LUENBERGER ALGORITHM BASED HARMONICS ESTIMATOR FOR FRONT END RECTIFIER AND PWM-VSI

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Abstract: In contemporary power systems, the one of cause for the disfigurement performance is the non-sinusoidal current and voltage waveforms plunged by the non-linear operations of equipments such as transformer, rotating electric machines, FACTS devices, power electronics components etc. Switched mode power conversions (ac-dc, ac-ac, dc-ac and dc-dc) have proliferated in the today's sophisticated industrial/commercial power systems and the alienation of harmonics causes de-rating, increased losses, mal-function etc. In this paper, a composite observers are devised for estimating the harmonics produced in rectifier- single phase pulse width modulation (PWM) voltage source inverter (VSI) when supplying a critical load. For extraction of fundamentals and harmonics from respective signals, a separate voltage and current observers are employed. Pole placement for current observer must be chosen faster than voltage observer so that inner loop current observer will respond to changes first than the voltage observer. In the proposed work, observer is implemented for the both continuous and discrete time domains. Real time implementation of Luenberger observer for single phase inverter is done in field programmable gate array (FPGA) Xilinx Spartan 3E board XC3S500 FG320. An intuitive harmonic elimination scheme is also suggested.

Keywords: Fast Fourier transform, direct and quadrature axis control, total harmonic distortion, Luenberger algorithm.

I. INTRODUCTION

Harmonics are multiples of fundamental frequency, for example, if ω is the fundamental frequency, then 3ω is a third harmonic component, likewise $n\omega$ is n^{th} harmonic component. These harmonics are produced by power electronic components when it is used for power conversion like ac-dc, dc-ac and so on for various applications and their usage will have various drawbacks [1]. There are four major types of harmonics, viz. (i) Sub-harmonics (harmonics below the fundamental frequency), (ii) Inter-harmonics (harmonics which is not integer multiple of fundamental frequency), (iii) Stationary harmonics (harmonics that do not vary with time i.e., steady state harmonics), and (iv) Non-stationary harmonics (harmonics that vary with time).

To estimate the harmonics, Fourier transform and wavelet transform methods are used, but fourier transform based harmonic estimation will not be accurate, when the system is subjected to an external disturbance, i.e., non-stationary condition [2]. Time varying harmonics and their sources are reported in [3]. Several methods to estimate harmonics such as neural networks [4], Recursive estimation [5]-[8] have been investigated. Composite observer [9] which is nothing but several

Luenberger observers connected in parallel format to extract fundamentals and its harmonics of selected signals. Composite observer will be advantageous when it is compared with FFT based harmonics estimation in stationary condition. To eliminate harmonics, DQ controller is used. In DQ control, a signal from observer is converted into synchronously rotating frame and its output resembles like dc signal. DC signal can be distorted, if harmonics is present in that signal and that erroneous signal is passed through a PI controller to reduce its error to zero, thereby zero steady state error can be achieved. To design DQ controller for single phase inverter, it needs real and imaginary signal unlike the three phase inverter. Hence the imaginary component which is needed for DQ control can be created by observer. A composite observer serves the purpose of estimating the harmonics and also creating an imaginary signal for DQ control of single phase inverter [10]. PI controller gain tuning is found by modelling the single phase inverter and its transfer function plotted in root locus, by Ziegler Nicholas method. Thus, the value of k_p and k_i can be found. FPGA implementation of single phase inverter was reported in [11] and [12].

In this proposed work, a composite observer for in single phase pulse width modulation (PWM) voltage source inverter (VSI) is analyzed. The developed observer for single phase inverter functions well in both continuous and discrete time domains. The single phase VSI in DQ axis is controlled to eliminate harmonics. The performance of the Luenberger observer is corroborated for a prototype single phase VSI supported by the field programmable gate array (FPGA) Xilinx Spartan 3E board XC3S500 FG320.

II. LUENBERGER OBSERVER DESIGN

State space equation for autonomous system is given by

$$X_m = A_m * X_m \tag{1}$$

$$Y_m = C_m^T * X_m$$

where, $A_m = \begin{vmatrix} 0 & m*\omega \\ -m*\omega & 0 \end{vmatrix}$

State vector of m^{th} block

$$X_m(t) = |X_m(t)| = \begin{vmatrix} X_{m1}(t) \\ X_{m2}(t) \end{vmatrix} \tag{2}$$

and $C_{m1}^T = \begin{vmatrix} 1 \\ 0 \end{vmatrix}$

$$Y_{m1}(t) = X_{m1}(t) \tag{3}$$

The closed loop poles are assumed to be equi-dominant and are located at

$$s = (-a\omega 1 + jm.\omega 1) \tag{4}$$

The observation speed and the bandwidth of the observer at the various notches m.ω1, increases with the factor "a", the real part of the observer poles.

$$\left[sI - A + De(t)\right] = 0 \tag{5}$$

Pole placement of observer play an important role in estimating harmonics, and also it depends on the factors like speed and stability. If speed has to be improved, place poles far away from left half of s-plane or if stability is considered, place the poles close to the origin of s-plane for reducing steady state error.

Luenberger observer shown in Fig.2 will estimate fundamental component of current $\hat{Y}$ and it is compared with actual output current of inverter Y and the resulting error is adjusted by gain, which is found by pole placement technique to make the steady state error zero. Observer play role of estimating the harmonics. To eliminate harmonics, we need DQ controller for single phase inverter, which is not easy to convert the output current in stationary frame into synchronously rotating frame as in three phase system. Hence it needs the real and imaginary signals to convert that impedance of inverter into DQ frame. The observer is also used to give real and imaginary signal for DQ control as shown in Fig.3. Output of the observer will not be in phase with its input, hence PLL synchronizing block is used to synchronize both the output and input so that imaginary signal will be made zero. This is shown as block diagram in Fig.4. Inverse park transform, shown in Fig.5, is used to give control signal which is compared with triangular carrier of frequency 10 kHz to give triggering pulse to the MOSFET.

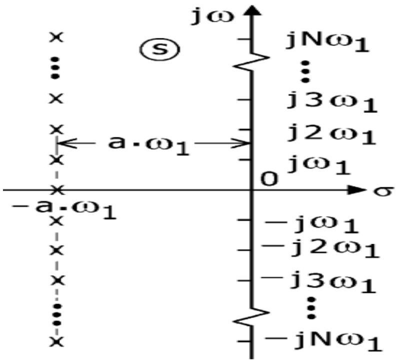


Figure 2.1. Observer design in continuous time domain

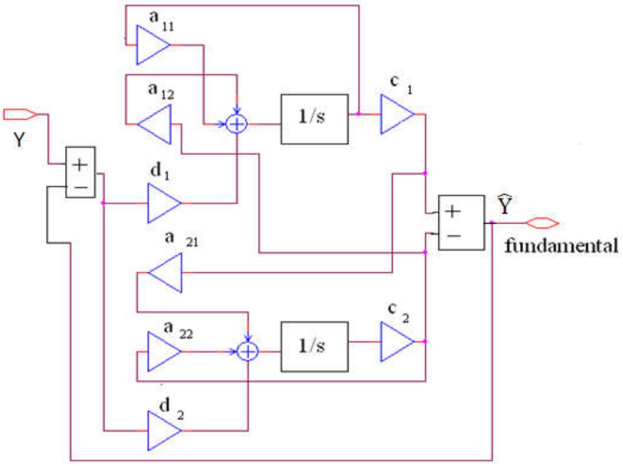


Figure 2.2 Block diagram of Luenberger observer for fundamental extraction

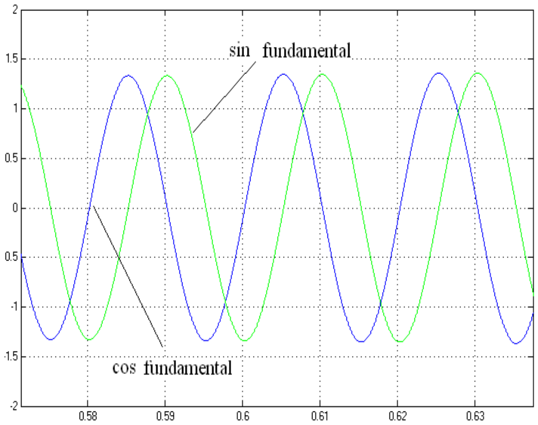


Figure 2.3 Real (sin) and imaginary (cos) signals for DQ control

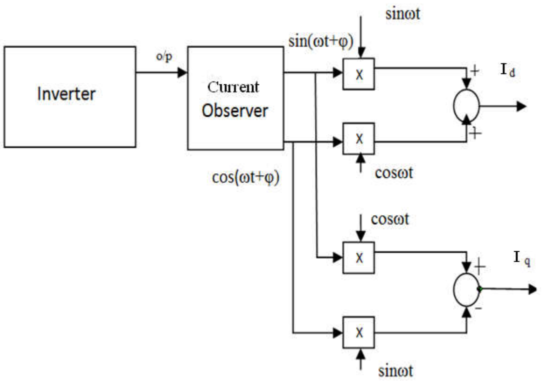


Figure 2.4 Block diagram of DQ controller

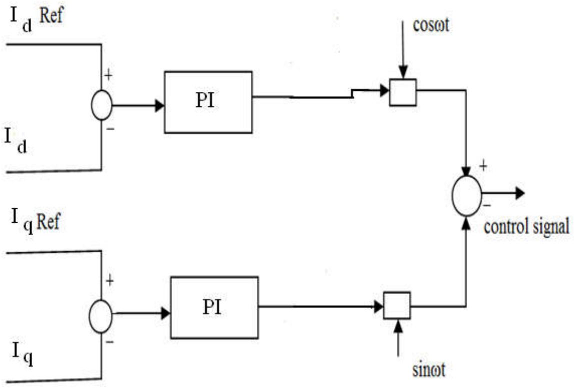


Figure 2.5 Block diagram of Inverse park transform

III. SIMULATION RESULTS

Simulation is carried on MATLAB-Simulink. The DC link voltage to the inverter (V_{dc}) is considered as 200V, load resistance is 100 Ω. Observer poles are selected optimumially so that it offers lesser total harmonic distortion (THD). Poles closer to the left half of the s-plane will make the operation fast, but response becomes sluggish, hence poles are placed at 5ω. Since, separate observer is used for voltage and current, the current observer should respond first to ensure that poles for current observer are placed at 0.1. The key specifications of VSI employed in simulation is listed in Table 1

Table 3.1 Inverter parameter for simulation

Input supply (DC Link)	200 V
Triangular frequency	10 kHz
Sampling frequency	20 kHz
Resistive load	100 Ω

3.1. Single phase square wave inverter

Square wave inverter shown in Fig.6 is simulated to estimate harmonics for various ranges of amplitude and frequency modulation index. Observer output is analyzed with FFT to test the performance of observer in stationary condition and its corresponding outputs for various modulation indices are shown in Figures 8, 10, 12, 14 and 16. Square wave inverter is used, since it will produce more harmonics than sine wave inverter. As the amplitude modulation index increases, fundamental component of output current increases and magnitude of its harmonics reduces.

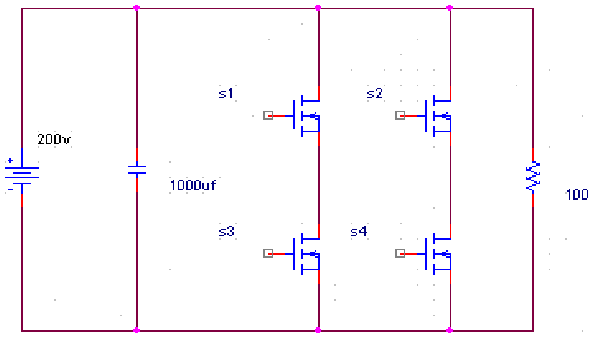


Figure 3.1 Square wave single phase inverter topology in H-bridge

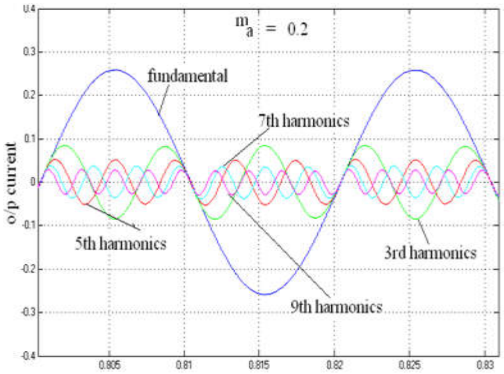
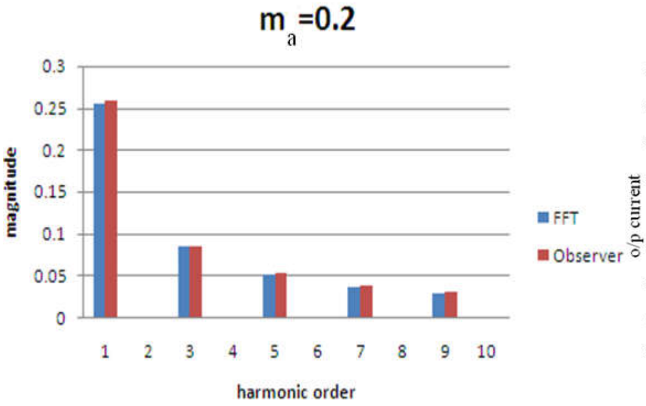


Figure 3.2 Separation of fundamentals & harmonics using observer for $m_a = 0.2$



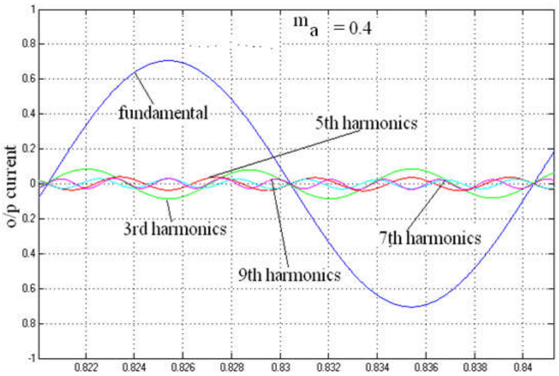
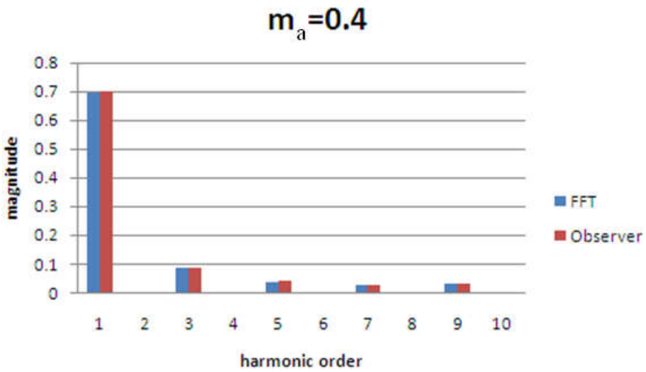


Figure 3.3 Comparison between observer & FFT for harmonic estimation ($m_a = 0.2$)

Figure 3.4 Separation of fundamentals & harmonics using observer for $m_a = 0.4$



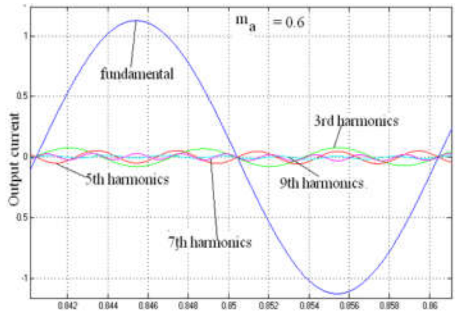
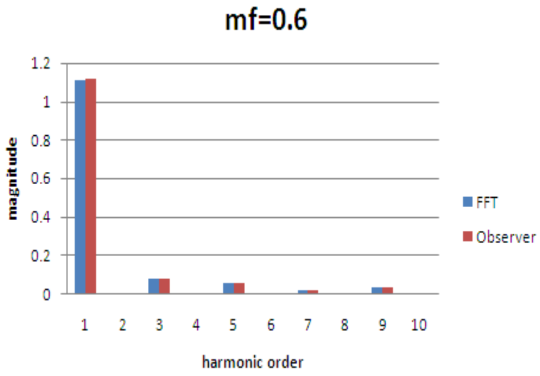


Figure 3.5 Comparison between observer & FFT for harmonic estimation ($m_a = 0.4$)

Figure 3.6 Separation of fundamentals & harmonics using observer for $m_a = 0.6$



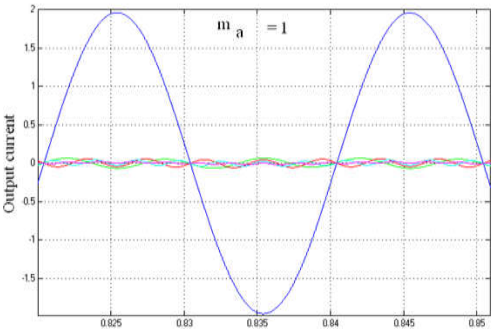


Figure 3.7 Comparison between observer & FFT for harmonic estimation ($m_a = 0.6$)

Figure 3.8 Separation of fundamentals & harmonics using observer for $m_a = 1$.

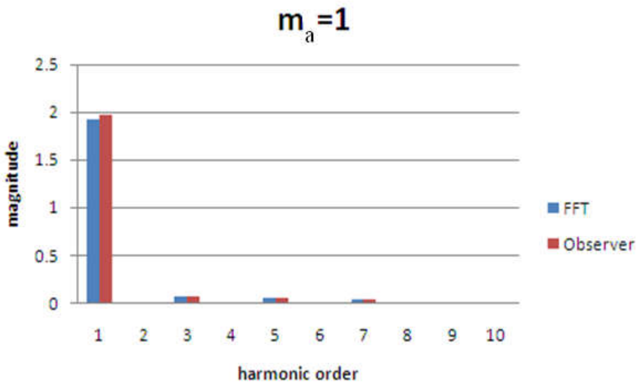


Figure 3.9 Comparison between observer and FFT for harmonic estimation ($m_a = 1$)

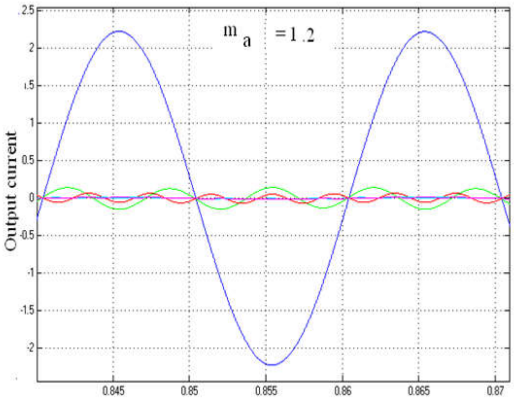


Figure 3.10 Separation of fundamentals & harmonics using observer for $m_a = 1.2$

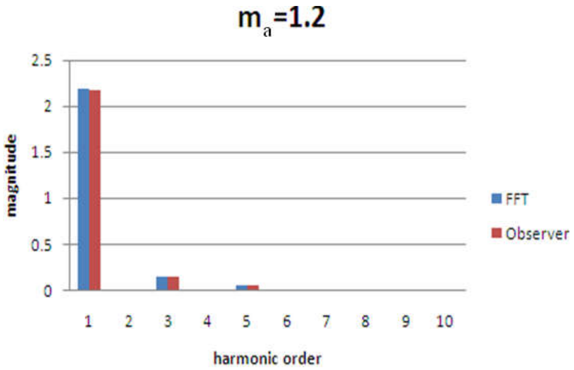


Figure 3.11 Comparison between observer & FFT for harmonic estimation ($m_a = 1.2$)

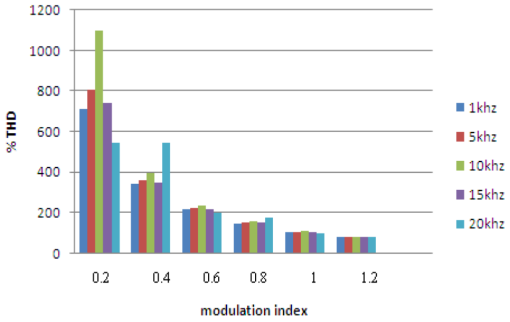


Figure 3.12 Comparison between %THD & amplitude modulation index for various carrier frequency ranges.

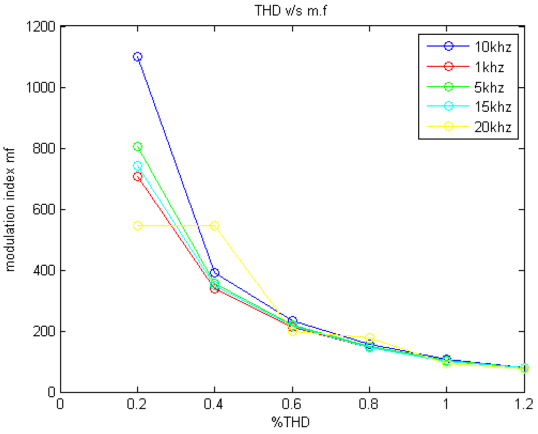


Figure 3.13 Comparison of THD with frequency modulation index

3.2. Single phase controlled rectifier

Rectifiers are used for power conversion from dc to ac. These loads will draw harmonics current and it will inject harmonics voltage into source, hence utility will get affected when rectifier is used as load. Some of the rectifier applications at home are TV, Computer, etc. Hence, Luenberger observer is used for estimation of harmonics produced by rectifier when it is fired at $\alpha = 0^0$ and 120^0. Higher value of firing angle will make the current discontinuous and it will produce more harmonics. The observer based estimated harmonics results are shown below.

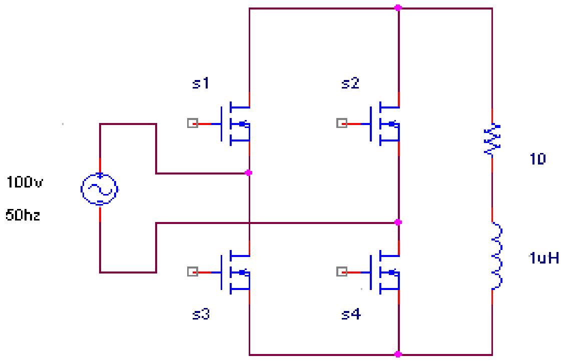


Figure 3.14 Single phase controlled rectifier topology

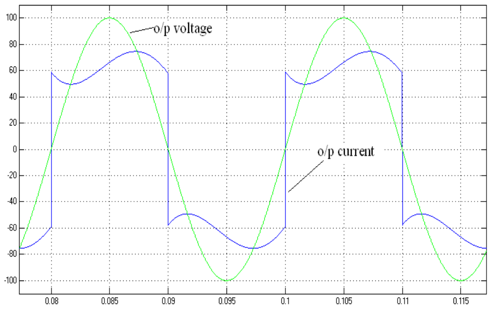


Figure 3.15 Input voltage and current for single phase rectifier fired at α=0^0

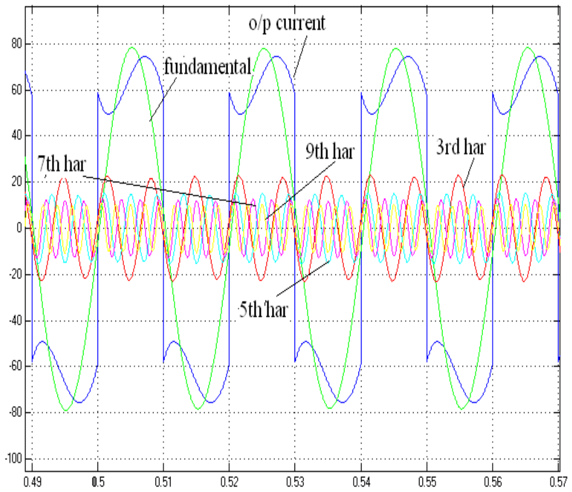


Figure 3.16 Observer extracting harmonics from input current for single phase rectifier fired at α=0^0

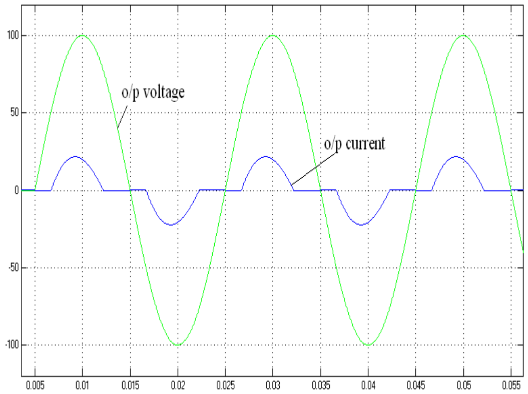


Figure 3.17 Input voltage and current for single phase rectifier fired at α=120^0

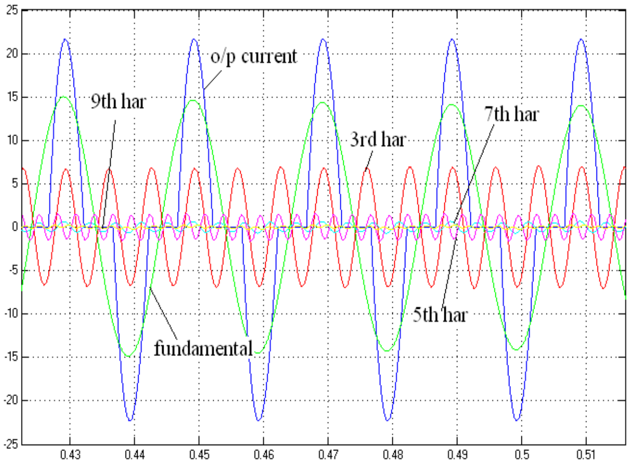


Figure 3.18 Observer extracting harmonics from Input current for single phase rectifier fired at α=120^0

3.3. Elimination of harmonics using DQ controller for inverter

Since, observer is used only for estimation of harmonics, it will not eliminate the harmonics. To eliminate the harmonics, a DQ controller is used and its design has been discussed earlier. A DQ controller is designed to convert output current in stationary frame into a synchronously rotating frame and its output is shown below. Error of DQ controller will be reduced by PI controller and its gain values are achieved by Ziegler Nicholas method.

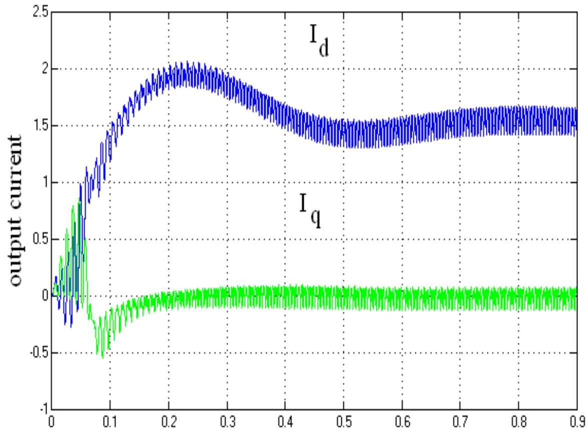


Figure 3.19 Direct and quadrature current waveform of park transform

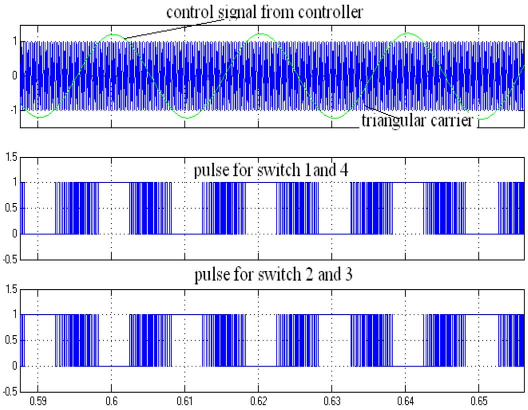


Figure 3.20Pulse generation for single phase inverter to eliminate harmonics

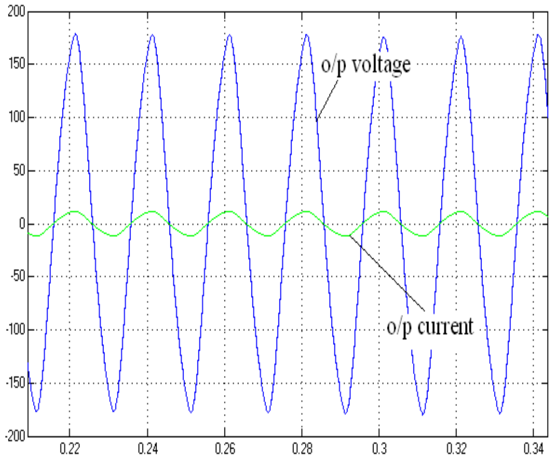


Figure 3.21 Output voltage and current of single phase inverter

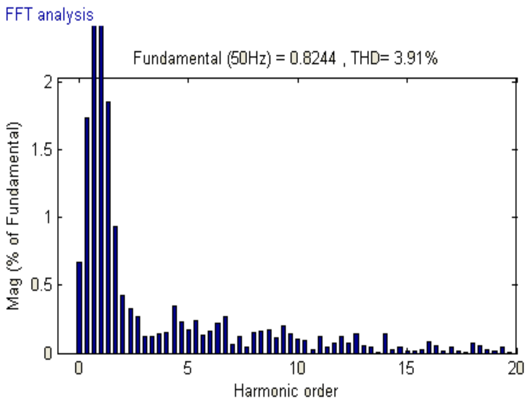


Figure 3.22 FFT analysis of single phase inverter with R load

Table 3.2 Simulation results

Load	%THD for voltage and current without controller		%THD for voltage and current with controller	
R (20 Ω)	35.25	36.25	3.91	3.70
RL (20Ω, 10mH)	39.65	41.68	4.57	7.20

Observer based harmonics estimation play an important role in power electronics, since to overcome the drawback of FFT in non-stationary condition. In simulation, observer based harmonics estimation will settle after 0.7s. Initially it will oscillate and values for harmonics are measured when observer output settles.

IV. HARDWARE SETUP AND RESULTS

Composite observer algorithm can be coded in VHDL language and that VHDL code is synthesized in Xilink ISE to generate bit file. Digilent Adept Software is used to download the bit file to program Xilink Spartan 3e board xc3s500e 5fg320. The FPGA based control system hardware has been programmed to control the output voltage of the single phase Inverter. The frequency of pulse being produced is 10 kHz. The PWM signals of the FPGA board are applied to the gate of MOSFET through gate driver circuit. The gate driver provides isolation, low impedance and high current supply to drive the MOSFET. The ordinary SPWM technique will not produce pure sinusoidal output voltage, but LC filters can be used to eliminate harmonics, but the cost of L and C will increase with output voltage to be controlled; hence, observer based harmonics elimination technique will be helpful in such economical condition. MOSFET IRF 840 was used to build single phase inverter in H bridge topology. The hardware setup was built in prototype of lesser rating whose value are tabled below and their results are analyzed.

Table 4.1 Hardware components

Components	Ratings
Input supply	28 V
Capacitor	1000 µf., 200 V
Inverter	MOSFET (IRF 840)
LC filter	L = 1 mH, C = 63 µF

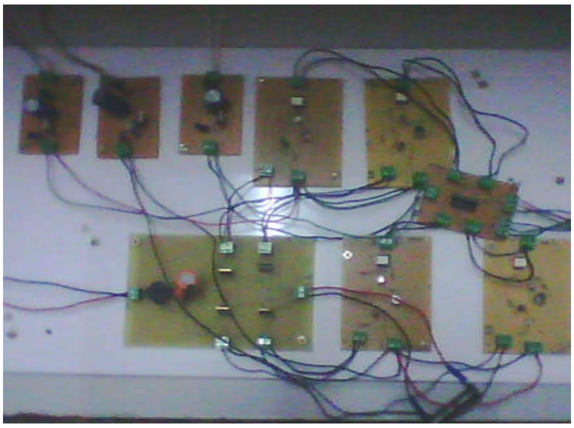


Figure 4.1 Overall view of single phase inverter

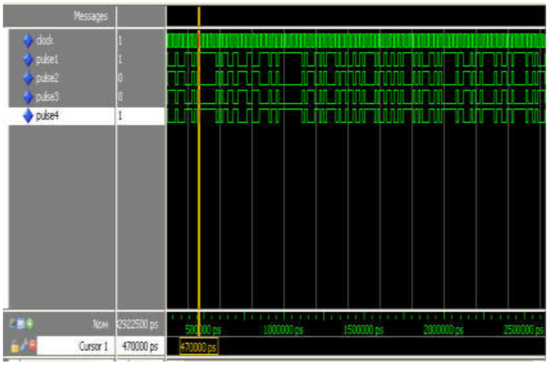


Figure 4.2 Observer based control pulse in modelsim

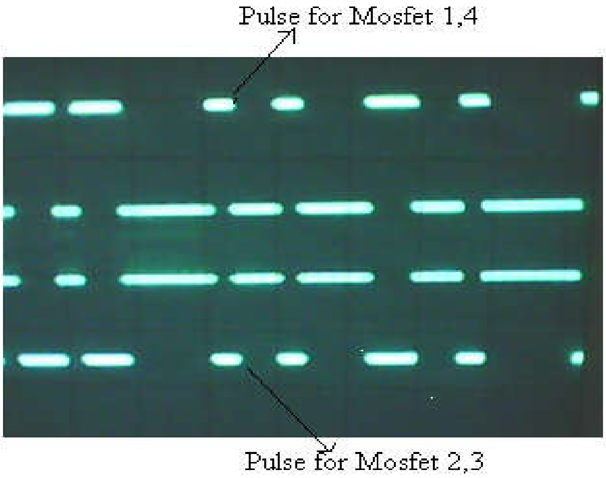


Figure 4.3 Observer based pulse for single phase inverter

The pulse obtained from FPGA board directly will not able to be triggered the MOSFET; hence, a driver circuit is used to boost its voltage upto to 10 V, so that its gate voltage is greater than the drain to source voltage. Hence, the MOSFET will be brought into conduction state. The pulses obtained from observer will be of unequal width which helps to reduce the harmonics.

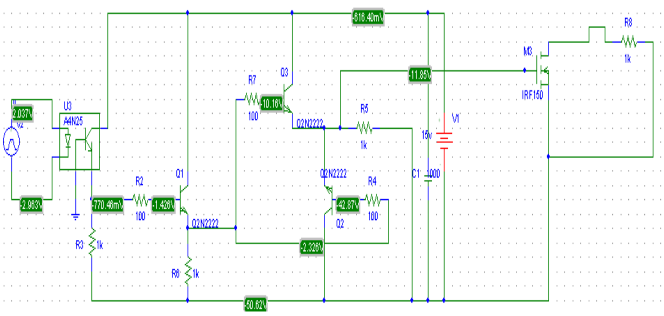


Figure 4.4 Psipce model of driver circuit

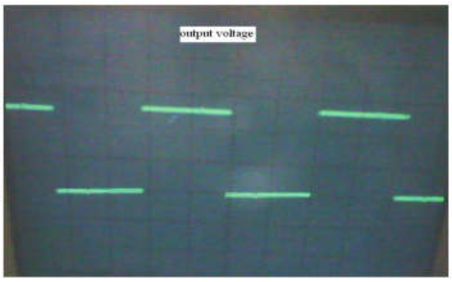


Figure 4.5 Output voltage of single phase inverter with ordinary SPWM technique (28V/div, 2 ms/div)

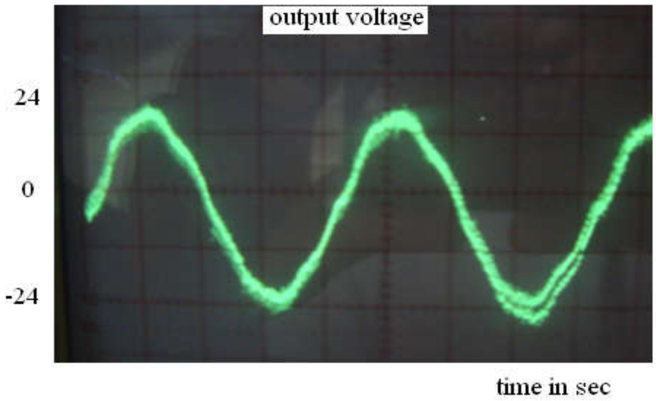


Figure 4.6 Output voltage of single phase inverter with observer based control technique (26V/div, 2 ms/div)

V. CONCLUSION

A Single phase square wave inverter supplying resistive load has its output voltage signal as square wave and hence it contains more harmonics. Therefore, observer based harmonics estimation compared with FFT for various ranges of amplitude and frequency modulation index found to be matched with FFT in stationary condition. The observer performance in non-stationary condition was not analyzed, but observer estimation is accurate in non-stationary condition where FFT based estimation fails. Hence, observer based harmonics control ensures harmonics within their limits, as per IEEE standard %THD should be less 5%. When load resistance increases, %THD also increases. D-Q control of single phase inverter ensures zero steady state error. By providing separate observer for voltage and current signals, it is possible to reduce voltage and current harmonics separately, and for non-linear loads, harmonics current drawn by its load will cause harmonics voltage to flow into the utility and affect the power factor, hence, both harmonics voltage and current compensation is needed here. Most of the residential loads such as refrigerators, freezers, washing machines, etc., requires current type compensation and loads such as T.V., computers, etc., requires voltage type of compensation.

Observer based harmonic estimation can be used only for known fundamental frequencies i.e., 50Hz and further sub-harmonics and inter-harmonics are not considered in observer design, hence, some other controllers have to be incorporated to eliminate sub-harmonics and inter-harmonics.

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