DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

REACTIVE POWER COMPENSATION

by

Olcay BALAMAN

October, 2012
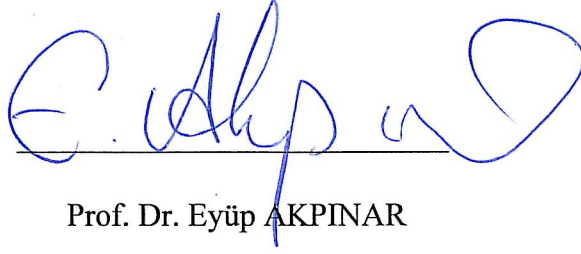
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REACTIVE POWER COMPENSATION

A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of Science in
Electrical and Electronics Engineering

by
Olcay BALAMAN
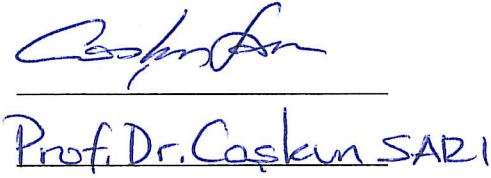
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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"REACTIVE POWER COMPENSATION"** completed by **OLCAY BALAMAN** under supervision of **PROF. DR. EYÜP AKPINAR** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.
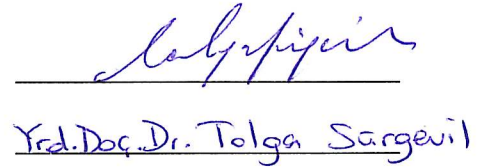
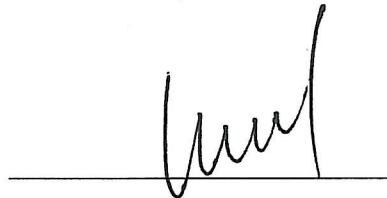Prof. Dr. Eyüp AKPINAR

Supervisor

Prof. Dr. Coşkun SARI

(Jury Member)

Yrd. Doç. Dr. Tolga Sargevil

(Jury Member)

Prof. Dr. Mustafa SABUNCU
Director
Graduate School of Natural and Applied Sciences

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REACTIVE POWER COMPENSATION

ABSTRACT

In this thesis, a single phase pulse width modulated (PWM) rectifier with instantaneous reactive power theory for single phase case, which is a commonly used method for three-phase networks, is designed and simulated for reactive power compensation. Direct and indirect control techniques of single phase instantaneous reactive power theory (p-q theory) are simulated with linear and nonlinear loads.

A model of the system is developed in MATLAB / Simulink software and the performance of hysteresis current controller is analyzed. Simulations are carried out in MATLAB / Simulink. The Simulink block diagrams are converted from MATLAB into TMS320F2812 eZdsp. The Matlab Simulink simulations and DSP based simulations are compared.

The system is implemented in Electrical Machinery Laboratory.

Keywords: Compensation, instantaneous reactive power, pwm rectifier, DSP F2812

REAKTİF GÜÇ KOMPANZASYONU

ÖZ

Bu tezde, üç faz sistemlerde yaygın olarak kullanılan anlık reaktif güç teorisinin tek faz bir sistem için yeniden elde edilmiş biçimi reaktif güç kompanzasyonu için uygulanmıştır. Tek faz darbe genişlik modülasyonlu (PWM) doğrultucu ile birlikte tasarımı ve simülasyonları yapılmıştır. Tek faz anlık güç teorisinin doğrudan ve dolaylı kontrol teknikleri, doğrusal ve doğrusal olmayan yükler ile birlikle simülasyonu yapılmıştır.

Sistem modeli Matlab / Simulink programı kullanılarak geliştirilmiştir ve Histerisiz akım kontrolunun performans analizi yapılmıştır. Simülasyonlar Matlab Simulink kullanılarak yapılmıştır. Simulink blok diagramları Matlab programından TMS320F2812 eZdsp ye dönüştürülmüştür. Matlab Simulink simülasyon sonuçları ve DSP tabanlı simülasyon sonuçları karşılaştırılmıştır.

Tasarlanan sistem Elektrik Makinaları Labaratuarında uygulanmıştır.

Anahtar sözcükler: Kompanzasyon, anlık reaktif güç, darbe genişlik modülasyonlu doğrultucu, DSP F2812

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CHAPTER ONE
INTRODUCTION

In recent years, power quality has become a serious problem in power systems with the increment of non-linear loads that draw non-sinusoidal currents and reactive power. Widespread use of power electronics components in electrical devices and industrial applications has become dominant effect in power quality. According to the working principles of power electronics components, there is no linear relationship between the applied voltage and drawn current, these circuit components are called non-linear components and loads that include these components are called non-linear loads. These types of loads draw non-sinusoidal currents from the network. Non-sinusoidal currents cause harmonic pollutions in electric systems. Passive or active filters are generally used to reduce or totally compensate the harmonic currents of non- sinusoidal loads. Although passive filters are not sufficiently efficient in terms of performance and size, active power filters (APF) can be utilized to compensate the reactive power, can be mitigating the harmonics provided from the load and regulating the voltage simultaneously. Because of the advantages mentioned above, active power filters have been a popular even though they are more expensive than passive filters.

This technology can be categorized into two main groups: single-phase or three-phase units. The single phase loads, which have harmonic and reactive components, can be compensated by using single-phase units to balance power quality problems. The most important parts for a single-phase system are reactive power and current harmonics, which are the major concerns for a power distribution system (Khadkikar, Chandra, & Singh, 2009). Three phase units are generally used for high power applications.

The basic operating principles of active power filters and reactive power compensating units are producing currents and/or voltages having the same amplitude and opposite phase with the harmonics and reactive power that non-linear load produce and also conveying these currents and/or voltages to the system using

power electronics components. Hence, the active power filters and static reactive power compensating systems are utilized to compensate load current related problems, such as reactive power and current unbalance, and harmonics. The active power filters can be mainly categorized into two parts: Series or parallel APFs. The parallel APFs, which are also named as shunt APFs, are used to compensate current unbalance and harmonics and reactive power.

Many control techniques such as the instantaneous p–q theory, notch filter, P–I method, sliding mode control, the synchronous d–q reference frame method and the frequency domain method have been introduced and applied to various configurations of active filters (Akagi, Watanabe, & Aredes, 2007, pg. 53, Vardar, 2009).

The p-q theory was firstly presented by Akagi, Kanazawa & Nabae (1983, 1984). The control methodologies of reactive power theory with PWM converters are presented by Akagi, Nabae & Satoshi (1986). Different types of the control algorithms are used in the applications and the results are compared in case of reactive power and harmonic currents of the active filter by Takeda, Ikeda & Tearamoto (1988). Instantaneous reactive power theory in single-phase system is performed. The single-phase p-q theory for the purpose of reactive power and harmonics compensation in case of single-phase loads is dealt and DSP based experimental results is discussed by Khadkikar, Chandra & Singh (2009).

The main objective of this thesis is to use Instantaneous Reactive Power Theory, which is a commonly used method for three-phase networks, for single phase case. A model of the system is built up by MATLAB / Simulink software and the performance of classic hysteresis band current controller is analyzed.

Classification of reactive power compensation is presented in chapter two. In chapter three, Instantaneous Reactive Power Theory that is a used to extract reference current is explained. In chapter four, the model of single phase system in MATLAB is explained. Then the MATLAB / Simulink program is converted to the

ones required for the DSPF2812 in chapter five. Finally, conclusions of the study are explained in chapter six.

CHAPTER TWO
REACTIVE POWER COMPENSATION TECHNIQUES

Reactive power compensation is an important subject in power electronic systems. In recent years static controllers and power electronics components are used in compensation to increase the capacity and controllability of transferred power and to satisfy the reactive power demand of the system efficiently. Devices that are used for compensation such as semi-conductor based switching type inverters and shunt reactive compensators are called FACTS (Flexible AC Transmission Systems).

FACTS (flexible ac transmission systems) controllers, which are based on high speed power electronics devices, are faster than traditional mechanical controllers. In these systems, static var compensators (SVCs) are used with fast response time characteristics to overcome compensation problems.

FACTS devices do not need capacitor or reactor groups to produce or absorb reactive power in the compensation of transmission lines. Many applications have been developed to enhance the stability of power systems with the utilization and development of FACTS devices in power transmission systems. FACTS devices can be used to increase the stability of the system and to control power flow. The main advantages of these devices are their flexibility and controllability. They are mainly implemented to increase the voltage stability, voltage control of power systems and to enhance the stability of power systems. These applications can be done with controlling the phase angle and voltage level.

FACTS instruments such as STATCOM, SSSC (Static Synchronous Series Compensator) and UPFC (Unified Power Flow Controller) reveal new power electronics equipments to control and increase the performance of power systems. These instruments are also known as new reactive power controllers instead of traditional VAR compensators like Thyristor-Switched Capacitor (TSC) and Thyristor-Controlled Reactor (TCR). If voltage-sourced converters are used these static VAR compensators are named as STATCOM or STATCON.

Loads absorb active and reactive power from the systems depending on their characteristics. Real power is the useful one but reactive power has to be compensated to ensure an efficient power system by improving the performance.

Generally, the principle of reactive power compensation is load compensation and voltage regulation. To improve the power factor, elimination of the current harmonics and balancing the system are the main aims of reactive power compensation. Dynamic reactive power compensation has been a rarely used technique in consequence of the developing technology in the power electronics components like Thyristor or GTO.

2.1 Reactive Power Compensation Principles

There are two ways of the implementation of the reactive power compensation: series connection or parallel (shunt) connection.

Parallel connected systems are generally used for reactive power compensation and to filter current harmonics whereas serial connected systems are used to filter voltage harmonics, voltage regulation and harmonic isolation.

2.1.1 Shunt Compensation

The shunt compensation system can be developed basically with a voltage source, nonlinear load and a shunt connected power system as shown in Figure 2.1.
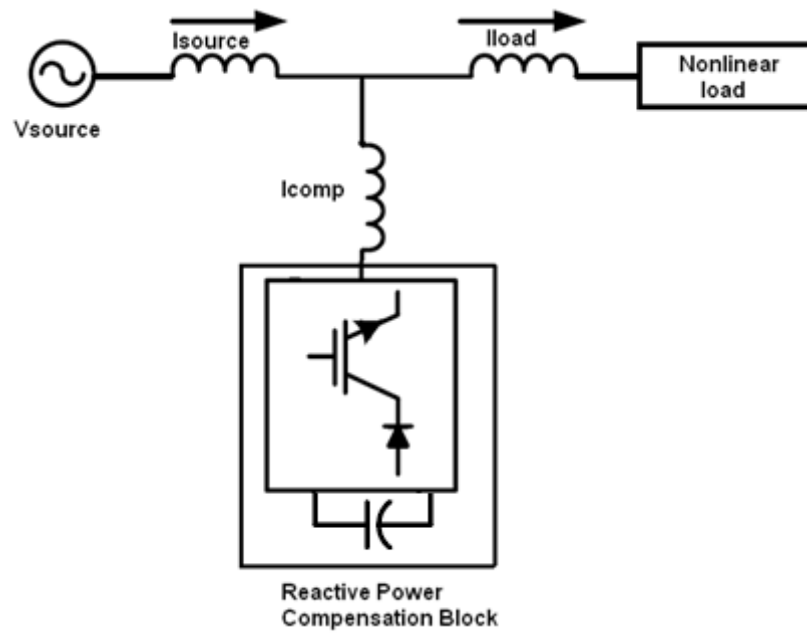
Figure 2.1 Parallel (shunt) connection

In this system, if the nonlinear load is inductive load, the power system need reactive power for precise operation as a consequence this demand should be delivered by the voltage source.

By connecting the shunt system, compensating current (Icomp) is injected with opposite direction at equivalent magnitude to the system and hence the reactive current of the load is compensated, voltage regulation is improved and the unity power factor can be reached (Dixon et al, 2005).

The most common shunt compensation systems are;
- Static VAR compensator (SVC)
- Static synchronous compensator (STATCOM)

2.1.2 Series Compensation

The series compensation system can also be developed basically with a voltage source, nonlinear load and a series connected power system as shown in Figure 2.2.
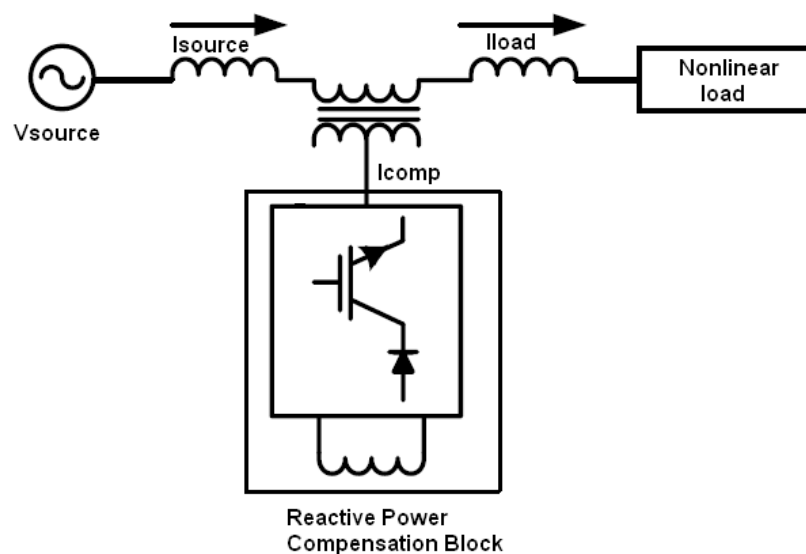
Figure 2.2 Series connection

In series compensation, the system can also be developed with a current source or voltage source. Figure 2.2 shows the series compensation with a current source to have unity power factor.

2.2 Static Var Compensators

Static VAR compensators (SVCs) are composed of shunt reactors and capacitors and mostly thyristor controlled systems and these systems satisfy fast response for regulating voltage and stabilizing in electric systems. SVCs can be accepted as the Flexible AC transmission system (FACTS) and, are used to make the system closer to unity power factor.

Capacitors produce reactive power and inductors absorb reactive power when they are connected to an AC power system. They are used with mechanical switches to control reactive power. In recent years, with the improvement of high power semi-conductors like thyristors, developments are observed in reactive power compensation. The systems that are composed with the use of semi-conductors are called static var generators.

The thyristor controlled static var generators that are used today obtain varying shunt impedance by inserting and ejecting capacitors and/or reactors to the network. Output of var generator can be changed to inductive from capacitive with the use of proper switching techniques.

In power systems, SVCs are generally used for voltage regulation and load compensation. The main purpose is to reduce the reactive power requirement at load side and to stabilize the real power absorbed from the AC supply.

SVCs are also used for regulating the system voltage in transmission applications. If the load is capacitive thus leading in the power systems, thyristor controlled reactors (TCRs) are used to absorb vars from the system thus reducing the system voltage. If the load is inductive thus lagging, thyristors switch on the capacitor banks thus increasing the system voltage. By connecting the TCR, which is continuously variable, along with a capacitor bank step, the net result is continuously-variable leading or lagging power.

SVCs have quick response and are reliable when compared with mechanically switched compensation techniques or synchronous condensers. However, they are high priced systems than these two types.

SVCs can be classified as; Thyristor switched capacitor (TSC), Thyristor controlled reactor (TCR), and Mechanically switched capacitor (MSC).

2.2.1 Thyristor-Controlled Reactor (TCR)

The thyristor and the reactor are connected in series. The equivalent reactance is changed incessantly by controlling the phase angles. For lower order harmonics, a capacitor is placed in the TCR compensator block. A simple configuration of TCR block is shown in Figure 2.3 (Kocamış, 2009).
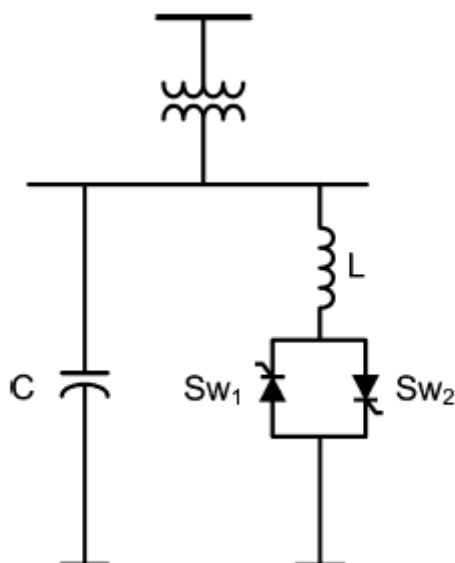
Figure 2.3 Thyristor Controlled Reactor

Compensation of the reactive power according to the varying loads is achieved by adjusting α. Basically, the disadvantage of TCR system is lower order harmonics therefore this makes using large harmonic filters.
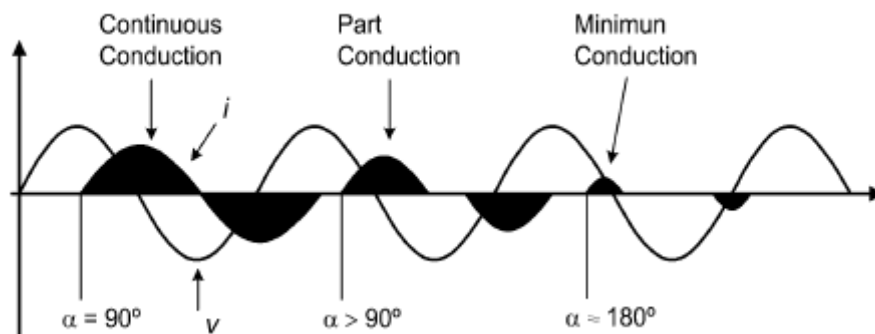

Figure 2.4 Results for different thyristor phase shift angles, α in TCR system.

2.2.2 Thyristor-Switched Capacitor (TSC)

The thyristor and the capacitor are connected in series and the equivalent reactance is changed in step by step. The basic block diagram of TSC is shown in Figure 2.5 below.
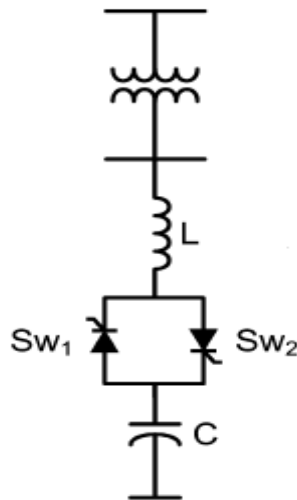
Figure 2.5 Thyristor Switched Capacitor

In three phase systems, each phase consists of thyristor switches (Sw1 & Sw2) and a capacitor. Also L can be placed to limit fault current through the thyristors and prevents resonance in the system.

This static var compensator system has disadvantages like var compensation is done step by step and each capacitor bank requires a separate thyristor switch which increase the cost (Dixon et al, 2005).

2.2.3 Mechanically Switched Capacitors

Mechanically switched capacitors were first used for power factor correction. Shunt capacitors are chosen depending on the total lagging reactive power absorbed by the load.
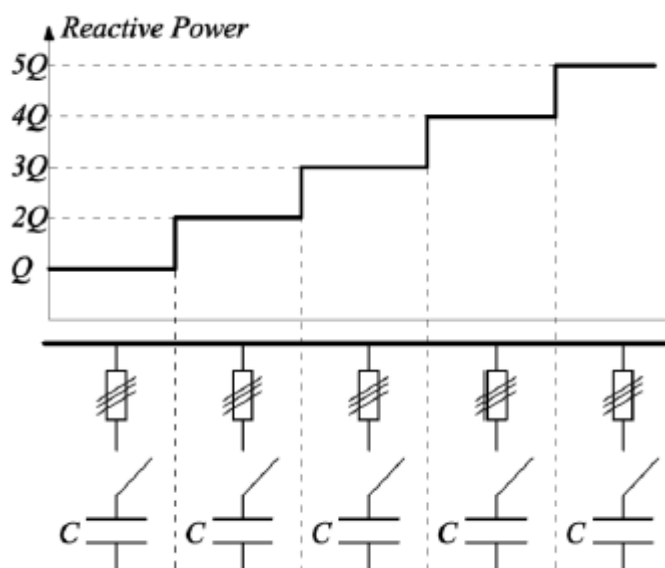
Figure 2.6 Mechanically Switched Capacitor Banks

Capacitors are switched on or switched off depending on the total Var requirement in the system. The reactive power is produced step by step according to the demand on the system. However, due to the delay in mechanical switches, the system response is not reliable and slow.

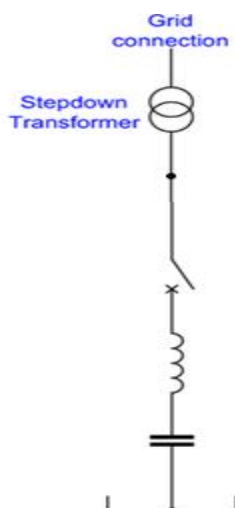An example of mechanically switched capacitor can be seen in Figure 2.7.

Figure 2.7 Mechanically switched capacitor

2.3 Synchronous Condensers

Synchronous condenser or synchronous compensator has an important part in reactive power compensation until 1970s. In these systems, synchronous machine is connected to the power system. After the synchronization of the synchronous compensator and the power system, according to the reactive power demand, the field current is arranged to produce or absorb reactive power for the system. One of the disadvantages of this system is slow response and higher losses. By changing the excitation current, reactive power requirement can be controlled. The main purpose to use synchronous condenser is to enhance stability and voltage regulation at different load conditions at transmission or distribution (Dixon et al, 2005).
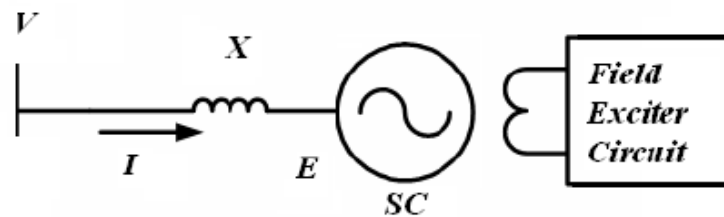

Figure 2.8 Synchronous Compensator

When the synchronous condenser is connected to the ac system and is under excited, it functions like an inductor, absorbing reactive power from the ac system. But if it is overexcited, it functions like a capacitor and injecting reactive power into the ac system.

Their losses and cost are much higher when compared with other SVC systems. Their advantage is the high temporary overload capability.

2.4 STATCOM

Static synchronous compensators (STATCOMs) are also known as static condenser (STATCON). STATCOM is one of the most preferred controllers among

FACTS devices. STATCOM is shunt connected reactive power equipment that can control the three phase voltage and phase angle quickly as it uses power electronics components.

With the improvement of semiconductor devices, STATCOMs are widespread research area to absorb or generate reactive power without using large capacitor or reactor banks. They also provide fast response reactive compensation among the FACTS controllers. Many approaches are available with voltage source converters (VSCs) and current source converters (CSCs). In Figure 2.9 and Figure 2.10, CSC and VSC topologies are implemented respectively.
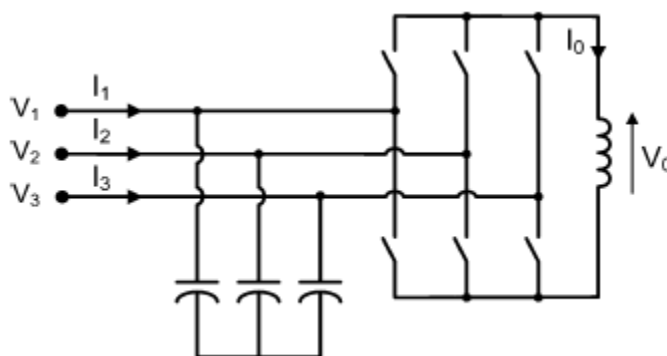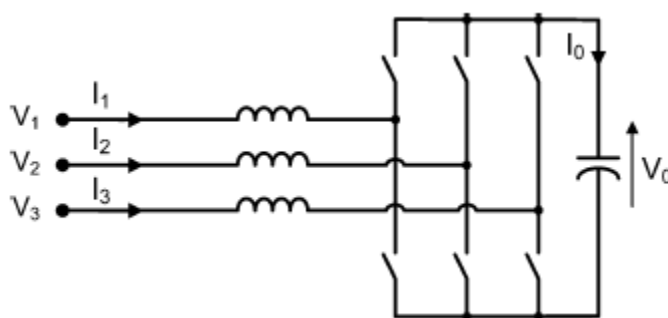

Figure 2.9 CSC topology

Figure 2.10 VSC topology

STATCOM is generally used for improving the power factor and voltage regulation. Generally a statcom is composed of a voltage source converter (VSC), with a reactor, switching devices and a voltage source.

An example of voltage source converter based STATCOM is shown Figure 2.11 which is implemented with an inverter, semiconductor devices and DC capacitor, and these devices are connected to the system in parallel through a coupling reactor.
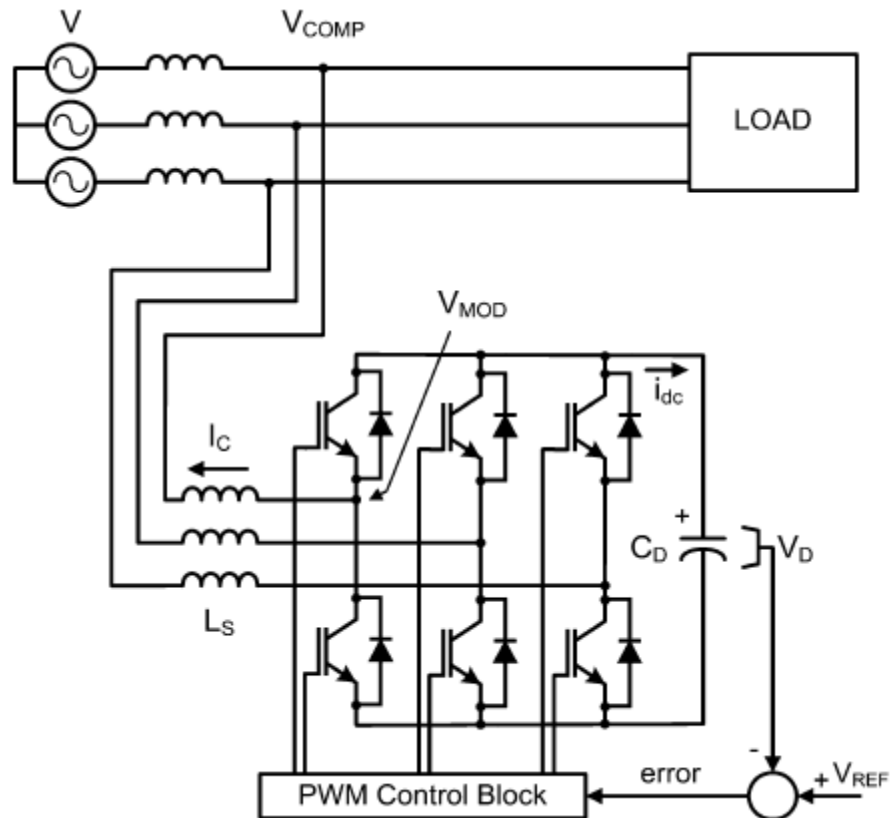

Figure 2.11 Voltage source STATCOM topology

The reactive power control is done by arranging the amplitude of the output voltage VMOD. The amplitude level can be adjusted by changing the PWM pattern. When the amplitude of the VMOD is higher than the VCOMP, the STATCOM acts as capacitive and reactive power is generated by the STATCOM but when the amplitude of the VMOD is smaller than the VCOMP, the STATCOM acts as inductive and reactive power is absorbed by the STATCOM. As a result, the transmission capacity and the voltage stability of the system can be increased.

STATCOMs are faster systems than other SVC systems when both are compared in case of their structure. STATCOMs are IGBT based systems and their response time is faster than SVCs. Moreover, at low voltage levels STATCOM satisfy better reactive power compensation than SVC.

CHAPTER THREE
INSTANTANEOUS REACTIVE POWER THEORY

Instantaneous reactive power theory, which is one of the most important control techniques, states the algebraic calculation of the current and voltage waveforms based on the abc to $\alpha\beta0$ transformation to eliminate harmonic current and reactive power compensation in power system (Akagi et al., 2007).

In this section, a commonly used technique, instantaneous reactive power theory is used and analyzed to calculate reference currents for the proposed system, and expressed in detail for three phase and single phase systems.

3.1 The P-Q Theory in Three Phases

Instantaneous reactive power theory, also known as p-q theory, was proposed by Akagi to control active power filters. Initially the theory was introduced for three phased systems without neutral wire that is shown in Figure 3.1, and then it was developed to apply also for three phase four wire systems.

The p-q theory is based on the set of instantaneous powers that are defined in time axis. There are no limits in voltage and current waveforms and it can be applied to current and voltage waveforms in three phase systems with or without neutral wires. Also, this theory is accurate for not only stable but also transient situations.
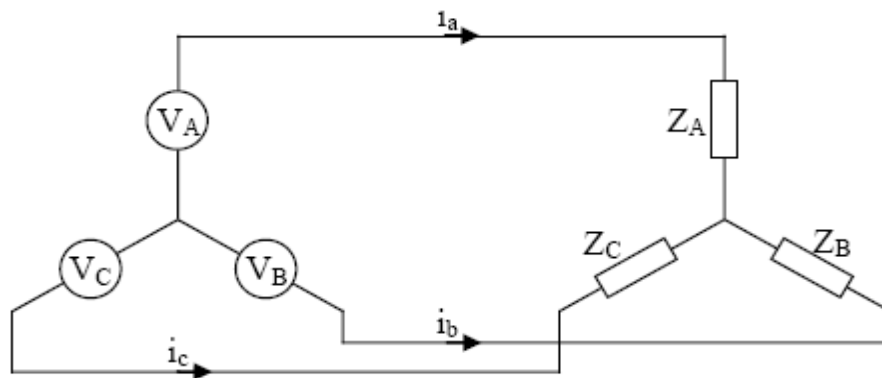

Figure 3.1 Three phase three wire system

In Figure 3.2, a-b-c axes at a-b-c coordinates are 120°phase shifted from each other on the same plane. Instantaneous space vectors v_a and i_a are on the a axis and their amplitudes and directions change with time. In the same way, v_b and i_b are on the b axis, v_c and i_c are on c axis.
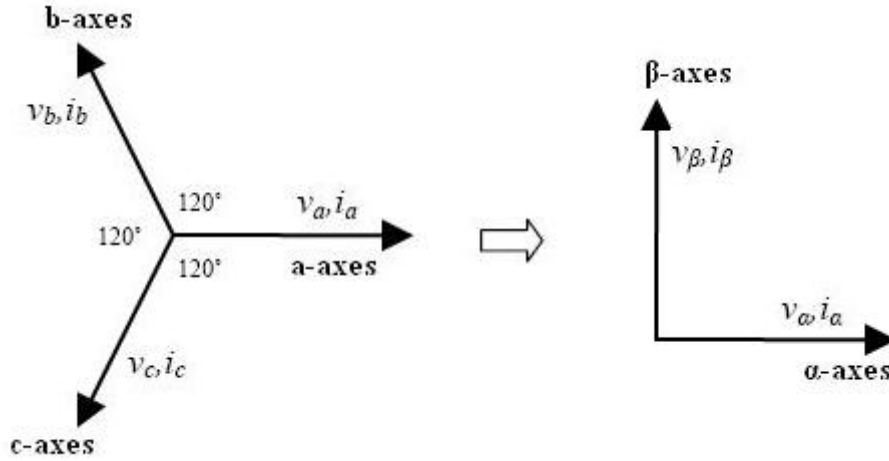

Figure 3.2 3-phase to 2-phase transformation

These space vectors can be simply converted to v_α, v_β and i_α, i_β instantaneous voltage and currents on α-β axes from 3-phase system to 2-phase system with $\alpha\beta$ transformation, also known as Clarke transformation.

Three-phase voltage transformation is used by Akagi et al. (2007) and Haque & Ise (2002) with Clarke Transformation and its inverse transformation to calculate the instantaneous real and reactive powers.

$$\begin{bmatrix} V_0 \\ V\alpha \\ V\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{3.1}$$

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{1}{\sqrt{2}} & 1 & 0 \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_0 \\ V\alpha \\ V\beta \end{bmatrix} \tag{3.2}$$

With the same formulations, three-phase instantaneous line current transformation is used by Liu et al. (1999) and Khadkikar et al. (2009) for power estimations.

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{1}{\sqrt{2}} & \dfrac{1}{\sqrt{2}} & \dfrac{1}{\sqrt{2}} \\ 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.3}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{1}{\sqrt{2}} & 1 & 0 \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3.4}$$

Basically, the advantage of the $\alpha\beta0$ transformation is to eliminate zero-sequence components from the balanced abc phase system and reduce the number of variables from three to two. Therefore, zero-sequence components do not make any complexity to α and β axes. Since, in a three phase three wire balanced system zero sequence current does not exist and this makes simplification (Akagi et al., 2007).

The Clarke transformation and its inverse transformation is as follow when v_0 is removed from the transformation matrixes;

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{3.5}$$

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} \tag{3.6}$$

Similarly the line currents can be formulated.

The Clarke transformation transforms currents and voltages from a-b-c coordinates to mutually perpendicular set of α-β-0 coordinates.
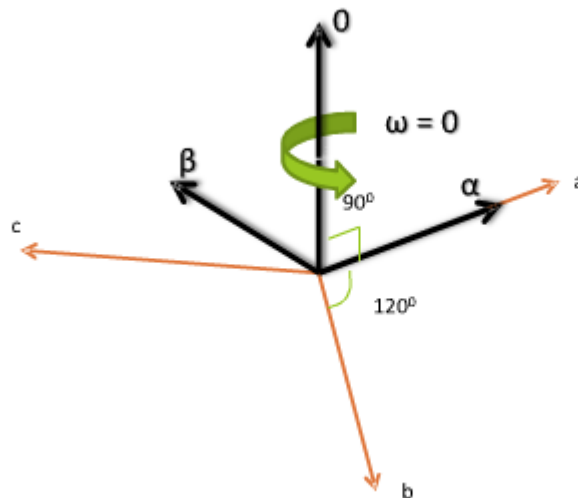

Figure 3.3 The abc to $\alpha\beta0$ transformation

If V_0 and i_0 are neglected, an instantaneous voltage vector and instantaneous current vector are defined in α *and* β axes as follows;

Voltage vector is

$$e = v_\alpha + jv_\beta \tag{3.7}$$

Current vector is

$$i = i_\alpha + ji_\beta \tag{3.8}$$

The complex power can be defined as follows;

$$S = e \cdot i^* = (v_\alpha + jv_\beta)(i_\alpha - ji_\beta) \tag{3.9}$$

Where;

The instantaneous real power (p) is;

$$\mathrm{p} = v_\alpha i_\alpha + v_\beta i_\beta \tag{3.10}$$

The instantaneous imaginary power (q) is;

$$q = v_\beta i_\alpha - v_\alpha i_\beta \tag{3.11}$$

The instantaneous zero-sequence power is

$$p_0 = i_o \cdot v_0 \tag{3.12}$$

The instantaneous real power, p and imaginary power, q related to the same α-β currents and voltages, therefore, it is written in matrix form as follows;

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.13}$$

In above equation, p corresponds to instantaneous real power at three phase circuits and its unit is [W]. On the other hand, q is assumed as to be new magnitude that should be defined and which has a different unit from [W], [VA] or [var].
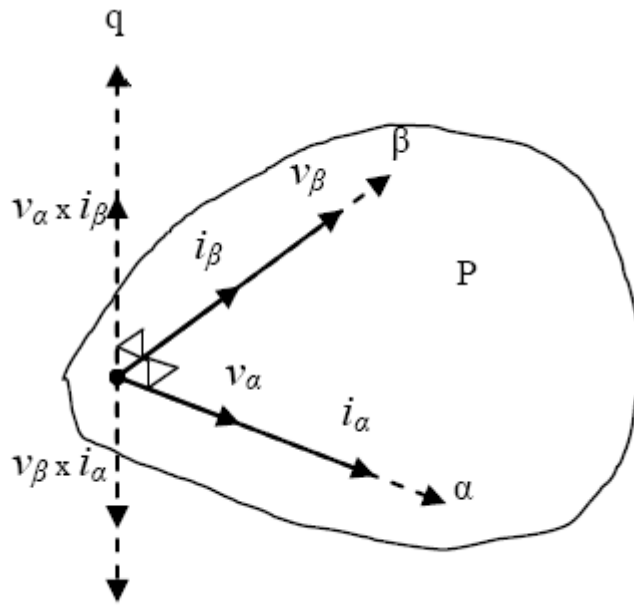
Figure 3.4 Instantaneous space vectors in α-β coordinates

Instantaneous space vectors of the current and voltage at $\alpha\beta$ coordinates are shown   in Figure 3.4. From the figure, it can be seen that q space vector is the imaginary axis vector that occurred with the application of right-hand rule and it is perpendicular to the real surface of the α-β coordinates. It can be also seen that, $v\alpha$ is parallel to the $i\alpha$ and $v\beta$ is parallel to the $i\beta$, $v\alpha$ is perpendicular to the $i\beta$ and $v\beta$ is perpendicular to the $i\alpha$. Therefore, instantaneous imaginary power q and instantaneous real power p can be written as (3.13).

From (3.13), it is possible to write;

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{3.14}$$

One of the most important advantages of p-q theory is that, the real and imaginary powers, which should be compensated, can be selected independently. The p and q can be expressed as;

$$p = \bar{p} + \tilde{p} \tag{3.15}$$
$$q = \bar{q} + \tilde{q} \tag{3.16}$$

Where;

$\bar{p}$ = mean value of the instantaneous real power

$\bar{q}$ = mean value of the instantaneous imaginary power

$\tilde{p}$ = alternated value of the instantaneous real power

$\tilde{q}$ = alternated value of the instantaneous imaginary power
(Afonso, Couto & Martins et al., 2000).

The expression (3.14) can be written as follows;

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{3.17}$$

If only harmonic compensation will be implemented with the active power filter, reference currents should be calculated using opposite signs of AC part of real power ($\tilde{p}$) and AC part of imaginary power ($\tilde{q}$) as shown in (3.18).

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix} \tag{3.18}$$

If only reactive power compensation will be implemented, the reference currents should be calculated using opposite sign of DC part of imaginary power ($\tilde{q}$) as shown in (3.19).

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ -\bar{q} \end{bmatrix} \tag{3.19}$$
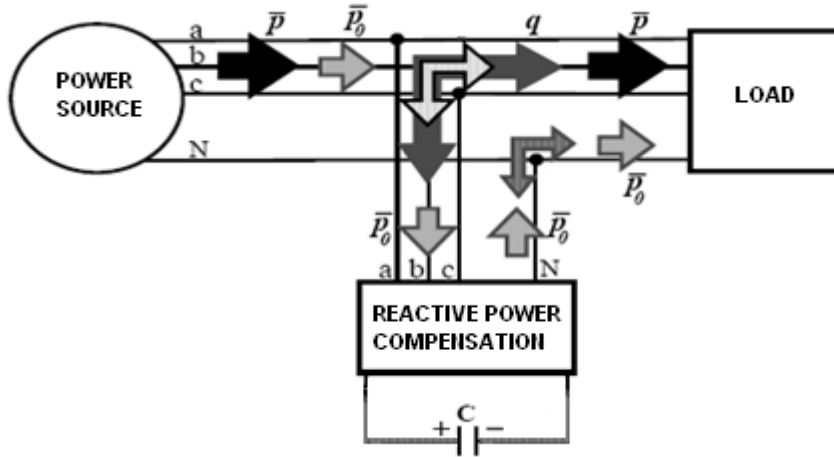
Figure 3.5 Reactive power compensation flow chart

Finally, if both harmonic compensation and reactive power compensation will be implemented, reference currents are calculated using AC part of real power ($\tilde{p}$), and both DC ($\bar{q}$) and AC parts of imaginary power ($\tilde{q}$) as shown in (3.20).

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix} \tag{3.20}$$

The inverse transformation given in equation (3.4) is used to find the reference compensation currents in the abc coordinates, and that is $i_{comp,\alpha}$ and $i_{comp,\beta}$;

$$\begin{bmatrix} i_{comp,a} \\ i_{comp,b} \\ i_{comp,c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \\ -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} \tag{3.21}$$

or the reference compensation currents in the abc coordinates can be written as;

$$\begin{bmatrix} i_{comp,a} \\ i_{comp,b} \\ i_{comp,c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{1}{\sqrt{2}} & 1 & 0 \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{comp,0} \\ i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} \tag{3.22}$$

The block diagram of instantaneous reactive power theory in three phase system is shown in Figure 3.6.
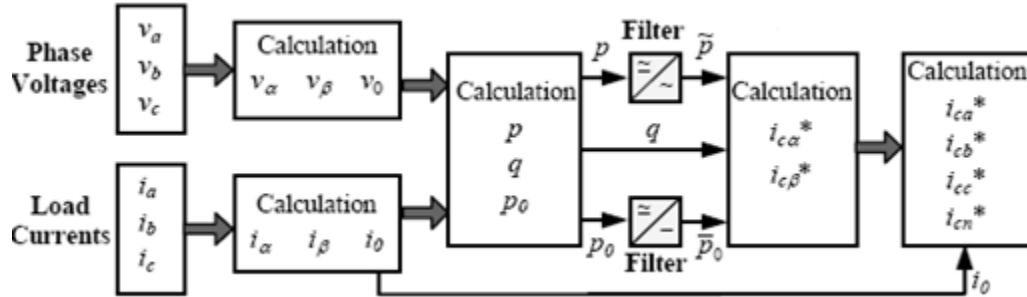

Figure 3.6 The p-q theory block diagram in three phases

3.2 The P-Q Theory in Single Phase

The three-phase p-q theory was expanded for single-phase systems such that the advantages of the multiphase p-q theory can be utilized in case of single-phase systems. The single phase p-q theory can also be used for multiphase system and this provides an advantage to control each phase individually under unbalanced conditions (Khadkikar et al., 2009).

For single phase system, we can neglect other two phases thus one phase current and voltage values are only needed. To make the system simple, if one phase current and voltage values are lag or lead 90" two-phase system can be obtained. This structure makes simplicity and suppresses complexity when compared with three phase systems. If we consider that two phase system is in α-β coordinates, the instantaneous active and reactive powers can be calculated precisely (Liu et al., 1999).

If we consider that the current and voltage on the β axis are π/2 phase lead according to α axis, the single phase load current and source voltage can be substituted in α-β coordinates with a π/2 lead as;

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} v_s \sin(wt) \\ v_s \sin(wt + \pi/2) \end{bmatrix} = \begin{bmatrix} v_s \sin(wt) \\ v_s \cos(wt) \end{bmatrix} \qquad (3.23)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_s \sin(wt) \\ i_s \sin(wt + \pi/2) \end{bmatrix} = \begin{bmatrix} i_s \sin(wt) \\ i_s \cos(wt) \end{bmatrix} \tag{3.24}$$

The single phase instantaneous reactive and active powers can be specified as in three phase p-q theory, and is represented as;

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.25}$$

The p and q can be specified as;

$$p = \bar{p} + \tilde{p} \tag{3.26}$$
$$q = \bar{q} + \tilde{q} \tag{3.27}$$

and expression (3.25) can be written as;

$$\begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.28}$$

Where $\bar{p}$ and $\bar{q}$ correspond to the instantaneous fundamental active and reactive power, however $\tilde{p}$ and $\tilde{q}$ correspond to the harmonic power. The reference compensating current is extracted by taking the inverse of (3.28) as;

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix} \tag{3.29}$$
$$= \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix}$$

There are two possible ways to extract the reference compensating currents in single phase system; Direct Current Control Technique and Indirect Current Control Technique (Khadkikar et al., 2009).

3.2.1 Direct Current Control Technique

A single phase load can produce harmonics and reactive power. To suppress the harmonics and compensate the reactive power, the single phase load can be controlled to produce required compensating current. The required compensating current is injected through the inductor that is equal but opposite with the reactive current and harmonics.

Reference compensating current is calculated by using the terms $\tilde{p}$, $\tilde{q}$ and $\bar{q}$. The alternating component of real power, $\tilde{p}$, can be derived by using a high pass filter (HPF) (Khadkikar et al., 2009). To reduce the voltage ripple and control the DC bus voltage, $\bar{p}_{dc}$,the active power that the single phase bridge converter should absorb from the supply, is added to the reference current of the bridge converter.

The instantaneous compensating currents $i_{comp,\alpha}$ and $i_{comp,\beta}$ on α and β coordinates can be extracted by using the expression (3.29) and in the terms of $\tilde{p}$, $\tilde{q}$, $\bar{q}$, $\bar{p}_{dc}$ as given below:

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \bar{p}_{dc} \\ -q \end{bmatrix} \tag{3.30}$$

Therefore;

$$i_{comp,\alpha} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \left[-v_\alpha \cdot \tilde{p} + v_\alpha \cdot \bar{p}_{dc} + v_\beta \cdot q \right] \tag{3.31}$$

The α-axis represents the actual signals and β-axis quantities are phase shifted by a $\pi/2$ lead, the $i_{comp,\alpha}$ gives the required reference current signal. In the above mentioned case, the converter current is directly controlled and, it is named as the direct current control technique (Khadkikar et al., 2009).

The block diagram to generate the reference current based on the direct current control technique in Matlab Simulink is shown in the below figure.
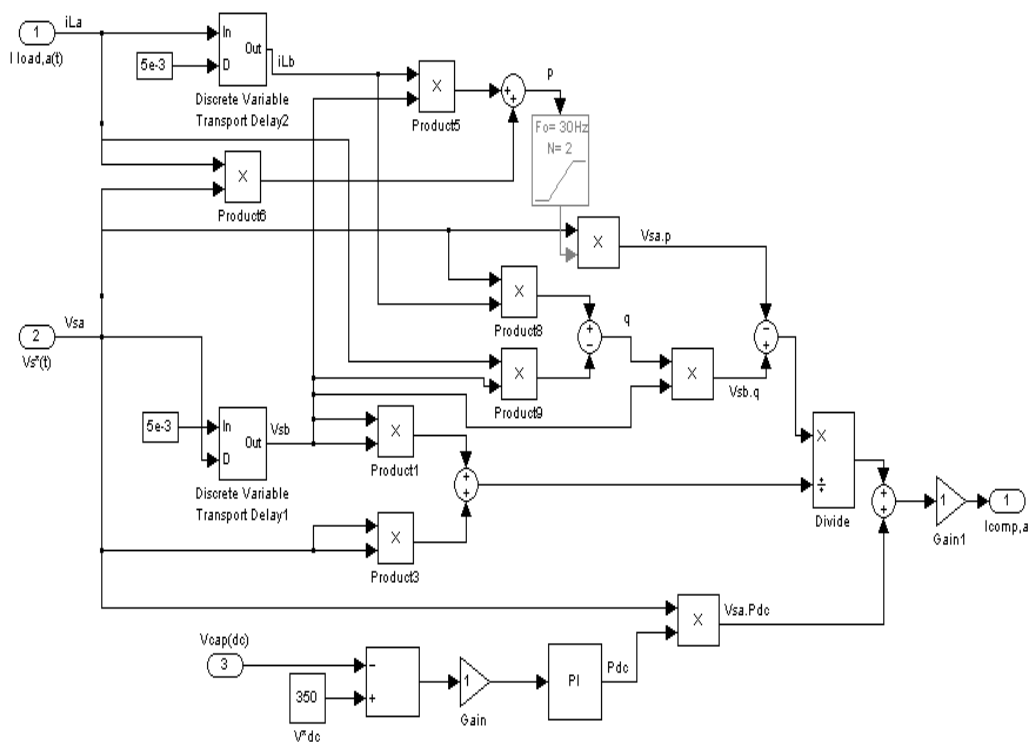

Figure 3.7 Direct current control in Matlab Simulink

With this technique, it is also practical to compensate only load reactive power or only load current harmonics by putting $\tilde{p}$ or q equal to zero in (3.30) and (3.31). This is one of the advantages of the single phase p-q theory where reactive power or harmonics compensation or simultaneously the reactive and harmonics compensation features can be chosen (Khadkikar et al., 2009).

$i_{comp,\alpha}$, shown in expression (3.31) and in Figure 3.7, represents the reference compensating current, which should be compared with the actual converter current (i_F) in order to produce the required switching cycle for the single-phase voltage source inverter (VSI) shown in Figure 3.8 below.
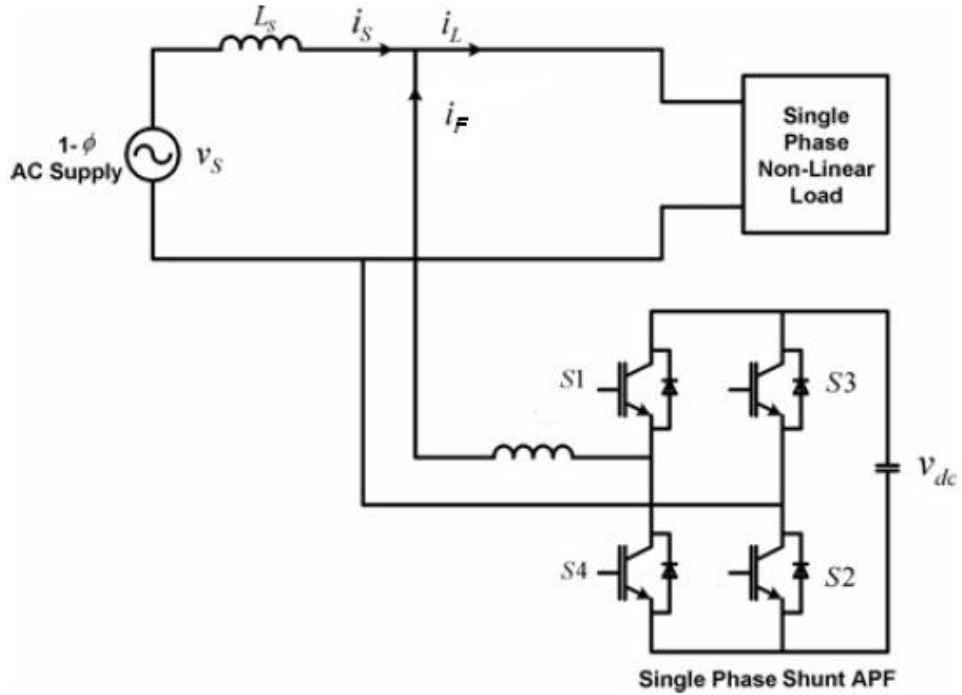
Figure 3.8 Single-phase voltage source inverter (VSI)

In above Figure 3.8, i_S is source current, i_L is load current that is drawn by the load, and i_F is the compensation current (filter current).

3.2.2 Indirect Current Control Technique

This control technique uses reference source current as reference compensating current. From the expression (3.28), $\bar{p}$ represents the instantaneous fundamental load active power that the source should supply. Thus, if term $\bar{p}$ is considered while deriving the reference compensating current, the source will supply only fundamental active power to the load, and compensating the reactive power and eliminating the harmonics indirectly. The term $\bar{p}$ in (3.28) can be extracted from p by using an LPF (Khadkikar et al., 2009).

By using the expression below;

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{3.32}$$

$$= \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix}$$

$\bar{p}$ term can be extracted by using LPF hence;

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \tag{3.33}$$

When the $\bar{p}_{dc}$ term is added to the expression (3.33) to overcome losses and avoid voltage ripple on DC bus voltage, that is;

$$\begin{bmatrix} i_{comp,\alpha} \\ i_{comp,\beta} \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} + \bar{p}_{dc} \\ 0 \end{bmatrix} \tag{3.34}$$

Therefore the reference source current, $i_{comp,s}$;

$$i_{comp,s} = i_{comp,\alpha} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} [v_\alpha . \bar{p} + v_\alpha . \bar{p}_{dc}] \tag{3.35}$$

The reference source current, $i_{comp,s}$, is compared with the actual source current in order to generate the required switching signals for voltage source inverter (VSI).

The block diagram of generating the reference source current in Matlab Simulink is shown in the Figure 3.9.
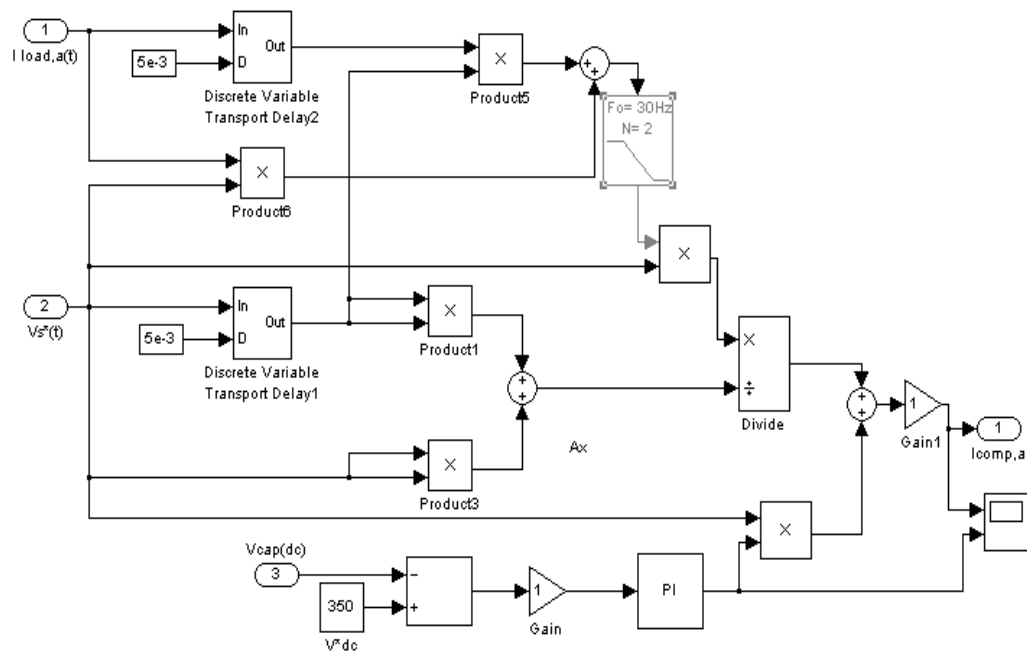
Figure 3.9 Indirect current control in Matlab Simulink

3.3 Control of DC Bus Voltage

Figure 3.8 shows that a dc capacitor is connected in parallel with PWM–VSI. DC link voltage control at the capacitor is provided by absorbing real power from the AC supply.

The $\bar{p}_{dc}$ term represents the required active power that the converter should draw from the supply in order to have a DC bus voltage and to overcome the losses associated with the converter. The peak value of the input voltage has to be smaller than the DC bus voltage for proper operation. The DC voltage control loop is shown in Figure 3.10.
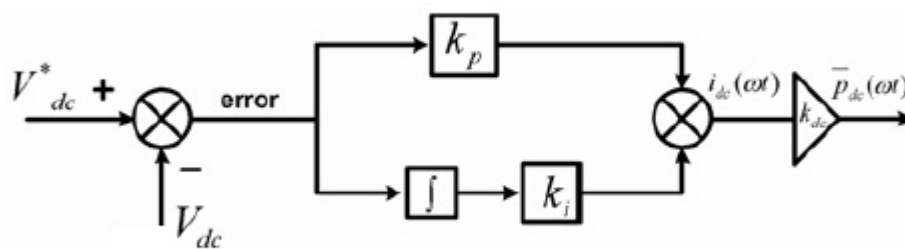
Figure 3.10 DC link voltage control

PI controller is usually used for controlling the DC energy storage component. In practice, the efficiency of converter is not 100%, and there are some losses at solid state switches and capacitor. The voltage of the capacitor decreases because of these losses. On the other hand, in each period, the DC capacitor absorbs or delivers energy to the power system. Therefore, there is voltage ripple across the capacitor. A control strategy must adjust the voltage of this capacitor. Therefore, for controlling the dc link voltage PI controller is sufficient. The difference between practical and reference values of the capacitor voltage is passed through a proper PI controller. The derived result is multiplied by the line voltage having unity peak value. Then the final result is added to the reference current value (Emadi et al., 2004).

The DC link voltage control block diagram in Matlab Simulink is shown in the Figure 3.11.
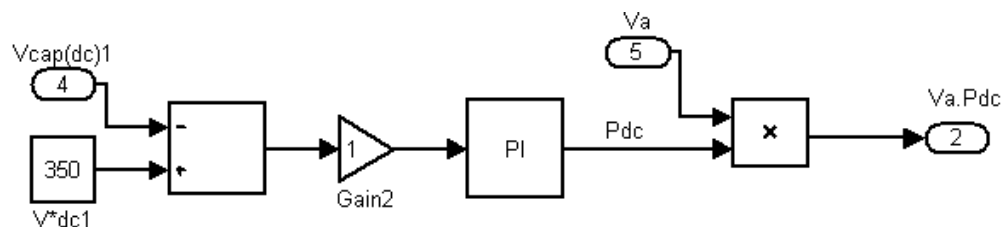
Figure 3.11 The DC link voltage control in Matlab Simulink

CHAPTER FOUR
SINGLE PHASE REACTIVE POWER COMPENSATION AND MATLAB SIMULATIONS

4.1 Circuit Topology

Reactive power compensation with a single phase voltage source PWM converter is the main concern of this research work (Figure 4.1). Single phase bridge converter is used to compensate reactive power and current harmonics.

The circuit mainly consists of two main blocks:

1. The PWM converter
2. Signal processing circuit
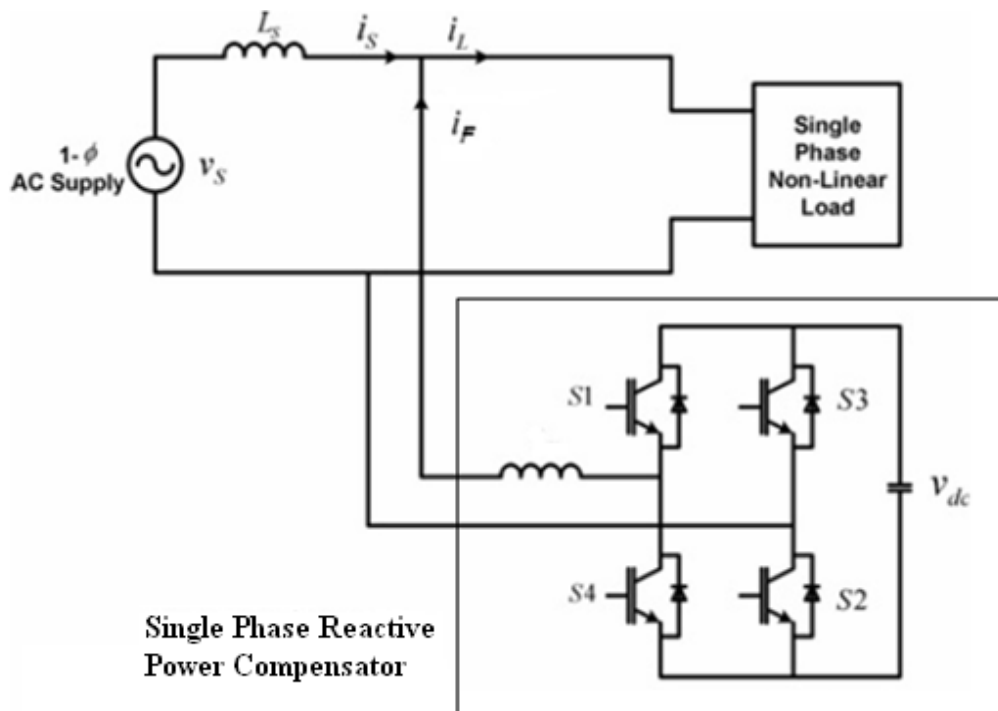
Figure 4.1 Single phase voltage source inverter

The PWM converter consists of controllable semiconductor switches, IGBTs, their antiparallel diodes and an energy storage element of a DC link capacitor. This

power electronics circuit injects compensation currents by operating as current controlled voltage source unit. So, the performance of the system is highly dependent on the accurate measurement and calculation of compensation current references. The coupling of a voltage source converter to the power system must be made through a series inductor, which is also named as coupling inductor or commutation inductor. In voltage source topology (Figure 4.1) the peak amplitude of the source voltage is required to be lower than the DC link capacitor voltage; otherwise the PWM inverter loses its controllability and generated compensation currents cannot be injected to the mains.

The signal processing circuit consists of mainly three functional parts:
1. Instantaneous power calculation
2. DC voltage regulator
3. Hysteresis band current controller

In the first part, the instantaneous powers (p & q) of the load are calculated with the p-q Theory which is given in Chapter 3. According to this theory, the real (p) and imaginary (q) powers exist. Also, the imaginary power of the load that should be compensated are generated or absorbed by the converter.

In the second part, the DC voltage regulator determines the real power represented by $\overline{p_{dc}}$ that causes an additional power flow to the system to keep the parallel capacitor voltage (Vdc) around the given reference value in the voltage source inverter (VSI). This real power is also added to the compensating real power related to harmonics and compensating imaginary power. All of them are used for calculating the reference compensation current.

In the third part, the calculated reference compensating currents are compared with the hysteresis control and the gate signals of semiconductor switches are generated.

4.2 Hysteresis Current Controller

In the compensation circuit of Figure 4.1, the inverter is a single-phase H-bridge inverter with four IGBT switches. To generate the compensation current that follows the current reference, a digital hysteresis controller is used.

The computed reference current is compared with the sensed supply current or filter current according to the control technique specified in a hysteresis current controller to produce the switching signals to the four IGBTs. In Figure 4.2, hysteresis controller is shown with Matlab blocks.
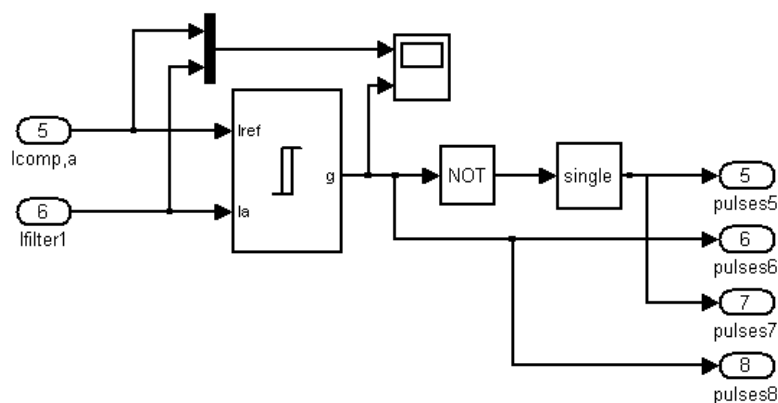
Figure 4.2 Hysteresis control blocks in Matlab

Generally hysteresis current controller is preferred due to its simple structure and high bandwidth in the reactive power compensation. In a hysteresis controller, lower limit ($-\Delta I$) and upper limit (ΔI) of the current error are defined. If the current error is between the limits, the position of the switch is preserved. However, if the current error exceeds one of the limits, 'on' or 'off' command based on the current error direction is sent to the switch.

In figures 4.3 and 4.4, the analogue hysteresis controller and principle of the proposed control scheme are shown.
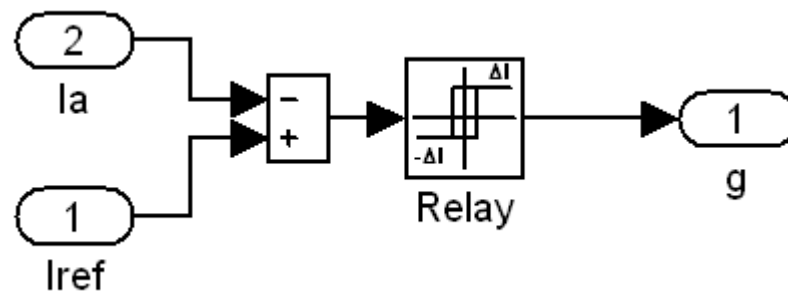
Figure 4.3 Hysteresis current controller
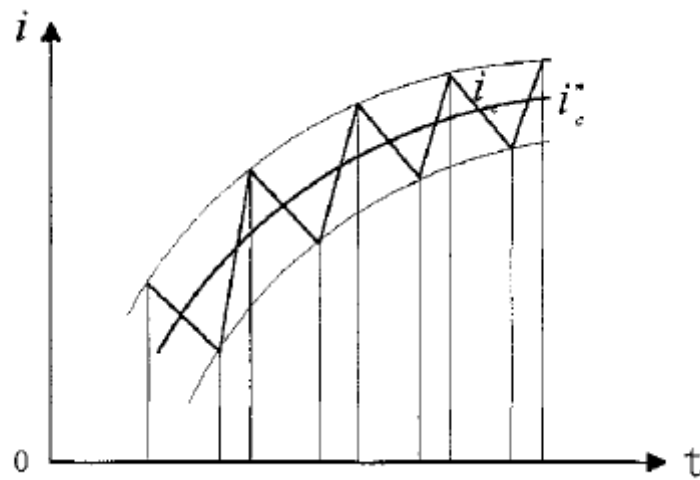
Figure 4.4 Principle of hysteresis control

The derived gate signal for one IGBT is shown in Figure 4.5 after the hysteresis control.
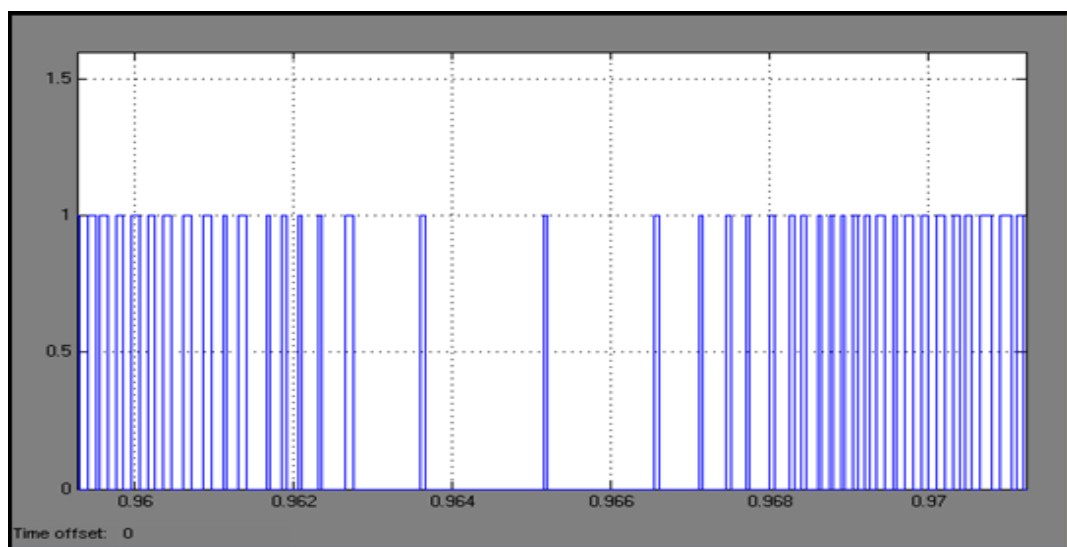
Figure 4.5 Gate signal for the IGBT

4.3 Modeling of Converter and its Controller in Matlab

The simulation results obtained for reactive power and harmonic compensating unit which is implemented with the proposed control methods are given in this section.

A discrete form of model is used in Matlab simulations to analyze the proposed control methods. The model of the load and converter with controller is obtained in the Matlab as follows;
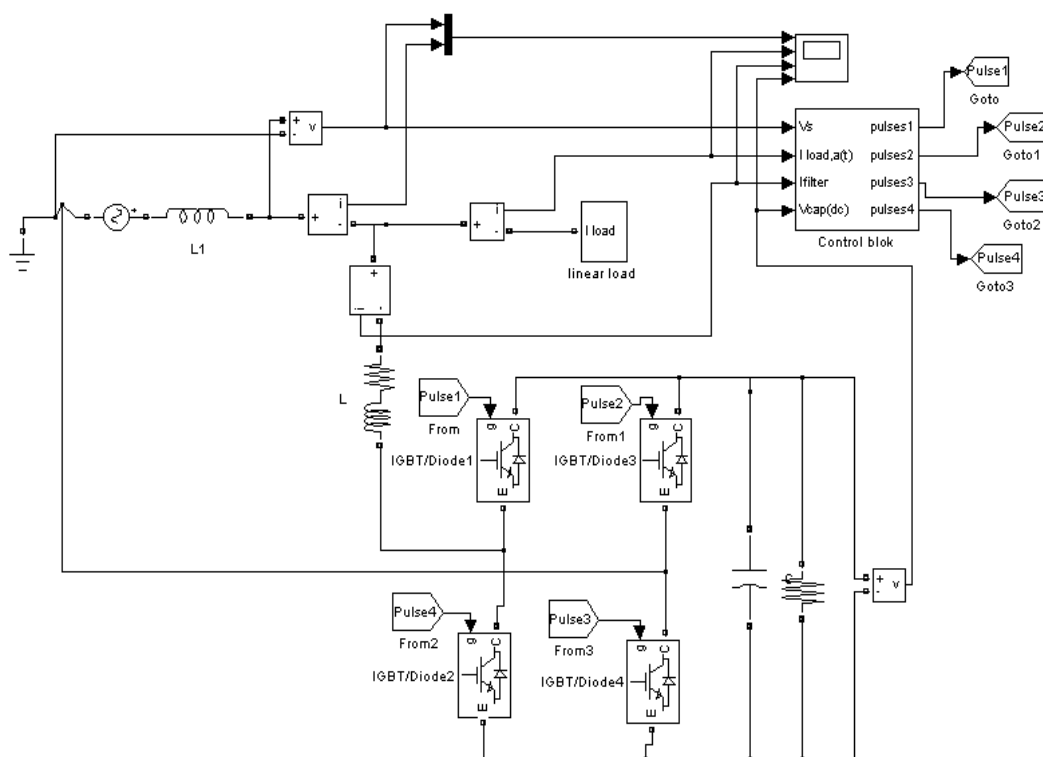
Figure 4.6 Voltage source converter with controller

The line voltage, load current, line current, filter current and dc link voltage values are measured from the system and compensating power is calculated with these measurements. The control algorithm can be selected either direct or indirect method or loads can be considered as linear or nonlinear. The single phase p-q theory is verified and simulated with combinations of these variables.

4.4 Matlab Simulation Results of the System

The results of Matlab simulations for the proposed system are given in this section.

4.4.1 Direct Current Control Technique with Linear Load

The system parameters used in the simulation are given in Table 4.1.

Table 4.1 System parameters

Parameters		Value
Source	Voltage	220Vrms / Phase-Neutral
	Frequency (f)	50 Hz
Load	Load Impedance 1 (Rs , Ls)	15 Ω , 30mH
	Load Impedance 2 (Rs , Ls)	15 Ω , 45mH
PAPF	C_{DA}	4700uF
	V_{DC} (DC link voltage)	350V
	Hysteresis Band	0.4A
	PI control parameters	Kp=0.001, Ki=0.05
	Inverter inductance	5mH

According to the loading conditions given in Table 4.2, second load will be active after 0.6sec and the system response is analyzed with instantaneous load changes.

Table 4.2 Load conditions

		Inductive Load	
0 < t < 0.3	No Load		
0.3 < t < 0.6	Load 1	R=15Ω , L=30mH	
0.6 < t < 1	Load 1 & Load 2	R=15Ω , L=30mH	R=15 Ω , L=45mH

The simulation results in Matlab are obtained with the sampling frequency (fs) of 10 kHz. Figures 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12 show the source voltage, source

current, load current, filter current, reference compensating current and dc link voltage during the compensation under linear loading conditions.
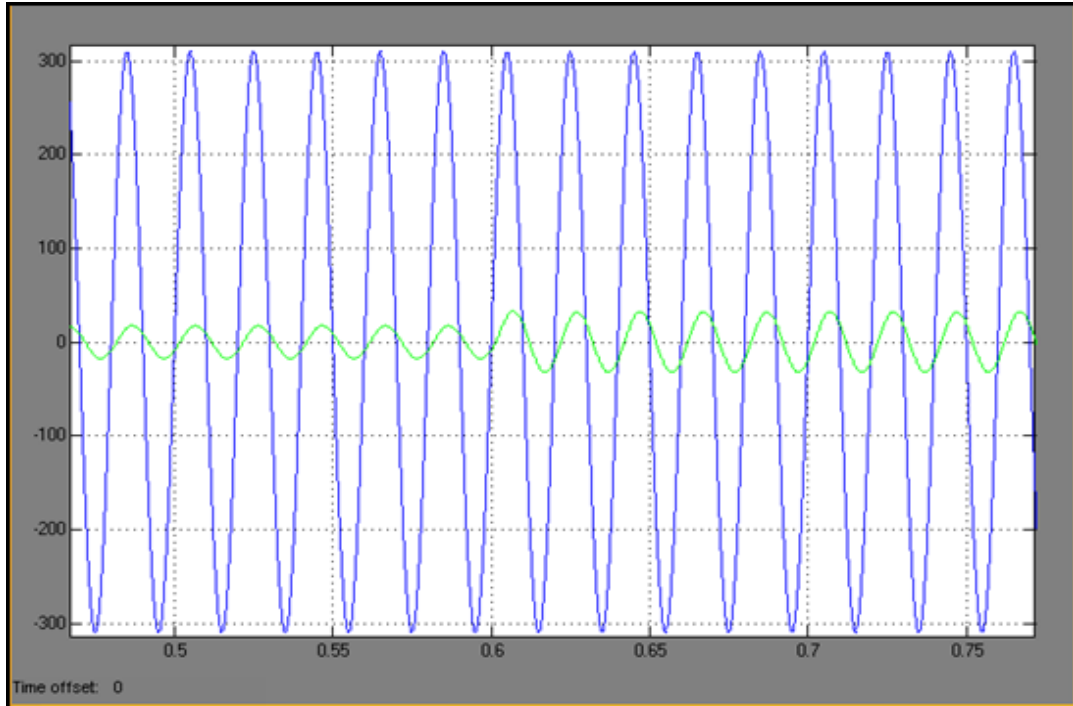
Figure 4.7 Supply voltage (v_S) and Supply current (i_S) (Before compensation)
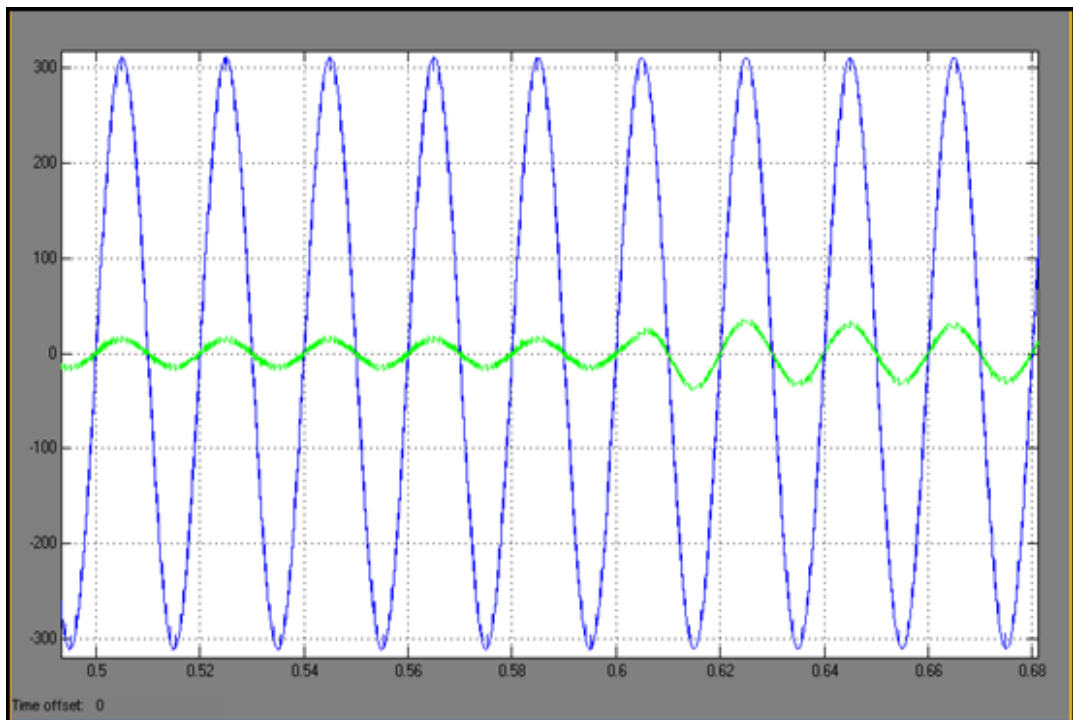
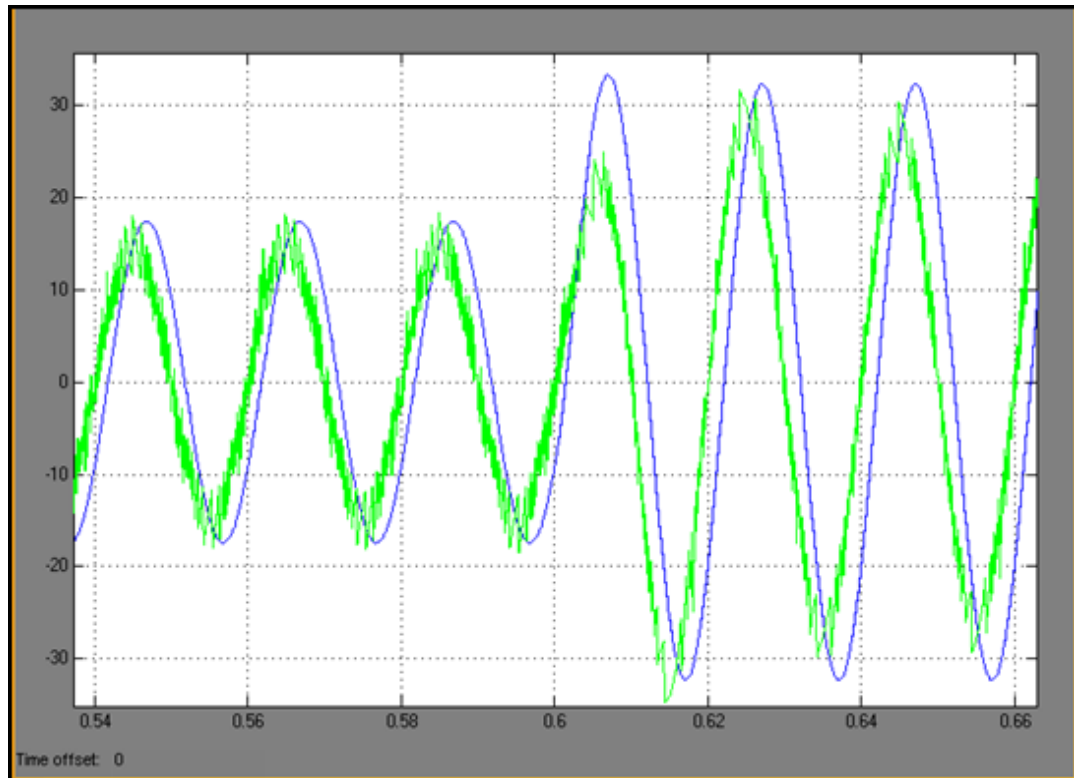Figure 4.8 Supply voltage (v_S) and Supply current (i_S) (After compensation)

Figure 4.9 Supply current (i$_S$) and load current (i$_L$)

It is clear that after compensation the current is in phase with voltage, while the current lags the voltage before compensation since the load is inductive load. The converter injects compensating current with the high frequency ripples. The frequency of the ripples is same as the switching frequency. There are many parameters specifying the switching frequency. Few dominant parameters are the execution time of program, level of dc link voltage, hysteresis band width and switching inductance.
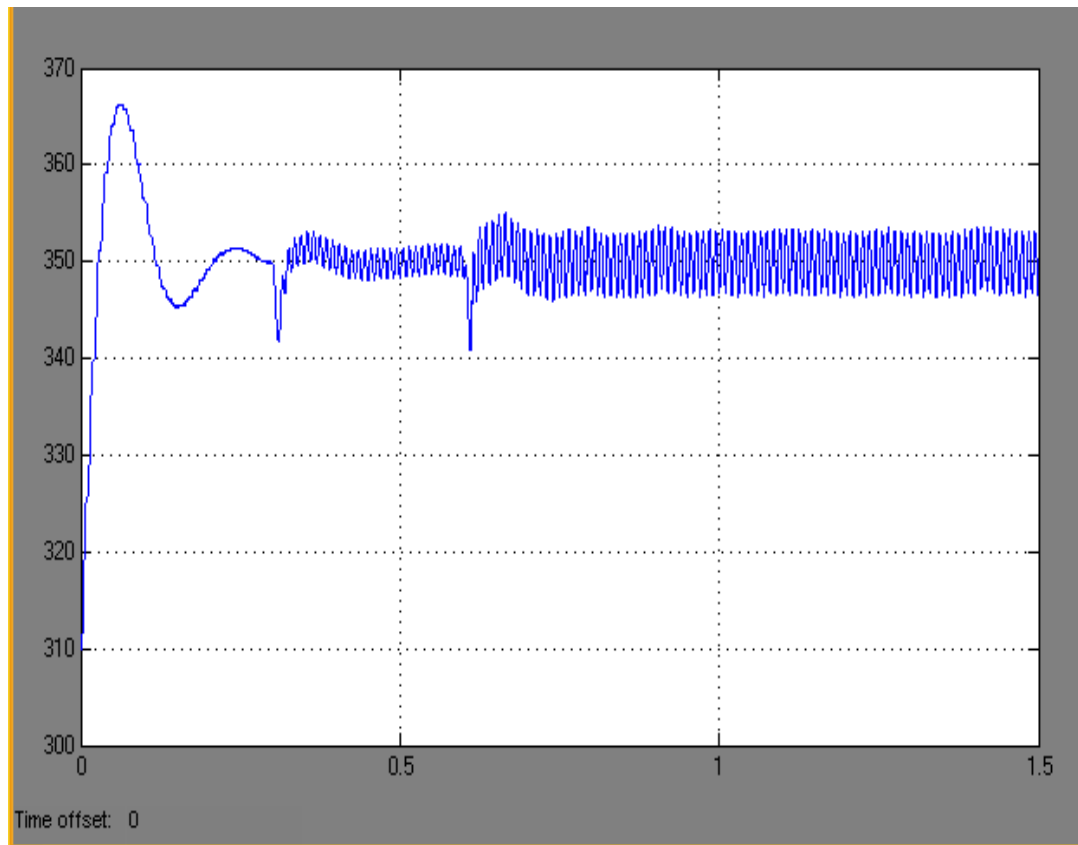
Figure 4.10 DC link voltage (V_{DC})
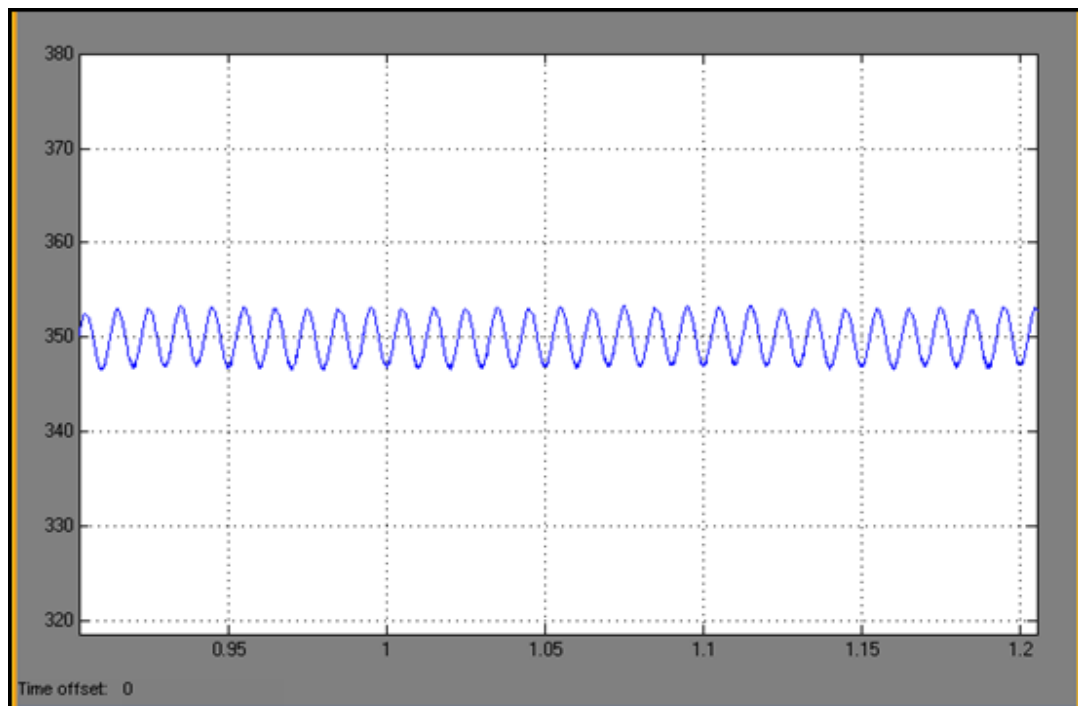
Figure 4.11 DC link voltage ripple ($V_{DC,ripple}$)

Figure 4.12 also shows that filter current tracks the reference compensating current.
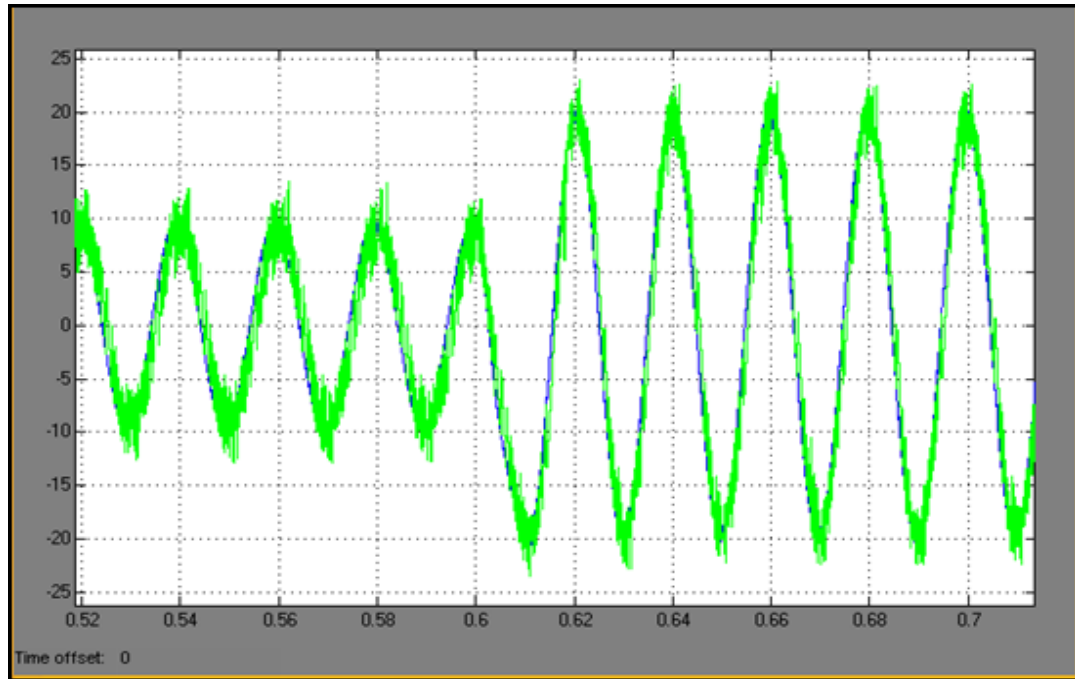
Figure 4.12 Filter current (i_F) and reference compensating current (i_{comp})

If the harmonic spectrum of IGBT switching pulse in Matlab is analyzed, which is given in Figure 4.13, the average switching frequency can be found around 2 kHz with the sampling frequency of 10 kHz.
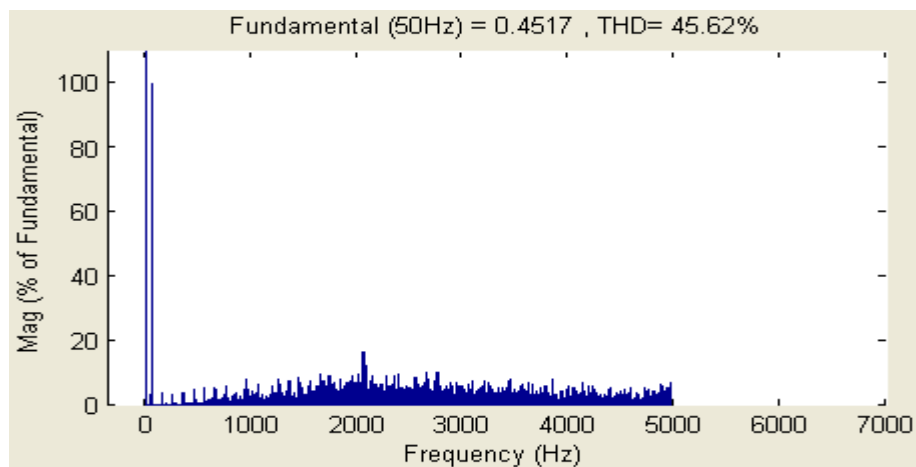
Figure 4.13 Frequency Spectrum of IGBT gate signal

4.4.2 Direct Current Control Technique with Non-Linear Load

The simulation results are given with a nonlinear load connected system. Figures 4.15, 4.16, 4.17, 4.18 and 4.19 show the source voltage, source current, load current, filter current, reference compensating current and DC link voltage during the compensation under nonlinear loading conditions. The results show that controller works properly under non-linear loading condition, too.
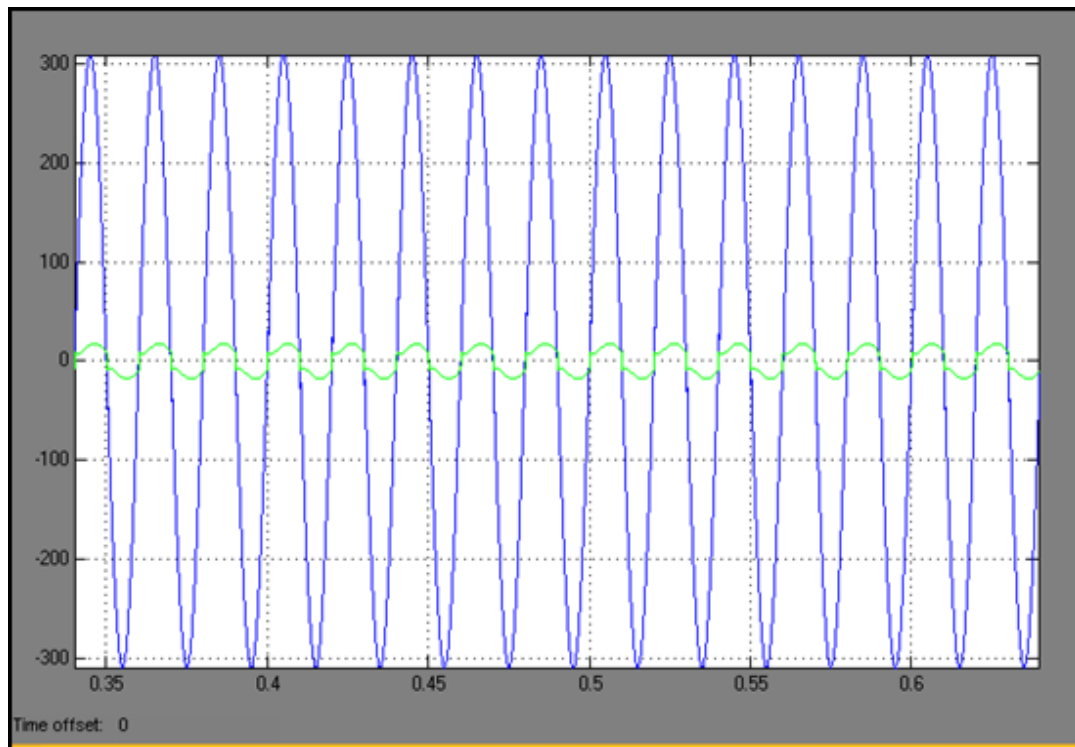
Figure 4.14 Supply current (i_S) and supply voltage (v_S) (Before compensation)
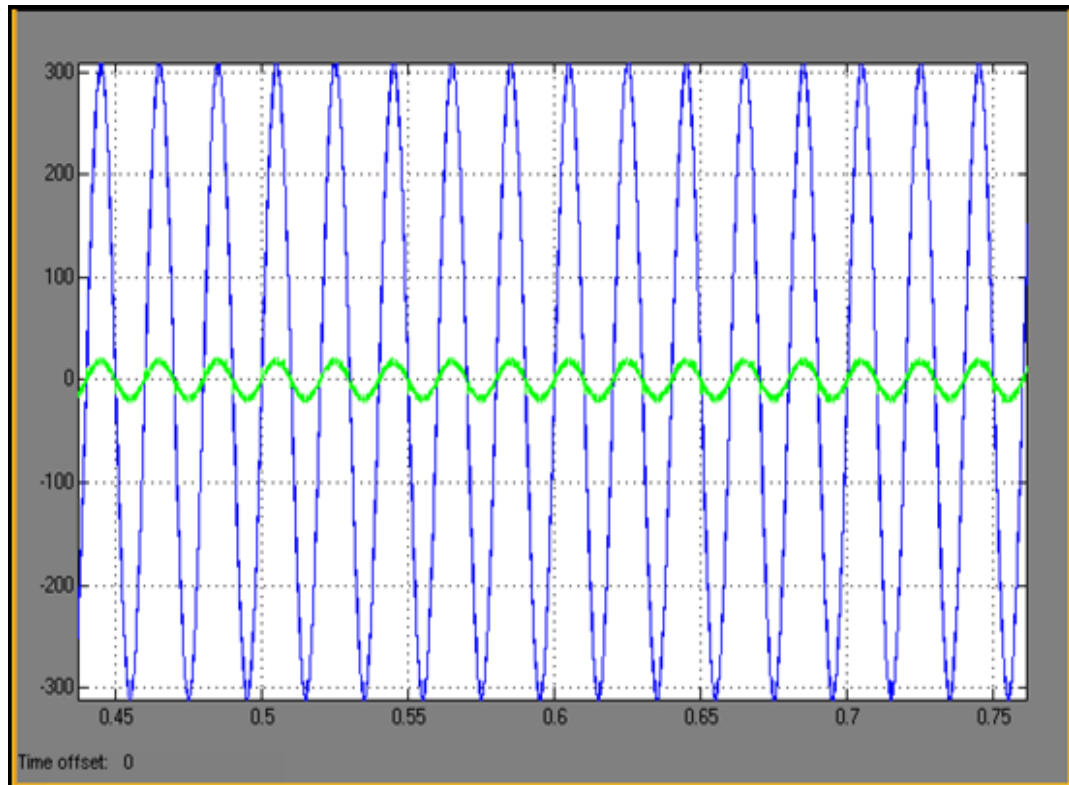
Figure 4.15 Supply current (i_S) and supply voltage (v_S) (After compensation)
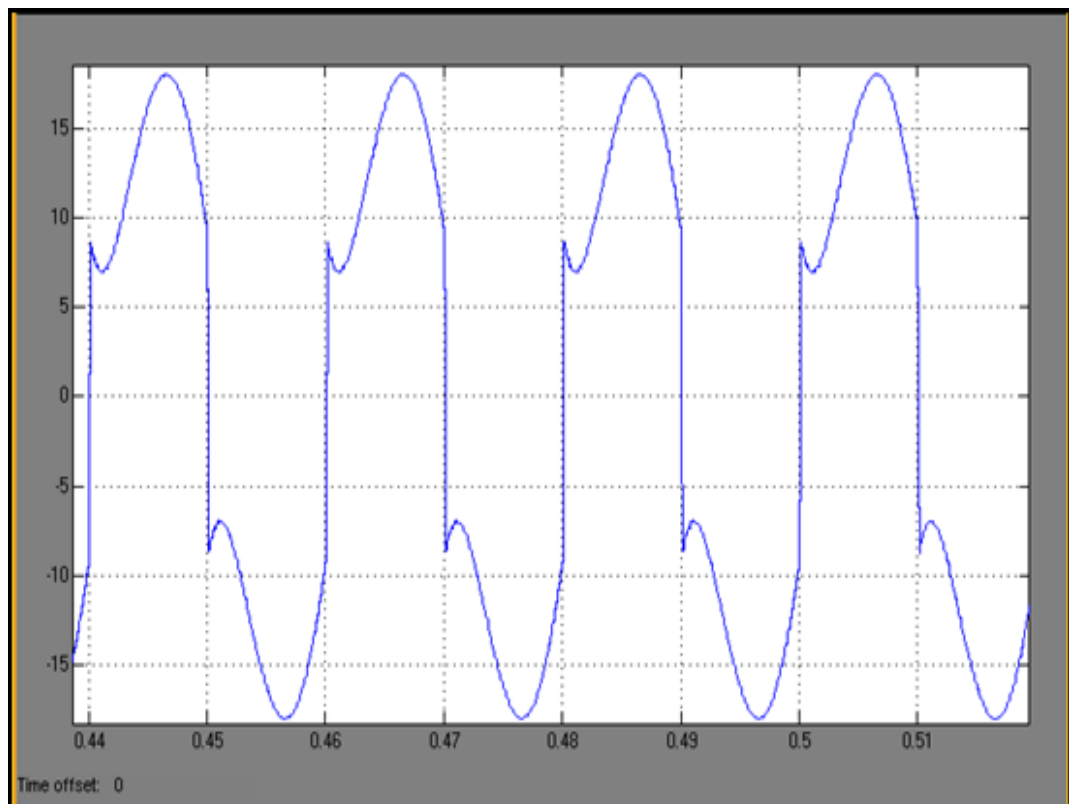
Figure 4.16 Load current (i_L)
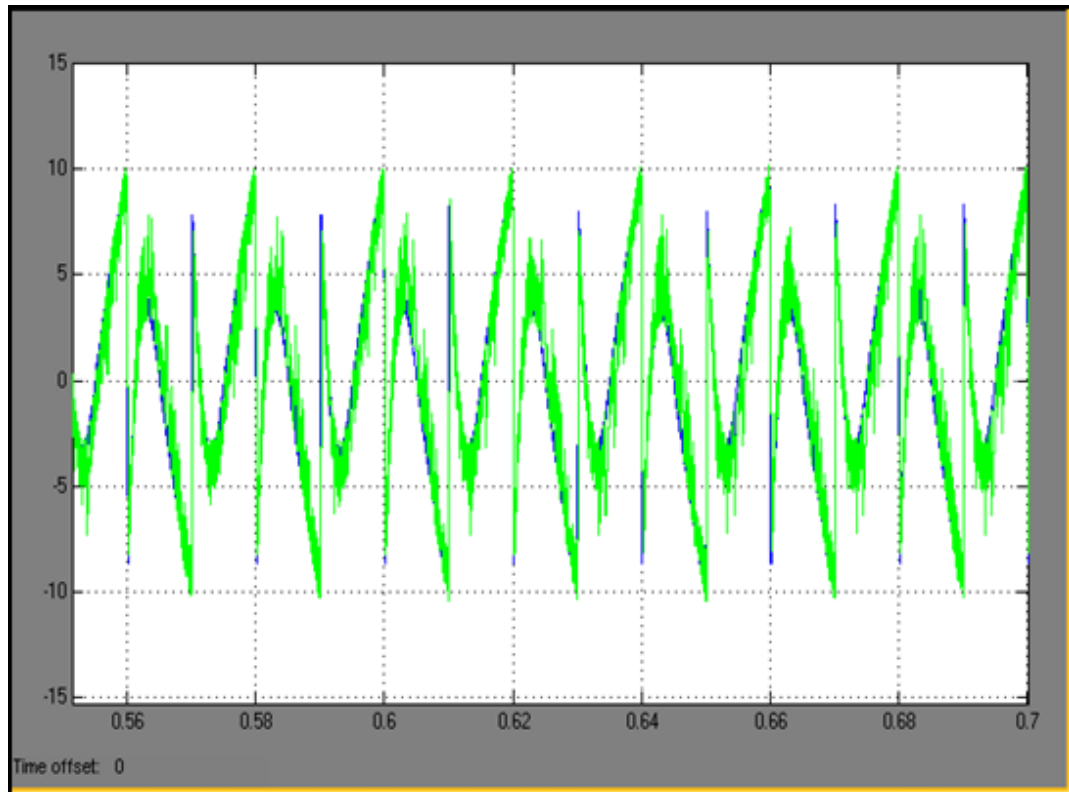
Figure 4.17 Filter current (i_F) and reference compensating current (i_{comp})
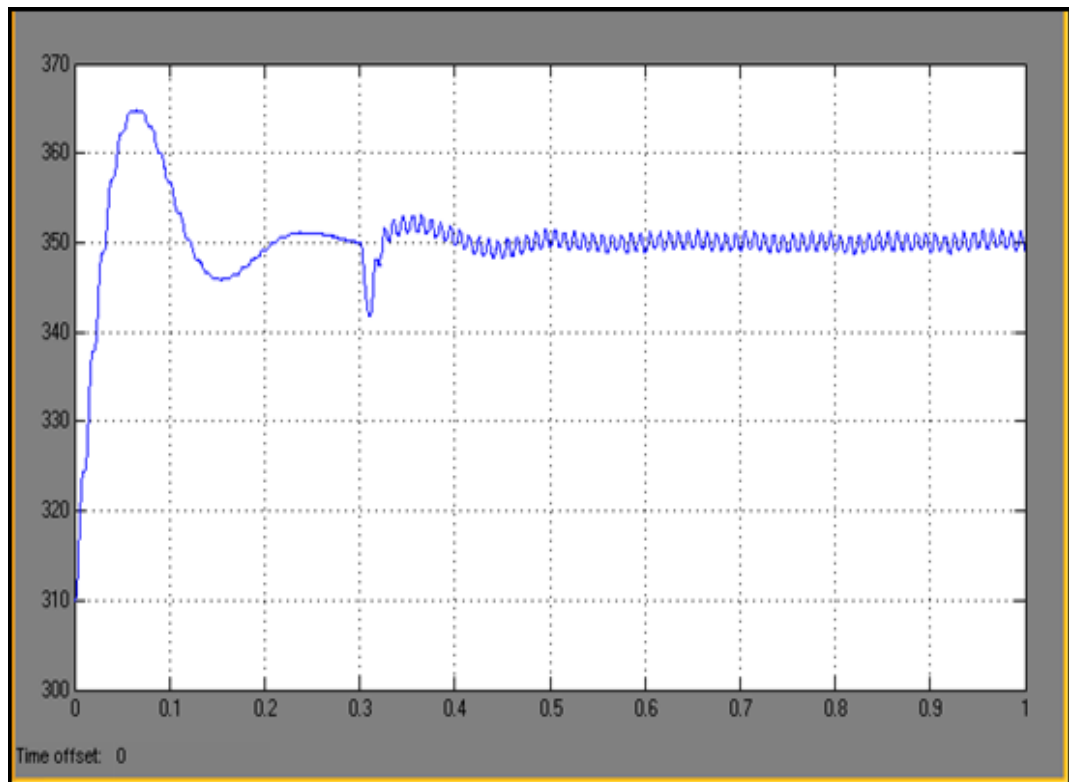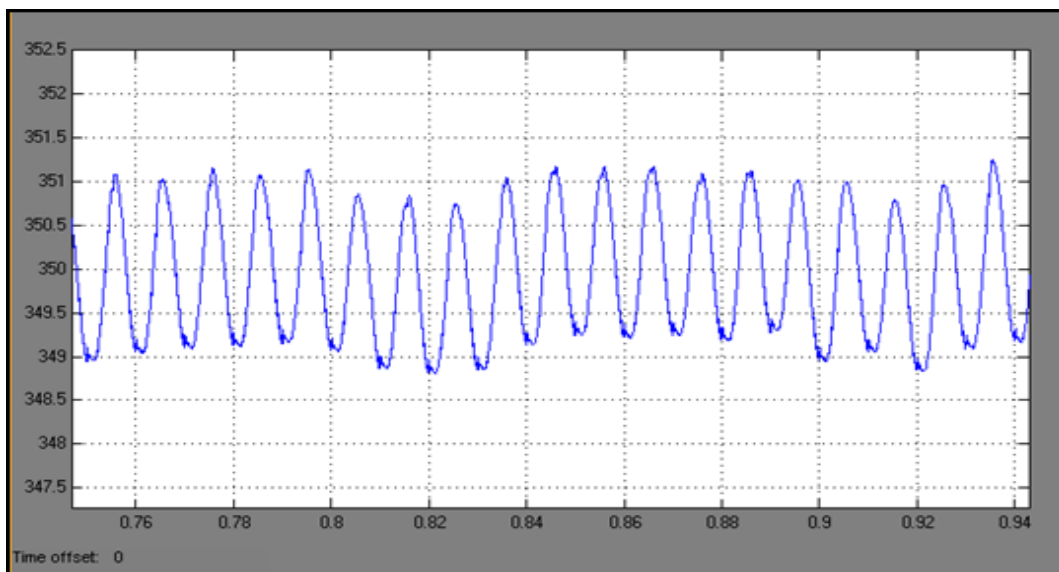

Figure 4.18 DC link voltage (V_{DC})

Figure 4.19 DC link voltage ripple ($V_{DC,ripple}$)

4.4.3 Indirect Current Control Technique with Linear Load

The simulation results are given with a linear load connected to the system. Figures 4.20, 4.21, 4.22, 4.23, 4.24 and 4.25 show the source voltage, source current, load current, filter current, reference compensating current and DC link voltage before compensation and after the compensation under linear loading conditions.
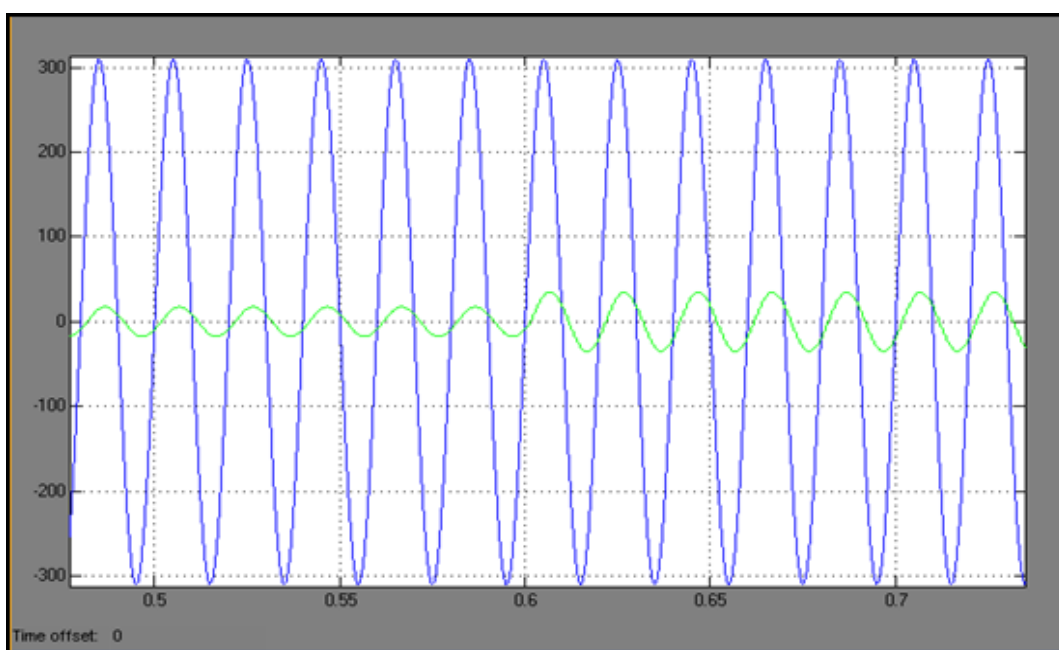

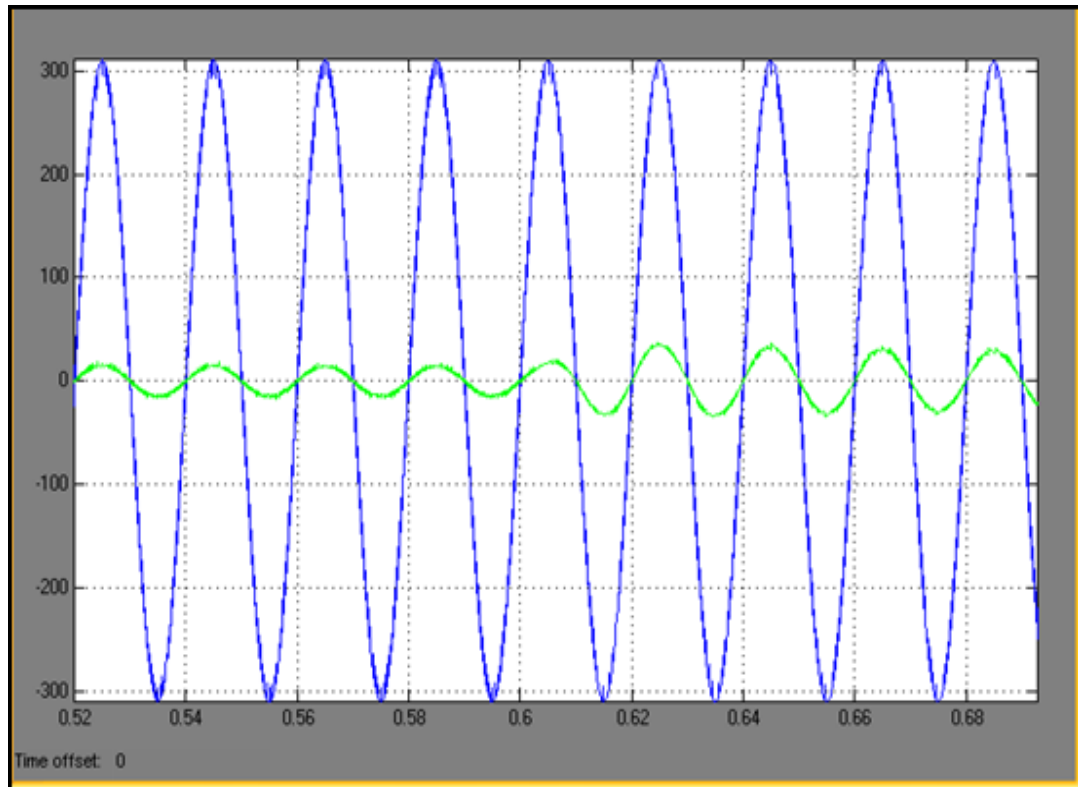Figure 4.20 Supply current (i_S) and supply voltage (v_S) (Before compensation)

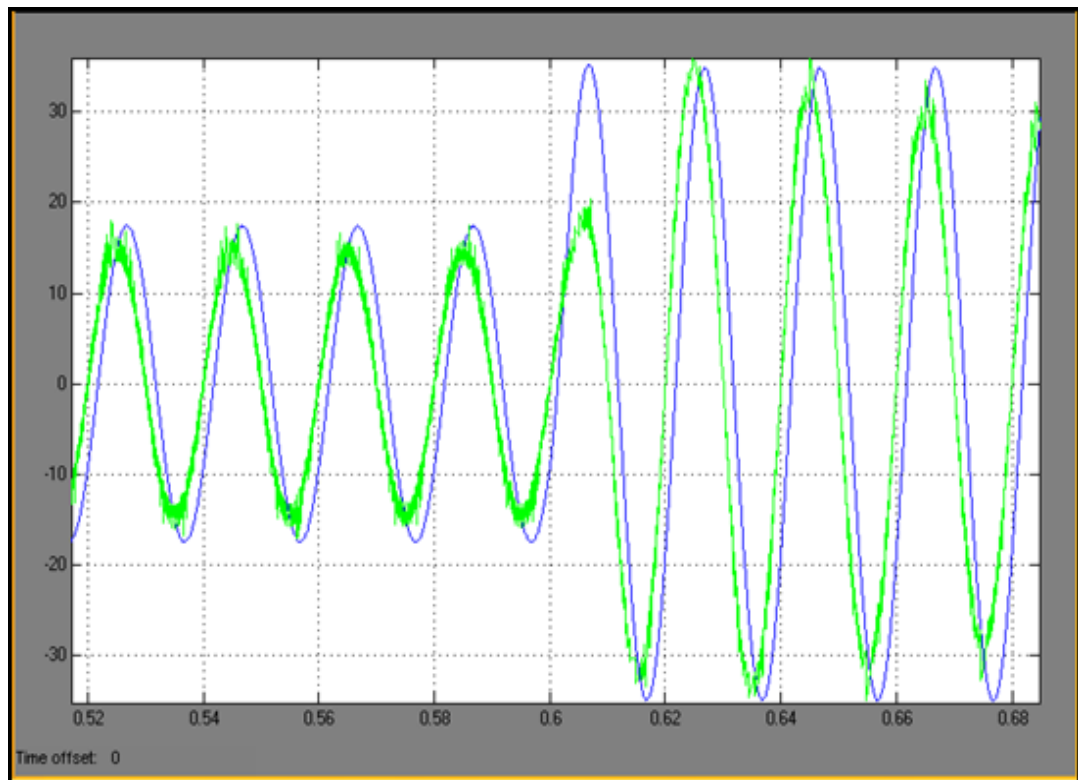Figure 4.21 Supply current (i_S) and supply voltage (v_S) (After compensation)

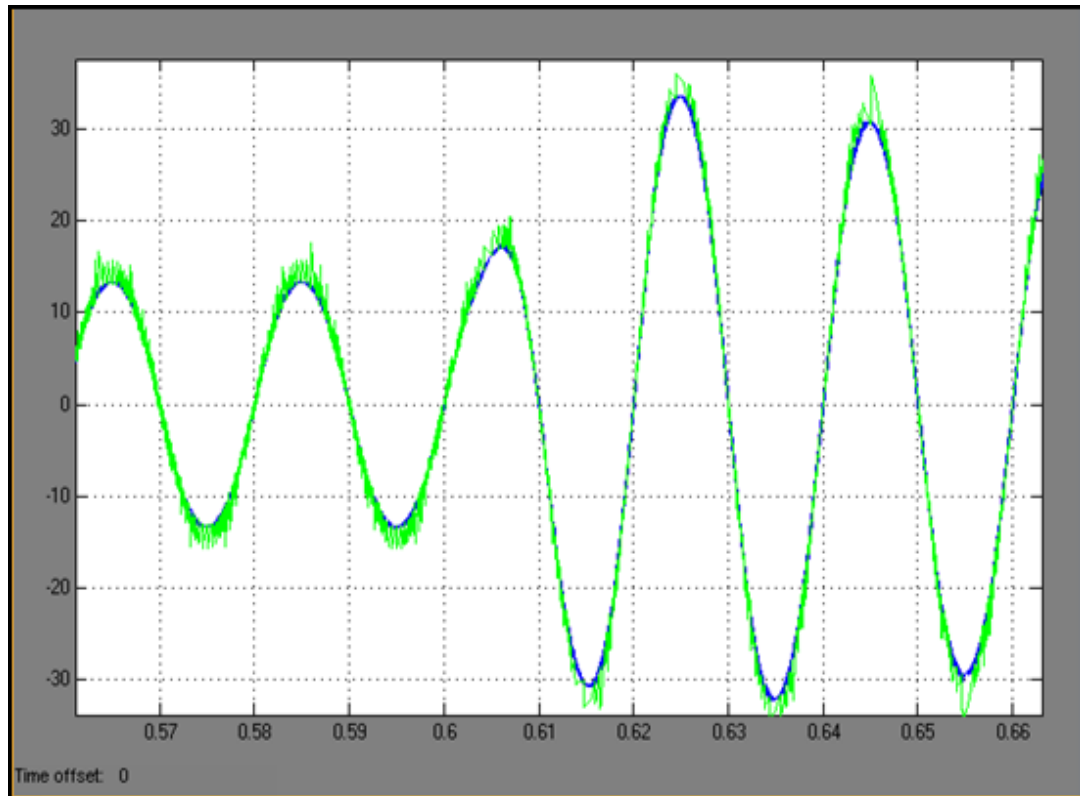Figure 4.22 Supply current (i_S) and load current (i_L)

Figure 4.23 Source current (i_S) and reference compensating current (i_{comp})
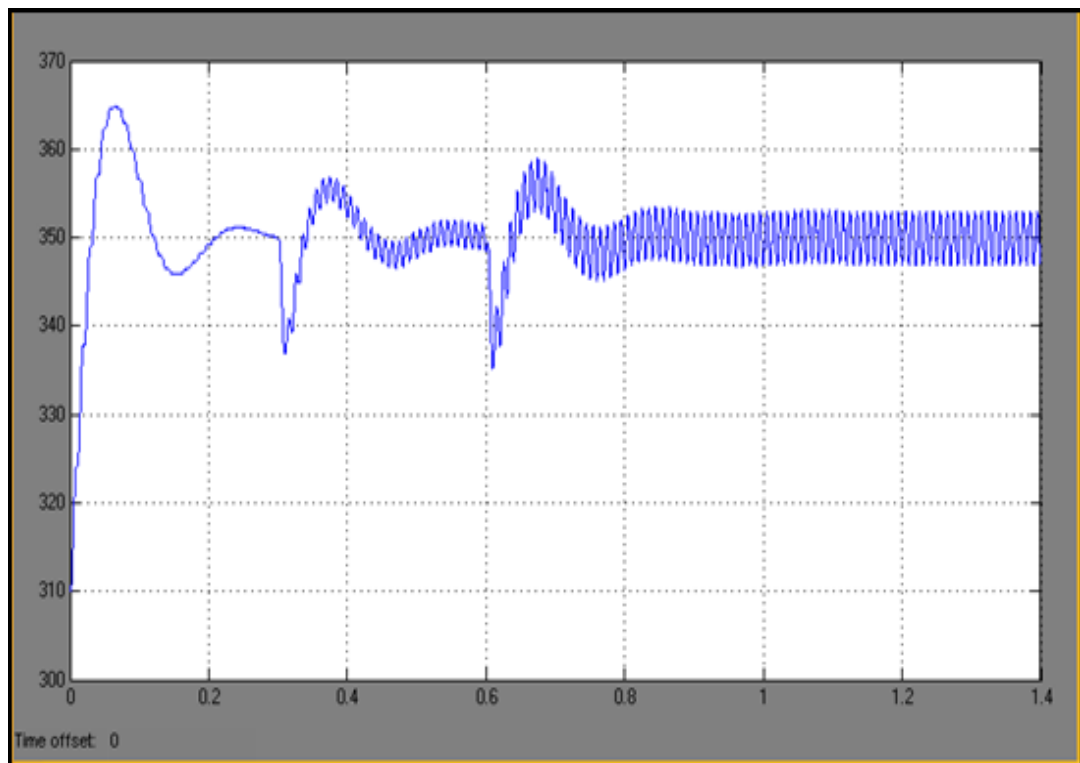

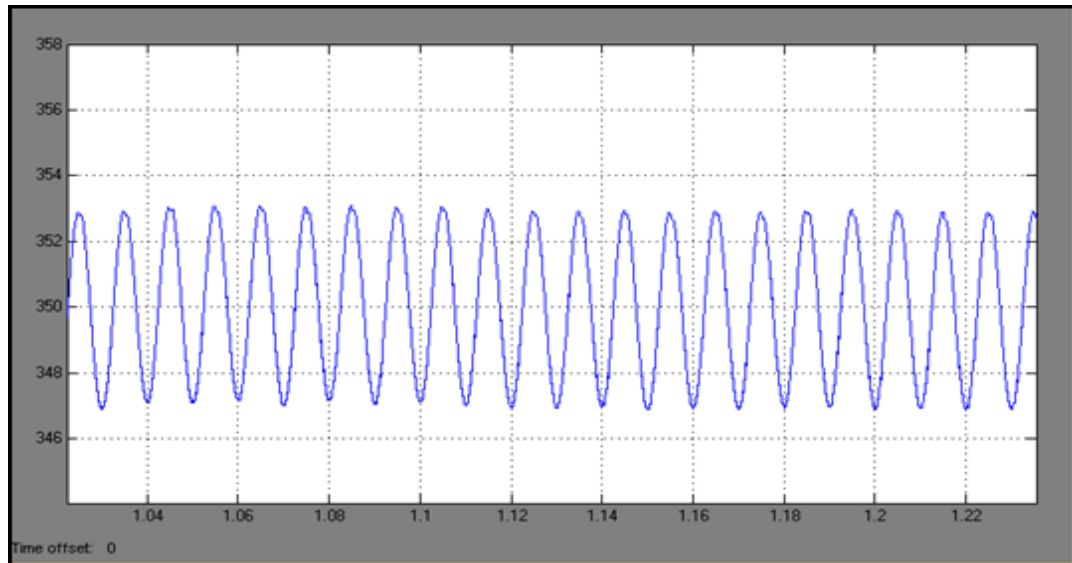Figure 4.24 DC link voltage (V_{DC})

Figure 4.25 DC link voltage ripple ($V_{DC,ripple}$)

4.4.4 Indirect Current Control Technique with Non-Linear Load

The simulation results are given with a nonlinear load connected system. Figures 4.26, 4.27, 4.28, 4.29, 4.30 and 4.31 show the source voltage, source current, load current, filter current, reference compensating current and DC link voltage during the compensation under nonlinear loading conditions.
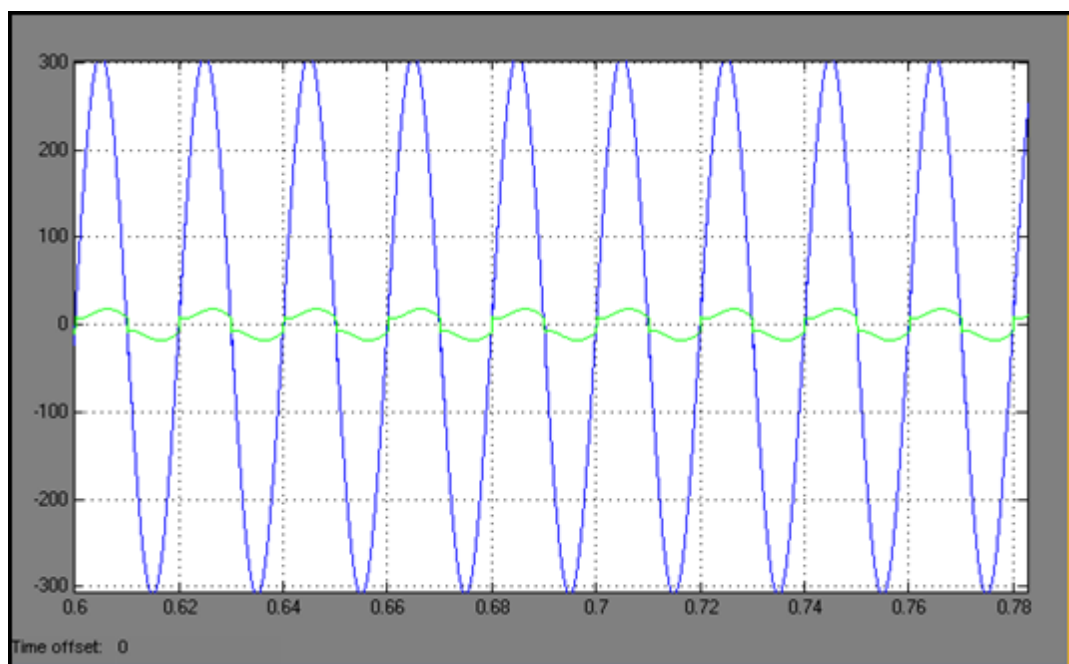

Figure 4.26 Supply current (i_S) and supply voltage (v_S) (Before compensation)
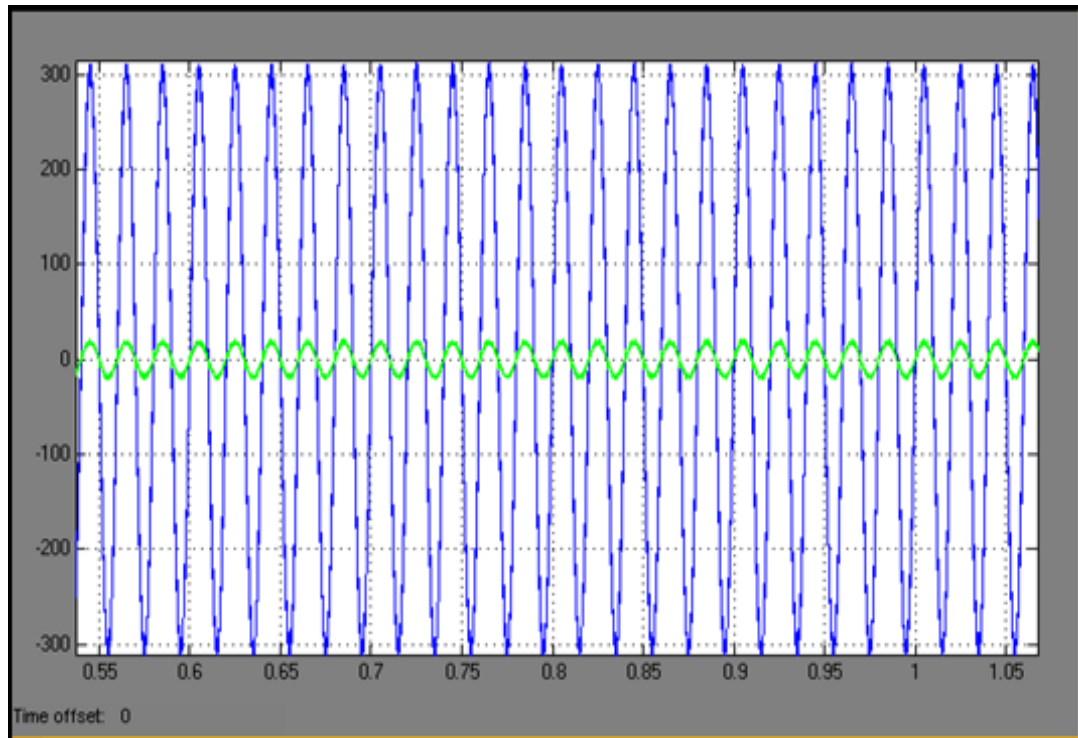
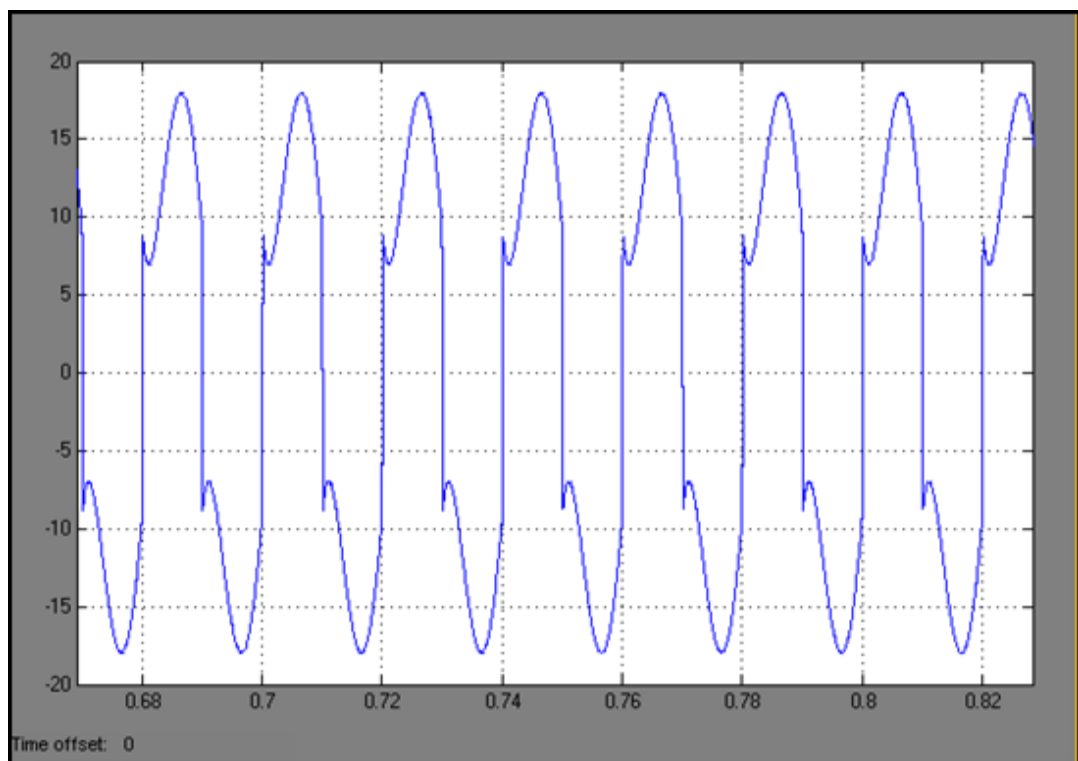Figure 4.27 Supply current (i$_S$) and supply voltage (v$_S$) (After compensation)
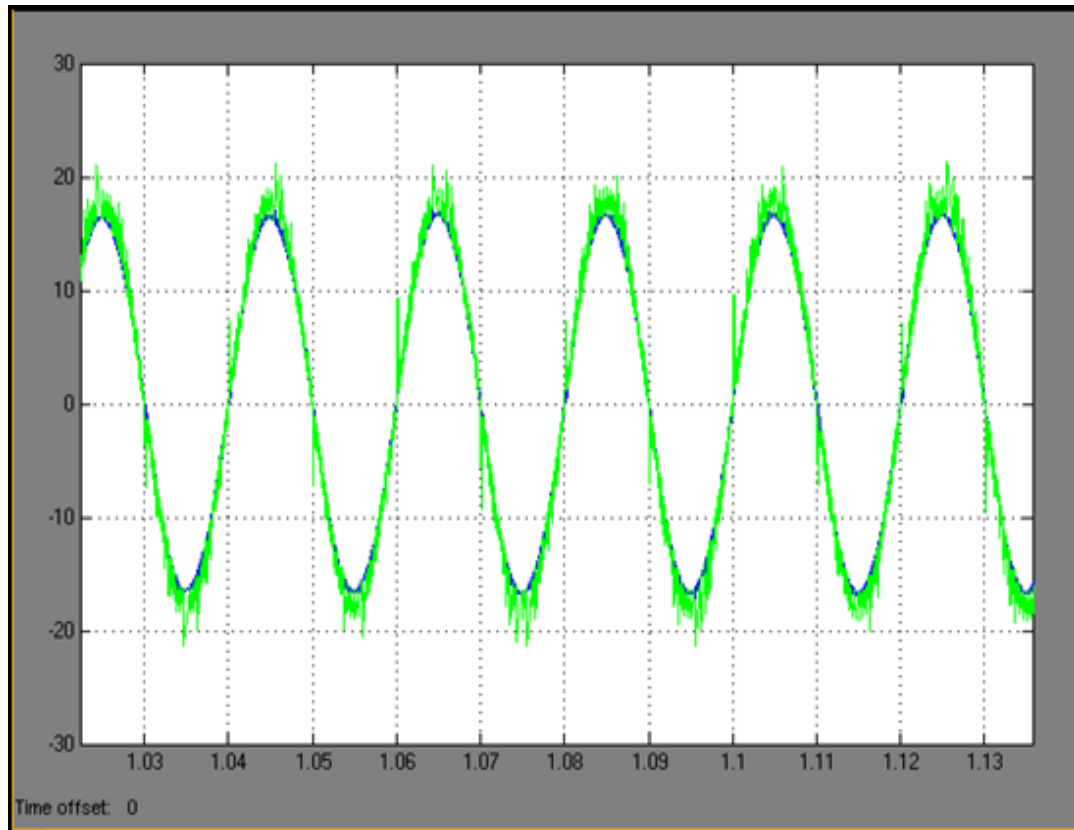

Figure 4.28 Load current (i$_L$)

Figure 4.29 Source current (i_S) and reference compensating current (i_{comp})
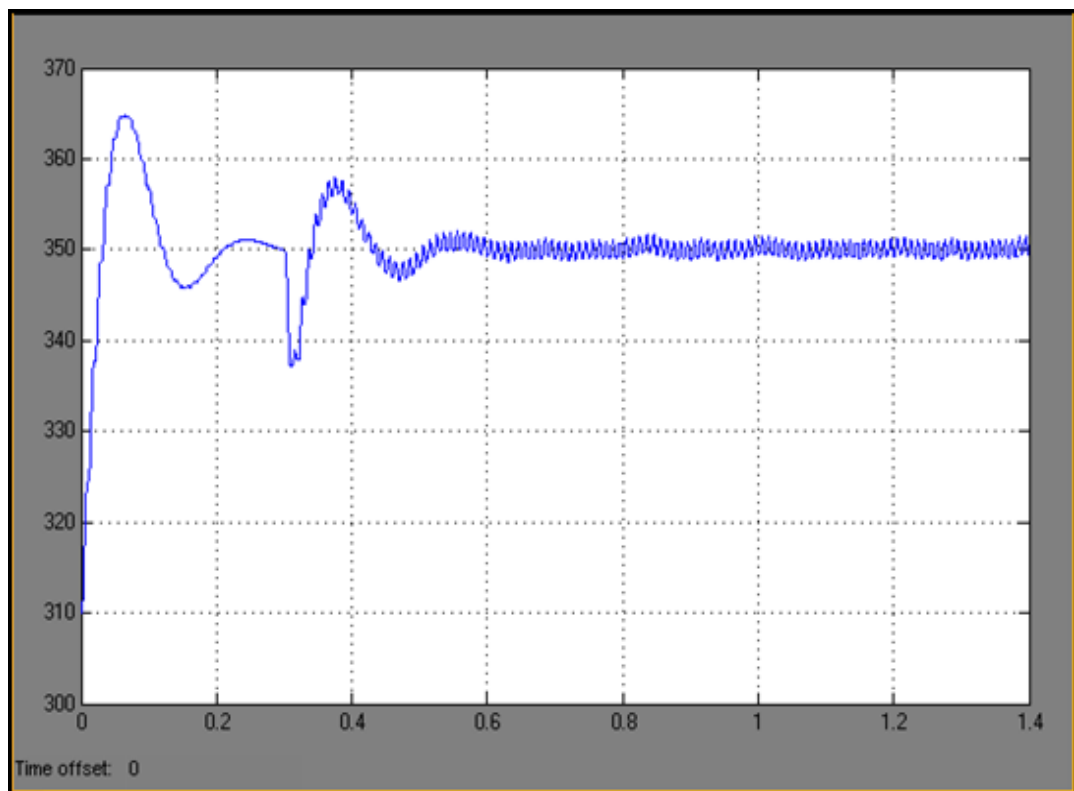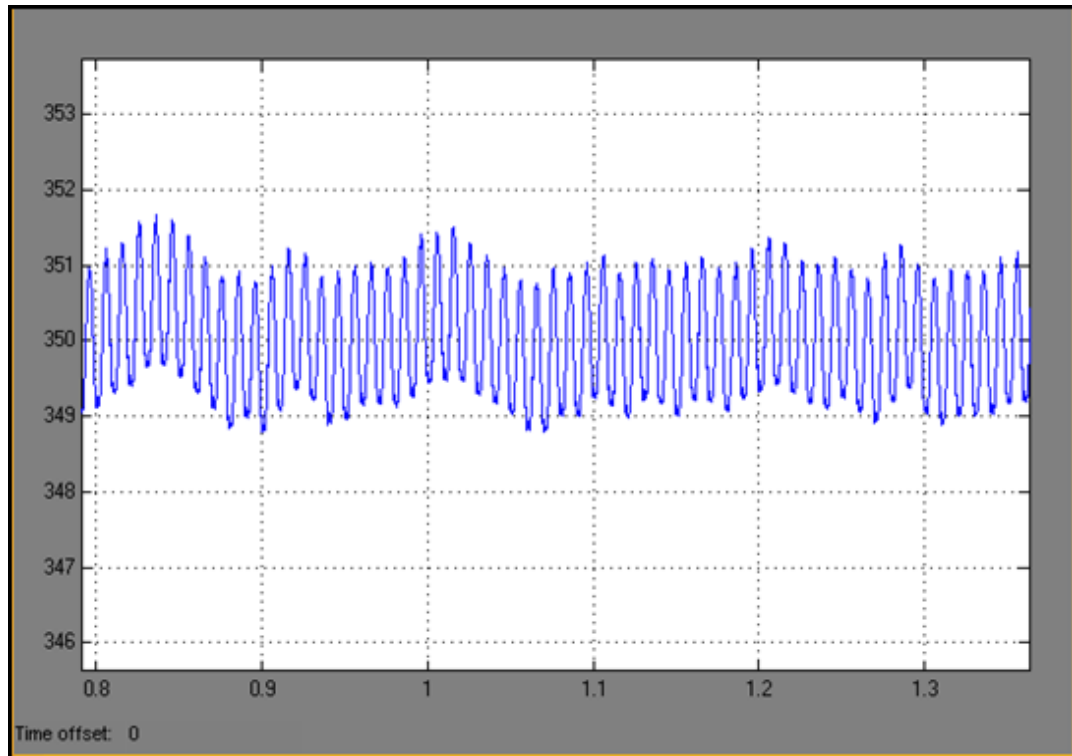

Figure 4.30 DC link voltage (V_{DC})

Figure 4.31 DC link voltage ripple ($V_{DC,ripple}$)

CHAPTER FIVE
DSP BASED SIMULATIONS AND CIRCUITS FOR APPLICATION

5.1 Modeling and Simulation with Matlab & DSP

The reactive power compensation with the proposed control algorithm has been implemented with TMS320F2812 eZdsp board by using C programming language in TI C2000 code composer studio (CCS). The DSP executes the control algorithm, develops the source codes and calculates the reference currents and IGBT gate signals. The main purpose is to test developed source code and compare the DSP based simulation results with Matlab simulation results before connecting the DSP to the real system.

To develop a source code by using Code Composer Studio, the memory locations for the ADC inputs and gate signal outputs are specified in Matlab. Simulink can access these memory locations while simulating the system with DSP. After specifying these memories, the control algorithm that will be used has to be located in DSP block as shown in Figure 5.1.
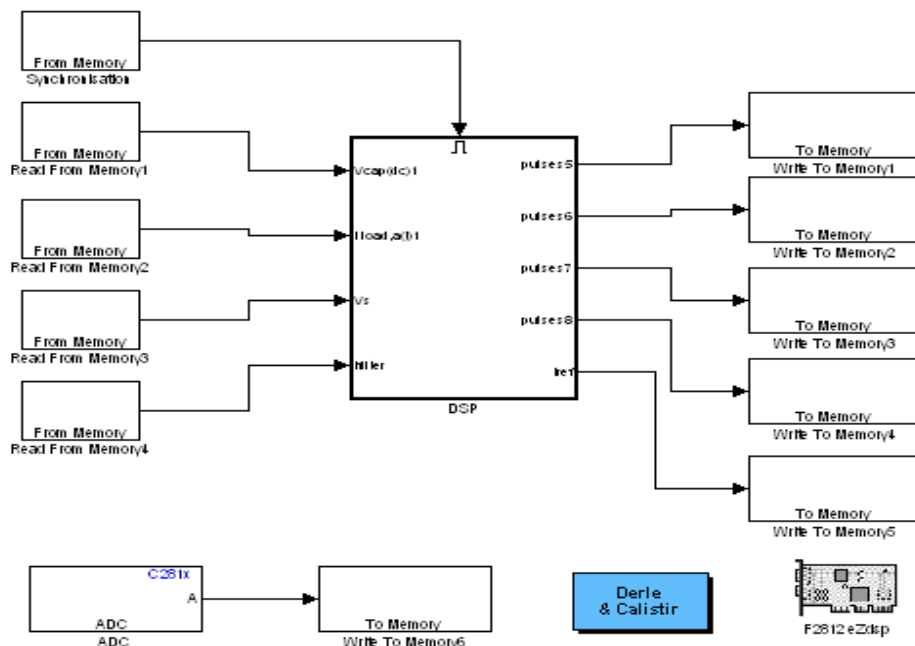

Figure 5.1 Block diagram of memory locations & control algorithm

The sampling frequency (Ts) is defined in Matlab and the developed Matlab block is executed through the C codes given in Appendix A & Appendix B, and the DSP source code is generated. The given C code m-files in Appendix A & B has to be in the same folder with the Matlab Simulink file. After generating the code, the developed DSP part in Matlab Simulink can be changed with Simulink & CCS Interface block. The proposed control algorithm and the simulation model of the system with linear / nonlinear loads and single phase voltage source PWM converter is modeled with Simulink & DSP as follows, given in Figure 5.2.
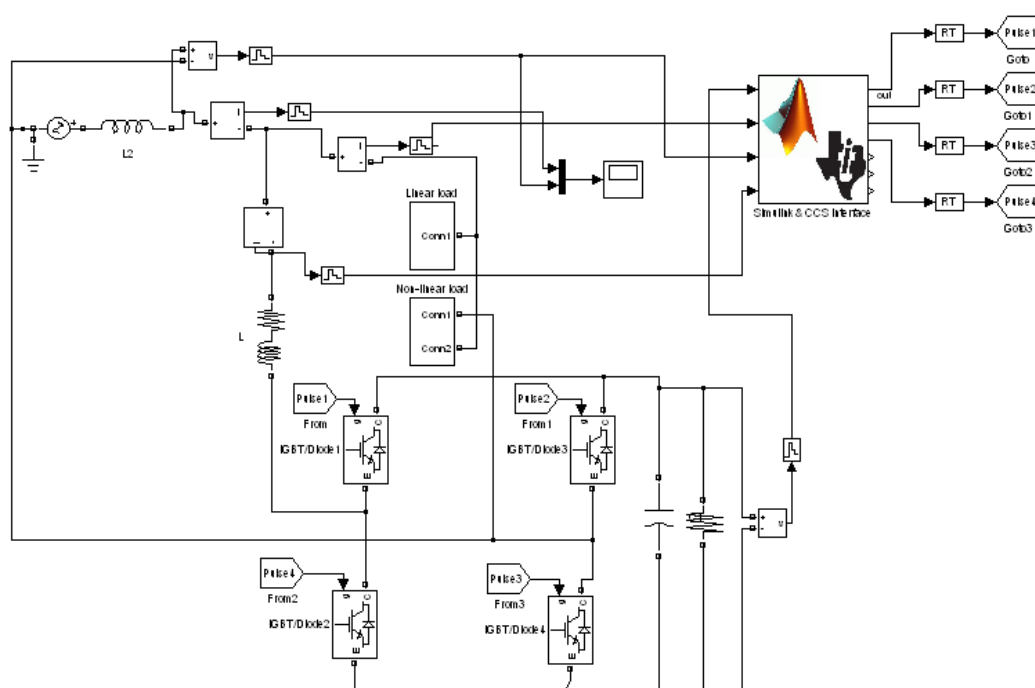
Figure 5.2 Block diagram of Simulink Matlab & DSP

The simulations for the reactive power compensation are obtained with the direct current control technique.

The circuit has three stages of operation as follows:
1. From zero to 0.2sec, there is no load
2. From 0.2sec to 0.6sec, linear R-L load is switched on
3. From 0.6sec to 1sec, the linear load is switched off and non linear R-L load is switched on

The implementation of the voltage source single phase converter for reactive power compensation is shown in below figures.
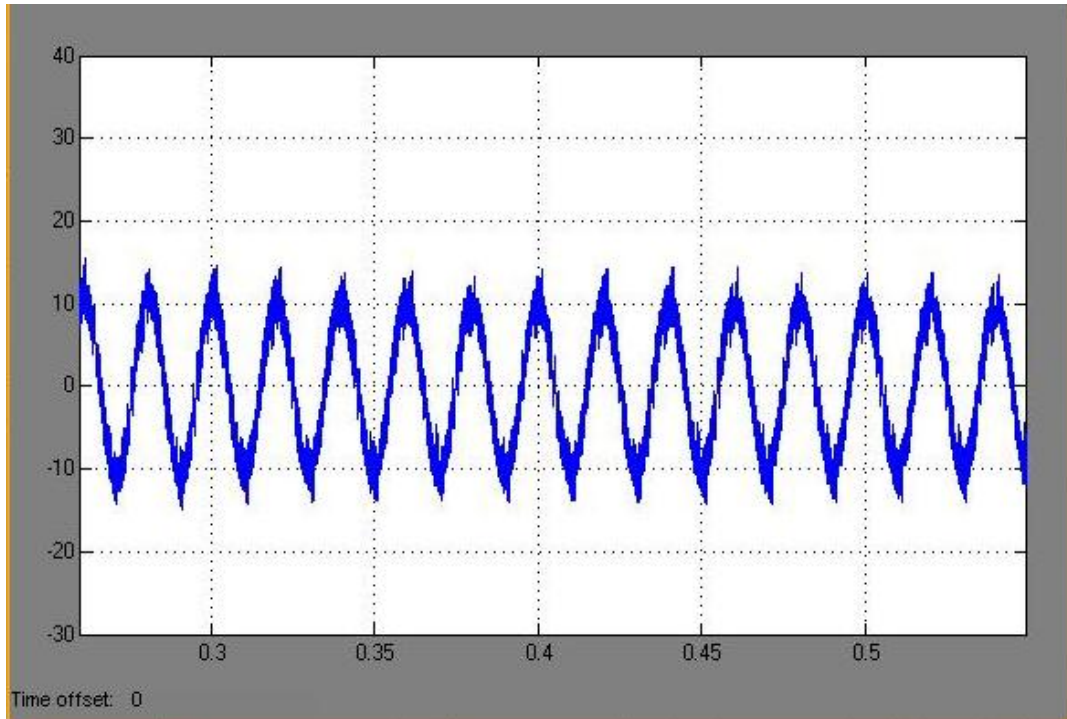
Figure 5.3 Filter current (i_F) for linear load
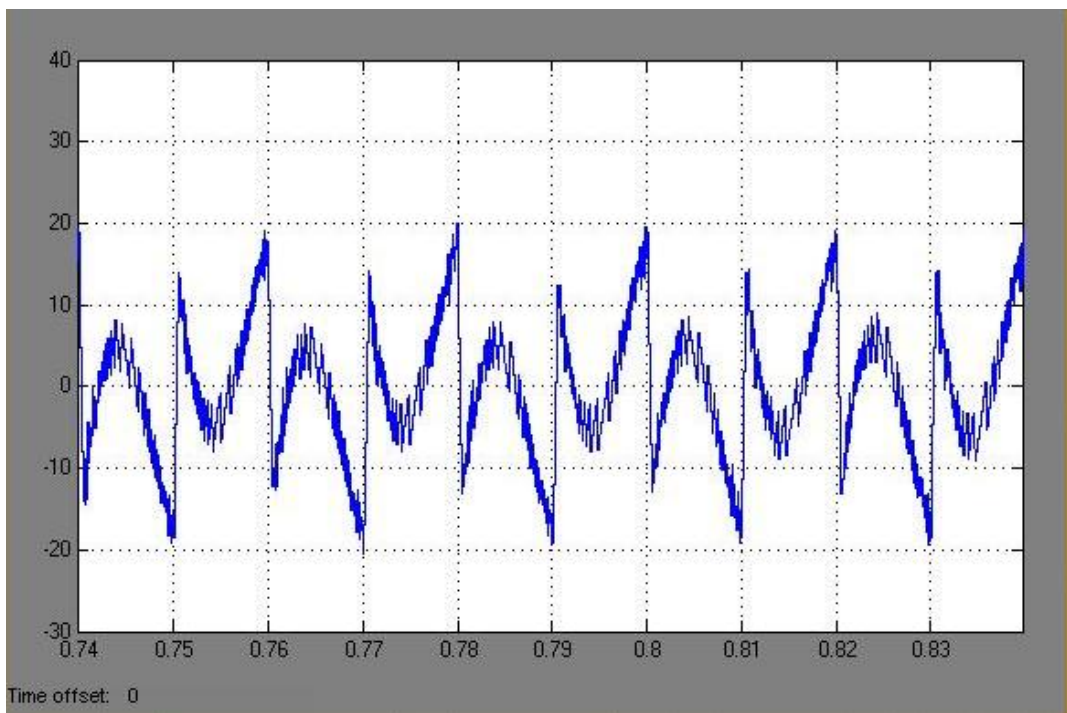
Figure 5.4 Filter current (i_F) for non-linear load
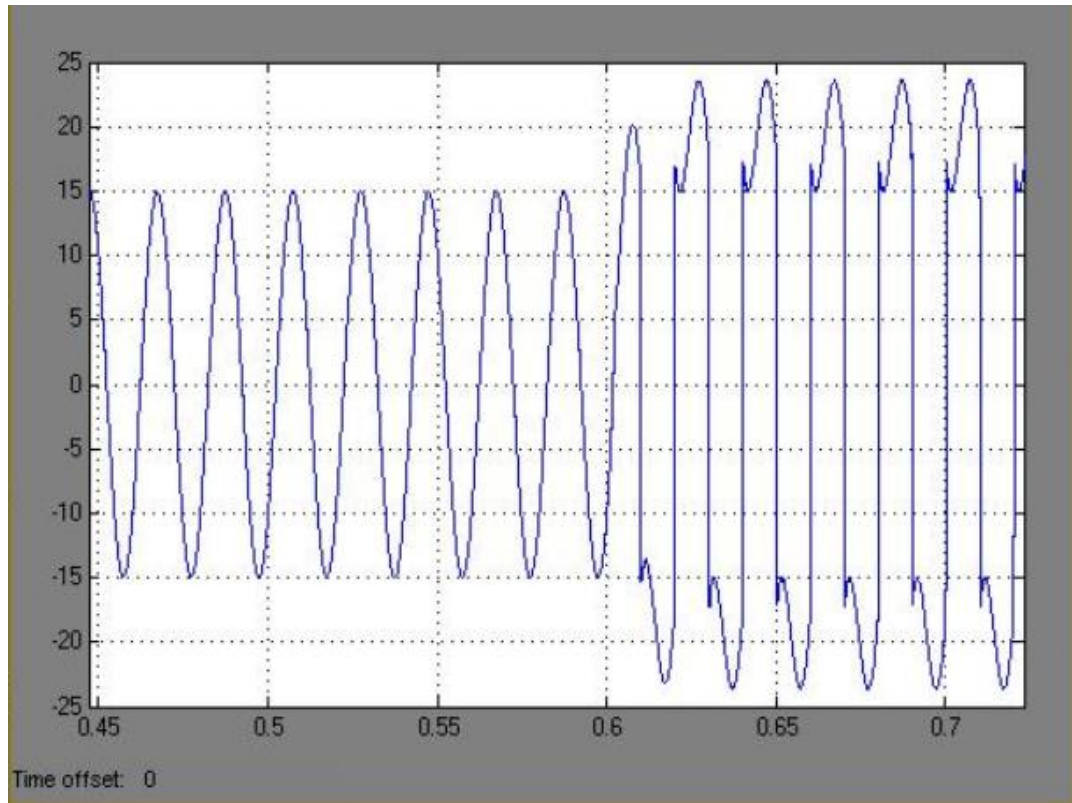
Figure 5.5 Load current (i$_L$) for linear & nonlinear load
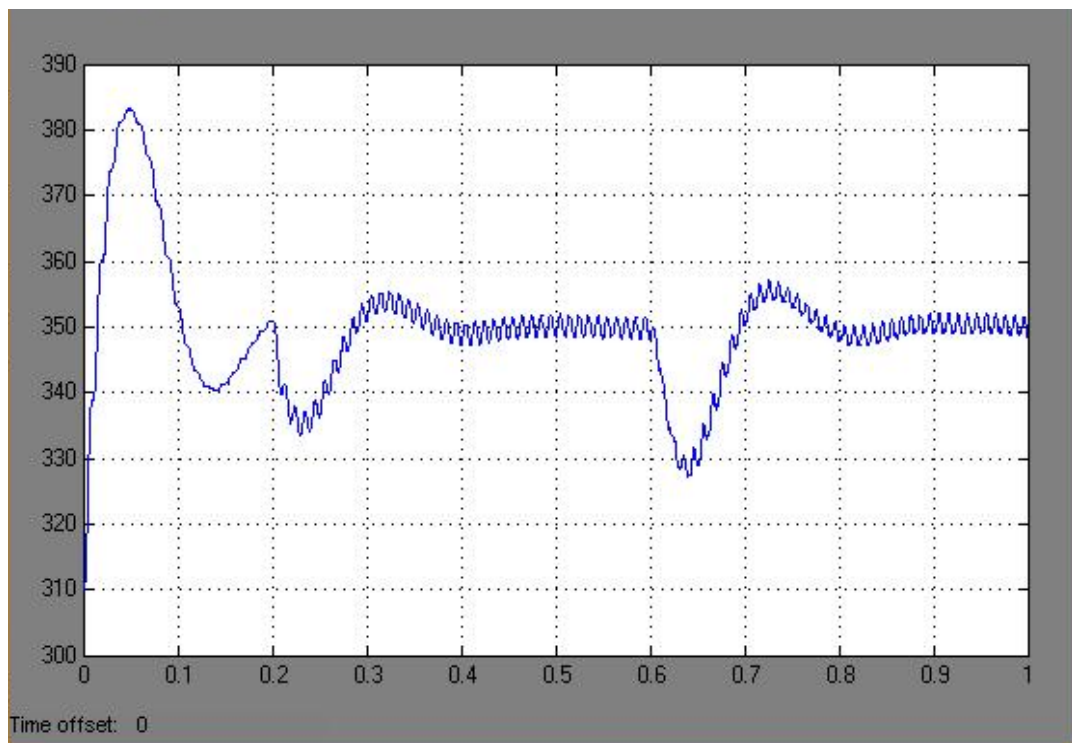
Figure 5.6 DC link voltage (V$_{DC}$)
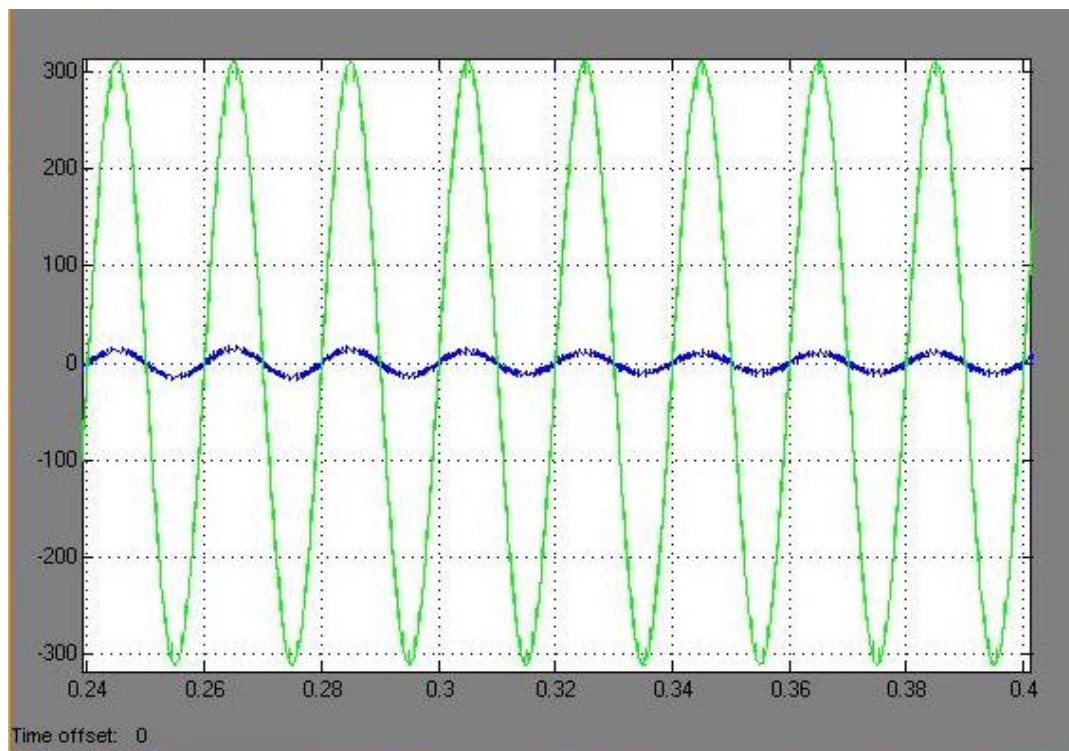
Figure 5.7 Supply current (i_S) and supply voltage (v_S) (After compensation)

It is clear that the voltage is in phase with current after the compensation. It can be observed that the simulation results of Matlab Simulink in Figure 4.8 and DSP based simulations in Figure 5.7 are identical.

5.2 Implementation Circuit and Operation Principle

The implementation circuit is composed of DSP board, buffer circuit, IGBT driver, current and voltage measurement circuits, and voltage source PWM converter with four IGBT switches, DC link capacitor and inductor. The hardware setup for the reactive power compensation is implemented as shown in Figure 5.8 below.
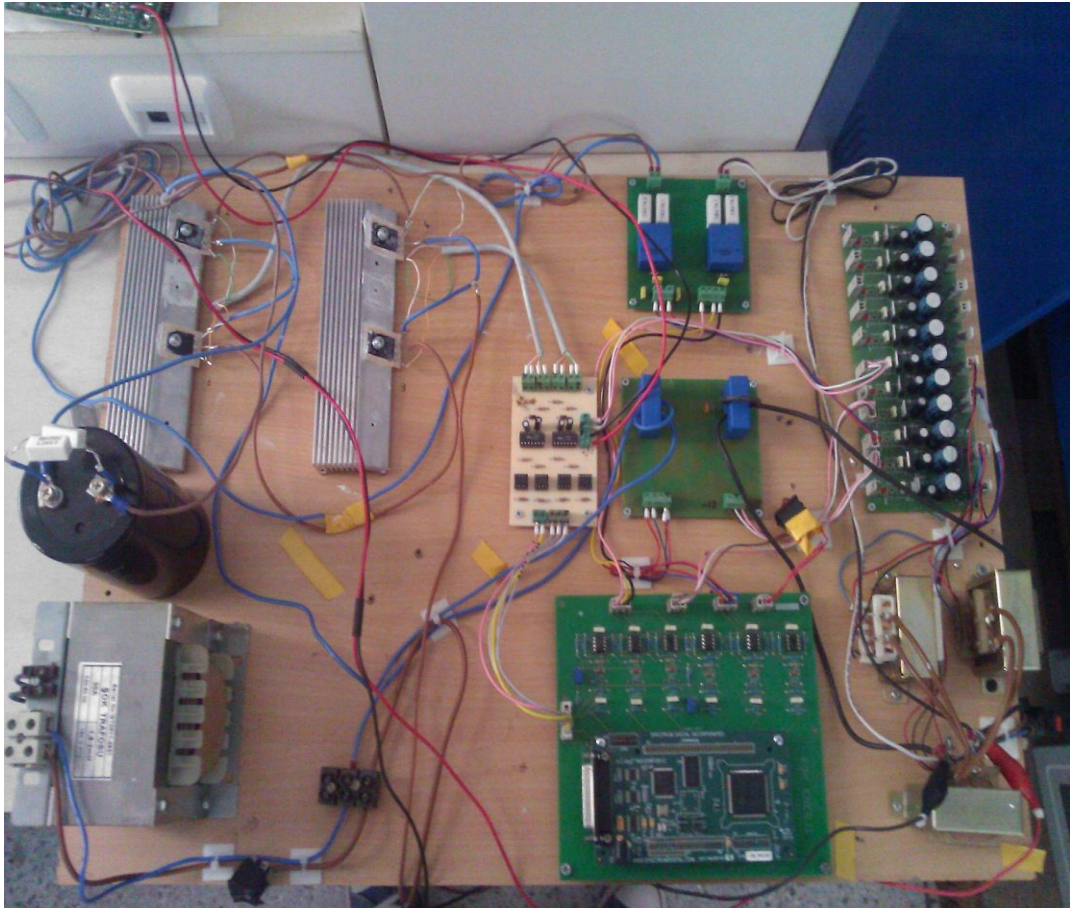
Figure 5.8 Implementation of Reactive Power Compensation Circuit

For real system, TMS320F2812 eZdsp is programmed to produce gate pulses for the IGBT switches by comparing computed reference current and actual converter current with hysteresis controller according to the control technique specified.

To develop DSP source codes for real system, DSP block, ADC input blocks, Digital output block and F2812 eZdsp flash chip are located in Matlab Simulink, shown in Figure 5.9.
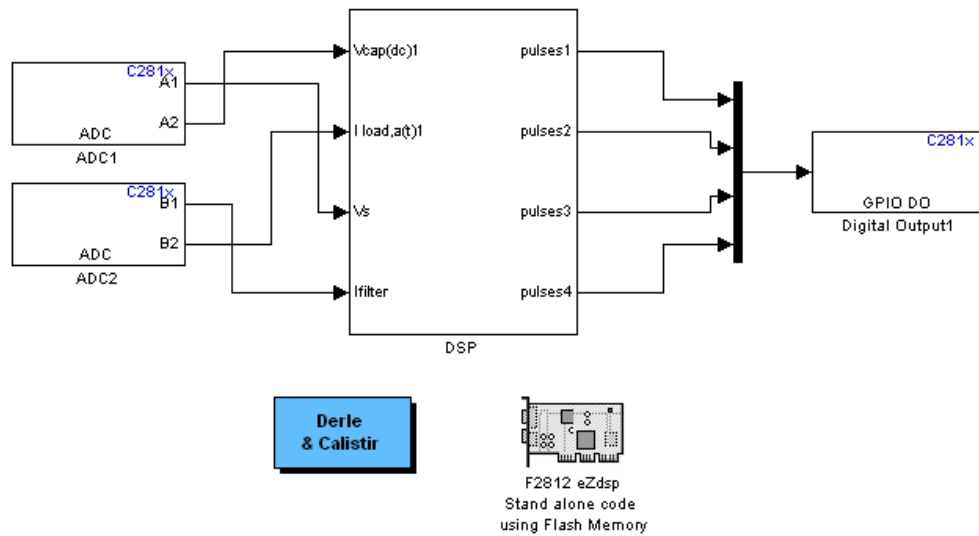
Figure 5.9 DSP I/O blocks and control algorithm for the real system

ADC input block is placed for source voltage, load current, filter current and DC link voltage, and Digital output block is placed for IGBT gate signals. The detailed control block converted to a programming in DSP is also shown in Figure 5.10.
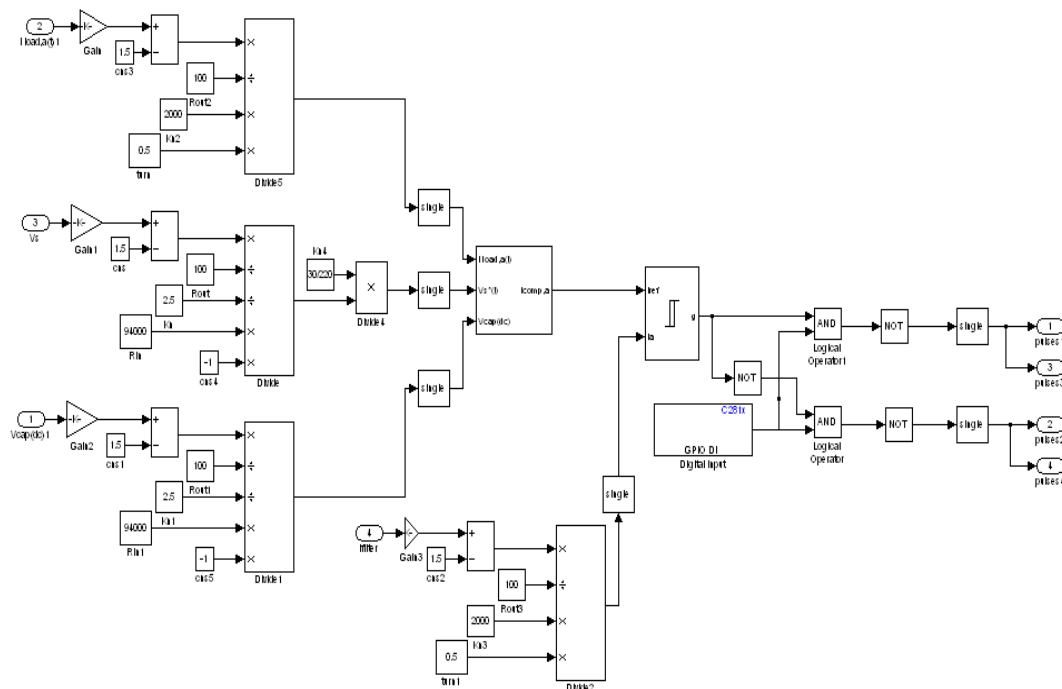
Figure 5.10 The control algorithm in DSP block for the real system

DSP block is composed of gain constants for current and voltage transducers, direct current control algorithm and hysteresis current controller which is shown in Figure 5.10. F2812 eZdsp flash chip is placed for executing the generated DSP source codes in stand alone for the real system.

The given C code m-files in Appendix A & B has to be in the same folder with the Matlab Simulink file as done in DSP based simulations. After executing the system, the project file is developed in F2812 eZdsp Code Composer Studio (CCS) through the C codes given in Appendix A & Appendix B.
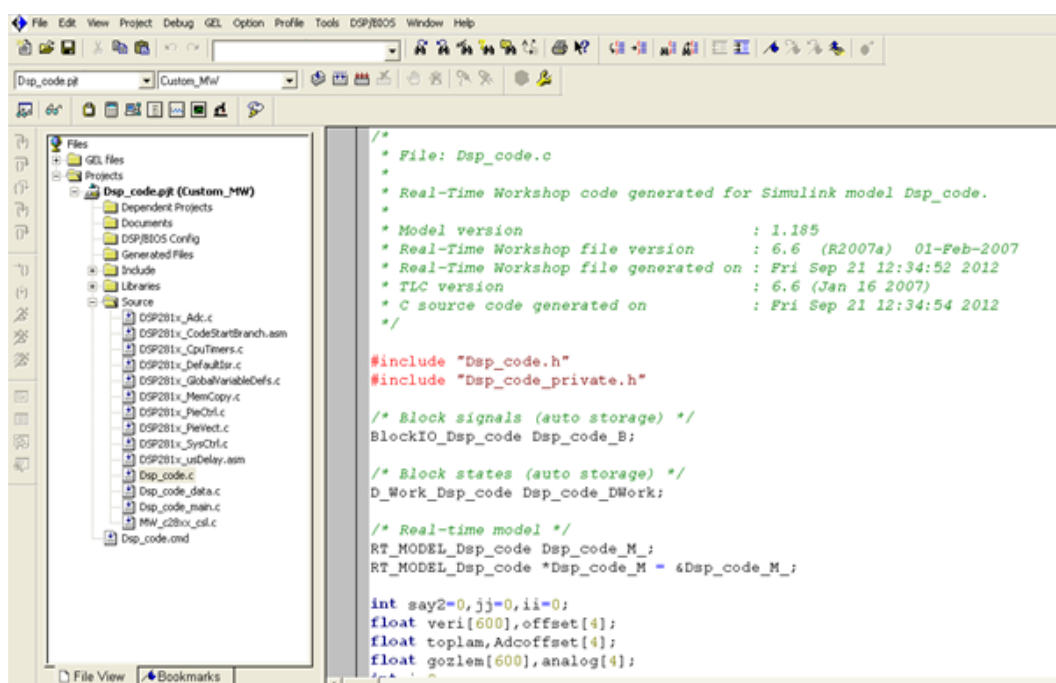
Figure 5.11 Schematic of CCS after generating C codes in DSP

Also, for all ADC inputs, offset calculations has to be done for current and voltage measurement circuits at start up. Each ADC input has different error and tolerance from these measurement circuits. So, this instability has to be compensated in software thus offset program given in Appendix C is added to the project file.
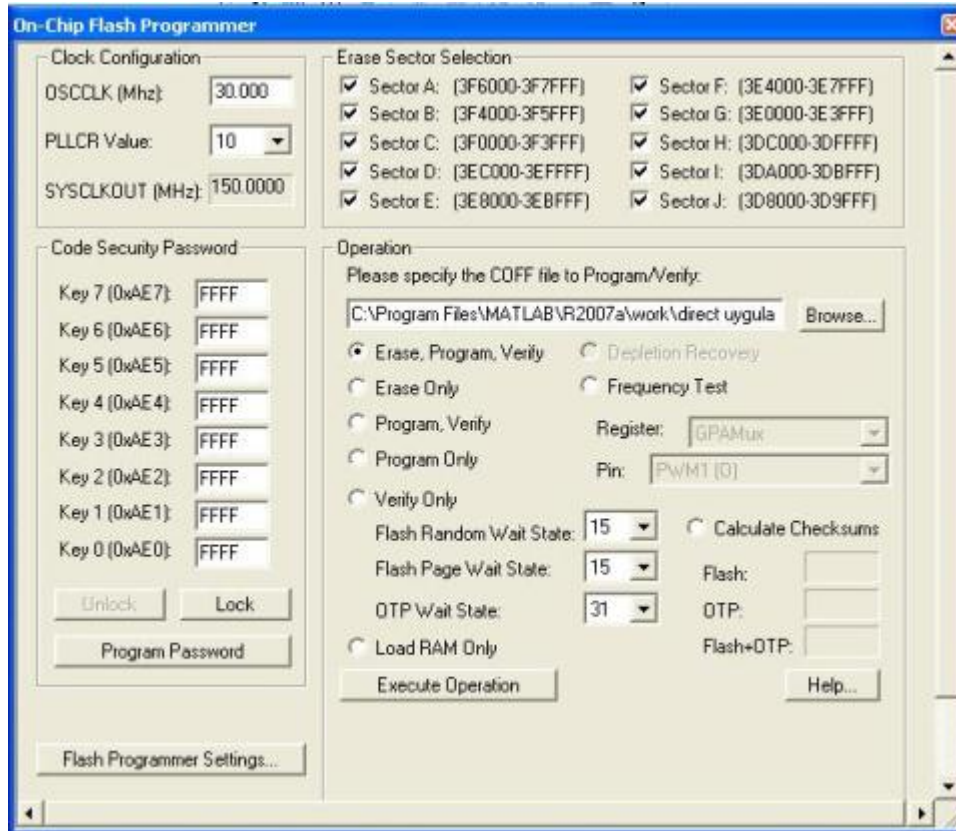
Figure 5.12 Executing the DSP source code with FlashProgrammer

When the DSP is executed with flash programmer, as in Figure 5.12, the following figures are obtained through the ADC inputs after offset calculations. Signals are sampled with 600sample / 3 periods at 10 kHz sampling frequency.
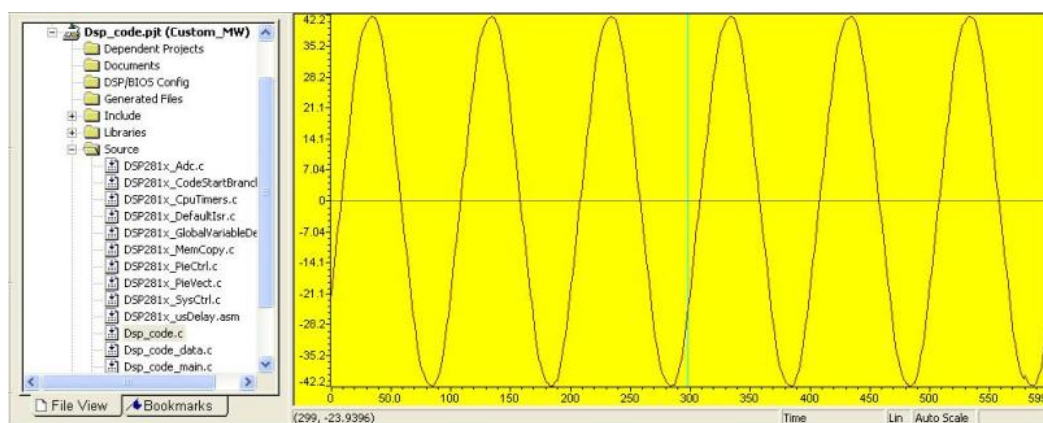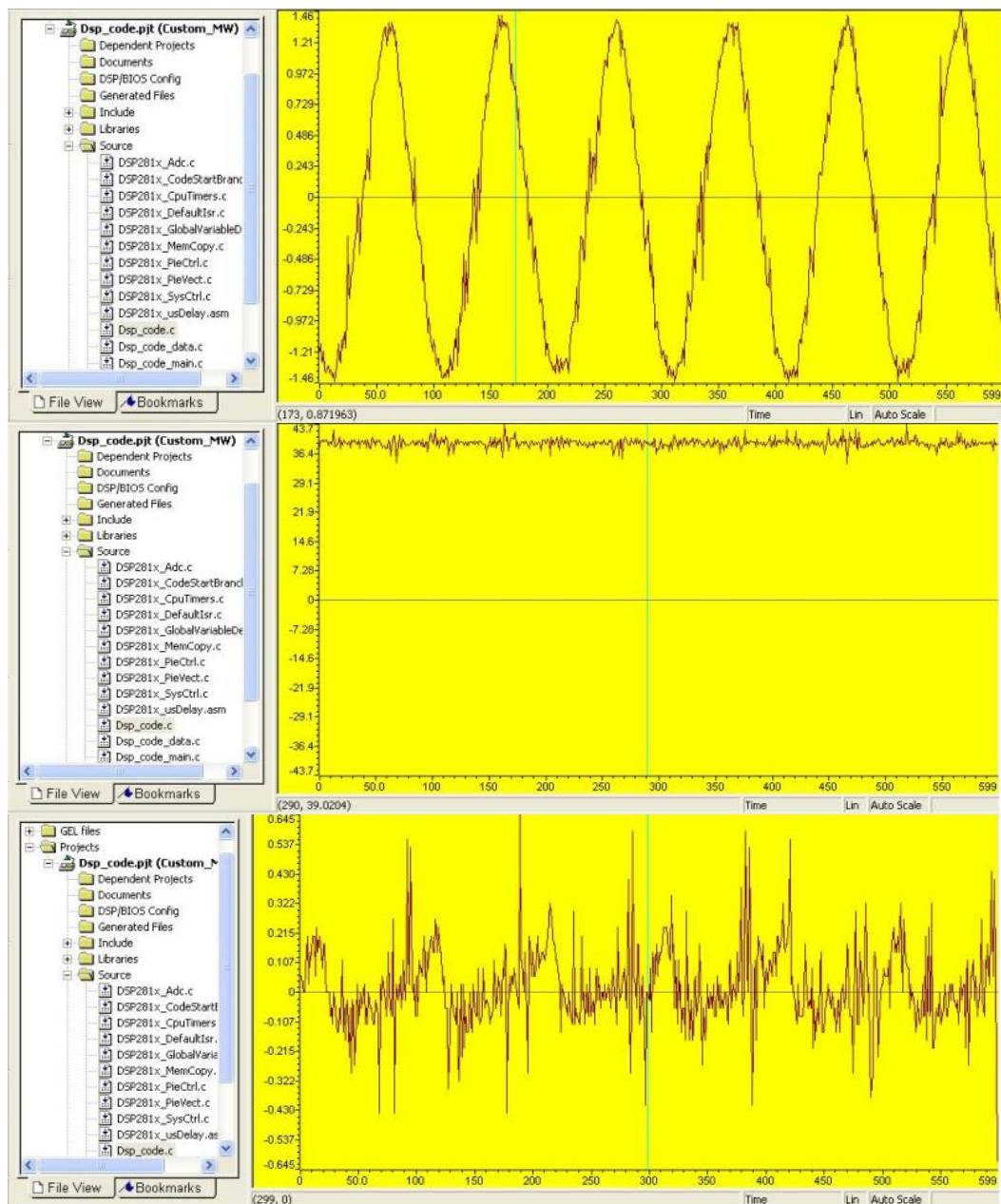
Figure 5.13 The source voltage, load current, DC link voltage and filter current graphs read from ADC input ports in real system

The above graphs are obtained at 30Vrms with 30ohm resistor. There is no switching on IGBTs and DC link capacitor is initially charged to 42V peak voltage through the 5.4mH inductor and antiparallel diodes on the IGBTs.

If the system starts switching, DC link voltage is boosted to the value around 50V peak voltage by PI controller, which is the defined reference DC link voltage in the

control algorithm, become steady state. The IGBT gate signals at DSP output ports are 3.3V after switching and shown in below figures.

Figure 5.14 Gate signals at DSP output ports

Figures 5.15 shows the source voltage and load current under balanced loading conditions.
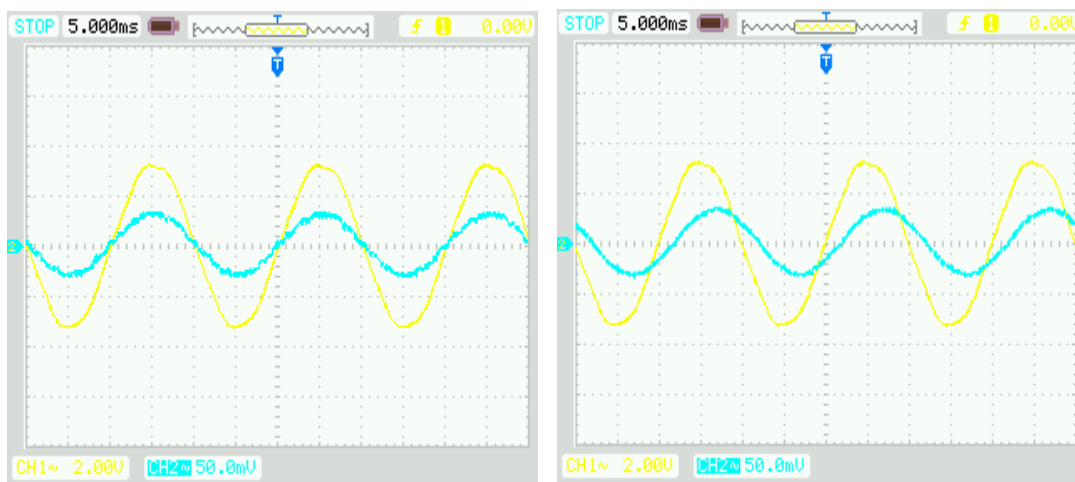
a)   b)

Figure 5.15 Source voltage and load current wave form with a) Resistive load b) R-L load

Figure 5.16 shows the DC link voltage and filter currents with no load and R-L load. It can be obtained that after R-L load; the parallel connected system injects compensating current through the inductor.

a)   b)
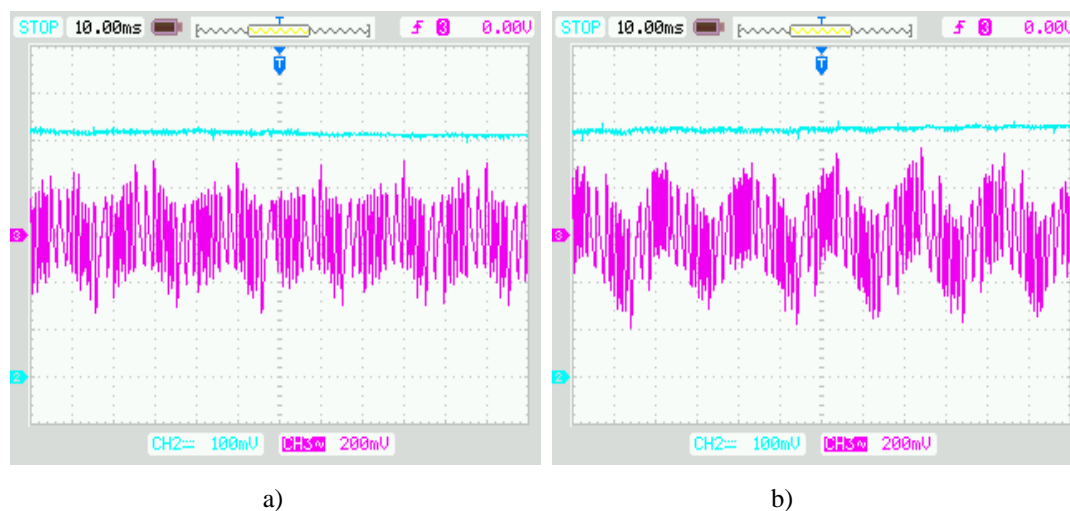
Figure 5.16 DC link voltage and filter current after switching a) with no load b) with R-L load

5.3 Current and Voltage Measurement Circuits

Current and voltage measurement circuits are used for sensing the required voltages and current for the proposed current control algorithm.

Single phase reactive power compensation with the proposed control algorithm needs the phase voltage and current measurements. For this purpose, the voltage and current sensors are used. LA100P current sensors are used for measuring the supply current and filter current. LV25P voltage sensors are used for measuring the DC link voltage and supply voltage.

The measured voltage and current waveforms are given to the ADC ports of the TMS320F2812 DSP by buffering these signals to 0-3V ADC voltage levels.

The current and voltage measurement circuits are given in Figure 5.17 and 5.18 respectively.
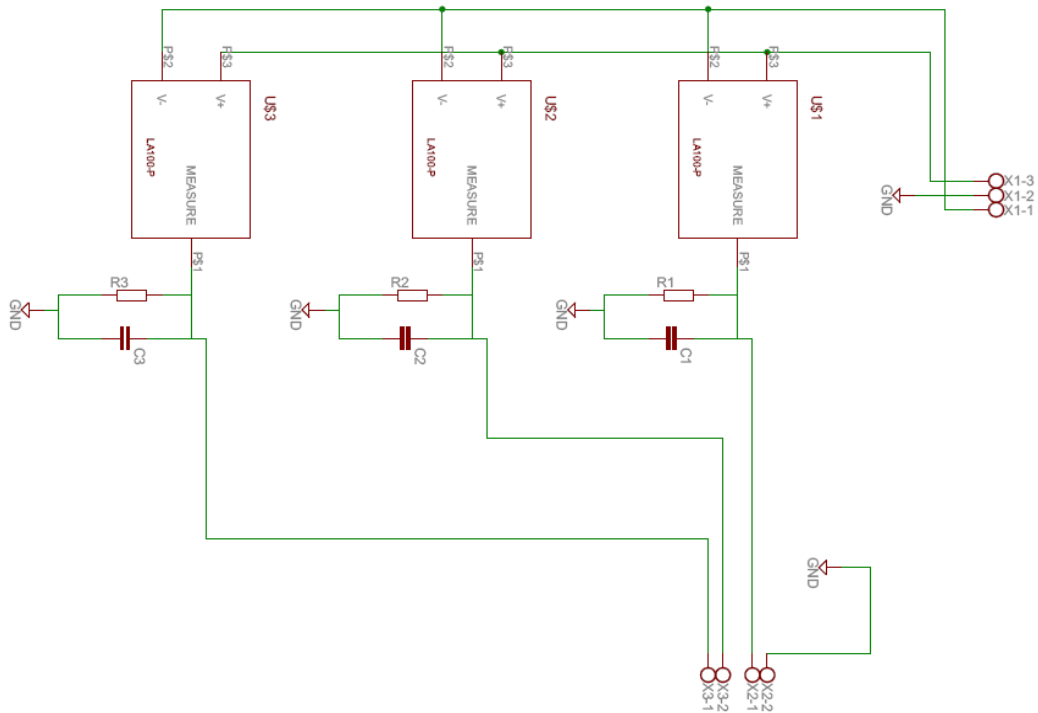
Figure 5.17 Current measurement schematic
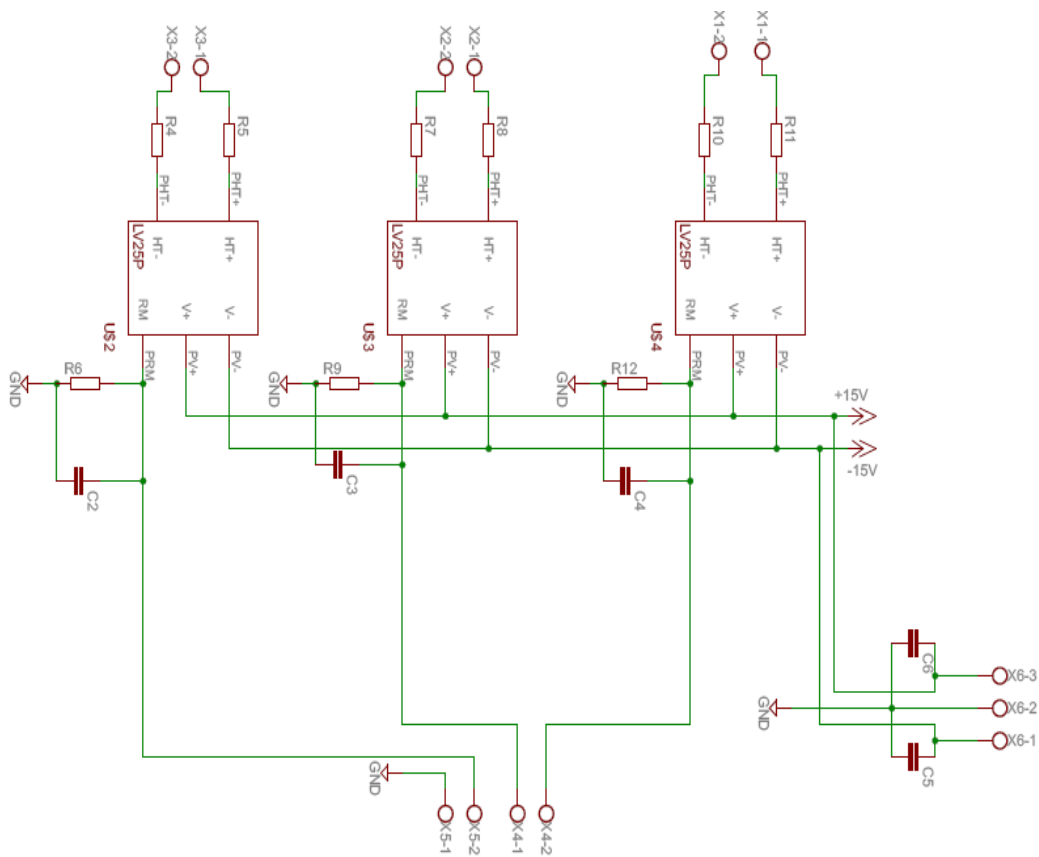
Figure 5.18 Voltage measurement schematic

5.4 Buffer Circuit

The outputs of these sensors are not convenient for analogue-digital converters (ADCs) which can do sampling between 0-5V so the signal has to be updated between these levels. So, buffer circuit is used. The measured current and voltage signals enter the buffer circuit. Then, the offset value is added to the signals. DSP uses these buffered signals for calculating the reference compensating currents.

The voltage and current measurements are buffered by the analog circuits in Figure 5.19.

a)

b)
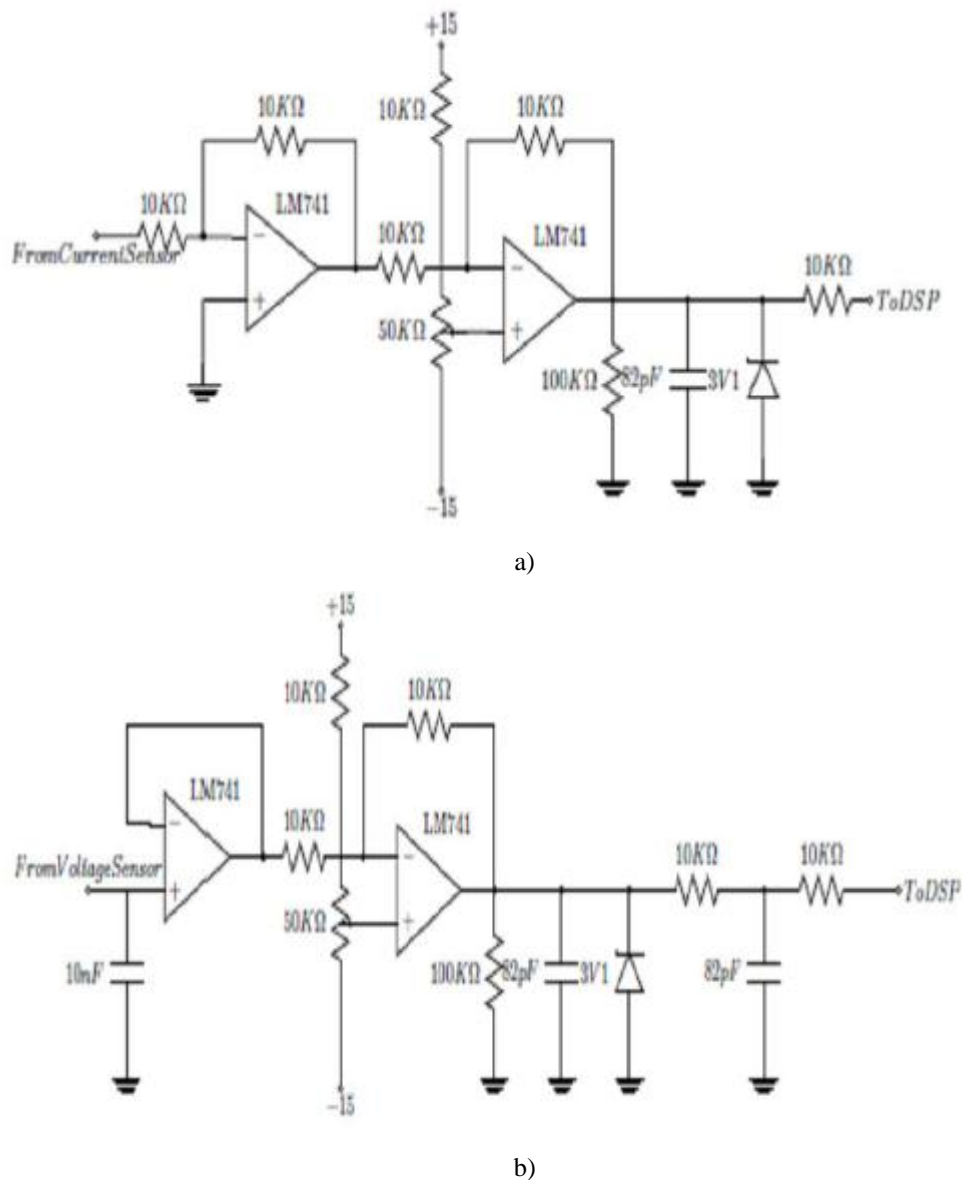
Figure 5.19 a) Buffer circuit for current waveform b) Buffer circuit for voltage waveform

5.5 IGBT Drive Circuit

IGBTs, which are voltage controlled devices from their gates, require a minimum gate threshold voltage of about 15V for generating the collector to emitter conduction. Voltage and current values of the DSP output signals are not enough for operating of IGBTs. So, IGBT driver circuit is used for amplifying the DSP output signals from 3.5 V to the value around 15V triggering levels. DSP and the power circuit are isolated with the help of opto-couplers.

The schematic diagram for the IGBT driver circuit is shown in Figure 5.20.
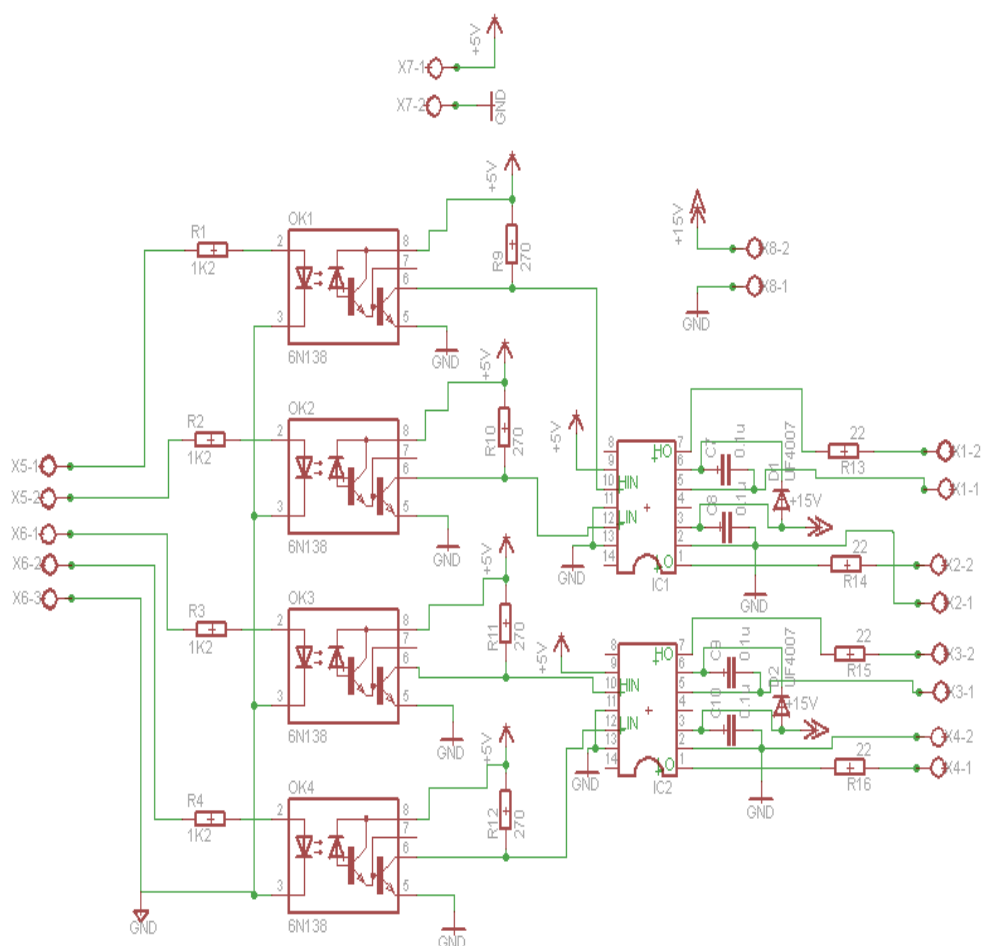
Figure 5.20 IGBT Drive Circuit

TMS320F2812 eZdsp controller and its PWM output ports are used for the drive circuit inputs. The four PWM signals feed two optocoupler (6N137) for the isolation

of gate drivers. To drive the IGBTs, IR2113 gate driver is used in the lower and upper side of the PWM inverter.

For high surge voltage protection, 0.1uf snubber capacitor is used across the inverter. Also, to prevent high inrush current a resistor is connected for the gate pin of IGBTs, as a result we can reduce the stress on DC link capacitor and rectifier diodes.

CHAPTER SIX
CONCLUSION

A bridge single phase pwm rectifier with instantaneous reactive power theory is designed and simulated for single phase case in this thesis. A model of the system is developed in MATLAB / Simulink software and the performance of hysteresis band current controller is analyzed.

The developed system can be used for reactive power compensation and to eliminate current harmonics in a non-linear load. Instantaneous reactive power theory, also named as p-q theory, has been used with the direct current control and indirect current control techniques. The reference compensating current signals are generated using these control techniques. Both current control techniques are simulated in Matlab Simulink. After converting the Matlab program to c-code and loading on DSP, the universal bridge structure of converter in Matlab is controlled by the DSP. This approach is being used as a "function test" for program in this thesis. Any possible mistake in the program is identified before connecting the control circuit to the bridge converter fed by grid. This technique developed here is considered as the useful test bench between prototype and manufacturing process.

The generated reference current signals are sent to the current regulator and the gating signals for the MOSFET driver circuit are determined. The performance of the system is highly dependent on the accurate measurement and the calculation of the compensation current references and DC bus voltage regulating current reference. The sampling frequency is the key parameter if the program is converted from Matlab automatically, because of long execution time.

In this thesis, a single phase voltage source pwm rectifier is designed with the control of p-q theory for reactive power compensation under linear / nonlinear loads. The simulation results are obtained from linear and nonlinear loading conditions. After the compensation, it is seen that the reactive power compensation system

improves the power factor; hence the phase voltage and current are observed in phase after the compensation.

Further work can be the implementation on the designed system for the different control algorithms.

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APPENDIX A

The following program is used for connecting Simulink and eZdsp.

```matlab
function aktar(block)

global cc
cc = ccsdsp('boardnum',0,'procnum',0);

    run(cc);
    setup(block);

%endfunction

function setup(block)
 global cc

  block.NumInputPorts  = 4;
  block.NumOutputPorts = 7;


  block.SetPreCompInpPortInfoToDynamic;
  block.SetPreCompOutPortInfoToDynamic;

  block.InputPort(1).Complexity   = 'Real';
  block.InputPort(1).DataTypeId   = 0;
  block.InputPort(1).SamplingMode = 'Sample';
  block.InputPort(1).Dimensions   = 1;
  block.InputPort(2).Complexity   = 'Real';
  block.InputPort(2).DataTypeId   = 0;
  block.InputPort(2).SamplingMode = 'Sample';
  block.InputPort(2).Dimensions   = 1;
  block.InputPort(3).Complexity   = 'Real';
  block.InputPort(3).DataTypeId   = 0;
  block.InputPort(3).SamplingMode = 'Sample';
  block.InputPort(3).Dimensions   = 1;
  block.InputPort(4).Complexity   = 'Real';
  block.InputPort(4).DataTypeId   = 0;
  block.InputPort(4).SamplingMode = 'Sample';
  block.InputPort(4).Dimensions   = 1;


  block.OutputPort(1).Complexity   = 'Real';
  block.OutputPort(1).DataTypeId   = 0;
  block.OutputPort(1).SamplingMode = 'Sample';
  block.OutputPort(1).Dimensions   = 1;
  block.OutputPort(2).Complexity   = 'Real';
  block.OutputPort(2).DataTypeId   = 0;
  block.OutputPort(2).SamplingMode = 'Sample';
  block.OutputPort(2).Dimensions   = 1;
  block.OutputPort(3).Complexity   = 'Real';
  block.OutputPort(3).DataTypeId   = 0;
  block.OutputPort(3).SamplingMode = 'Sample';
  block.OutputPort(3).Dimensions   = 1;
```

```matlab
  block.OutputPort(4).Complexity   = 'Real';
  block.OutputPort(4).DataTypeId   = 0;
  block.OutputPort(4).SamplingMode = 'Sample';
  block.OutputPort(4).Dimensions   = 1;
  block.OutputPort(5).Complexity   = 'Real';
  block.OutputPort(5).DataTypeId   = 0;
  block.OutputPort(5).SamplingMode = 'Sample';
  block.OutputPort(5).Dimensions   = 1;
  block.OutputPort(6).Complexity   = 'Real';
  block.OutputPort(6).DataTypeId   = 0;
  block.OutputPort(6).SamplingMode = 'Sample';
  block.OutputPort(6).Dimensions   = 1;
  block.OutputPort(7).Complexity   = 'Real';
  block.OutputPort(7).DataTypeId   = 0;
  block.OutputPort(7).SamplingMode = 'Sample';
  block.OutputPort(7).Dimensions   = 1;

  block.InputPort(1).DirectFeedthrough = true;


  %% Set block sample time to inherited
  block.SampleTimes = [-1 0];

  %% Run accelerator on TLC
  block.SetAccelRunOnTLC(true);

  %% Register methods
  block.RegBlockMethod('Outputs',                 @Output);

%endfunction


function Output(block)
global cc

write(cc, [hex2dec('8210')], single(block.InputPort(1).Data) );

write(cc, [hex2dec('8220')], single(block.InputPort(2).Data) );

write(cc, [hex2dec('8230')], single(block.InputPort(3).Data) );

write(cc, [hex2dec('8240')], single(block.InputPort(4).Data) );

write(cc, [hex2dec('8200')], single(1) );

pause(0.000001)

block.OutputPort(1).Data = double(read(cc, [hex2dec('8250')],
'single', 1 ));

block.OutputPort(2).Data = double(read(cc, [hex2dec('8260')],
'single', 1 ));

block.OutputPort(3).Data = double(read(cc, [hex2dec('8270')],
'single', 1 ));
```

```matlab
block.OutputPort(4).Data = double(read(cc, [hex2dec('8280')],
'single', 1 ));

block.OutputPort(5).Data = double(read(cc, [hex2dec('8290')],
'single', 1 ));

block.OutputPort(6).Data = double(read(cc, [hex2dec('82A0')],
'single', 1 ));

block.OutputPort(7).Data = double(read(cc, [hex2dec('82B0')],
'single', 1 ));

%endfunction
```

APPENDIX B

The following program is used for generating DSP code from Simulink block diagrams.

```matlab
function derle_grn(action)

 try
    % Steps not needed in Simulation mode.
    if ~strcmpi(action,'Simulation')
        modelName = gcs;
        disp('### Code Composer Studio(tm) Baglaniliyor...');
        CCS_Obj = connectToBoard(modelName);
        CCS_Obj.visible(1);
        % construct full path name of demo
        fullModelName = fullfile('.', [modelName '_ccslink'],
modelName);
    end
    switch(action)
        case 'Reload_Run'
            if exist([fullModelName '.out']),
                % save warning present state, and turn off warning
                saveState = warning;
                warning off
                % close previous version of project found in ANY
board
                projectName = [fullModelName '.pjt'];
                try
                    p_closeAnyProj(CCS_Obj, projectName);
                catch
                    % projectName is not open in any board
                end
                try
                    % reload previously generated project
                    CCS_Obj.open(projectName,'project');
                catch
                    % don't error if project does not exist
                end
                % restore warning state
                warning(saveState);
            else
                errordlg({'Could not find COFF file for model. You
need to build the model first.'},...
                    'Load Error');
                return;
            end
        case 'Build_Run'
            load_system(modelName);
            make_rtw
        case 'Simulation'
            hfig = figure;
            pos = get(hfig,'position');
            set(hfig,'position', [pos(1) pos(2) 358 429]);
```

```matlab
            subplot(3,1,1);
            evalin('base','plot(yout1.signals.values(1:200));')
            title('Sine wave approximation with different IQ
formats');
            ylabel('Magnitude')
            xlabel('Time')
            legend('I32 Q4');

            subplot(3,1,2);
            evalin('base','plot(yout2.signals.values(1:200));')
            ylabel('Magnitude')
            xlabel('Time')
            legend('I32 Q5');

            subplot(3,1,3);
            evalin('base','plot(yout3.signals.values(1:200));')
            ylabel('Magnitude')
            xlabel('Time')
            legend('I32 Q15');
            return;
        otherwise
            error('Invalid option.');
    end

    % Change directory to target demo directory
    CCS_Obj.cd(fullfile(pwd,[modelName '_ccslink']));
    outFile = [modelName '.out'];
    % Open target file
    if exist([fullModelName '.out'])
        fprintf('### COFF dosyasi DSPye yukleniyor...\n');
        try
            CCS_Obj.reset;
            pause(1.0);
            CCS_Obj.load(outFile,100)
        catch
            clear CCS_Obj;
            errordlg({'There is a problem loading the COFF file for
the selected processor.';...
                    'You may need to reset your hardware and rebuild
project.'},...
                'Load Error' );
            return
        end
    else
        errordlg({'You need to build the project before running.'},
'Load Error' , 'modal');
        return
    end

    disp('### Islem Tamam ;)')
catch
    errordlg(lasterr);
end
```

APPENDIX C

The following program is used for offset calculations for ADC inputs at start up.

```c
extern int say2,jj,ii;
extern float veri[600],offset[4];
extern float toplam,Adcoffset[4];
extern float gozlem[600],analog[4];
extern int i;
extern int offset_hazir;
void offset_hesap(void)
{
if(offset_hazir == 0){   veri[say2]=analog[0];
say2=say2+1;}
if(offset_hazir == 1){   veri[say2]=analog[1];
say2=say2+1;}
if(offset_hazir == 2){   veri[say2]=analog[2];
say2=say2+1;}
if(offset_hazir == 3){   veri[say2]=analog[3];
say2=say2+1;}
if (say2 == 600)
    {
    say2=0;
    toplam=0;
    for (jj=1;jj<600;jj++){toplam=toplam+veri[jj];}
    offset[ii]= (toplam/599) - 2048;
    ii=ii+1;
    offset_hazir=offset_hazir+1;
    say2=0;
    }
Adcoffset[0]=analog[0]-offset[0];
Adcoffset[1]=analog[1]-offset[1];
Adcoffset[2]=analog[2]-offset[2];
Adcoffset[3]=analog[3]-offset[3];
}
```