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Mitigation of Lower Order Harmonics in a Grid- Connected Single-Phase PV Inverter

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Abstract: In this paper, among from the all topologies ordinary single-phase PV inverter topology considered which is grid-connected, also single-phase inverter with an inductive filter, and a step-up transformer interfacing is considered. Generally, this configuration will not introduce any lower order harmonics into the grid due to high-frequency PWM operation. However, an Unconventional factors in the system like core saturation-induced distorted magnetizing current of the transformer and the dead time of the inverter, etc., participate to a significant amount of lower order harmonics in the grid current. A proposed system of inverter current control that reduced lower order harmonics is observed in this paper. An adaptive technique is used for the lower order harmonic compensation. Furthermore, a proportional-resonant-integral (PRI) controller and its design are also presented. This controller removes the dc component in the control system, which inject even harmonics in the grid current in the topology considered. The complete design has been validated with Simulation results.

Keywords: Adaptive filters, harmonic distortion, inverters, solar energy, PRI, THD.

Nomenclature

L_{boost}	Inductor of boost stage
L_{filt}	AC side filter inductor
ΔV	Voltage ripple on dc bus
V_a; V_b	Outputs of SOGI
V_g	Grid Voltage
$K_{p;PR}$; K_r	Gains of PR controller
K_v; T_v	Gains of PI controller

1. Introduction

Renewable sources of energy such as solar, wind, and geothermal have gained popularity due to the depletion of conventional energy sources. Hence, many distributed generation (DG) systems making use of the renewable energy sources are being designed and connected to a grid. The topology of the solar inverter system is simple. It consists of the following three power circuit stages:

1) A boost converter stage to perform maximum power point tracking (MPPT);
2) A low-voltage single-phase *H*-bridge inverter;
3) An inductive filter and a step-up transformer for interfacing with the grid.

The system will not have any lower order harmonics in the ideal case. However, the following factors result in lower order harmonics in the system: The distorted magnetizing current drawn by the transformer due to the nonlinearity in the *B*–*H* curve of the transformer core, the dead time introduced between switching of devices of the same leg [2] – [6], on-state voltage drops on the switches, and the distortion in the grid voltage itself. There can be a dc injection into the transformer primary due to a number of factors. These can be the varying power reference from a fast MPPT block from which the ac current reference is generated, the offsets in the sensors, and A/D conversion block in the digital controller. This dc injection would result in even harmonics being drawn from the grid, again contributing to a lower power quality. The advantage of the adaptive filter-based method is the inherent frequency adaptability which would result in same amount of harmonic compensation even when there are shifts in grid frequency. The implementation of adaptive filters is simple. Thus, in this paper, an adaptive filter-based method is proposed. This method estimates a particular harmonic in the grid current using a least-mean-square (LMS) adaptive filter and generates a harmonic voltage reference using a proportional controller. This voltage reference is added with appropriate polarity to the fundamental voltage reference to attenuate that particular harmonic.

This paper includes an analysis to design the value of the gain in the proportional controller to achieve an adequate level of harmonic compensation. The effect of this scheme on overall system dynamics is also analyzed. This method is simple for implementation and hence it can be implemented in a low-end digital controller.

2. "Origin of Lower Order Harmonics and fundamental current control"

This section discusses the origin of the lower order harmonics in the system under consideration. The sources of these harmonics are not modeled as the method proposed to attenuate those works independent of the harmonic source.

2.1 Origin of Lower Order Harmonics

1) *Odd Harmonics:* The dominant causes for the lower order odd harmonics are the distorted magnetizing current drawn by the transformer, the inverter dead time, and the semiconductor device voltage drops. Other factors are the distortion in the grid voltage itself and the voltage ripple in the dc bus. The magnetizing current drawn by the transformer contains lower order harmonics due to the nonlinear characteristics of the *B*–*H* curve of the core.

2) *Even Harmonics:* The topology under consideration is very sensitive to the presence of dc offset in the inverter terminal voltage. The dc offset can enter from a number of factors such as varying power reference given by a fast MPPT block.

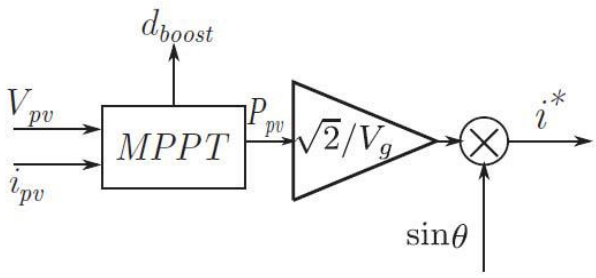

Figure 1: Generation of an inverter ac current reference from an MPPT block.

In Fig. 1, *d*boost is the duty ratio command given to the boost converter switch; *V*pv and *i*pv are the panel voltage and current respectively.

2.2. Fundamental Current Control

1) Introduction to the PRI Controller: Conventional stationary reference frame control consists of a PR controller to generate the inverter voltage reference. a modification to the PR controller is proposed, by adding an integral block, *GI* as indicated in Fig. 2. The modified control structure is termed as a PRI controller.

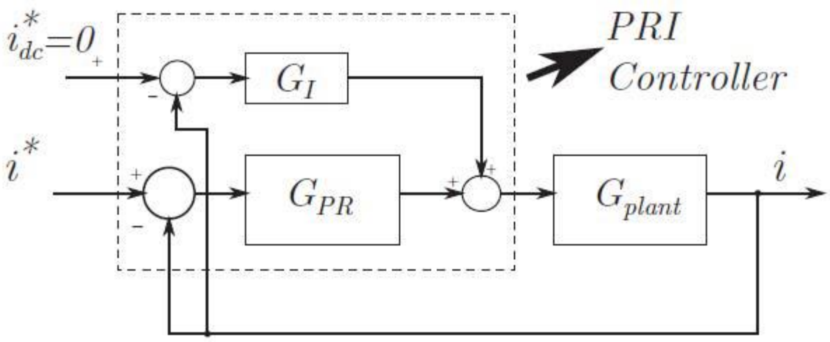

Figure 2: Block diagram of the fundamental current control with the PRI controller.

Here

$$GI = KI/s \quad (1)$$

$$GPR(s) = Kp + (Kr\, s/(s^2+ \omega^2)) \quad (2)$$

The plant transfer function is modeled as

$$Gplant(s) = Vdc/(Rs + sLs) \quad (3)$$

This is because the inverter will have a gain of to the voltage reference generated by the controller and the impedance offered is given by (*Rs* + *sLs*) in s-domain. *Rs* and *Ls* are the net resistance and inductance referred to the primary side of the transformer respectively.

2) Design of PRI Controller Parameters: The fundamental current corresponds to the power injected into the grid. The control objective is to achieve UPF operation of the inverter. First, a PR controller is designed for the system assuming that the integral block is absent, i.e., KI = 0. Design of a PR controller is done by considering a PI controller in place of the PR controller.

Let

$$GPI(s) = Kp1\,((1 + sT)/sT) \quad (4)$$

With the PI controller as the compensator block and without integral block, the forward transfer function will be

$$Gforw(s) = Kp1\,((1 + sT)/sT))(\,Vdc/(Rs + sLs)) \quad (5)$$

If is the required bandwidth, then Kp1 can be chosen to be

$$Kp1 = \omega_{bw} R_s T\,/Vdc \quad (6)$$

Now, if the PI controller in (5) is written as

$$GPI(s) = (Kp1 + Ki1)/s \quad (7)$$

The closed-loop transfer function is given as

$$Gcl,PRI = i(s)/i^*(s) = Gplant\ GPR/(1 + Gplant(GPR + GI\,)) \quad (8)$$

Without the integral block, the closed-loop transfer function would be

$$Gcl,PR = G_{plant}\ G_{PR}/(1 + GplantG_{PR}) \quad (9)$$

$$Gplant = M/(1 + sT) \quad (10)$$

Where M=Vdc/Rs. The numerators in both (8) and (9) are the same. Thus, the difference in their response is only due to the denominator terms in both. The denominator in (8) can be obtained as

$$den_{PRI} = [(T_s^4 + (1 + MKp\,)s^3 + (\omega_0{}^2T + M(Kr + KI\,))s2)/s(1 + sT\,)(s^2 + \omega_0{}^2)\,] + [\,(\omega_0{}^2\,(1 + MKp\,)s + MKI\omega_0{}^2)/s(1 + sT\,)(s^2 + \omega_0{}^2\,)\,] \quad (11)$$

Similarly, the denominator in (9) is given by

$$den_{PR} = [T_s^3 + (1 + MKp\,)s^2 + (\omega_0{}^2T + MKr\,)/s(1 + sT\,)(s^2 + \omega_0{}^2\,)] + [\,(MKp + 1)\omega_0{}^2/(1 + sT\,)(s^2 + \omega_0{}^2\,)\,] \quad (12)$$

2.3 Comparison of Mitigation Techniques

Sr. No	Mitigation Technique	Features	Drawbacks
1.	Passive Harmonic Filtering	• Most commonly used and inexpensive	• Very bulky. • Cause resonance at selected frequency
2.	Active Harmonic Filtering	• Very efficient in suppression of harmonics. • Can eliminate more than one harmonic at a time. • Do not resonate with power system. • Can also provide PF correction and voltage regulation.	• More expensive than passive filters. • Large and complex.
3.	Selective Harmonic Elimination	• Selected harmonics of low order are eliminated completely. • Significant reduction in cost, size and weight of the filtering system	• Only a limited number harmonics are eliminated and unconsidered harmonics can reach very high amplitudes. • Maximum switching frequency is limited to a few hundreds of hertz.
4.	Voltage flicker tracking using algorithms	• Accurate, fast, and easy to implement. • Flexible. Eliminates use of APF and DSTATCOM. • Can also compensate for reactive power, harmonic and unbalance.	• Complex calculations increase computational burden on controller.
5.	Z-source inverter (ZSI) based DG system	• Provides the unique buck-boost feature to the inverter. • Optimizes the power output better than conventional VSI. • Low switching losses and improved reliability.	• Increases complexity of system.

3. Adaptive Harmonic Compensation

In this section, the concept of lower order harmonic compensation and the design of the adaptive harmonic compensation block using this adaptive filter are explained.

A. Review of the LMS Adaptive Filter

The adaptive harmonic compensation technique is based on the usage of an LMS adaptive filter to estimate a particular harmonic in the output current. This is then used to generate a counter voltage reference using a proportional controller to attenuate that particular harmonic.

B. Adaptive Harmonic Compensation

The LMS adaptive filter discussed previously can be used for selective harmonic compensation of any quantity, say grid current. To reduce a particular lower order harmonic (say i_k) of grid current:
1) i_k is estimated from the samples of grid current and phase locked loop (PLL) unit vectors at that frequency;
2) A voltage reference is generated from the estimated value of i_k ;
3) Generated voltage reference is subtracted from the main controller voltage reference.
The Fig.3 shows the power circuit topology considered. This topology has been chosen due to the following advantages: The switches are all rated for low voltage which reduces the cost and lesser component count in the system improves the overall reliability.

This topology will be a good choice for low-rated PV inverters of rating less than a kilowatt. The disadvantage would be the relatively larger size of the interface transformer compared to topologies with a high-frequency link transformer.

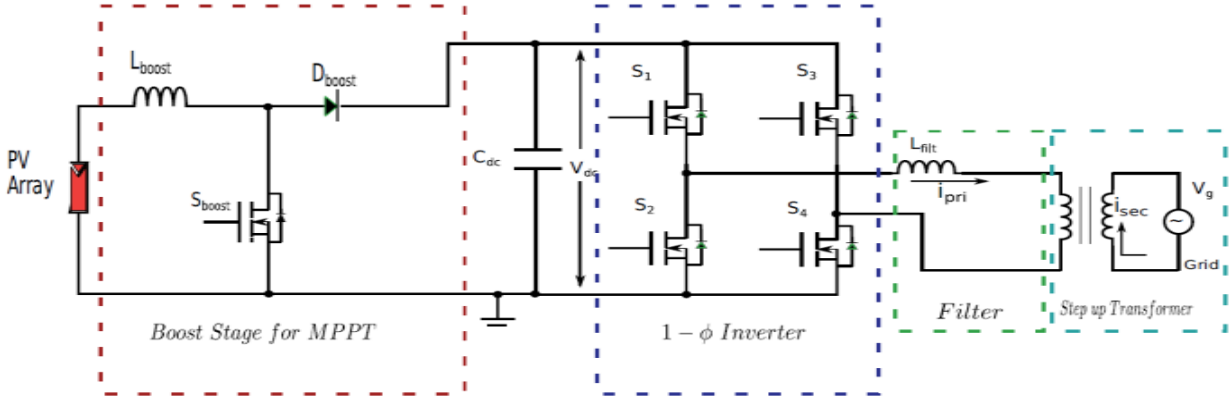

Figure 3: Power circuit topology of the 1 − phase PV system for a low-voltage inverter with 40V dc bus connected to 230V grid using a step-up transformer

4. Simulation Results

4.1 Grid connected single-phase PV inverter before compensation

The grid connected single-phase PV inverter before compensation is shown in fig.4.

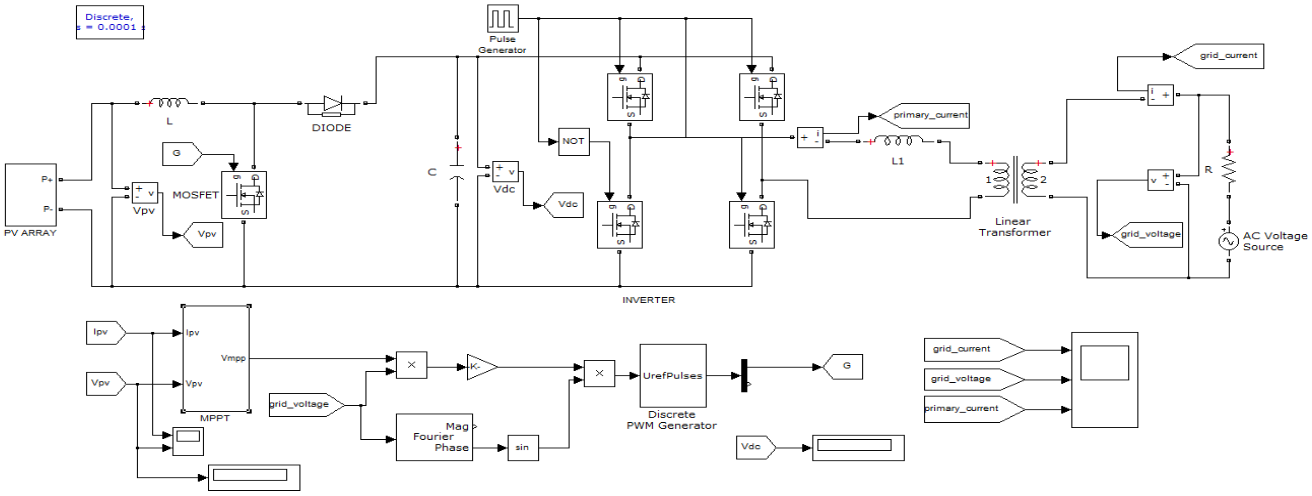

Figure 4: Grid connected single-phase PV inverter before compensation

The Fig.4. Consists of PV array, boost converter, single phase inverter, an inductive filter& a step-up transformer for interfacing with the grid. The PV array gives the values are V_{pv}=10.69v, I_{pv}=10.09A, V_{dc}=14.55 v. The boost converter boost up the voltage & current. The capacitor is used to the purpose of continuous current flowing. The inverter converts DC power to AC power. In the inverter each IGBT has resistance of 0.1Ω.the transformer having nominal power of 150VA; operating frequency is 50HZ, $L=500_e^{-3}$, $C=6600_e^{-6}$, R=0.1Ω, in ac voltage source, peak amplitude=230V.

4.2 Block Diagram OF PV Array

The block diagram of PV array is shown in fig.5

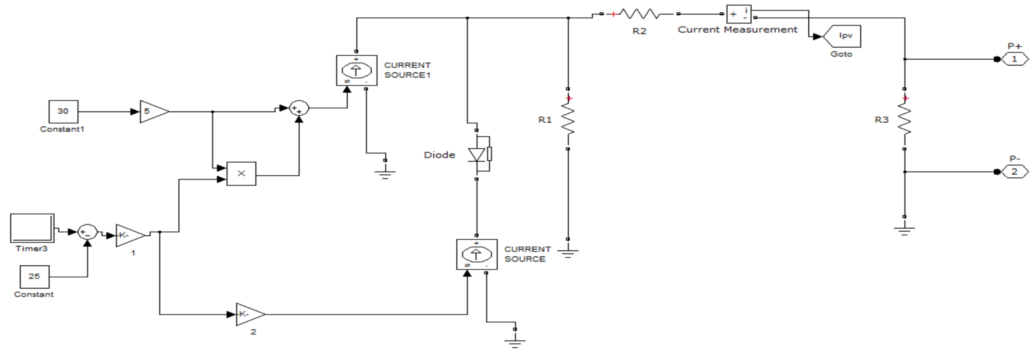

Figure 5: block diagram of PV array

In the PV array, R_1=1Ω, R_2=100Ω, R_3 =5Ω.For diode R=0.001Ω,V_f =0.8V, snubber resistance R_s =500Ω, snubber capacitance $C_s = 250_e^{-6}$.

4.3 Block Diagram of MPPT Algorithm

The block diagram of MPPT algorithm is shown in fig.6

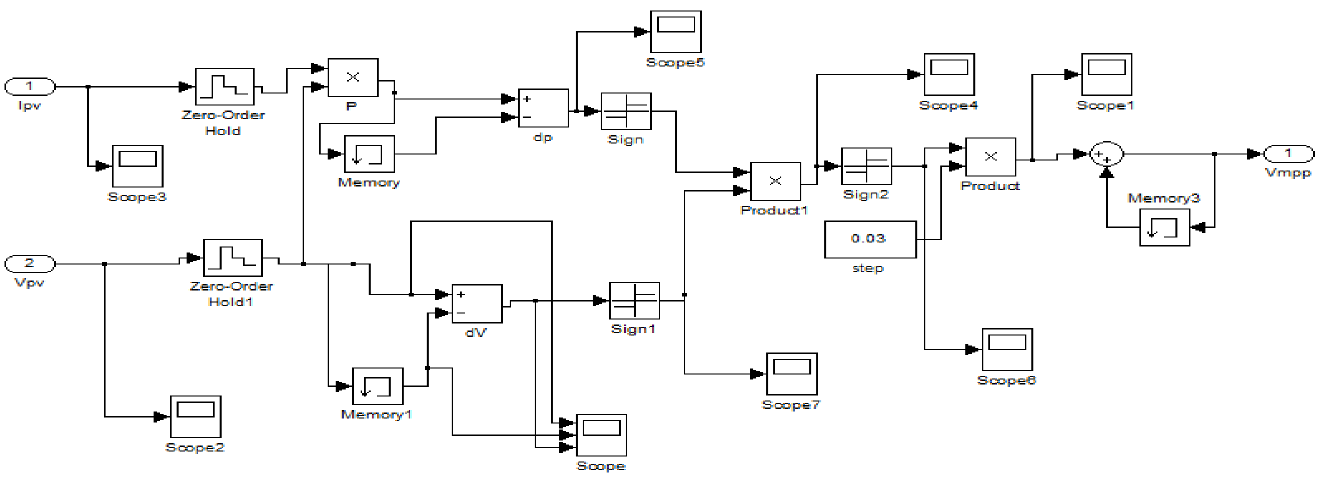

Figure 6: Block diagram of MPPT Algorithm

The Fig.6. Shows Block diagram of MPPT Algorithm. It gives the max. power to the circuit.

5. Grid Connected Single-Phase PV Inverter with PR Controller

The grid connected single-phase PV inverter with PR controller is shown in fig.7.

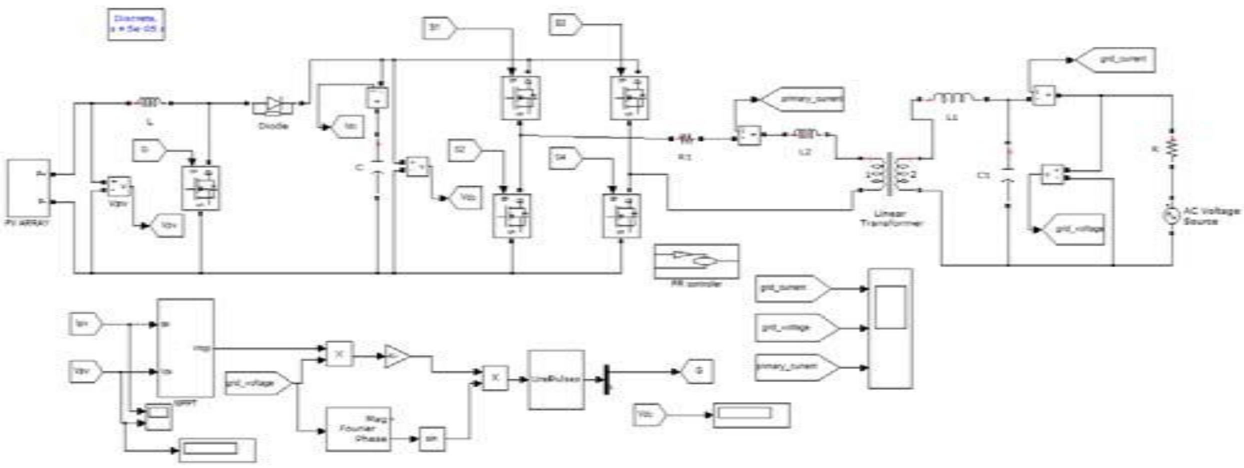

Figure 7: Grid connected single-phase PV inverter with PR controller

The Fig.7. Consists of PV array, boost converter, single phase inverter, an inductive filter& a step-up transformer for interfacing with the grid. The PV array gives the values are V_{pv}=29.62V,I_{pv} =9.90A, V_{dc}=41.7v. The boost converter boost up the voltage & current. The capacitor is used to the purpose of continuous current flowing. The inverter converts DC power to AC power. The transformer having nominal power of 150VA; operating frequency is 50HZ, $L=500_e^{-3}$,$L_1 =1_e^{-3}$ $L_2=100_e^{-3}$, $C=6600_e^{-6}$,$C_1 =100_e^{-6}$, R=0.1Ω, R_1=90Ω.In ac voltage source, peak amplitude=230V.it is also consists of PR controller.

5.1 Block diagram of PR Controller

The block diagram of PR controller is shown in fig.8.
PR controller means proposed resonant controller. It gives the values of K_p=3,K_r =594.

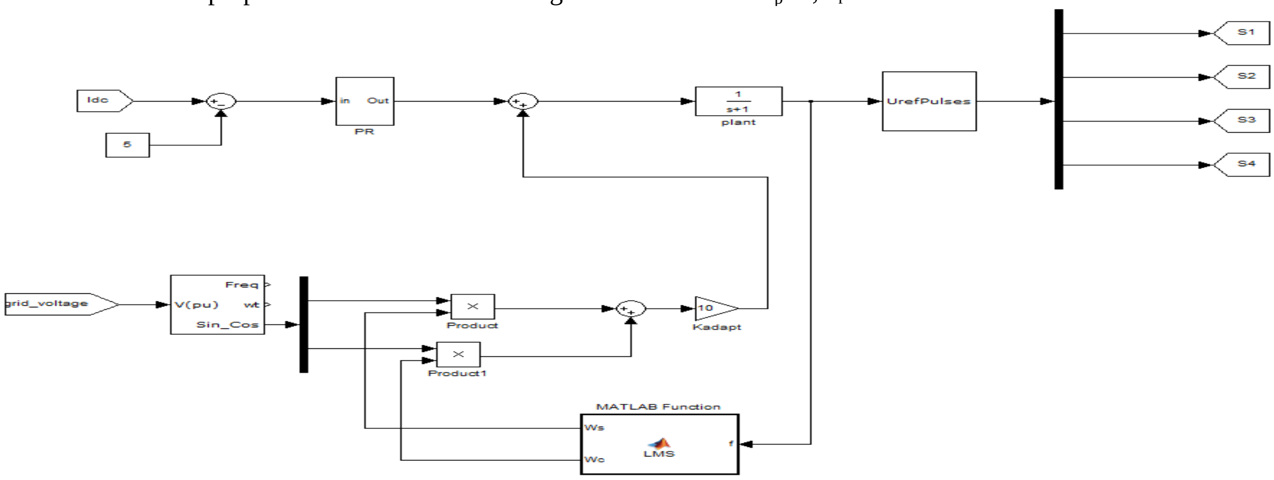

Figure 8: block diagram of PR controller

6. Grid Connected Single-Phase PV Inverter with PRI Controller

The grid connected single-phase PV inverter with PRI controller is shown in figure 9.

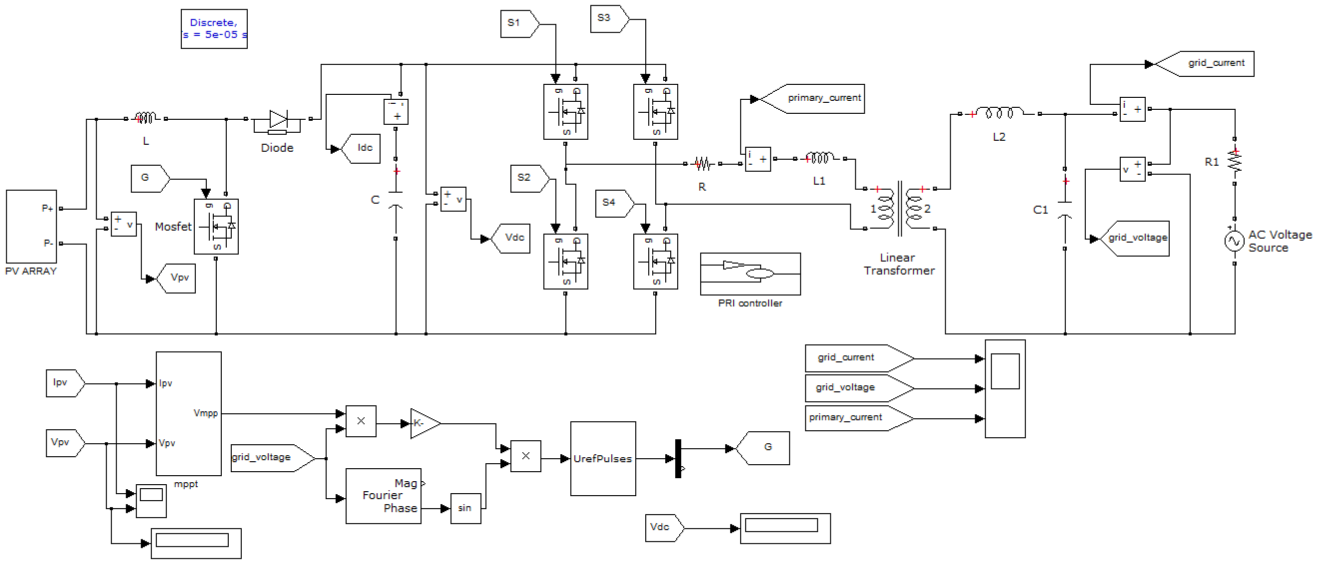

Figure 9: Grid connected single-phase PV inverter with PRI controller

The Fig.9, Consists of PV array, boost converter, single phase inverter, an inductive filter& a step-up transformer for interfacing with the grid. The PV array gives the values are V_{pv}=29.62V, I_{pv}=9.903A, V_{dc}=43.77v.The boost converter boost up the voltage & current. The capacitor is used to the purpose of continuous current flowing. The inverter converts DC power to AC power. In the inverter each IGBT has resistance of 0.1Ω. The transformer having nominal power of 150VA; operating frequency is 50HZ, L=500_e^{-3}, L_1=$100_e^{-3,}$ $^{L}{}_{2}$ =1_e^{-3} , C=6600_e^{-6} , C_1=200_e^{-6} , R=200Ω, R_1=0.1Ω.In ac voltage source, peak amplitude=230V.it is also consists of PRI controller.

6.1 Block diagram of PRI controller

The block diagram of PRI controller is shown in fig.10.

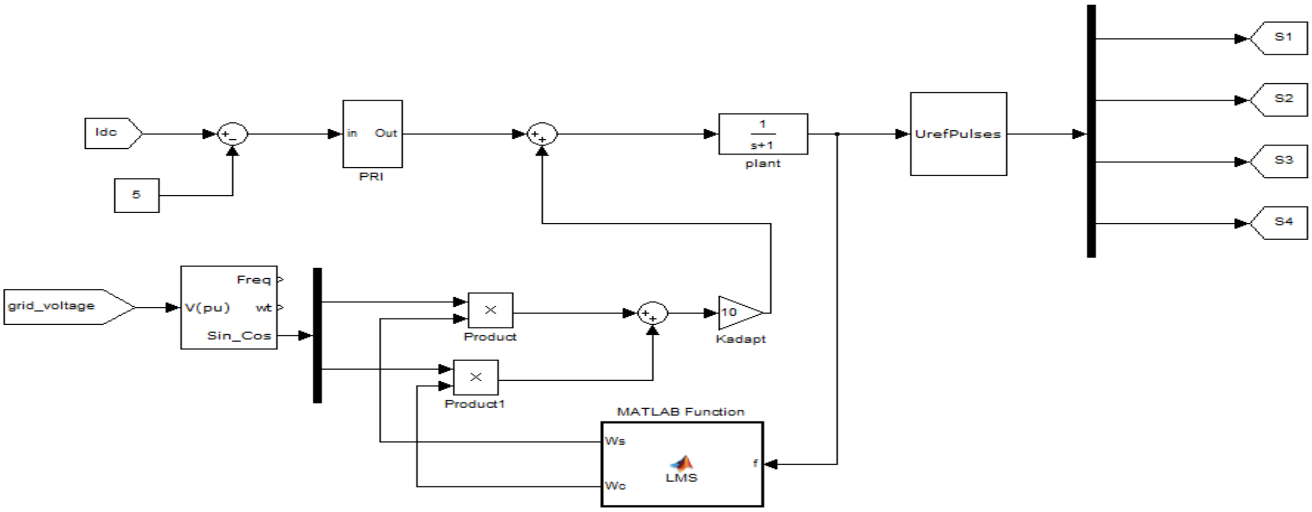

Figure 10: Block diagram of PRI controller

From the Fig.10 PRI controller means Proportional Resonant Integral controller. In this controller the values of K_p =3, K_r=594,K_I =100.

6.2 Simulink results of Grid connected single-phase PV inverter before compensation

The Simulink results of namely PV current, PV voltage, Grid current, Grid voltage, Primary current of Grid connected single-phase PV inverter before compensation are shown in the Fig.11.

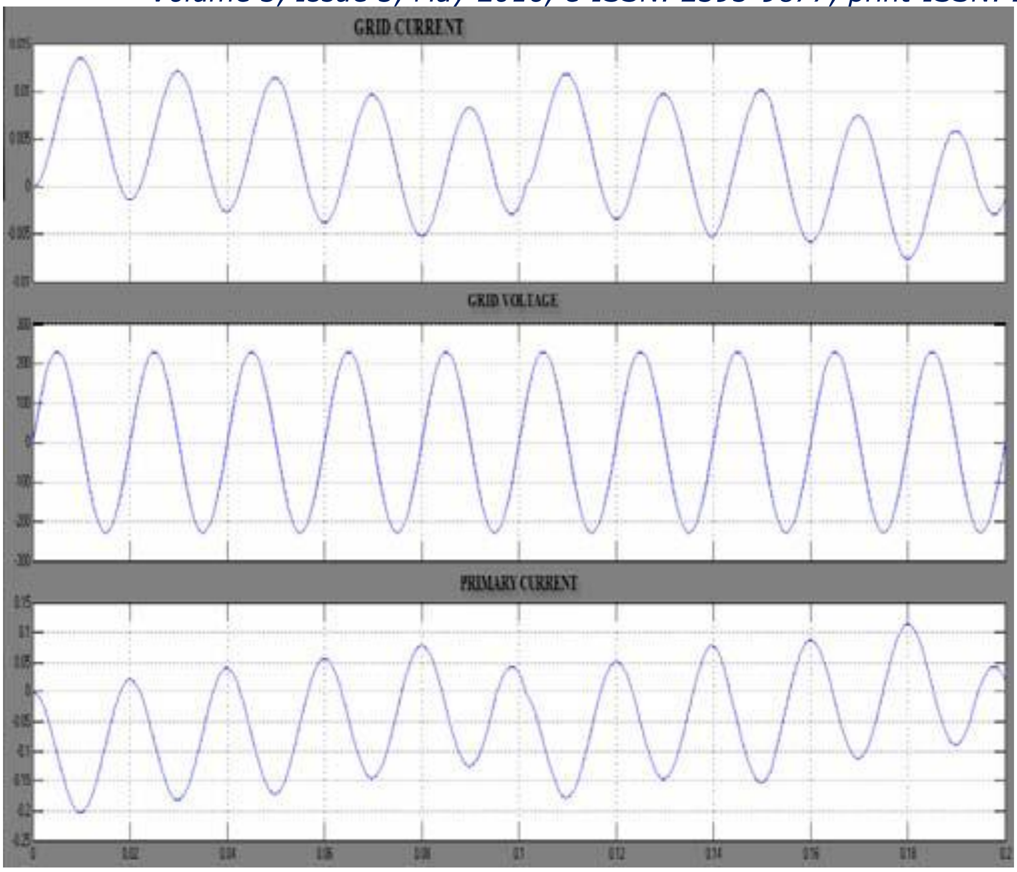

Figure 11: Output waveforms of PV inverter before compensation

From the output waveforms Shown in Fig.11. It is observed that the grid current, grid voltage & primary current are in sinusoidal form. Total harmonic distortion in Grid current of single-phase PV inverter before compensation. It is observed that the THD in Grid current is 9.14%.

6.4 Simulink results of Grid connected single-phase PV inverter with PR controller

The Output waveforms of Grid connected single-phase PV inverter with PR controller is shown in fig.12.

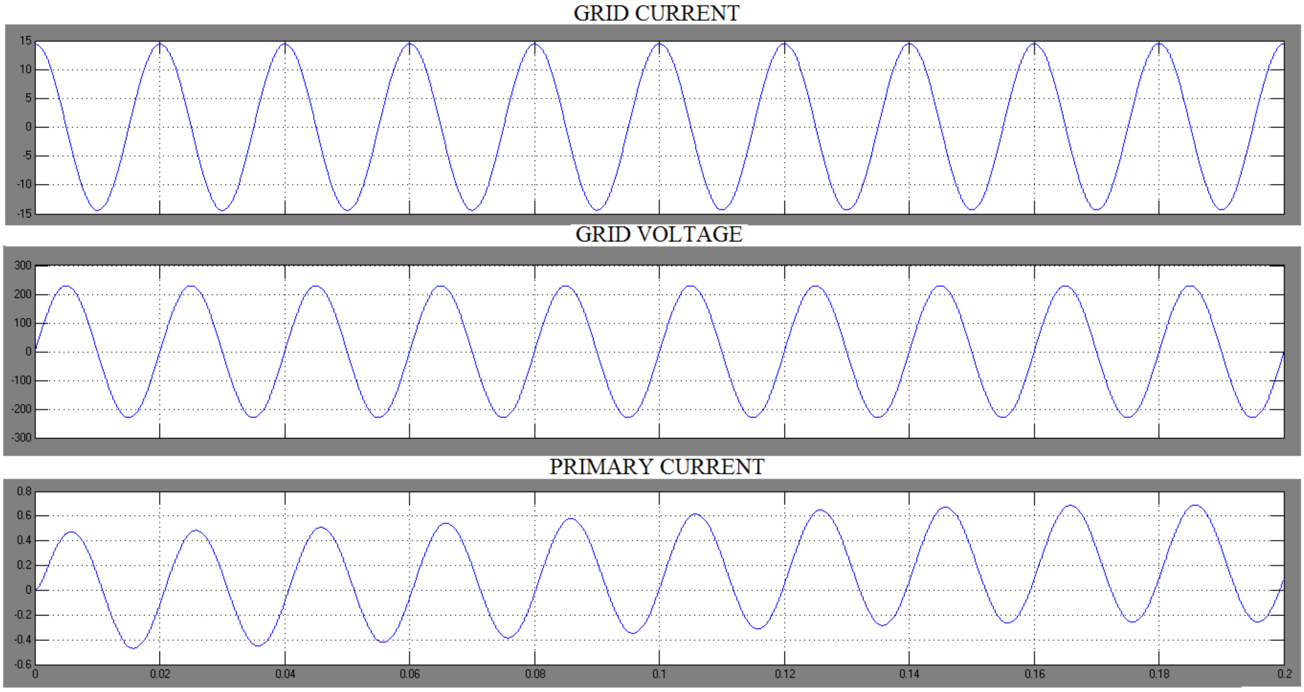

Figure 12: output waveforms of Grid connected single-phase PV inverter with PR controller

From the output waveforms Shown in Fig.12. It is observed that the grid current, grid voltage & primary current are in sinusoidal form. Total harmonic distortion in Grid current of single-phase PV inverter with PR controller. It is observed that the THD in Grid current is 2.90%.

6.5 Simulink results of Grid connected single-phase PV inverter with PRI controller

The Output waveforms of Grid connected single-phase PV inverter with PRI controller is shown in fig.13.

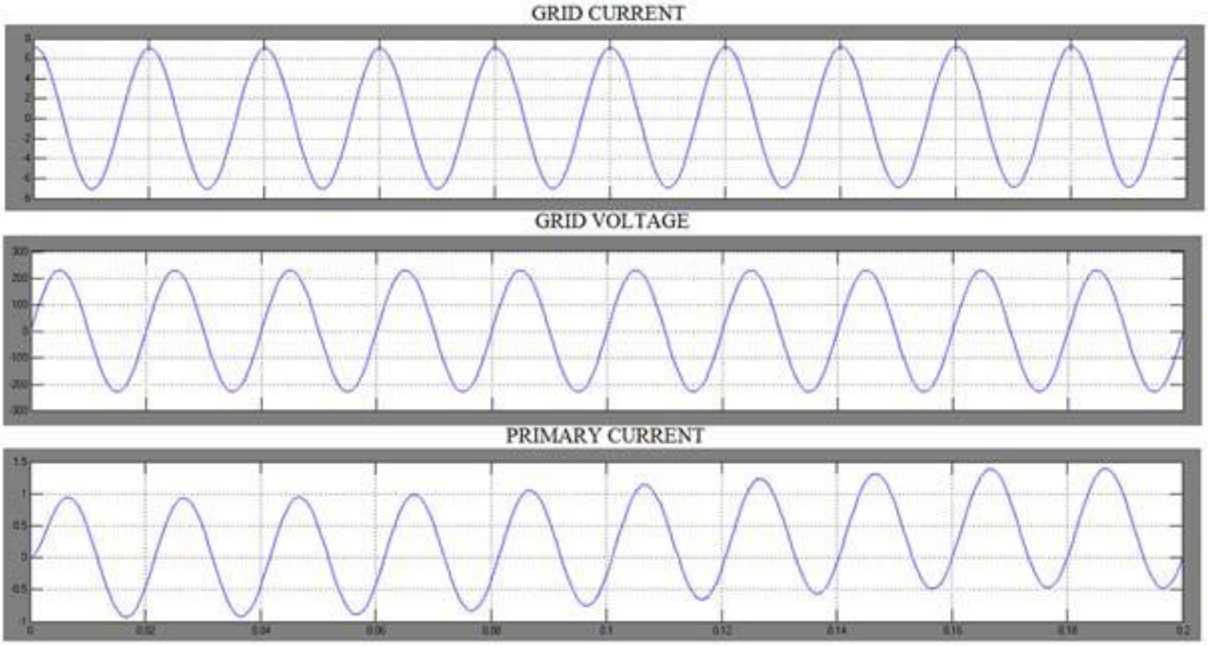

Figure 13: Output waveforms of Grid connected single-phase PV inverter with PRI controller.

From the output waveforms Shown in Fig.13. It is observed that the grid current, grid voltage & primary current are in sinusoidal form. Total harmonic distortion in Primary current of single-phase PV inverter with PRI controller. It is observed that the THD in Grid current is 1.85%.

Table 1: THD Analysis

	Total Harmonic Distortion (THD) (%)		
	Grid current	Grid voltage	Primary current
Before compensation	9.13	0	9.14
PR controller	0.16	0	2.91
PRI controller	0.03	0	1.85

The proposed single-phase PV inverter is simulated using MATLAB/SIMULINK. The corresponding results are showed before compensation, during PR& PRI controllers. Then the THD analyses for the proposed single-phase PV inverter with compensation and without compensation are compared.

7. Conclusion

The new inverter current control for a grid connected single-phase PV inverter has been proposed in this paper, for he purpose of high accuracy and profile of the current injected into the grid. For the system topology considered, the main reason for lower order harmonic injection are described as the distorted transformer magnetizing current and the dead time of the inverter. It's also shown how DC offset result into even harmonics. A new solution is presented to mitigate all the dominant lower order harmonics in the system. An unconventional method uses an LMS adaptive filter to estimate a particular harmonic in the grid current that needs to be reduced. The estimated current is transform into an equivalent voltage reference using a proportional controller. The design of the gain of a proportional controller to have an adequate harmonic compensation has been studied. To avoid dc biasing of the transformer, a novel PRI controller has been proposed and its design has been presented. The PRI controller and the adaptive compensation technique together enhance the quality of the current injected into the grid.

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