

Solar PV Battery Storage Integration Using a Three-Level NPC Inverter with Space Vector Pulse Width Modulation

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ABSTRACT

This paper presents a novel topology of a three-level neutral-point-clamped (NPC) inverter for the integration of solar photovoltaic (PV) with battery storage in a grid-connected system. The main advantage of the proposed topology is a new extended unbalance three level vector modulation technique that can generate the proper ac voltage under unbalanced dc voltage conditions. The design analysis of the proposed configuration and the theoretical framework of the proposed modulation technique are presented in this paper. A new control algorithm for the proposed system is also presented to control the power delivery between the solar PV, battery and grid, while providing maximum power point tracking (MPPT) operation for the solar PV. The effectiveness of the proposed methodology is investigated by the simulation of several scenarios, including battery charging and discharging with different levels of solar irradiation with MATLAB /SIMULINK environment.

Index Terms— solar photovoltaic (PV), Neutral-point-clamped (NPC),Maximum power point tracking (MPPT), Space vector modulation(SVM).

1.INTRODUCTION

Considering the world energy crisis and the environmental problems caused by the conventional power generation, the renewable energy sources, such as the photovoltaic (PV) and wind generation systems, are becoming more attractive alternatives to replace the conventional generation units for the electricity generation [1], [2]. The development and deployment of renewable energy sources depend on advanced power electronic systems. One of the most important functions of the power electronic systems for solar PV or wind energy applications is to harvest maximum power from the source [3]–[5]. For three-phase applications, the transfer of the power from the renewable energy

resource to the grid is largely achieved by two types of power electronic configurations, namely, single-stage and double-stage conversion. In the double-stage conversion for a PV system, the first stage is usually a dc/dc converter and the second stage is a dc/ac inverter. The function of the dc/dc converter is to facilitate the maximum power point tracking (MPPT) of the PV array and to produce the appropriate dc voltage for the dc/ac inverter. The function of the inverter is to generate three-phase sinusoidal voltages or currents to transfer the power to the grid in a grid-connected solar PV system or to the load in a stand-alone system [3]–[5].

In the single-stage connection, only one converter is needed to full fill the double-stage functions, and hence the system will have a lower cost and higher efficiency, however, a more complex control method will be required. The current norm of the industry for high power applications is a three-phase, single stage PV energy systems by using a voltage-source converter (VSC) for power conversion [4]. One of the major concerns of solar and wind energy systems is their unpredictable and fluctuating nature. Grid-connected renewable energy systems accompanied by battery energy storage can overcome this concern. This also can increase the flexibility of power system control and raise the overall availability of the system [2]. Usually, a converter is required to control the charging and discharging of the battery storage system and another converter is required for dc/ac power conversion; thus, a three phase PV system connected to battery storage will require two converters.

In this paper [1], a novel configuration of a three-level neutral-point-clamped (NPC) inverter that can integrate solar photovoltaic (PV) with battery storage in a grid-connected system is proposed. The strength of the proposed topology lies in a novel, extended unbalance three-level vector modulation technique that can generate the correct ac voltage under unbalanced dc voltage conditions. This paper presents the design philosophy of the proposed configuration and the theoretical framework of the proposed modulation

technique. A new control algorithm for the proposed system is also presented in order to control the power delivery between the solar PV, battery, and grid, which simultaneously provides maximum power point tracking (MPPT) operation for the solar PV.

It [2] focuses on micro-generation complexes using battery storage—specifically sodium-sulphur (NaS) batteries—to manage solar intermittency, improve power quality, and enable load leveling within electrical distribution networks. The work emphasizes that combining distributed PV with storage systems helps in managing the intermittent nature of solar power, which is critical for enhancing grid reliability and increasing the penetration of renewable energy.

The continuously growing amount of renewable sources starts compromising the stability of electrical grids. Contradictory to fossil fuel power plants, energy production of wind and photovoltaic (PV) energy is fluctuating. Although predictions have significantly improved, an outage of multi-MW offshore wind farms poses a challenging problem. One solution could be the integration of storage systems in the grid. After a short overview, this paper focuses on two exemplary battery storage systems, including the required power electronics. The grid integration, as well as the optimal usage of volatile energy reserves, is presented for a 5- kW PV system for home application, as well as for a 100- MW medium-voltage system, intended for wind farm usage. The efficiency and cost of topologies are investigated as a key parameter for large-scale integration of renewable power at medium- and low-voltage [3].

This paper is concerned with the design and study of a grid-connected three-phase solar PV system integrated with battery storage using only one three-level converter having the capability of MPPT and ac-side current control, and also the ability of controlling the battery charging and discharging. This results in lower cost, better efficiency and increased flexibility of power flow control.

II. STRUCTURE OF A THREE-LEVEL INVERTER AND ITS CAPACITOR VOLTAGE CONSIDERATIONS:

2.1 Three-Level Inverter:

Since the introduction of three-level inverters in 1981 [6], [7], they have been widely used in several applications, such as motor drives, STATCOM, HVDC, pulse width modulation (PWM) rectifiers, active power filters (APFs), and renewable energy applications [7],

[8]. 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 behaviour on system parameters such as even-harmonic injection and power ripple [7], [9]. Several papers have discussed methods of balancing these capacitor voltages in various applications [6], [7], [9]–[16].

2.2 Balanced Capacitors Voltage:

Various strategies have been proposed to balance the capacitor voltages using modulation algorithms such as sinusoidal carrier based PWM (SPWM) or space vector pulse width modulation (SVPWM) [17]. In SPWM applications, most of the strategies are based on injecting the appropriate zero-sequence signal into the modulation signals to balance the dc-link capacitors [12], [13], [16], [18]. In SVPWM applications, a better understanding of the effects of the switching options on the capacitor voltages in the vector space has resulted in many strategies proposed to balance capacitors voltages in the three-level NPC inverter. These include capacitor balancing using conventional SVPWM, virtual SVPWM (VSVPWM) and their combination.

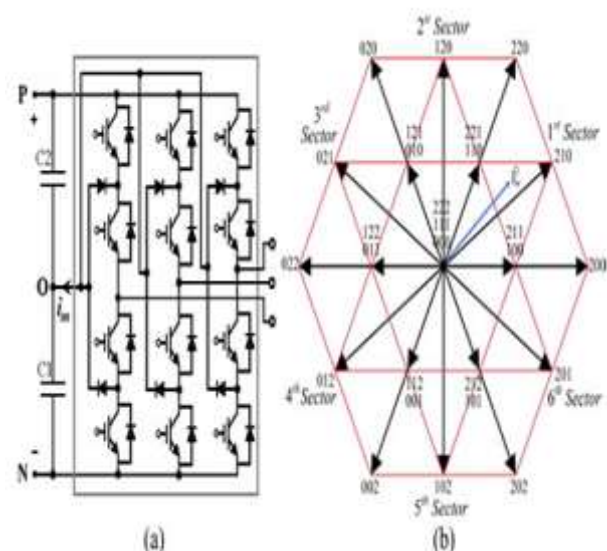


Fig.2.1. Typical three-level inverter (a) structure of circuit, and (b) three-level inverter space vector diagram for balanced dc-link capacitors

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 (SVM) scheme such as SVPWM and VSVPWM, the reference vector (V_{ref}) 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.

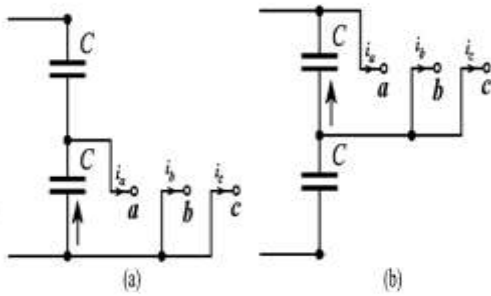


Fig. 2.2. Equivalent circuit and capacitors current with two different short vector.

(a) Short vector—100. (b) Short vector—211.

III.PROPOSED TOPOLOGY

A new neutral-point-clamped pulse width modulation (PWM) inverter composed of main switching devices which operate as switches for PWM and auxiliary switching devices to clamp the output terminal potential to the neutral point potential has been developed. This inverter output contains less harmonic content as compared with that of a conventional type. In addition, a new PWM technique suitable for an ac drive system is applied to this inverter. The neutral-point-clamped PWM inverter adopting the new PWM technique shows an excellent drive system efficiency, including motor efficiency, and is appropriate for a wide-range variable-speed drive system.

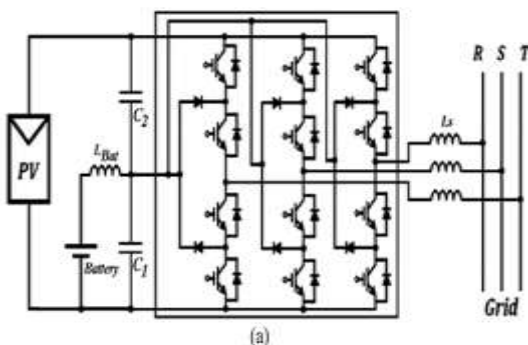


Fig. 3.1. Proposed configurations for integrating solar PV and battery storage:

Fig. 3.1 shows the diagram of the proposed system, power can be transferred to the grid from the renewable energy source while allowing charging and discharging of the battery storage system as requested 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 condition and at the same time will be able to control independently the lower capacitor voltage (V_{C1}) 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.

Although this configuration can operate under most conditions, however when the sola PV does not produce any power, the system cannot work properly with just one battery. However, when the renewable energy is unavailable, both relays can be closed allowing the dc bus to transfer or absorb active and reactive power to or from the grid. It should be noted that these relays are selected to be ON or OFF as required; there is no PWM control requirement. This also provides flexibility in managing which of the two batteries is to be charged when power is available from the renewable energy source or from the grid. When one of the batteries is fully charged, the relay connected to this battery can be open while closing the relay on the or battery to charge. Special consideration needs to be made to ensure that current through the inductor L_{batt} ues be zero prior to opening any of these Relays to avoid disrupting the inductor current and also to avoid damaging the relay.

IV.SIMULATION CIRCUITS AND RESULTS

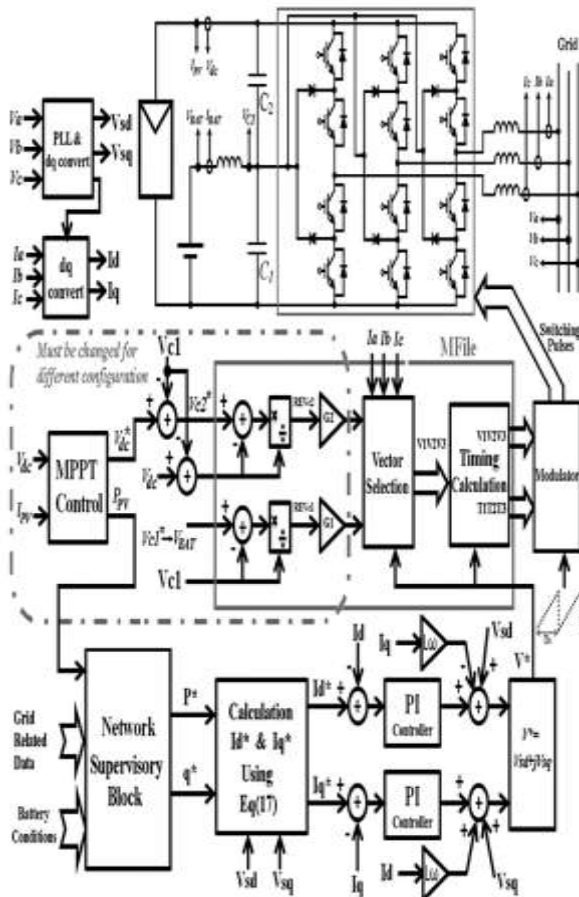


Fig. 3.2. Control system diagram to integrate PV and battery storage.

B. Control Topology

In Fig.3.2,three different relay configurations can be obtained: 1) when the top relay is closed; 2) when the bottom relay is closed; and 3) when both relays are closed. Fig. 7 shows the block diagram of the control system for configuration 1). In Fig. 7.2, the requested active and reactive power generation by the inverter to be transferred to the grid will be determined by the network supervisory block. This will be achieved based on the available PV generation, the grid data, and the current battery variables.

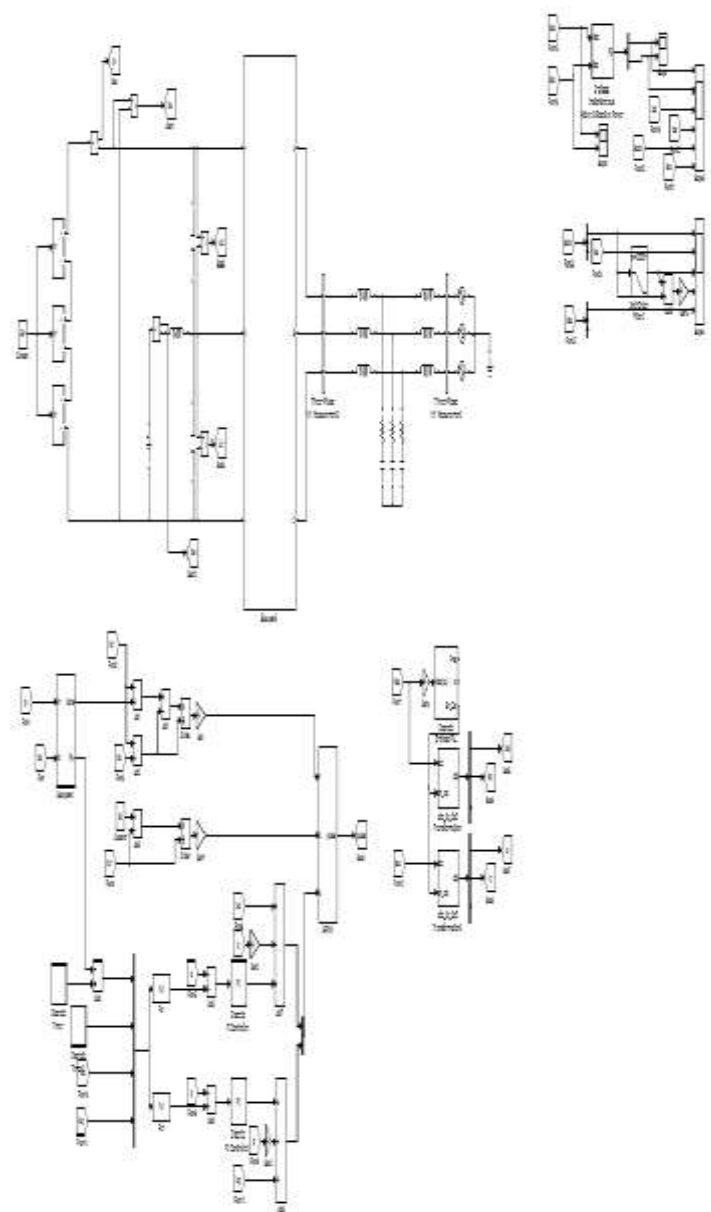


FIG 4.1: Simulation of block diagram and Control system diagram to integrate PV and battery storage.

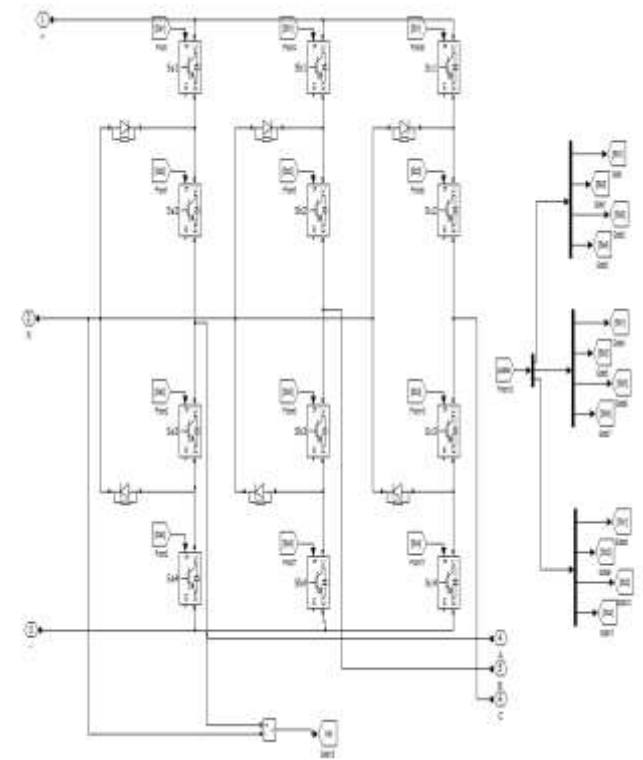


FIG 4.2:NPC INVERTER

A.First Theoretical Scenario

In the first scenario, it is assumed that the solar irradiation will produce $I_{SC} = 5.61$ A in the PV module according to (21). The MPPT control block, shown in Fig. 6, determines the requested PV module voltage V_{*dc} , which is 117.3 V to achieve the maximum power from the PV system that can generate 558 W of electrical power. The requested active power to be transmitted to the grid is initially set at 662W and is changed to 445W at time $t = 40$ ms and the reactive power changes from zero to 250 VAR at time $t = 100$ ms. Fig. 8 shows the results of the first scenario simulation. Fig. shows that the proposed control system has correctly followed the requested active and reactive power, and Fig.4.3 shows that the PV voltage has been controlled accurately (to be 177.3 V) to obtain the maximum power from the PV module. Fig.4.3 (d) shows that battery is discharging when the grid power is more than the PV power, and it is charging when the PV power is more than the grid power. Fig.4.3(d) shows that before time $t = 40$ ms, the battery discharges at 1.8 A since the power generated by the PV is insufficient. After time $t = 40$ ms, the battery current is about -1.8 A, signifying that the battery is being charged from the extra power of the PV module. Fig. 4.3(e) shows the inverter ac-side currents, and Fig. 8(f) shows the grid-side currents with a THD less than 1.29% due to the LCL filter. The simulation results in Fig. 4.3 show that the whole system produces a very good dynamic

response. Fig. 10 shows the inverter waveforms for the same scenario. Fig. 4.3(a) shows the line-to-line voltage V_{ab} , and Fig. 4.3(b) shows the phase to midpoint voltage of the inverter V_{ao} . Fig.4.3(c) and (e) shows V_{ao} , V_{on} , and V_{an} after mathematical filtering to determine the average value of the PWM waveforms.

B. Second Theoretical Scenario

In the second scenario, it is assumed that the solar irradiation will change such that the PV module will produce $I_{SC} = 4.8, 4$, and 5.61 A. The MPPT control block determines that V_{*dc} needs to be 115.6, 114.1, and 117.3 V to achieve the maximum power from the PV units which can generate 485, 404, and 558 W, respectively. The requested active power to be transmitted to the grid is set at a constant 480 W and the reactive power is set to zero during the simulation time. Fig.4.4 shows the results of the second scenario simulation. Fig. 4.4(a) shows that the inverter is able to generate the requested active power. Fig. 4.4(b) shows that the PV voltage was controlled accurately for different solar irradiation values to obtain the relevant maximum power from the PV modules. Fig. 4.4(c) shows that the charging and discharging of the battery are correctly performed. The battery has supplemented the PV power generation to meet the requested demand by the grid. Fig. 4.4(d) illustrates that the quality of the waveforms of the grid-side currents are acceptable, which signifies that the correct PWM vectors are generated by the proposed control strategy. By using the proposed strategy, the inverter is able to provide a fast transient response. Fig.4.4 (e) shows the a -phase voltage and current of the grid, which are always in-phase signifying that the reactive power is zero at all times.

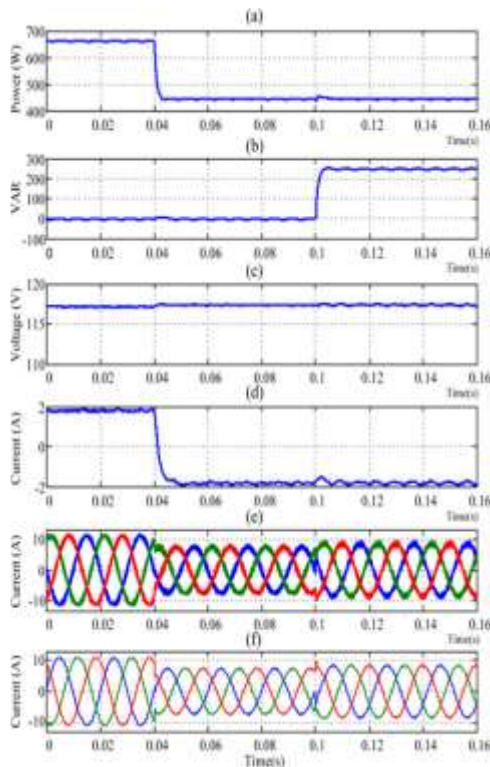


Fig. 4.3.Simulated results for the first scenario. (a) Active power injected to the grid. (b) Reactive power injected to the grid. (c) PV module DC voltage. (d) Battery current. (e) Inverter AC current. (f) Grid current.

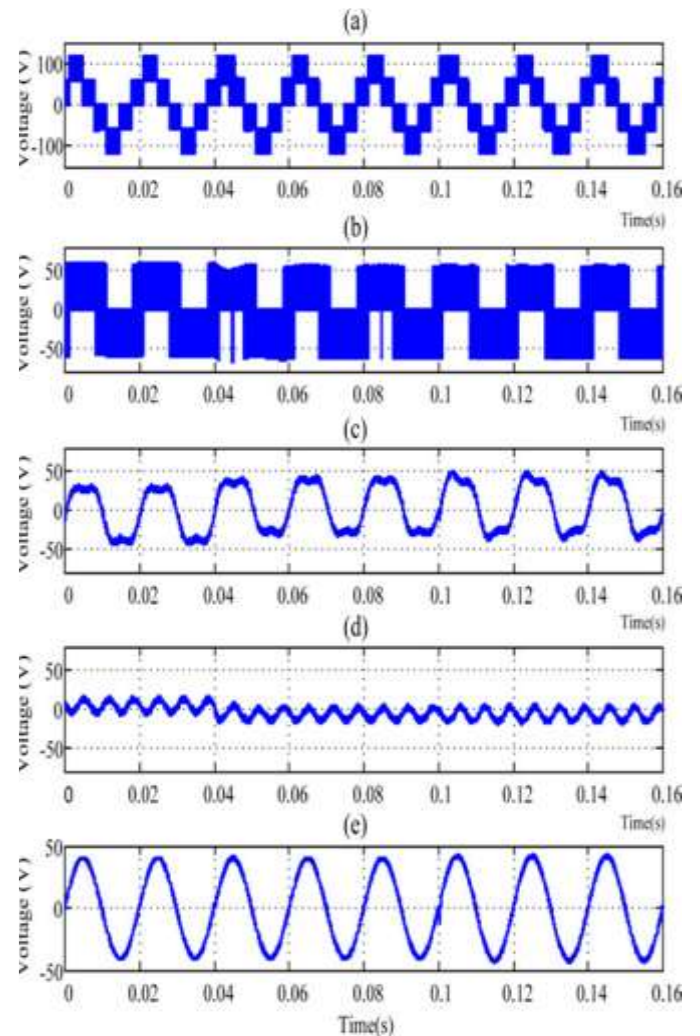


Fig. 4.4: Simulated inverter waveforms. (a) Vab-Phase to phase inverter voltage. (b) Vao-Inverter phase voltage reference to midpoint. (c) Filtered Von-Filtered inverter phase voltage reference to midpoint. (d) Filtered Von-Filtered midpoint voltage reference to neutral. (e) Filtered Van-Filtered phase voltage reference to neutral.

Table3:comparison of for different scenario's

THD FOR	1ST SCENARI O	2ND SCENARI O	3RD SCENARI O
VOLTAGE	4.16%	4.13%	4.19%
CURRENT	3.58%	3.29%	7.66%

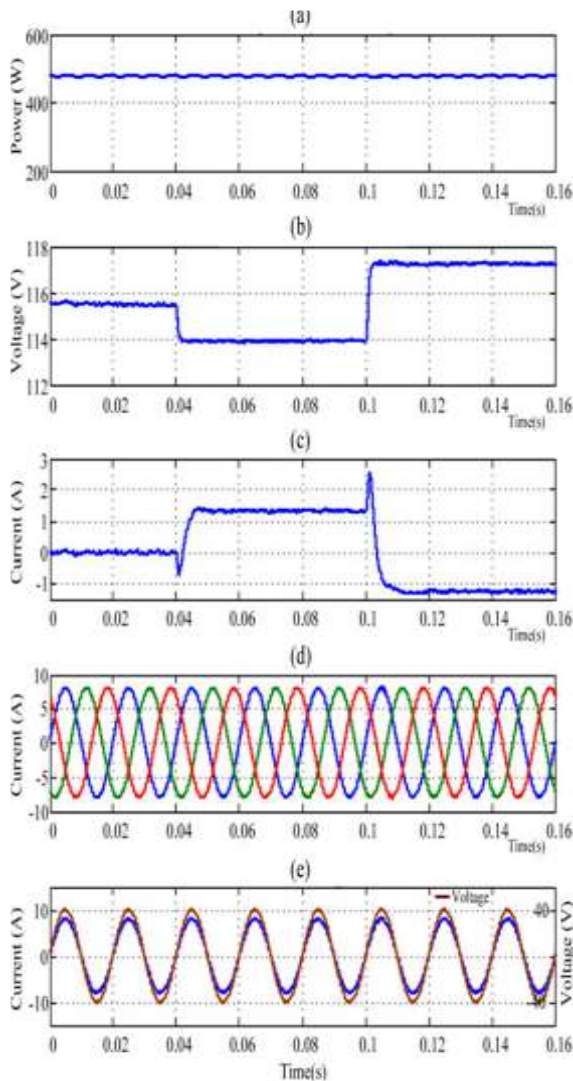


Fig. 4.5. Simulated results for the second scenario. (a) Active power injected to the grid. (b) PV module DC voltage. (c) Battery currents. (d) Grid side currents. (e) Grid side Phase (a) voltage and its current.

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. The results from experiments using a prototype built in the lab have validated the proposed

topology to control both PV and battery storage in supplying power to the ac grid.

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