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A Novel Grid Connected Photovoltaic System

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ABSTRACT: In this paper, a novel grid connected photovoltaic system is proposed which can function as an Active Power Filter (APF) with Maximum Power Point Tracking (MPPT). Filter reference current is derived using Fourier Transform. Considering 33% reduction in inverter switches, cost of the gridconnect photovoltaic power plant can be reduced considerably. Using this approach, it is also possible to compensate for reactive and harmonic components of the local loads; moreover it can inject generated active power into grid at maximum power point of the photovoltaic cells. According to this, during daytime, the proposed system injects active power to the grid and at the same time compensates for the reactive power of the load. When there is no sunlight, the inverter only compensates local loads. Considering cost reduction, such capabilities may result in more application of the grid connected photovoltaic systems. Main novelty of the proposed system is simultaneous APF and MPPT functioning using single DC/AC converter. In fact, extra DC-DC converter is not required in the proposed system for MPPT. In order to verify the performance of the proposed method, some simulation is done using MATLAB/Simulink software. Also, some experimental results are presented for practical verification of the proposed grid connected inverter.

***Keywords*:** reactive and harmonic compensation, active power filter, Fourier Transform, grid connected photovoltaic, B_4 inverter, cost reduction, MPPT and DC-DC converter elimination

INTRODUCTION

Power electronics converters application in industrial and commercial utilizations have been resulted in the problem of drawing non-sinusoidal current the grid [1]. These power electronic devices, together with the application of non-linear controllers, inject harmonics to the power system and presence of these harmonics may result in increased loss. Different equipment can be used to eliminate harmonics in power networks e.g. active and passive filters, shunt, series and hybrid compensators. Shunt Active Power Filter (SAPF) is used more widely considering better performance and its reliability [2]. In SAPFs, principal of operation is based on appropriate harmonic current injection at the point of common coupling. Hence, load required harmonic currents is supplied from SAPF instead of the grid. Therefore, grid current will be purely sinusoidal. In SAPFs, Load compensation depends on three important factors: accurate measurement of the load current and voltage, calculation of the reference current and finally appropriate switching strategy [3]-[4]. Reference current may be calculated in three different domains. First approach is time-domain method. For example in [5], a d-q transformation is proposed for reference currents calculations in SAPF which is based on the in instantaneous reactive power theory. The compensation currents are extracted using p-q transformation. However, application of these transformations may cause complexity in implementation of shunt active power filters. In 1996 Peng et al. [6] have presented a general theory

of the instantaneous reactive power in abc coordinates. Although this method doesn't require consecutively transformation, but still extra calculations should be done for generation of the instantaneous reactive power vector. In fact, time-domain calculations are based on some measurements and transformations of the three phase quantities [7]. The second method is frequency-domain technique such as: fast Fourier transform [8], discrete Fourier transform [9] and recursive discrete Fourier transform [10]. It should be noted that, main advantage of the time-domain methods, compared with the frequency-domain methods is its fast response. On the other side, frequency-domain methods provide accurate individual and multiple detection of the load harmonic current [11]. The third approach is based on time-frequency domain. Wavelet Transform (WT) is a powerful signal processing tool for computing time-frequency representation of power signals [12]. In [13], in order to obtain the reference current for SAPF based on fundamental positive sequence, discrete wavelet transform is used.
Among different switching methods, current controllers are more popular in grid connected photovoltaic systems due to: a) Since utility is a fixed voltage source, in order to control power flow between photovoltaic systems and the utility, it is only enough to control the current flow [14], b) If the voltage control method is used, small phase error in the output voltage of the inverter may cause very large power error [15].

Various current control techniques are proposed for grid connected inverters such as Hysteresis Current Control
(HCC) [16]-[17], Adaptive-Fuzzy Hysteresis Current Control [18], Delta Modulation Control [19]-[20] and CarrierBased PWM Control [21]-[22]. The performance index for comparison of different methods is THD value of the source currents after compensation.
The requirements for generation of the clean energy resulted in application of the renewable energy resources such as wind and solar systems. It should be noted that, invention of the low-cost thin film panels, may increase application of photovoltaic power plants in the future [23]. There are some advantages in motivation toward grid-connected photovoltaic system:

1) Cost reduction
2) Reactive and harmonic compensation of the load.
3) Elimination of the backup battery

In order to improve performance of the grid connected PV system, it is possible to compensate local loads using photovoltaic power plants [24]. A controller that combines the photovoltaic grid-connected generation and power quality managements is proposed in [25]. Also in [26], an efficient method for power factor correction of the local loads with grid connected photovoltaic systems has been introduced. In [27], a simple control approach has been proposed for PV system which is capable of local load compensation. A model reference based adaptive controller for SAPFs is present in [28] to cancel the harmonic/reactive components in the line current. Also in [29], another method for combination of the SAPF with photovoltaic system is proposed. In this case, grid connected inverter can inject active power into grid and compensates load. In [14], instead of the traditional threephase inverters, a novel inverter is used which can reduce total cost of the system considerably.
Primary version of this research is published by author of this paper in [30]. In this paper, some modifications are considered for improvement of the system capability. Main objectives of this paper which are different from previously published papers can be summarized as:

1- MPPT capability is added to the control system. in fact, in the proposed system extra DC-DC converter is not required and APF and MPPT functions are accomplished using a single DC/AC converter.
2- For practical investigation of the presented system, some experimental results are presented.

In this paper, a novel method for calculation of the reference current in low-cost grid connected PV system with active power filtering capability is proposed. In the following, at first SAPFs are reviewed

in Section II. Then in the Section III, reference current calculation by Fourier series expansion is developed. Finally, the accuracy of proposed control strategy has been verified using the MATLAB / Simulink software.

MATERIAL AND METHODS

low cost grid connected pv system

The main idea of this paper is control of the proposed system for simultaneous APF and MPPT functions. In APF, the reference current is calculated to eliminate harmonic and reactive components in point of common coupling. Also the system injects active power of the photovoltaic panels into grid at maximum power point of the photovoltaic cells. The structure of low-cost grid connected photovoltaic system is illustrated in Fig.1. It is implemented using a B4 three-phase DC to AC inverter which is connected to the DC-link capacitors and photovoltaic cells in the input port of the inverter. In order to analyze performance of the proposed system as a harmonic filter, a three phase uncontrolled rectifier is connected to the inverter as a nonlinear local load at the point of common coupling.

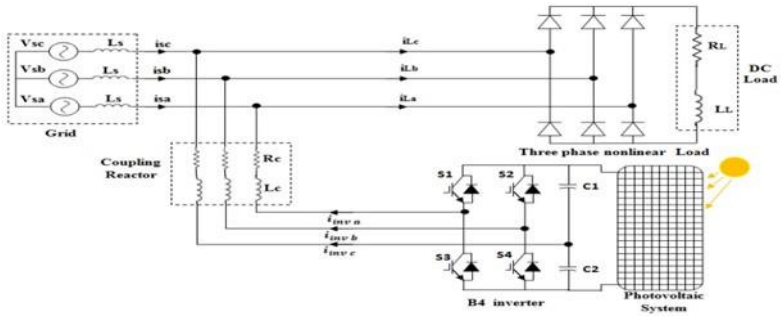


Figure 1. Proposed grid connected PV system using B4 inverter

Calculation of the reference current [30]

Reference compensation current is determined mainly using the information about both the fundamental and the harmonic contents of the measured load current. This method is based on time-domain analysis. In this paper, Fourier series expansion method is used to extract magnitude of the fundamental component of the load current.

In this approach, on-line samples of the load current and voltage is used in the Fourier series expansion. Load current can be written as follows: $i_L \quad t \quad i_{sin} \quad t \quad i_h \quad t$ (1)

where i_{sin} , i_h are ideal current of the source and harmonic components respectively. Fundamental component magnitude of the load current is:

$$i\ (t)L1 \quad \alpha 1| \quad b| \ \sqrt{\qquad} \qquad 1 \qquad (2)$$

where:

$$a_1 \quad \frac{2}{T} \int_t^{t+T} i\ (t)\cos_L \quad \omega t\ dt \qquad (3)$$

$$b_1 \quad \frac{2}{T} \int_t^{t+T} i\ (t)\sin(_L \omega t)dt \qquad (4)$$

$$\frac{1}{T} \qquad (5)\ f_1$$

In (5), f_1 is the fundamental frequency. Calculation process of the reference current is shown in Fig 2. For calculating of the ideal source current, equation (2) will be multiplied to a unit sinusoidal waveform which is in phase with network voltage. To obtain such a waveform, value of the network instantaneous voltage is divided to its peak voltage:

$$v\,t^{L}(\,) \qquad (6)\ v_{\text{unit}} \quad t$$

$$\frac{vL1(\,)t}{}$$

where $v_L(t)$ is the instantaneous load voltage.

$$v\,(\,)_{L1}\,t \quad \alpha_1 \quad b \quad \sqrt{\qquad} \quad {}_1 \qquad 7$$

Considering (2), (6), desired current of the source can be calculated as follows:

$$(8)\ i_{\sin} \quad i\ (t)_{L1} \quad v_{\text{unit}} \quad t \quad i\ (t)_{L1} \quad \frac{v\,t^{L}(\,)}{vL1(\,)t}$$

It is clear that the reference current of the grid connected inverter can be calculated as:

$$(9)\ i_{ref1}^{*} \quad t \quad i_h \quad \frac{i_L \quad t}{vL1(\,)t} \quad i^{L1}(\,)t \quad v_L \quad t$$

It is well-known that distance of switching losses in inverter result in reduction of the capacitor voltage. To solve this problem, PI controllers is used for capacitor total voltage regulation and voltage balance between capacitors. Considering voltage error $v_{DC} \quad v^{*}_{DC} \quad v_{DC}$:

$$\frac{dt}{} \qquad (10)\ v^{*}\ v \quad k \quad \sim \ {}_{k}\sim x_{DC} \quad k_p\,v_{DC} \quad k_I \quad v_{DC}$$

where $_{DC}$, $_{DC}$, $_{p}$ and $_{I}$ are desired DC-link voltage, total DC-link voltage, proportional and integral PI gains respectively. Transfer function of the PI compensator is:

$$G_v \quad S \quad v_{\sim}\,DC \quad {}_s \qquad \frac{kI}{s \quad x^{DC}\,k_p k^{p}} \qquad (11)$$

Thus, the closed-loop transfer function can be written as follows:

$$v\frac{x^{DC}}{}{}^{*}DC \quad \frac{\overline{2}}{2\omega_n\,s2 \quad s2 \quad \omega\omega_n\,n \quad \omega 2n} \qquad (12)$$

In equation (11) and (12):

$$kp \quad 2 \quad n\,DCC \quad kI \quad \omega n2CDC \qquad (13)$$

In order to control voltage of the DC link capacitors designed controller should be considered. so: $i^{*}reftotal\ a \quad iref\ a^{*}\ 1 \quad xDC\sin(\quad t)$ (14)

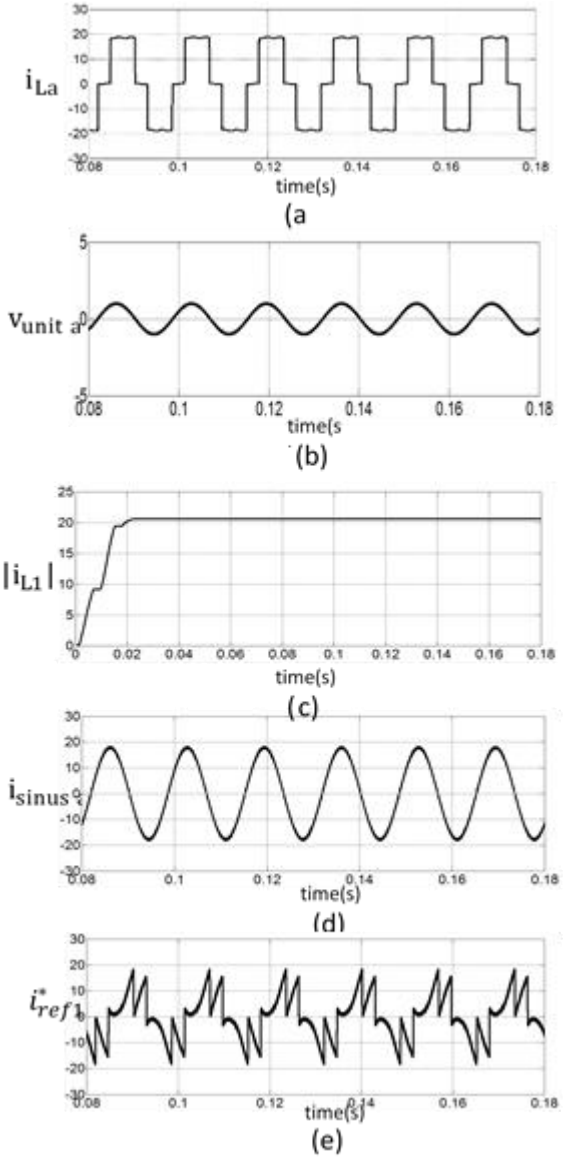


Figure 2. Calculation of the reference current: (a) Load current (b) Amplitude of the load current (c) Unit sinusoidal voltage in phase with the grid voltage (d) Desired current of the source (e) reference current (i^*_{refl})

$$i^*_{reftotal\ b} \quad i_{ref\ b}^* 1 \quad x_{DC}\sin(\quad t \quad 120) \qquad (15)$$

After adjusting total voltage of the capacitor, another PI controller should be used for voltage balancing: ~

$$v_{DC1} \quad v^*_{DC1} \quad v_{DC1} \qquad (16)$$

$$\sim \ \sim x_{DC1} \quad k_{p1} v_{DC1} \quad k_{I1} \quad v_{DC1}$$

dt (17) v^*_{DC1} v^*_{DC2}

(18)

where v^{DC1}, k^{p1} and k^{I1} are voltage of k^{I1} , proportional and integral PI gains respectively. Hence final reference current can be written as:

$$i^*_{reftotal\ a} \quad i_{ref\ a}^* 1 \quad x_{DC1} \sin \quad t \quad x_{DC1}$$

(19) $i^*_{reftotal\ b} \quad i_{ref\ b}^* 1 \quad x_{DC1} \sin \quad t$

$120 \quad x_{DC1}$ (20)

MPPT in the proposed controller

Considering environmental conditions maximum generate power by photovoltaic cells, is changed. Also, there is only one point where power generation of PV is maximum. Beside reactive and harmonic compensation, the control strategy of the grid connected photovoltaic systems should inject active power generated by the photovoltaic arrays into the grid. In this paper, the Perturb and Observe method is combined with proposed system which is widely used approach to MPPT. As the name suggests, this method works by perturbing the system by increasing or decreasing the PV module operating voltage and observing its impact on the output power supplied by the module. As shown by the flow chart in Figure 3, PV system controller change PV module output with a small step in each control cycle. The step size is generally fixed and it can be increased or decreased. Both PV module output voltage and output current can be the control object, so this process is called “perturbation”. Then, by comparing PV array output power of the cycles before and after the perturbation, this method determines the maximum power point.

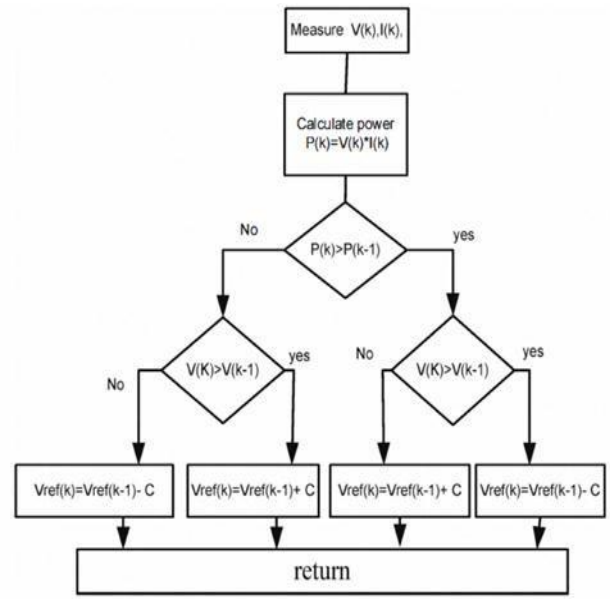


Figure 3. PI control loop for regulation of the capacitors voltage

If the power output is increased at a particular cycle, then according to this method, the system controller will change the step in the same direction as the previous cycle and checks for further increase in power of PV module. While if the output power observed is decreased, then the system controller change the step in direction opposite to the previous cycle. In this way, the actual operating point of PV module can move closer to the maximum power point, and finally in steady state, oscillates around the maximum power point in a very small area. This causes a power loss which depends on the step width of a single perturbation. If the step width is large, the MPPT algorithm will be responding quickly to sudden changes in operating conditions with the tradeoff of increased losses under stable or slowly changing conditions. If the step width is very small the losses under stable or slowly changing conditions will be reduced, but the system will be only able to respond very slowly to rapid changes in temperature or insolation. The value for the ideal step width is system dependent and needs to be determined experimentally.

According to the maximum power point of photovoltaic cells, total active power which should be injected into grid could be determined as follows [31]:

$$P_m \quad V I_{m\,m} \qquad \frac{P_m}{V_m} \qquad I_m \tag{21}$$

In the above equation V_m and I_m are voltage and current of photovoltaic cell in maximum power point and these both could be measured/calculated easily[32]. In this case, reference current is calculated as follows: $i_{refpv\ a}^{*} \quad i_{reftotal\ a}^{*} \quad I_m \sin(\ t)$ (22)

$$iref\ pvb^{*} \ , \qquad ireftotal\ b^{*} \qquad Im \sin(\ t \ 120) \tag{23}$$

where I_m is peak value of the injected active power. Output power of the PV panel in different conditions is illustrated in Fig.4 versus output voltage.

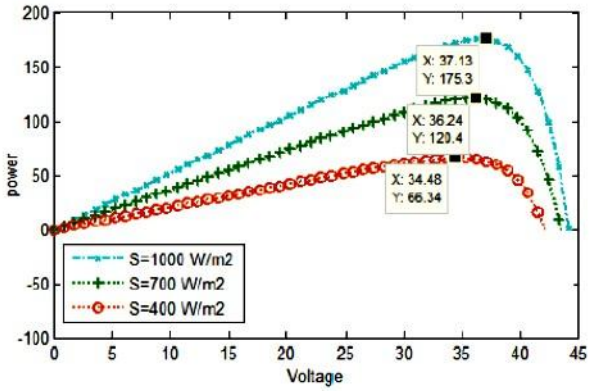


Figure 4. Output power of the PV panel in different conditions

RESULTS AND DISCUSSION

simulation and experimental results

In this section, the control scheme for three-phase shunt active power is shown in Fig. 5. In order to investigate accuracy of the proposed control strategy, grid connected photovoltaic system is simulated according to developed equations with MATLAB / Simulink. simulation the parameters are listed in Table 1.

THD values of the source current before and after compensation are shown in Fig.6. It can be seen that THD is reduced considerably. (from 30.17% to 1.79% after compensating)

Operation of the proposed low cost grid connected PV system is illustrated in Fig.7 in more detail. It is clear that, before and after compensation, it is completely sinusoidal. Also it can be seen that during active power injection, source current and voltage phase differ 180º.

In Fig.8, output voltage versus output current of the converter in different compensating modes are illustrated during practical tests. Also response of the MPPT system is shown in Fig.9 for different conditions. It is clear that the proposed system has good dynamic and steady-state behavior.

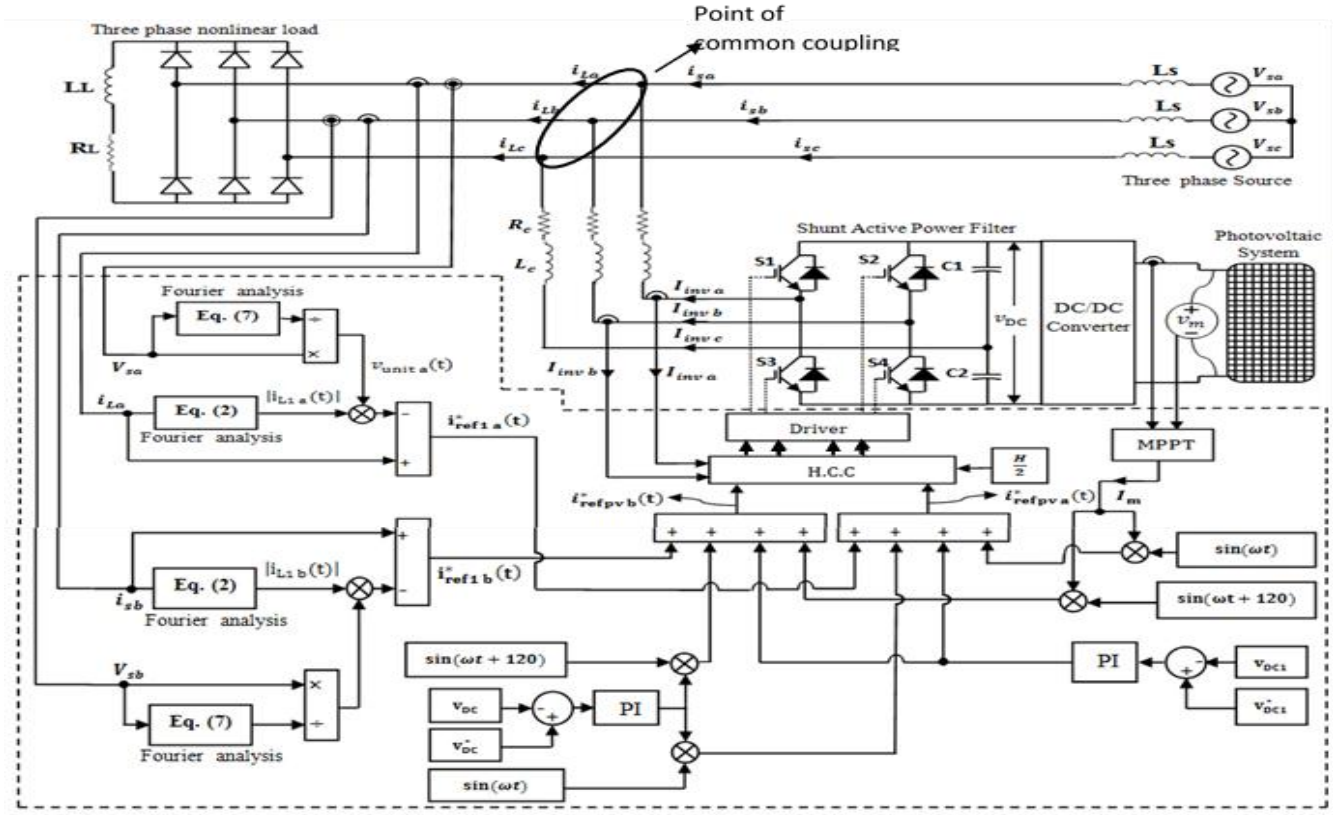


Figure 5. Proposed Controller

Table 1.simulation parameters

Components	Table Column Head	
	Part name/ Manufacturer	Rating values
VS(Peak	Phase Voltage	120V
f	Frequency	60Hz
L_S	Line Impedance	0.006mH
L_L , R_L	DC-load	10mH ,6Ω
L_C	Parameters	1.2mH
I_m	Coupling Reactor	35A
v_{DC}	Maximum power current Nominal	800V
C1 ,C2	DC link voltage DC-link capacitors	2000µF

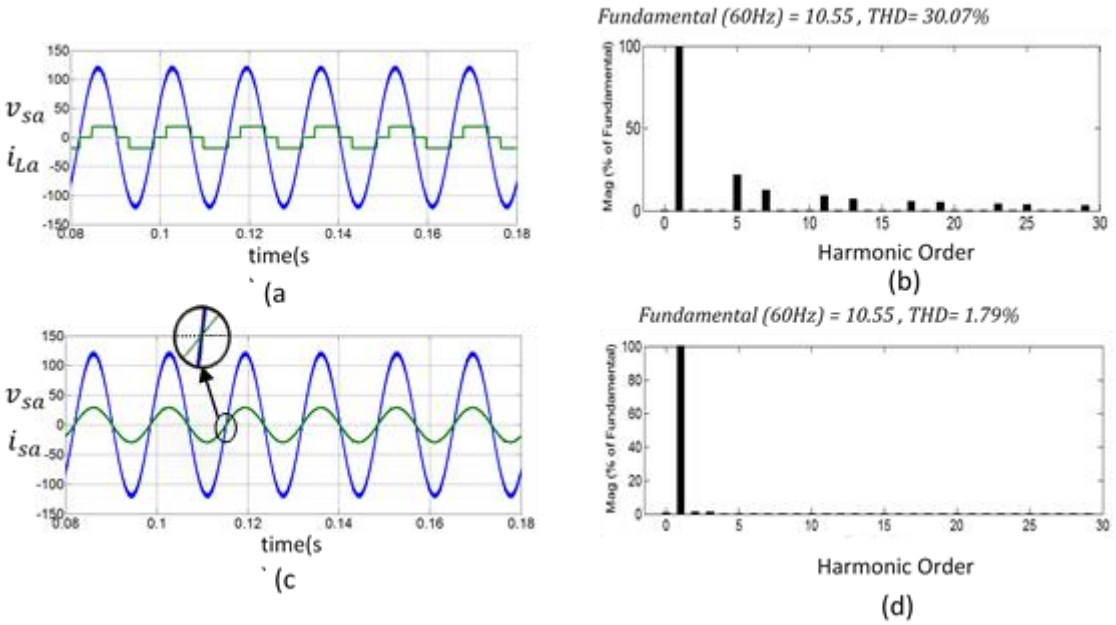


Figure 6: (a) Load voltage and current (phase a) (b)THD value of the source current before compensation (phase a) (c) source current and load voltage (phase a) (d) THD value of the source current after compensation (phase a)

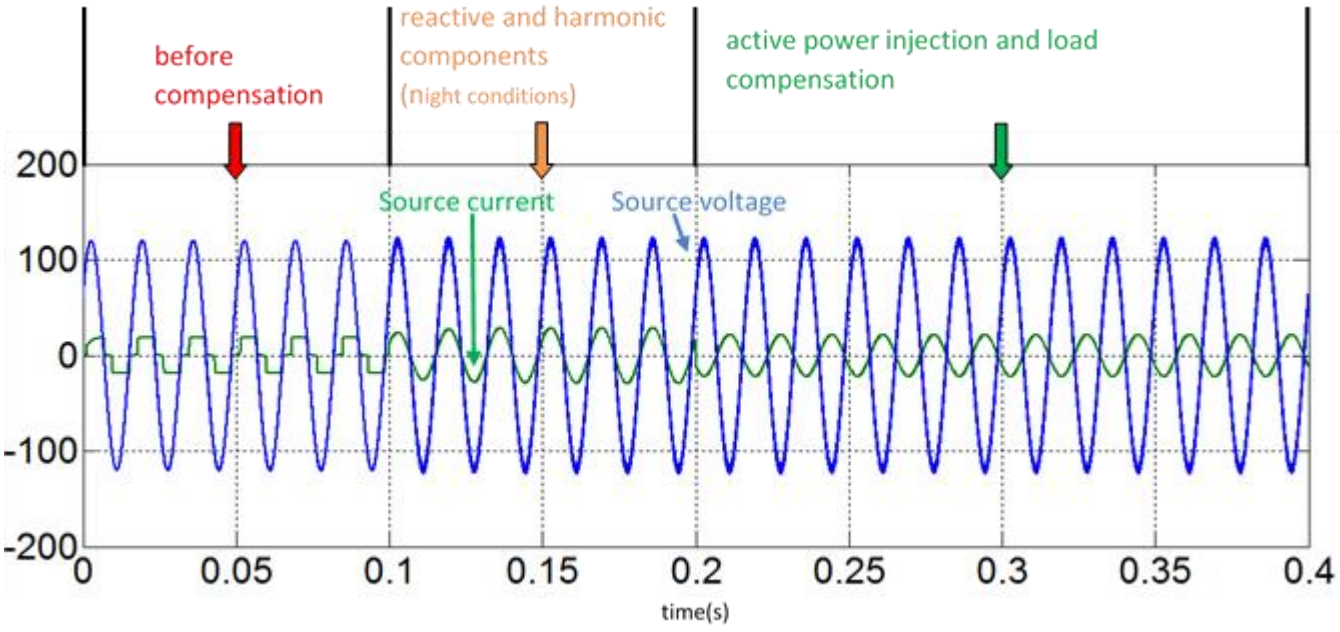


Figure 7. source voltage and current (phase a)

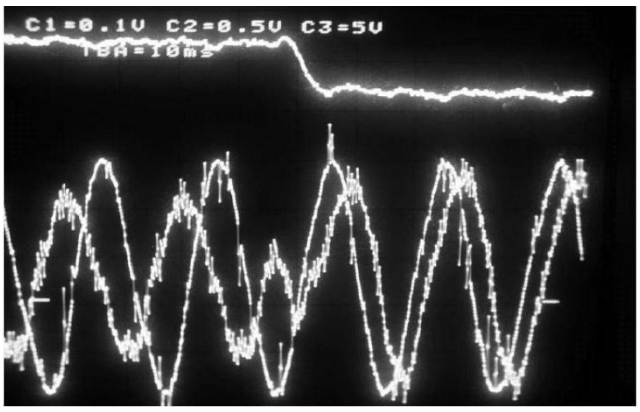


Figure 8. Experimental result, output voltage versus output current of the converter in different compensating modes

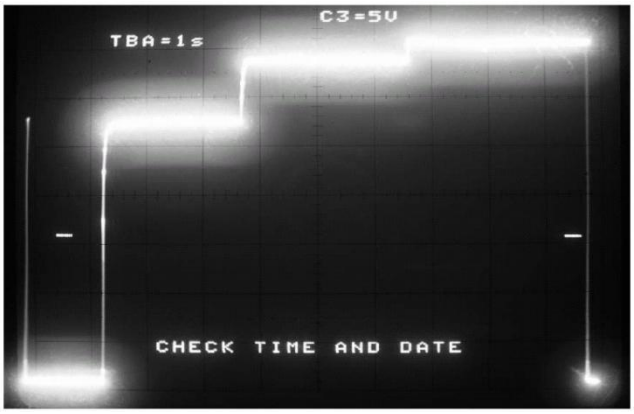


Figure 9. Response of the MPPT controller in different conditions

CONCLUSION

In this paper, a novel method for grid connection of the PV systems is proposed with Active Power Filter (APF) and Maximum Power Point Tracking (MPPT). Filter reference current is derived using Fourier Transform. Considering 33% reduction in inverter switches, cost of the grid-connect photovoltaic power plant can be reduced considerably. Designed system can inject generated power of the solar cells in to grid at maximum power point, compensates reactive power of the load and eliminates load harmonic components all at the same time. Accuracy and effectives of the proposed system is verified using MATLAB/Simulink software. Also, some experimental results are added to verify practical behavior of the converter.

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