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Advanced Control Strategy for Solar PV and Battery Storage Integration using a Three-Level NPC Inverter

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***Abstract*—This paper introduces a grid-connected solar photovoltaic (PV) system and battery storage, which is implemented using a three level neutral-point-clamped (NPC) inverter. A new simplified space vector PWM method for a three phase three level inverter is to be proposed. The number of switching states is a larger number in case of three-level inverters as compared with a two-level inverter. In the proposed scheme, three-level space vector PWM inverter can directly use. This control algorithm will be used to control power delivery between solar PV, and grid. It also has the capability of MPPT. The proposed control topology can generate the correct AC voltage under unbalanced DC voltage conditions by using a vector modulation technique. It can also control the charging and be discharging of battery storage systems in different levels of solar irradiation. In this project area, a three phase three-level inverter using space vector modulation strategy has been modeled and simulated. Simulations are done using Matlab Simulink.**

Index Terms Battery storage, solar photovoltaic (PV), vector modulation

I. INTRODUCTION

THE most concerns about the environment-friendly electricity generation in the modern world has to replace the conventional energy generation. Decreasing the fossil fuels, the renewable energy sources such as solar and wind energy generations have to lead as a green method [1].In the modern world, there has increased in power generation from renewables. Normally renewable-energy sources like photovoltaic (PV) or wind power systems. They are essentially endless and environmentally friendly. Among these renewable-energy sources, solar energy is the most attractive in standalone applications. The green power generation is nature related and cannot control easily. By applying renewable energy resources into the power system, many changes may occur. Advanced power electronic systems are needed to utilize to overcome these crises [2]. In PV and wind energy generation system utilizing maximum power from the source is one of the most important functions of power electronic system. The rapid development of the advance of the power electronics technology has made several changes in static power converter arrangements and industrial motor drive areas.

The Mainly Generating system requires two types of a converter. Among these converters usually using dc/dc converter is to facilitate the maximum power point tracking (MPPT) of the PV array and also to use DC/AC inverter to produce the appropriate dc voltage [3]. The solar and wind energy systems are unpredictable and fluctuating nature. To overcome this concern the grid-connected renewable energy system has accompanied by a battery energy storage system. Grid connected system required converters for controlling the battery charging and discharging system and another converter required for DC/AC power conversions. Thus here required many converters and system will have higher cost and lower efficiency.

In this paper design and study of a three-phase solar PV system and

Battery storage is integrating into the grid and here taking only one three-level converter which having MPPT capability and ac-side current control and also have the ability to control the battery charging and discharging. This structure will be better flexibility, reducing the cost, better efficiency and also the power flow control. There are several inverter topologies like transformer-based or transformer-less inverters. These inverter topologies can also have different levels of switching pattern. Among this transformer-less inverters, the NPC is applying to photovoltaic (PV) panels and the controlling of these inverters. Several types of pulse-width modulation (PWM) techniques are available. Neutral Point Clamped Multilevel Inverter is a most popular technology in all applications. The NPC can directly connect to the grid. There is no need for any additional converters. Controlling of NPC can be down based on SVPWM technique.The modulation strategies to employ with PV inverters are SPWM and SVPWM. SVPWM has wide range of switching frequencies, and ease to the implementation in multilevel inverters

The rest of this paper is organized as follows. Section II introduces the concept of a three-level inverter and its capacitor voltage considerations and Concept of a space vector pulse width modulation method for three level invertersThe section III is explain about the proposed topology to integrate solar and battery storage .In section IV describes Simulation and validation of proposed topology

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

A. Concept of an equivalent three level inverter

The neutral point clamped (NPC) three-level inverter was first introduced by A. Nabae, I. Takahashi, and H. Akagi in 1980 and published in 1981 [4]. They have been widely used in several applications, like STATCOM, HVDC, pulse width modulation (PWM) rectifiers, motor drives and renewable energy applications [5], [6]. NPC was also known as Diode Clamped Multilevel Inverter. It is suitable for medium and high-level voltage applications. As the No.of levels are increased switching frequency will be reduced. NPC can be connected directly to the grid. Fig. 1(a) Shows circuit topology for a three phase three-level neutral-point-clamped inverter. Mainly the converter has two capacitors in dc side to produce the three-level ac-side phase voltages [6].

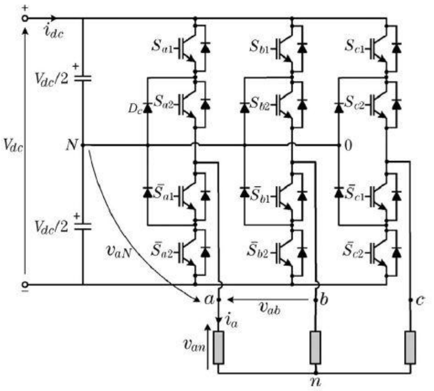
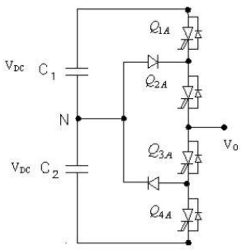


Fig. 1(a) Power circuit of the three-level diode clamped inverter



Switches on	Switches off	Output voltage
Q_{1A}-Q_{2A}	Q_{3A}-Q_{4A}	$+V_{DC}$
Q_{2A}-Q_{3A}	Q_{1A}-Q_{4A}	0
Q_{3A}-Q_{4A}	Q_{1A}-Q_{2A}	$-V_{DC}$

Fig. 1(b) Phase A of a 3 level inverter Table 1 Switching pattern of a phase A of 3 level inverter

B. Concept of a space vector pulse width modulation method for three level inverters

In recent years controlling of three level NPC has been a hot topic and some strategies have been proposed in [8], [9].In these various control strategies space vector modulation (SVM) is one of the most commonly used modulation strategies. These have many advantages of low switching frequency and better output voltage quality [10]. Among this SVM method SVPWM is to be taken here. However
medium vectors will affect the neutral-point voltage when SPWM applied to the model. It will result to cause low-frequency oscillations in the neutral-point voltage under high modulation conditions [11].

The total number of switching states of an " n Level inverter is "N^3", So the total number of switching states in a "3" level inverter is "3^3 ".Normally 27 switching states in the 3 level inverter but 24 states are active states and 3 zero states.

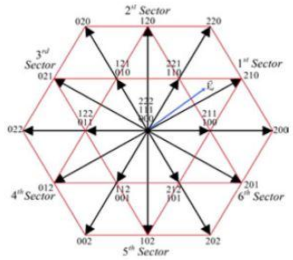


Fig. 2 Space vector diagram for the three-level diode clamped inverter

From these Three switching states [1], [0] and [-1] can represent the operation of each leg. Fig. 2 shows the space vector diagram for the three-level neutral point clamped inverter. Here the plane can be dividing into six major triangular sectors (I to VI) by large voltage vectors and zero voltage vectors. There each major sector represents 60^0 of a fundamental cycle. Within each major sector, there are four minor triangular sectors [12].Table II shows the option of three phase switching states that are characterized by three inverter phases A, B, and C. Here The voltage has four sets[13],[12].

(a) Zero vector - (V_1, V_2, V_3)

which representing three switching states [1 1 1], [-1 -1 -1] and [0 0 0]. The magnitude of V_1, V_2, and V_3 stays Zero.

(b) Small vector -(V_4 -V_{15})

Magnitude is $V_d/3$.

(c) Medium vectors-(V_{17}, V_{19}, V_{21}, V_{23}, V_{15}, V_{27})

the magnitude is $\frac{\sqrt{3}}{3}$ V_d.

(d) Large vectors-(V_{16}, V_{18}, V_{20}, V_{22}, V_{24}, V_{26}), having the magnitude of 2/3 V_d.

Various steps for applying for three level SVPWM inverter. They are

- No of switching states
- No of voltage vectors & equivalent voltages.
- Sector identification.
- Determining the region in the sector.
- Calculating the active vectors switching time periods.
- Generation of gating signal

Each major sector can be recognized by using space vector phase angle (α). α is calculated and then find sectors. In which the command vector V* is found. Also it is determined as,If α is between 0 ≤ α < 600, and V* will be in major sector I. If α is between 60 ≤ α < 1200, and V* will be in major sector II. If α is between 120 ≤ α < 1800, and V* will be in major sector III. If α is between 180 ≤ α < 2400, and V* will be in major sector IV. If α is between 240 ≤ α < 3000, and V* will be in major sector V. If α is between 300 ≤ α < 3600, and V* will be in major sector VI.

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TABLE II
SWITCHING STATES OF 3 LEVEL INVERTER

Switching states	S_a	S_b	S_c	Voltage Vectors
S_1	0	0	0	V_o
S_2	1	1	1	V_o
S_3	2	2	2	V_o
S_4	1	0	0	V_1
S_5	1	1	0	V_2
S_6	0	1	0	V_2
S_7	0	1	1	V_3
S_8	0	0	1	V_4
S_9	1	0	1	V_5
S_{10}	2	1	1	V_6
S_{11}	2	2	1	V_7
S_{12}	1	2	1	V_8
S_{13}	1	2	2	V_9
S_{14}	1	1	2	V_{10}
S_{15}	2	1	2	V_{11}
S_{16}	2	1	0	V_{13}
S_{17}	1	2	0	V_{14}
S_{18}	0	2	1	V_{15}
S_{19}	0	1	2	V_{16}
S_{20}	1	0	2	V_{17}
S_{21}	2	0	1	V_{18}
S_{22}	2	0	0	V_{19}
S_{23}	2	2	0	V_{20}
S_{24}	0	2	0	V_{21}
S_{25}	0	2	2	V_{22}
S_{26}	0	0	2	V_{23}
S_{27}	2	0	2	V_{24}

III. PROPOSED TOPOLOGY TO INTEGRATE SOLAR AND BATTERY STORAGE

New control configurations of a three-level inverter are integrated to a battery storage and solar PV. A new control will be applied in there and shown in fig. 3 is proposed, there is no other converter is required to connect the battery storage to the grid-connected PV system. It is the major advantage in the medium and high power applications. This model can reduce the cost And improve the overall efficiency of the whole system. In the Fig.3 new proposed configuration of a solar PV is integrated with battery storage system: In these figures, fig (a) represents basic configuration; fig (b) improved the configurations of the model. In this intended system, the power can shift to the grid from the renewable energy source.

As per the same time control of the system will request to allowing charging and discharging of the battery storage system. The suggested control system will able to control the lower capacitor voltage (*VC*1), and this control method is used for the charging and discharging of the battery storage. This system has an ability to control the sum of the capacitor voltages (*VC*1 + *VC*2 = *Vdc)* to reach the MPPT condition. These conditions are done at the same time of control operations. The total harmonic distortion (THD) relatively low output of the inverter. The outputs of the inverter have the correct voltage waveform. In this system will reduce the total harmonic distortion (THD) current on the AC side even under disturbed capacitor voltages on the dc side of the inverter. The solar PV does not produce any power continuously so the system cannot work correctly. Add up a battery storage system in the model for continues process. Here a single battery storage system cannot be work properly. The improved configuration is shown in the figure that is two battery connected across the two capacitors. Where the relays are used to connect this battery. When one of the relays is closed, and the other relay is open, the configuration in fig. 3(b) is similar to that in fig. 3 (a)

The accessibility of renewable energy source can be produce power then the battery can be charge or discharge. However, the solar energy is unobtainable the two relays are closed and also allowing to the DC bus to transfer the active or reactive power to the grid, or dc bus is absorbed power from the grid side. It can be noted that these relays are selected to be ON or OFF as essential; there is no PWM control necessity. This PWM control condition it has a flexibility of managing the two batteries. This PWM control condition it has a flexibility of managing the two batteries. The battery to be charging when power is accessible from the renewable energy sources or the grid side. The battery is has connected across the relay, when the battery is fully charged, then the relay is opened while closing the relay the battery is to be charged. The attention needs to the current through the inductor *L*batt must be zero before the opening of any these relays to avoid disrupting the inductor current and avoid of damaging relay.In fig. 3(b), three different relay configurations can be obtained: 1) When the top relay closed; 2) when the bottom relay is closed, and 3) when both relays closed.

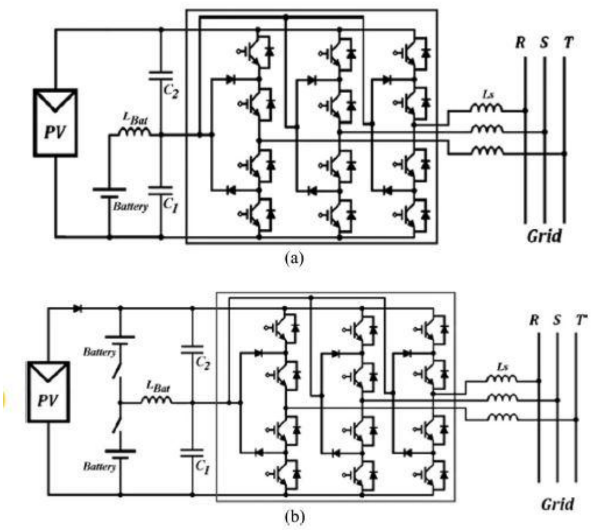

Fig. 3 Proposed Configurations for Solar PV and Battery Storage Integration(a) Basic Configuration; (b) Improved Configuration

C. Control topology

In this control topology, the inverter can be controlled by using the SVPWM method. The process of creating gate signals for the NPC inverter can generate after the SVPWM control method. Here primarily find the active and reactive power generation by the inverter to be transferred to the grid. This can be determined using a network supervisory block. This block will obtain based on the solar PV generation, present battery variables also the grid related data. Here figure 4 shows the useful block diagram of the control scheme of "solar PV and battery storage integration system to grid through three phase NPC inverter”. The block MPPT used for getting the maximum power from solar PV. To finding the requested active and reactive power generation by the inverter

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Vol. 6 Issue 04, April-2017

here using the MPPT algorithms. Then Network supervisory blocks also study about the MPPT state. Using the MPPT blocks to maximum power from solar PV systems. The MPPT algorithms based on the requested active ($p*$) and reactive power ($q*$), and the grid voltage in the dq-axis,vsd and vsq and the requested inverter current in the dq-axis, id and iq can be obtained using

$$p^* = V_{sd} I_d + V_{sq} I_q$$

$$q^* = V_{sq} I_d + V_{sq} I_q$$

$$id^* = \frac{p^* v_{sd} - q^* v_{sq}}{{v_{sd}}^2 + {v_{sq}}^2}$$

$$iq^* = \frac{q^* V_{sd} - p^* v_{sq}}{{v_{sd}}^2 + {v_{sq}}^2}$$

Firstly find the reference value based on the balanced operations of the system. The control technique performs based on this value. After approaching the requested reference voltage vector, a suitable sector in the vector diagram can evaluate. The relative errors of capacitor voltages are using for determining which short vectors. Relative errors of capacitor voltages given as,

$$e_{vc1} = \frac{v_{vc1}{}^* - v_{c1}}{v_{c1}}$$

$$e_{vc2} = \frac{v_{vc2}{}^* - v_{c2}}{v_{c2}}$$

Where V_{c1} and V_{c2} are the desired capacitor voltages, and $VC1$ and $VC2$ are the actual capacitor voltages for capacitor $C1$ and $C2$, respectively. The selection of the short vectors will determine which capacitor is to be charged or discharged. To determine which short vector must be selected, the relative errors of capacitor voltages and their effectiveness on the control system behaviour are important. A decision function "F," as given, can be defined based on this idea

$$F = G_1 e_{vc1} - G_2 e_{vc2}$$

Where $G1$ and $G2$ are the gains associated with each of the relative errors of the capacitor voltages $G1$ and $G2$ are used to determine which relative error of the capacitor voltages is more important and consequently allows better control of the chosen capacitor voltage. For example, for an application that requires the balancing of the capacitor voltages as in traditional three-level inverters, $G1$ and $G2$ must have the same value with equal reference voltage values, but in the proposed application where the capacitor voltages can be unbalanced, $G1$ and $G2$ are different and their values are completely dependent on their definitions of desired capacitor voltages By using $V^*_{c2} = V^*_{dc} - V_{c1}$ and $V^*_{c1} = V_{BAT}$ selecting $G2$ much higher than $G1$, the PV can be controlled to the MPPT, and $C1$ voltage can be controlled to allow charging and discharging of the battery. In each time step, the sign of F is used to determine which short vectors are to be chosen. When F is positive, the short vectors need to be selected that can charge $C1$ or discharge $C2$ in that particular similarly, when F is negative, the short vectors need to be selected that can charge $C2$ or discharge $C1$ in that particular time step. The role of L_{BAT} is to smooth the battery current, especially in the transient condition. A wide range of values is acceptable for the inductor value, however, decreasing its value will increase the current overshoot of the battery.

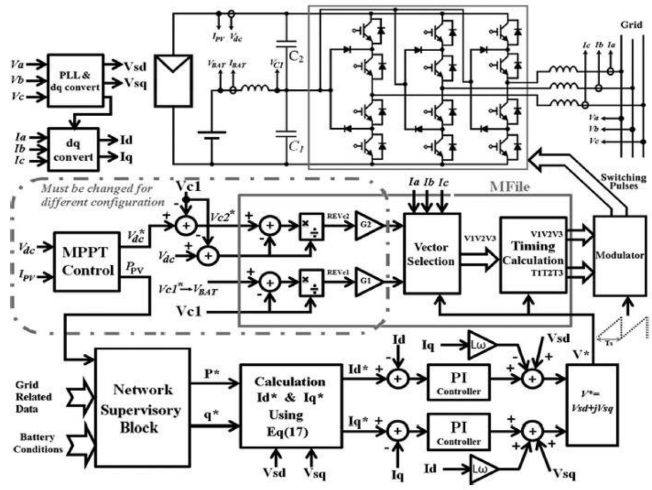

Fig. 4. Functional block diagram of control scheme.

Also, this value dependents capacitor value and also transient voltages. Due to the practical considerations like size and cost,The value of LBAT is preferred to be low and has been chosen to be five mH based our simulation studies

TABLE III
PARAMETERS OF THE SIMULATED SYSTEM

V_{BAT}	Vs (line)	L_{BAT}	C_1,C_2	L_f	L_s
60 V	50 V	5 mH	1000 uF	500 uH	900 uH
r_f	C_f	K_p	K_i	G_1	G_2
3 Ω	14 uF	2.9	1700	1	200

IV. SIMULATION AND VALIDATION OF PROPOSED TOPOLOGY

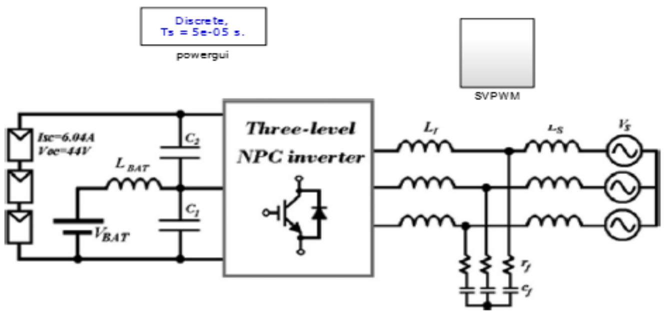

Fig. 4. Block diagram of the simulated system.

RESULTS

Simulations performed using MATLAB/Simulink for the proposed system is shown in Fig.5. SVPWM switching strategy applied to the system configuration and the results. Fig.5 (a) shows phase voltage of three level inverter. Fig 5(b) Shows the synchronization between current injected to grid and grid voltage

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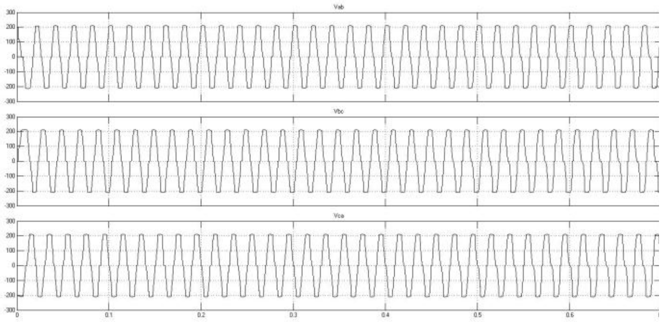


Fig 5(a)

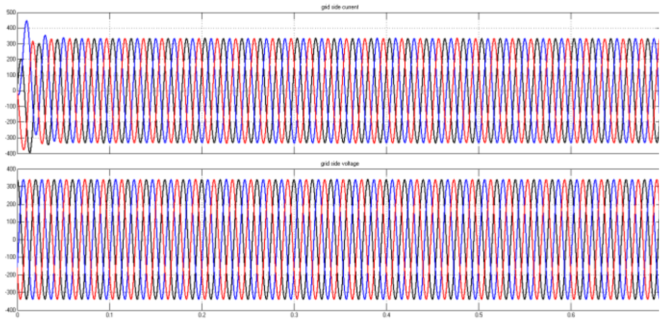
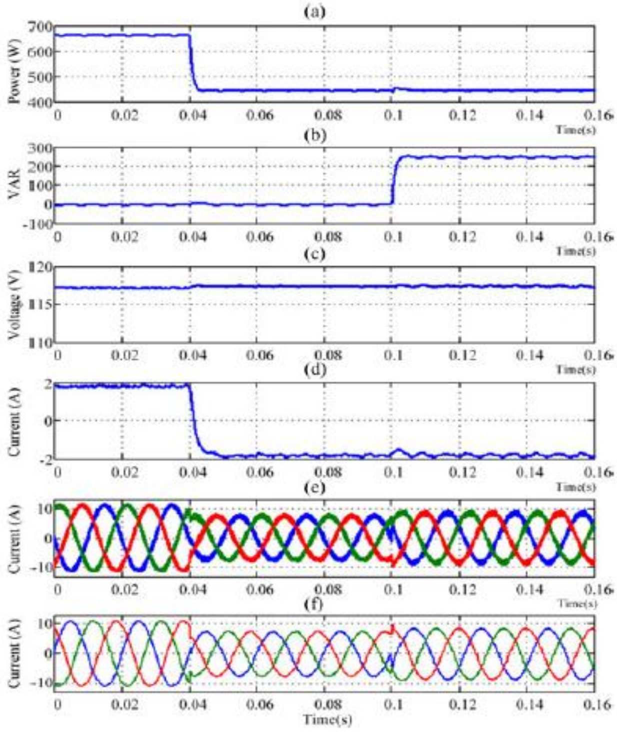


Fig 5(b)

Fig.5 simulated inverter waveforms (a) Vab, Vbc, Vca-phase to phase inverter voltage (b) grid side response



Simulated results Fig 6 fig (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. 6(a) and (b)requested active and reactive power, and Fig. 6(c) show that PV voltage is controlled and getting the maximum power from the PV module fig 6(d) shows the battery charging and discharging. The power from PV is more than grid power the battery to be charging, and PV power is less than the grid power the battery is starting to discharging Fig. 9(e) shows the inverter ac-side current, and Fig. 9(f) shows the response of grid-side currents with a THD .

Fig. 10 shows the inverter waveforms in the required system model.Fig. 10(a) shows the line-to-line voltage *Vab* , and Fig. 10(b) shows the phase to midpoint voltage of the inverter *Vao*. Fig. 10(c) and (e) shows *Vao, V*on, and *Van* the average value of the PWM waveforms

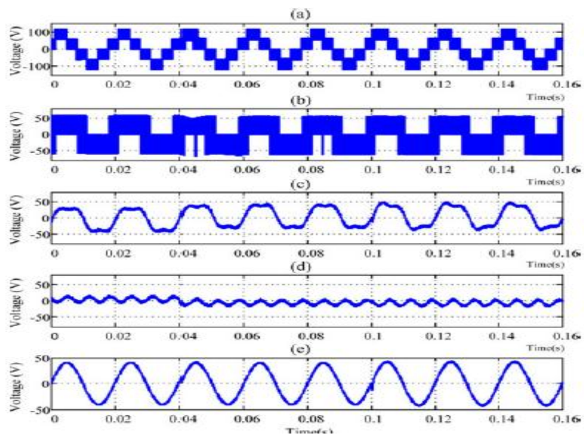


Fig 7 Simulated inverter waveforms. (a) Vab-Phase to phase inverter voltage. Fig (b) Vao-Inverter phase voltage reference to midpoint. (c) Filtered Von-Filtered inverter phase voltage reference to midpoint. (d) Filtered Von-Filtered midpoint voltage reference to neutral. (e) Filtered Van-Filtered phase voltage reference to neutral.

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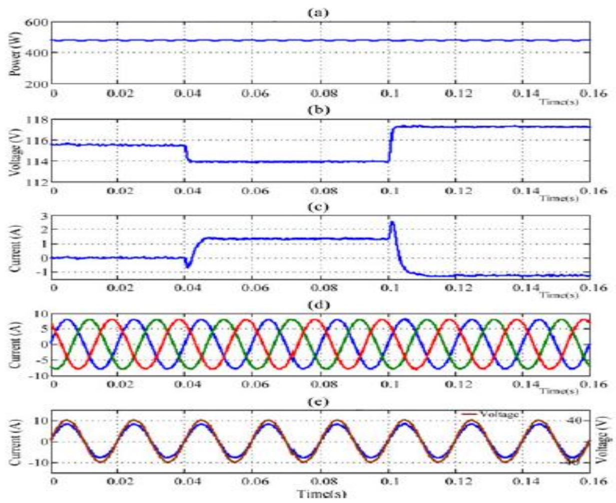

Fig 8 Simulated results for the second scenario. (a) Active power injected to the grid. (b) PV module DC voltage. (c) Battery currents. (d) Grid side currents.(e) Grid side Phase (a) voltage and its current.

V.CONCLUSION

In this paper, the performance of three level NPC is integrating with renewable energy resource into AC grid was presented. A new control algorithm of space vector modulation has also been accessible to controlling the power flow between solar PV and battery storage system, and grid system, while MPPT operation for the solar PV achieved instantaneously. Three-level NPC voltage source inverter can integrate both renewable energy and battery storage system. Three-level vector modulation technique that can generate the correct AC voltage under unbalanced dc voltage conditions has proposed. The system can control ac-side current, and battery is charging and discharging currents at different levels of solar irradiation. A detailed implementation and the analysis done concerning the application of the SVPWM control strategy on the three-level voltage inverter presented using MATLAB/SIMULINK and also created to simulate the switching patterns.

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