MITIGATION OF LOWER ORDER HARMONICS IN A GRID CONNECTED THREE PHASE PV INVERTER

Dr. B. Suresh Kumar[1] **G.Avinash[2]**

Asst.Professor-CBIT Hyderabad *PG Student- CBIT- Hyderabad*

***Abstract*: In this paper simple single-phase grid connected photovoltaic (PV) inverter topology consisting of a boost section, a low voltage Three-phase inverter with an inductive filter, and a step-up transformer interfacing the grid is considered. Ideally, this topology will not inject any lower order harmonics into the grid due to high-frequency pulse width modulation operation. However, the non ideal factors in the system such as core saturation-induced distorted magnetizing current of the transformer and the dead time of the inverter, etc., contribute to a significant amount of lower order harmonics in the grid current. A novel design of inverter current control that mitigates lower order harmonics is presented in this paper. An adaptive harmonic compensation technique and its design are proposed for the lower order harmonic compensation. In addition, a proportional-resonant-integral (PRI) controller and its design are also proposed. This controller eliminates the dc component in the control system, which introduces even harmonics in the grid current in the topology considered. The dynamics of the system due to the interaction between the PRI controller and the adaptive compensation scheme is also analyzed**

Keywords—adaptive filter, harmonic distortion, Inverters, Solar energy.

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. In this paper, one such DG system with solar energy as the source is considered.

The topology of the solar inverter system is simple. It consists of the following three stages:

- A boost converter stage to perform maximum power point tracking (MPPT).
- A low-voltage Three-phase H-bridge inverter.
- An inductive filter and a step-up transformer

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.

The basic circuit 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–HCurve of the transformer core, the dead time introduced between switching of devices of the same leg, 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.

II REVIEW OF LITERATURE

1. Adaptive harmonic compensation technique in Three phase PV Inverter

PWM inverters ideally shift the output voltage spectrum around the switching frequency. Thus ideally PWM inverters do not introduce any significant lower order harmonics. However, in real systems, due to dead-time effect, device drops and other non-idealities lower order harmonics are present. In order to attenuate these lower order harmonics and hence to improve the quality of output current, this paper presents an adaptive harmonic elimination technique

2. Review of Three-Phase Grid-Connected Inverter for Photovoltaic Modules

This review focuses on inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid. The inverters are categorized into four classifications: The number of power processing stages in cascade. The type of power decoupling between the PV module(s) and the single phase grid.

3. Compensation Method Eliminating Voltage Distortions in PWM Inverter

The switching lag-time and the voltage drop across the power devices cause serious waveform distortions and fundamental voltage drop in pulse width-modulated inverter output. These phenomenon's are conspicuous when both the output frequency and voltage are low. To estimate the output voltage from the PWM reference signal it is essential to take account of these imperfections and to correct them. In this paper, on-line compensation method is presented.

4. Systematic Method for Damping of the LCL Filter for Three-Phase Grid-Connected PV Inverters

The Proportional Resonant (PR) current controller provides gains at a certain frequency (resonant frequency) and eliminates steady state errors. Therefore, the PR controller can be successfully applied to single grid-connected PV inverter current control. On the contrary, a PI controller has steady-state errors and limited disturbance rejection capability. Compared with the L- and LC filters, the LCL filter has excellent harmonic suppression capability, but the inherent resonant peak of the LCL filter may introduce instability in the whole system.

5. A strategy for harmonic reduction using complete Solution:

One of the major problems in electric power quality is the harmonic contents. There are several Methods of indicating the quantity of harmonic contents. These parameters of power quality measurement are four in number, of which Total Harmonic Distortion is most widely used. In electrical systems, harmonics increase business operating costs by increasing downtime, placing burden on the electrical infrastructure, making power factor correction difficult and causing poor total power factor. Harmonics are a circumstance of progress, and they affect all the operating systems.

6. Harmonic Reduction in Cascaded Multilevel Inverter

It presents method of selecting switching angles of a cascaded multilevel inverter so as to produce required fundamental voltage along with improved staircase waveform in terms of harmonics. Cascaded multilevel inverter uses number of DC sources, for k sources number of levels will be 2k+1 and leads to k number of non-linear equations to be solved. Many approaches can be made regarding the solution but this focuses on Specific Harmonic Elimination (SHE) technique for angle optimization. Newton- Raphson method is used and the difficulty with this method is a closed initial guess. Variation of angles with modulation index is observed and THD is calculated for selected modulation indexes and all attempts are made so as to get lowest THD. Results are simulated in MATLAB/Simulink environment.

CONVENTIONAL POWER CIRCUIT TOPOLOGY

2.1 CIRCUIT DIAGRAM:

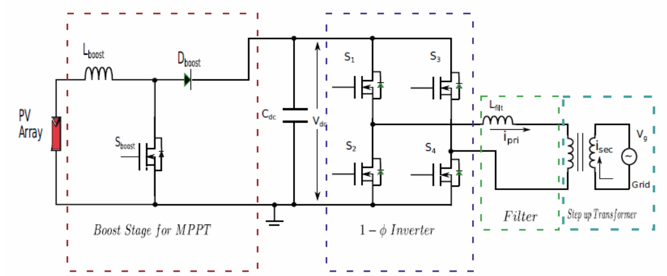


Fig.2.1 Power circuit topology of the single phase PV system connected to grid

2.2 PULSE WIDTH MODULATION (PWM):

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller's power devices. When in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging needs consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.

Similarly, if the switches keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of 12v - or 9v, as shown below and if the output pulse of 12v lasts only 25% of the overall time, then the average is by varying - or 'modulating' - the time that the output is at 12v (i.e. the width of the positive pulse) we can alter the average voltage..

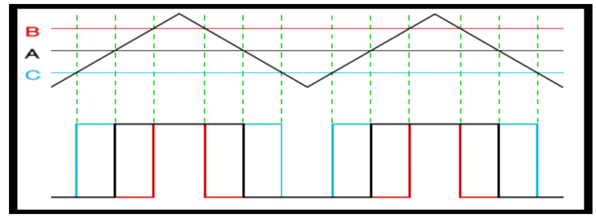


Fig2.2. Pulse width modulation

The triangle waveform, which has approximately equal rise and fall slopes, is one of the commonest used, but you can use a saw tooth (where the voltage falls quickly and rinses slowly). .

(Figure2.3)

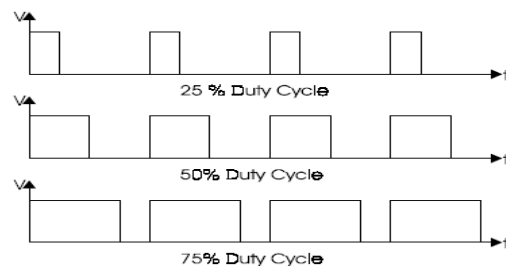


Fig2.3.Different dutycycles

A solenoid is a length of wire wound in a coil. Because of this configuration, the solenoid has, in addition to its resistance, R, a certain inductance, L

2.4 PWM FREQUENCY IS IMPORTANT:

The PWM is a large amplitude digital signal that swings from one voltage extreme to the other. And, this wide voltage swing takes a lot of filtering to smooth out. When the PWM frequency is close to the frequency of the waveform that you are generating, then any PWM filter will also smooth out your generated waveform and drastically reduce its amplitude. So, a good rule of thumb is to keep the PWM frequency much higher than the frequency of any waveform you generate.

Finally, filtering pulses is not just about the pulse frequency but about the duty cycle and how much energy is in the pulse. The same filter will do better on a low or high duty cycle pulse compared to a 50% duty cycle pulse

2.5 PWM CONTROLLER FEATURES:

This controller offers a basic "Hi Speed" and "Low Speed" setting and has the option to use a "Progressive" increase between Low and Hi speeds. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded. Low Speed can vary anywhere from 0% PWM to 10%.

2.6 MULTIPLE PULSE WIDTH MODULATION

The harmonic content can be reduced by using several pulses in each half cycle of output voltage. The generation of gating signals for turning ON and OFF transistors by comparing a reference signal with a triangular carrier wave. The frequency F_c, determines the number of pulses per half cycle. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation.

2.7 SINUSOIDAL PULSE WIDTH MODULATION

Instead of, maintaining the width of all pulses of same as in case of multiple pulse width modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The distortion factor and lower order harmonics are reduced significantly. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency F_c.

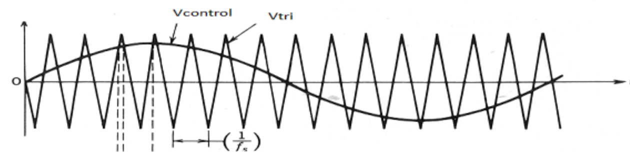


Fig.2.4 Desired frequency is compared with a triangular waveform

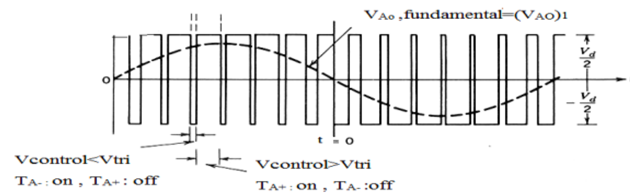


Fig.2.5 Pulse-width Modulation (PWM)

In this scheme, the triangular carrier waveform is compared with two reference signals which are positive and negative signal.The basic idea to produce SPWM with unipolar voltage switching. The different between the Bipolar SPWM generators is that the generator uses another comparator to compare between the inverse reference waveform−Vr

2.9 Three-Phase Inverter

The dc to ac converters more commonly known as inverters, depending on the type of the supply source and the related topology of the power circuit, are classified as voltage source inverters (VSIs) and current source inverters (CSIs). The single-phase inverters and the switching patterns were discussed elaborately in Chapter two and so the three phase inverters are explained in detail here.

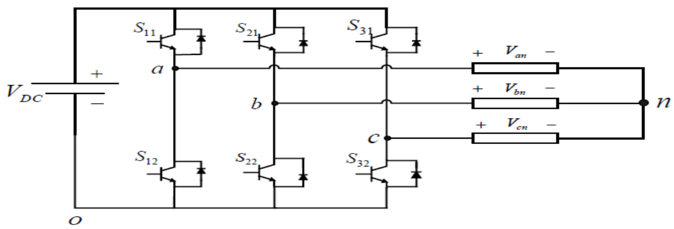


Fig. 2.7 Three-phase Full –Bridge Inverter

The inverter has eight switch states given in Table 4.1. As explained earlier in order that the circuit satisfies the KVL and the KCL, both of the switches in the same leg cannot be turned ON at the same time, as it would short the input voltage violating the KVL. Thus the nature of the two switches in the same leg is complementary. In

Table 2.1: The switching states in a three-phase inverter

S_{11}	S_{12}	S_{31}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0
0	0	1	0	$-V_{DC}$	V_{DC}
0	1	0	$-V_{DC}$	V_{DC}	0
0	1	1	$-V_{DC}$	0	$-V_{DC}$
1	0	0	V_{DC}	0	$-V_{DC}$
1	0	1	V_{DC}	$- V_{DC}$	0
1	1	0	0	V_{DC}	$-V_{DC}$
1	1	1	0	0	0

2.10 Sinusoidal PWM in Three-Phase Voltage Source Inverters

As in the single phase voltage source inverters PWM technique can be used in three-phase inverters, in which three sine waves phase shifted by 120° with the frequency of the desired output voltage is compared with a very high frequency carrier triangle, the two signals are mixed in a comparator whose output is high.

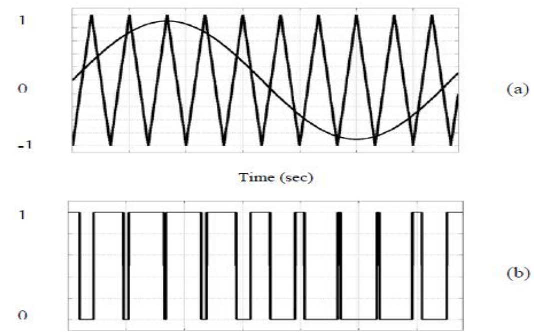
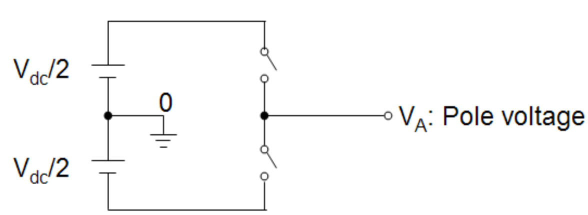


Figure 2.8: PWM illustration by the sine-triangle comparison method (a) sine-triangle comparison (b) switching pulses.

2.11 PWM Techniques

The fundamental methods of pulse-width modulation (PWM) are divided into the traditional voltage-source and current-regulated methods. Voltage-source methods more easily lend themselves to digital signal processor (DSP) or programmable logic device (PLD) implementation. However, current controls typically depend on event scheduling and are therefore analog implementations which can only be reliably operated up to a certain power level. In discrete current-regulated methods the harmonic performance is not as good as that of voltage-source methods. A sample PWM method is described below

.



2.12 ADVANTAGES OF PWM

The output voltage control is easier with PWM than other schemes and can be achieved without any additional components.
The lower order harmonics are either minimized or eliminated altogether.

2.13.1 MULTIPLE PULSE WIDTH MODULATION

The harmonic content can be reduced by using several pulses in each half cycle of output voltage. The generation of gating signals for turning ON and OFF transistors by comparing a reference signal with a triangular carrier wave. The frequency Fc, determines the number of pulses per half cycle. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation (UPWM)

COMPENSATION OF DC OFFSET VOLTAGE AND HARMONICS

3.1 ORIGIN OF LOWER ORDER HARMONICS AND

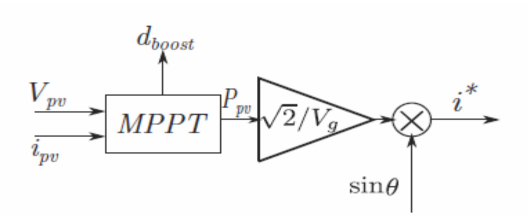


Fig.3.1 Generation of an inverter ac current reference from an MPPT block.

The device drops also will cause a similar effect but the resulting amount of distortion is smaller compared to that due to the dead time. Thus, for a single-phase inverter topology considered, net error voltage is the voltage between the poles and is out of phase with the primary current of the transformer. The harmonic voltage amplitude for an h_{th} harmonic can be expressed as

$$V_{error} = \frac{4}{h\pi} \frac{2V_{dc}t_d}{T_s} \quad (3.1)$$

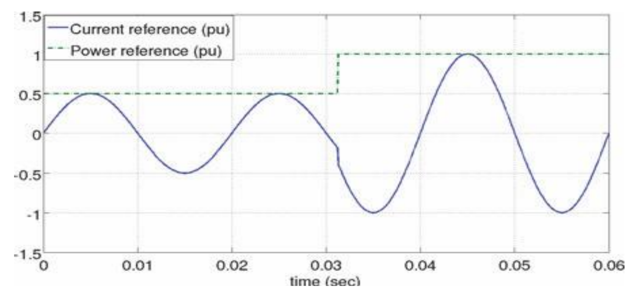


Fig.3.2 Occurrence of nonzero average in current reference due to a fast

Changing power reference from MPPT.

Assume that a certain amount of dc exists in the current control loop. This will result in applying a voltage with a dc offset across the *L*-filter and the transformer primary. The net average current flowing in the filter and the transformer primary loop will be determined by the net resistance present in the loop. This average current will cause a dc shift in the *B*–*H* curve of the transformer. This shift would mean an asymmetric nonlinear saturation characteristic which causes the transformer magnetizing current to lose its half-wave symmetry. The result of this is occurrence of even harmonics. The dc in the system can be eliminated by using the PRI controller which is discussed next.

3.2 Fundamental Current Control

3.2.(a). Introduction to the PRI Controller:

Conventional stationary reference frame control consists of a PR controller to generate the inverter voltage reference. In this paper, a modification to the PR controller is proposed, by adding an integral block, GI as indicated in Fig 3 .3. The modified control structure is termed as a PRI controller.

Here,

$$G_I = \frac{K_I}{S}$$

$$G_{PR}(s) = Kp + \frac{K_r}{s^2 + w0^2}$$

The plant transfer function ismodelled as

$$G_{PRI}(s) = \frac{V_{dc}}{Rs+sLs} \quad (3.2)$$

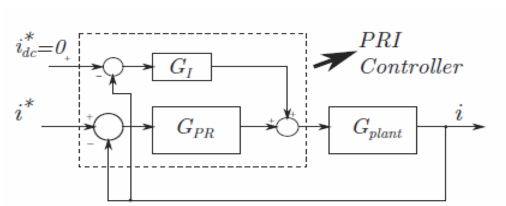


Fig.3.3 Block diagram of the fundamental current control with the PRI controller

This is because the inverter will have a gain of V_{dc} to the voltage reference generated by the controller and the impedance offered is given by (R_s+ sL_s) in s-domain. $R_s$and $L_s$are the net resistance and inductance referred to the primary side of the transformer, respectively. $L_s$include the filter inductance and the leakage inductance of the transformer. $R_s$is the net series Resistance due to the filter inductor and the transformer. The PRI controller is proposed toensure that the output currentof the system does not contain any dc offset. The PRIcontroller introduces a zeroat s = 0in the closed-loop transferfunction. Hence, the output current will not contain any steady statedc offset.

3.2(b) 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. A PR controller is designed for the system assuming that the integral block is absent, i.e., K_I= 0. Design of a PR controller is done by considering a PI controller in place of the PR controller.

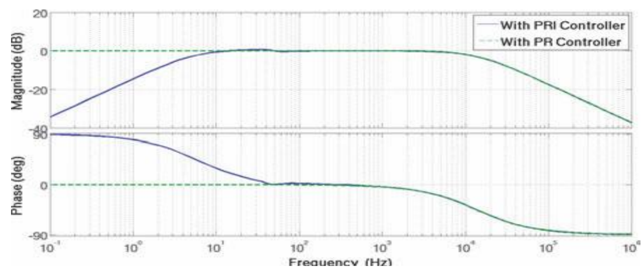


Fig. 3.4. Comparison of a Bode plot of the closed-loop transfer function with the PRI ($G_{cl,PRI}$) and PR controllers ($G_{cl,PR}$).

3.3 ADAPTIVE HARMONIC COMPENSATION

In this section, first the LMS adaptive filter is briefly reviewed. Then, the concept of lower order harmonic compensation and the design of the adaptive harmonic compensation block using this adaptive filter are explained. Next, complete current control along with the harmonic compensation blocks is presented. Finally, the stability considerations are discussed.

3.4 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

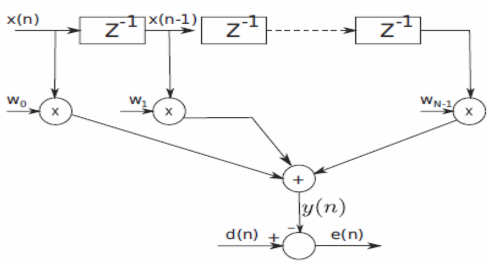


Fig 3.5 Structure of a generalized adaptive filter with adaptation weights w_i

The error signal is

$$e(n)=d(n)-y(n) \quad (3.9)$$

Fig 3.5 represents $x(n)$ input vector samples $y(n)$ de-notes the output of the adaptive filter, $d(n)$ is the desired response, $e(n)$ represents the error signal (estimated error), w_i represents the weighting coefficients vector transversal FIR filter z^{-1} represents a delay. In this work, the input signal in the form of a column vector defined by the equation.

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.

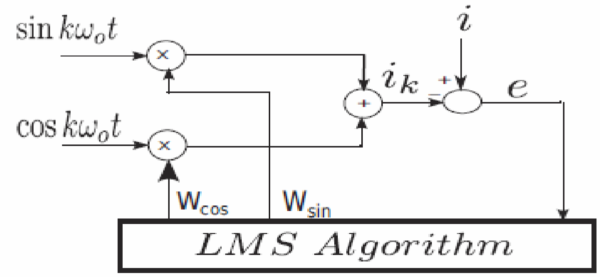


Fig 3.6 Block diagram of estimation of a particular harmonic of grid Current.

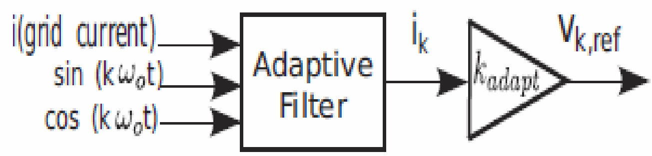


Fig.3.7 Generation of voltage reference from estimated k_{th} harmonic component of current using the LMS adaptive filter.

REFERENCE SIGNAL ESTIMATION TECHNIQUES:

The reference signal to be processed by the controller is the key component that ensures the correct operation of APF. The reference signal estimation is initiated through the detection of essential voltage/current signals to gather accurate system variables information. The voltage variables to be sensed are AC source voltage, DC-bus voltage of the APF, and voltage across interfacing transformer. Typical current variables are load current, AC source current, compensation current and DC-link current of the APF. Based on these system variables feedbacks, reference signals estimation in terms of voltage/current levels are estimated in frequency-domain or time-domain.

3.5 Computation of k_{adapt}:

Based on the estimated net k_{th} harmonic in the grid current, the voltage reference $v_{k,ref}$is generated by multiplying the estimated harmonic with k_{adapt}. The effect of this voltage reference is that it results in an amplified voltage at that harmonic frequency at the inverter terminals and this will inject a current at that frequency in the primary side. The reflected secondary current will oppose the original current that was present in the secondary and hence there will be a net reduction in that particular harmonic in the grid current. Consequently, the primary side current will be more distorted. The amount of reduction of the harmonic in grid current will depend on k_{adapt} .

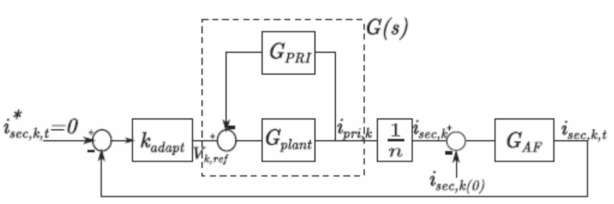


Fig.3.8 Block diagram of k_{adapt}

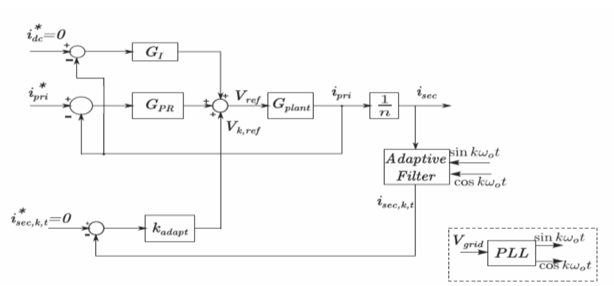


Fig.3.9 Complete ac current control structure of the inverter

3.6 Interaction between the PRI Controller and the Adaptive Compensation Scheme:

It can be recalled that while designing Kp,Kr and K_I, the control block diagram considered did not include the effect of adaptive compensation. In fact, from it can be observed that the primary current control is linked to the adaptive compensation section and the actual transfer function for the primary current control including the model for adaptive compensation

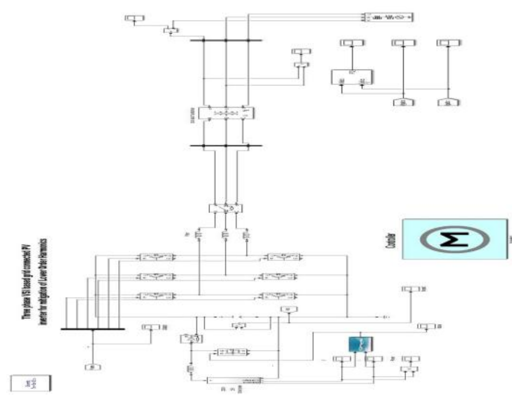


Fig.4.1 simulation Diagram of Three Phase PV Inverter

SIMULATION RESULTS:

Output wave forms of Three-phase circuit:

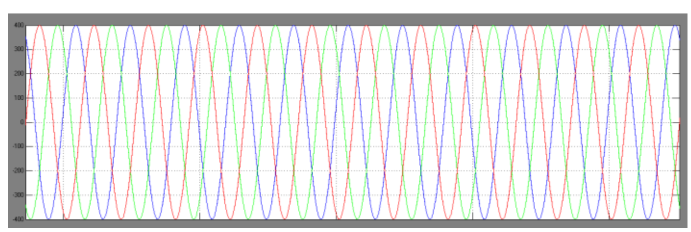


Fig.Inverter Output Voltage For 3-phase With PRI and adaptive filter

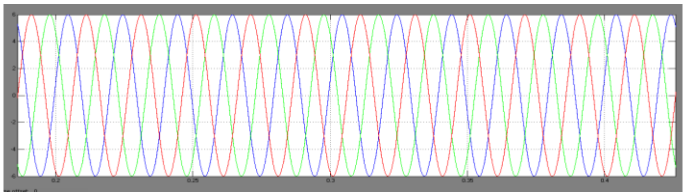


Fig. Inverter Output Current With For 3-phase PRI and Adaptive Filter

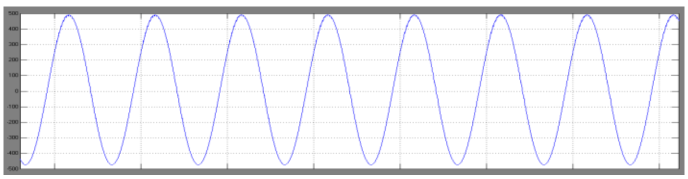


Fig.Per Phase primary side Voltage With PRI and Adaptive Filter

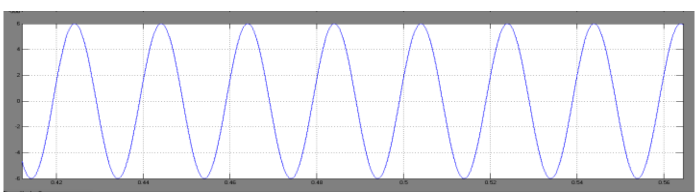


Fig. Per Phase primary side Current With PRI and Adaptive Filter

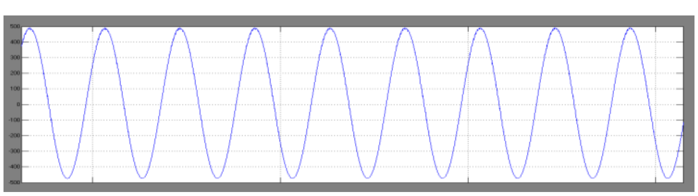


Fig. Per Phase Grid side Voltage with PRI and Adaptive Filter

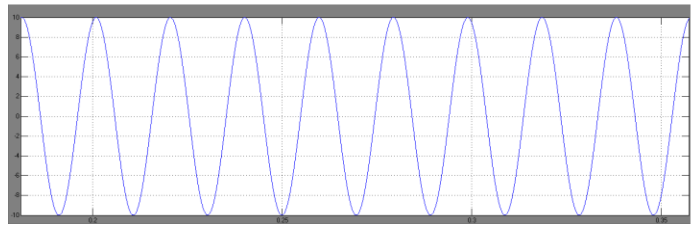


Fig. Per Phase Grid side Current With PRI and Adaptive Filter

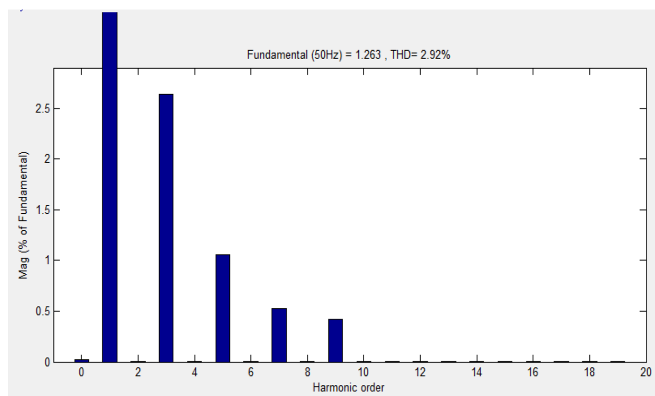


Fig. FFT Analysis of Grid Current (THD)

Conclusion:

Modification to the inverter current control for a grid connected single-phase photovoltaic inverter has been proposed in this paper, for ensuring high quality of the current injected into the grid. For the power circuit topology considered, the dominant causes for lower order harmonic injection are identified as the distorted transformer magnetizing current and the dead time of the inverter. It is also shown that the presence of dc offset in control loop results in even harmonics in the injected current for this topology due to the dc biasing of the transformer. A novel solution is proposed to attenuate all the dominant lower order harmonics in the system.

REFERENCES

[1] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," IEEE Trans. Ind.Appl., vol. 41, no. 5, pp. 1292–1306, Sep./Oct. 2005.

[2] S.G.Jeung and M.-H.Park, "The analysis and compensation of dead time effects in PWM inverters," IEEE Trans. Ind. Electron., vol. 38, no. 2,pp. 108–114, Apr. 1991.

[3] J.-W.Choi and S.K.Sul, "A new compensation strategy reducing voltage/current distortion in PWM VSI systems