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Study Total Harmonic Distortion in PI-Controlled Single-Stage Grid-Connected Photovoltaic Systems Under Non-linear Load

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Abstract
Concerns about power quality, particularly effects of Total Harmonic Distortion (THD) caused by non-linear loads, have increased due to the rapid integration of solar energy into the power grid. This paper presents a detailed study of THD content in grid-connected single-stage photovoltaic (PV) systems using proportional-integral (PI) controllers. Single-stage systems are preferred due to their simplicity and efficiency. The LCL filter is designed to attenuate the harmonic content. This paper employs a PI current-controlled strategy in conjunction with an LCL filter to maintain grid power quality. The system's performance is assessed under non-linear loading conditions with simulation-based modelling in MATLAB/Simulink for a single-stage grid-connected photovoltaic system.

Keywords: Power Quality, Total Harmonic Distortion (THD), PI Controller, Single Stage Grid-Connected Photovoltaic System

1. Introduction

A thorough analysis of power quality has become necessary due to the growing use of grid-tied solar systems worldwide, especially as the growth of non-linear loads introduces notable current harmonics [1, 2]. By causing the grid current to deviate from an ideal sinusoidal waveform, these harmonic components degrade power quality and could lead to equipment overheating and reduced system efficiency [3]. Single-stage topologies provide a simpler & more straightforward architecture for energy conversion in this situation, and proportional-integral controllers are commonly used to manage the output current and keep Total Harmonic Distortion within the bounds required by IEEE 519 standards [4-6]. Using thorough MATLAB/Simulink modelling, study assesses how well these PI-regulated structures mitigate harmonic distortion brought on by non-linear loading circumstances [7]. The study illustrates the crucial importance of controller parameters in guaranteeing steady grid current injection and harmonic suppression by examining the voltage source inverter's dynamic response under various non-linear load profiles [8,9]. Additionally, our simulation-based investigation how traditional control systems function poorly when exposed to non-linear current distortions and changing irradiance [10]. This thorough evaluation demonstrates that maintaining stability of the DC-link voltage during transient load transitions requires maximizing the gain margins of the PI regulator [11, 12]. Additionally, the synchronous reference frame of these controllers efficiently reduces current harmonics, guaranteeing that grid-injected power complies with strict regulations even in the face of severe load-induced disruptions [13]. In addition to maximizing active power from the photovoltaic array, these control techniques enable accurate grid current conditioning, which efficiently compensates for non-linear load demands [14]. The system shows an improved ability to suppress order components injected by rectifiers and power electronics by carefully adjusting the proportional and integral gains, confirming the appropriateness of PI control for preserving signal integrity [15]. The study also shows that minimizing error during harmonic compensation requires exact synchronization between the grid voltage and the PI-regulated current loop [16, 17]. Additionally, the use of improved gains guarantees accurate harmonic mitigation and a decrease in transient overshoot, enabling reliable system performance under varying load profiles [18]. Furthermore, the simulated performance metrics show that IEEE 519 compliance under various operational conditions depends critically on the tuning of these control loops [19].

Previous research has extensively examined the performance of single-phase grid-connected PV systems, often emphasizing the operational efficiency of single-stage topologies over complex double-stage alternatives [20, 21]. The total harmonic distortion metric is widely used in existing research to assess system power quality, emphasizing the difficulty of preserving low harmonic levels when integrating non-linear loads [22, 23]. While proportional-resonant and predictive methods have been investigated in previous control efforts to reduce these distortions [24]. One crucial area for optimization is the resilience of traditional PI controllers under sudden non-linear loading [25]. Despite being extensively documented, traditional PI tuning techniques frequently have limited tracking capabilities and slow dynamic reactions when exposed to abrupt load changes [26, 27]. In order to improve transient stability and successfully suppress harmonic injection, recent studies have suggested hybridizing PI frameworks with fuzzy logic or sophisticated synchronization techniques [28]. Additionally, research has shown that decoupling voltage and current loops is essential for peak performance [29], the effect of particular non-linear load profiles on the harmonic profile of single-stage inverters is still not well-defined. [30].

This study examines the performance of a PI-controlled single-stage grid-connected PV system in nonlinear load conditions. The proposed system is modeled in MATLAB/Simulink, and simulation results are analyzed.

2. System Description

For enhanced power quality under nonlinear load conditions, the suggested system is a single-stage, three-phase, grid-connected photovoltaic (PV) system that is PI-controlled and combined with an LCL filter. A PV array, a DC-link capacitor, a three-phase voltage source inverter (VSI), an LCL filter, a utility grid, a nonlinear load connected at the point of common coupling (PCC), a phase-locked loop (PLL), Perturb and Observe (P and O) a maximum power point tracking (MPPT) algorithm, and a PI-based current control scheme compose the entire system.

Solar radiation is transformed into DC electrical power by the PV array. The suggested setup uses a single-stage power conversion, instead of traditional two-stage PV systems, where the PV array is directly connected to the VSI via a DC-link capacitor. By eliminating the intermediary DC–DC converter, this system improves conversion productivity while lowering switching losses, system complication, setting up costs, and maintenance requirements. As an energy buffer, the DC-link capacitor reduces voltage swings brought on by abrupt change in solar irradiation and load demand.

An (P and O) MPPT algorithm always identifies the operating point corresponding to the maximum available solar power in order to maximize energy extraction from the PV array. In the synchronous reference frame (dq-frame), the generated reference power is transformed into reference grid currents. A Phase-Locked Loop (PLL), which accurately determines the grid voltage angle and frequency, allows the inverter output and the utility grid to be synchronized. PI controllers working in the synchronous rotating reference frame process the current errors that arise from comparing the reference currents with the observed inverter currents. In order to regulate the VSI, the PI controllers produce the necessary voltage references, which are then converted into switching pulses using a Pulse Width Modulation (PWM) approach.

To reduce high-frequency switching harmonics produced by the PWM inverter, an LCL filter is placed between the inverter and the utility grid. The LCL filter offers far greater harmonic attenuation with lower inductance values than traditional L-filters, which leads to better current quality, less inverter-side current ripple, and a smaller filter overall.

The PCC is where the nonlinear load and the utility grid are connected. The PCC voltage and current waveforms are distorted by the harmonic currents introduced by the nonlinear load, which is represented by a three-phase diode bridge rectifier with an R load. The suggested PI-controlled inverter supplies the active power produced by the PV array while injecting balanced sinusoidal currents into the grid under these operating conditions.

MATLAB/Simulink is used to model and simulate the entire system under nonlinear loading. PV power extraction, DC-link voltage control, grid-current quality, and total harmonic distortion (THD) are all included in performance evaluation.

3. LCL Filter Design

With the help of the research articles [31, 32, 33, 34], the LCL filter has been designed.

P = Active Power;

V_{dc}= Dc voltage;

f_{sw}= switching frequency;

V_{ac}=Grid line to line Voltage;

f = Grid frequency;

f_{res}= resonance frequency;

L_1= Inverter side inductance;

L_2= Grid side inductance;

C_f = Filter capacitance;

Rated current is allowed to fluctuate 20%

i.e. $\Delta I_l = 0.2\frac{P}{V_{ac}}$ (1)

$$L_1 = \frac{V_{dc}}{6 f_{sw} \Delta I_l} \quad (2)$$

$$L_2 = \frac{0.1 V_{ac}^2}{2\pi f P} - L_1 \quad (3)$$

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \quad (4)$$

Considering Reactive power requirement is 10% of the rated power.

Reactive power (Q) =10% of rated power(P)

$$C_f = \frac{0.1 P}{2\pi f V_{ac}^2} \quad (5)$$

4. Power balance equation

$P_{pv} - P_{grid} - P_l = C_{dc} V_{dc} \frac{dV_{dc}}{dt}$ (6)

P_{pv}=Power generated by PV cell

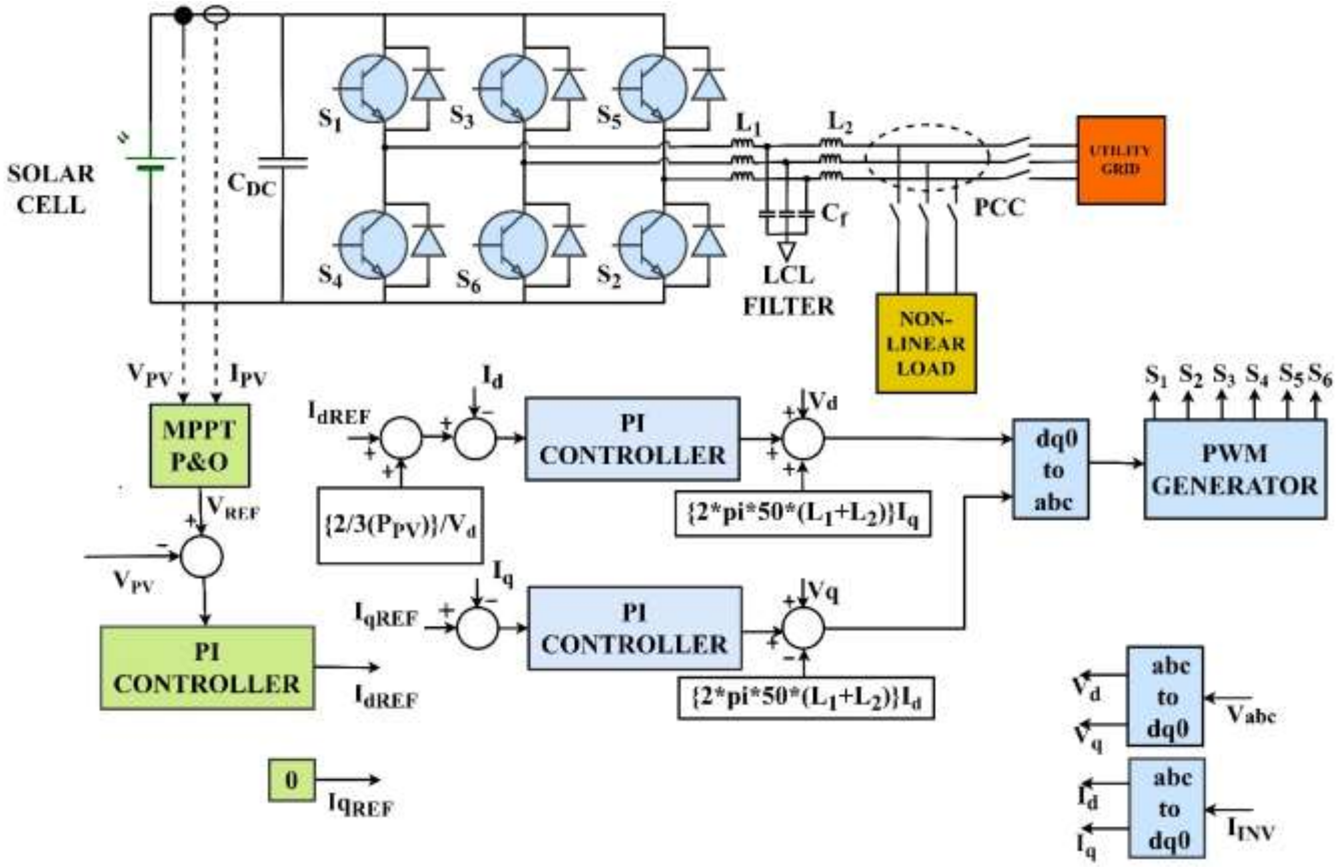
P_{grid}=Injected active power to the Grid

P_l=load power

The extra PV power that is available at the common bus is transmitted to the utility grid by the proposed grid-connected system. The utility grid makes up any gap between PV power and load demand.

5. PI current controller

Figure 1: PI current controlled Single Stage Grid connected PV System with Non Linear load



MPPT(P&O) output reference voltage $=V_{REF}$

Voltage error in DC link, $E_{DC} = (V_{REF} - V_{PV})$ (7)

Active current reference, $I_{dREF} = E_{DC}\ (K_p + K_i \int dt)$ (8)

Feed forward term(PV), $I_{fft} = (\frac{2}{3} \times \frac{P_{pv}}{V_d})$ (9)

Current error to the d-axis, $E_d = \{(I_{dREF} + I_{fft}) - I_d\}$ (10)

Current error to the q-axis, $E_q = (I_{qREF} - I_q)$

Controller output,

Along the d axis, $V_d^* = E_d\,(K_p + K_i \int dt) + V_d + \{2\times \pi \times 50 \times (L_1 + L_2)\} I_q$ (11)

Along the q axis, $V_q^* = E_q\,(K_p + K_i \int dt) + V_q - \{2\times \pi \times 50 \times (L_1 + L_2)\} I_d$ (12)

The controller output voltage is transformed V_{dq0} to V_{abc} by applying the inverse Parks transformation and further sent to the 2-level-6-pulse PWM generator.

6. System parameter

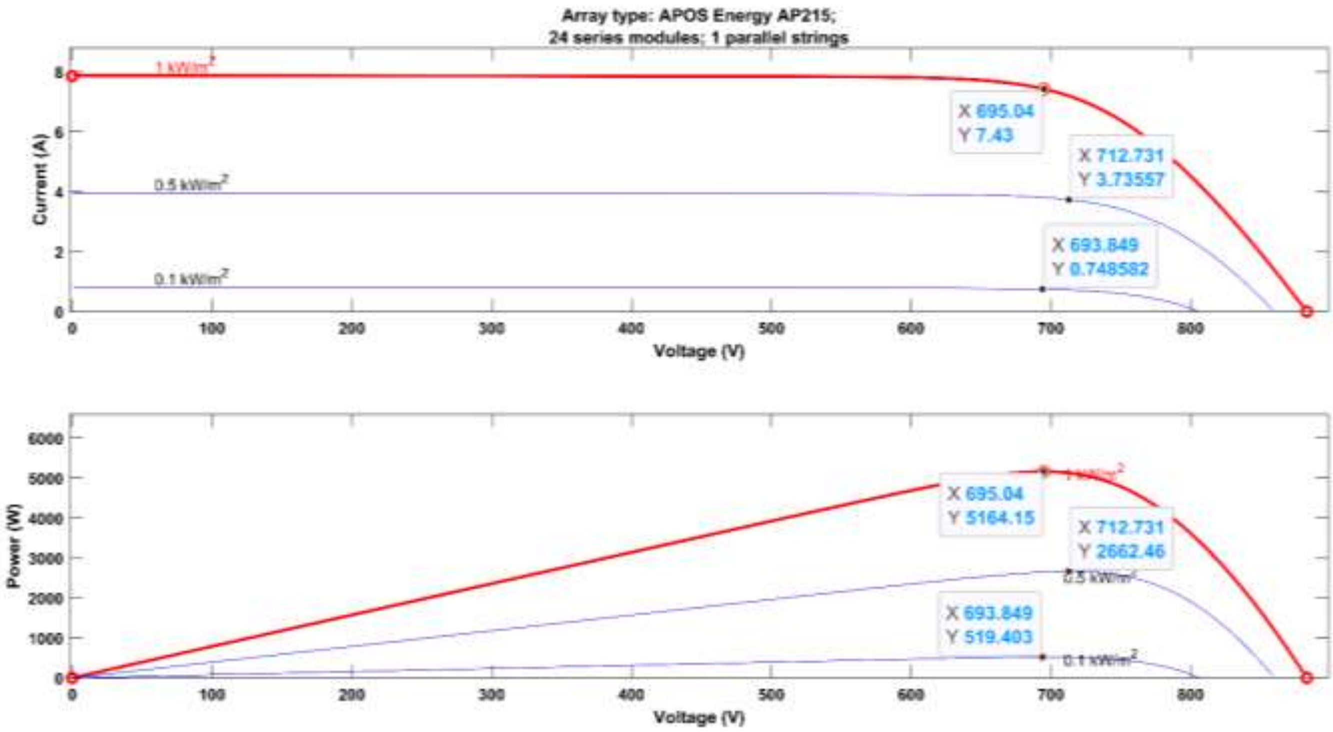
Table 1: PV cell Data

Parameter	Irradiance	Value
P_{pv}	1 KW/m^2	5164 Watt
V_{PV}	1 KW/m^2	695 V
I_{PV}	1 KW/m^2	7.43 A
P_{pv}	0.5 KW/m^2	2662 Watt
V_{PV}	0.5 KW/m^2	712.73 V
I_{PV}	0.5 KW/m^2	3.74 A

Table 2: Other Parameter

Item	Parameter	Value
LCL filter	L_1	5164 Watt
LCL filter	L_2	695 V
LCL filter	C_f	7.43 A
DC link Capacitor	C	1000 µF
Grid Voltage	V_{rms} (Phase to Phase)	400 V
Grid frequency	f	50 Hz

Figure 2: Solar panel Characteristics



7. Studying Simulation

Figure 3: Active Power

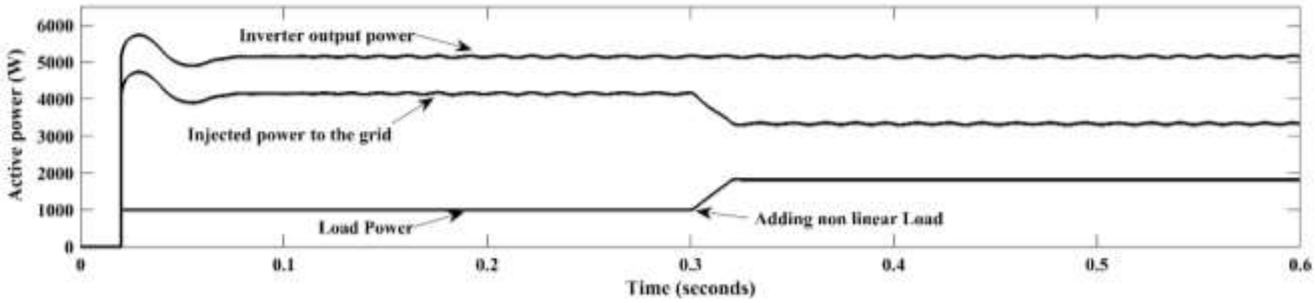


Figure 4: Grid Current

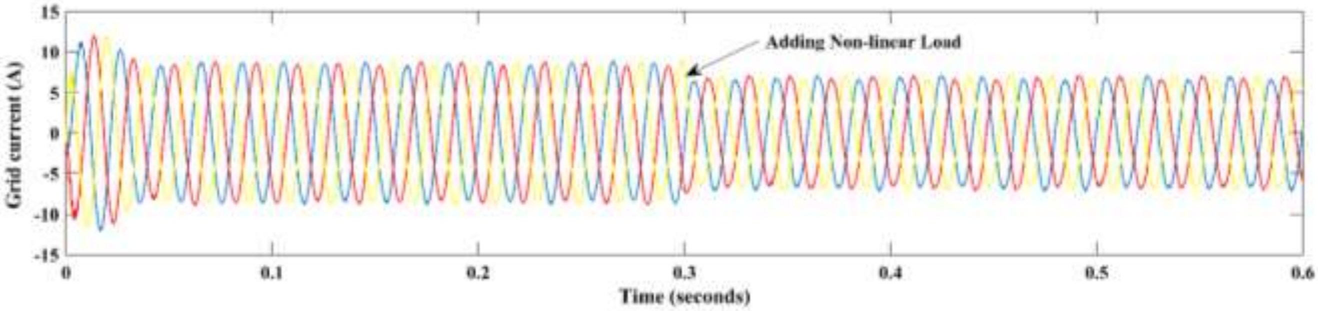


Figure 5: Load Current

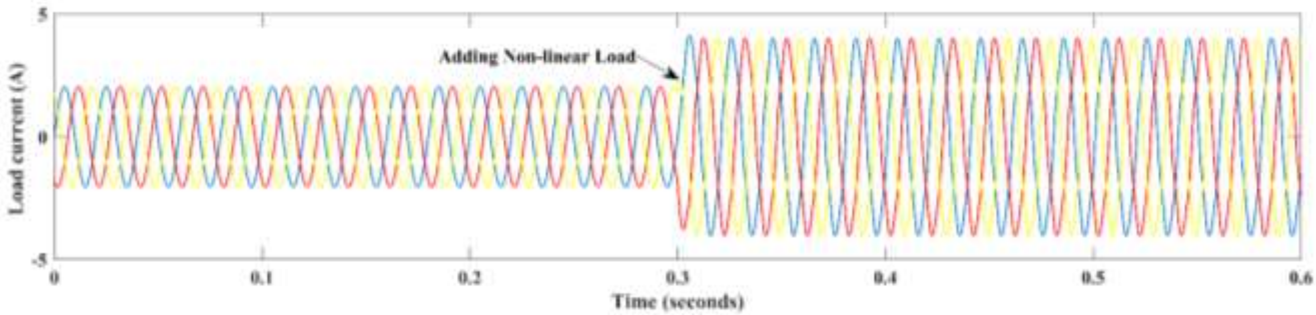


Figure 6: PV voltage

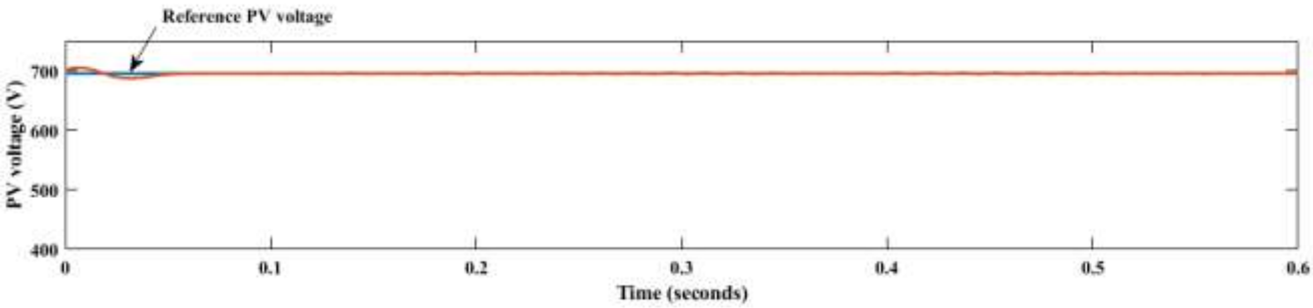


Figure 7: PV current

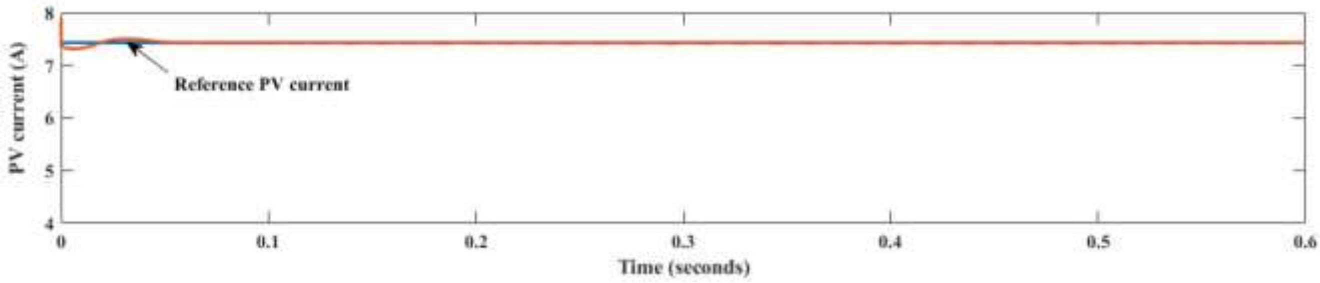


Figure 8: FFT

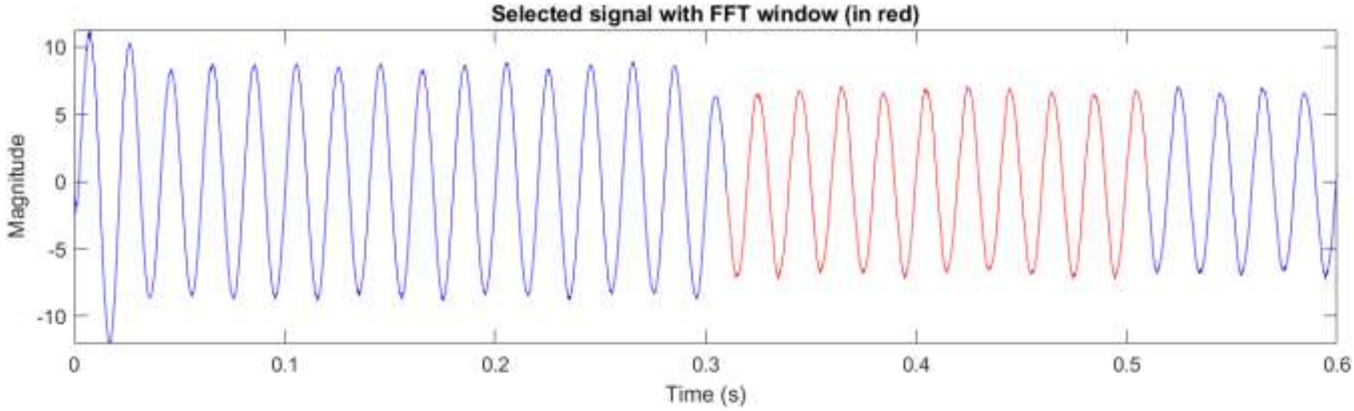
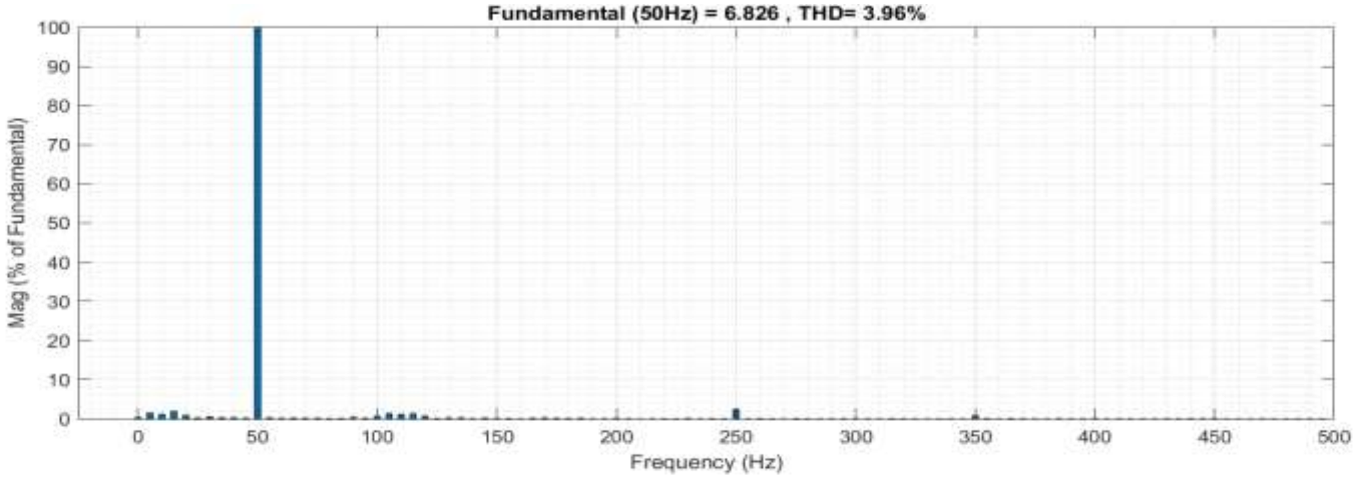


Figure 9: THD



Single stage grid ties solar PV system with LCL filter has been designed and simulated in MATLAB R2021a/simulink simulation 2021 version under non-linear load. Specification of the system and others parameter are shown in table 1 and table 2.

Test: In this study in simulation up to 0.3 second a resistive load of 1kw is connected at the point of common coupling (PCC) and at 0.3 second a non-linear load is switched on.

Case-1: At the time when 1kw load connected load is consumed the required power and remaining power is delivered to the connected grid as shown in figure 3.

Case-2: At the time when at 0.3 second non-linear load is switched on load power is shifted 1kw to 2kw and remaining power is delivered to the grid. When load power is increased at 0.3 second grid current is

decreases and load current is increased as shown in the figure 4 and 5. And PV voltage and PV current is unaltered during change in load power at PCC.
Case-3: Total Harmonic Distortion (THD) is analyzed in FFT window in MATLAB for the selected cycle marked in red during non-linear load connected at PCC using PI current controller. THD is 3.96% as shown in figure 9 during non-linear load connected at PCC which is less than 5% and content of THD in the system acceptable as IEEE 519 standard.

8. Conclusion

This study is presented analysis of harmonic performance of the PI controlled single stage grid connected PV system with LCL filter operating under nonlinear load. Grid current harmonic reduction is done using PI Current controlled strategy combined with LCL filter together. The proposed system was examined using MATLAB simulation under non-linear load to measure its effectiveness to maintaining quality of power.
Results from the simulation show that the PI controller confirms stable regulation of dc-link voltage and accurate tracking of grid current, although the presence of nonlinear loads. The combination of the LCL filter noticeably cuts high-frequency switching harmonics and a waveform of grid current that closely a sine wave. As an outcome, the total harmonic distortion (THD) of the grid current stays within the acceptable limit by IEEE 519 standard, indicating operative harmonic suppression and to maintain the quality of power criteria.
Adaptive current control technique will be focused instead of PI current control in the future.

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