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Control of a Multi-Functional Inverter for Grid Integration of PV and Battery Energy Storage System

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Abstract — **This paper presents a multi-functional control of a DC/AC inverter for Power Quality compensation of nonlinear and unequal local loads and grid integration of hybrid photovoltaic (PV) and battery energy storage systems. Multi-layer neural network estimator and a DC/DC converter are used for maximum power point tracking (MPPT) of PV array. The power system is 3-phase 4-wires and the DC/AC inverter is chosen 4-leg three phase inverter which has good performance in presence of zero sequence components. Battery energy storage is connected to PV system in common DC bus and a power management strategy is used for delivering desire power to the grid. For compensation aim, instantaneous active and reactive power theory (p-q) is used. Via the algorithm, the DC/AC inverter not only can be controlled to inject the power of battery and PV, but also it is used as shunt active filter for compensating unequal and nonlinear local loads. The simulation results which implemented in MATLAB/SIMULINK software verify the effectiveness of the system.**

Index Terms — Photovoltaics systems, baterry energy storage, power quality compensation, Maximum power point tracking, instantaneous active and reactive power theory (p-q).

I. INTRODUCTION

IN recent years, Renewable energy resources such as PV and wind systems attract more attention rather than fossil fuel because of environmental pollution and extinction of the conventional fuels [1-3]. The cost of PV module and their related power electronics devices have been decreased in recent years, while the efficiency of them have been increased, Hence the investment in PV systems has been increased [1]. Since the maximum power point (MPP) of the PV system is changed in different temperature and sun irradiance, for increasing the efficiency of PV modules a maximum power point tracking (MPPT) system is required. Different MPPT methods such as perturb and observe (P & O), incremental conductance (InCon) have been proposed [4].

Due to intermittent nature of PV system, energy storage systems can compensate the fluctuating power delivered to grid by PV systems and standalone operation of microgrids in fault or sever power quality condition [5], [6]. In the hybrid connection of renewable energy and battery energy storage power management system according to state of Charge of battery is essential [6].

In other hands, increasing usage of nonlinear and unbalance loads have made power quality a major concern in microgrids and distribution systems [7]. Active power filters have been proposed for mitigating and compensation of power quality related problems [8]. The main component of active filters is their inverter. In other hand for integration of PV and battery energy storage to the grids, an inverter is required. Many researchers have been proposed multi-functional inverters which not only can inject the generated power to grids or microgrids but also can compensate nonlinear and unbalanced loads [9]. An investigation on combined operation of active power filter with photovoltaic arrays is presented in [10]. In [11], the multifunction of the battery energy storage's inverter is proposed for nonlinear loads in 3-wires three phase system. In this papers multi-functional grid tied hybrid battery and PV systems is proposed. The grid connected system not only can support the active power of nonlinear and unbalance loads in three phase 4-wire system but also can compensate the harmonics and unbalance components of these loads. The zero sequence components of unbalance and nonlinear loads and neutral current of it can also compensated by using p-q theory. The PV system is implemented in MPP by using Nero-Fuzzy maximum power estimation and a boost DC/DC converter.
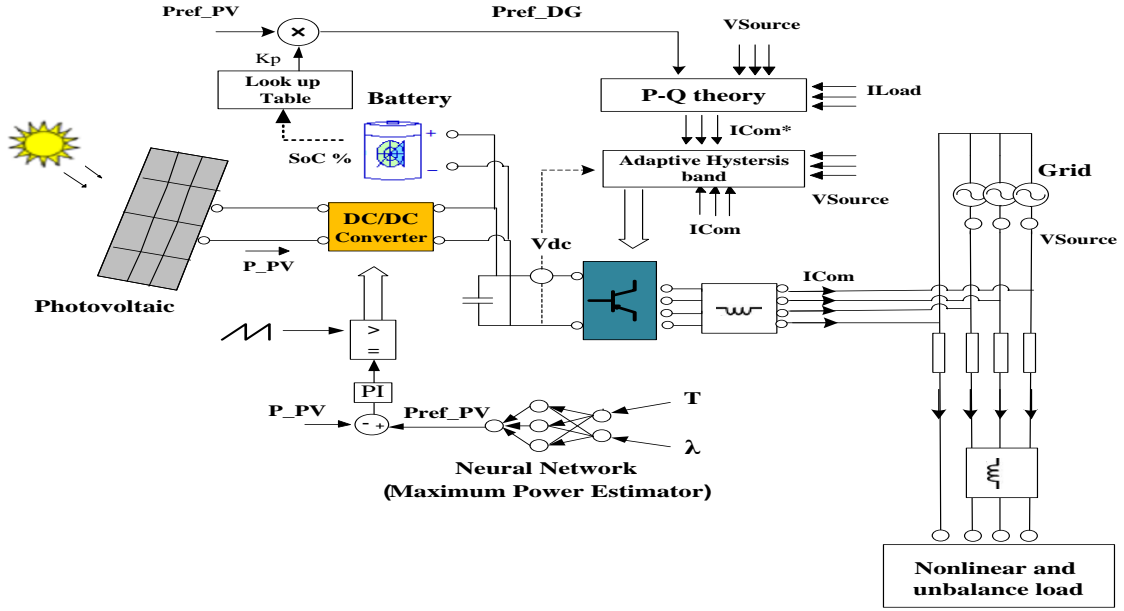
Fig. 1. Proposed configuration.

A power management algorithm with considering of SoC is applied to the systems. Fig. 1 shows the proposed configuration. As shown in this figure, hybrid PV and battery energy storage are connected to the grid by a three phase 4-legs inverter. Single and three phase nonlinear and unbalance loads are considered in this study. The reference signal is generated using p-q theory and adaptive hysteresis band controller.

II. PV AND MPPT SYSTEMS

A. PV SYSTEM

The photon energy of solar irradiance can be converted to electricity by PV systems. The power is generated in direct current (DC) form. The equivalent circuit of a PV module is depicted in Fig.2. In this figure, photo current, internal resistance and parallel leakage resistance is presented by I_{ph}, R_S and R_{SH}, respectively.
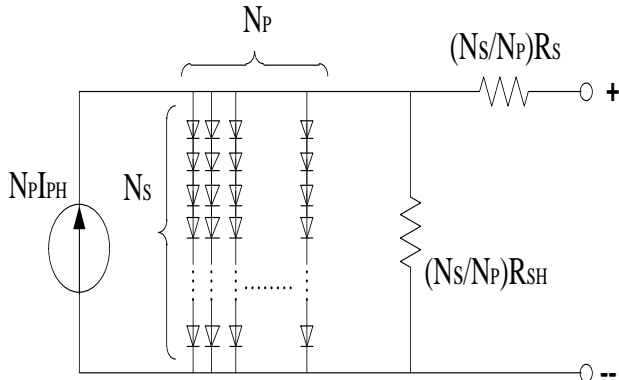

Fig.2. Equivalent circuit for a PV module.

The current versus voltage equation is written as (1):

$$I = N_P I_{PH}$$
$$- N_P I_S [\exp(q(V / Ns + IR_S / N_P) \quad (1)$$
$$/ kT_C A) - 1] - (N_P V / N_S + IR_S) / R_{SH}$$

Where m, k, q, T, I_S and are the ideality factor, Boltzmann's constant of the diode, electron charge, temperature of the module and the dark saturation current of the cell, respectively.

The photo current generated by semiconductor device is changed in different temperature and sun irradiance. Equation (2) describes the relation between photo current, temperature and solar irradiance.

$$I_{PH} = [I_{SC} + K_I (T_C - T_{Ref})]\lambda \quad (2)$$

Where I_{SC} is the short circuit current in standard 25° C and 1000 W/m² solar irradiance. K_I is temperature coefficient of short circuit current. The sun irradiance level is also represented by λ in this equation.

B. Maximum power tracking system

The maximum power generated by PV systems changed in different temperature and sun irradiance conditions; hence, a system that can track the MPP is required. DC/DC boost converters have been proposed by researchers for MPPT purpose, since, these converters not only can track MPP, but also can boost the voltage of the PV.

In this paper, a multilayer neural network is used as estimator in the maximum power point tracking process.

Fig.3 shows the maximum power can generated in different temperature and irradiance of the photovoltaic system. The data set, extracted from the simulation of PV in different weather conditions, is used to train the neural network [12].
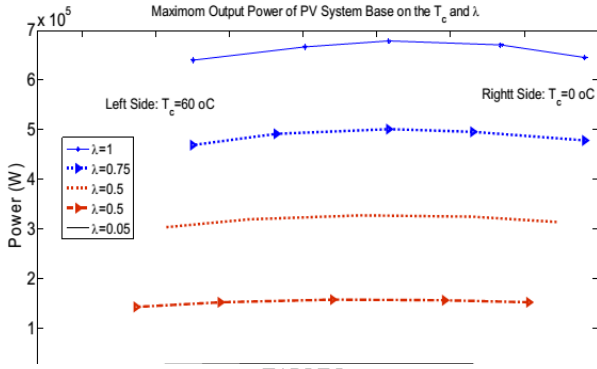
Maximom Output Power of PV System Base on the T_c and λ

Left Side: $T_c=60$ oC

Rightt Side: $T_c=0$ oC

- $\lambda=1$
- $\lambda=0.75$
- $\lambda=0.5$
- $\lambda=0.5$
- $\lambda=0.05$

Power (W)

TABLE I
COEFFICIENT OF THE INJECTED POWER TO THE NETWORK

SOC (%)	100	95	90	85	80	75	70
K_p	1.5	1.5	1.25	1.15	1	0.75	0.5

The method has better dynamic respond and can track MPP with more precise than pervious MPPT methods.
Neural networks are employed to model nonlinear functions and detect inner nonlinear parameters. In this study, neural network is used to estimate nonlinear behavior of solar cells,
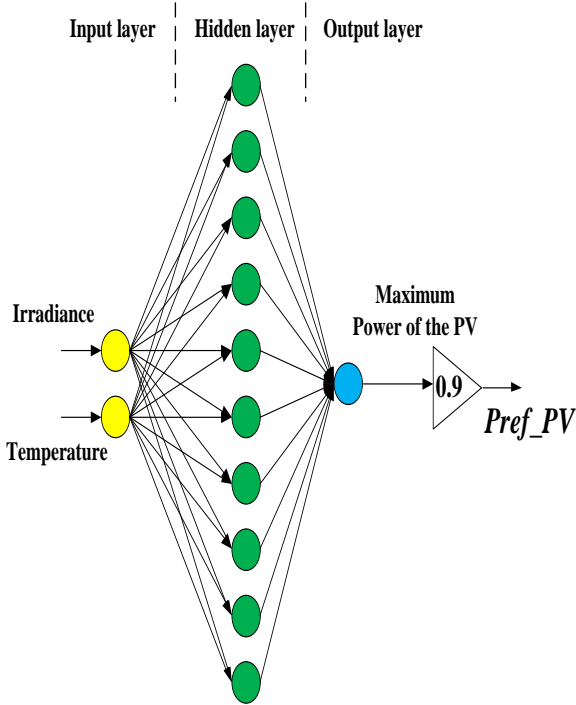

Fig. 4. Neural network implemented for MPPT estimation.

in order to calculate the maximum power of PV in different temperatures and irradiations. After training the neural network, it is used to maximum power estimation according to Fig.4. The number of hidden layer neurons, is selected 10 after several trials.

Fig.5 shows the control block of the DC/DC converter. In this figure, *Pref_PV* represents the reference power which the DC/DC converter should deliver to the dc link from PV system. Considering 10% security margin, 90% of maximum power is injected. This reference power is the reference signal of DC/DC boost converter control loop which is shown in Fig.5 [12]. In this figure, *P_PV* is generated power of PV system which is calculated by multiplying of output current and voltage of the PV system. After comparing of the *Pref_PV* and *P_PV*, and using a PI controller, the switching pulse of DC/DC boost converter will produce via a saw form wave.

III. BATTERY ENERGY STORAGE

The battery model used in [12] is simulated in this paper. This model is based on two internal resistances for charge and discharge states. The values of these resistances and internal voltage of battery are dependent on battery state of charge (SoC), so output voltage and resistances should be defined base on SoC.
SoC is one of the most important control signals and it is defined as these [12]:

$$SoC = \frac{A.h - Ah_{used}}{A.h} \qquad (3)$$

$$Ah_{used} = Ah \times (1 - SoC_{(0)}) + \int \frac{I_b}{3600} dt \qquad (4)$$

$$I_b = \frac{V_{oc} - \sqrt{4R_{int}.P_{el}}}{2R_{int}} \qquad (5)$$

Where $A._h$, Ah_{used} and P_{el} are battery nominal capacity, battery used capacity and battery output power, respectively.
Fig. 6 shows the power management system. As shown in this figure, the hybrid distributed resource reference power is determined from battery *SoC* and PV reference power. A look up table is designed according to Table. I for determining a coefficient.
While the PV system is operated in its maximum power and the reference output power of the hybrid battery and PV system (*Pref_DG*) is greater than the reference value of PV (*Pref_PV*), battery will discharge. But if the reference output power of the hybrid system is smaller than the reference power of PV, battery will consume power of PV.
It is seen in Table I that the total power of PV and battery system (*Pref_DG*) can increase up to 150% of *Pref_PV*, in
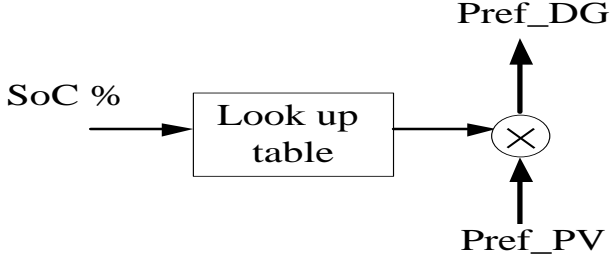
Fig. 6. Power management system.

full charge mode of battery. But in lower charge modes, battery will use some power of PV, so the output of the system will decreased (50 % in SOC=70%)..

IV. MULTIFUNCTIONAL CONTROL OF GRID TIED INVERTER

In this paper multifunctional control of a grid tied inverter as a power quality compensator and hybrid PV and battery energy storage system integrator is presented. The control is implemented using instantaneous active and reactive (p-q) theory in three phase 4-wire system. In other words, by proper control, not only power generated by the hybrid PV and energy storage system can be delivered to the grid, but also the power quality compensation of the unbalanced and nonlinear loads is achieved. In p-q theory, firstly three phase voltage and current should be converted to α-β-0 using (6):

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

The instantaneous real and imaginary power can be written as:

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta & 0 \\ -V_\beta & V_\alpha & 0 \\ 0 & 0 & V_0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \quad (7)$$

Where p, and q represent instantaneous real and reactive power respectively; furthermore the zero sequence real power is represented by p_0. These instantaneous real and imaginary powers contain two dc and oscillation part as (8):

$$p = \bar{p} + \tilde{p}$$
$$q = \bar{q} + \tilde{q}$$

$$p_0 = \bar{p}_0 + \tilde{p}_0 \quad (8)$$

Where $\bar{p}$, $\bar{q}$ and. $\bar{p}_0$ correspond to dc part of real and imaginary powers. $\tilde{q}$, $\tilde{p}$ and $\tilde{p}_0$ represent oscillation parts of these powers.

$\bar{p}$ in watt is the conventional active power and represents the effective power delivered between two systems (i.e. source and load). The power should be equal to the power generated by hybrid PV and battery energy storage system (*Pref_DG*).

$\bar{q}$ is the conventional reactive current and can be compensated by the multifunctional system. The oscillation terms of real and imaginary power are related to harmonics and unbalance condition; hence, the part of power should be compensated. For compensation of neutral current both $\tilde{p}_0$ and $\bar{p}_0$ should be compensated.

The reference current in α-β-0 is given based on (7):

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{1}{(v_\alpha^2 + v_\beta^2)v_0} \begin{bmatrix} v_\alpha v_\beta & -v_0 v_\beta & 0 \\ v_0 v_\beta & v_\alpha v_0 & 0 \\ 0 & 0 & v_\alpha^2 + v_\beta^2 \end{bmatrix} \begin{bmatrix} \tilde{p} + p_{ref} \\ q \\ p_0 \end{bmatrix} \quad (9)$$

The reference signal in α-β-0 should be converted to a-b-c three phase current by inversing (5). These reference currents compare to real currents and according to hysteresis band switching methods, proper pulses for IGBT switches are obtained. Hysteresis band controller is used due to its simplicity and good dynamic. Despite hysteresis controllers are simple; they generate non-fixed switching frequency and harmonics, which can be problematic to the grid. For mitigating the problem adaptive hysteresis band control which presented in [13] is applied in this paper.

V. SIMULATION RESULTS

The system shown in Fig.1 is considered as simulation case study. The PV and battery parameters are available in [12]. The parameters of the grid tied inverter and power system is listed in Table. II. The unbalanced and nonlinear loads are obtained by three and single phase uncontrolled diode-bridge rectifier. Two scenarios which are described later are implemented to the system.

TABLE II
PARAMETERS OF THE SIMULATION STUDY

Average Switching frequency	12KHZ
Fundamental frequency	60 HZ
AC supply phase voltage	127 V
Load side inductance	1mH
Inverter side inductor	1mH
DC link capacitor	1 mF

A. Scenario I

In the first scenario, at t=.05s the hybrid PV and battery energy storage system is connected to DC link. After t=.12s the compensation part of the injected current is activated and the current THD is compared. The initial temperature and sun irradiance is considered 40° C and 0.6 kW/m^2, respectively. For evaluation the effectiveness of the MPPT system, sudden change in sun irradiance is exerted to the simulation at t=.2s.

Fig. 6 shows the simulation results of the scenario. As shown in Fig.7.a and fig.7.b, before connection of the hybrid PV and battery energy storage system, the entire load fed by source and the total harmonics distortion (THD) of source current is about 6.25%. After integration of the hybrid battery and PV systems to grid, not only the power delivered by the hybrid system can supply local loads but also it can inject power to the grid. In this condition, the inverter can only inject (*Pref_DG*) to grid and other part of real and imaginary power describe in pervious section is not compensated. The THD of the source current is about 9.65% in this condition; furethermore, The peak of neutral current is about 100 A in both aforementioned conditions (see Fig.7.c).
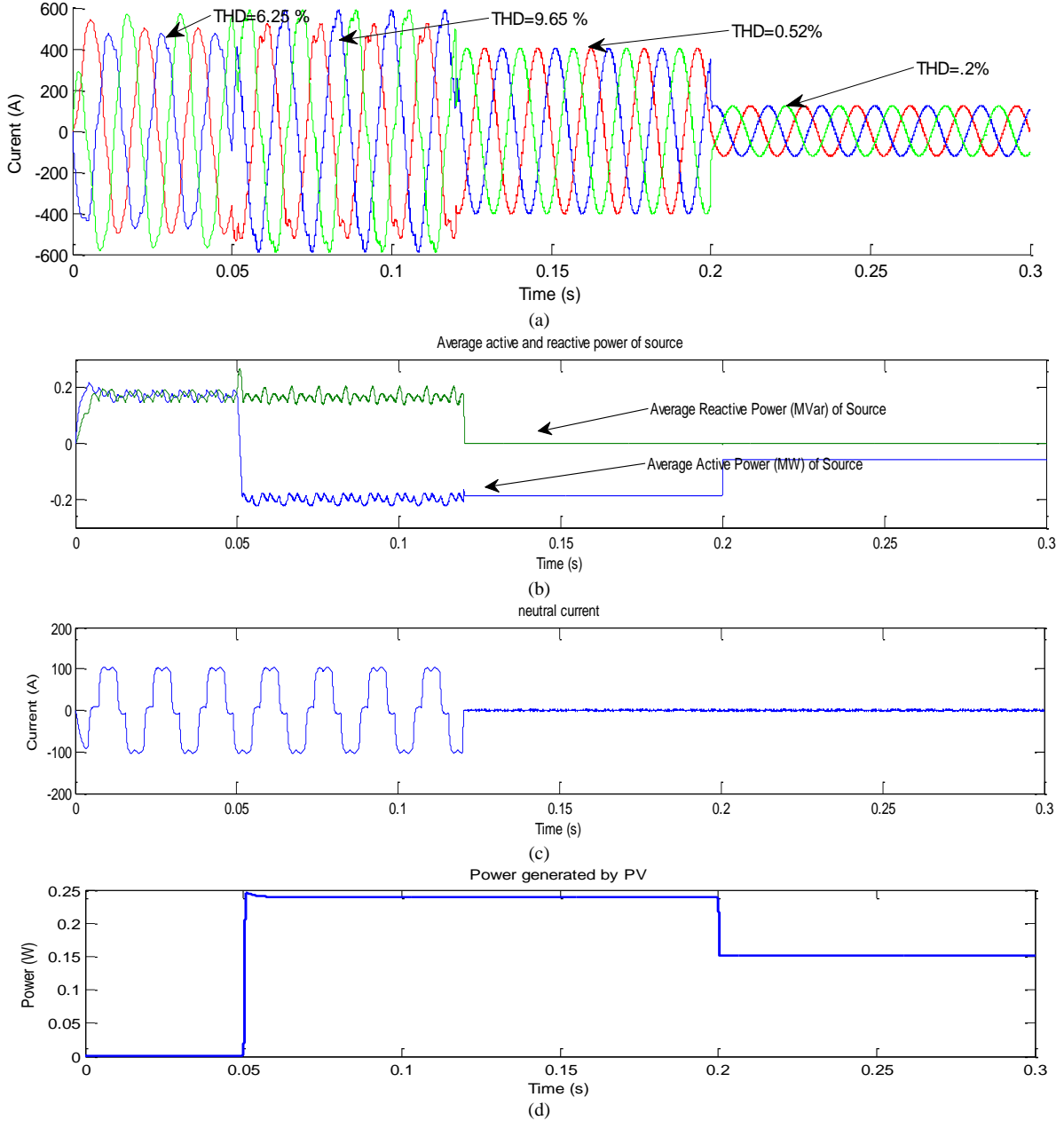

Fig.7. First scenario simulation: a) three phase current of source, b), average active and reactive current of source, c) neutral current, d) power generated by PV

After activation of power quality compensation using p-q theory at T=0.12s, the current THD is mitigated to .52% and the neutral current is also decreased to about 1 A. Fig.7.b shows that the reactive current is also compensated using the multifunctional control of inverter.

Furthermore, the effectiveness the MPPT system is depicted in Fig.7.d with changing the sun irradiance suddenly. After the change, the grid current harmonics is about .2 % and the injected power to grid is decreased.

B. Scenario II

In order to verify the effectiveness of PV and battery energy management system, the state of charge of battery is also considered. Two different SoCs are applied as initial values to the simulation. Firstly the initial value of SoC is considered 100%. Since the SoC is high, the battery energy storage power should be injected to the grid. After that the 70% SoC is applied to the simulation. In this condition, since the SoC is low, the Battery energy storage should consume the PV power. Fig.8 depicts the SoC and the power of battery energy storage system that validate the aforementioned analysis. As shown in these figure, while the SOC is 70 % the battery energy storage consumes the power to increase the SOC. Furthermore the battery injects power to grid in high rates of SOC (for instance SOC=100%).
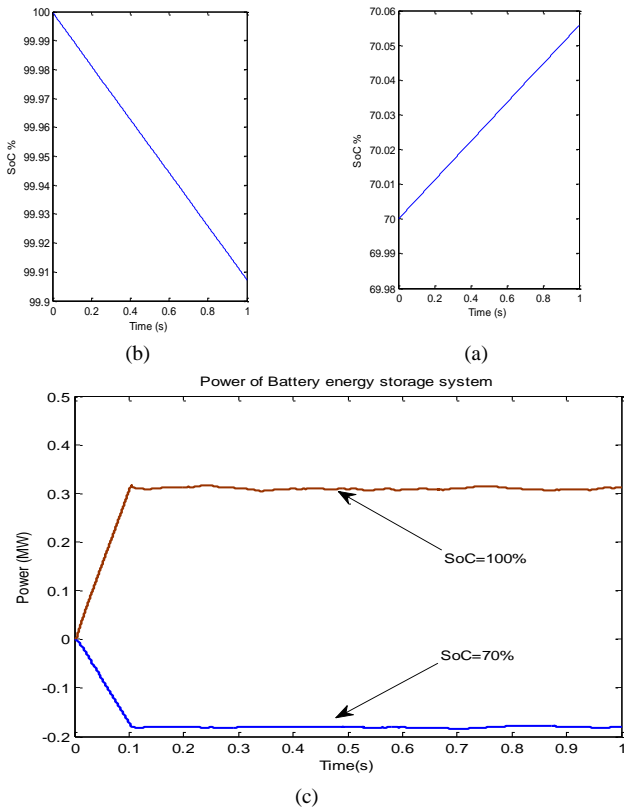

Fig. 8. Simulation results in Scenario II: (a) SoC for initial value of 70% (b) SoC for initial value of 100%, (c) power of battery energy storage.

VI. CONCLUSION

In this paper control of a multifunctional grid tied inverter to inject the power of hybrid battery energy storage and PV is presented. The simulation results show that using p-q algorithm, not only the power of the distributed hybrid energy resource can be delivered but also the power quality problem of local nonlinear and unbalance loads can be obtained considering SoC of battery energy storage. Two scenarios are implemented in this paper. The simulation results of first scenario show that after activation of compensation function of the inverter, the THD decreased from 9.65% to .52% that is under IEEE-519 recommendation value of 5%. Furthermore unbalance and neutral current compensation is achieved by this algorithm. Effectiveness of MPPT algorithm is validated by changing sun irradiance suddenly. The second scenario is implemented to validate the effectiveness of power management system. Simulation results show that in full charge condition (i.e. SoC=100%), battery injects power to grid, while in low charge condition battery consume the power of PV system.

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