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Italian Journal of Science & Engineering

Vol. 1, No. 3, October, 2017

Three-Phase Multistage System (DC-AC-DC-AC) for Connecting Solar Cells to the Grid

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Abstract

Inverter systems that feed electrical power from photovoltaic (PV) system into the grid must convert the direct current of the PV array into the alternating current of the grid. In many applications, it is important for a converter to be lightweight, highly reliable, input/output isolated, flexible and operable in a boost mode. These features can be achieved by using a High-Frequency inverter which involves an isolated DC-DC stage and DC-AC section, which provides AC output. This paper proposes a new three phase topology, based on multi stage converter and PV system in order to use in medium and high power applications. The Perturb and Observe (P&O) method is used for maximum power point tracking (MPPT) control of PV array. The switching control signals for three-phase inverter are provided by hysteresis control method. Also, the comparison between the proposed topology and traditional structures has been conducted and finally the simulation researches are performed in a closed-loop control system by MATLAB/Simulink software to verify the operation of the proposed structure. The results represent better performance of the introduced system over traditional topologies.

Keywords:

Photovoltaic (PV); Boost Inverter; Current-Source Inverter; High-Frequency Inverter; Maximum Power Point Tracking (MPPT).

Article History:

Received: 10 September 2017

Accepted: 02 November 2017

1- Introduction

As available amount of fossil fuels in the world is decreasing and on the other hand their negative effects on the environment are completely obvious to everyone, applications of the renewable energy sources are gaining more traction continuously. As a renewable-energy source, photovoltaic (PV) energy has achieved rapid growth, and grid-connected has become one of the major applications of solar energy [1]. These systems get connected to the main grid via power inverters. In applications where the power is 5 kW and higher, network is usually in the form of a three-phase system [2]. The principle structure of this system is shown in Figure 1. There are several inverter topologies in order to connect the DC input of the solar cells to the grid. Three fundamental structures of these topologies are as follows:

- PV system with a line-frequency transformer
- PV system without transformer
- PV system with a high-frequency (HF) transformer

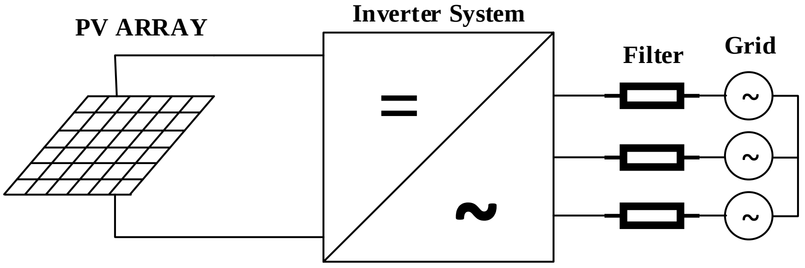

Figure 1. Principle structure of photovoltaic system

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DOI: http://dx.doi.org/10.28991/ijse-01116

1-1- PV system with a line-frequency transformer

The applied DC voltage is converted to a line frequency AC voltage via a full-bridge inverter [3]. This is then transmitted via a line frequency transformer and subsequently fed into the main grid [4]. Figure 2 shows a three-phase structure of this converter. The advantages and disadvantages of this topology can be listed as follows:
Benefits:

- Highly reliable due to having fewer components
- Safety through galvanic isolation of the DC and AC sides

Disadvantages:

- Low degree of efficiency due to high transformer losses
- Heavy weight and volume (e.g., due to 60 Hz transformer)

1-2- PV system without transformer

The existing DC voltage is converted to a square line frequency (for example 60 Hz) AC voltage via a full-bridge converter, then smoothed to a sinusoidal 60 Hz AC voltage via the chokes (L1, L2) and fed into the main grid [4-5]. The principle structure of this system is shown in Figure 3. In [5], the benefits and the drawbacks of this topology are expressed as follows:

Benefits:

- Compact and light because of the transformer
- Very high degree of efficiency (due to absence of transformer losses)

Disadvantages:

- Additional safety measures (residual current circuit breaker) required. In some countries, omitting galvanic isolation between the DC and AC sides is not permitted.
- Complicated lightning protection
- Not compatible with modules that must be grounded

Furthermore, this topology can be designed by two stages of boost DC-DC and DC-AC converters. As a result, this topology has some problems; First, DC and AC sides are not isolated. Second, the output voltage is limited (1:1 to 1:3).

1-3- PV system with a high-frequency (HF) transformer

The full-bridge topology generates a high-frequency square-wave signal, which is transmitted via the HF transformer. The bridge rectifiers convert the square-wave signal back to DC voltage. The second full-bridge inverter then generates an AC voltage, which is smoothed to a sinusoidal line frequency AC voltage and fed into the main grid [5-6]. The benefits of this topology can be written as follows:

- Compact and light, due to the small dimensions and less weight of HF transformer
- High degree of efficiency through reduction of transformer losses
- More degree of safety because of galvanic isolation between the DC and AC sides
- Suitable for all module technologies, as module grounding (positive and negative) is possible
- Achieving high voltage gain

Table 1. shows a summary of different characteristics of the mentioned topologies. Therefor it is obvious that PV system with a HF transformer called DC-AC-DC-AC converter is more preferential than another topologies due to its reliability, isolation and high output voltage range. The AC-AC converter consists of a high-frequency rectifier and an inverter as shown in Figure 4. Of course, the multistage power conversion is somewhat more expensive. The electrical isolation in the high-frequency link is essential because it allows easy array grounding flexibility in selecting array voltage range, array isolation from the utility in case of fault, and safety of personnel.

Table 1. different characteristics of the mentioned topologies

Features	System with a line-frequency transformer	System without transformer	System with a high-frequency transformer
Isolation	YES	NO	YES
Reliability	HIGH	LOW	HIGH
Weight	HIGH	LOW	LOW
Efficiency	LOW	HIGH	HIGH
Cost	High	Low	High

The main blocks of this topology include:

- DC-DC isolation stage
- DC-AC converter section

For DC-DC isolation stage, push-pull, half-bridge or full-bridge converter can be used.

In applications where the power is 1 kVA and higher, the full-bridge converter is the ideal choice because of the following reasons [5-7]:

- For a given input voltage, the voltage stress on the transistors is double in case of the push-pull topology than half-bridge and full-bridge converters.
- The center tapped primary in the push-pull topology limits the operation for a higher VA rating for the same core size when compared to the half-bridge and full-bridge converters.
- In order to prevent flux walking in the DC-DC stage, the current in both halves needs to be sensed and the duty cycle needs to be corrected accordingly.
- Output voltage in full-bridge is doubled compared to the half-bridge converter.

In the DC-AC section, any type of the inverters such as Voltage-Source Inverter (VSI), Current-Source Inverter (CSI) and Z-Source Inverter (ZSI) can be used [8-9].

2- Description of Selected Power Converter

2-1- Inverter System

As mentioned before, a DC-AC-DC-AC converter topology was selected to connect solar cells to the grid. This paper proposes a Current-Source Inverter (CSI) for the DC-AC section due to its operation in boost mode and growing up the flexibility of the converter. The use of input inductor of the DC-AC section leads to eliminate the large output filter to connect to the grid. The proposed topology is shown in the Figure 5. Basically, the DC array power is converted to 50-Hz or 60-Hz ac line power through an isolated high-frequency transformer link. The DC voltage of the photovoltaic array is at first converted to high-frequency AC by an inverter, which is then transformer-coupled and converted to AC line current through a DC link of an AC-AC converter.

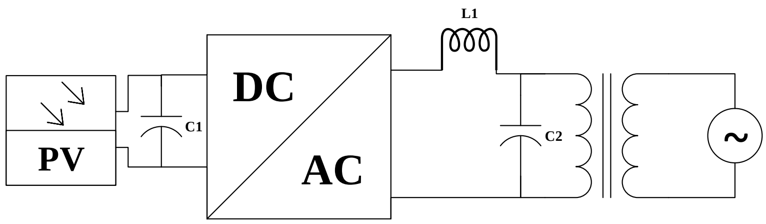

Figure 2. PV system with a line-frequency transformer

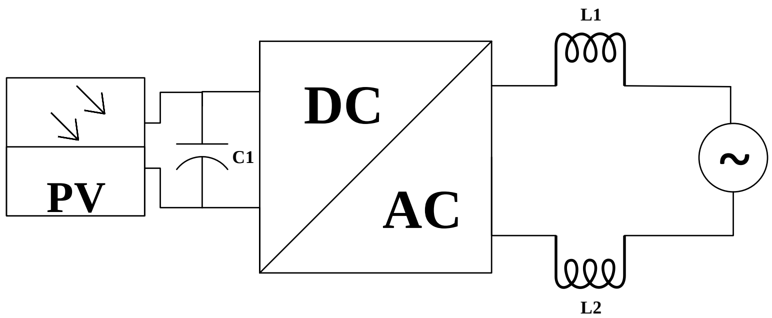

Figure 3. PV system without transformer

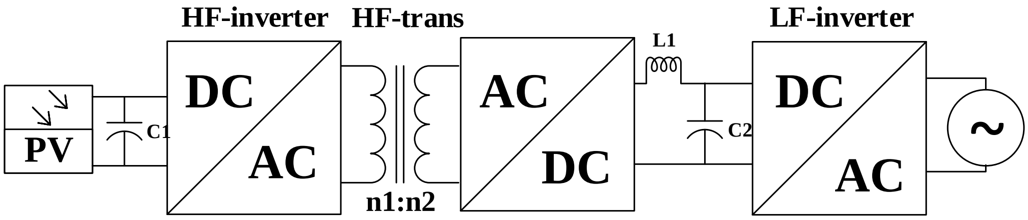

Figure 4. **PV system with a high-frequency (HF) transformer.**

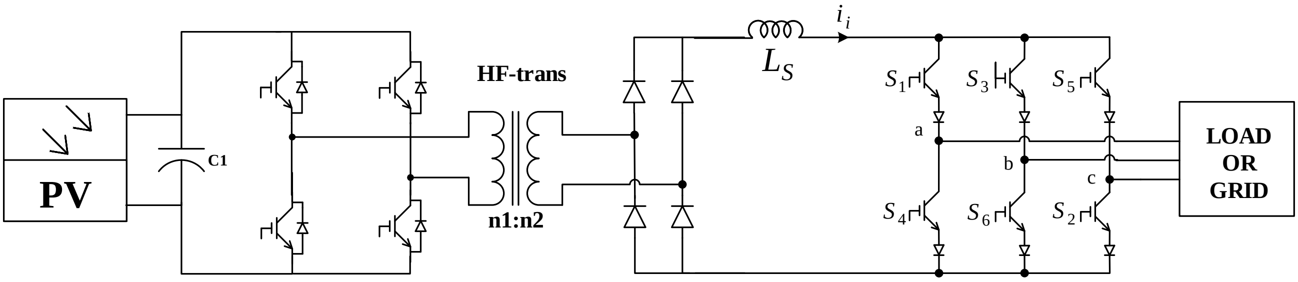

Figure 5. **The proposed topology with Current-Source Inverter.**

2-2- Control System

There are three steps for the control system of this converter:

- Maximum power point tracking control
- In-phase synchronization of the current with the utility Line-Voltage
- Creating the reference

First, it is essential to calculate the maximum output power of the PV array in different environmental conditions. According to the following equations, the output power of the solar cells depends on two environmental factors, light intensity and temperature [10].

$$I = I_{LG} - I_0\{\exp[\frac{q}{AKT}(V + I_A P_s) - 1\} \quad (1)$$

Where,

$$I_0 = I_{or}[\frac{T}{T_r}]^3 exp[\frac{qE_{G0}}{BK}\{\frac{1}{T_r} - \frac{1}{T}\}] \quad (2)$$

$$I_{LG} = [I_{scr} + K_1(T_c - 28)\, \lambda\, /100] \quad (3)$$

All the symbols in equation (1) to (3) can be defined as:

I	cell output current,
V	cell output voltage,
I_0	cell saturation current,
T	cell temperature in K,
K/q	Boltzmann's constant divided by electronic charge
T_C	cell temperature in °C,
K_1	short circuit current temperature coefficient at I_{SCR}
λ	cell illumination (mW/cm2),
I_{SCR}	cell sort circuit current at 28°C and 100 mW/cm^2 2.52A,
I_{LG}	light-generated current,
E_{GO}	band gap for silicon = 1.11 eV,
B	= A, ideality factors = 1.92,
Tr	reference temperature = 301.18 K,
Ior	saturation current at Tr = 19.9693 x 10-6,
R_S	series resistance = 0.001.

There are several ways to calculate the maximum power of solar cells. In this paper, perturb and observe (P&O) method is used to calculate the maximum power. This method has true MPPT and low implementation complexity. In addition, this algorithm does not need prior knowledge of PV panel characteristics. Besides, it shows good performance when the sun light does not change quickly [11]. This algorithm is shown in Figure 6.

In [12], it is demonstrated that the algorithm also works when instantaneous (instead of average) PV array voltage and current are used, as long as sampling occurs only once in each switching cycle. The next step is to obtain the unity power factor which can be achieved by in-phase synchronization of the current with the utility line-voltage. Generating the reference current by control of inverter switching with hysteresis method is the last step [13]. A block diagram of the control system is shown in Figure 7.

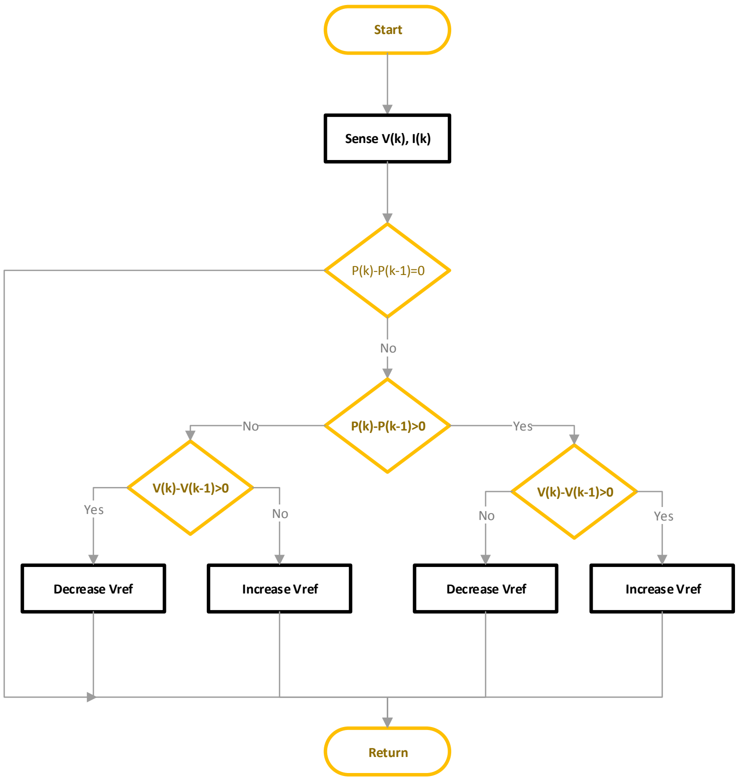

Figure 6. **Perturb and Observe (P&O) algorithm**

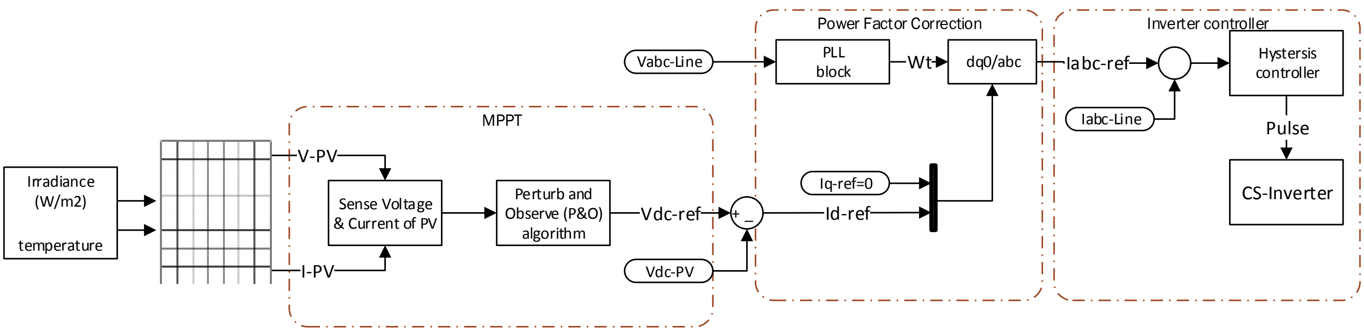

Figure 7. **Block diagram of control system**

3- Simulation Results

A Three-phase multistage system (DC-AC-DC-AC) with HF-transformer and Current-Source inverter rated at 240kW/480V is simulated using Simulink/MATLAB. The structure parameters are presented in Table II. Simulations are performed to verify the performance of the proposed multistage converter. In the simulations, the 240kW resistive load is simultaneously connected to the grid and PV system. Figure 8 shows the volt-ampere and power curves of the used PV array.

As mentioned in section II, the output power of the solar cells depends on temperature and irradiance. So, it is considered that the test temperature is set on 45 $°C$ and the irradiance varies based on the curve that is shown in Figure 9. The maximum amount of the irradiance is $1000\ W/m^2$ before $t = 0.4\ s$. At $t = 0.4\ s$ the irradiance starts to decrease by 200 W/m^2 and the analogous output power of the PV array decreases to 48 kW. At $t = 1\ s$, the irradiance returns to its maximum value and the output power reaches to the point of 240 kW.

Figure 10. shows the waveforms of the PV array. Figure 10a. is the PV-arrays output voltage and Figure 10 (b) is the PV-arrays output current. Also, Figure 10a. exhibits very small voltage fluctuations around the maximum power point. As it can be seen from Figure 10b, the PV-arrays output current alters between 100 to 500 A. Figure 10 (c) shows the PV-arrays output power waveform and its variation between 48 to 240 kW due to irradiation changes.

Table 2. Simulation parameters of the multistage converter with current source inverter

Simulation enviroment	Simulink
Temperature	45 °c
Irradiance	200 - 1000 W/m^2
Number of panels in parallel and series	88×7
Rated power of each panel	400 (W)
Input nominal voltage	480 (v)
Voltage range	465 (v) - 485 (v)
Maximum output power of the PV system	240 (kW)
Rated ac output voltage of converter	480 (v)
Input inductor of CSI	300 µH
Line frequency	60 Hz
Line-to-Line grid voltage (rms)	20 (kv)
Power factor	1
Inverter control method	Hystersis
Switching Frequency	10 - 16 kHz

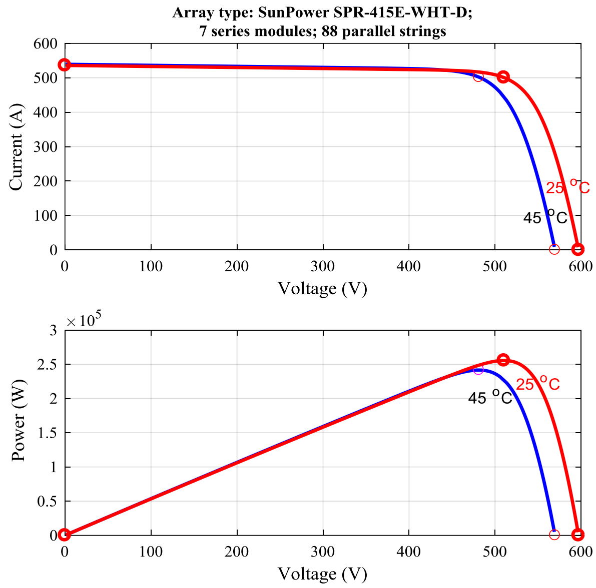

Figure 8. Volt-ampere curve and characteristic PV array power curve

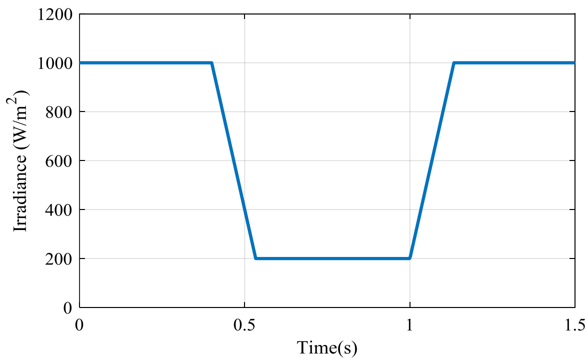

Figure 9. Changes of irradiance

Figure 11. shows the generated reference voltage for achieving the maximum power point and the emulated output voltage of the solar cells. Correspondingly Figure 12 shows the results for the generated reference current in dq0 frame. The output power of AC-side is shown in Figure 13. This figure shows the equality of the output power of the solar cells and delivered power to the load. The converter is connected to the grid using a boost transformer (480v/20kv).

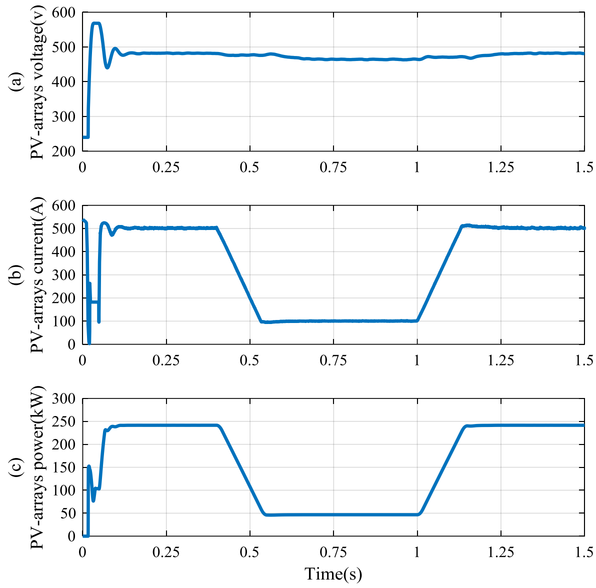

Figure 10. Simulation waveforms of PV-arrays. (a) Output voltage (v); (b) Output current (A); (c) Output power (kW)

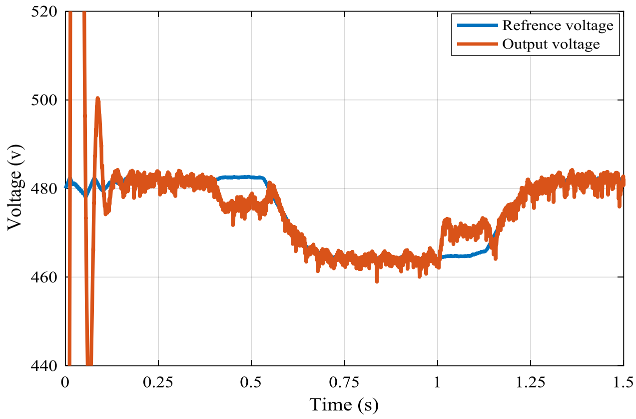

Figure 11. Following the reference voltage by output voltage.

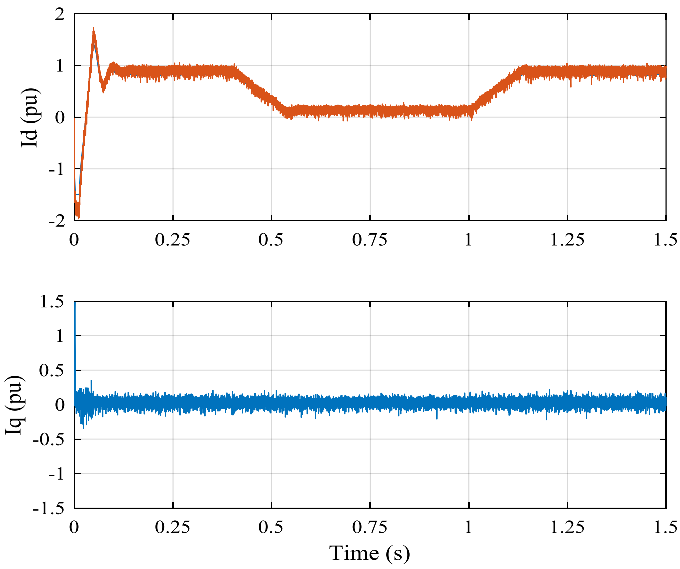

Figure 12. Per-unit currents in dq0 reference frame

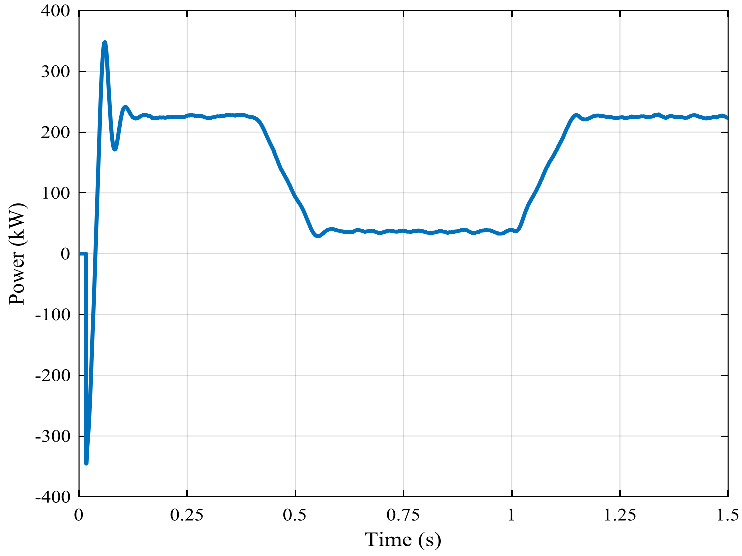

Figure 13. Output power at AC side

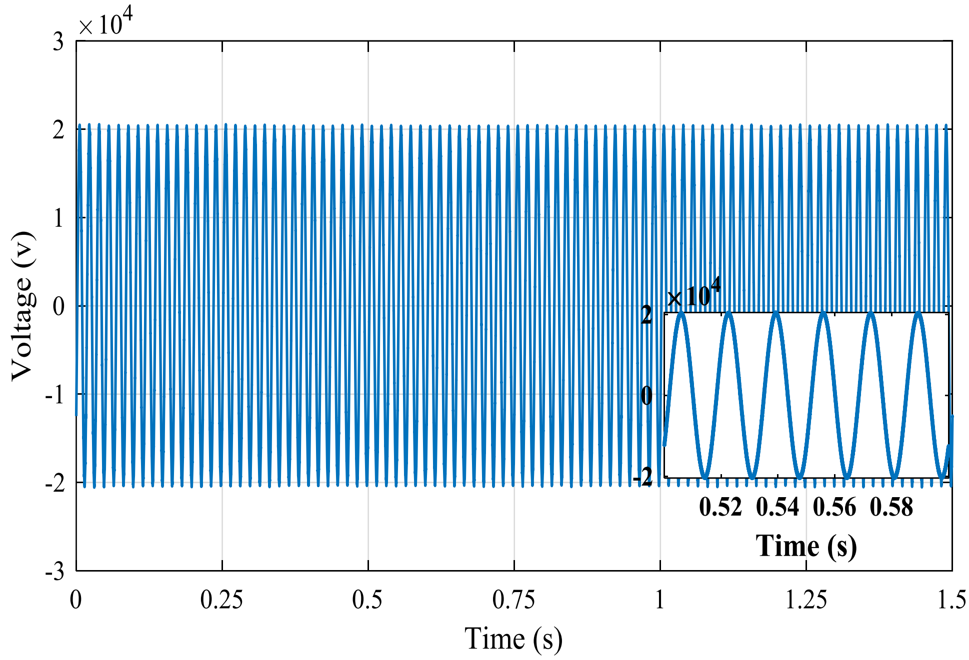

Figure 14. Voltage of connection point to the grid

Figure 14. shows the voltage of the connection point to the grid. The output current made by hysteresis control method is shown in Figure 15. The results show a desired waveform for the output current.

Figure 16a and 16b. show the Total Harmonic Distortion (THD) of the output voltage and output current respectively. The results show the good performance of the proposed topology in condition without output filter.

4- Conclusion

This paper has proposed a new three phase multistage converter for medium or high power applications supplied by PV systems. The comparison between the proposed topology and traditional structures was done and the analytical results have shown the superiority of the proposed topology. The MPPT control of PV arrays is conducted by P&O method and CSIs' switching signals are captured by hysteresis control method. Simulation results have verified that the proposed converter can achieve high efficiency over a wide load range.

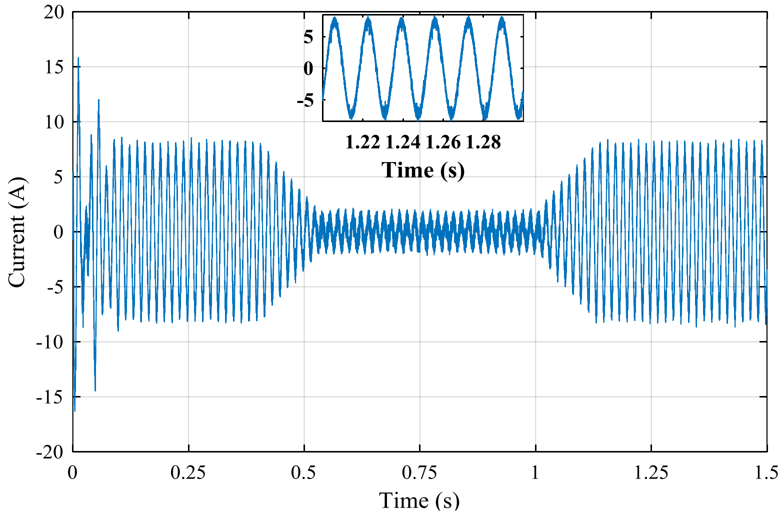

Figure 15. Current of connection point to the grid

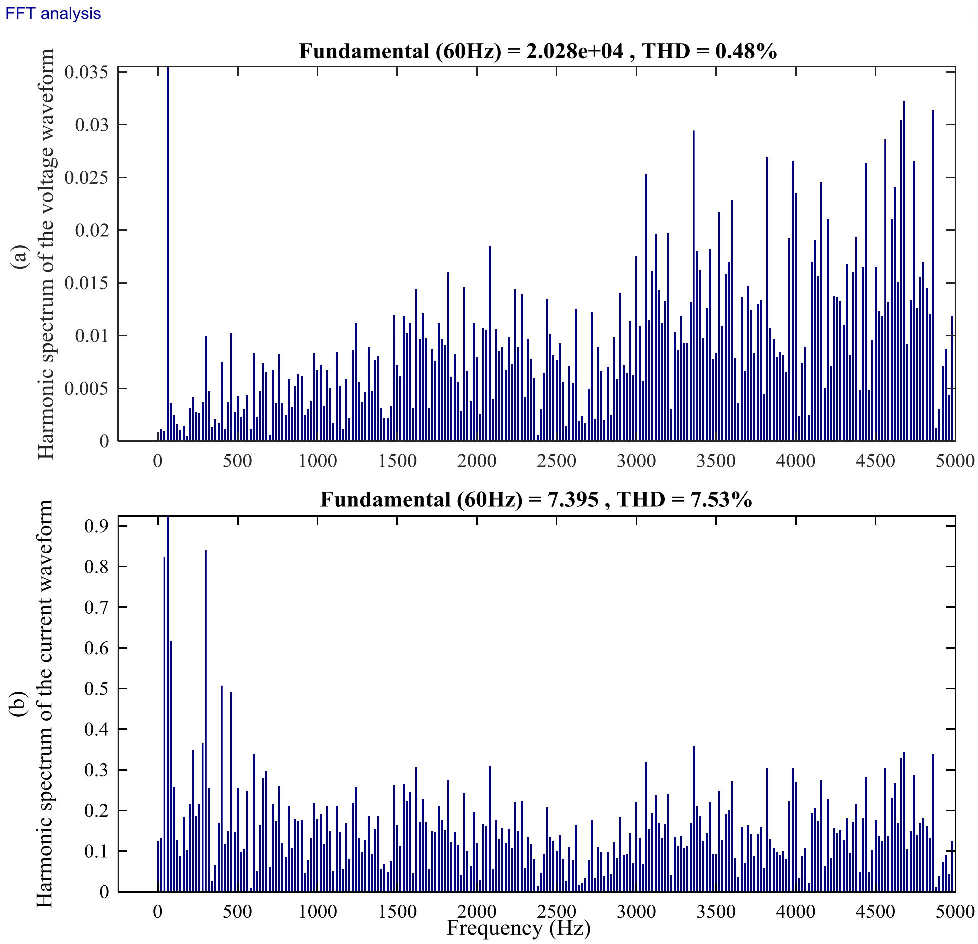

Figure 16. The Total Harmonic Distortion (THD) of output waveforms

5- References

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