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Design and Development of Prototype Three Level NPC Inverter for Industrial Application

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Abstract: **The requirement of electricity in India is increasing at a high rate. Severe energy crisis has forced the world to develop new and alternative methods such as the use of advanced power electronic systems. Therefore most of the utilities utilizes sufficient electricity and transmit the additional power to grid. One of the methods proposed is solar photovoltaic integrated with the battery storage. Here, solar photovoltaic are integrated with battery using a three level Neutral Point Clamped (NPC) Inverter. A three level Neutral Point Clamped Inverter is integrated using two new configurations or techniques-New Configuration i.e., Space Vector Modulation Technique, which generates balanced capacitor voltage under unbalanced DC voltage. Design and theoretical framework of the modulation technique has been proposed. A new control algorithm has been introduced in order to control the power delivery between the solar PV, battery, grid which uses Maximum PowerPoint Tracking (MPPT) technique.**

Keywords: **Photovoltaic, MPPT, SVPWM, Three levels NPC Inverter.**

I. INTRODUCTION

Due to world energy crisis and environmental problems, renewable energy such as solar photovoltaic, wind etc. are replaced by conventional power resources for the generation of electricity. We mainly consider solar photovoltaic here.

In solar PV application, utilization of maximum power from the source is the most important function of the power electronic system. The type of electronic configuration used here are- single stage conversion, consists of DC-DC converter which provides Maximum PowerPoint Tracking (MPPT) of the PV array and to produce DC voltage and double stage conversion which generates three-phase sinusoidal voltage or current to transfer the power to a grid.

Unpredictable and fluctuating nature of solar energy system can be overcome by integrating solar PV with the battery storage using three level inverter which is connected to the grid. Usually a converter is used for charging and discharging of the battery. Here, we mainly design and study the grid connected three phase solar PV system integrated with the battery storage using three level inverter having the capability of MPPT, AC side current control and ability to control the charging and discharging of battery.

II. STRUCTURE OF NEW CONFIGURATION (SVPWM)

Fig. 1(a) shows a typical three phase three-level neutral-point-clamped (NPC) inverter circuit topology. The converter has two capacitors in the DC side to produce the three-level AC side phase voltages. Normally, the capacitor voltages are assumed to be balanced, since it has been reported that unbalance capacitor voltages can affect the AC side voltages and can produce unexpected behavior on system parameters such as even-harmonic injection and power ripple. Several methods have been introduced to balance the capacitor voltage. They are as follows:

Various strategies have been proposed to balance the capacitor voltages using modulation algorithms; one among them is sinusoidal carrier-based PWM (SPWM) or Space Vector Pulse-Width Modulation (SVPWM).

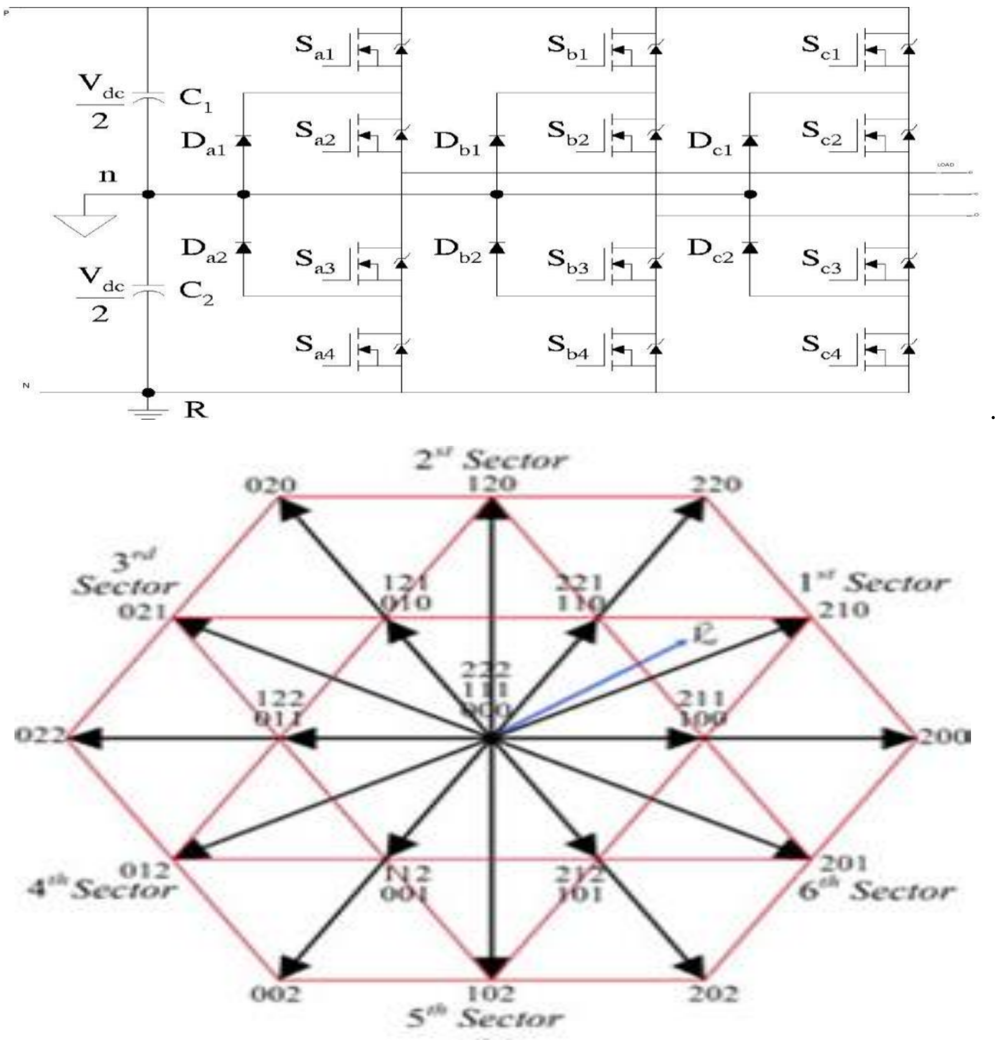

Fig. 1. Typical three-level inverter (a) structure of circuit, and (b) three-level Inverter space vector diagram for balanced dc-link capacitors

In SPWM applications, most of the strategies are based on injecting the appropriate zero-sequence signal in to the modulation signals to balance the DC-link capacitors.

In vector control theory, ideally, the inverter must be able to generate the voltage output instantaneously, following the reference vector, (V_{ref}), generated by the control system. However because of the limitation of the switches in the inverter, it is not possible to guarantee that any requested vector can be generated; as a matter of fact, only a limited number of vectors (27 vectors for three-level inverter) can be generated.

To overcome such difficulties, in any space vector modulation scheme such as SVPWM and SVPWM, the reference vector, is generated by selecting the appropriate available vectors in each time frame in such a way that the average of the applied vectors must be equal to the reference vector.

Equation (1) shows the mathematical relation between the timing of the applied vectors and the reference vector:

$$\begin{cases} T_s\vec{V}_{ref} = \sum_{i=1}^{n} T_i \vec{V}_i \\ T_s = \sum_{i=1}^{n} T_i \end{cases} \qquad (1)$$

Where, T_s is the time frame and preferred to be as short as possible. It can be considered as a control update period where an average vector will be mathematically generated during this time duration. T_i is the corresponding time segment for selected inverter vector $_{Vi}$ and n is the number of applied vectors. Capacitor balancing in most reported three-level NPC inverter applications is achieved by the proper selection of the short vectors. The DC capacitor voltages are assumed to be balanced.

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Fig. 1(b) shows the space vector diagram of a three-level inverter for balanced dc-link capacitors. It is made up of 27 switching states, from which 19 different voltage vectors can be selected. The number associated with each vector in Fig. 1(b) represents the switching state of the inverter phases respectively. The voltage vectors can be categorized into five groups, in relation to their amplitudes and their effects on different capacitor voltages from the view of the inverter ac side. They are six long vectors (200, 220, 020, 022, 002, and 202), three zero vectors (000, 111, and 222), six medium vectors (210, 120, 021, 012, 102, and 201), six upper short vectors (211, 221, 121, 122, 112, and 212), and six lower short vectors (100, 110, 010, 011, 001, and 101). For generating _*V*ref , when one of the selections (_*Vi*), is a short vector, then there are two choices that can be made which can produce exactly the same effect on the ac side of the inverter in the three wire connection (if voltages are balanced).

For example, the short vector "211" will have the same effect as "100" on the ac side of the inverter. However, this choice will have different effect on the dc side, as it will cause a different dc capacitor to be chosen for the transfer of power from or to the ac side, and a different capacitor will be charged or discharged depending on the switching states and the direction of the ac side current.

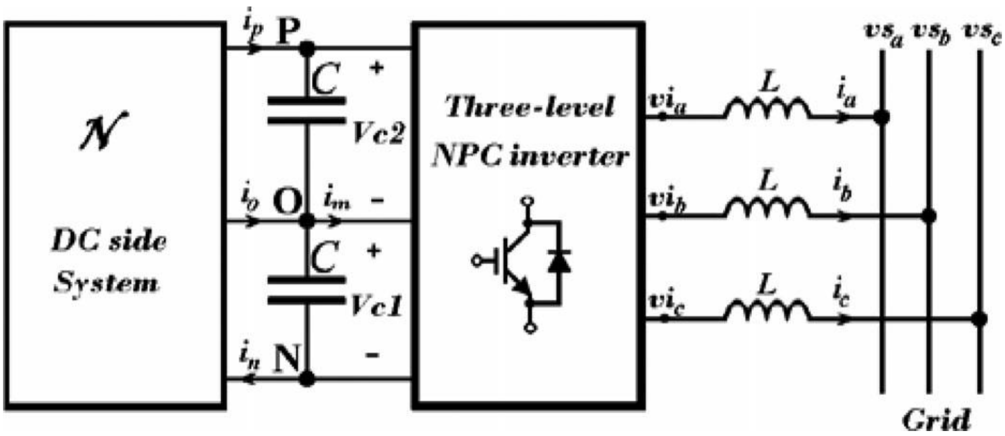


Fig: 2. General diagram of a grid connected three-wire three-level inverter

Fig. 2 shows a general structure of a grid-connected three-level inverter showing the DC and AC sides of the inverter. The DC side system, shown as N can be made up of many circuit configurations, depending on the application of the inverter. For instance, the DC side system can be a solar PV, a wind generator with a rectifying circuit, a battery storage system or a combination of these systems where the DC voltage across each capacitor can be different or equal.

Mathematically, in a three-wire connection of a two-level inverter, the dq_0 field, V_d , V_q and V_0 of the inverter in vector control can be considered as having two degrees of freedom in the control system; because the zero sequence voltage, $V_{0,}$ will have no effect on the system behavior in both the DC and the AC side of the inverter.

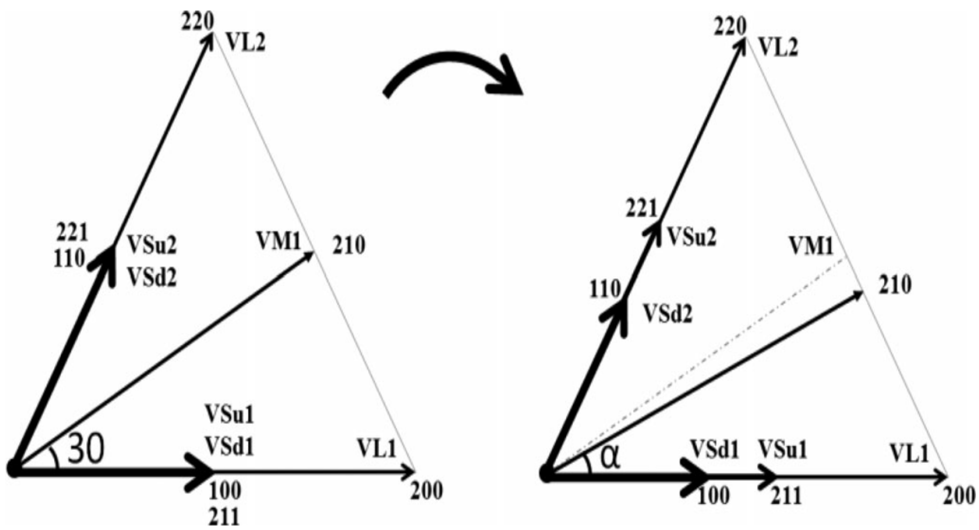


Fig: 3. Vector diagram in the first sector of Fig. 1(b) showing the change of the vectors using balanced dc and unbalanced dc assuming *Vc*1 < *Vc*2

In the vector diagram shown in Fig. 1(b), capacitor voltage unbalance causes the short and medium vectors to have different magnitudes and angles compared to the case when the capacitor voltages are balanced. Fig. 3 shows the differences between twocases as highlighted in the first sector of the sextant in Fig. 1(b) for *VC*1 < *VC*2 . Vector related to the switching state _*VI* can be calculated as follows :

$$\vec{V}_I = \frac{2}{3}\left(V_{aN} + \vec{a}V_{bN} + \vec{a}^2 V_{cN}\right)$$

Whereas = *ej*(2 *π*3) and *VaN* , *VbN* and *VcN* are the voltage values of each phase with reference to "*N*" in Fig. 1(a). Assuming that the length of the long vectors ((2/3)*V dc*) is 1 unit and the voltage of capacitor *C*1, *V c*1 = *hV dc*, for 0 ≤ *h* ≤ 1, then the vectors in the first sector can be calculated using (2) and the results are given in (3)–(9)

$$\vec{V}sd1 = h \quad (3)$$

$$\vec{V}su1 = 1 - h \quad (4)$$

$$\vec{V}l1 = 1 \quad (5)$$

$$\vec{V}l2 = \frac{1}{2} + \frac{\sqrt{3}}{2}j \quad (6)$$

$$\vec{V}sd2 = h\left(\frac{1}{2} + \frac{\sqrt{3}}{2}j\right) \quad (7)$$

$$\vec{V}su2 = (1 - h)\left(\frac{1}{2} + \frac{\sqrt{3}}{2}j\right) \quad (8)$$

$$\vec{V}m1 = \left(1 - \frac{h}{2}\right) + h\frac{\sqrt{3}}{2}j. \quad (9)$$

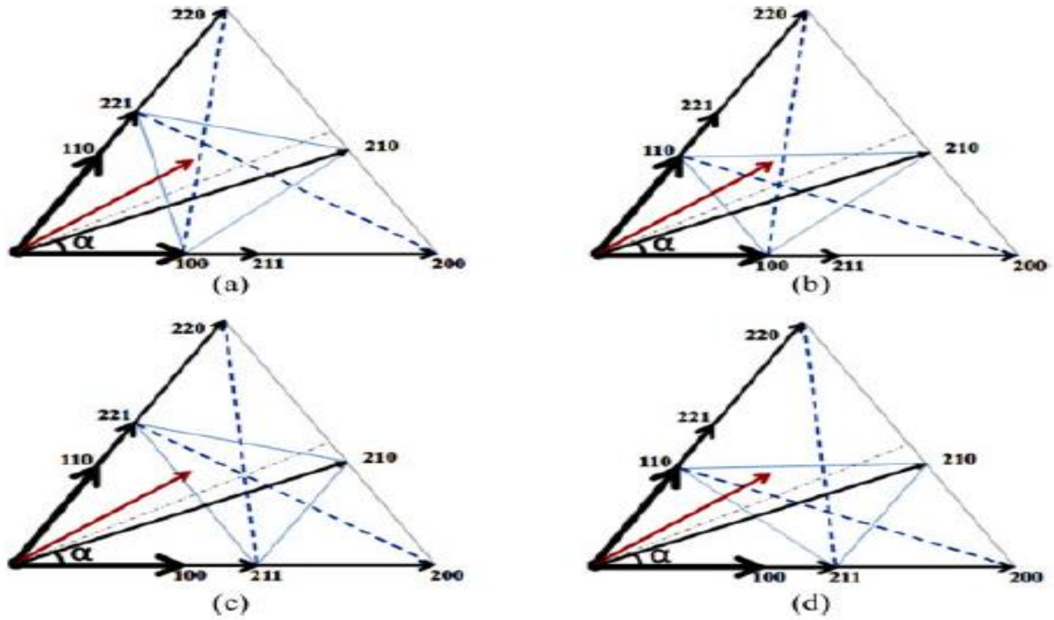


Fig: 4. Different possible vector selection ideas

Fig. 4 shows different possible vector selections to generate a reference vector (_*V* ∗) in the first sector based on the selections of different short vectors. For example, to generate _*V* ∗ based on Fig. 4(a), one of following combinations can be selected with proper timing based on (1). The combinations are: (221–210–100), (221–220–100), (221– 200–100), (221–200–Zero), (000–220–Zero), (220–200–Zero), where "Zero" can be "000" or "111" or "222". This demonstrates that there is flexibility in choosing the correct vector selections. Although all of these selections with suitable timing can generate the same reference vector, they have different impacts on the dc and ac side of the inverter in their instantaneous behavior.

III. PROPOSED TOPOLOGY TO INTEGRATE SOLAR PV WITH BATTERY STORAGE INTEGRATION

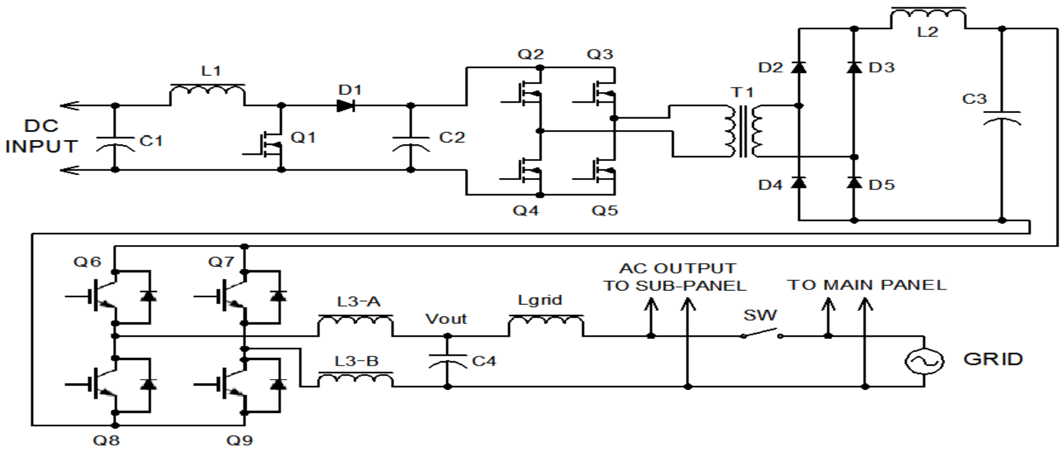
Based on the discussions, two new configurations of a three-level inverter to integrate battery storage and solar PV are proposed, where no extra converter is required to connect the battery storage to the grid connected PV system. These can reduce the cost and improve the overall efficiency of the whole system particularly for medium and high power applications.

The proposed system will be able to control the sum of the capacitor voltages ($VC1 + VC2 = Vdc$) to achieve the MPPT condition and at the same time will be able to control independently the lower capacitor voltage ($VC1$) that can be used to control the charging and discharging of the battery storage system. Further, the output of the inverter can still have the correct voltage waveform with low total harmonic distortion (THD) current in the ac side even under unbalanced capacitor voltages in the dc side of the inverter.

IV. SIMULATION AND VALIDATION OF THE PROPOSED TOPOLOGY

Simulations have been carried out using Proteus to verify the effectiveness of the proposed topology and control system. An *LCL* filter is used to connect the inverter to the grid.

A grid Tie Inverters basically takes a variable voltage from a DC source, such as solar panels array or a wind system, and inverts it to AC synchronized with the mains. It can provide power to your loads and feed an excess of the electricity into the grid. Depending on power and voltage levels. Grid Tie Inverters circuits normally have from one to three stages. A conceptual power train schematic diagram below illustrates the principles of operation of a three-stage grid tie inverter. Such a topology can be useful for low-voltage inputs (such as 12V) in grounded systems.



The input voltage is first raised by the boost converter formed with inductor L1, MOSFET Q1, diode D1 and capacitor C2. If a PV array is rated for more than 50V, generally one of the input direct current busses has to be grounded. Although in theory either of two busses can be connected to earth, usually it is a negative one. It is important to remember that if DC input has a conduction pass to ground, the output AC conductors in utility-interactive configurations should be isolated from DC. In our example, a galvanic isolation is provided by a high frequency transformer in the second conversion stage. This stage is a basically a pulse-width modulated DC-DC converter. The schematic above shows a full bridge (also known as H-bridge) isolating converter comprised of Q2-Q5, T1, D2-D5, L2, and C3. For power levels under 1000 watt it could also be a half-bridge or a forward converter. Some commercial models use low-frequency (LF) transformer in the output stage instead of a high frequency one in the DC-DC section. With such a method, input is converted to 60 Hz AC, and then a LF transformer changes it to a required level and provides isolation at the same time.

The equipment with an LF transformer has a significantly larger weight and size, but it will not inject a DC component into the load. Here is a lesser known detail: UL 1741 does allow transformerless inverters and exempts them from dielectric voltage withstand test between input and output. Therefore the isolating stage can be eliminated. It is important to note that the conductors from PV array in non-isolated designs can't be bonded to earth. NEC® 690.41 allows ungrounded configurations are they comply with Article 690.35. The transformerless inverters of course feature lower weight and cost. They are especially popular in Europe where ungrounded electrical systems are common. However, because of the lack of the galvanic isolation, these models present potential electrical hazards. In such a setup if a person touches a terminal of the PV panel or the battery, he will appear under AC line potential. The transformerless systems require additional protection devices per NEC® Article 690.35 and special warning labels placed wherever energized circuits may be exposed during service.

T1 can be a so-called step-up type to amplify the input voltage. With a step-up T1, the first stage (boost converter) may be omitted. However, high turns ratio leads to large leakage inductance. This in turn causes voltage spikes on the FETs and rectifiers as well as other undesirable effects.

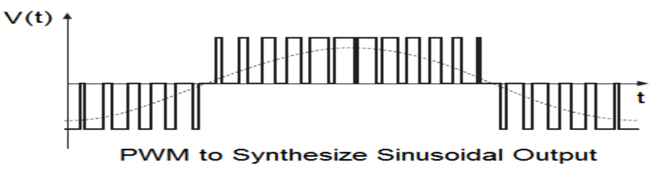
The regulated converter provides a DC-link to the output AC inverter. Its value must be higher than the peak of the utility AC voltage. For example, for 120VAC service, the Vdc should be >120*√2=168V. Typical numbers are 180-200V. For 240VAC you would need 350-400 V.

The third conversion stage turns DC into AC by using another full bridge converter. It consists of IGBT Q6-Q9 and LC-filter L3, C4.

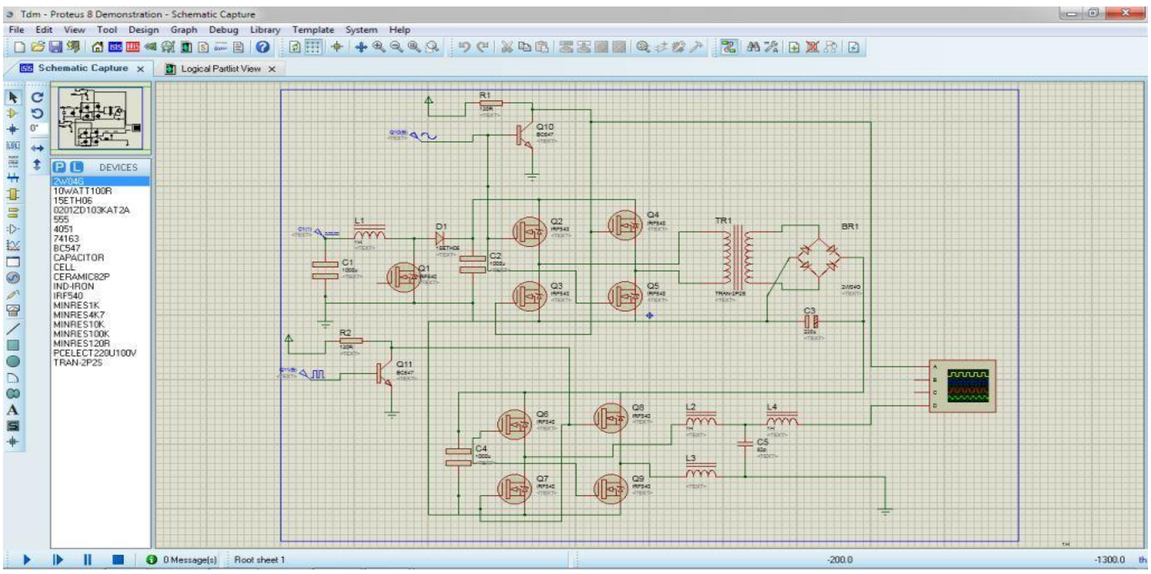
The IGBTs Q6-Q9 work as electronic switches that operate in PWM mode. This topology requires anti-parallel freewheeling diodes to provide an alternate path for the current when the switches are off. These diodes are either included within IGBTs or added externally. By controlling different switches in the H-bridge, a positive, negative, or zero potential can be applied across inductor L3. The output LC filter then reduces high frequency harmonics to produce a sine wave.

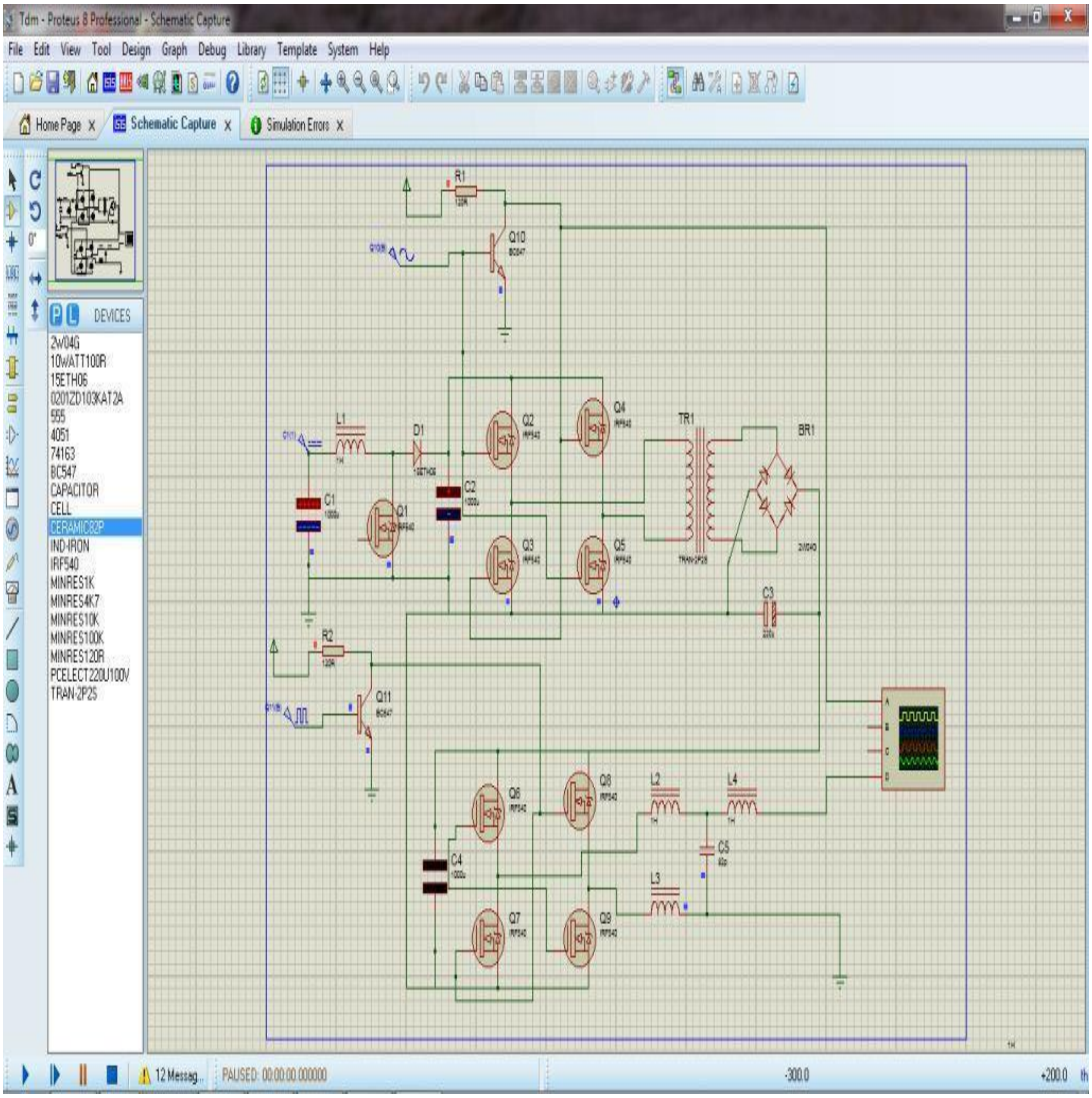
In solar applications, to maximize the system efficiency, a GTI also has to meet certain requirements defined by the photovoltaic panels. Solar panels provide different power in different points of their volt-ampere (V-I) characteristic. The point in the V-I curve where output power is maximum is called maximum power point (MPP). The solar inverter must assure that the PV modules are operated near their MPP. This is accomplished with a special control circuit in the first conversion stage called MPP tracker (MPPT).

A GTI also has to provide so-called anti-islanding protection. When mains fails or when its voltage level or frequency goes outside of acceptable limits, the automatic switch should SW quickly disconnect the system output from the line. The clearing time depends on the mains conditions and is specified by UL 1741. In the worse cases, when utility voltage drops below 0.5 of nominal, or its frequency deviates by +0.5 or -0.7 Hz from the rated value, GTI should cease to export power back to the grid in less than 100 milliseconds. An anti-islanding can be accomplished for example via AC undervoltage or output overcurrent detection functions. Our example depicts a system with power backup option: when contactor SW opens, the GTI will supply critical loads connected to the sub-panel.



V. SIMULATION RESULTS

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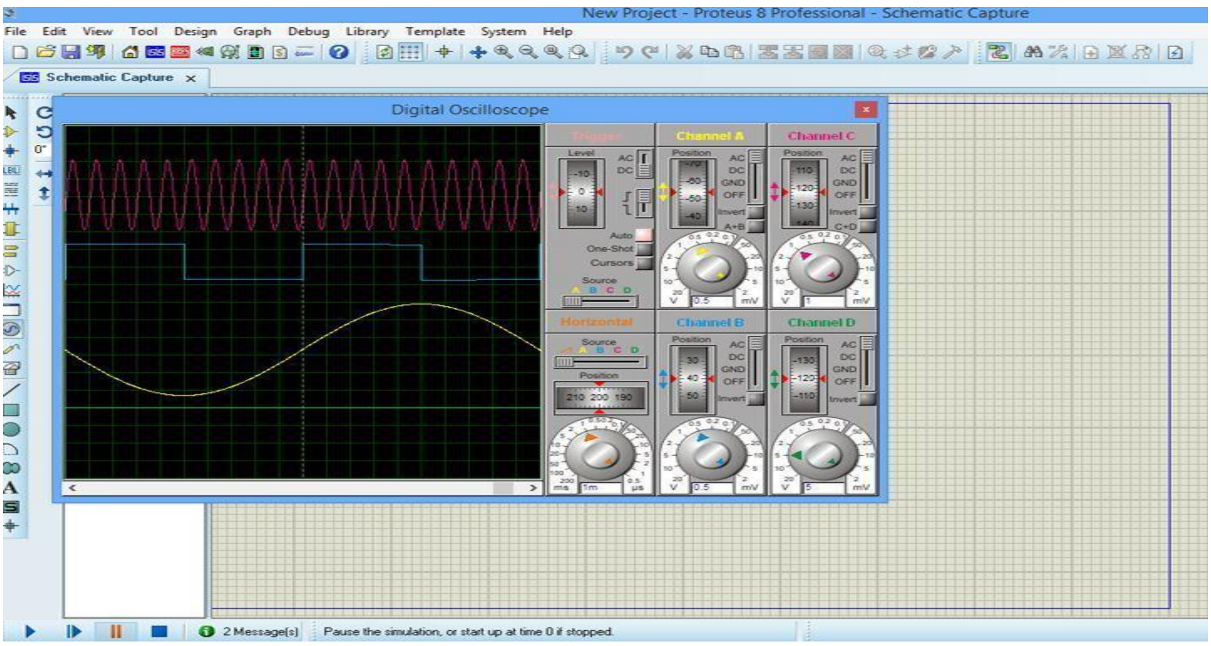
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VI. CONCLUSION

A novel topology for a three-level NPC voltage source inverter that can integrate both renewable energy and battery storage on the dc side of the inverter has been presented. A theoretical framework of a novel extended unbalance three-level vector modulation technique that can generate the correct ac voltage under unbalanced dc voltage conditions has been proposed. A new control algorithm for the proposed system has also been presented in order to control power flow between solar PV, battery, and grid system, while MPPT operation for the solar PV is achieved simultaneously. The effectiveness of the proposed topology and control algorithm was tested using simulations and results are presented. The results demonstrate that the proposed system is able to control ac-side current, and battery charging and discharging currents at different levels of solar irradiation.

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