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Two Stage Five Level Inverter for Grid Connected Application

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Abstract:

Modern trend in power generation is the use of two-stage configuration i.e., allocating a single PV cell to a converter to produce grid voltage of adequate requirement and then to convert DC to AC voltage for grid cnnection. Usually, the first stage is a DC-DC boost type converter which is responsible for extracting maximum power from panel and boosting PV voltage to a value higher than peak of grid voltage. A converter is proposed, which is derived from an active network based converter, is chosen as the first stage and a five level inverter is used as the second stage of the configuration. Thus, in overall, the converter used is having high gain and reduced switching stress. The Inverter used is having the advantage of low filter requirement, reduced stress, EMI and reduced THD level. A closed loop control of the converter is done to maintain constant output voltage under varying input voltage. MATLAB R2014a version software is used to simulate the model. The prototype of the two stage configuration was developed and tested in the laboratory and results were verified using PIC 16F877A.

Keywords-- **Active network based converter, closed loop, five level inverter, two-stage configuration, THD**

I. INTRODUCTION

Modern trend in power generation is the use of two-stage configuration i.e, we are allocating a single PV cell to a converter so as to produce grid voltage of adequate requirement. Normally DC voltage generation from single PV is few tenths of required and therefore, cannot be used alone to generate adequate voltage. With increased penetration of renewable energy sources and energy storage, high voltage gain dc-dc power electronic converters find increased applications in green energy systems. They can be used to interface low voltage sources like fuel cells, photovoltaic (PV) panels, batteries, etc., to provide high conversion ratio. To achieve high voltage gains, classical boost and buck-boost converters require large switch duty ratios. Large duty cycles result in high current stress in the boost switch[1]. The maximum voltage gain that can be achieved is constrained by the parasitic resistive components in the circuit and the efficiency is drastically reduced for large duty ratios. Typically high frequency transformers or coupled inductors

This leads to voltage spikes across the switches and voltage clamping techniques are required to limit voltage stresses on the switches. Consequently, it makes the design more complicated. However, traditional transformerless high step-up voltage gain converters also bring some drawbacks: the converters are large, the voltage stress of the power devices is very high, the voltage gain is still limited and the control strategies are complicated.

Figure 1 presents the typical structure of a two-stage inverter which is composed of two parts[2], the first stage is the DC/DC module, it upgrades the output voltage of single PV module to meet the demand of secondary inverter, and the DC/DC module should track the maximum power point in order to obtain the maximum power of the solar cell. The second stage is the DC/AC module which achieves the function of grid-connected. A new converter which is derived from an active network DC/DC Boost converter based on switched-inductor is chosen as the first stage, which has the following advantages: higher voltage-conversion ratio, lower voltage stress, simpler control strategy. The conventional single-phase inverter topologies for grid connection include half-bridge and full bridge. The output ac voltage of the half-bridge inverter is two levels. The voltage jump of each switching is the dc bus voltage of the inverter. The full-bridge inverter is configured by two power electronic arms. The output ac voltage of the full-bridge inverter is two levels if the bipolar modulation is used and three levels if the unipolar modulation is used. The voltage jump of each switching is double the dc bus voltage of the inverter if the bipolar modulation is used, and it is the dc bus voltage of the inverter if the unipolar modulation is used. All power electronic switches operate in high switching frequency in both half-bridge and full-bridge inverters.

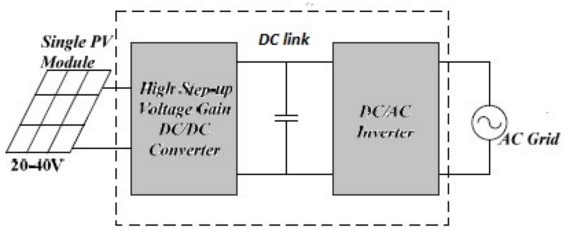


Figure 1: Schematic of two stage configuration

The switching operation will result in switching loss. The loss of power electronic switch includes the switching and the conduction losses. The conduction loss depends on the handling power of power electronic switch. The switching loss is proportional to the switching frequency, voltage jump of each switching, and the current of the power electronic switches. The power efficiency can be advanced if the switching loss of the DC-AC inverter is reduced.

II. TWO STAGE GRID CONNECTED INVERTER

A. *Proposed High Gain Converter*

This section elaborates a novel high step-up voltage gain converter for the micro-inverter, which has following advantages: high voltage-conversion ratio, low voltage stress, easy to control. In the first part, the operation principle of the converter is illustrated. Secondly, the steady state analysis regarding the converter gain and stresses across switches and diodes is done.

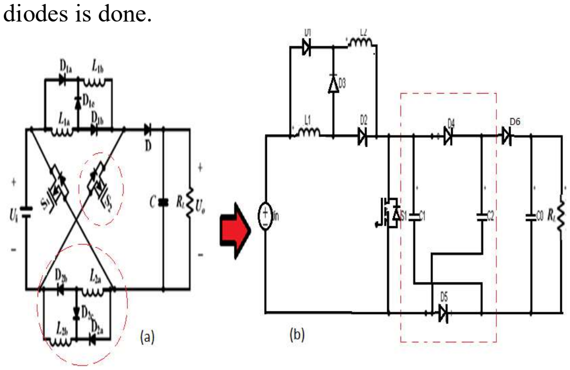


Figure 2: (a) Active network derived converter (b) Proposed converter

The proposed converter is derived from an active network DC-DC converter based on switched-inductor
Cell (shown in Figure 2). The active network based converter is having a gain of (1+3D) times the gain of a conventional boost converter[2]. The switched inductor cells have a property of charging in parallel and discharging in series so as to produce high gain. Also, the stress across the switches was half the sum of input and output voltage. The proposed converter is derived by removing one switched inductor cell and switch, then adding a voltage doubler cell to increase the gain and reduce stress across the switch. Table 1 shows the comparison of the performances between active network based converter and proposed converter. The proposed converter has two modes of operation based on the status of the switch (ON or OFF).

Table 1: Comparison of the performances of the converters

Performance	No. of switches	No. of inductors and diodes	No of Capacitors	Gain	Voltage stress
Converter based on active network	2	4 & 7	1	$\frac{(1+3D)}{(1-D)} = 5$	$\frac{(V_{IN}+V_O)}{2}$
Modified converter	1	2 & 5	3	$\frac{2(1+D)}{(1-D)} = 6$	$\frac{(V_O)}{2}$

* For Duty cycle, D = 0.5

i. Principle of operation

When Switch S_1 is ON the switched inductor cell charge in parallel i.e., inductors L_1 and L_2 which share the same level of inductance are charged in parallel from the DC source. The diode D_6 is forward biased and as similar to the classic boost converter the capacitors C_1 and C_2 discharges through output capacitor C_0 to supply load as shown in Figure 3. Diodes D_3, D_4 and D_5 are reverse biased during this mode. When the switch is ON, following are the equations that evaluate the converter,

$$V_{in} = V_{L1} = V_{L2} = V_L \quad (1)$$
$$V_o = V_{Co} = V_{C1} + V_{C2} \quad (2)$$

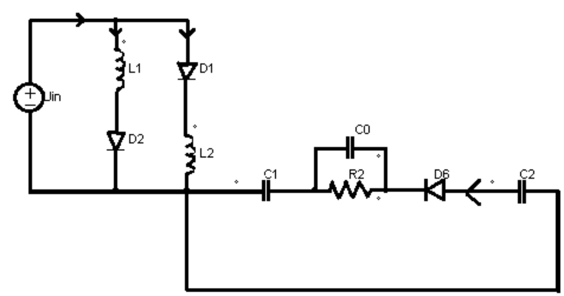


Figure 3: Mode 1 of the proposed high gain converter

When switch S_1 is OFF the switched inductor cell discharge in series i.e., inductors L_1 and L_2 which share the same level of inductance are discharged in series from the DC source towards the capacitors C_1 and C_2 . The diodes D_4 and D_5 are forward biased in that case and as similar to the classic boost converter, the output capacitor C_0 discharges to supply load as shown in Figure 4. When the switch is OFF following are the equations that evaluate the converter,

$$-V_{in} - 2V_L + V_C = 0 \quad (3)$$
$$V_o = V_{Co} = V_{C1} + V_{C2} \quad (4)$$

Considering the energy balance equation of the inductor, we get

$$V_{in} * D = \frac{(1-D)(V_C - V_{in})}{2} \quad (5)$$

Considering equations from 1 to 5 we get the following.

$$V_C = \frac{V_O}{2} \quad (6)$$

Therefore the Voltage Gain of the converter is obtained as

$$\frac{V_O}{V_{in}} = \frac{2*(1+D)}{(1-D)} \quad (7)$$

The Voltage stress will be reduced automatically by the use of C-D cell and the analysis shows that, the stress V_{SW} can be found as,

$$V_{SW} = \frac{V_o}{2} \quad (8)$$

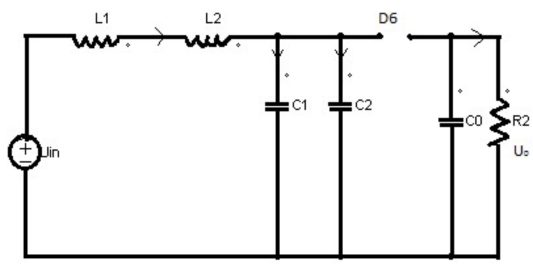


Figure 4: Mode 2 of the proposed high gain converter

B. Five Level Inverter

As the second stage, a DC-AC inverter is employed that generate a sinusoidal current compiled with international standard to be either injected into grid or to fed local and remote load. A five-level bidirectional converter is developed and applied for PV integration to the power grid. The converter is configured by two dc capacitors, a three-level converter part, an unfolding bridge and a filter. It will operate in two modes, rectifier mode and inverter mode. During the start-up, the grid acts as the source and the 5-level converter works in rectifier mode.

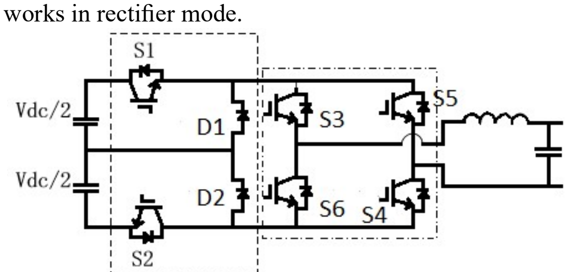


Figure 5: Five level inverter

After the PV optimizer stage starts, the converter will automatically work in inverter mode and generate an output voltage with five levels. In both modes, only two high frequency switches will operate and the unfolding bridge will work at grid frequency. The Five level inverter is developed from this bidirectional converter [1], considering only the inverter mode of operation. With the control strategy, the dc link capacitor voltages are balanced and therefore only one source is required compared to other multilevel topology and the number of switches is reduced compared to the diode clamped, flying capacitor and cascade H-bridge 5-level inverters with the same voltage levels.

i. Operating Modes

The operation of the five-level converter can be divided into rectifier and inverter mode. The converter operates mainly in inverter mode as a grid-tie inverter. In this mode, only S_1 and S_2 operate at high frequency. The switches S_3 and S_4 will be ON only during positive half cycle and S_5 and S_6 will be ON only during the negative half cycle. The inverter mode could be further divided into eight modes.

a. INV Mode 1

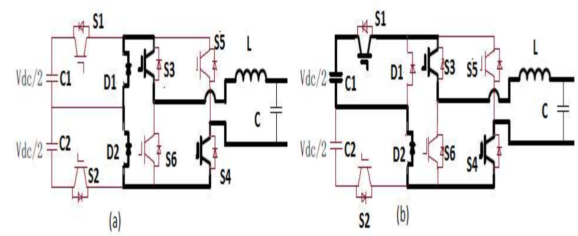
Figure 5 (a) shows operation circuit of INV Mode 1. Both S_1 and S_2 are turned off. The current of the filter inductor flows through S_3, utility, S_4 and the two body diodes of D_1 and D_2. The inverter output is 0.

b. INV Mode 2

Figure 5 (b) shows operation circuit of INV Mode 2. S1 is turned on and S_2 is turned off. DC capacitor C_1 is discharged through S_1, S_3, filter inductor, utility, S_4 and the body diode of S_4 to form a loop. The inverter output is Vdc/2.

c. INV Mode 3

Figure 6(a) shows operation circuit of INV Mode 3. Both S_1 and S_2 are turned on. DC capacitors C_1 and C_2 are both discharged through S_1, S_3, filter inductor, utility, S_4 and S_2. The inverter output is Vdc.



d.INV Mode 4

Figure 6(b) shows operation circuit of INV Mode 2. S_1 is turned off and S_2 is turned on. DC capacitor C_2 is discharged through the diode of D_1, S_3, filter inductor, utility, S_4 and S_2 to form a loop. The inverter output is Vdc/2.

The operations of the converter under INV mode 5-8 are similar to that under INV mode 1-4. The inverter output is 0, Vdc/2 and Vdc, respectively. The inverter therefore, can have a five-level voltage output, which is Vdc, Vdc/2, 0, -Vdc/2 and Vdc. The PWM strategy is used in the control section which helps balance the DC link capacitors. In PWM strategy, S_1 and S_2 will be turned on, turned off, turned on alternatively or turned off alternatively. The voltage balance issue is important for multi-level inverter. If the capacitor voltages are not balanced, the output voltage may become unsymmetrical and result in high harmonics in load current. No shoot through issues for the two high frequency switches, and no dead zone needed, which reduces the harmonics of the output and simplifies the control.

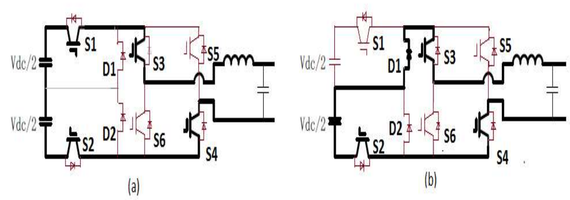


Figure 6. Modes of operation (a) Mode 3 (b) Mode 4.

C. Two Stage Configuration

The maximum voltage that can be obtained from a single PV cell is in the range of 20-40 V. Therefore, to produce a grid connected voltage from a single PV cell requires the integration of a converter section and inverter section i.e, two stage configuration. The main advantage of choosing two stage configuration is that the switching frequency of the converter can be chosen independent of the inverter. So, the converter section is used, to boost the PV voltage to the value required for conversion by the inverter. Therefore based on the above mentioned analysis, we are choosing the proposed converter as the first stage of two-stage configuration and as the central inverter we are choosing a multi-level inverter as the second stage because of benefit of low Total Harmonic Distortion (THD), small filter size and low voltage stress can effectively reduce the switching losses and improve the power efficiency. Three basic topologies of multilevel inverter are normally used: diode-clamped, flying capacitor or cascaded H-bridge. However, the number of power electronics switches applied in the multilevel inverter is greater than half and full bridge inverters. Moreover, the control strategy is more complicated, which requires more detailed design consideration to reach the expected advantage of better power efficiency, lower switching harmonics and smaller filter size compared with half and full bridge inverters. For diode clamped and flying capacitor multilevel inverter, the voltages of two dc capacitors are used to form the voltage level of the inverter, thus the voltages of these two dc capacitors must be controlled and balanced, which is typically hard and complicated. The cascade H-bridge circuit has advantages of fewer components required over other multilevel inverters under the output voltage with same levels and easy to be modularized. However, the topology has the disadvantage of multiple independent dc voltage sources requirement. So, considering all these disadvantages, a five-level multilevel inverter is chosen as the central inverter. It has reduced switches compared with other multilevel topologies and requires only single independent supply. So that the output voltage of the converter can serve as the input of the inverter and control strategy is in such a way that the capacitor voltage is balanced, so as to give five level output voltage which is then filtered. Therefore a five level inverter is selected as the second stage of the two-stage configuration.

The converter output may not be constant always because the input voltage from PV will vary in accordance with irradiation and temperature. Therefore a closed loop control is necessary, so as to maintain reference voltage. A closed loop control of the converter is done in the paper so as to produce a constant voltage for varying input voltage in a range of 15-40 V using PI control where Kp = 0.0001 and Ki = 0.019. Figure 7 shows the integrated two stage inverter for grid connected application.

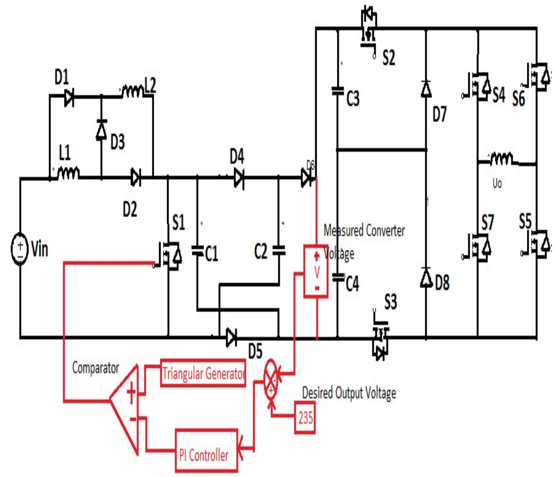


Figure 7: Two stage configuration of five level inverter

III. SIMULATION RESULTS

For the converter section, there is only one switch and the switching frequency is chosen to be 50 Khz and Duty ratio, D = 71% inorder to get grid connected voltage. The stress across the switch of the converter is half the output voltage of the converter. For the second stage i.e, for five level inverter, there are two high frequency switches S_2 and S_3 and switches S_4 to S_7 operate at line frequency. Table 2 shows the parameters used for simulation.

The switching is done in such a way that capacitor balancing is done inherently along with DC-AC conversion. The converter output is obtained as 235 V , as calculated and the switching stress across the switch was almost 118 V i.e; half the output voltage. Figure 9 and 10 shows the five level output voltage before and after filtration. The THD analysis obtained was 29.3 % before filtration and 1.5% after filtration (with L = 5 mH and C= 21 μF).

Table 2: Simulation Parameters

PARAMETERS	SPECIFICATION
Input Voltage	20 V
Duty Ratio	71 %
Switching Frequency	50 KHz
Inductor Value	300 μH
Doubler Capacitor Value	100 μF
Capacitor Value	100 μF
Output Voltage	235 V

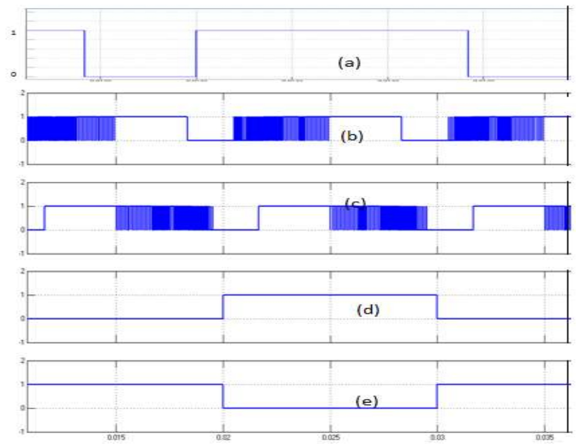


Figure 8: Gate signal to two stage micro grid five level inverter for switches (a) S_1 (b) S_2 (c) S_3 (d) S_4 (e) S_6

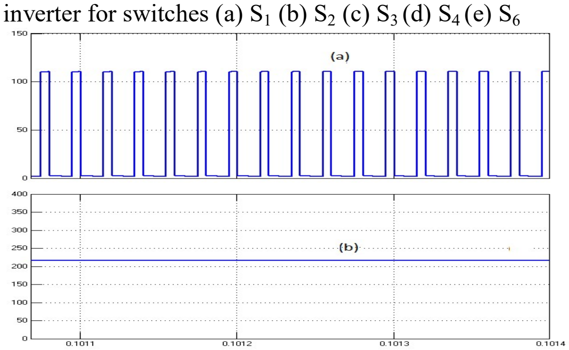


Figure 9: a) Voltage stress across switch S_1
(b) The Output Voltage of the converter

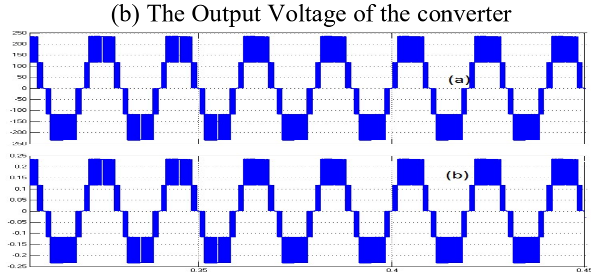


Figure 10: (a) Output Voltage (b) Output Current of the Inverter

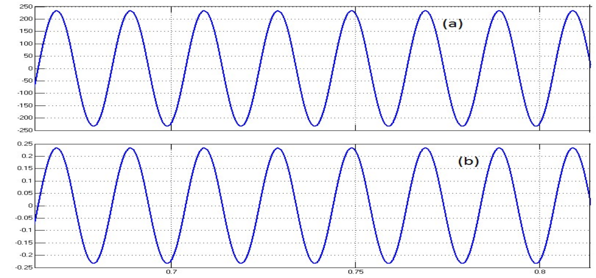


Figure 11: (a) Output Voltage (b) Output Current of the Inverter after filtration

IV. EXPERIMENTAL RESULTS

Prototype with reduced voltage had been developed. For converter section an input voltage of 5 V is given with a duty ratio of 40% and with a switching frequency of 10 KHz. For inverter switches, S_2 and S_3 carrier frequency chosen was of 5 KHz and switches from S_4 to S_7 were triggered at line frequency. The switching pulses were developed using PIC 16F877A and driver IC used is TLP250. An output voltage of about 21 V was obtained. Table 3 shows the prototype parameters used for experimental verification. For an input voltage of 5 V the stress was calculated to be obtained as 11.665 V. Experimentally obtained value is 12.18 V which is nearly equals to the calculated value.

Table 3: Prototype Parameters

PARAMETERS	SPECIFICATION
Input Voltage	5 V
Duty Ratio	40 %
Switching Frequency	10 KHz
Inductor Value	600 μH
Capacitor Value	100 μF
Output Voltage	23.33 V

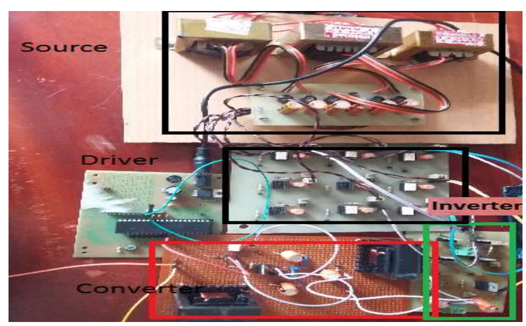


Figure 12: Laboratory prototype of the two stage configuration

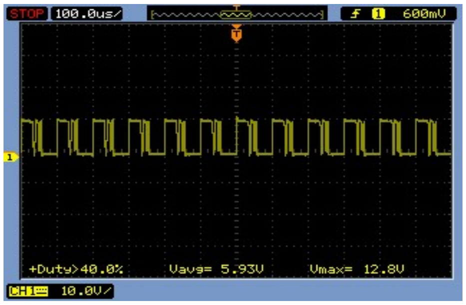


Figure 13: The voltage stress across converter switch

Figure 14: The output voltage of the converter

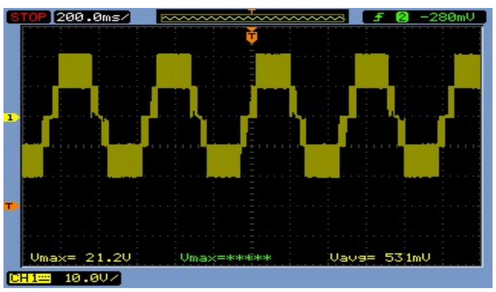


Figure 15: The output voltage of the inverter

CONCLUSIONS

This paper is based on the development and analysis of the two stage configuration. Compared with popularly used multi-level converters, Diode-clamped, Flying capacitor and Cascade H-bridge converter, the inverter topology has less high frequency active switches. Single switch converter circuit with reduced stress, less component count and high gain is proposed. For an input voltage of 20 V, an output voltage of 235 V was obtained. The THD was found to be 29 % before filtration and 1.5 % after filtration. Based on the irradiation and temperature difference the output voltage of a PV cell vary. Therefore, the closed loop control of converter session was done to maintain constant voltage at the output of the converter. As the number of C-D cell increases, the output voltage will increase and stress will get reduced. A prototype of inverter and converter section is tested and results are experimentally verified. Future scope involves increasing the level of inverter with less complexity in control.

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