SoC-based Controller of B4 Inverters for a Low-Cost PV System in Grid-connected Mode

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SoC-based control unit for B4 inverters in a cheap grid-connected Photovoltaic (PV) system is proposed in this paper. Because the inverter is the main element of Photovoltaic module, we utilized the B4 one here for decrement of entire expenditure of Photovoltaic system. This paper also coupled the Photovoltaic system to the main grid via IGBT switches for removing the bulky transformers. Besides, in order to inject the real energy to the main grid, this kind of inverter is able to compensate the real power and mitigate the harmonics related to the non-linear loads. Instead of the conventional PV systems on which a DSP processor is used to control the B4 inverter, we applied a zynq-7020 SoC-base control unit to effective control of the B4 inverter. Several characteristics of such control units such as dedicated low power and fast 32bit×32bit multipliers, with modified algorithm, enable the application of the required control methods. The operation of the proposed control unit in a PV system is implemented on zynq-7020. Implementation of the control unit in the SoC zync-7020 is the main contribution of this paper. Comparison with the conventional DSP-based control systems, TMS320F28335 DSP processor, demonstrated the high efficiency of the proposed SoC-based control unit for B4 inverters.

Keywords: *B4 inverter, SoC-based controller, Grid-connected PV system*

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1. Introduction

In recent years, many studies are performed in the field of green power resources chiefly the photovoltaic energy that is because of the growing crisis of conventional power sources [1]. Due to this growing crisis, the governments must focus on green power sources. The constant increment of power usage in addition to requirement for the clean environment needs distributed green power generation. Growing of power use can lead to overload in the distribution network and energy stations. Moreover, energy attainability, security and its quality can be influenced by this growing negatively. Integration of green power sources such as solar, water and wind with the network is the single alternative for solving this challenge.

The connection of network to the green generations is as per the availability of green generations. The solar resource is taken into consideration broadly in recent years, because of its higher efficiency in comparison to traditional resources like fossil fuels, as well as environmental issues. The most important challenge in utilizing the photovoltaic modules is their operating in just sunny weather. So, combining of this system with some other energy production units or connecting of that to the utility network is essential in order to promote its efficiency and also to procure the energy in the whole day by this system. In order to integrate the photovoltaic system with the main grid, we need a pulse width modulation (PWM) voltage source converter [2]. This system in grid-connected mode converts the solar power straightly to the electrical power that is injected into the network without saving the power in storage systems. This way is so helpful for promotion of existent power generation capacity that is utilized mainly for hydro and heating power resources. The solar power as a green power generates the electricity with no contamination. Therefore, this power resource is very helpful to reduce the negative impacts of pollution and improve the renewable power [3]. Figure 1 depicted the universal cumulative cases, moderate and policy-driven respect to the EPIA [4]. After further about thirty GW of photovoltaic modules in 2011s, its market is getting in a cross point in its improvement.

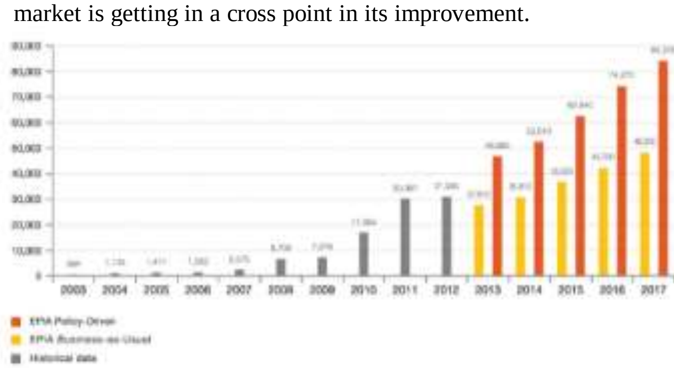

Fig. 1. Global cumulative scenarios until 2017 - Moderate and Policy-Driven (MW). Source: EPIA

The anticipated increment of markets beyond European cannot make up the slowdown in Europe prior to 2016 in the pessimistic moderate case. It considers a minus prospect in often markets in 5 future years chiefly in the European. Based on the situations of the moderate case, the capacity can achieve to 100GW in 2012s or 2013s, whereas respect to the policy-driven case, in future 5 years a capacity higher than 350GW of photovoltaic systems can be coupled to the network. A large permeation of photovoltaic systems is anticipated about 2015s, where the expenditure of photovoltaic power is predicted to be almost equal with the expenditure of traditional power [5].

There are many complications in designing and application of photovoltaic systems even in small scales. In this way, some main parameters like optimal real energy injection, reactive energy, the harmonics of current, voltage dip compensation, decrement of power factor, dynamic responses, max power point tracking (MPPT) as well as entire expenditure must be considered to achieve an efficient photovoltaic energy station in the design phase. So far, many investigations are performed for the optimization of various sections of PV system containing the panels, DC-Dc converters, DC-AC inverters, control systems, and many other sections. In [6], a photovoltaic system in grid-connected mode is suggested with a great voltage gain. Reference [7] utilized a synchronization method for grid-connected converter controller to make up the non-ideal procured voltage and obtain a greater frequency mutability. Also, an SRPC (denoting the simplified reactive power control) method is adopted in [8] for inverters and one-phase photovoltaic system in grid-connected mode. In this reference, the CASDM (denoting the current mode asynchronous sigma-delta modulation) is proposed for enhancement of transient condition of current signal and decrement of harmonics of the current signal as well as electromagnetic interruptions. As well, [9] proposed a one-phase one-step current-source inverter-based plant for the photovoltaic module. This reference also suggested a system using transformer-less one-step conversion in order to MPPT and interface the photovoltaic systems to the network.

Moreover, a one-phase transformer-less inverter in grid-connected mode and with great reliability is proposed in [10], which employs super-junction MOSFET to achieve great effectiveness for photovoltaic utilities. This offered converter uses two apart ac-coupled inductors, which work in positive/negative half-cycles of the network. This can eliminate the shoot-through problem faced with the conventional voltage-source inverters (VSIs) that result in growth of system reliability. The authors in [11], analyzed the effectiveness of various real/reactive energy control methods in grid-connected photovoltaic systems from technical and financial aspects. Reference [12] provided a novel method for optimal designing of transformer-less photovoltaic inverters in order to reach an economically efficient development of the grid-connected photovoltaic system. In this reference, optimum switching frequency, optimum amounts and optimum kinds of inverter elements are computed so that the photovoltaic inverter LCOE (denoting the levelized cost of electricity) is minimized in the lifespan of the photovoltaic system. This LOCE method as well computed the fail rates of the elements, which affect the reliability efficiency, and lifespan maintenance expenditure of the inverter. Reference [13] also suggested a new transformer-less grid-connected converter based on a negative grounding for photovoltaic modules, where the negative end of the PV system in the suggested converter is straightly grounded for ignoring the lucid conducting oxide corrosion, which is a kind of thin-film PV modules. The suggested converter consisted of a DC-DC converter and a DC-AC inverter. In [14], a developed MPPT with higher efficiency is proposed for solving the fast-varying radiation issue that is based on the VOC (voltage oriented control). In the voltage oriented control, a cascade construction is utilized, where the outer loop is the DC-couple voltage and the inner one is the current loop. Controlling of currents is performed in synchronous orthogonal d and q frameworks by a decoupled feedback control. In [7] and [15], the digital control method is utilized for a converter in order to make up the greater frequency mutability, non-ideal procure voltage as well as the ground leak current. Reference [16] controlled the converter in grid-connected mode by a DSP for enhancement of the efficiency in distortions of the network. System on chip (SoC) is another effective system for better design of control unit of the grid-connected PV systems.

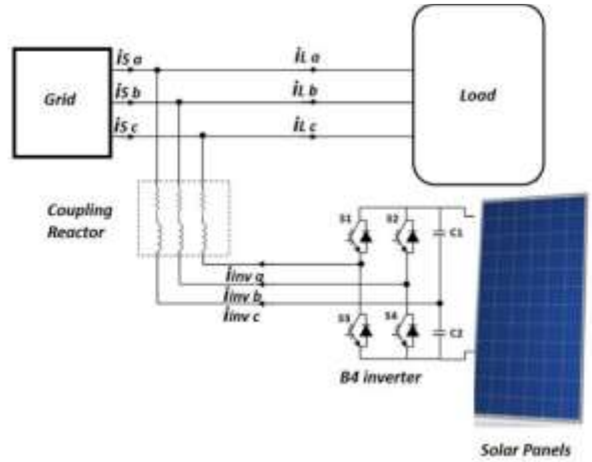

Fig. 2. Grid-connected PV system

Accordingly, in this paper, a SoC-based control unit for the B4 inverter in a low-cost grid-connected Photovoltaic (PV) system is proposed. The basic novelties of present work are the SOC-based control unit in a grid-connected photovoltaic module with the ability of load compensation. The harmonics and reactive elements can be compensated while real photovoltaic energy perfusion into the network. Besides, we utilized B4 inverter here that is able to decrease significantly the entire expenditure of the photovoltaic system. The main contributions of the proposed PV system contain the following aspects: 1) the inverter can inject real electricity to the grid (day-mode), 2) the inverter compensates the reactive electricity of the load (night-mode), 3) a SoC-based zynq-7020 is utilized for controlling of the system operating. Accordingly, this paper is organized as follows. In section II, the design methodology is proposed. The SoC-based control unit, the required parts and the experimental results are presented in section III. Finally, conclusions are discussed in section IV.

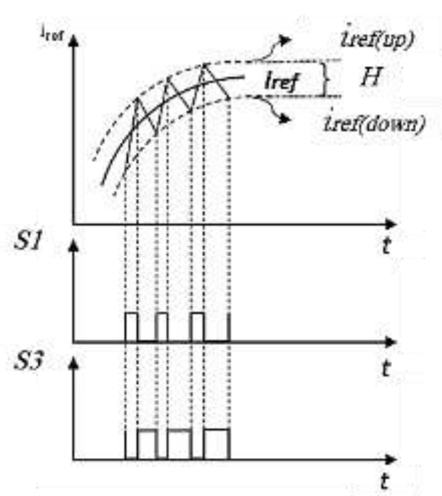

Fig. 3. Grid-connected PV system

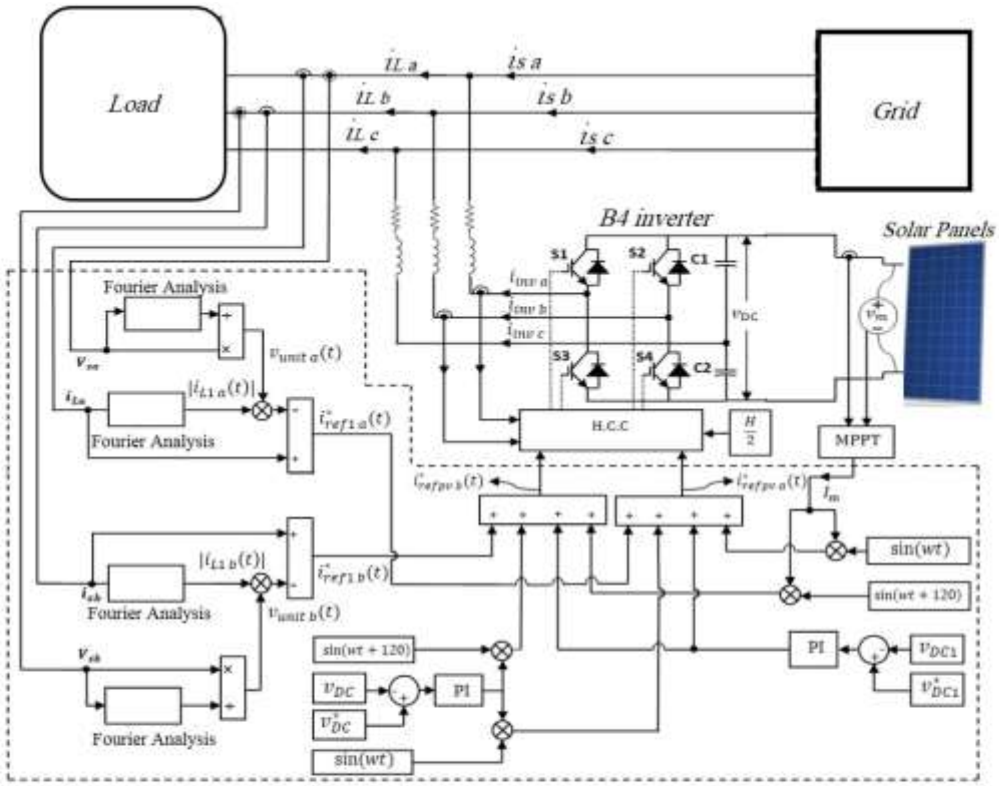

Fig. 4. The control strategy of the grid-connected PV system

2. Proposed grid-connected photovoltaic system

2.1. An introduction of grid-connected photovoltaic system

Figure 2 depicted the configuration of considered PV system. It's demonstrated that the PV modules are able to feed the max energy into the network once they're straightly coupled with no DC-DC converter through a DC-AC inverter. So, we can eliminate this converter that leads to growing the performance of the system. Each photovoltaic system consists of some important sections such as panels, DC-link, the B4 inverter as well as connection filters that used for coupling to the network. Also, choosing the capacitors for DC-link and filters is according to the control method of considered inverter [17]. Much expenditure of network linked with the photovoltaic system is for the used inverter. So, present work utilized the B4 type that considerably reduces the entire expenditure of the system. In the construction of this type of inverter, we have 4 IGBT switches, which this number is six for B6 type inverter. Not only this inverter decreases these switches, but also it reduces the expenses of start-up, snubber and protection circuits as well as the heat sink. Many approaches are introduced for controlling the output current of this inverter. Among these methods, present work employed the HCC (denoting the hysteresis current control) approach. This method is selected here due to its simple application and low conservatism. Figure 3 illustrates the operation of the one-phase inverter, in which, i_{ref} denotes the desired current that is provided via desirable switch in the control system. Besides, H indicates the hysteresis band that specifies the switching frequency and current error of the inverter. Obviously, with implementing proper switch, controlling the oscillations of current will be plausible. So, that lies in a given interval at all times. This is obtainable by introduction of H in vicinity of i_{ref}:

$$\begin{cases} i_{ref\,(up)} = i_{ref} + \dfrac{H}{2} \\ i_{ref\,(down)} = i_{ref} - \dfrac{H}{2} \end{cases} \quad (1)$$

In proposed control approach, the inverter output current is contrasted with i_{refup} and $i_{refdown}$. Obviously, decreasing the H leads to reduce the error of current. In contrary, switch frequency as well as energy loss will grow. Present work utilized a constant hysteresis band for controlling the compensators.

This paper utilized the start-up circuit for starting switch of IGBT switches. Also, the inverter must be secured from failures below:

1) Growth the peak level of output current.
2) Growth the mean value of output.
3) Growth and reduction in the capacitor voltage of DC-link.
4) Growth the temperature of heat-sink.

In the suggested HCC approach, the desired output is limited to a determined interval. So, the output can't violate from this interval.

Furthermore, we used an LM35 sensor to measure the temperature of heat-sink. The max allowable temperature for this component is set to 80 degree Celsius. As well, the system is protected versus the great and small capacitor voltage of DC-link. So, if this voltage falls or the output violates from determined level, the inverter will be turned off. Because the max level of capacitor voltage is great around 800 V, an isolated sampling circuit is utilized in this paper.

2.2. Inverter control method

For injection of real electricity from the PV system to the network,

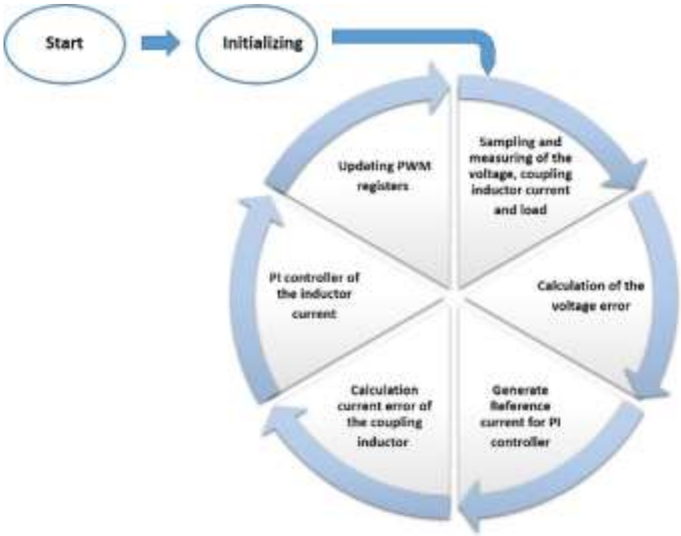

Fig. 5. Flowchart of the control algorithm

and providing reactive energy for local loads, the photovoltaic system can make up the current harmonics of loads. The considered system operating in grid-connected mode is entirely reliant on the control method of VSI. This control method generates the desired current and regulates the voltage of the DC-link capacitor.

Figure 4 shows the main construction of control method. Here, the reactive instantaneous power theory is utilized, which is firstly introduced in [18] for computing the desired output current. PV system fed the real power to the network. Moreover, the reactive energy, as well as current harmonic, is made up by the B4 inverter. Computing the desired outputs in αβ coordination is in form below:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}_L & p_{active} \\ \bar{q}_L & \tilde{q}_L \end{bmatrix} \quad \textbf{(2)}$$

Here, V_α and V_β denote the voltages of the load; i^*_α and i^*_β indicate the desired output currents; P_L and q_L determined the instantaneous energy of load in $\alpha\beta$ coordination. Also, p_{active} denotes the output signal of the DC-link control system. Besides, these currents can be computed in abc coordination by:

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

By assuming that the inverter outputs are same as i^*_a and i^*_b, regarding the formation of i^*_c in the neutral line with no switch, the generated energy by PV modules is fed into the network. The used inverter also produces the harmonics and reactive energy. So, the power factor will be close to 1. Subsequently, the produced harmonics can't go in the network. When the produced energy by the PV system is low, the control system allows the capacitor to give real energy from the network pending to stop the capacitor voltage dropping. In this scenario, the panels can produce reactive energy and harmonic currents.

3. Applied control system over ZYNQ-7020 SoC

Here, a small scale of the suggested photovoltaic system is applied with one KVA capacity. The considered control system for this prototype system is designed in the SoC-based control system as explained below.

3.1. Zunq-7020 SoC-based control unit

The Xilinx SoC configuration is the base of Zunq-7000 systems. Zunq-7000 family unifies a feature-rich equipped with dual-core (or one-core) ARM Cortex-A9 PS (processing system) and 28nm Xilinx PL (programmable logic) in an integrated system. The center of the processing system is the ARM processors, and it as well contains on-chip memory, an interface for external memory and a wealthy collection of external connectivity interfaces. These systems are flexible and scalable similar to FPGAs. In addition, they are near to ASIC and ASSP devices in efficiency and easy to use. The variety in this kind of systems permits the designer to select one of them for low-cost or high-efficiency utilities. However the devices in this family have equal processing system, they are different in programmable logic and I/O pins. Therefore, a large range of utilities can be covered by series of Zunq-7000 and SoC-based Zynq-7000s with fast 32-bit x 32-bit multipliers.

Moreover, the configuration of these devices allows applying the custom login and software in the programmable logic and processing system, respectively. Combination of PS with PL permits the efficiency levels that double-chip solutions (like ASSP with FPGA) can't match. This is because of that, their I/O band-width, latency and power budgets are bounded. The Xilinx suggests a high count of soft IP to the Zynq-7000 devices. The autonomous and Linux device drivers are accessible for the external connections in the processing system and programmable logic. Moreover, the Vivado Design suite development software offers a fast product improvement to the software, hardware, and engineers. As well, assumption of processing systems equipped with ARM CPUs brings a wide range of third-party tools as well as IP providers in blending with Xilinx's existent programmable logic ecosystem. Inserting a utility processor permits high-level operation system support (like Linux). Also, other standard systems based on ARM Cortex-A9 CPU are attainable for Zunq-7000 devices. The processing system and programmable logic have apart powers that permit the user to power-down the programmable logic to manage the power if needed. In a PS, firstly the processor boot permits the software-centric method to structure the programmable logic. Management of programmable logic architecture is by executing the software on CPU. Therefore, its booting will be like to the ASSP. Figure 5 demonstrated the steps of the control method. Primarily, the Zynq-7000 must be initialized. For this purpose, the SoC registers, PLL as well as the clock of SoC must be initialized. The sampling frequency of the analog parameters, currents and voltages, is 50 kHz. The main loop of the program is also performed at 50 kHz. Furthermore, A/D converter and PWM are setup and interrupts are set. Then, the voltage of DC-link and network must be sampled. As the third step, a comparison is made between the voltage of DC-link and desired voltage and error value is computed. Therefore, the desired voltage of the PI controller is obtained. Following that, a comparison is done between the current of the coupling inductor, and the desired one and also the error value is computed. As the 6th stage, precise commands are prepared for the considered control system. Final step is updating of PWMs. Eventually, control loop returns to the third step, and steps 3-8 will be iterated.

3.2. Elements and hardware of photovoltaic system

A comprehensive detail of elements and variables are provided in Table 1.

3.3. Obtained results

For assessment of photovoltaic system efficiency, we performed four experiments (Figure 6). As the first one, responses of the inverter to oscillations on the voltage of DC-link capacitors is appraised, where the input voltage of it varies in the range of 200-600V in each 0.2s periods. Its frequency is also considered 12KHz. It's appropriately inferred that the inverter could track imposed variations according to its current waveform.

As the 2th experiment, we assessed a load with some non-linearity. So, the input voltage of the inverter is assumed 350 V. Also, we utilized a circuit with capacitors, resistors and bridge rectifiers in the form of a non-linear load. According to the obtained results, the inverter can track the desired current appropriately (Figure 7).

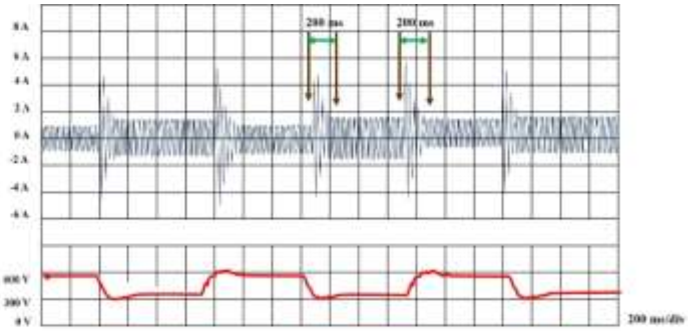

Fig. 6. Input voltage variation of the B4 inverter (voltage loop test), Inverter current (up), DC link capacitor voltage (down).

Table 1. Experimental test bench specifications

Description	SPECIFICATIONS
solar Panel	10 panel (in series); 100W; 5A; 22.5V
DC-link capacitors	1000 µF
IGBTs	BUP314 (1200V, 42A)
Switching frequency	12 kHz with 2 µs dead time
Coupling Inductors	3.2 mH (iron core with 0.73 Ω parasitic resistance)
Current sensors	LA100 from LEM Co.

As the 3th experiment, the produced reactive electricity by solar panels is assessed. Here, it's considered that the PV systems can't generate real electricity (that denotes the night state) and demanded real power is provided from the network. Also, required reactive electricity of the photovoltaic system is supplied by loads. The semi-sinusoidal voltage, as well as the network's current, is evaluated in this case. The grid sinusoidal current and the load non-sinusoidal current are shown in Figure 8. The difference between these two signals is provided from the inverter.

In the 4th experiment, we implemented the load on the photovoltaic system and then disconnected that. In disconnection mode of the load, the inverter will be disabled. Subsequent to apply the load, the inverter begins operating and generates energy to the load (Figure 9). Following that, by disconnecting the load, the inverter is disabled (Figure 10). Here, the input voltage is assumed equal to the 3th experiment. In instant of application and disconnection of load we will have a sway in input voltage, and then it goes back to its constant value. In the last experiment, reactive power compensation by PV system is investigated (three phase). So, a nonlinear load is connected to the PV system. The three-phase voltages and currents of the grid (50 Hz) are shown before and after compensation (Figure 11).

4. Conclusions

This paper suggested a control system equipped with a SoC for B4 inverter in the grid-connected mode of a cheap PV system. Here, the B4 type inverter has been utilized, which decreased significantly the total cost of the system. The main contributions of the proposed PV system contain the following aspects: 1) the inverter can inject real electricity to the grid (day-mode), 2) the inverter compensates the reactive electricity of the load (night-mode), 3) a SoC-based zynq-7020 is utilized for controlling of the system operating. Because of multitude abilities of used SoC like fast multipliers, application of various control methods is plausible. Finally, the obtained results demonstrated the proper performance of the SoC-based zynq-7020 control unit in different operational situations.

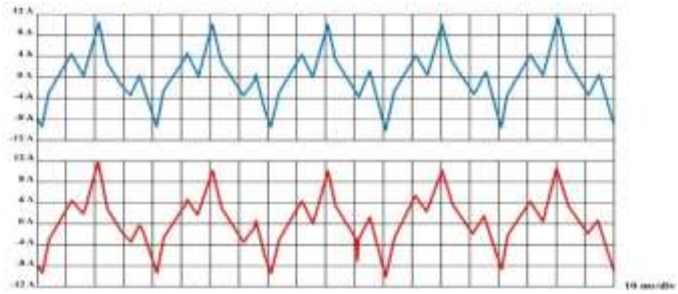

Fig. 7. The test of the PV system under nonlinear load, reference current (up), inverter current (down).

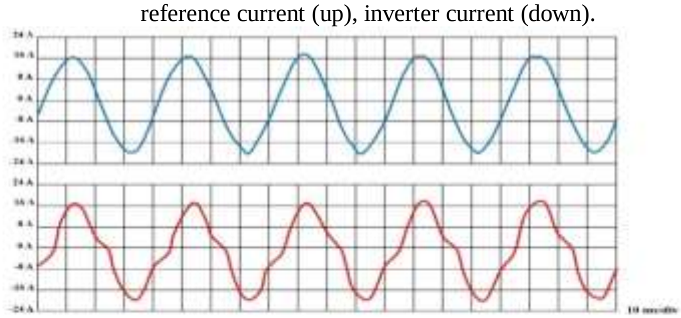

Fig. 8. The PV system in night mode, grid current (up), load current (down).

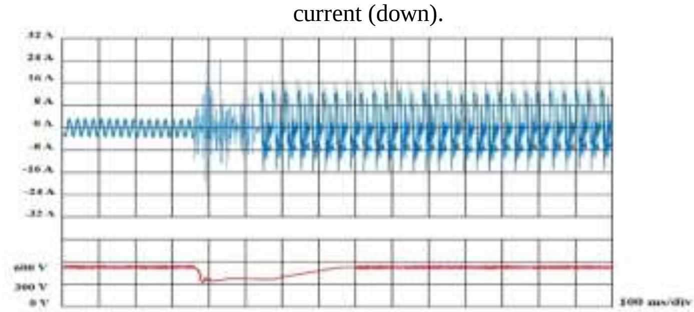

Fig. 9. A load connected to the PV system, Inverter current (up), DC link capacitor voltage (down).

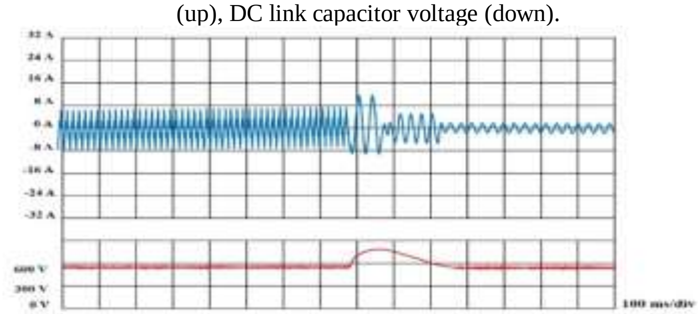

Fig. 10. A load disconnected from PV system, Inverter current (up), DC link capacitor voltage (down).

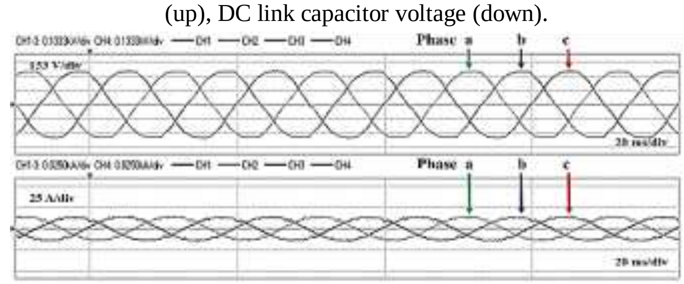

Fig. 11. Reactive power compensation by PV system (three phase). (a) before compensation (b) after compensation

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