A Non-isolated Hybrid Boost Three Level DC-DC Converter with High Step-up Conversion Ratio

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Abstract— Nowadays renewable energy sources are increasingly used to meet the world's increasing demand for energy. In grid connected photovoltaic (PV) generation systems, a single PV array can supply lower dc voltage. In order to connect PV array to the grid, the voltage has to be boosted to higher levels that is demanded by the grid side. A hybrid boost three level dc-dc converter based on traditional single phase three level diode clamped inverter can be used to connect low voltage PV array to the high voltage grid. Only one inductor, two capacitors in series, and those power switches and diodes, which are needed to establish the topology with high voltage gain. Pulse width modulation (PWM) control method is used for the control of power switches. Power switches of this converter works with duty cycles closer to 0.5. This hybrid three level dc-dc converter works with high gain without a transformer or coupled inductor. In addition, voltages across the capacitors in series are balanced in both steady and dynamic states. Therefore capacitor voltage balancing circuitry can be avoided. Also, blocking voltages of the power switches are half of the output dc voltage. This hybrid converter is suitable for PV generation systems connected to the grid with parallel-connected low-voltage PV arrays.

Key words: PV photovoltaic, NPC- neutral point clamped, Pulse width modulation

I. INTRODUCTION

The generation systems based on the renewable energy sources have rapidly developed in recent years. Photovoltaic is an important part of renewable energy sources.

It is a fast growing renewable energy source in many countries since it is clean, pollution-free and highly reliable.

A PV array can generate only low output voltage. This generated voltage of PV doesn't satisfy high voltage requirements [4]. To connect PV array to the grid, the generated PV voltage must match with the grid voltage. There are several solutions for connecting PV to the grid.

For satisfying high voltage requirements, series-connected PV arrays are the conventional solution. It requires more number of power devices and the cost is high. Also, power level of series-connected PV system is affected by shadows, which are caused by trees, clouds, buildings, power line cables etc. Thus efficiency of series-connected PV system is greatly reduced [5]. This solution is not effective for grid-connected applications. Due to the limitations of series-connected PV system, parallel-connected PV configuration is used as a solution. For residential applications, parallel-connected PV is most suitable. It is more efficient than series-connected PV due to PV performance. Low voltage is generated with the parallel-connected system. The power generation level can be improved by extending the parallel-connected PV arrays [6]. Due to limited output, parallel- connected PV system alone cannot be used for grid-connected applications. Since above two solutions are not effective for high voltage requirements, some energy conversion systems have to be used in between the parallel-connected PV systems and existing grids.

Non-isolated high step-up DC-DC converters are required in the industrial applications. In photovoltaic grid connected systems, boost converters with high voltage gain is needed to connect PV arrays with the high voltage grid. This high step-up boost converters eliminates the voltage mismatch between PV arrays and grid.

Commonly used boost converters are two level and three level boost converters. In two level boost converters, the extreme duty cycles of the power switches limits its voltage gain. Also voltage stress of the power switch is high. So these two level boost converters are not suitable for photovoltaic generation applications.

Conventional three level boost converter reduces the voltage stress of the power switches. Its operation at large duty cycles limit its voltage gain and switching frequency.

In order to obtain high voltage gain operation, a new hybrid boost three level dc-dc converter is proposed. This hybrid boost converter is based on conventional neutral point clamped (NPC) inverter. It is a combination of three level converters. The operation of this converter is such that the duty cycles of the power switches closer to 0.5 and thus provides high voltage gain. Voltage stress across the power switches are also reduced in this converter. The high voltage gain of the converter makes it suitable for photovoltaic generation applications.

II. HYBRID BOOST THREE LEVEL CONVERTER

The hybrid boost three-level converter is derived from a conventional three-level neutral point clamped inverter. This converter includes the advantages of conventional three-level boost converters with some added features.

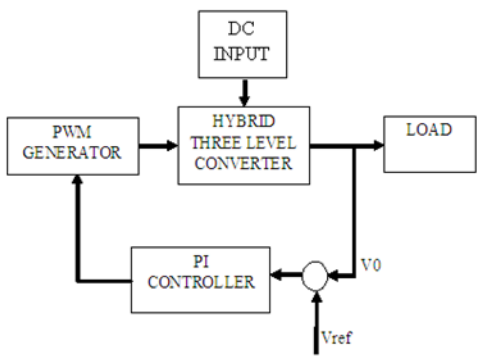

Fig. 1: Block diagram of Hybrid boost three-level dc–dc converter.

Fig.1 shows the block diagram of hybrid boost three level dc-dc converter. DC input is given to the converter and boosted output is obtained across the load. Pulse Width Modulation (PWM) control method is used for producing switching pulses. Hybrid boost converter with controller is needed for making constant voltage at the output side. Proportional-Integral (PI) controller controls the output by a feedback mechanism.

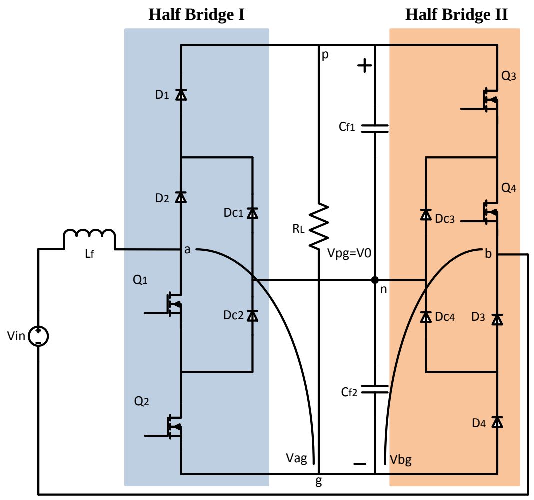

Fig. 2: Hybrid Boost Three-Level Dc–Dc Converter

Fig. 2 shows the hybrid boost three-level dc-dc converter. It is a combination of two half bridges, each half bridge is a three level boost converter. This hybrid converter consists of four switches Q1-Q4, diodes, one inductor Lf, two capacitors (Cf1, Cf2) and a load RL. Vin is the DC input to the converter and Vo is the DC output voltage. Vag and Vbg are the three level voltages of the two half bridges. Vab is the output voltage of the hybrid converter, which is obtained by the difference between Vag and Vbg.

A. A. Switching Sequences for Operating States:

Table 1 shows the switching sequences for the hybrid boost three-level dc-dc converter. By proper switching of the power switches different operating modes are obtained.

Mode	V_{ag}	V_{bg}	V_{ab}	Q_1-Q_4	D_1-D_4	L_f	D_{c1}-D_{c4}	C_{f1}	C_{f2}
1	Vcf1+Vcf2	0	Vo	0000	1111	tr.	0000	ch. together	
2	Vcf1+Vcf2	Vcf2	Vo/2	0001	1100	tr.	0010	ch.	disch.
3	Vcf2	0	Vo/2	1000	0011	tr.	0100	disch.	ch.
4	0	0	0	1100	0011	st.	0000	disch. together	
5	Vcf1+Vcf2	Vcf1+Vcf2	0	0011	1100	st.	0000	disch. together	

Table 1: Switching Sequence for Hybrid Converter

1) Mode1:

In this mode, switches Q1-Q4 are in OFF position and diodes D1-D4 are conducting. Capacitors Cf1 and Cf2 in series are charged together through Vin-Lf-D2-D1-Cf1-Cf2-D4-D3-Vin. Inductor Lf transfers energy during this mode. Output voltage V0 is the voltage across capacitors (Vcf1+vcf2). Output voltage of the hybrid converter (Vab) is equal to V0.

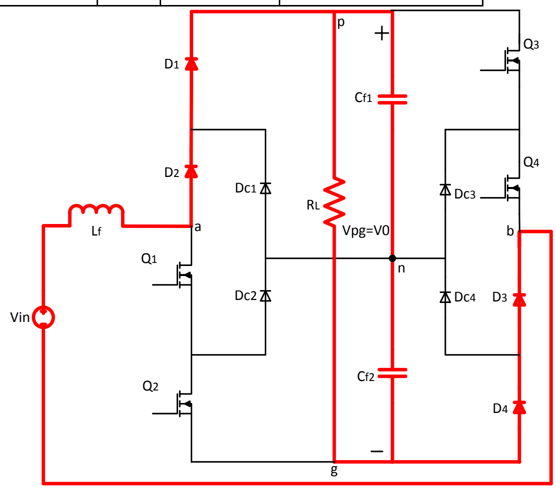

Fig. 3: Equivalent Diagram of Mode 1

2) Mode2:

In this mode, switches Q1-Q3 are in OFF position and switch Q4, diodes D1, D2, Dc3 are conducting. Capacitor Cf1 is charged by Vin and Cf2 is discharged for the load. Inductor Lf transfers energy during this mode. Output voltage of the hybrid converter (Vab) is equal to V0/2, which is the voltage across Cf1.

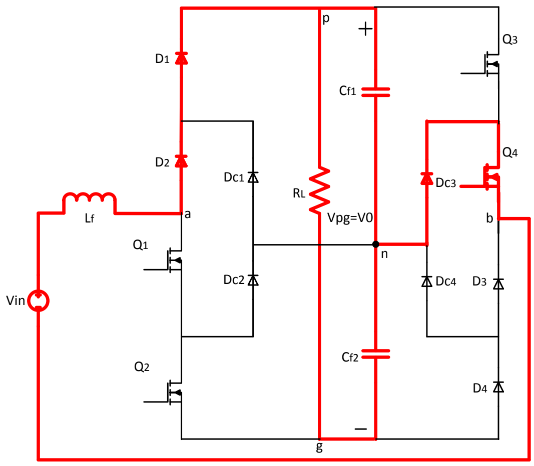

Fig. 4: Equivalent diagram of mode 2

3) *Mode 3:*

In this mode, switch Q1 and diodes Dc2, D3, D4 are conducting. Capacitor Cf1 is discharged for the load and Cf2 is charged by Vin. Inductor Lf transfers energy during this mode. Output voltage of the hybrid converter (Vab) is equal to V0/2, which is the voltage across Vcf2.

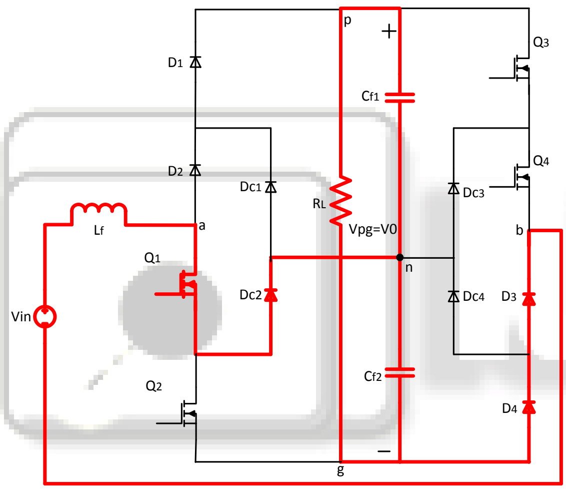

Fig. 5: Equivalent diagram of mode 3

4) *Mode 4:*

In this mode, switches Q1, Q2 and diodes D3, D4 are conducting. Capacitors Cf1 and Cf2 are discharged together for the load. Inductor Lf stores energy through diodes D4 and D3 during this mode. Output voltage of the hybrid converter (Vab) is equal to 0.

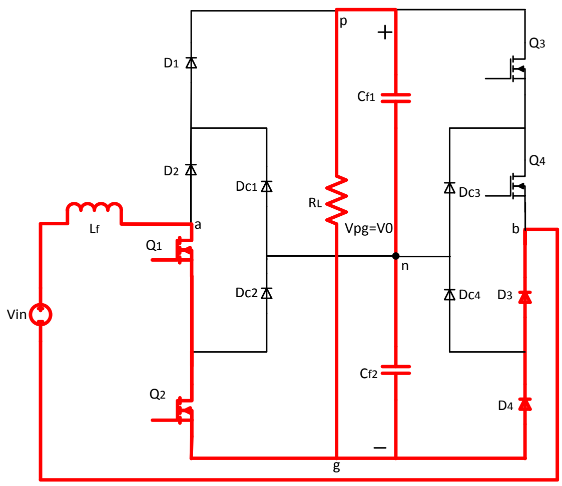

Fig. 6: Equivalent diagram of mode 4

5) *Mode 5*

In this mode, switches Q3, Q4 and diodes D1, D2 are conducting. Capacitors Cf1 and Cf2 are discharged together for the load. Inductor Lf stores energy through diodes D2 and D1 during this mode. Output voltage of the hybrid converter (Vab) is equal to 0.

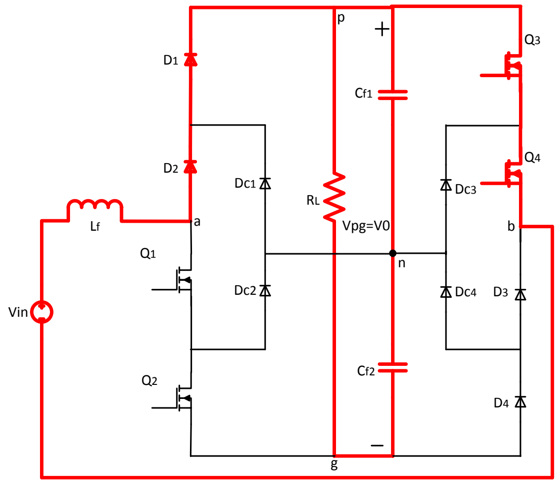

Fig. 7 Equivalent diagram of mode 5

B. *PWM Control Technique:*

The output three-level voltage V_{ab} of the hybrid converter can be described as

$$V_{ab} = V_{ag} - V_{bg}$$

The switching functions of three level voltages Vag and Vbg based on Table 1 is given by

$$Vag = (1 - Q1.Q2).(Vcf1 + Vcf2) - (Q1 - Q2).Vcf1$$

$$Vbg = Q3.Vcf1 + Q4.Vcf2$$

Where Q1-Q4 are the corresponding switching state.

According to the above equations, the switching function of *Vab* for the hybrid converter can be written as

$$Vab = [(1 - Q1).(1 + Q2) - Q3].Vcf1 + (1 - Q1.Q2 - Q4).Vcf2$$

Fig. 8 shows the PWM method of pulse generation. For PWM signal generation, two triangular carriers that are phase shifted by 180 degrees are used. These carriers are compared with constant values ma and mb and thus produce switching pulses.

mb > Vcarrier 1, Q1 = 0
ma > Vcarrier 2, Q2 = 1
ma > Vcarrier 1, Q3 = 1
mb > Vcarrier 2, Q4 = 0.

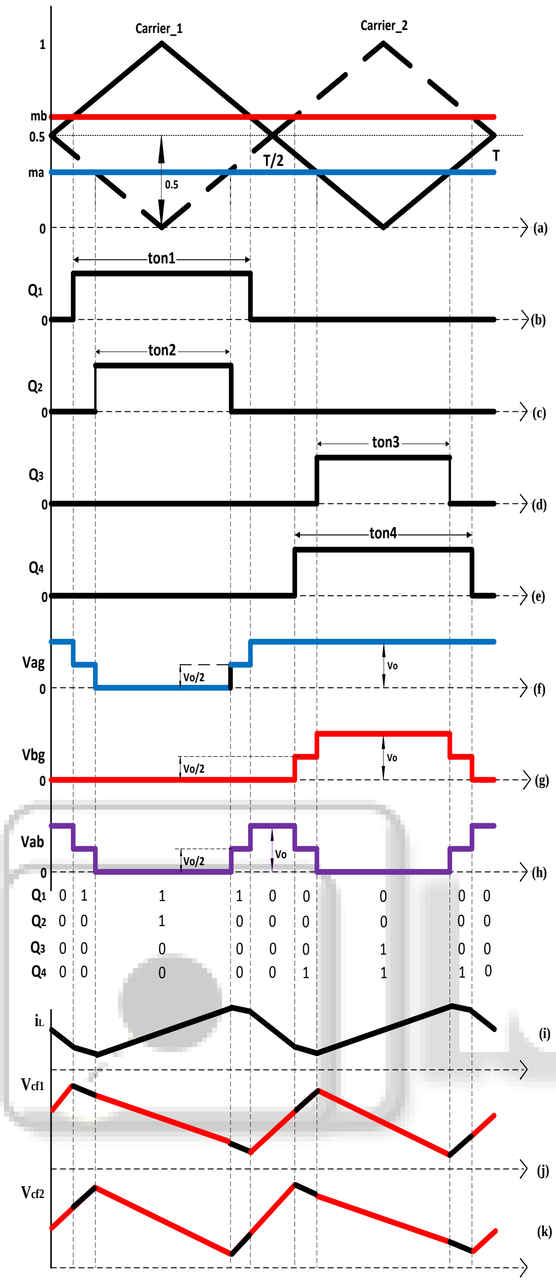

Fig. 8: Operating States

C. *Modified Hybrid Boost Converter:*

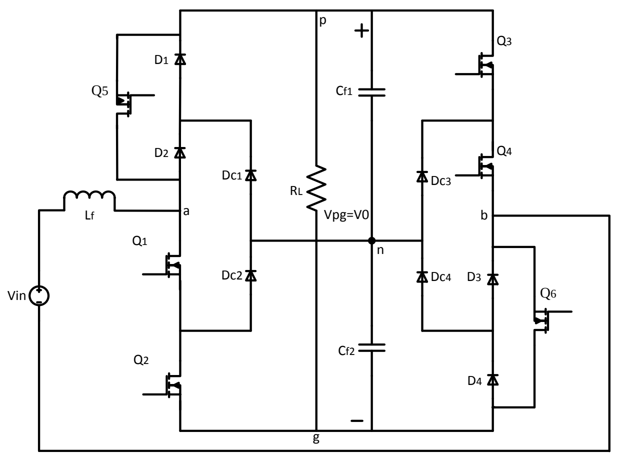

Fig. 9: Modified Circuit Diagram of Hybrid Boost Converter

From the working of the hybrid converter, it is clear that, two diodes in the same bridge conducts together in all operating modes. During the operation of converter, when two diodes D1, D2 or D3, D4 conduct together, there occurs an increased voltage drop across these diodes. To reduce the power loss due to diodes, we are connecting power switch across these diodes. By using power switches instead of diodes, we can reduce the voltage drop. Fig. 9 shows the new hybrid boost three-level dc-dc converter with reduced voltage drop. Working of this converter is similar to that of basic hybrid boost three-level converter. Only difference is the conduction of switches instead of diodes. This new topology is most suitable for high power applications. For low voltage applications, cost is high and power saving is less. When two diodes conduct together, each diode has a voltage drop of about 0.7V. Also, high current flows through the diodes. This causes a large power loss in diodes. To reduce these power losses, power switches are used instead of diodes.

The switches are gated on the period when the two diodes conduct together. By using switches instead of diodes during the operation of the converter, some amount of power can be saved. Even though the number of switches increases, the control mechanism is simple. Using simple logic gates, we can generate the switching pulses for the switches Q5 and Q6. Only AND and NOR gates are needed to generate switching pulses for additional switches. Thus control is not complicated. Disadvantage is the increased cost for additional components.

D. *Operation High Voltage Gain:*

When Vab = 0, energy is stored in the inductor Lf otherwise, energy is transferred from the inductor Lf.

For the analysis, consider that energy stored in the inductor and energy transferred from the inductor are same. Duty cycles of power switches can be described as

$$d1 = d4 = 1 - m_b$$

$$d2 = d3 = m_a$$

where, d1-d4 are the duty cycles of the power switches Q1-Q4.

Voltage gain of the topology is given by

$$M = \frac{Vo}{Vin} = \frac{1}{1-(d1+d2)} = \frac{1}{mb-ma}$$

By adjusting the values of ma and mb, duty cycles of the power switches can be varied and thus voltage gain of the converter can be adjusted. Wide range of voltage gain can be achieved by using this converter.

As to the given voltage gain M, there is an infinite number of solutions to mb and ma. However, a tradeoff between the non-extreme duty cycles of power switches and the fluctuating amplitude of the inductor current must be well considered, and the better solution in this letter is described as

$$m_b = 0.5 + \frac{1}{0.4M}$$

$$m_a = 0.5 - \frac{3}{4M}$$

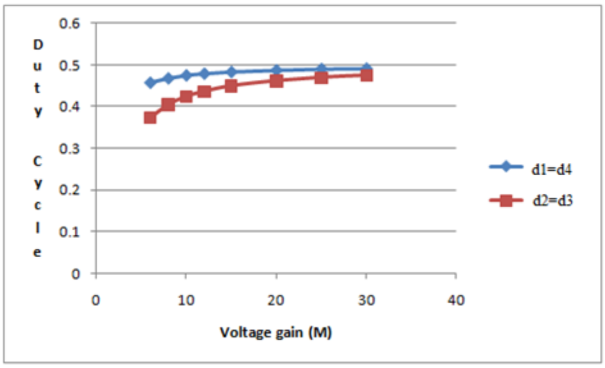

Fig. 10: Duty Cycles Curves Versus Voltage Gain

By using the above mentioned equations, the relationship between the duty cycles of the power switches and the voltage gain can be depicted in Fig.10. It is indicated that the higher M occurs when the duty cycles of switches closer to 0.5.

III. SIMULATION RESULTS

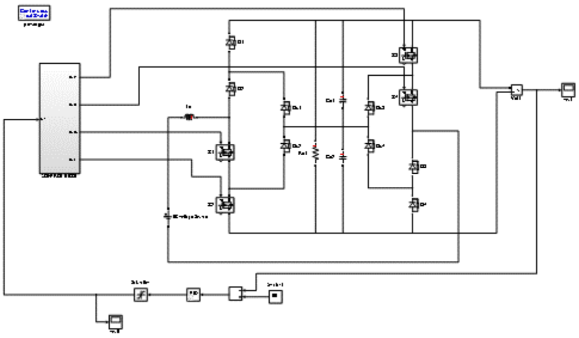

Fig.11: Simulation Model of Three Level Hybrid Boost Converter

Fig. 11 shows simulation model of three level hybrid boost converter in closed loop. It consists of 4 switches, 8 diodes, one inductor, 2 capacitors and a load. PWM control method is used to generate switching pulses. Proportional-Integral (PI) controller is used to control the output voltage. Input DC voltage of 5V is given as the input to the converter.

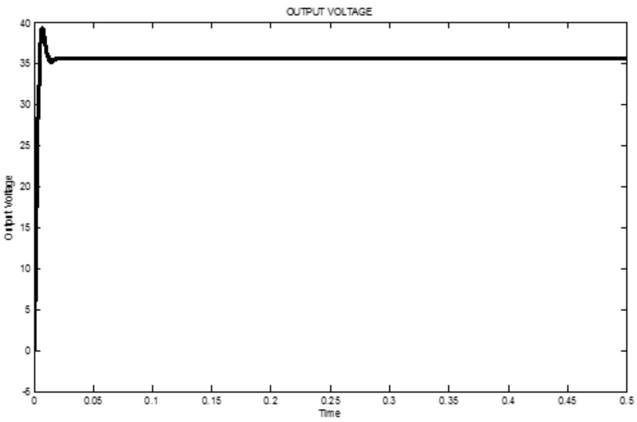

Fig. 12: Output Voltage of Three Level Hybrid Boost Converter

Fig 12 shows the output voltage of the hybrid three level converter. Here an input voltage of 4.2V is given and an output of 35V is obtained. Here the converter operates with a switching frequency of 7.4kHz.

Fig 13 shows the three-level voltages of the converter. From figure, Vag and Vbg are the three level voltages of the two half bridges. Vab is the output voltage of the hybrid converter, which is also a three level one. Vab is obtained as the difference between Vag and Vbg.

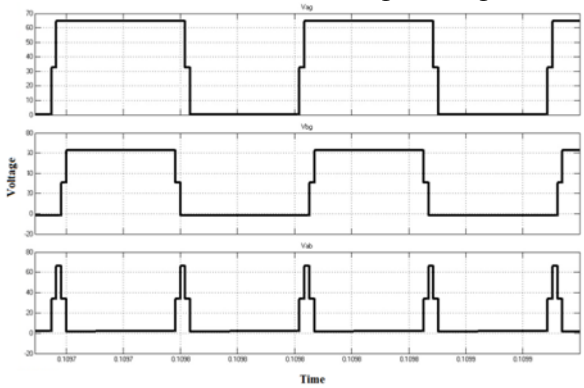

Fig. 13: Three Level Voltages of Hybrid Boost Converter

IV. HARDWARE ANALYSIS

Fig. 14 shows the experimental set up of the hybrid three-level boost converter.

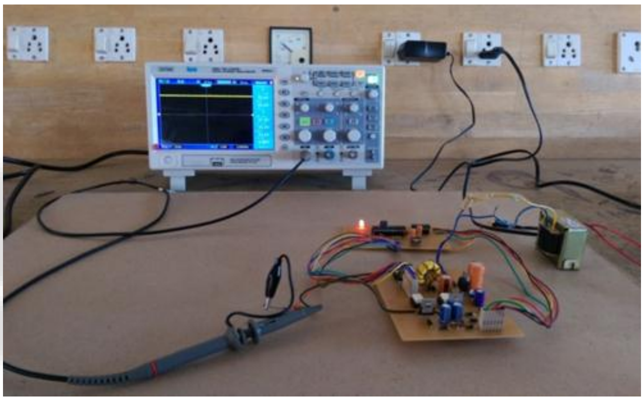

Fig. 14: Experimental Set Up of The Hybrid Converter

It consists of power circuit, driver circuit, and control circuit. The results of the hardware arrangement are analyzed with the help of DSO.

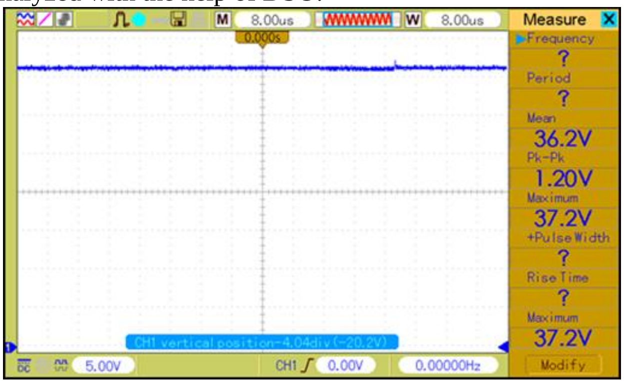

Fig. 15: Output Voltage Waveform

This hybrid boost three-level converter operates at a switching frequency of about 7.4 kHz. Fig. 15 shows the output voltage waveform of the hardware. An input voltage of about 4.2V is given to the hybrid converter and an output voltage of about 36.2V is obtained in the output.

V. CONCLUSION

The hybrid boost three-level dc–dc converter is based on the conventional single-phase diode clamped three-level inverter. It operates with duty cycles power switches closer to 0.5 and provides increasing voltage gain. By adjusting duty cycles, voltage gain can be varied. Moreover, the capacitor voltages can be balanced both in dynamic and steady states by the proposed PWM control method and the blocking voltages of the power switches are half of the output dc voltage. The proposed converter is suitable for PV generation systems connected to the grid with parallel-connected low-voltage PV arrays.

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