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Three Level Neutral-Point-Clamped (NPC) Inverter for a Grid Connected Solar Photovoltaic (PV) and Battery Storage Integration

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Abstract:
Photovoltaic (PV) generation systems are becoming more promising alternatives to conventional electricity generation. Advanced power electronic systems are needed to utilize and develop renewable energy sources. This paper proposes the new configuration of a three level Neutral Point Clamped (NPC) inverter using only one converter to integrate PV system with battery storage in a grid connected system. The structure of a three level inverter and associated capacitor voltages, algorithm to integrate solar PV and battery storage in a grid connected system with simultaneous maximum power point tracking (MPPT) for solar PV system is presented. The strength of the proposed scheme is to extend unbalance three-level vector modulation technique that can generate the correct ac voltage under unbalanced dc voltage conditions. To calculate proper multilevel voltage waveforms, a fast and simplified space vector modulation is adopted. The proposed control strategy ensures the injection of a reference power in the distribution grid. The report presents the design consideration of the proposed configuration and the theoretical frame-work of the proposed modulation technique. A new control algorithm of system having space vector pulse width modulation (SVPWM) is also presented in order to control the power delivery between the solar PV, battery storage systems, and grid, which simultaneously provides maximum power point tracking operation for the solar PV. This paper is concerned with the study and analysis of a grid connected three phase solar PV system integrated with battery storage using only one three level inverter. This will result in lower cost, better efficiency and increased flexibility of power flow control. The effectiveness of the proposed topology and control algorithm will be tested using MATLAB simulations and results, including ac side current control and battery charging and discharging currents at different levels of solar irradiation.

Keywords: Photovoltaic (PV), Space Vector Pulse Width Modulation (SVPWM), Three Level Neutral Point Clamped (NPC) inverter and Maximum Power Point Tracking (MPPT).

I. INTRODUCTION

As the environmental problems and world energy crisis caused by non-renewable power generation, unconventional energy sources such as solar photovoltaic (PV), wind generation, hydro systems are becoming more promising alternatives to replace non-renewable generation units for electricity generation. Hence power electronic systems are required, to use and develop renewable energy sources. In solar PV or wind energy applications due to fluctuating and unpredictable nature, utilizing maximum power from the unconventional source is one of the most vital and special function of the power electronic systems. Types of power electronic configurations are regularly used to transfer power from the renewable energy resource to the grid are two; in three-phase applications:a) single-stage, b) double-stage (step) conversion. In the double-step conversion for a PV system, the first step is usually a dc/dc converter and the second step is a dc/ac inverter. The function of the dc/dc converter is to avail the maximum power extraction of the PV array and to produce the appropriate dc voltage for the dc/ac inverter. The duty of the inverter is to generate three-phase sinusoidal voltages or currents to transfer the power to the grid in a grid integrated solar PV system or to the load in a stand-alone system [1]. In the single-stage connection, only one converter is needed to fulfill the double-stage functions, and hence the system will have a lower cost and higher efficiency, however, a more complicated control method will be required. For high power applications the recent norm of the market is a three-phase, single step PV energy systems by using a voltage source converter for power conversion. Unpredictable and fluctuating nature is one of the major concerns of solar and wind energy systems. Grid-connected unconventional energy systems connected by battery energy storage systems can overcome this situation. This solution can also increase the accessibility of power system control and rise in the overall availability of the system. Usually, a converter is required to handle the charging and discharging of the battery storage system and another different converter is required for dc to ac conversion of power; hence, a three phase solar PV system integrated to battery storage will require two converters. The control strategy here is to design and study of a grid-connected three-phase solar PV system connected with battery storage with the use of only single three-level converter having the capability of MPPT with ac-side current control scheme, and also the ability of handling the battery charging and discharging. This will result in minimized investment, best efficiency and increased flexibility of power flow control. To inject power on demand, certain energy storage equipments must be included into the system. These devices like batteries must store PV energy in surplus of electricity demand and in consequence meet electricity demand in excess of PV energy. The more common lead-acid battery is the most commonly used energy storage device at the present time. Another very important view of the systems that are connected to the grid is to select a right power factor according to the grid demands i.e. active or reactive power. The most efficient and user friendly systems are those, which allows variation in the active and reactive power supplied into the grid, depending on the power grid requirements.

II. GRID CONNECTED THREE-LEVEL NPC INVERTER SYSTEM

The configuration of the grid-connected PV battery storage system, which consists of PV panels, a battery bank connected to the DC bus and the three-level NPC inverter connected to the grid through a traditional three phase transformer. [1]

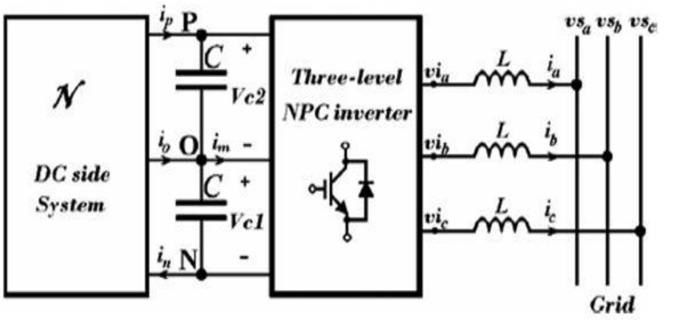


Figure. 2.1: General diagram of a grid connected three-wire three-level inverter. [1]

In the proposed system, power can be transferred to the grid from the renewable energy source while allowing charging and discharging of the battery as signaled by the control system. The proposed system will be able to control the sum of the capacitor voltages (V_{C1} + V_{C2} = V_{dc}) to achieve the MPPT and at simultaneously be able to control independently the voltage across lower capacitor (V_{C1}) that can be used to control the charging and discharging of the battery storage system. Further, the inverter output can have the correct voltage waveform with low total harmonic distortion (THD) current in the ac side even with unbalanced capacitor voltages in the dc side of inverter. This configuration can operate under most conditions, but when the solar PV does not produce any power, the system is unable to work properly with just one battery. For improved configuration, two batteries are now connected across two capacitors through two relays. When one of the relays is closed and the other relay is open, the configuration is similar to that which can charge or discharge the battery storage while the renewable energy source can generate power. However, when the renewable energy is unavailable, both relays can be closed thus allowing dc bus to absorb or transfer reactive and active power to or from the grid. It should be noted that these relays are selected to be ON or OFF as required; and PWM control requirement is absent. This also provides flexibility in managing which of the two batteries is to be charged when power is available from the renewable source or from the grid. With one of the batteries fully charged, the relay connected to the battery can be opened while closing the relay on the other battery to charge. Special consideration needs to be made to ensure that current through the inductor L_{bat} must be zero prior to opening any of these relays to avoid disrupting the inductor current and also to avoid damaging the relay. [1]

III. CONTROL SYSTEM DIAGRAM TO INTEGRATE PV AND BATTERY STORAGE

In Figure 3.1 the requested active and reactive power generation to be transferred to the grid will be determined by the supervisory block for the inverter. This will be achieved based on the available PV generation, the grid data, and the current battery variables. The MPPT block determines the requested dc voltage of the PV to have the MPPT condition. This voltage can be determined by using another control loop, with slower dynamics, using the measurement of the available PV power. Based on the requested active (p*) and reactive power (q*), and the grid voltage in the dq-axis, v_{sd} and v_{sq}, the requested inverter current in the dq-axis, id and iq can be obtained using following equations.

$$p = v_{sd} i_d + v_{sq} i_q \quad (3.1)$$

$$q = v_{sq} i_d + v_{sd} i_q \quad (3.1)$$

$$i^*_d = \frac{p^* v_{sd} - q^* v_{sq}}{{v_{sd}}^2 + {v_{sq}}^2} \qquad i^*_q = \frac{q^* v_{sd} - p^* v_{sq}}{{v_{sd}}^2 + {v_{sq}}^2} \quad (3.3)$$

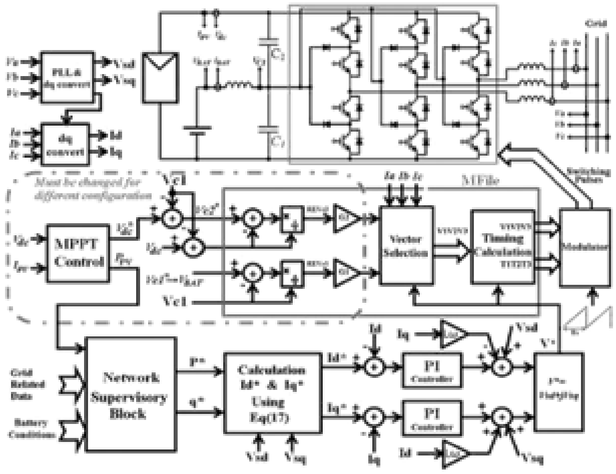


Figure. 5.7: Control system diagram to integrate PV and battery storage.

By using a proportional and integral (PI) controller and decoupling control structure, the requested voltage vector for inverter can be calculated. In the proposed system, to transfer a desired amount of power to the grid, the battery will be charged using extra energy from the PV or will be discharged to support the PV when the available energy cannot support the requested power. After deciding the requested reference voltage vector, the exact sector and subsector in the vector diagram can be decided. To find which short vectors are to be selected the capacitor voltage relative errors is given by following equations.

$$eV_{c1} = \frac{{V_{c1}}^* - V_{c1}}{V_{c1}} \quad (3.4)$$

$$eV_{c2} = \frac{{V_{c2}}^* - V_{c2}}{V_{c2}} \quad (3.5)$$

Where, ${V_{c1}}^*$ and ${V_{c2}}^*$are the desired capacitor voltages, and V_{c1} and V_{c2} are the capacitor voltages for capacitor C1 and C2 respectively. The short vector selection will determine the capacitor to be charged or discharged. To determine which short vector must be selected, the capacitor voltage relative errors and effectiveness on the control system behavior are important. A decision function 'F' can be defined based on this idea,

$$F = G_1 eV_{c1} - G_2 eV_{c2} \quad (3.6)$$

Where, G_1 and G_2 are the gains associated with each of the relative errors of the capacitor voltages. G_1 and G_2 are used to determine which relative error of the capacitor voltages is more dominating and hence allows better control of the selected capacitor voltage. For example, for an application that requires the balancing of the capacitor voltages as in traditional three-level inverters, G_1 and G_2 must have the same value with equal reference voltage values, but in the proposed application where the capacitor voltages can be unbalanced, G_1 and G_2 are different and their values are be completely dependent on their definitions of desired capacitor voltages. By using V_{c2} = V_{dc} - V_{c1} and V_{c1} = V_{BAT} and selecting G_2 much higher than G_1, the PV can be controlled to the MPPT, and C1 voltage can be controlled to allow charging and discharging of the battery. Based on the control system, on the ac side, the requested active power (p), and reactive power (q), will be generated by the inverter by implementing the requested voltage vector and applying the exact timing of the applied vectors. On the dc side, MPPT control can be done by control of V_{c2} (G_2 >> G_1) with reference value of (V_{dc}^* - V_{c1}) and more flexible control of V_{c1} with reference value of the battery voltage, V_{BAT}. By using the decision function (F) with the given reference values, the proper short vectors to be applied to implement the requested vector can be determined. With MPPT control, the PV arrays can transfer the maximum available power (P_{PV}), and with generating the requested vector in the ac side, the requested power P is transferred to the grid. Then, the control system will automatically control V_{c1} to transfer excess power (P_{PV} – P^*) to the battery storage or absorb the power deficit (P*- P_{PV}) from the battery storage. [1]

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

Table. 3.1: Parameters of the simulated system [1]

V_{BAT}	V_s (line)	I_{BAT}	C_1, C_2	L_l	L_s
60 V	50 V	5 mH	1000 µF	500 µH	900 µH
r_f	C_f	K_p	K_i	G_1	G_2
3!	14 F	2.9	1700	1	200

Three series-connected PV modules are used in the simulation. The mathematical model of each of the PV units is given by equation (5.15) where I_{SC} is the short circuit current of the PV. [7]

$$I_{PV} = I_{SC} - 10^{-7} \left(e^{\left(\frac{V_{PV}}{2.574}\right)} - 1\right) \qquad (3.7)$$

Two important points of the current-voltage characteristic must be pointed out: the open circuit voltage V_{OC} and the short circuit current I_{SC}. At both points the power generated is zero. V_{OC} can be approximated when the output current of the cell is zero, i.e. I = 0 and the shunt resistance R_{SH} is neglected. The short circuit current I_{SC} is the current at V = 0 and is approximately equal to the light generated current I_L. The maximum power is generated by the solar cell at a point of the current-voltage characteristic where the product VI is maximum. This point is known as the MPP and is unique. With a solar irradiation of 1000 W/m^2, I_{SC} is equal to 6.04 A and the open circuit voltage of the PV panels will be equal to V_{OC} = 44 V. The main parameters of the simulated system are given in Table 5.1. G_2 must be much more than G_1 in order to achieve the MPPT condition and to have the flexibility to charge and discharge of the battery. Any value > 100 is suitable for this ratio. On the other hand, because the ratio of G_2 / G_1 will only affect the selection of short-vector, higher ratio value will not affect other results. This value has been selected to be 200 to have good control on V_{dc} , as shown in Table 3.1. L_{BAT} is used to smooth the battery current, in the transient condition. A large range of values are acceptable for the inductor value, however, decreasing its value will increase the overshoot of the battery current. Also, this value is dependent of value of its adjacent capacitor and transient voltages. Due to the practical considerations (such as size and cost), the value of L_{BAT} is preferred to be low and has been chosen to be 5 mH. The values of K_p and K_i are selected by modeling the system in the dq-frame. The current control loop can be converted to a simple system after using the decoupling technique.

IV. MATLAB / SIMULINK IMPLEMENTATION OF SVPWM TECHNIQUE

Three switching states [1], [0] and [-1] can represent the operation of each leg. By taking into account all three phases, the inverter has a total of twenty seven possible switching states. The voltages have four groups as:

1. Zero vector (V1, V2, V3) representing three switching states [1 1 1], [-1 -1 -1] and [0 0 0]. The magnitude of V1, V2, V3 is zero.
2. Small vectors (V4 to V15), all having magnitude of Vd/3. Each small sector has two switching states, one containing [1] and other containing [-1] and they classified into P or N type of small vectors.
3. Medium vectors (V17, V19, V21, V23, V15, V27) whose magnitude is $\frac{\sqrt{3}}{3}V_d$.
4. Large vectors (V16, V18, V20, V22, V24, V26) all having magnitude of (2/3) V_d.

To describe the reference voltage vector V_{ref} , the space vector transformation is given as,

$$\vec{V_l} = \frac{2}{3}\left(V_{aN} + \propto V_{bN} + \propto^2 V_{cN}\right) \qquad (4.1)$$

Where, $\propto = e^{j2\pi/3}$ and V_{ref} can be described with the three nearest voltage space vectors. This selection is based on the magnitude of the V_{ref} and its angle.

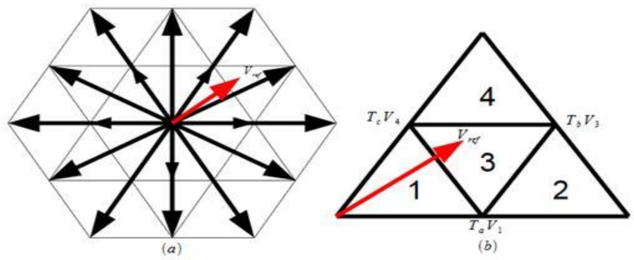


Figure. 4.1: Space vector diagram for (a) all sectors (b) sector 1

For one cycle, $V_{ref} = T_1 V_x + T_2 V_y + T_3 V_z$ (4.2)

If V2 is chosen as the reference axis (maximum magnitude as units) the voltage vectors on the axis can be described as:

$$V_x = V_1 = \frac{1}{2} \qquad (4.3)$$

$$V_y = V_3 = \frac{\sqrt{3}}{2} e^{j\frac{\pi}{6}} \qquad (4.4)$$

$$V_z = V_4 = \frac{1}{2} e^{j\frac{\pi}{3}} \qquad (4.5)$$

V_{ref} in the form of the real and imaginary axis,

$$V_{ref} = V_u e^{j\theta} \qquad (4.6)$$

$$V_u(\cos(\theta) + j\sin(\theta)) = \frac{1}{2} T_1 + \frac{\sqrt{3}}{2}\left[\cos\left(\frac{\pi}{6}\right) + j\sin\left(\frac{\pi}{6}\right)\right] T_2 + \frac{1}{2}\left[\cos\left(\frac{\pi}{3}\right) + j\sin\pi 3T3 \qquad (4.7)$$

Now modulation index is given by,

$$h = \frac{2V_u}{\sqrt{3}} \qquad (4.8)$$

Each sector has four regions (1 to 4), with the switching states of all vectors. By using the strategy that, the sum of the voltage multiplied by the interval of choose space vector equals the product of the reference voltage V_{ref} and sampling period T_S.

$$T_s \overrightarrow{Vref} = \sum_{i=1}^{n} T_i \vec{V_i} \qquad (4.9)$$

$T_1 = 1 - 2h\sin(\theta)$ (4.10)

$T_2 = 2h\sin(\theta + \frac{2\pi}{3})$ (4.11)

$T_2 = 2h\sin\left(\theta + \frac{2\pi}{3}\right) + 1$ (4.12)

Due to the practical considerations value of L_{bat} is preferred to be low and chosen to be 5mH. The proposed system will be able to control the sum of the capacitor voltages ($V_{C1}+V_{C2} = V_{dc}$) to achieve the MPPT condition and at the same time will be able to control the charging and discharging of the battery storage system. The simulation diagram implemented in MATLAB for the new single converter configuration with fault conditions implementation. The MPPT is being achieved by the system itself with network supervisory block which gathers the data of power demand on grid and battery conditions.

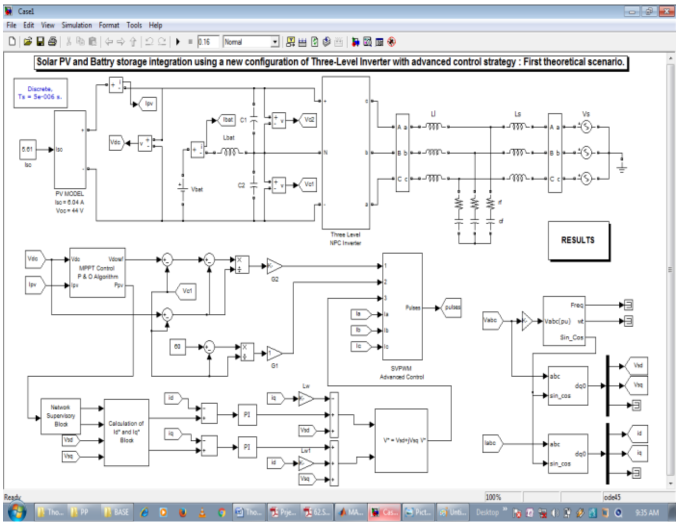


Figure.4.2: MATLAB / Simulink model of solar PV and battery storage integration using NPC inverter.

V. SIMULATION RESULTS

Simulations have been carried out using MATLAB / Simulink to verify the effectiveness of the proposed topology and control system.

5.1. First theoretical case

In the first case study solar irradiation producing I_{sc} = 5.61 A is assumed for the PV system as represented by equation 5.15. The PV system voltage V_{dc} = 117.3 V is tracked by MPPT P&O algorithm to receive maximum power output of 558 W. The active power requirement of the grid is initially considered to be 662 W and then reduced 445 W at 0.04 sec. The reactive power requirement of the grid is initially considered to be 0 VAR and then increases to 250 VAR at 0.1 sec. Fig. 5.1 shows the simulation results of the first case with above mentioned parameters. Fig. 5.1(a) and (b) displays that the active and reactive power requirement of the grid is successfully supplied. Fig. 5.1(c) results that the PV module voltage is tracked at 117.3 V to get the maximum power output. Fig. 5.1(d) results that discharging of the battery takes place if grid power is higher than PV module output, and charging is done in the reverse case. It also shows that the battery discharging current is 1.8 A ahead of 0.04 sec as the PV module output is less than grid required power. The battery current is around –1.8 A after 0.04 sec, means that the battery is getting charged from the excess power of PV system. Fig. 5.1(e) shows the inverter current, and Fig. 5.1(f) results the grid current. Good dynamic response is observed from the simulation results as shown in Fig. 5.1.

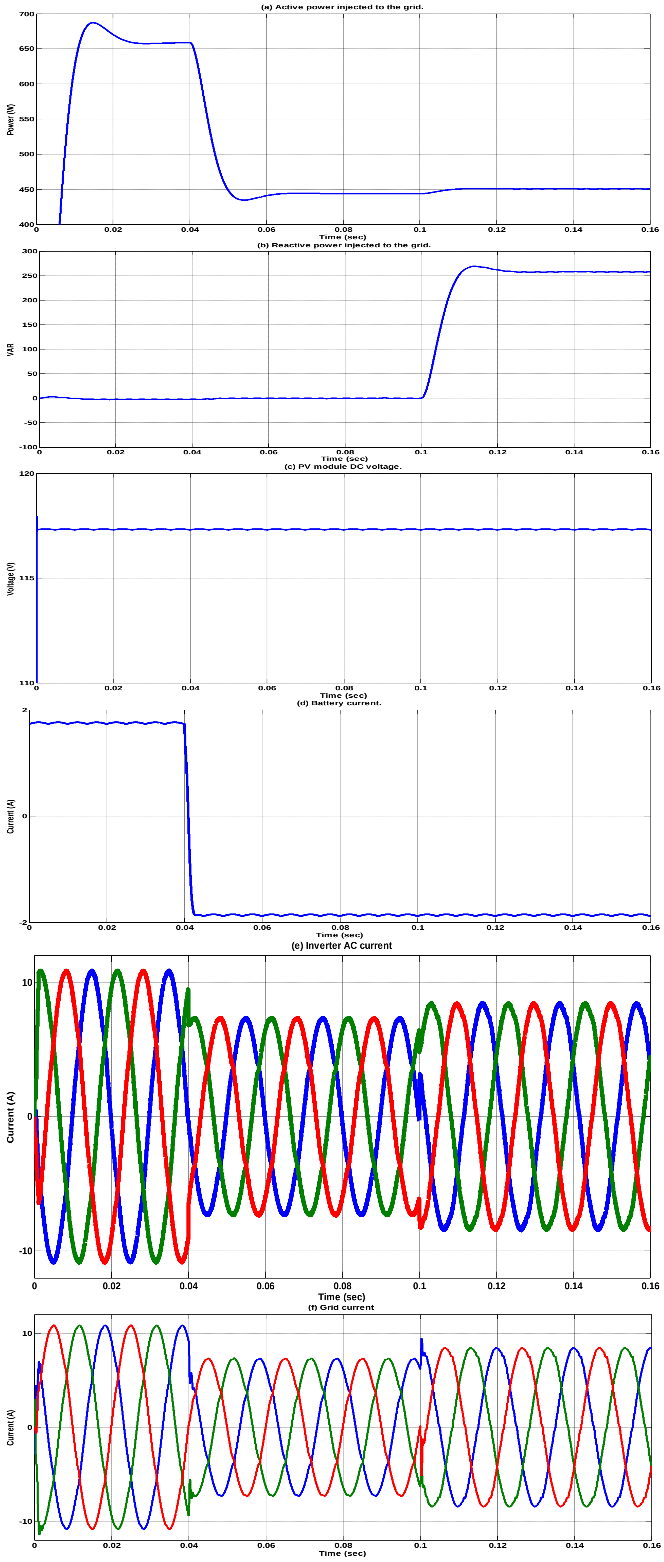
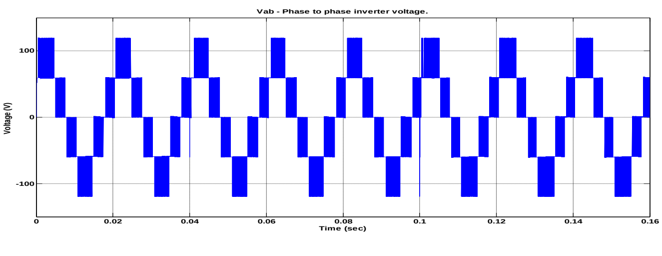


Figure .5.1. Simulated results for the first scenario (a) Active power injected to the grid. (b) Reactive power injected to the grid. (c) PV module DC voltage. (d) Battery current. (e) Grid current.



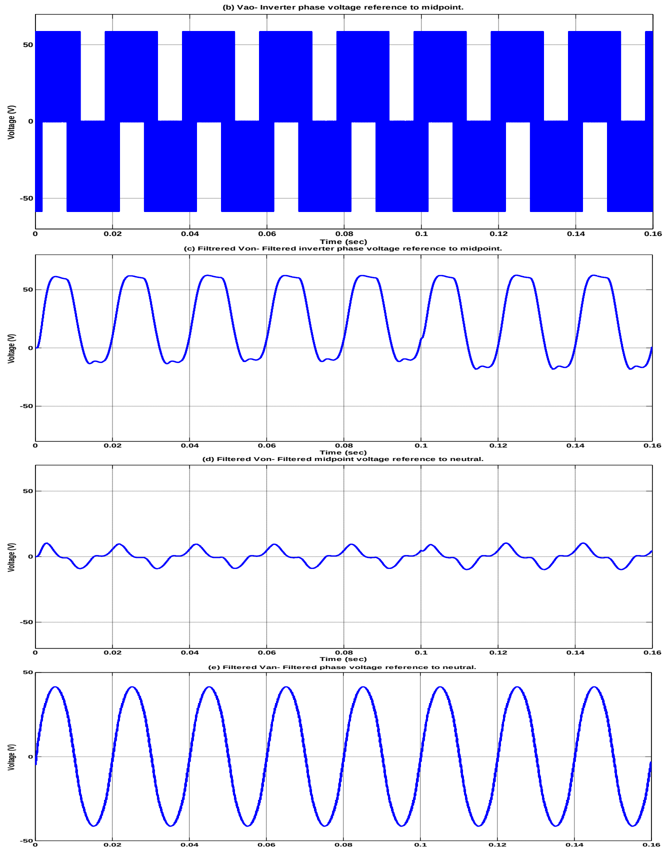
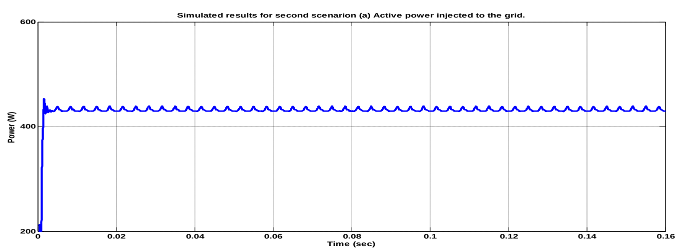


Figure. 5.2. Simulated inverter waveforms. (a) Vab-Phase to phase inverter voltage (b) Vao- Inverter phase voltage reference to midpoint. (c) Filtered Von- Filtered midpoint voltage reference to midpoint. (d) Filtered Von- Filtered midpoint voltage reference to neutral. (e) Filtered Van- Filtered phase voltage reference to neutral.

7.2 Second theoretical case

In the second case study solar irradiation is varying with values of I_{sc} = 4.8 A, 4 A and 5.61 A at 0 - 0.04 sec, 0.04 - 0.1 sec and after 0.1 sec respectively. The PV system voltage V_{dc} = 115.6, 114.1 and 117.3 V is tracked by MPPT P & O algorithm to receive maximum power output of 485, 404 and 558 W respectively. The active power requirement of the grid is considered to be constant at 480 W. The reactive power requirement of the grid is considered to be 0 VAR. Fig. 5.3 shows the simulation results of the second case with above mentioned parameters. Fig. 5.3(a) displays that the active power requirement of the grid is successfully supplied. Fig. 5.3(b) results that the PV module voltage is successfully tracked at to get the maximum power output. Fig. 5.3(c) results that discharging and charging of the battery is performed correctly. Fig. 5.3(d) shows the result of the grid current. Fig. 5.3(e) shows the grid side phase voltage and its current of phase a, which are in phase with each other signifying that reactive power supplied is zero as demanded by the system and proposed control method as generating correct PWM vectors.



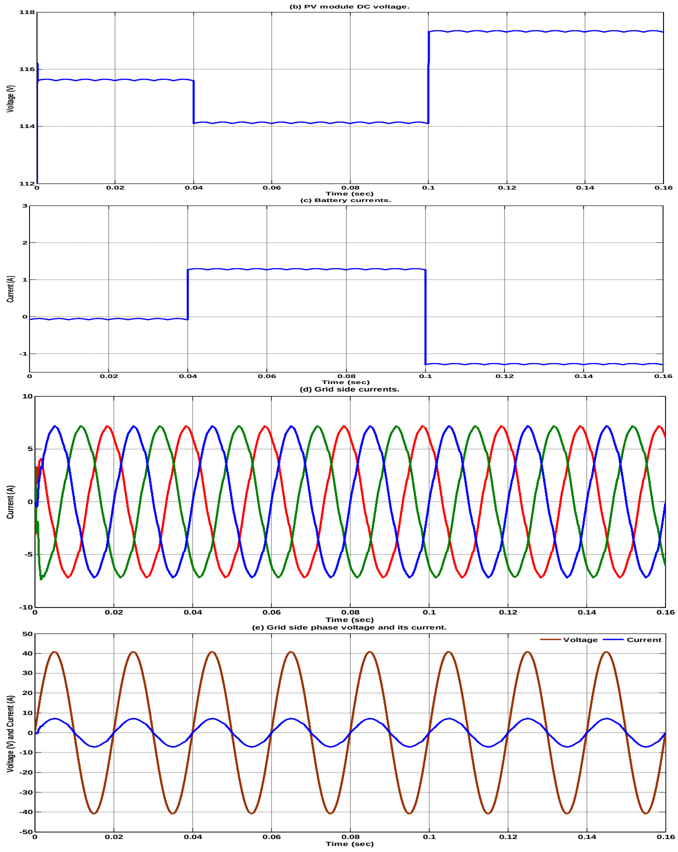
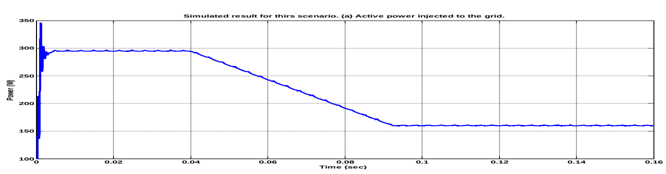


Figure.5.3. Simulated results for the second scenario. (a) Active power injected to the grid. (b) PV module DC voltage. (c) Battery currents. (d) Grid side currents. (e) Grid side phase voltage and its current.

7.2 Third Practical Case

In the third case study, solar irradiation producing I_{sc} = 2.89 A is assumed for the PV system. The PV system voltage V_{dc} = 112.8 V is tracked by MPPT P&O algorithm to receive maximum power output of 305 W. The active power requirement of the grid is initially considered to be 295 W and then reduced with a controlled slope to 165 W at 0.09 sec and then stays at 165 W after 0.09 sec. Fig. 5.4 shows the simulation results of the third case with above mentioned parameters. Fig. 5.4(a) displays that the active power requirement of the grid is successfully supplied. Fig. 5.4(b) results that the ahead of 0.04 sec, battery current is 0.1 A and after that due to slope wise reduction power requirement of the grid for constant PV module voltage, charging current of battery is finally settled at 2.2 A. Fig. 5.4(c) results that inverter current are drooping gradually from 3.4 A to 1.9 A from 0.04 sec to 0.09 sec and settles at 1.9 A beyond 0.09 sec. Practical systems have reference input with slope control than a step input change to avoid transients and activation of protection systems. In practical cases, solar irradiation change is gradual and not the steep one. Standard input signals like step input are used in theoretical analysis only. Hence the third case is relevant to practical situations and results are presented below.



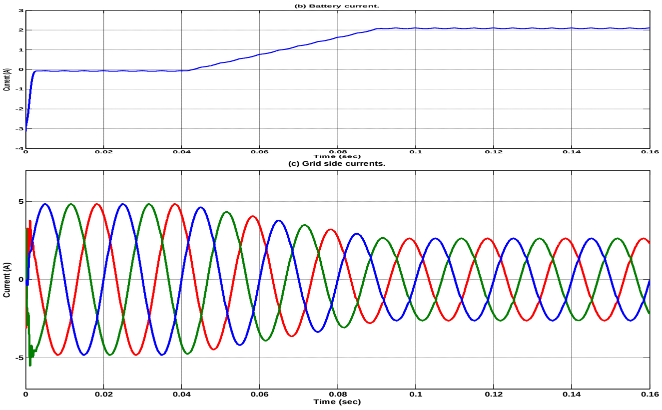


Figure.5.4. Simulated result for third scenario. (a) Active power injected to the grid. (b) Battery current. (c) Grid side currents.

VI. CONCLUSION

A three phase three-level diode clamped i.e. neutral point clamped voltage source inverter to integrate both renewable energy source such as solar photovoltaic and battery storage on the dc side of the inverter is proposed, studied and applied. An unbalance three-level space vector modulation scheme that can manipulate the correct AC voltage under unbalanced dc voltage conditions has been proposed. A control block diagram for the proposed system has also been presented in order to control smooth power delivery between solar PV, battery, and load connected grid system, while MPPT operation for the solar PV is obtained simultaneously. The usefulness of the proposed system and control technique is tested using simulation in MATLAB / Simulink environment and results are presented for different theoretical and practical cases. The results show that the presented technique is able to control grid side current of the inverter and charging and discharging current of battery at different levels of solar irradiation tracking MPPT correctly.

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