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New Strategy of Grid Connected Photovoltaic System Using Module Integrated Converters with B4 Inverter to Overcome Partial Shading Effect

Reza Rezaii[1], Mohammad Amin Abolhasani[2], Ali Yazdian Varjani[3], Reza Beiranvand[4]

Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran
[1]reza.rezaii@modares.ac.ir, [2]m.abolhassani@modares.ac.ir,[3]yazdian@modares.ac.ir, [4]beiranvand@modares.ac.ir

Abstract

This paper proposes a new configuration for solar energy conversion systems. One challenging issue of the photovoltaic (PV) systems is partial shading, and in this paper Module Integrated Converters (MIC) are used to overcome this problem in PV arrays. A few boost converters are employed as MICs to mitigate the shading effect. Furthermore, to reduce the cost and to increase the system performance the B4 inverter is used. This inverter is a four-switch, three-phase inverter. To validate the performance of the proposed system and simulation results, a typical prototype has been made and experimental results have been carried out. The results confirm the effectiveness of the circuit in mitigating the effects of partial shading.

Keywords: B4 inverter; module integrated converter (MIC); partial shading; photovoltaic (PV).

1. Introduction

World-wide demand for clean electric energy is rapidly increasing during last few years and among all renewable energy sources, solar energy is the most favorable endless resource, which is most available and easy to use. The global expectation is that the Photovoltaic energy sources will become the biggest renewable energy source to produce electricity by 2040 [1].

To modify the operation of the photovoltaic interfaces so that the load and the photovoltaic array match their operating characteristics at the Maximum Power Point (MPP), and in order to extract the maximum power delivered by a PV module, there are Maximum Power Point Tracking (MPPT) control techniques. P—V characteristic of a typical PV panel under full solar irradiance have a single power peak (MPP) which is shown in Fig. 1 [2]. However, there are some non-ideal conditions that cause problems in determining and tracking the MPP. One challenging issue is the effect of the partial shading occurrence on PV panels.

When this phenomenon is occurred in a PV module, current of the un-shaded cells passes through the shaded cells and cause massive power dissipation in the module resulting in hotspot and cell breakdown. By using some bypass diodes in parallel with the connected in series cells, hotspot breakdown on PV cells due to partial shading can be avoided [3]. However, they cause presence of multiple peaks in the P—V characteristics of the PV array [4], and they eliminate the available amount of power that shaded modules can deliver even in the presence of partial shading effect. Fig. 2 (b) shows that how the P—V characteristics of the array with bypass diodes changes due to partial shading.

There are number of different methods that have been employed and developed over the last years to overcome the shading effect problem [5]. Among all techniques, using the MICs has attracted a lot of attention from researchers due to its specific characteristics. MIC systems present "plug and play" concept and greatly optimizes the energy yield. Considering these advantages, the MIC concept has become the trend for the future PV system development, but challenges remain in terms of cost,

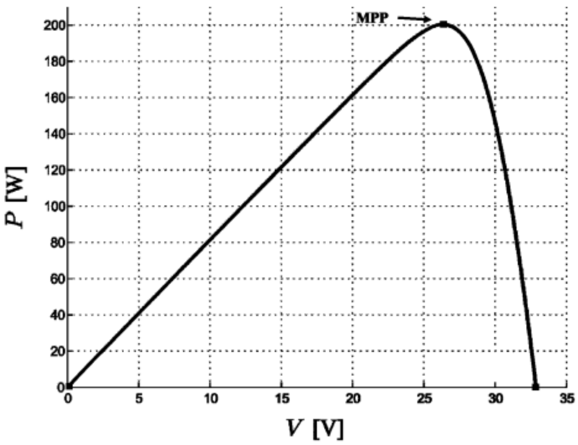


Fig. 1. V characteristics of a module under full solar irradiation [2]

Reliability, and stability for the grid connection [6]. Thus, the cost of using solar energy systems is rather high.

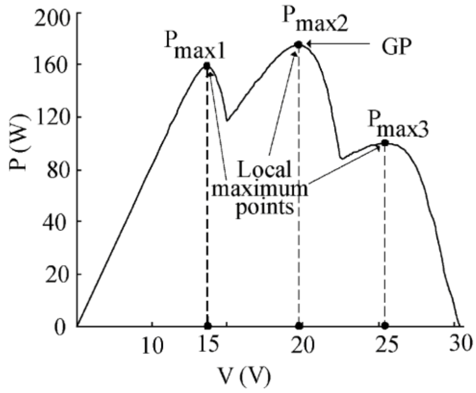
Although, as the result of increasing production capacity, prices of the PV panels are decreased in the last few years, the whole systems costs are still high. Thus, the power electronics engineers are trying to reduce cost and power dissipation in PV panel converters. Considering the cost and power dissipation challenges, B4 inverter is an interesting candidate because of reducing number of the power semiconductor devices. By comparison with B6 inverter, power switch counts of B4 inverter are reduced to 2/3; hence, the switch gate drives and the overall conduction loss are reduced, and the circuit cost is decreased, too. However, one disadvantage of the B4 inverter is reduction of the voltage gain [7].

According to the above paragraphs, to reduce the cost and power dissipation, and to mitigate the effect of partial shading, a series connection of a few Module Integrated Boost Converters is combined with the B4 inverter as the interface between PV array and the grid.

The characteristics and operation of the used MICs will be discussed in section II. Then, the B4 inverter operation principle will be demonstrated in section III. Next, the topology of the proposed system is described in section IV. At the end, the simulation results are brought to ensure the proper operation of the proposed system in section V.

2. Module Integrated Converters

In MIC topology, a DC-DC converter is combined with the PV module such that the module is no longer connected in series with neighboring modules, directly. The converter and the module both constitute an integrated element which can be connected to other elements in the whole array by output terminals of the converter, and constitute a series-connected string. In this topology, each converter is controlled by a local autonomous MPPT controller in other to extract the maximum possible amount of power from each single module [5].



P—V characteristic of a module with bypass diodes in partial shading condition [4].

By using MICs, power dissipation resulting from each unbalancing between modules is eliminated, and the module level MPPT is provided so that it contributes to higher efficiency than the central inverters. In different current levels of every single module (either the module is prone to the shading or different level of irradiance) performance of the system will not be changed, and the current control will be facilitated because series connection of MICs has a high degree of controllability. In corresponding situations compared with other topologies MICs have more capability of harvesting solar energy. Under different irradiance conditions, it is demonstrated that MICs are capable of delivering the output power by 30% more when a single MIC per panel is used and 45% more when there are two MICs per panel [8].

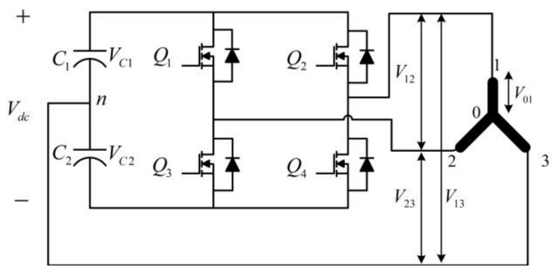


Fig. 2. B4 inverter configuration [12]

The multiple peaks problem is avoided by using MICs because instead of bypassing the module. The converter can process the reduced amount of power until there is no serious harm for cells. Thus, a simple algorithm can be exploited to track the single MPP. For this purpose the conventional Hill Climbing technique is used in this paper. In this approach, which is defined in [9], by periodic measurement of current and voltage of a single module and calculating the corresponding power, the duty cycle for converter switches can be determined so that the PV module always deliver its maximum available power.

3. B4 Operation Principle

Fig. 3 shows the B4 inverter configuration connected to a three phase load. This inverter uses four IGBT switches to produce two line-line voltages namely V13 and V23. Moreover, dc link produces V12 voltage according to Kirchhoff's voltage law [10]. In the other hand, the maximum line-line voltage is determined by Vdc/2.

In Fig. 3, it is assumed that switching states are shown by binary variables of Q1 to Q4. Binary code of "1" represents the close state and binary code of "0" demonstrates the open state of the switches with Q1, Q3 pairs and Q2, Q4 pairs being complements of each other [11, 12]. The following relationships are defined:

$$Q_3 = 1 - Q_1 \tag{1}$$

$$Q_4 = 1 - Q_2 \tag{2}$$

It is assumed that a regulated voltage is available across the two dc-link capacitors, and their values are equal to Vc1=Vc2=Vdc/2, in which Vdc is defined as the regulated dc-link voltage. Pole voltages of V1, V2and V3 (line voltage to middle point of the dc link "n") depend on the states of the switches. They can be expressed according to the binary variables of Q1 and Q2 as follows:

$$V_1 = (2Q_1 - 1)\times\frac{V_{dc}}{2} \tag{3}$$

$$V_2 = (2Q_2 - 1)\times\frac{V_{dc}}{2} \tag{4}$$

$$V_3 = 0 \tag{5}$$

There are four switching states for Q1 and Q2, which can be defined as (0,0), (0,1), (1,0), and (1,1). Based on these conditions the values of V1 and V2 are varied between Vdc/2 and –Vdc/2. Phase to neutral voltages are defined as follows:

$$V_{01} = V_1 - V_{n0} \tag{6}$$

$$V_{02} = V_2 - V_{n0} \tag{7}$$

$$V_{03} = V_3 - V_{n0} \tag{8}$$

The above voltages can be defined by binary variables of Q1 and Q2, and voltage of the dc link [10], as demonstrated in equations (9) to (11):

$$V_{01} = \frac{V_{dc}}{6}\times\left[4Q_1 - 2Q_2 - 1\right] \tag{9}$$

$$V_{02} = \frac{V_{dc}}{6}\times\left[4Q_2 - 2Q_1 - 1\right] \tag{10}$$

$$V_{03} = \frac{V_{dc}}{6}\times\left[-2Q_1 - 2Q_2 + 2\right] \tag{11}$$

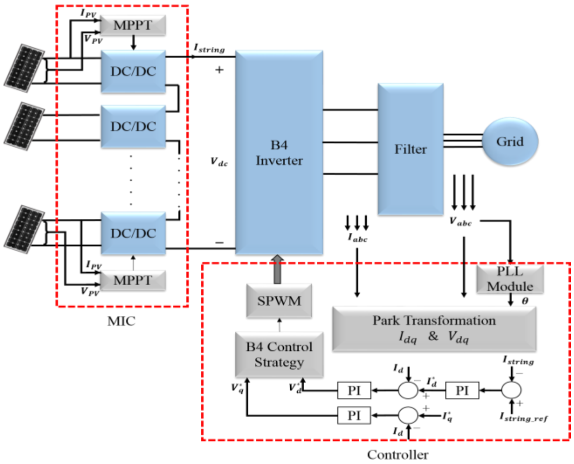


Fig. 3. Block diagram of the proposed system.

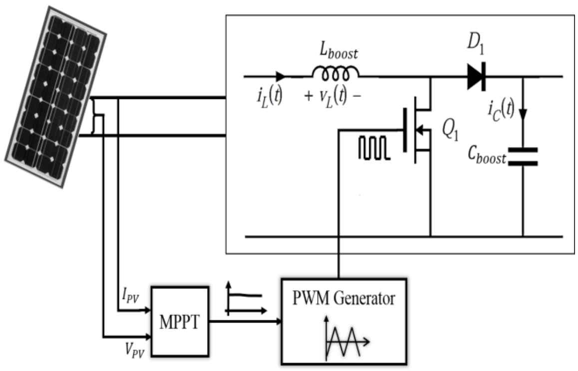


Fig. 4. Module integrated boost converter with MPPT and PWM control blocks.

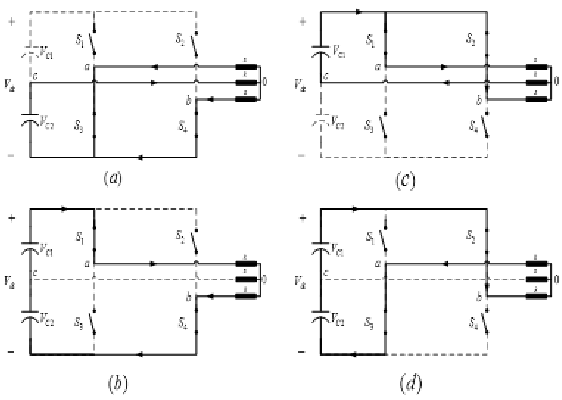


Fig. 5. Sub-operating modes of B4 inverter (a) mode I, (b) mode II, (c) mode III, and (d) mode IV [12].

4. Proposed System

The block diagram of the proposed system is depicted in Fig. 4. The main purpose of this paper is to provide a strategy for connecting the possible amount of power that can be extracted from a PV module to the grid in a more efficient way. For this purpose it is necessary to track the real maximum power point of solar array in every situation including occurrence of partial shading on PV modules at first stage. Accordingly, the proposed structured is consist of series connection of several PV MICs, connected in parallel with every module, to ensure tracking of the real MPP with highest efficiency. The circuit topologies suitable for using as MICs are different and among the various topologies that are proposed, in this paper, boost dc-dc converter due to its several special merits has been exploited. Capability of increasing the output voltage without using a transformer makes the boost converter as the most popular converter for MIC applications.

The boost convert benefits the advantage of having low part count and simple design. This converter allows reaching the input voltage required for the inverter with fewer PV panels. If the desired converter output voltage is designed so high that the open circuit voltage of the PV panel sets below it, a boost characteristic ensures that the maximum power point (MPP) will always be tracked. The boost inductor which is located on the PV module side will reduce electromagnetic interference (EMI) noises and losses resulting from current ripple in the converter. The series connection of boost converters causes the output current for all converters to be the same. Also, it allows every converter to reduce its voltage boosting factor, so it will reduce the voltage stress on the power switches and contribute to higher efficiency and better performance of the whole system. The block diagram of the typical boost converter that is exploited in this paper as MIC is shown in Fig. 5.

The block diagram of the typical boost converter that is employed in this paper as MIC is shown in Fig. 5. The control architecture employed for MPPT control of the module integrated boost converter uses a single variable Hill Climbing algorithm which is experienced in [10]. Inputs of the MPPT unit are voltage and current of the PV module which are measured, periodically. The operating point for maximum power extraction is calculated by the aforesaid algorithm. The output of the MPPT box creates the input signal for the pulsed width modulation (PWM) generator, and it is crisscrossed by the saw-tooth wave in a comparator. Then, the PWM generates the duty cycle for the power switch gate driver so that the converter can run in the calculated operating point of the algorithm. This procedure along with the concept of module level MPPT that is exploited in the system, ensures the tracking of real maxima in both shading and non-shading conditions.

In order to reduce the cost, the output of the series connection of MICs is connected to an efficient B4 inverter as the next step. Values of line to neutral voltages and the switching functions of the inverter are tabulated in Table 1. In this inverter, as shown in Fig. 6 (a) and (c), the third phase of the grid (phase C) is connected to the point "n" in modes I and III ((0, 0) and (1, 1) state), so in the inverter's zero state supply the grid. In other hand, in the modes II and IV (states of (0, 1) and (1, 0)), the currents of the other two phases flow through dc link, as shown in Fig. 6 (b) and (d) [12].

Table 1.
Switching functions and output voltages of the B4 inverter.

Switching Function		***Output Voltage Vector***		
Q_1	Q_2	V_{01}	V_{02}	V_{03}
0	0	$-V_{dc}/6$	$-V_{dc}/6$	$V_{dc}/3$
0	1	$-V_{dc}/2$	$V_{dc}/2$	0
1	0	$V_{dc}/2$	$-V_{dc}/2$	0
1	1	$V_{dc}/6$	$V_{dc}/6$	$-V_{dc}/3$

Table 2.
Characteristics of the employed PV module in simulation.

Parameter	***Value***
Open circuited voltage	21 V
Short circuited current	3.4 A
V_{mpp}	18 V
I_{mpp}	3.2 A
a	1.3
K_I	0.065
K_V	-0.08
R_S	0.221 Ω
R_P	116.1 Ω
N_S	60

5. Simulation Results

In this paper, the MATLAB/Simulink is used for simulating the system containing five PV modules with the characteristics that is given in Table2 (that a is the diode ideality constant, KV is the open-circuit voltage/temperature coefficient, the KI is short circuit current/temperature coefficient, RS is the series resistance, RP is the parallels resistance, NS is number of the connected in series cells).At first, all PV modules are operating under normal irradiance of 1000 W/m2, at room temperature, i.e., 25^0 C. So the system is in its steady state condition. These modules are connected to five integrated boost converters which are employed as MICs and provide the dc voltage for the B4 inverter. Table 3 shows the parameters of the boost converter, dc link capacitors, and switching frequency in the simulation. Then, for validating the correct operation of the proposed strategy under partial shading condition, the first and second PV modules' irradiance is reduced by 100 W/m2, so the current of these modules is reduced, consequently.

Because the other modules are working in their normal conditions, it is favorable that the string current does not change. The most suitable merit of this condition is that these two modules work in their real maximum power points. So, the inverter which is working in current control mode will force the string current to be constant by its control loop. On the other hand, due to the reduction of irradiance on two PV modules, their currents will reduce proportional to the reduction in their related irradiances.

Table 3.
Different parameters values used in the simulation.

Parameter	***Value***
Switching frequency	20 kHz
C_1& C_2 *(capacitance)*	460μF
L_{boost}	100 μH
C_{boost}	200 μF

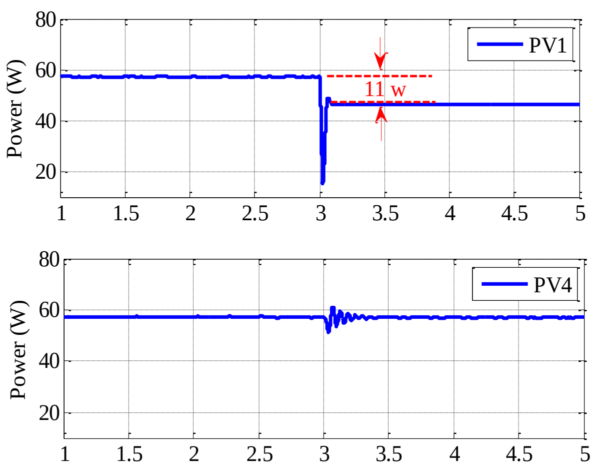


Fig. 6. First and fourth PV module's power.

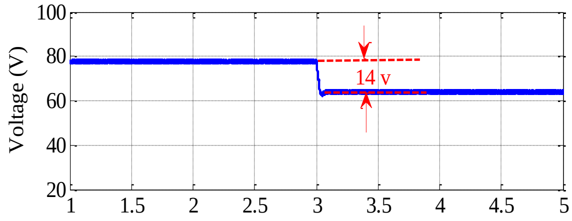


Fig. 7. Variation of the output voltage of the first Boost converter under the partial shading condition.

The boost converter connected to the shaded module changes its duty cycle to equate its output current to the string current, while un-shaded module converters still operate at their nominal operating points. As shown in Fig.7 in t=3s of operation the output power of the converter, which is prone to shading effect, reduces from 57 W in steady state operation to 46Wdue to the shading condition.

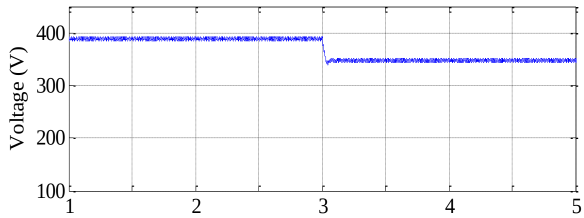


Fig. 8. Variation of the dc link voltage under the partial shading condition.

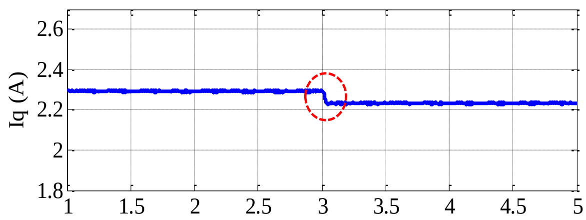
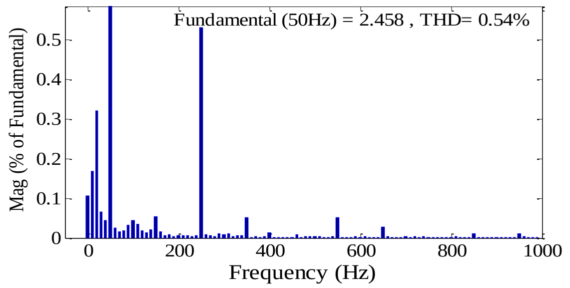


Fig. 9. Current of the q-axis (Iq) in Park Transformation.

It should be mentioned that by using bypass diodes instead of this boost converter, all of this power would be avoided. But, the MIC topology can process this power and deliver it to the next part of the system.

Considering the fact that the string current will rarely change, the output voltage of the converter will reduce to 12 V due to the shading effect and reduction of its input power. The waveform of the boost converter voltage is drawn in Fig.8. It can be seen that the converter changes its output voltage because its input voltage is changed by the MPPT controller such that maximum power point is tracked. Fig.9 shows variations of the input voltage of the B4 inverter applied across the input capacitors.

The inverter uses current control approach to control the grid injected currents. They are sensed and converted to the grid currents reference frame by park transformation. Then, the difference between idq and



the reference value (idq*) is applied to a PI controller, and output of the PI controller is applied to the B4 control unit to identify the switches states. Thus, the inverter should regulate the injected current to the grid in an approximately constant value. However, for the given step change in the capacitor link voltage the inverter output current slightly changes. Variations in iq and ic are shown in Figs. 10 and 11. These variations are quite moderated, as illustrated in these figures.

As shown in Fig. 12, the current of the proposed system injected to the grid have an acceptable low Total Harmonic Distortion (THD). The measured value of THD for current is equal to 0.54%, which is a reasonable value for grid connection applications.

Fig. 10. Phase C current (Ic) that is inject to grid.

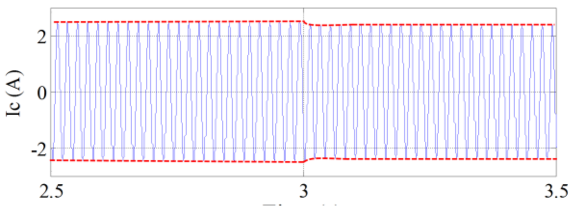


Fig. 11. Total harmonic distortion (THD) of phase C current.

6. Experimental Results

The typical prototype used in the laboratory to validate the simulation results is consisting of two Boost converters as MICs. These converters are employed in order to increase the voltage and decrease the effects of partial shading as described in previous sections. Also, to inject the extracted energy from PV panels to the grid, a DC-AC converter parallel to DC-link of two series Boost converters is needed. Thus, the B4 inverter is constructed and connected to the output DC-link of Boost converters. Fig. 13 shows the laboratory implementation of the proposed system, and the components used in the prototype are listed in Table 4. Moreover, Fig. 14 illustrates the waveform of injected current to the grid for phase a, and the current of two other phases b and c are displaced by 120 degrees, so these waveforms are not depicted here due to prevention of repetition.

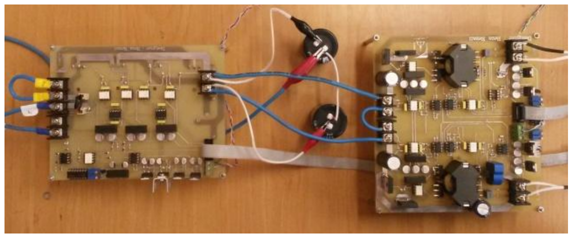


Fig. 12. Implementation of the proposed system.

7. Conclusion

A new strategy for tracking the maximum power point of PV arrays under partial shading conditions is investigated in this paper. It has some benefits such as: reducing the number of active power semiconductor switches in the inverter section, a very low THD value, and simple control, as compared to the other configurations. Also, using MICs provides the ability to track the real maxima per module that improves the system performance. Thus, the whole system is a reliable choice for household and industrial applications. The simulation results illustrate that the proposed system configuration is able to deliver maximum power to the grid even under partial shading conditions.

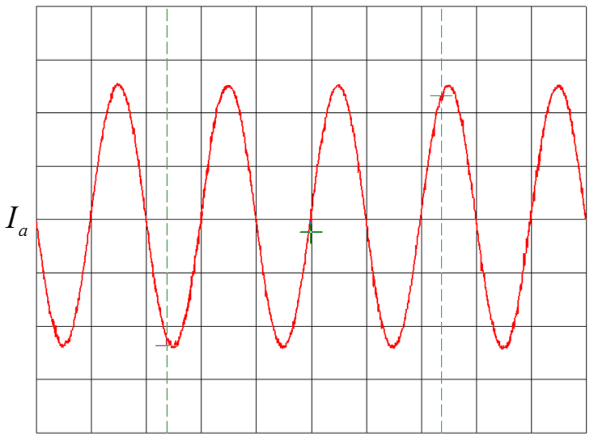


Fig. 13. Current of phase (a) injected to the grid.

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