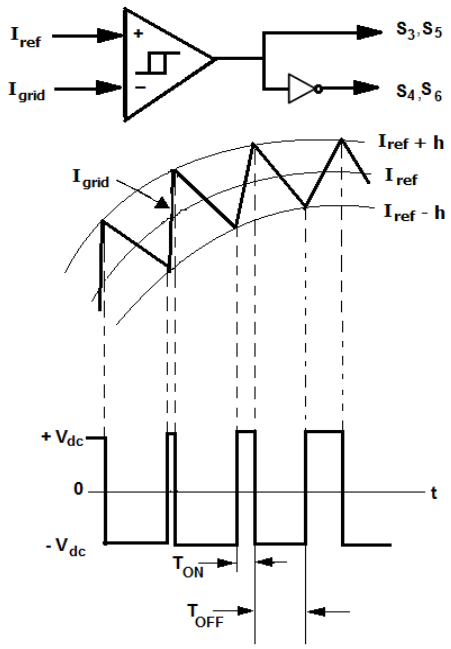


Fig. 5. Working principle of a HCC

The auxiliary switch enables the availability of the $V_{dc}/2$ and $-V_{dc}/2$ levels of voltage at the output. To implement the desired control strategy, a half cycle needs to be divided into two regions: (I) 0° to 60°, 120° to 180° and (II) 60° and 120°.

The switching is based on the error voltage obtained by comparing the grid current to the reference current. HCC is designed to give a bipolar waveform at the output of the multilevel inverter. In region I, switch S_2 is kept ON while S_6 and S_5 are switched alternatively depending on the value of theerror voltage. In this region, the output of the inverter switches between $V_{dc}/2$ and $-V_{dc}/2$.

In region II, switch S_2 is turned off. Switches S_3 and S_6 are triggered with a common pulse and switches S_4 and S_5 are triggered with another common pulse. Switches S_3-S_6 and S_4-S_5 are alternatively switched depending on instantaneous value of the error voltage.

The hysteresis band is set initially itself as (I_{ref} + h) and (I_{ref} – h). The instantaneous grid current (or load current) I_{grid}, measured with the help of a current sensor is compared with a reference sine wave, I_{ref}. When the output of the comparator V_0 is tending to be more positive than + h, then a pulse is generated called V_x, which is used to trigger switches S_2-S_6 in region I and S_3-S_6 in region II. This increases the grid current and if V_0 is trying to be more negative than –h, pulse is generated called V_y, which is used to trigger S_2-S_5 in region I and S_4-S_5 in region II. This pulse reduces the grid current and increases the error. Hence the error is always maintained between – h and + h. The switching logic employed to implement hysteresis control in the proposed system is achieved with the help of V_{angle} and is shown in Fig. 6.

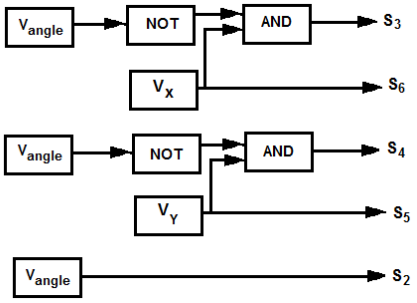


Fig. 6. Triggering pulses for each switch, using HCC

D. Calculation of I_{ref} for MPPT control

The MPPT control in the proposed scheme is achieved by changing the reference current (I_{ref}) in the HCC. The grid power

$$P_{grid} = I_{grid} * V_{grid} \quad (4)$$

where, I_{grid} is the grid current and V_{grid} is the grid voltage.

At maximum power, grid power (P_{grid}) and solar PV array power (P_{pv}) are equal, i.e., $P_{grid} = P_{pv}$

The grid current at MPP which is reference current,

$$I_{ref} = \frac{V_{pv} * I_{pv}}{V_g} \quad (5)$$

Hence for the implementation of MPPT control, V_{pv} and I_{pv} are sensed through Hall sensors of voltage and current.

III. Simulation and Experimental Results of the Proposed Scheme

The proposed scheme has been modeled using MATLAB/Simulink blocks and a simulation has been carried out with a Hysteresis band of +0.1A to -0.1A.The other parameters used for the simulation study are as shown in Table 1. A single phase, 110V, 50Hz supply is assumed for utility grid.

In the proposed scheme, there is a need to identify the period from 60° to 120° of a half cycle. This is required so that proper switching action can be provided to the switches in the circuit. This is identified by comparing a unit-amplitude, rectified sine wave with a dc value of 0.866. This is accomplished in simulation by comparing a rectified sine wave with 0.866 dc value in a relational operator block. Whenever the sine wave is less than the dc value, the output is high. The output is low when this condition is not satisfied. This pulse is named as V_{angle}. The switching pulses for the proposed scheme are obtained from the interaction between V_x, V_y and V_{angle} as shown in Fig. 6. Pulse to the switch S_6 is 'V_x' and pulse to switch S_5 is 'V_y'.

The quality of grid current tracking using a HCC depends on various factors like the input side dc level of the inverter, the value of the filter inductor, the hysteresis band etc. The duty cycle of the boost converter is adjusted to maintain a constant dc voltage of 175V at the output, with changing irradiation of PV array. This enables the MLI output to be obtained as $110V_{rms}$ which is fed to the utility grid. The grid voltage (MLI output) and grid current waveforms along with the reference current waveform obtained through simulation are shown in Fig. 7.

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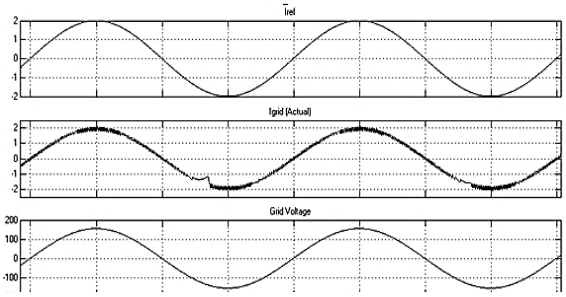


Fig. 7. Output voltage and current waveforms

It can be seen from the waveforms that the power is being delivered to the grid at unity power factor. The FFT analysis of the current waveform for grid connection of the inverter system has given the THD as 3.6%.

The experimental setup for the proposed system is built using a boost converter, inverter and an auxiliary switch. HCC is implemented using analog and digital devices. In the experimental setup, a *Semikroninverter* with its inbuilt driver circuitry is used as the H-Bridge structure. The auxiliary switch and its driver circuit are separately designed and connected to the H-Bridge to obtain the MLI structure. A PV array with 5 Solar PV panels of 21V, 5A each in series, with the total output power of 105W is used as the source. The solar PV array voltage is boosted up by a boost converter, whose switching frequency f_s is 10kHz and split into two equal voltages using two capacitors.

IV. Implementation of the HCC

The sinusoidal signal from the grid is reduced in magnitude to obtain unit amplitude using a trim-pot. The rectified sine wave is obtained using a precision rectifier. This unit amplitude sinusoidal signal is given as an input to the precision rectifier circuit as shown in Fig. 8.

The output obtained is a rectified sine wave which is compared to a dc value of 0.866 to obtain V_{angle} pulse. The precision rectifier and the comparator are designed using TL084 op-amps. The T_{on} period of V_{angle} gives the region II, between 60° and 120°.

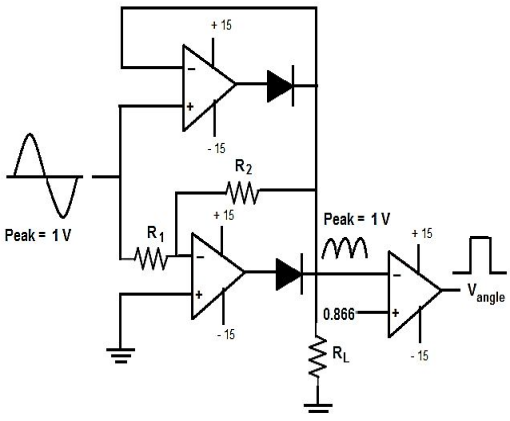


Fig. 8. Circuit to obtain V_{angle}

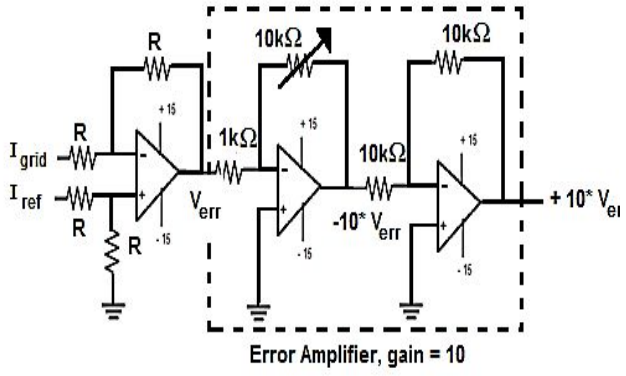


Fig. 9. Circuit to obtain error signal

The error voltage is obtained by using a circuit shown in Fig 9. I_{ref}–I_{grid} is obtained by using a difference amplifier. The output from the difference amplifier is amplified ten times. This is done so as to get an easier control of the hysteresis band.

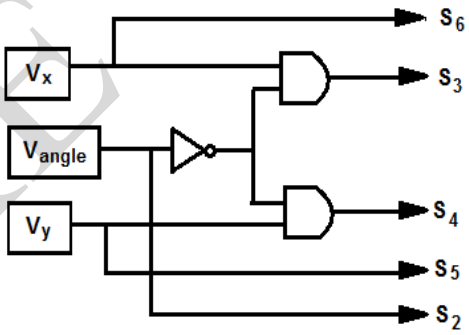


Fig. 10. Digital logic to produce the switching pulses

The output from the error amplifier is fed to a Schmitt trigger circuit to produce the hysteresis pulses. TL081 ICsareemployed to design this circuit.

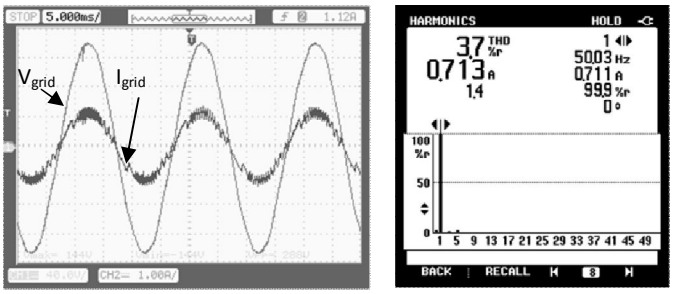
The switching logic for proposed HCC is obtained by manipulating the V_{angle}, V_X and V_Y pulses, using digital NOT and AND gates as shown in Fig. 10.

The digital output signals have a level of 5 V. This is converted to pulses with voltage level of +15 V by using the appropriate gate driver circuit.

The experimentally obtained value of grid voltage (V_{rms}) is 110V and grid current (I_{rms}) is 1.12A (at 800W/m^2)and these waveforms are shown in Fig. 11, along with harmonic spectrum of grid current. It can be seen from the waveform that the HCC transports the power of 100W from dc side to the ac utility grid at unity power factor.

Desired value of dc link voltage to the MLI is obtained by adjusting the duty ratio of the boost converter using MPPT technique. The driver circuit for the auxiliary switch is designed using an IR2110 IC.

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(a) (b)

Fig. 11. (a) UPF operation of MLI, (b) THD of the system

The photograph of the experimental setup of MLI and the accompanying components are shown in Fig. 12. The pulses to the switches are provided as discussed earlier.

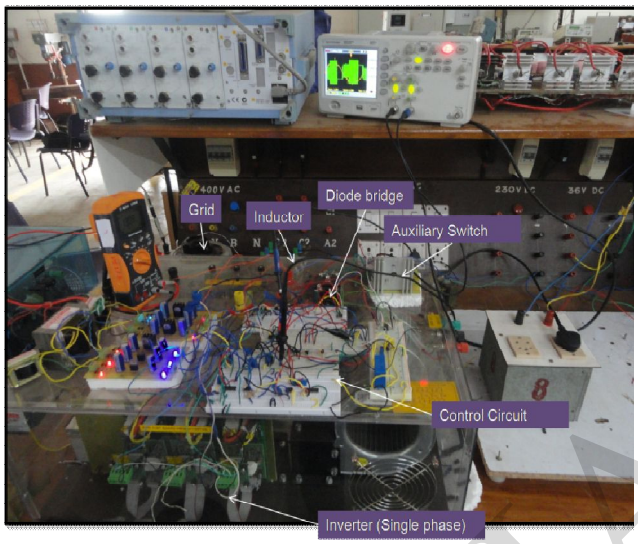


Fig. 12. Photograph of the experimental setup

V. Conclusion

A grid-connected solar PV system using a power electronic interface with boost converter and MLI is proposed. The salient feature of the system is the use of HCC for MLI. The proposed system is simulated using MATLAB/Simulink and its working is ascertained. Experimental implementation of the proposed system is carried out and power is fed from the solar PV to the utility grid at UPF. In the proposed system, a solar PV array of five panels in series, each rated for 21 V and 5A, is used. The hardware implementation of HCC is done using simple analog and digital circuits. The MPPT in HCC is achieved by appropriately changing the reference current of the grid. It is envisaged that the simplicity of this control will make its utility high in PV fed grid connected systems.

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