Torque Ripple Suppression in presence of 50 Hz Measurement Noise in a Variable Frequency Drive (VFD) with a Pump Load

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It is here by declared that the thesis entitled "**Torque Ripple Suppression in presence of 50 Hz Measurement Noise in a Variable Frequency Drive(VFD) with a Pump Load**" contains literature survey and original research work by the undersigned candidate , as part of his degree in Master of Nuclear Engineering.

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Abstract:

An Induction Motor, driving a pump, and controlled by the Voltage/Frequency (V/F) control methodology, has its inherent advantages. In industry, such motor driving a centrifugal pump set-up is largely affected by unwanted 50Hz noise signal, the sources of which are very difficult to identify. Such unwanted noise signal may result in motor vibration, motor heating-up, fluctuation in the coolant flow, etc. Therefore, it is necessary to design a filter which is capable of mitigating the 50Hz noise from the system. In this dissertation, an induction motor driving a centrifugal pump has been modelled using the standards equations and a 50Hz noise signal has been injected in the feedback loop. The responses generated by this practical set-up, has been analysed in details to identify the dominant frequencies in the spectrum under both ideal and with injected noise conditions. The spectrum established in this regards, are used to design an adaptive filter to filter out unknown 50 Hz noise. The efficacy of the designed filter has been established with credible offline simulations.

Keyword: Induction Motor ,Variable Frequency Drive, Centrifugal Pump , Noise, LMS filter

Contents

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Nomencleture:

Q =Flow Rate ;

N=Speed ;

P= Pressure ;

HP=HorsePower

d-axis= Direct axis

q-axis= Quadrature axis

$V_a V_b V_c$ = Three Phase Voltage displaced with each other by 120^0

V_d^s = Direct axis voltage at stator reference frame

V_q^s = Quadrature axis voltage at stator reference frame

θ_e = Angle between the fixed and rotating co-ordinate system at any

Instant of time.

V_{ds} =Direct axis stator voltage

V_{qs} = Quadrature axis stator voltage

i_{ds} =Stator direct axis current at stationary reference frame

i_{qs} = Stator quadratic axis current at stationary reference frame

R_s = Stator Resistance

R_r =Rotor Resistance

ψ_{ds} = Direct axis stator flux linkage

ψ_{qs} = quadrature axis stator flux linkage

V_{dr} = Direct axis rotor voltage

V_{qr} = Quadrature axis rotor voltage

ψ_{qr} =Flux linkage of rotor in quadratix axis

ψ_{dr} = Flux linkage of rotor in direct axis

L_{ls} = Stator leakage inductance

L_{lr} = Rotor leakage Inductance

L_m = Mutual inductance

ψ_{dm} = Mutual direct axis flux linkage

ψ_{qm} = Mutual quadrature axis flux linkage

T_e = Electromagnatic Torque

T_l =Load torque

P= Number of pole

J = Moment Of Inertia

B = Frictional co-efficient

N_s = Synchronous Speed

s = Slip

E = Rotor induced emf

$u(1)$ u(2) u(3) = Three output of SPWM for three phase

k_p = Proportional Constant

k_i = Integration Constant

V_f = Peak Voltage ,

V_h = Harmonic Peak Voltage ,

I_f = Peak Current

I_h = Harmonic peak current

$\phi = Phase\ Difference$

ψ_f =Fundamental Stator Flux

ψ_h = Harmonic content of stator flux

δ = Torque Angle

μ =Step-size parameter

$\lambda_{\max}$ =Maximum value of the correlation matrix of the tap inputs

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CHAPTER 1

Introduction

1.1 Variable Frequency Drive for a Pump Load:

Three phase induction motors are the most widely used device for industrial control and automation. They are preferred due to their robustness, reliability, less maintenance and high durability [1]. Upon supplying rated voltage at rated frequency, the induction motor runs at its rated speed. However, many applications require variable speed operation [1]. Most popular techniques of induction motor control [2] are:

- Scalar or V/F control methodology
- Vector or Field Oriented Control methodology

In Scalar or V/F control methodology, the torque developed by the motor is directly proportional to the stator magnetic field and the voltage applied to the stator is directly proportional to the product of stator flux and frequency. As a result, the flux produced by the stator becomes proportional to the ratio of applied voltage and frequency [3]. Therefore, by varying the voltage (V) and frequency (F) keeping the V/F ratio constant, the torque and speed can be varied [1] [3].

Besides the Induction Motor (IM), the centrifugal pump is also widely used in the industry because of its high efficiency and energy saving attributes. Speed of the pump can be adjusted to control the flow which also improves the controlling efficiency [4]. Integration of Variable Frequency Drive (VFD) with power pumps for adjusting the flow-rate of the pumps, have attracted the attention of the contemporary researchers and industry personnel across the globe due to its significant energy saving feature [5].

While considering a centrifugal pump or fan, the Affinity Laws should be kept in mind. These are

Law 1: $$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \tag{1.1}$$

Law 2: $$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{1.2}$$

Law 3: $$\frac{HP_2}{HP_1} = \left(\frac{N_2}{N_1}\right)^3 \quad (1.3)$$

where

Q Flow Rate ;

N=Speed ;

P= Pressure ;

HP=HorsePower [6].

Use of a VFD drive is advantageous in this regard; for example, if the speed of a fan is reduced to half, the horsepower required to run the fan at same load is reduced by a factor of 1/8. In order to duplicate this advantage with a standard induction motor would require some type of mechanical throttling device, such as a vane or damper; but the motor would still be running full load and full speed (full power) [8].

The basic operating schematic diagram of the V/F control pump load is as shown in Fig. 1.1

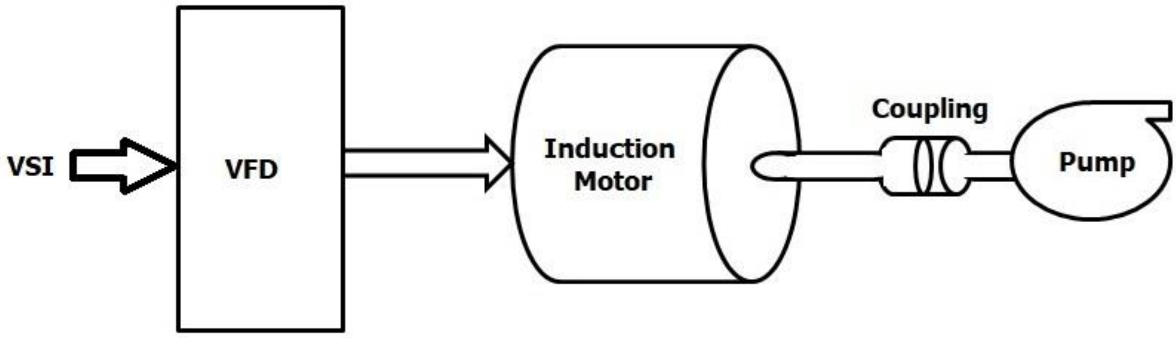

Fig.1.1 V/F Control pump load

Here, the speed of the IM is being controlled by the V/F technology and the pump is coupled with the motor to drive the fluid [9] . Depending upon the requirement of the flow rate, the speed of the induction motor is being controlled.

1.2 Advantages and Disadvantages of VF Drive

A VFD is capable of driving a various types of load using the popular control techniques like Constant Torque, Variable Torque, Constant Power [7] etc. The main advantages [8] of using a VFD are:

- Controlled Starting Current

  When an AC motor starts "across the line," it can take up to as much as seven-to-eight times the motor full-load current. Such a huge starting current flexes the motor windings and generates heat, which will, over time, reduce the longevity of the motor. Whereas, a VFD drive starts a motor with zero frequency and voltage and as the frequency and voltage increases, it takes 50-70% of full load current.

- Lower Power Demand during start-up

  As discussed before, the starting current of an AC motor is very high. As a result the staring power requirement is also enormous. The fluctuation of the supply voltage depends on the size of the motor and the capacity of the power distribution system. The equipment connected on the same distribution system are sensitive to such fluctuations. Items such as computers, sensors, proximity switches, and contactors are voltage sensitive. Using VFD eliminates this voltage sag, since the motor is started at zero voltage and ramped up.

- Controlled Acceleration

  A VFD starts at zero speed and accelerates smoothly in accordance to the reference speed. Conversely, an AC motor started “across the line” generates higher mechanical shocks which are undesirable and deadly for both the motor and mechanical load connected to it.

- Adjustable Operating Speed

  Use of VFDs driving a pump is advantageous in terms of smooth adjustments of speed over the entire operating regime as per the requirement.

- Adjustable Torque Limit

  Use of a VFD can protect machineries from damage because the amount of torque being applied can be controlled accurately.

  Energy Savings

  Variable torque loads, such as, Centrifugal fans and pump loads operated with a VFD will reduces energy consumption. A VFD controlling a pump motor that usually runs less than full speed can substantially reduce energy consumption over a motor running at constant speed for the same period.

Apart from the advantages discussed above, a VFD drive can reduce noise and vibration level [10], reduce thermal and mechanical stress, power factor etc. [11].

A VFD, though useful in making a system more efficient, also bring with it some disadvantages [12]. These are

- It dramatically increases the noise in the system.
- It induces the power line Harmonics.
- Due to these harmonics, the motor gets heated up resulting in excessive vibration.
- Can reduce the service factor on the motor it’s used on.

However, these disadvantages can be mitigated to an extent by correct application, maintenance and by modifying the circuit.

1.3 ***Sources of 50 Hz noise in a process control setup:***

Noise is defined as a random unwanted signal that gets added up to the actual signal from the different sources. Power-line voltage normally consists of a broad spectrum of harmonics and noises in addition to the pure 50 Hz sine wave. Depending on noise induction in the circuit, it can be classified into two parts [13]:

- *Externally Generated Noise & Interference*:

These are generated by power supplies in electronic equipment, fluorescent lights, light dimmers, and intermittent or sparking loads such as switches, relays, brush type motors etc. Externally generated interference includes mains line sources such as spikes of interference caused by arcing contacts when heavy currents are switched. Thyristor and Triac control of mains power can also generate mains line interference as well as interference transmitted by electromagnetic radiation. While most of this type of interference is low frequency, around 50Hz to 120Hz, the widespread use of switch mode power supplies where high frequency switching takes place, may also generate noise.

Noise may also induced from entirely natural sources such ‘static’ noise in the form of hissing and crackling that is continually radiated from space, and atmospheric noise generated by lightning discharges in thunderclouds. Sometimes Radio frequency amplifiers may also be subject to interference from transmissions broadcasting at similar frequencies to the required signal. Apart from that, noise can be introduced from the measurement channel also..

- *Internally Generated Noise*

  There are again the problem of noise generated within the components that make up the amplifier. Transistors will generate noise from a variety of causes which includes Thermal noise due to molecular agitation of the semiconductor material caused by heat, and 'Shot noise' which is caused by charge carriers (electrons and holes) randomly diffusing across the semiconductor junctions.

The presence of internally generated noise is most noticeable when it is generated in the earliest stages of the amplifier. Noise produced in the first stage of a series of amplifiers will receive the greatest amplification as it passes through the most stages.

1.4 Literature Survey:

In industry variable speed control drives take an important part & it's purpose is very broad. So, researchers and authors already did a lot of research on this topic.

In [14], Billade and Chopade have proposed cheaper and power efficient wireless speed control of the motor. They used GSM Technique for long distance transmission of reading using PIC16F7X7 microcontroller. The control principle of constant V/Hz has been discussed in detail in which supply frequency as well as supply voltage has been varied keeping voltage to frequency ratio constant.

In [15], Bhatt and Hajari have used VFD for flow control of fluid in industries. In this paper using MATLAB Simulink comparison of various performance characteristics is shown. The characteristics with and without VFD like speed waveform of stator, speed waveform of rotor, stator current response and rotor current response are studied.

Energy conservation graph and torque waveform of with VFD and without VFD are compared using simulator.

Tamal Aditya [16] designed and simulated 3 HP, 4Pole motor with inverter using PWM technique in MATLAB. Analysis of output waveforms of VFD viz. voltage, current, speed and torque waveforms was discussed.

In [17], harmonic analysis was performed using FFT tool of MATLAB/POWERGUI which depicts decrease in Total Harmonic Distortion due to decrease in speed. The developed hardware is tested for 3 phase induction motor using PLC.

Deepa in [18] designed a VFD for speed control of 3Phase Induction motor for energy saving. Different control platforms like PWM V/Hz scalar control, PWM field-oriented control (FOC) or vector control, Direct torque control (DTC) along with testing methods were listed and explained in brief. Three different optimization technique Conventional Optimization Techniques, AI Based Optimization Techniques and NIA Based Optimization Techniques were discussed. Experimental setup of the circuit was done with components current transformer, induction motor, energy meter, timer, clamp meter, motor controller and operator interface. Comparison of result of energy consumption of motor with and without VFD was done showing low voltage and current consumption.

Shinde et al. in [19] have discussed the use of VFD in speed control of induction motor using microcontroller. Explanation of different stages of VFD such as rectifier stage, inverter stage and control stage was done in detail. Rectifier stage explained working of diode bridge rectifier. Inverter used here was Inverter Bridge using IGBT. Control stage included different control methods like constant ratio of voltage to frequency to control the output voltage. PWM technique is used to control inverter output. Microcontroller was used for adjustment of output frequency by changing the switching time cycle.

In [20], dynamic simulation of an Induction-Motor Centrifugal-Pump System under variable speed conditions, was put forward by Xiwen Guol , Yuliang Wul where they simulated the Induction Motor (IM) to drive a pump by rotor field oriented control .

Similarly a lot of work had done on the adaptive filter design

Mitov IP in [21] described a method for reduction of power line interference (PLI) in electrocardiograms with sampling rate integer multiple of the nominal power line frequency and tested using simulated signals .The method involves parabolic detrending of the ECG, estimation of the signal components with frequencies corresponding to PLI by discrete Fourier transform, and minimum-squared-error approximation of decimated series of averaged instantaneous values of PLI using appropriately defined weights by the LMS algorithm

Ziarani AK and Konrad A. in [22] suggested the adaptive digital filtering method for the power line interference reduction by the LMS Algorithm. This method employs a recently developed signal processing algorithm capable of extracting a specified component of a signal and tracking its variations over time. Superior performance has been observed in terms of effective elimination of noise under conditions of varying power line interference frequency. This method is a simple and robust structure which complies with practical constraints involved in the problem such as low computational resource availability and low sampling frequency.

Yen-Tai Lai, et. al in [23] showed how adaptive filtering scheme are generally used in the fields of signal processing and communication such as noise cancellation and speech coding. Adaptive filters usually need real-time ability to process signal. The filter can be designed using the digital adaptive finite impulse response filter based on the delayed error least mean square algorithm. The architecture has good hardware utilization efficiency and it can be easily scaled the filter without reducing the throughput rate.

1.4 <u>Motivation of the Thesis:</u>

From the above discussion it is evident that in most of the cases, the motor is controlled either by giving a step load or a predefined function of load torque. It has not been used for the practical scenario i.e by giving a practical load. Moreover in some works it has been shown that with a practical load to the induction motor (IM), since V/F drive is for open-loop control leading to a poor dynamic response, field oriented vector controlled method performs better. So it is clear that controlling the speed of the IM by the V/F method with a practical industrial load such as a centrifugal pump considered in this dissertation is really a challenging job. Apart from that most researchers have not considered that there may be a source of unwanted signal , noise or interferences for which the system may be generate low frequency torque ripples with consequent flow variations that may cause damage to flow circuits. A solution using Adaptive Filtering [21] has been proposed in this dissertation..

1.5 Dissertation Outline:

The rest of the dissertation is organized as follows:

Chapter Two introduces the dynamics of an Induction Motor and the basic concepts behind its V/F control using a VFD. The motor is then assumed to be connected to a centrifugal pump and the operation of the plant comprising the pump and the motor is studied and the response analysed to identify the dominant frequencies in the spectrum under both ideal and with injected noise conditions.

In Chapter Three , the spectra established in Chapter Two are used to design an adaptive filter to filter out unknown 50 Hz. noise in the VFD. The efficacy of the filter is established with credible Matlab Simulation in the Results and Discussion section of this Chapter. The Chapter concludes the dissertation with the Conclusion and Scope for Further Work section.

CHAPTER 2

2.1 Target System Development:

In this chapter the test system used in this dissertation is discussed. The system under consideration is a pump of 1.1KW driven by a 5HP induction motor(IM) controlled by a Variable Frequency Drive(VFD) where dynamic model of Induction Motor is designed and the motor speed is being controlled by the Voltage/Frequency method for which Variable Frequency Drive controller is designed. The motor is used here to drive a centrifugal pump. The overall block diagram of the system and its control is presented in Fig. 2.1 below in the form of a MATLAB/Simulink model. The detailed description of the individual components and their integration is provided in the following sub-sections.

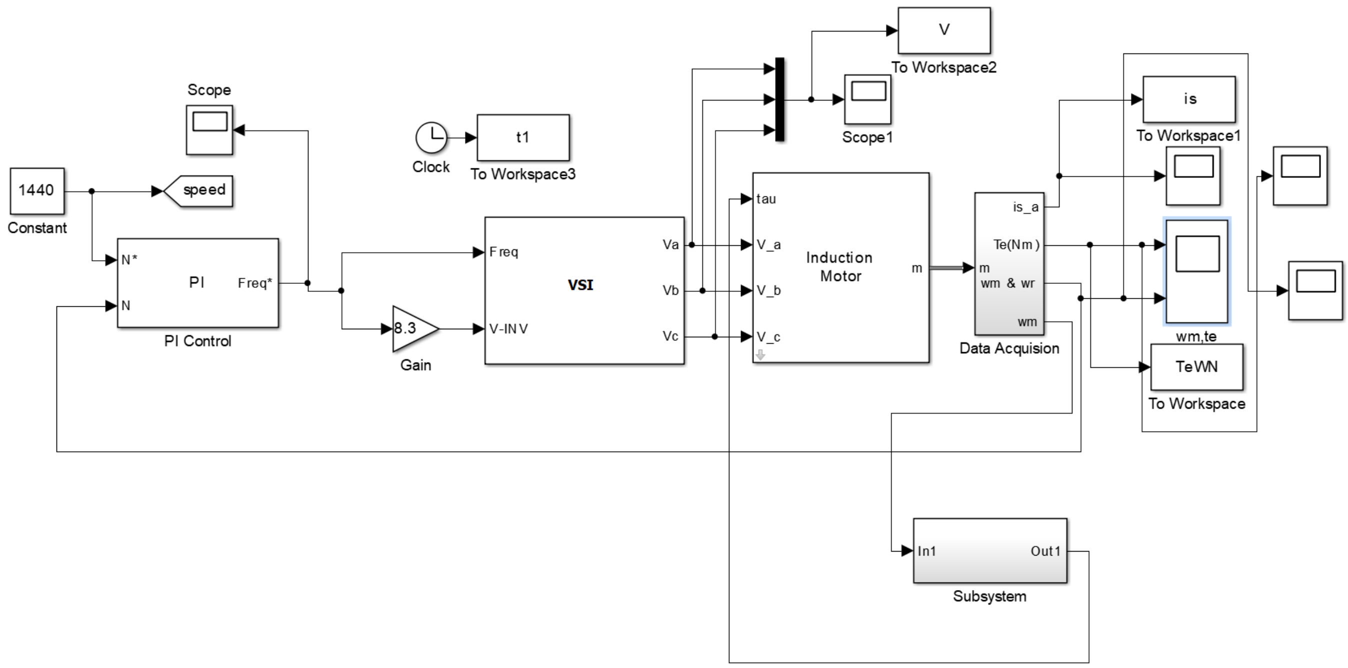

Fig 2.1 Target System

2.1.1 The Induction Motor:

As mentioned earlier, the centrifugal pump in Fig. 2.1 above is assumed to be driven by a 5hp induction motor controlled by a VFD. In this section, the modelling of the motor and its VFD is presented. The model is tested with Matlab simulation first by introducing a stepped load torque and then replacing the load with a simulated pump[20] whose model is also described subsequently.

The mathematical model of the Induction Motor is necessary to study the phenomena like oscillatory torque response, huge inrush of current and other operations of the motor etc. Various modelling approaches have been proposed , out of which ‘d-q’ modelling or two-axis modelling has gained importance because of its simplicity[24][25]. The ‘d-q’ axis can be considered in any of the following reference frames[26]:

a. Stationary frame when d-q axis rotate at synchronous speed
b. Synchronously rotating frame
c. Rotor rotating reference

An induction motor can be modelled in any of the above reference frames but among this the stationary frame is more common since it is easy for computation and implementation and in this dissertation this has been adopted.

2.1.1.1 Reference Frame Theory & Transformation:

Dynamic modelling of an IM can carried out in a synchronously rotating reference frame (as proposed by Park et. al.), or in stationary reference frame as proposed by Stanley et. al,, or in a reference frame that rotates at any arbitrary speed proposed by Krause et. al. As mentioned before, in this dissertation, modelling using a stationary reference frame has been adopted and the basic concepts are first presented as follows:

- ***Clarke's Transform***:

The Clarke ($d^s - q^s$) transform is a space vector transformation of time –domain signal (like voltage, current, flux etc.) from a natural three-phase co-ordinate system into a stationary two phase frame ($d^s - q^s$). It is named after Electrical Engineer Edith Clarke.

In the natural reference frame the three voltages V_a, V_b, V_c are displaced in phase with respect to each other by 120°. Cartesian axis is also represented by V_d^s which is called the directed axis and it is aligned with the V_a . Simultaneously another axis is the quadrature axis which is 90° apart from V_d^s anti-clockwise and is denoted as V_q^s .

Now, the above referred 3-phase axis can be converted to 2-phases by the following transformation matrix

$$\begin{pmatrix} V_d^s \\ V_q^s \\ V_0^s \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{2.1}$$

Similarly V_a, V_b, V_c can be obtained by the inverse transform of V_d^s & V_q^s as

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{pmatrix}\begin{pmatrix} V_d^s \\ V_q^s \\ V_0^s \end{pmatrix} \tag{2.2}$$

- ***<u>Park's Transform:</u>***

The (d^e - q^e) transform is a space vector which is represented in a stationary reference frame. A general rotating reference frame has then been introduced which rotates at a synchronous speed and for this reason it is called "Synchronous Reference Frame ". This frame is described by d & q axes and described by the Park transform[27]. The Park transformation is used to realize the transformation of the currents from the stationary to the rotating reference frame.

The transformation may is defined by the following equation

$$\begin{pmatrix} V_d^e \\ V_q^e \\ V_0^e \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ -\sin\theta_e & -\sin(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{2.3}$$

where θ_e is the angle between the fixed and rotating co-ordinate system at any instant of time.

Similarly, by the inverse transformation is defined as

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} \cos\theta_e & -\sin\theta_e & 1 \\ \cos(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\theta_e + \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) & 1 \end{pmatrix}\begin{pmatrix} V_d^e \\ V_q^e \\ V_0^e \end{pmatrix} \tag{2.4}$$

With these basic concepts defined, it is now attempted to establish a $d-q$ model of an induction motor.

A simplified, per phase equivalent circuit representation of an Induction Motor is helpful in the analysis of steady state response, but fails to provide effective insight into dynamics of the response. Therefore in order to study dynamic analyses of machines, a dynamic model is a necessity.

Now, as balanced three phase currents is transformed to balanced two phase currents, it is seen that the mmf produced by both the systems are identical. Also, the transformations are made such that per phase impedances are also same. Therefore it can be concluded that a three phase induction motor can be studied as a two phase IM can be transformed back to 3 phase.

Before modelling the induction motor some assumptions are enumerated

- The air gap is uniform.
- Each stator winding is identical and uniformly distributed i.e space harmonics is negligible.
- Mutual inductances are equal.
- Voltage and current harmonics are negligible.

- All the losses of the motor are neglected i.e Eddy current loss, Hysteresis loss, frictional and windage loss are neglected. We are consider an ideal motor.

Now the d-q axis stator equation of voltages can be formulated as

$$V_{ds}^{s} = i_{ds}R_{s} + \frac{d\psi_{ds}^{s}}{dt} \quad (2.5)$$

$$V_{qs}^{s} = i_{qs}R_{s} + \frac{d\psi_{qs}^{s}}{dt} \quad (2.6)$$

The voltage equation of the rotor in the d-q axis is given by

$$V_{dr}^{s} = i_{dr}R_{r} + \frac{d\psi_{dr}^{s}}{dt} + \omega_{r}\psi_{qr}^{s} \quad (2.7)$$

$$V_{qr}^{s} = i_{qr}R_{r} + \frac{d\psi_{qr}^{s}}{dt} - \omega_{r}\psi_{dr}^{s} \quad (2.8)$$

Now for the squirrel cage induction motor ,since rotor terminals are short circuited by a slip ring so $V_{dr}^{s} = V_{qr}^{s} = 0$

The flux linkage equations for the stator and rotor can be represented in the d-q axis as

$$\psi_{ds}^{s} = L_{ls}^{s} i_{ds}^{s} + L_m (i_{ds}^{s} + i_{dr}^{s}) \tag{2.9}$$

$$\psi_{qs}^{s} = L_{ls}^{s} i_{qs}^{s} + L_m (i_{qs}^{s} + i_{qr}^{s}) \tag{2.10}$$

$$\psi_{dr}^{s} = L_{lr}^{s} i_{dr}^{s} + L_m (i_{ds}^{s} + i_{dr}^{s}) \tag{2.11}$$

$$\psi_{qr}^{s} = L_{lr}^{s} i_{qr}^{s} + L_m (i_{qs}^{s} + i_{qr}^{s}) \tag{2.12}$$

$$\psi_{dm} = L_m (i_{ds}^{s} + i_{dr}^{s}) \tag{2.13}$$

$$\psi_{qm} = L_m (i_{qs}^{s} + i_{qr}^{s}) \tag{2.14}$$

$$\psi_m = \sqrt{\psi_{dm}^2 + \psi_{qm}^2} \tag{2.15}$$

The inductance calculations are done as

$$L_m = \frac{3}{2} L_{ms} \text{......................}(2.16)$$
$$L_s = L_{ls} + L_m \text{..................}(2.17)$$
$$L_r = L_{lr} + L_m \text{..................}(2.18)$$

Now substituting the values from equation (9),(10) in (5),(6) yields

$$V_{ds}^{s} = R_s i_{ds}^{s} + \frac{d(L_s i_{ds}^{s} + L_m i_{dr}^{s})}{dt}$$

$$V_{ds}^{s} = R_s i_{ds}^{s} + L_s \frac{di_{ds}^{s}}{dt} + L_m \frac{di_{dr}^{s}}{dt} \qquad (2.19)$$

and

$$V_{qs}^{s} = R_s i_{qs}^{s} + \frac{d(L_s i_{qs}^{s} + L_m i_{qr}^{s})}{dt}$$

$$V_{qs}^{s} = R_s i_{qs}^{s} + L_s \frac{di_{qs}^{s}}{dt} + L_m \frac{di_{qr}^{s}}{dt} \qquad (2.20)$$

Also by substituting the value of equation (11) & (12) in equation (7) & (8) produces

$$V_{dr}^{s} = R_r i_{dr}^{s} + \frac{d}{dt}(L_r i_{dr}^{s} + L_m i_{ds}^{s}) + \omega_r (L_r i_{qr}^{s} + L_m i_{qs}^{s})$$

$$\Rightarrow \quad 0 = L_m \frac{d}{dt} i_{ds}^{s} + \omega_r L_m i_{qs}^{s} + R_r i_{dr}^{s} + L_r \frac{d}{dt} i_{dr}^{s} + \omega_r L_r i_{qr}^{s} \qquad (2.21)$$

Also

$$V_{qr}^{s} = R_r i_{qr}^{s} + \frac{d}{dt}(L_r i_{qr}^{s} + L_m i_{qs}^{s}) - \omega_r (L_r i_{dr}^{s} + L_m i_{ds}^{s})$$

$$\Rightarrow \; 0 = L_m \frac{d}{dt} i_{qs}^{s} - \omega_r L_m i_{ds}^{s} + R_r i_{qr}^{s} + L_r \frac{d}{dt} i_{qr}^{s} - \omega_r L_r i_{dr}^{s} \qquad (2.22)$$

Now from the above four equations i.e 15,16,17,18 the dynamic modelling of induction motor is carried out in MATLAB. The above four equations can be expressed in the form of matrix as

$$\begin{pmatrix} V_{ds}^{s} \\ V_{qs}^{s} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_r & R_r + L_r p \end{pmatrix} \begin{pmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{pmatrix} \ldots(2.23)$$

It is known to that the torque is formed by the interaction of air gap flux and rotor mmf. Thus in the stationary frame the torque can be expressed as

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{dm}^{s} i_{qr}^{s} - \psi_{qm}^{s} i_{dr}^{s})$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{dm}^{s} i_{qs}^{s} - \psi_{qm}^{s} i_{ds}^{s})$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds}^{s} i_{qs}^{s} - \psi_{qs}^{s} i_{ds}^{s})$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)L_m(i_{qs}^{s} i_{dr}^{s} - i_{ds}^{s} i_{qr}^{s})$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{dr}^{s} i_{qr}^{s} - \psi_{qr}^{s} i_{dr}^{s})\ldots\ldots\ldots\ldots\ldots\ldots..(2.24)$$

The electromechanical equation of the motor can be

$$T_e = T_l + \frac{2}{P}(J\frac{d\omega_r}{dt} + B\omega_r)\ldots\ldots\ldots\ldots\ldots.(2.25)$$

The parameters for the IM used in this dissertation are enumerated in Table 2.1

Parameter Of the Motor	***Values Chosen***
• Voltage per phase(RMS)	440 V
• Frequency	50 Hz.
• Per Phase Stator Resistance	1.77 Ω
• Per Phase Rotor Resistance	1.34 Ω
• Stator Leakage Inductance/phase	0.0167 H
• Rotor Leakage Inductance/phase	0.0145 H
• Air Gap Leakage (Magnatising) Inductance	0.4424 H
• No. Of Pole	4
• Moment of Inertia	0.025 kg-m^2
• Frictional Co-efficient	0.01 N-m-s
• Power of the Motor	5 HP

The Simulink model of the IM in Fig. 2.1 is represented by Fig. 2.2

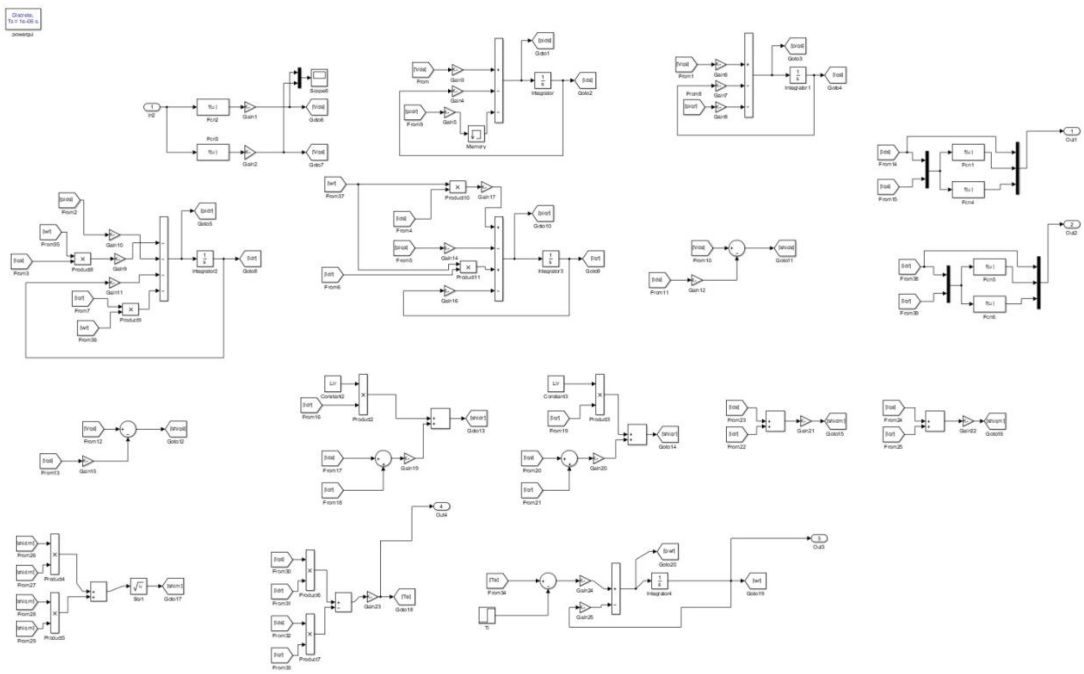

Fig 2.2 Dynamic Model of the Induction Motor

The operation of the motor is studied in simulation by running the motor in no load with a stepped load insertion of 40 N-m at 5 *sec* and the stator and rotor currents , torque and speed are shown in Fig. 2.3 to Fig 2.6.

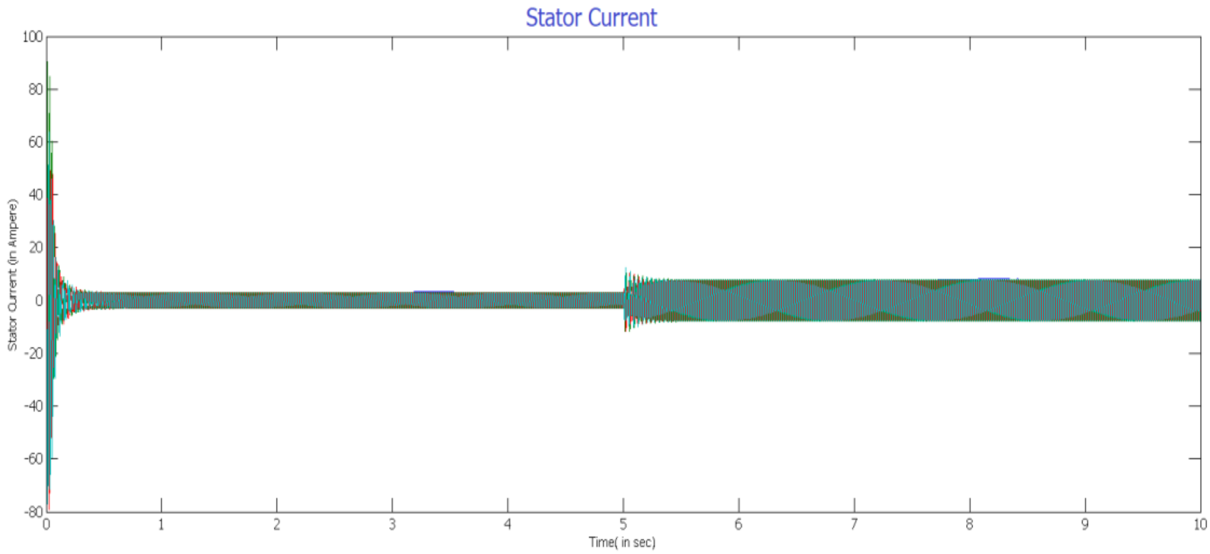

Fig 2.3 Stator Current

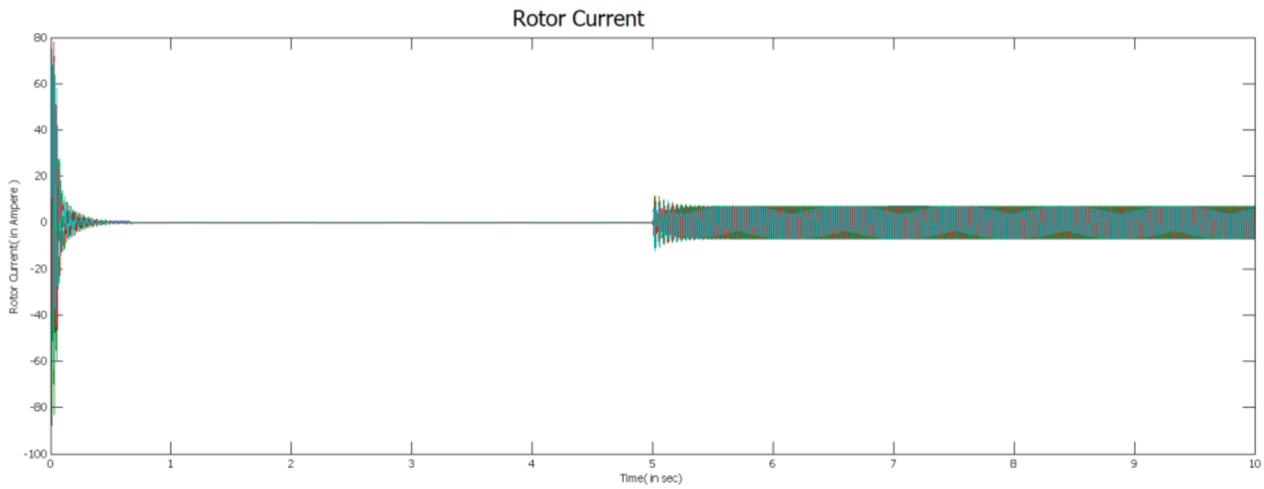

Fig 2.4 Rotor Current

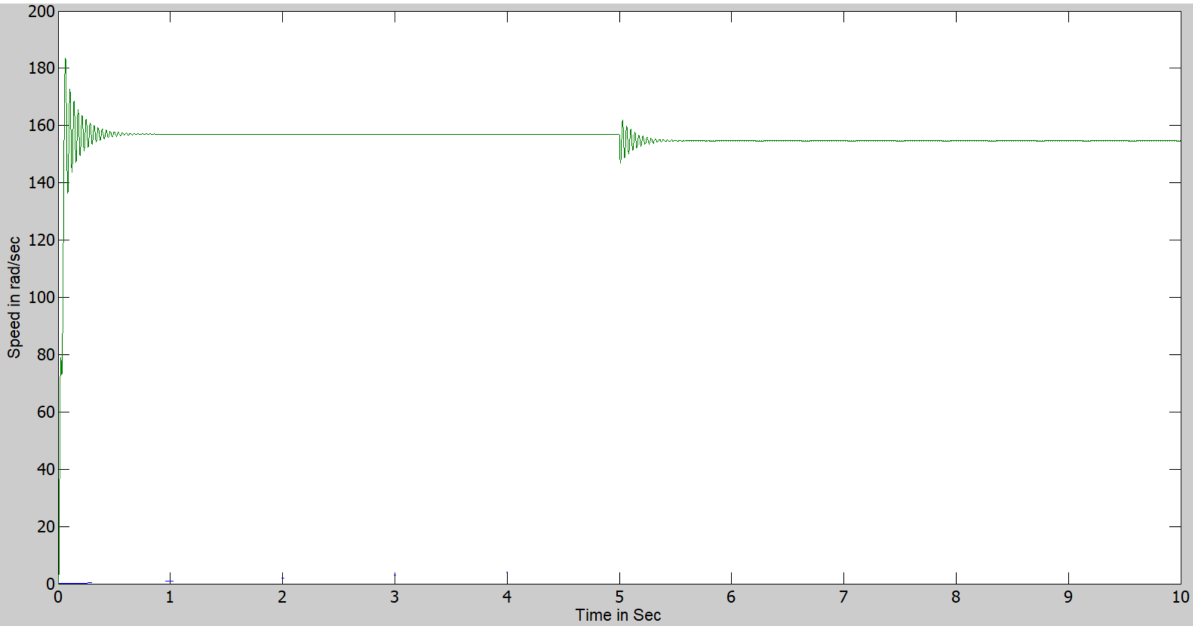

Fig 2.5 Speed

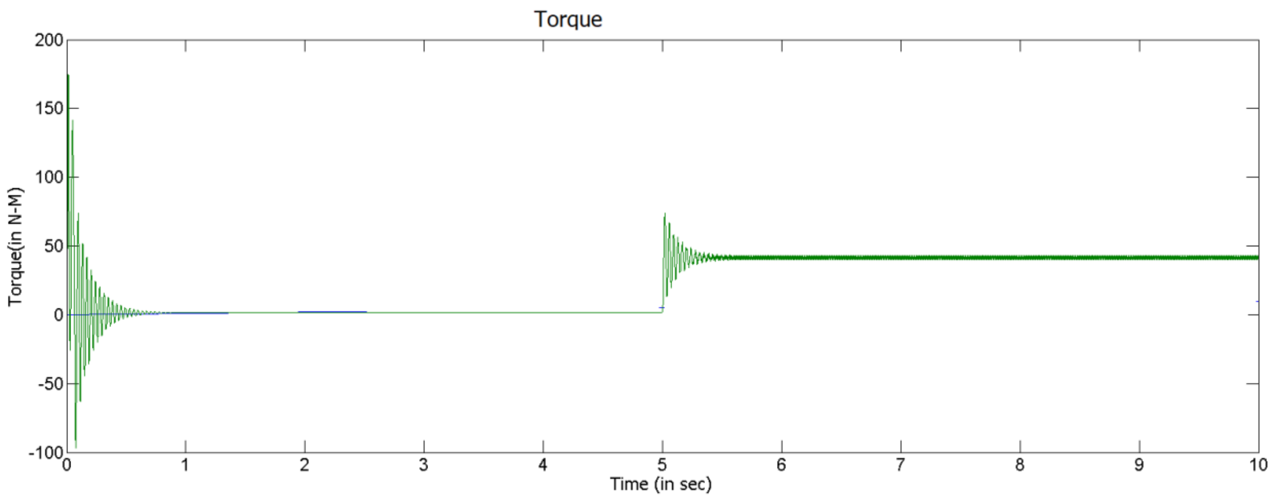

Fig 2.6 Electromagnatic Torque

2.1.2 Variable Frequency Drive(VFD)

Fig. 2.7 shows the schematic representation of the VFD used in this dissertation

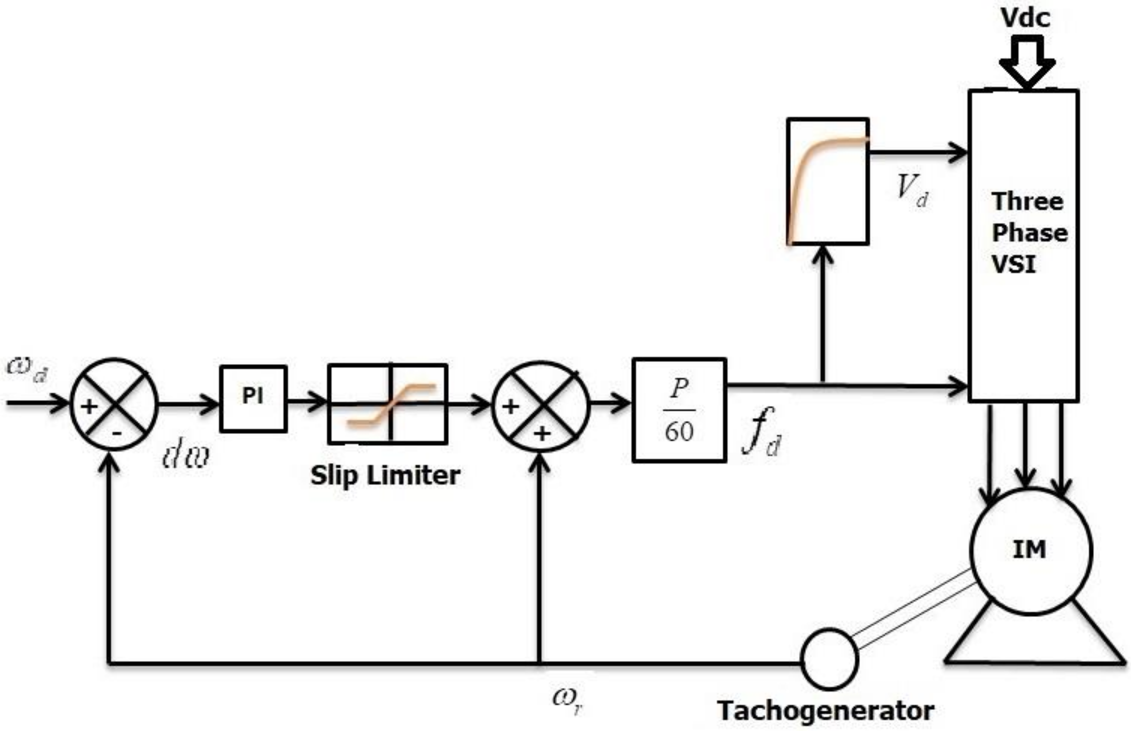

Fig 2.7 Schematic of variable Frequency Drive

It is a well known fact that the shaft speed of a motor driving a load depends on its electromagnetic torque which can be represented as:

$$T_e = \frac{3}{2\pi N_s} * \frac{sE^2 R_r}{\sqrt{R_r^{\ 2} + (\mathrm{sX}^2)}} \tag{2.26}$$

From (26) it is seen that if the frequency is changed , the electromagnetic torque will change . However, change of speed by varying the frequency is not possible because the motor's magnetic circuit will be saturated by this phenomenon .Again to change the speed by varying the voltage is also not feasible because due to the very high current winding will be burned out.

In a VFD , the frequency and the voltage will be changed in such a way so that the ratio of the voltage/frequency is always same.

Because $\frac{T}{\omega} \alpha \frac{V}{f}$ (2.27)

The basis of constant V/F speed control of induction motor is to apply a variable magnitude and variable frequency voltage to the motor. both the voltage source inverter and current source inverters are used in adjustable speed ac drives. The above block diagram shows the closed loop V/F control using a Variable Source Inverter (VSI). The closed-loop method offers a more precise solution to controlling the speed than the open-loop method. Furthermore, the closed-loop technique controls the torque, too. A major disadvantage of the open-loop control method is that this technique does not control the torque, so the desired torque is only accessible at the nominal operating point. If the load torque changes, the speed of the motor will change . The VSI is explained in the next sub-section.

2.1.2.1 Variable Source Inverter

The VSI that uses PWM switching techniques have a DC input voltage that is usually constant in magnitude. The inverter's job is to take this DC input and to produce an AC output, with the magnitude and frequency controlled by the V/F technique.

Among the many other techniques , in this dissertation the Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be used to directly control the inverter output voltage and output frequency.

Generally, three sinusoidal waves are used for a 3 phase inverter. The sinusoidal waves are called the reference signal and 120^0 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50Hz). The carrier triangular wave is usually a high frequency wave. In this case it is 500Hz. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches.

So. according to the circuit the output voltage equations for VSI with a constant V/F ratio can be represented as[29]

$$V_a = (2*sqrt(2/3)*\mathrm{u}(4)/3)*(2*\mathrm{u}(1)-\mathrm{u}(2)-u(3)) \quad (2.28)$$

$$V_b = (2*sqrt(2/3)*\mathrm{u}(4)/3)*(2*\mathrm{u}(2)-\mathrm{u}(1)-u(3)) \quad (2.29)$$

$$V_c = (2*sqrt(2/3)*\mathrm{u}(4)/3)*(2*\mathrm{u}(3)-\mathrm{u}(2)-u(1)) \quad (2.30)$$

2.1.3 The PI CONTROLLER

In the circuit a PI controller is basically introduce to reduce the error i.e the differences between the given rated speed of the system and the actual speed of the motor that is being fed back to the input to zero.

The basic purpose of a PI controller is to eliminate the forced oscillations and steady state error of P controller besides introducing the integral mode will have adverse effect on the stability of the system and speed of response. So the PI controller will not increase the speed of response and also the PI controller cannot predict what will happen with the error in near future which can be predicted by a derivative part. PI controllers are usually used to reduce the error between the actual and the desired value. Also this controller can be used when there is a large transport delays in the system and when there is only one energy storage process is present. PI controller can effectively work when there is a presence of a noise or large disturbance during the operation of a process. Here PI speed controller gains are selected by Z-N method on an identified system and the controller equation is

$$k_p + \frac{k_i}{s} = 3.5 + \frac{1.2}{s} \tag{2.31}$$

2.1.4 The Centrifugal Pump:

The centrifugal Pump used in this dissertation has been simulated using SimHydraulics in Matlab[20].

The main parameters of the centrifugal pump are the pump flow rate (Q), head (H), efficiency (η) and speed (n). The analysis of the external characteristics of the centrifugal pump consists of two parts: the rated-speed analysis and the variable-speed analysis.

$$H_0 = f(Q_0)$$
$$H_0 = f(Q_0) = a + bQ_0 + cQ_0^2 \tag{2.32}$$

The characteristics of the pump used for simulation are enumerated in Table 2.2:

Parameter	n_N	P_n	H	Q
Rated Value	1415 RPM	1.1 KW	67.5 m	2.0 m^3/h

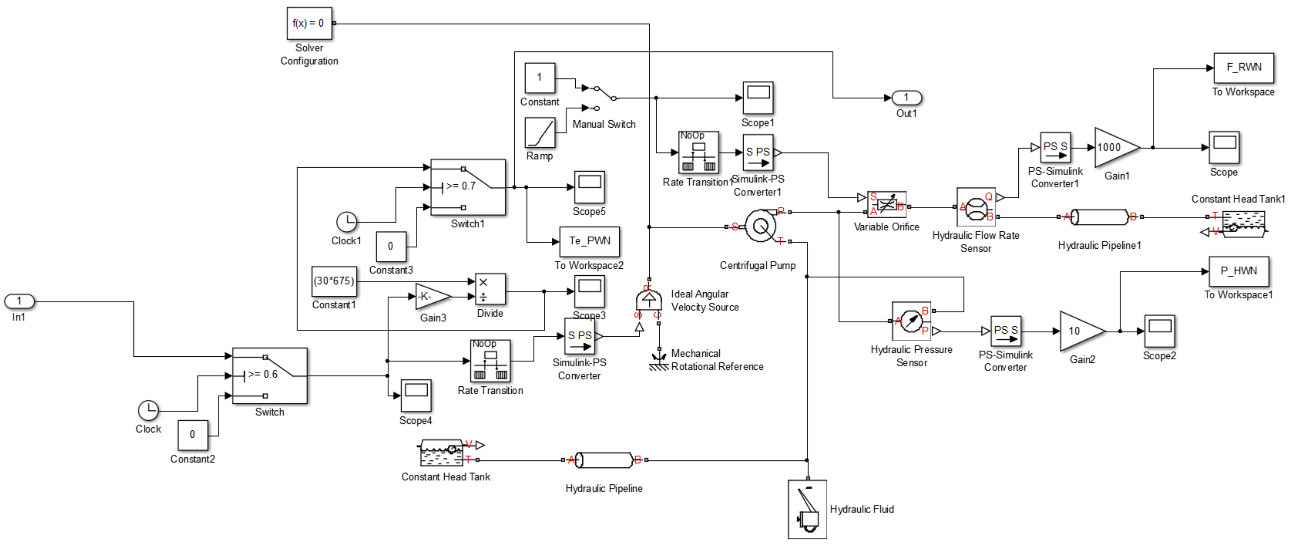

Fig 2.8 Schematic of the Centrifugal Pump

2.2 Analysis Of the System:

The system presented in Fig. 2.1 prises a main Voltage Source Inverter that is assumed to be delivering the full power to the motor at rated frequency and rated voltage. Inverters based on PWM strategy produce much higher harmonic order depending on the frequency modulation ratio.

So, the applied voltage of the IM can be written as

$$V_m = V_f \sin(\omega \mathrm{t}) + V_h \sin(\omega \mathrm{t} - \phi) \tag{2.33}$$

where V_f = Peak Voltage , V_h = Harmonic Peak Voltage , $\phi = Phase\ Difference$

It is known that the stator flux is proportional to the applied voltage

So it can be written that the fundamental stator flux will be

$$\psi_f = 4.44 V_f \sin \omega_f t \tag{2.34}$$

And for any harmonic content the stator flux will be

$$\psi_h = 4.44 V_h . \sin(\omega_h \mathrm{t} - \theta) \tag{2.35}$$

Due to the harmonic content it can be seen that both voltage and flux has been distorted ; since torque is the multiplication of current and flux it is also seen that there will be low frequency beats Fundamental torque can be expressed as

$$T_{e1} = K\psi_f I_f \sin\delta \tag{2.36}$$

And the pulsating torque due to presence of harmonics is

$$T_{eh} = K[\psi_f I_f \sin\delta + \psi_h I_h \sin(\delta + \omega_h \text{ t})] \tag{2.37}$$

The FFT of the instantaneous torque signal is presented in Fig. 2.9

Which is shown in Appendix ‘A’.

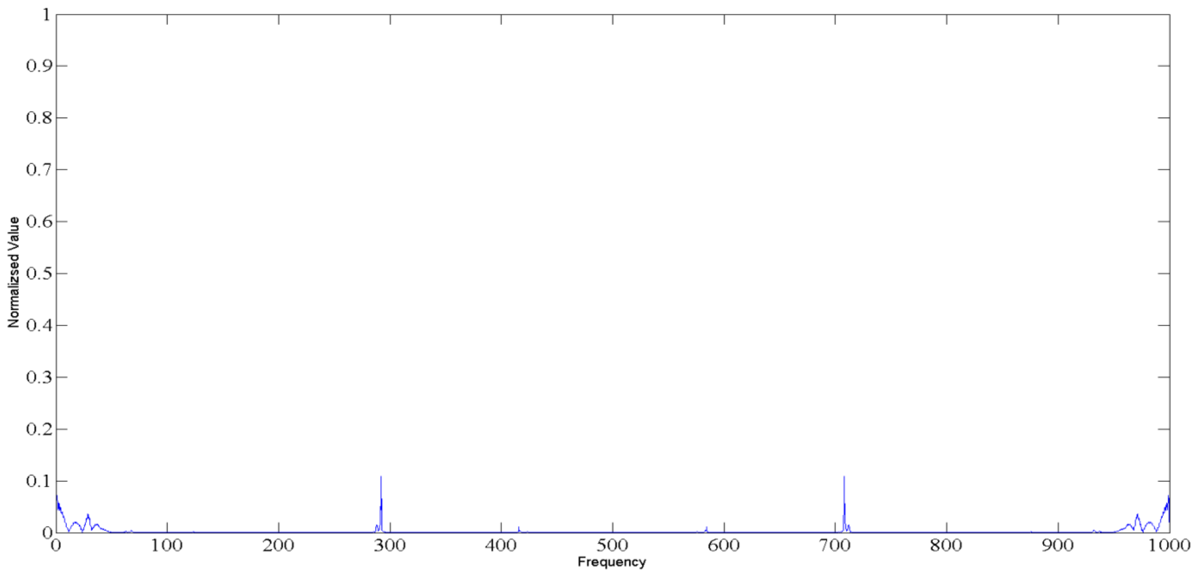

Fig 2.9 instantaneous torque signal

And the FFT diagram of the stator current will be

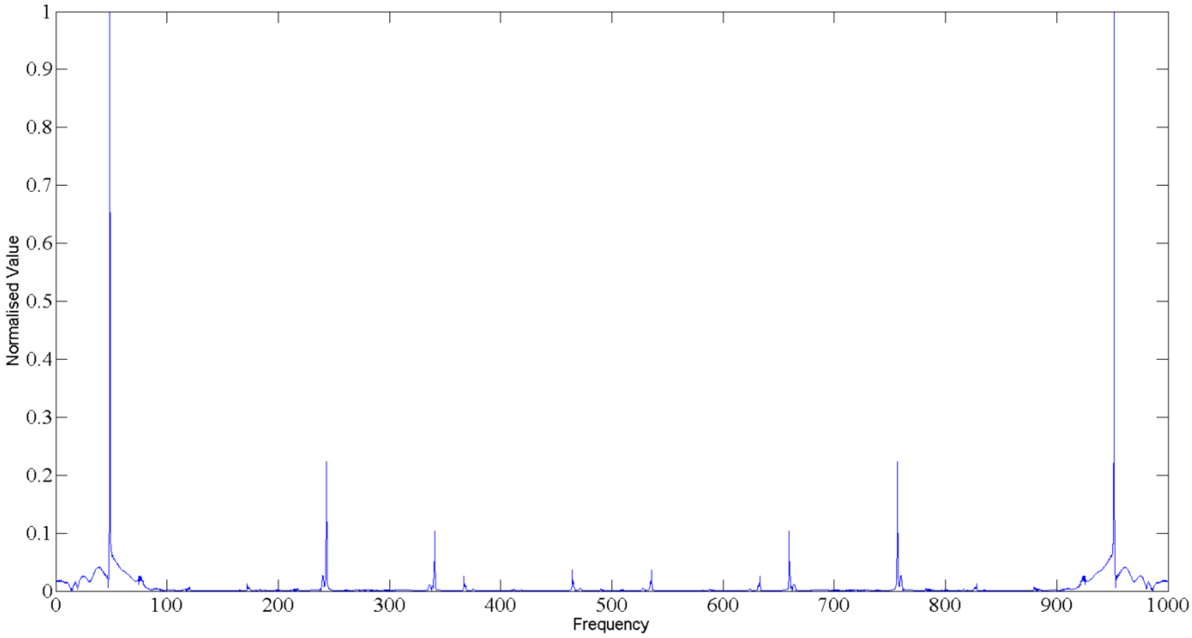

Fig 2.10 Stator current diagram

The actual simulation of the instantaneous electromagnetic torque for the pump-motor system under load is shown in the following figure along with the stator current.

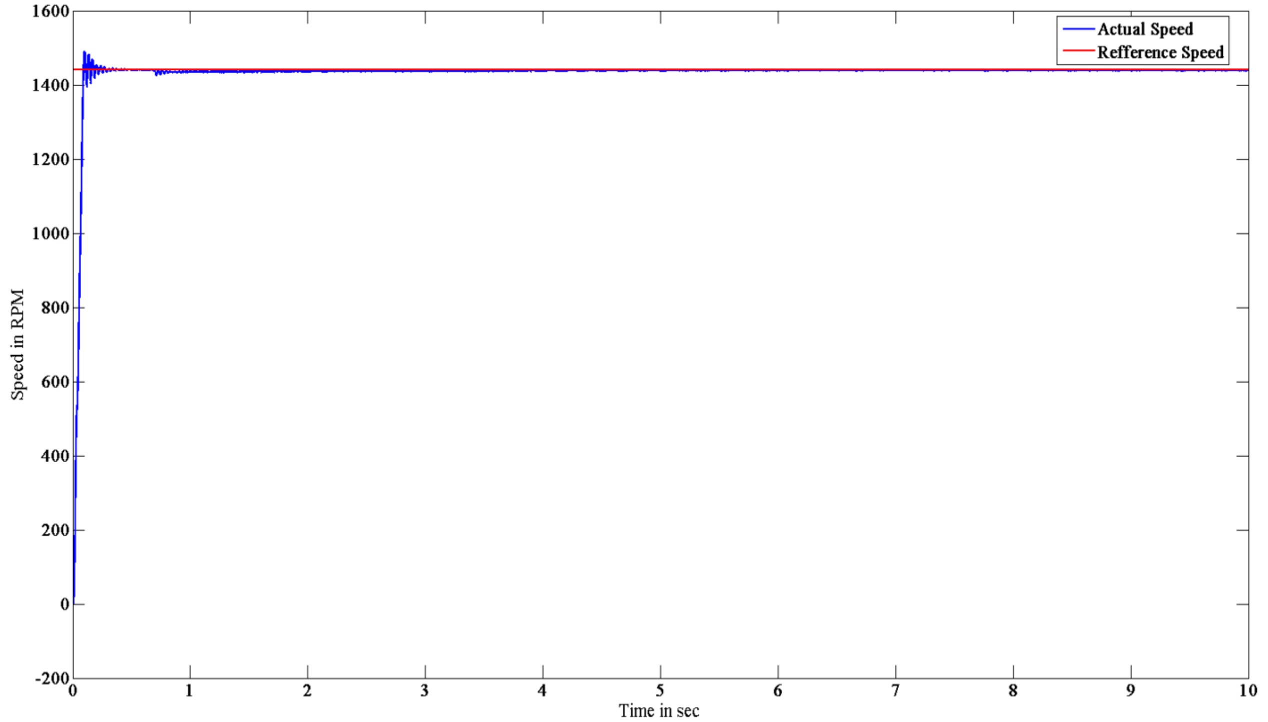

Fig 2.11 Speed diagram without noise

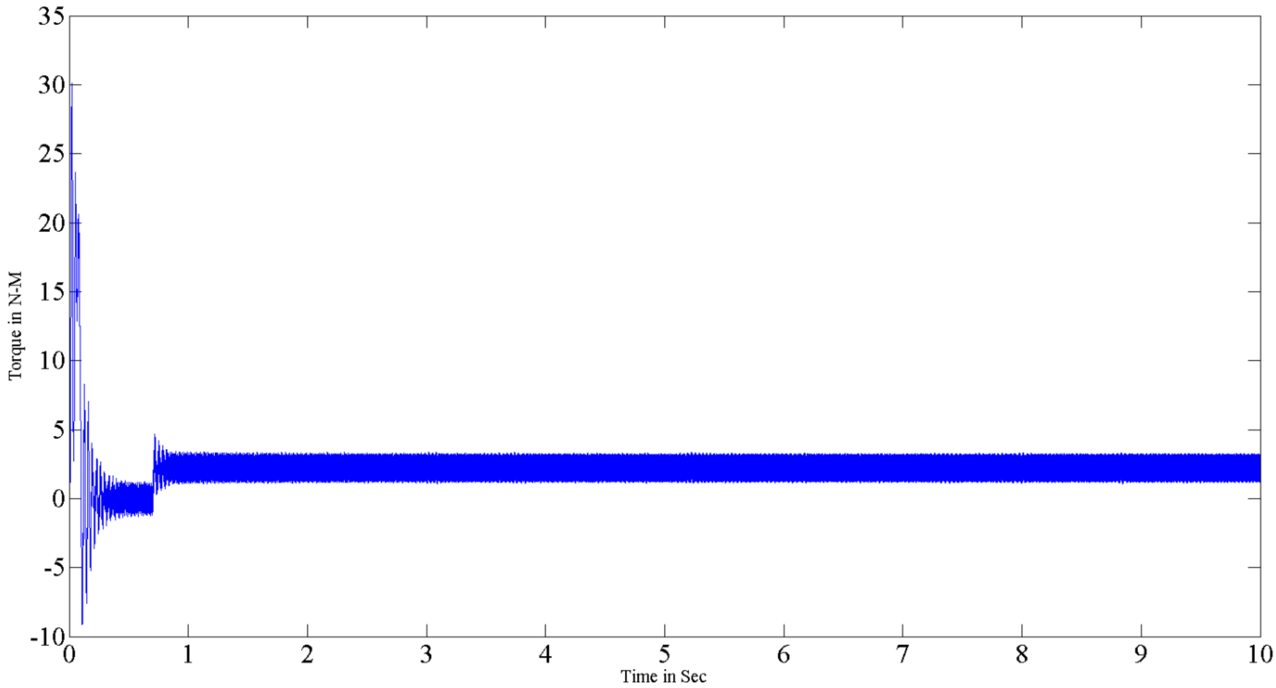

Fig 2.12 Torque diagram without noise

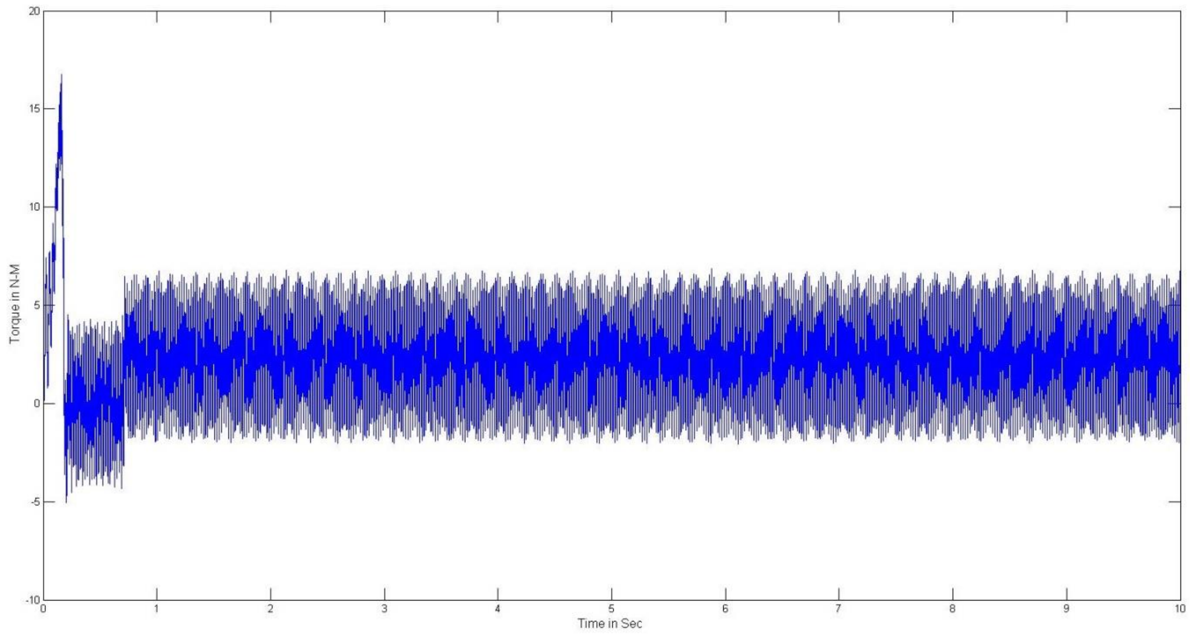

Fig 2.13 Torque diagram with noise

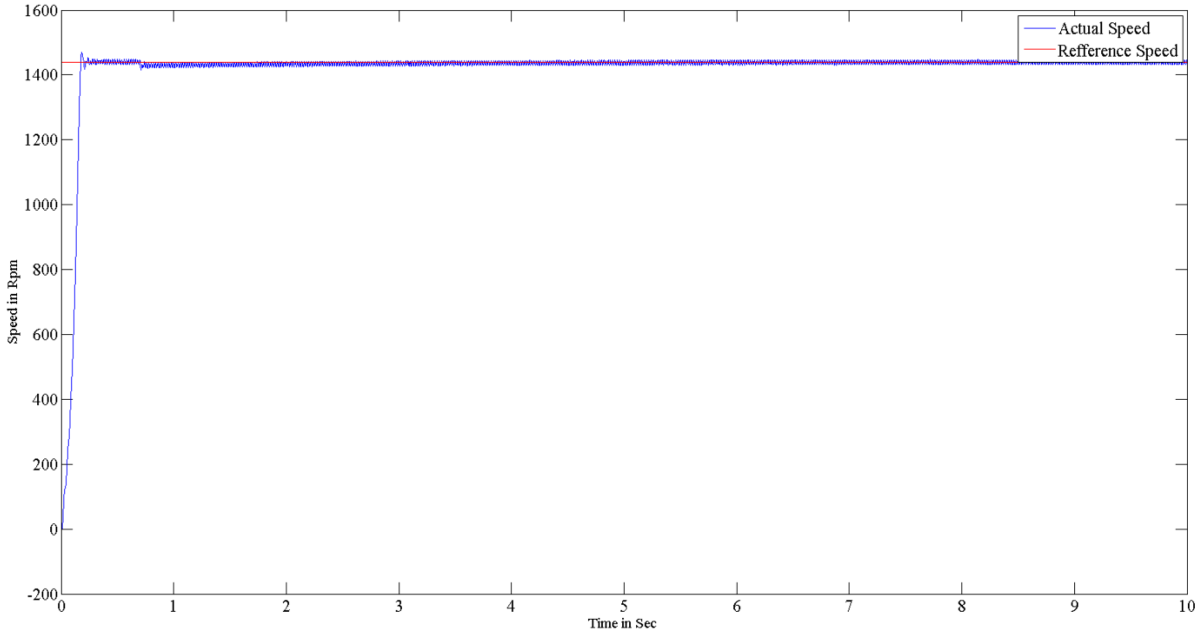

Fig 2.14 Speed diagram with noise

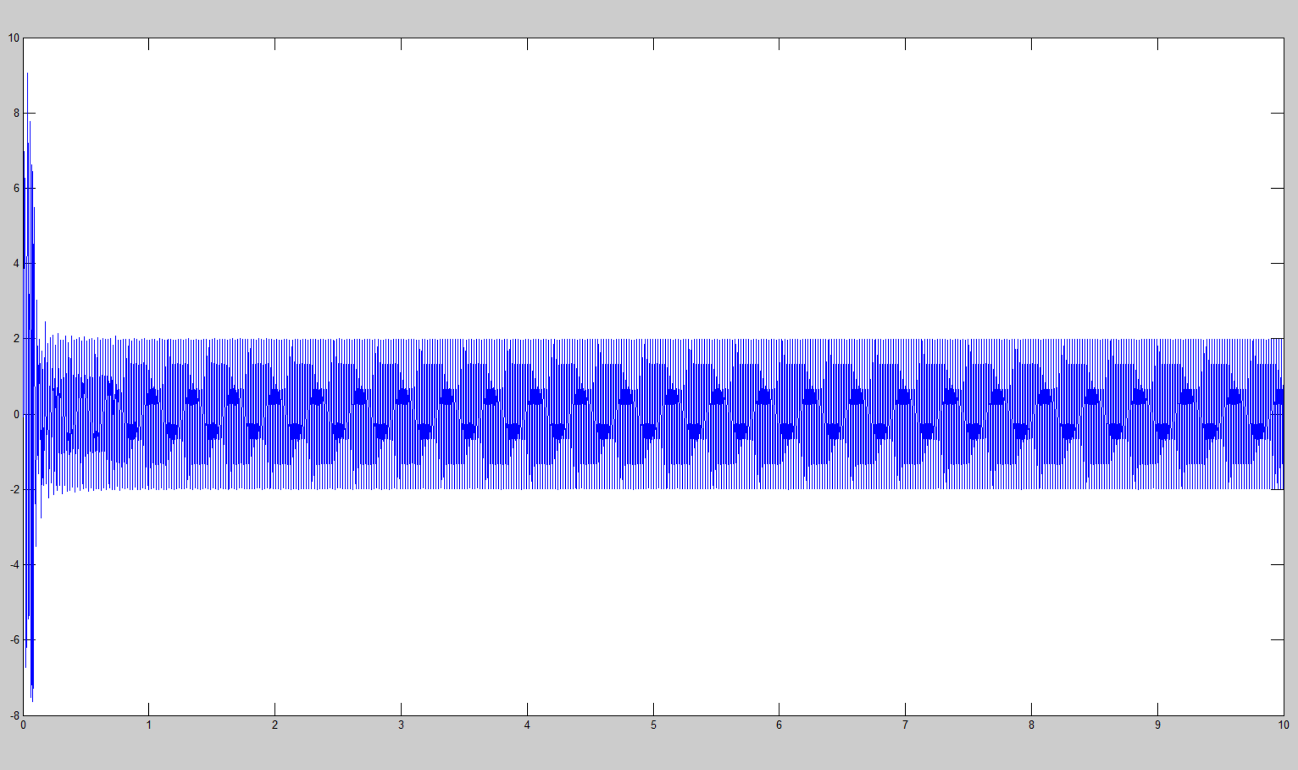

Fig 2.13 Stator Current without noise

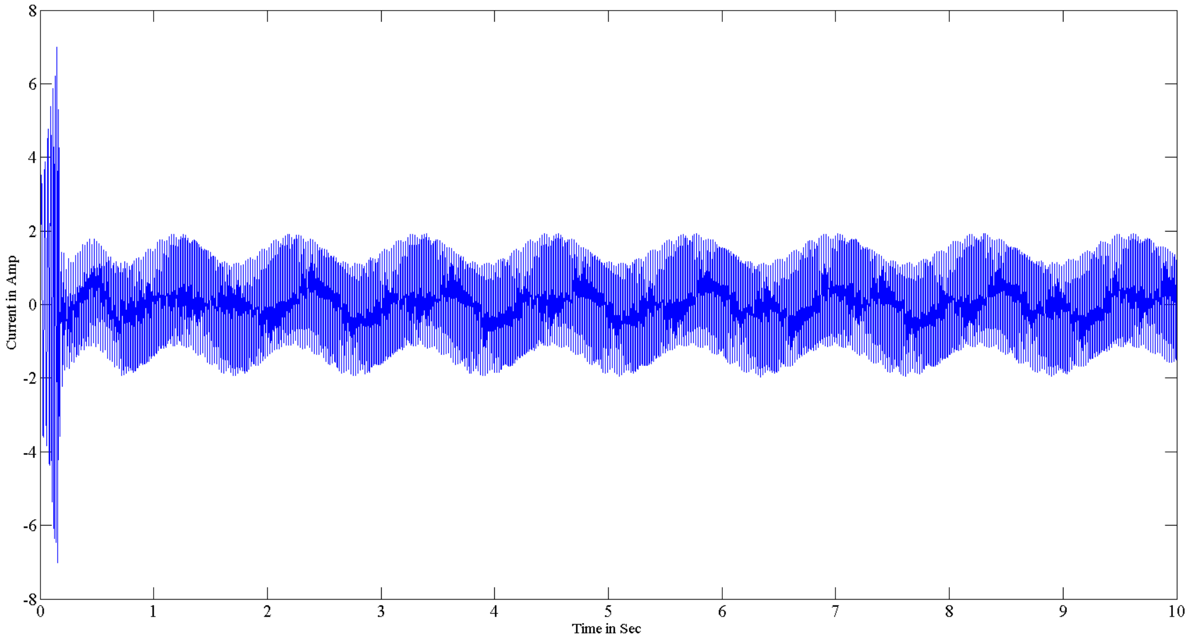

Fig 2.14 Stator current with noise

So it is seen that with the 50Hz noise injection the high frequency components as well as the low frequency beats are reinforced . The motivation of this dissertation, therefore is to devise a filtering mechanism to supress these torque ripples which lead to flow fluctuations in a flow circuit and also cause motor Vibration. This is explained in the next Chapter.

CHAPTER 3

3.1 Filter Design Introduction:

As mentioned in the previous chapter, a 50 Hz noise in the measurement channel increases the torque and current ripples in a VFD. While the high frequency components do not affect the speed, due to damping , the low frequency(beat frequency) components in torque cause a serious problem if one considers a viscous fluid e.g. a molten metal which can cause a rupture of piping and serious damage to the pump. In a physical plant, the sources of a 50 Hz noise are various [like power supplies in electronic equipment, intermittent or sparking loads such as switches, relays, brush type motors, Thyristor and Triac control of mains power etc.[13]] and may be varying e.g. a motor drawing a large starting current through a power cable close to the measurement channel, multiple grounding of the signal zero etc. and therefore, designing a filter becomes a very difficult task. In this chapter, the technique developed for suppression of enhanced torque ripples in presence of a 50 Hz. noise is first introduced and its effectiveness is demonstrated with MATLAB Simulation using the target system introduced in the previous chapter.

3.2 Suppressing Torque and Current Ripples:

In this section, the design of a filter for supersession of torque and current ripples induced by a 50 Hz. noise is presented. It is to be noted that the source of the 50Hz noise is not known it may come from the measurement channel, may come in the feedback loop and can also come parts of exposed wiring in the system. But from the analysis point of view a lumped insertion of 50 Hz noise in the feedback channel is assumed.

The first issue in filter design is the position of the filter where it will produce a better response .Filter may be applied after the PI controller so that the distorted error signal will not enter into the VSI and perfect switching pulses are obtained. Placing the filter after the VSI has certain associated constraints viz. the odd harmonics like the 3^{rd}, 5^{th}, and 7^{th} which come into consideration. In that case the system noise that is 50 Hz will be also multiplied with the higher order harmonics and more distorted response can be resign and the filter design will be more complicated and in-efficient. Also in the VSI 5th harmonic will cause losses in output voltage along with increased ripples in the instantaneous electromagnetic torque, while in case of 7th harmonics the losses are more.

So, filter should be designed in such a way so that the self-adjusting capability of that the filter can update it's parameters or filter co-efficients depending upon the circuit condition using adapting filtering [29][30][31] concepts. For this type of cases adaptive filter is best suitable. An adaptive filter has the ability to adapt to the change in the signal over time. Therefore adaptive filtering is very well suited for non-linear problems such as removal of Power Line interferences and noises.

There is basically two types of adaptive filter algorithms [32]

- Least Mean Square(LMS) Algorithm
- Recursive Least Square (RLS) Algorithm

Among the two adaptive filter realization techniques , the Least Mean Square Algorithm is preferred because this is a useful estimated gradient method as well as steepest descent algorithm. It's prominent advantages include small amount of real-time computation using, only the input signal and a reference response .

3.3 Filter Design:

In this sub-section, the filter design methodology is presented. Fig. 3.1 shows the filter schematic.

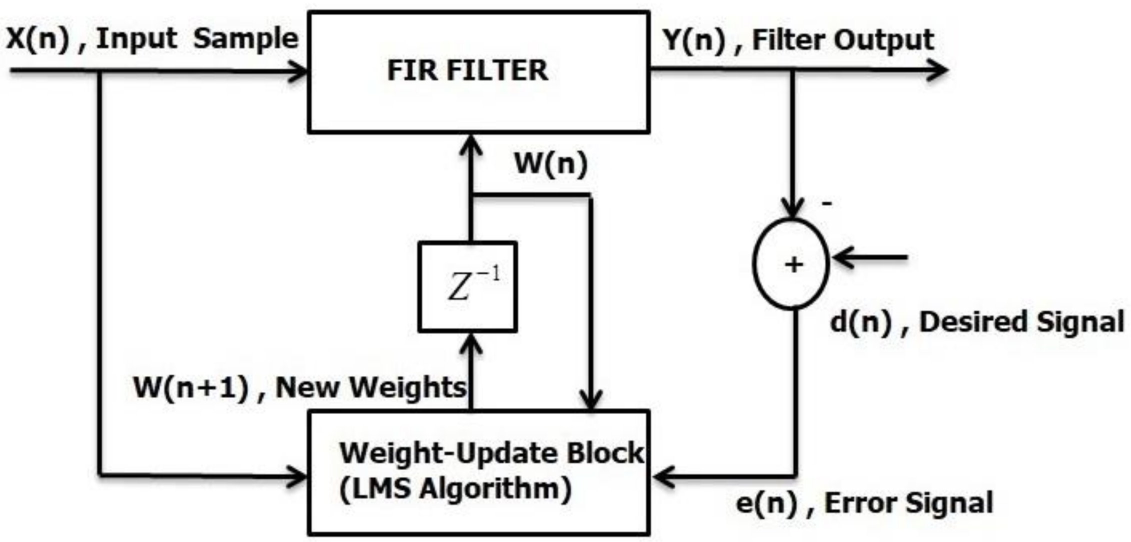

Fig. 3.1 LMS filter algorithm

.The Fig. 2.3 and Fig 2.4 showing the spectrum of instantaneous electromagnetic torque without and with 50 Hz noise and the corresponding stator currents shown in as shown in Fig. 2.5 and Fig. 2.6 are reproduced in this chapter as Fig. 3.2 to Fig3.5 for ready reference.

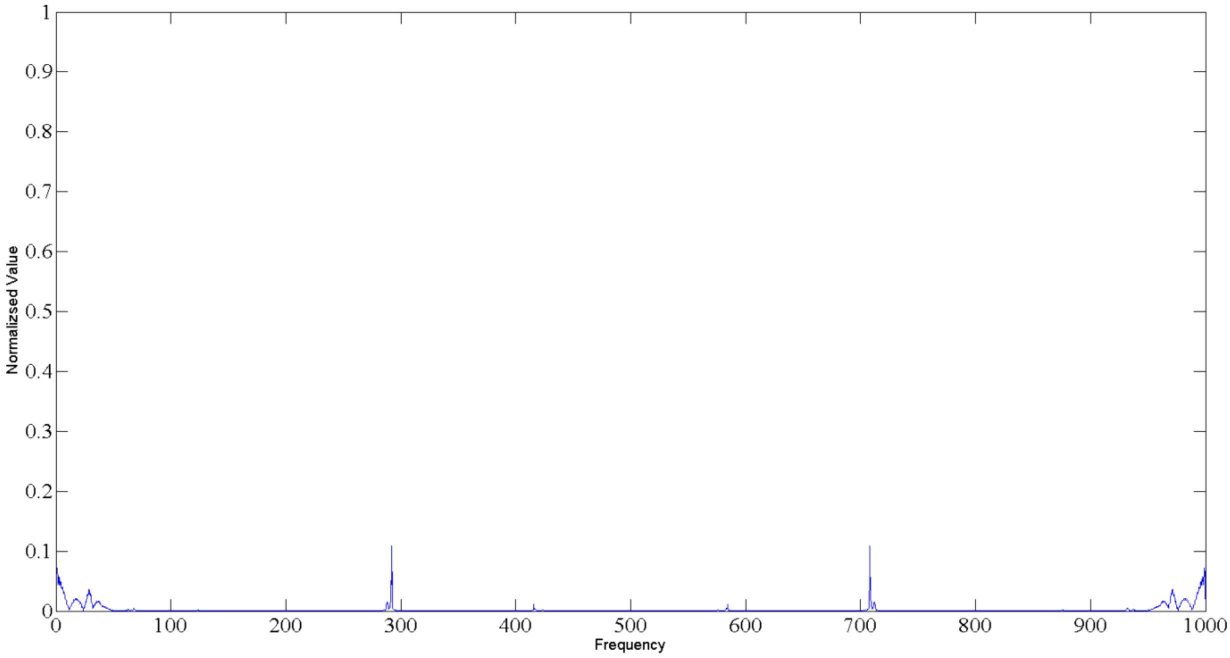

Fig 3.2 Torque without noise

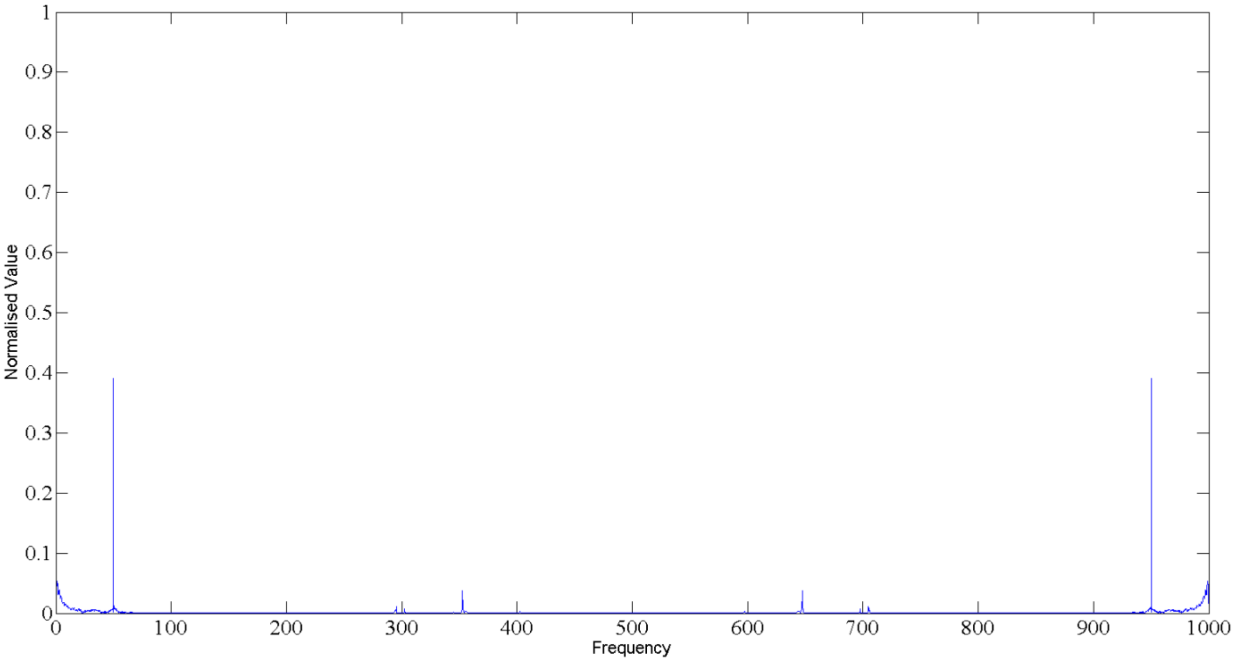

Fig 3.3 Torque with 50Hz noise

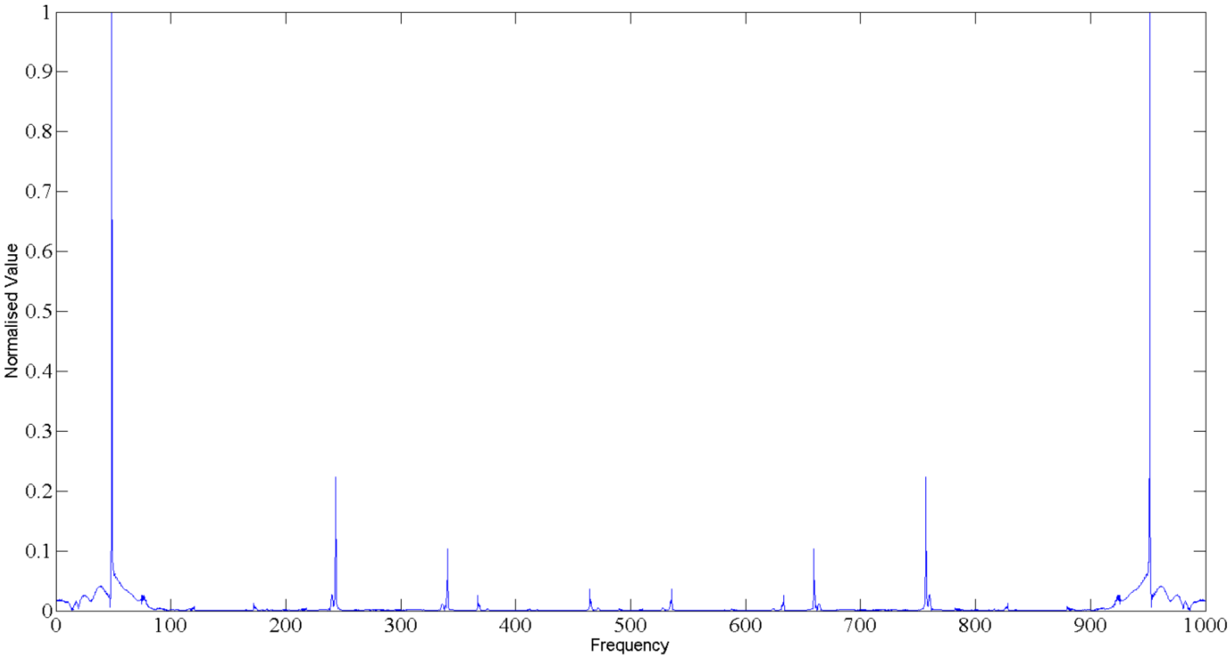

Fig 3.4 Stator Current without noise

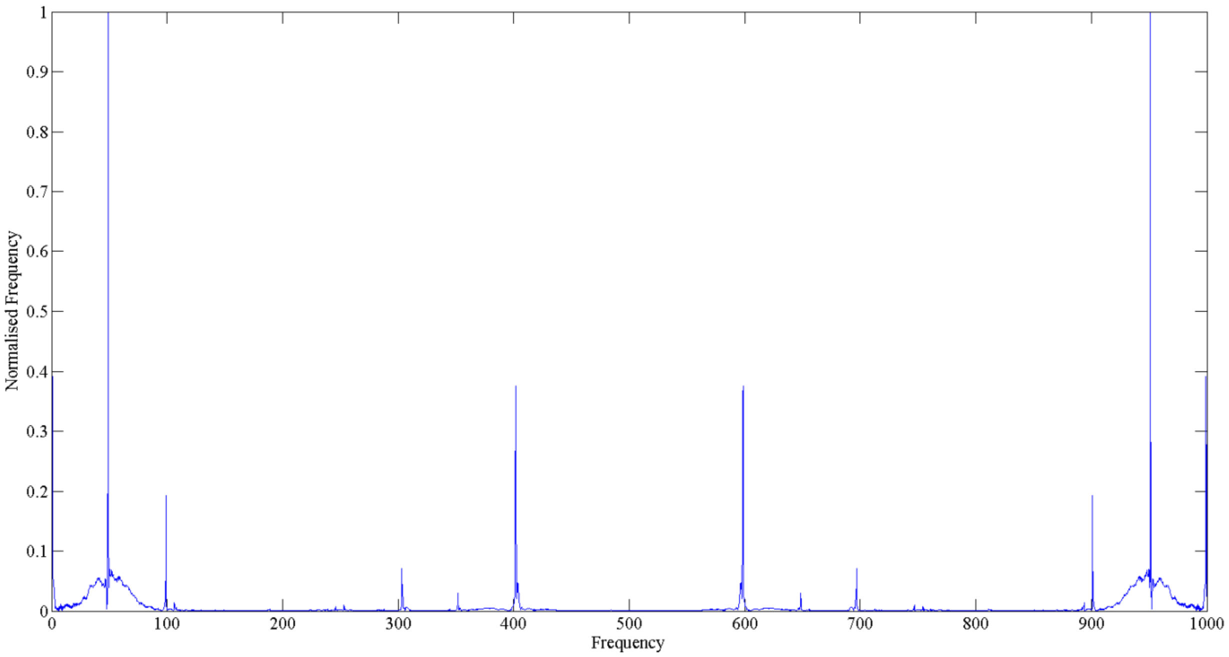

Fig 3.5 Stator Current with 50 Hz noise

As per the schematic shown in the fig 3.1 is an M-taps FIR filter [33][34] with tap weights

$w_k(\mathrm{n}), \mathrm{k} \in \{0,1,......,M-1\}$ and tap inputs

$x(\mathrm{n}) = [x(\mathrm{n}), \mathrm{x(n-1)}, ..., \mathrm{x(n-M+1)}]$

From the above schematic, it can be seen that the output at each time instant can be written as

$$y(\mathrm{n}) = \sum_{k=0}^{M-1} w_k(\mathrm{n}).\mathrm{x(n-k)} \qquad (1)$$

From eqn1 it can be seen that weights are a function of the time instant $'n'$. From Fig. 3.1 it is clear that the error signal is

$$e(\mathrm{n}) = \mathrm{d(n)} - \mathrm{y(n)} \qquad (2)$$

$d(\mathrm{n}) = \textit{Desired Signal}$ $\qquad y(\mathrm{n}) = \text{Filter Output}$

Now, the error e(n) is used by the LMS algorithm to determine the updated version of the filter tap weights $w_k(\mathrm{n})$ and it can be represented as

$$w_k(\mathrm{n+1}) = w_k(\mathrm{n}) - \mu.\mathrm{e(n)}.\mathrm{x(n-k)} \qquad (3)$$

where μ is the step-size parameter, determining a trade-off between the convergence speed and the convergence error of the algorithm[34] .

Now the value of μ has a particular range and cannot take the random values. The rate of convergence and MMSE (Minimum Mean Squared Error) is arrived with a trade off between each other i.e. the optimum result is produced when the step size is considered to be as small as possible but it should also be kept in mind while designing adaptive filter that step size should not be taken very small because it will decrease the rate of convergence.

The value of μ has a certain range and it is

$$0 < \mu < \frac{2}{\lambda_{\max}} \qquad (4)$$

where $\lambda_{\max}$ is the maximum value of the correlation matrix of the tap inputs $u(n)$ and the filter length M is moderate to large .

Now in the targeted system filter is applied after the PI controller and the overall SIMULINK schematic is represented by Fig. 3.6

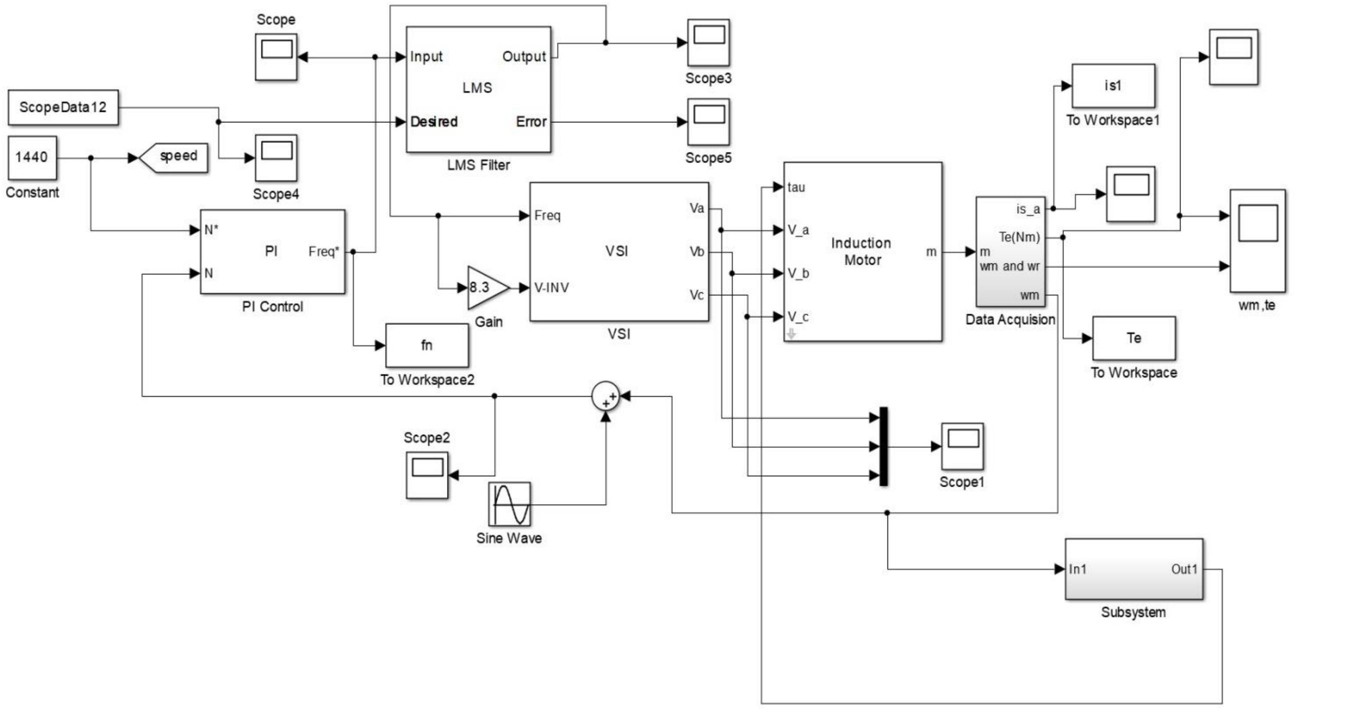

Fig 3.6 SIMULINK schematic diagram with filter

Here the input to the filter is the output of the PI controller which is distorted by 50 Hz noise and the desired input is our noise free circuit which has shown earlier. Here the desired input to the LMS filter is the input of the PI controller when the system is free from 50Hz noise that is the 'ScopeData12' in the above schematic which is shown previous chapter in fig 2.1.

So, firstly it is necessary to find out the co-relation matrix of the input of the filter for that reason workspace is taken in the above Simulink block named as ’fn’[30]. This block is used in the process of finding the co-relation matrix. Now by the following command in the Matlab workspace the maximum value of the correlation matrix of the tap inputs can be found.

$$r = xcorr(fn);$$
$$e = max(r)$$

by doing this e can be found which is nothing but the $\lambda_{\max}$ as described earlier is 2.6190×10^{7}

so in our circuit the value of μ will lie between

$$0 < \mu < \frac{2}{2.6190 \times 10^{7}}$$
$$\Rightarrow 0 < \mu < 7.63 \times 10^{-8} \qquad (5)$$

It is chosen as M= Filter Length = 512

μ= step size parameter= 8×10^{-9} for the best performance .

As the filter tap weights $w_k(\text{n})$ vary from {0 to M-1} so number of $w_k(\text{n})$ is also increased with the increase of filter taps.

From the equation (1) it can be seen that as $w_k(n)$ is increased the output will be more accurate and close to the actual signal but for this reason the value of filter taps that is 'M ' can not be increased to very large value because of the cost will increase and the execution time will be more. So, here an optimal value of 'M' is chosen based upon the circuit response and economical point of view.

If the filter tap changed from 512 to 128 then from FFT diagram from the figure 3.7 it can be seen that there is still a 50Hz noise spike is present because the output signal is close to the desired signal when the number of taps is going to increase as discussed earlier.

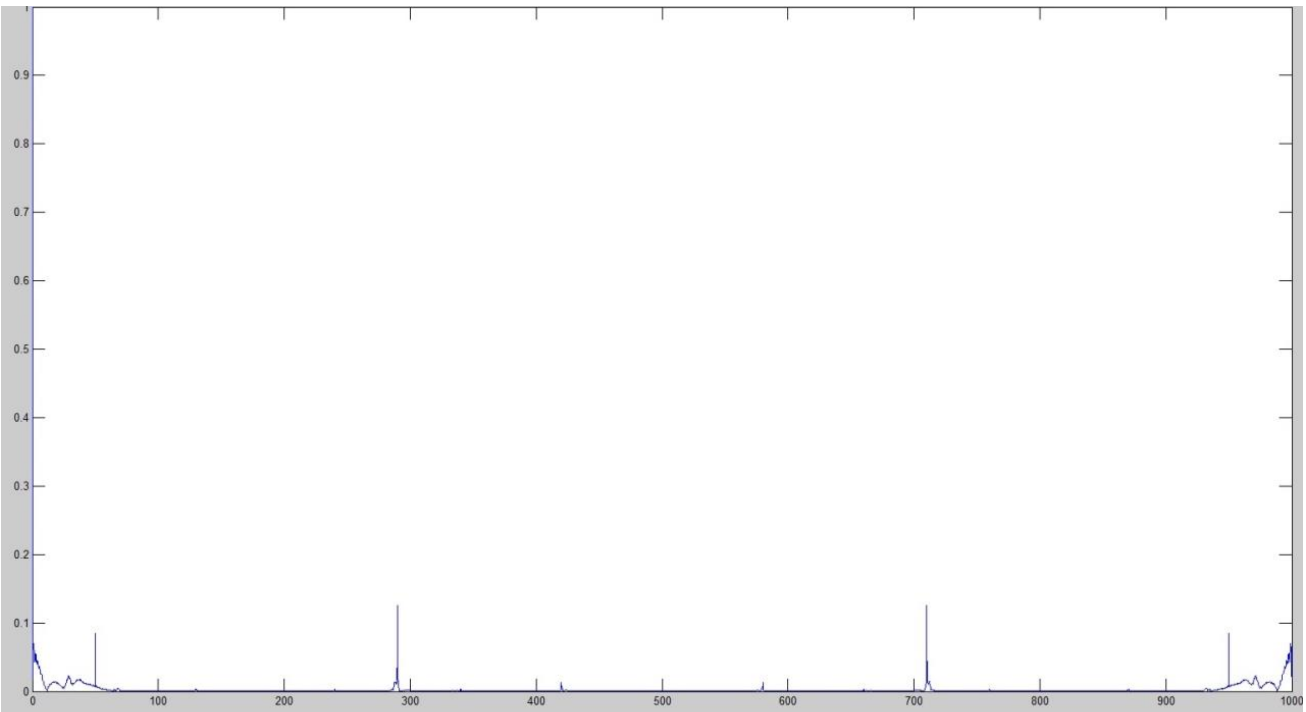

Fig 3.7 Torque output when filter length is 128

3.4 Result and Discussion :

In this section simulation results are discussed.

3.4.1) Response of the system without Noise

Here the target system is as described in the last chapter is presented again

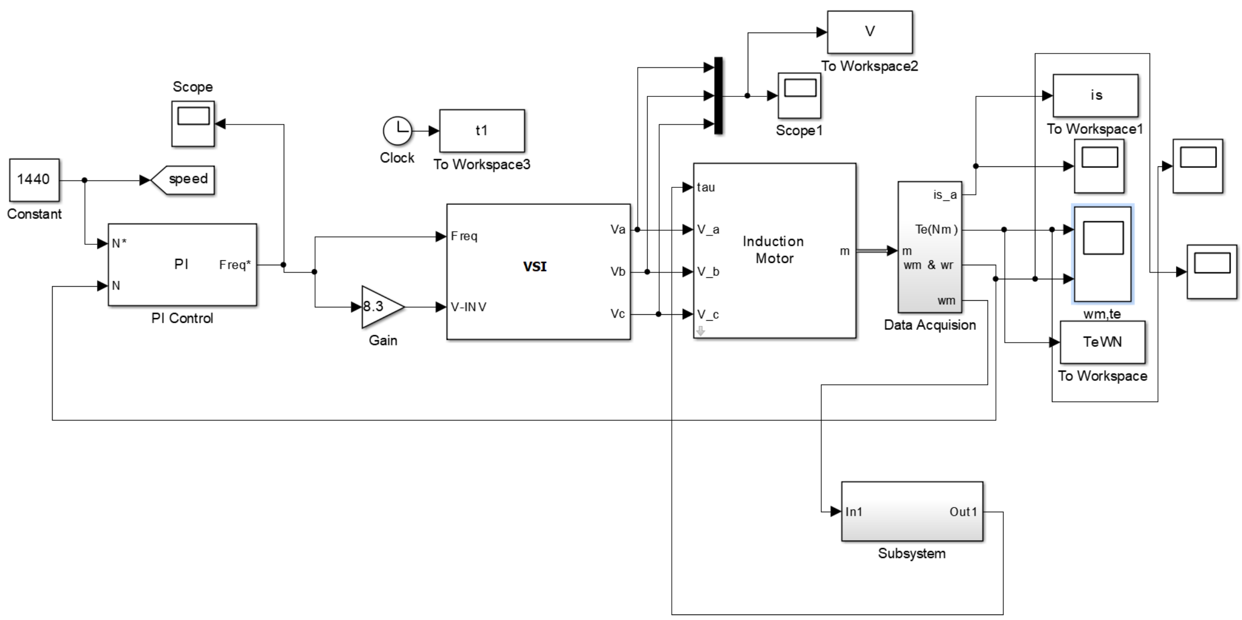

Fig 3.8 Fundamental Target System

In the normal noise-free condition there is a centrifugal pump load which is coupled with the designed IM to circulate the fluid. From the FFT diagram of the figure 3.2 & 3.4 of the two most important parameter of the model i.e Electromagnatic Torque and Stator current it can be seen that there are a 50Hz spike in the current diagram which is nothing but the power frequency that is given to the IM and since electromagnetic torque of any motor is the multiplication of stator flux and current that's why there is a high frequency spectrum in the Torque diagram and a beat frequency component which are is clearly shown in the fig 3.2. As shown in fig 3.6 that a three phase induction motor is connected to supply through VFD which led the harmonics to the system[35]. In the inverter, the triggering pulse is given by the discrete pulse generator SPWM(sinusoidal Pulse Width Modulator) now the output values are changed as shown in results and waveforms. In the resulting torque and stator current the frequency spectrum contains a number of low amplitude higher harmonics generated by VFD.

Harmonics are increased in the system so that the motor torque becomes pulsating. As the percentage of harmonics increases in the system the distortion of input voltage and input current increase. This distorted nature of current leads to pulsation in torque of the rotor [35].

3.4.2) Response of the System with 50Hz Noise

Now a 50Hz noise is added to the system in the feedback loop and for that the ‘Torque’ and the ‘Stator Current’ diagram is already given in this chapter in the fig no. 3.3 & 3.5.

In the diagram of the toque (Fig.3.3)with noise it is clearly shown a 50 Hz frequency spectrum due to the external noise.

Simultaneously in the fig 3.5 there is an unwanted frequency at 100Hz i.e at the double frequency due to this noise because the external 50Hz is getting superimposed with the existing power-line frequency.

Now this distorted diagram of torque which is pulsating at the 50hz make the motor vibrated and the motor became heated up also for that the flow rate of the fluid by the centrifugal pump is also affected.

3.4.3) *Response of the system with the filter:*

Here an adaptive filter which has been designed in the previous section using the LMS algorithm is applied after the PI controller as shown in the fig 3.6 . After applying the filter the torque and stator current FFT is as shown.

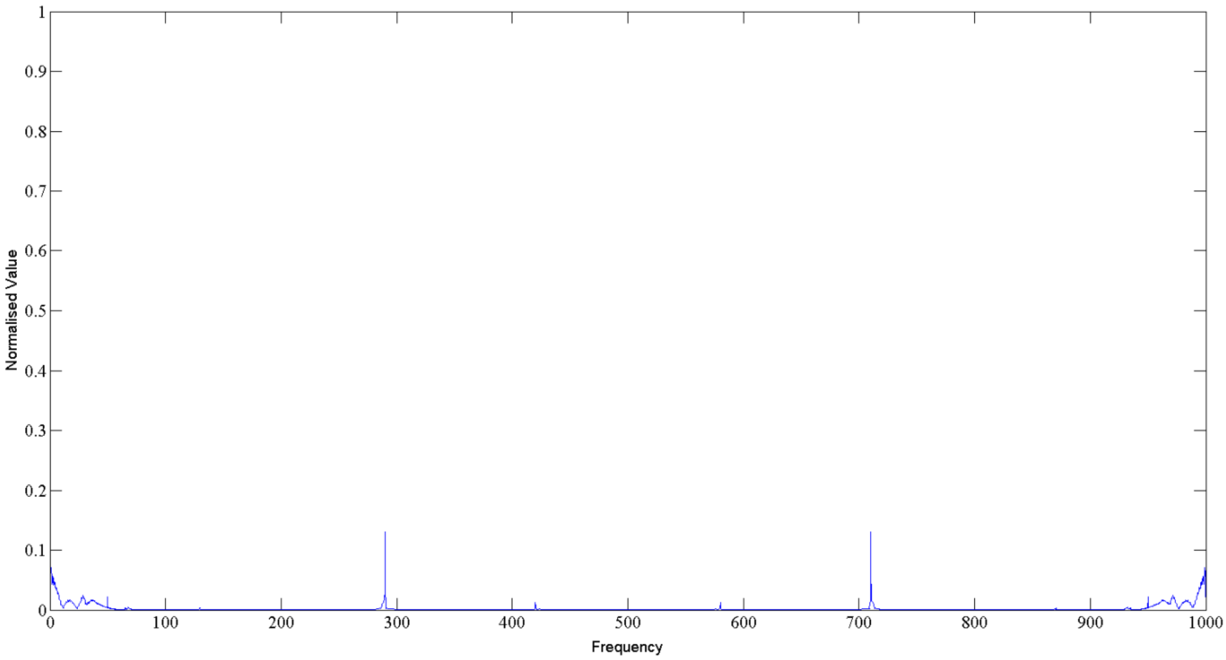

Fig 3.9 Torque diagram with filter

Here the LMS filter eliminates the unwanted 50Hz noise from the diagram and the frequency spectrum is exactly same as that in fig 3.2 where no 50 Hz noise was added.

In the below fig3.10 the output torque and speed is shown and there is no low frequency unwanted beat frequency in the torque or the speed.

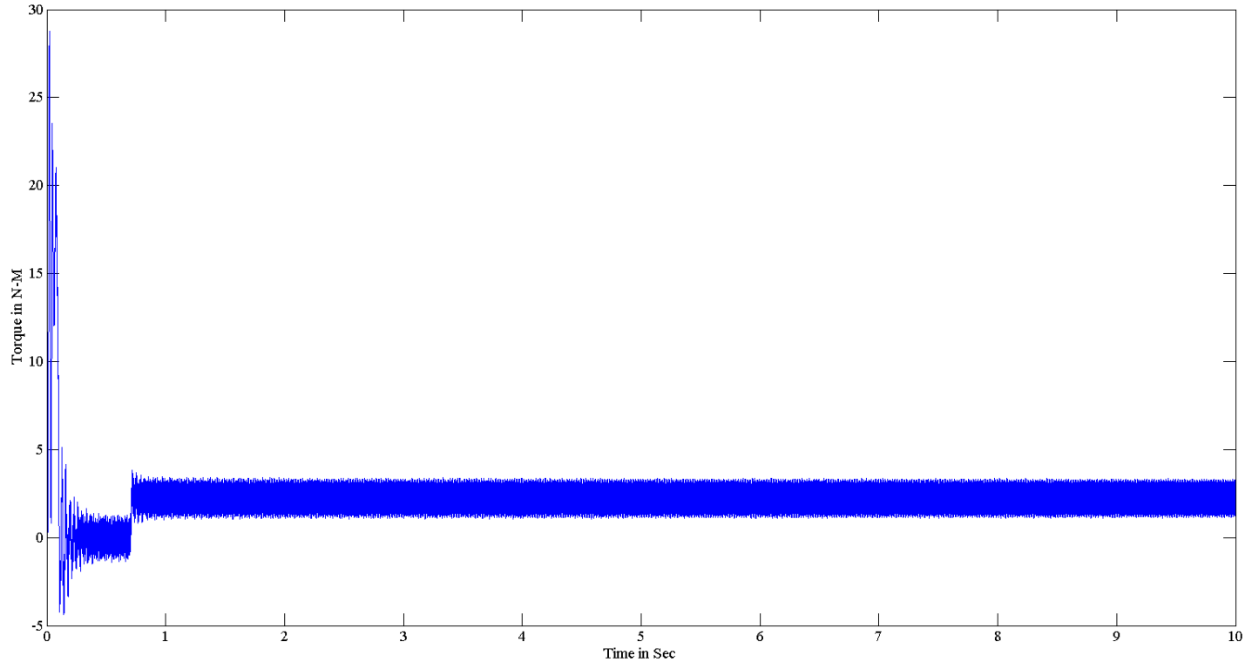

Fig 3.10 Torque Signal without noise

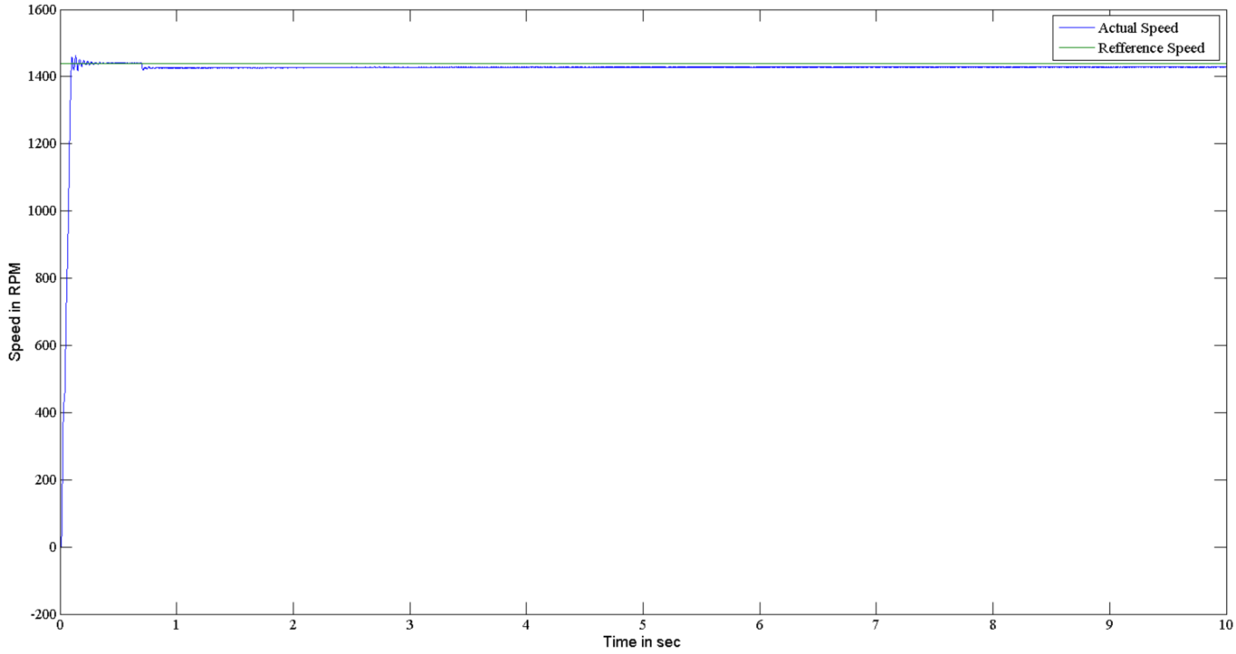

Fig 3.11 speed diagram without Noise

Now in the stator current also, there is no 100Hz component due to the 50Hz noise as it can be seen from the fig 3.11 .So, the circuit parameters i.e stator current , the electromagnetic torque all are matched with the actual target system described in fig 2.1 where no noise was introduced .

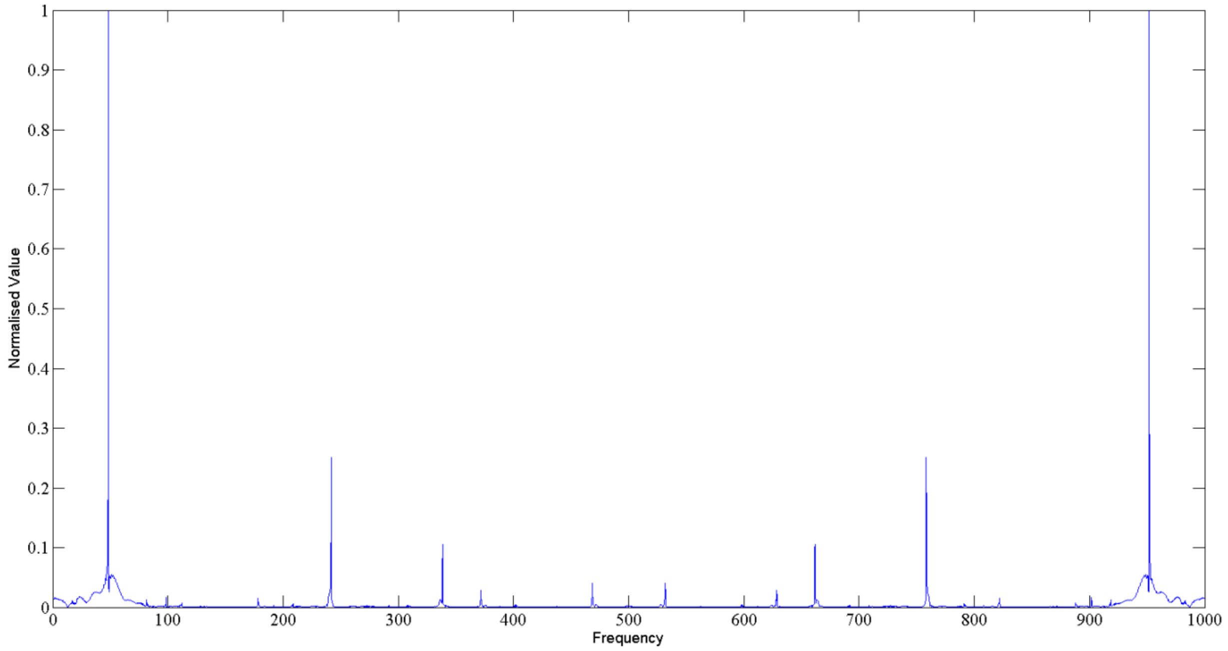

Fig 3.12 Stator current with Filter

3.5 ***Response of the system with different filter position:***

Apart from the desired position where the filter actually placed in the fig3.6 if the filter is placed after the VSI then the response of the electromagnetic torque is given below in fig 3.12 where it can be seen that there is a 50Hz noise still present in the diagram though it's magnitude is less from the non filter diagram still it is there which is not purposefully solved the target apart from that a wide band of frequency spectrum near the 300 Hz frequency is also present . This is because the harmonic content of the VFD[35] which get associated with the system along with the external noise at this portion the design of the filter is really a challenging job.

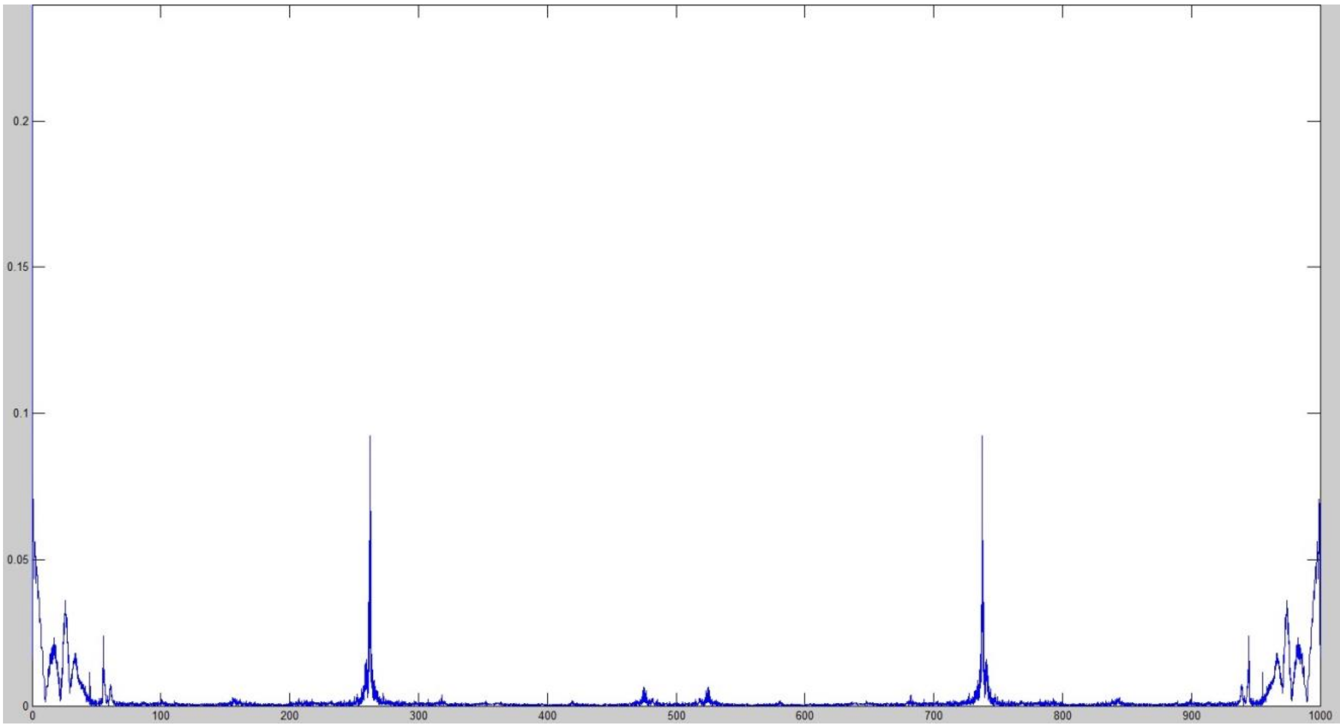

Fig 3.13 Torque diagram; filter placed after VSI

Again in the following diagram of current in the fig3.13 it can be seen that there is a large content of higher order harmonics present in the frequency spectrum due to the harmonics of the VFD and also significant low frequency components which will lead to beat frequency torque rippls causing flow oscillations.

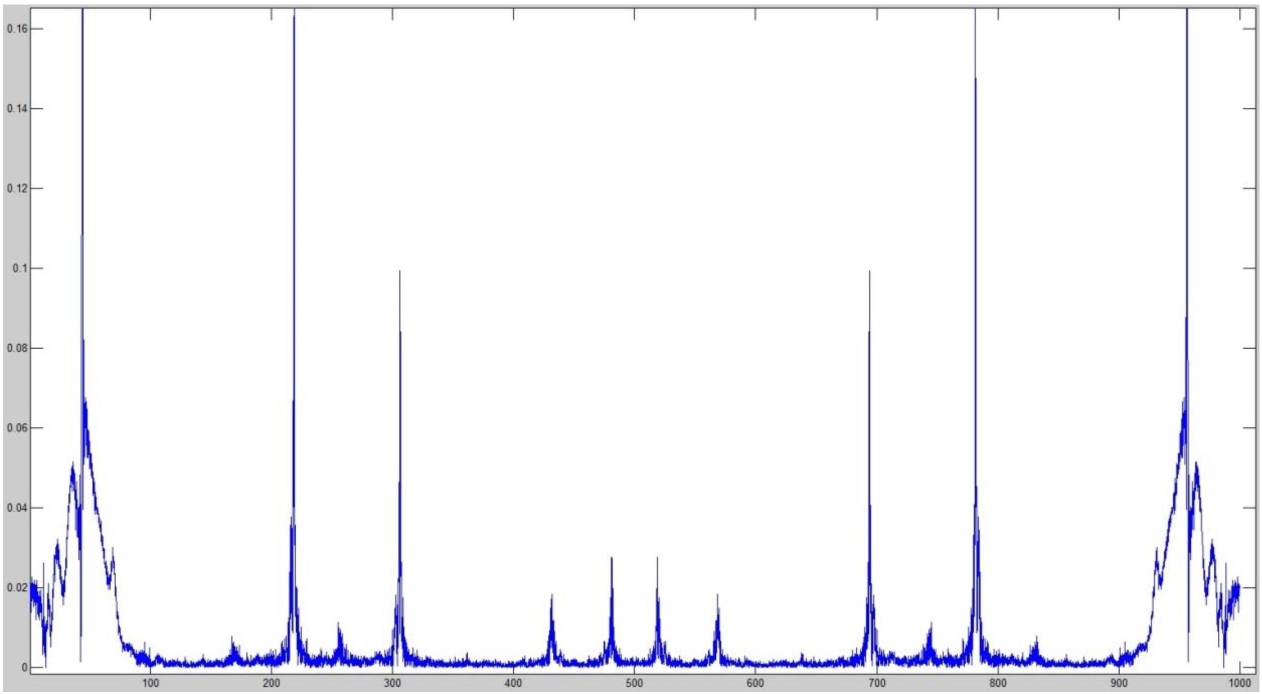

Fig 3.14 Stator Current ; filter placed after VSI

The results presented in the figures …. to establish the effectiveness of the adaptive filter presented in this dissertation.

3.6 Conclusion and scope of the future work:

At first, this dissertation puts forward the details of the mathematical modelling of an induction motor followed by the basic concept of V/F control using a Variable Frequency Drive. The induction motor drives an industrial centrifugal pump and the responses generated by this practical set-up, has been analysed in details to identify the dominant frequencies in the spectrum under both ideal and with injected noise conditions. The spectrum established in this regards, are used to design an adaptive filter to filter out unknown 50 Hz noise in the VFD. The results presented in the dissertation supports the fact the designed adaptive filter is capable of mitigating the 50Hz noise signal present in the system.

In the present case, the adaptive filter has been designed using the LMS methodology. As a scope of future work, the adaptive filter design can be realized using like RLS methodology and a comparative work can be carried out in this regard. Also the positioning of the filter in VFD drives is important. The filter performance can be tested by placing the filter in various locations, for e.g. after the inverter.

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APPENDIX:

The Fast Fourier Transform (FFT) can be done in “MATLAB Command Window” by the following programme:

```
L = length(Te);
fs=1000;
frange = linspace(0,fs,L);
i_s_f = fft(Te);
i_s_f_a = abs(i_s_f);
i_s_f_nr = i_s_f_a/max(i_s_f_a);
plot(frange,i_s_f_nr)
```