Simulation Studies On Performance Analysis Of Variable Frequency Induction Motor Drive And Incipient Fault Diagnosis Using Wavelets

D Venkata Ramana, P.Chandrasekar, R.Sreedhar

Abstract: The advent of Power Electronic Devices capable of handling high currents, aided the design of Variable frequency drive (VFD) with Induction motor or inverter fed induction motor drive, which can be characterized by increased reliability and reduced cost. Though taken care highly, such type of drive system is prone for different kinds of faults. When fault occurs, the drive operation has to be stopped if it is designed for general fault detection. The cost of this schedule can be high, and this justifies the development of incipient fault diagnosis. Finding the fault immediately after it occurs is general method of diagnosing the fault. In this case the damage occurs to component or system. If the fault is detected just before it damages the component or system is much better than general fault diagnosis. i.e. diagnosing the fault at developing stage. It saves the system or component from damage. In turn the cost of damage is reduced. This is called the incipient fault detection. In this paper, general fault detection as well as incipient fault detection using the wavelets has been simulated using MATLAB/SIMULINK package. Simulation results are presented showing both the general fault detection and incipient fault detection using the Wavelets.

Index Terms: Fast Fourier Transform (FFT), Insulated Gate Bipolar Transistor (IGBT), perfect reconstruction (PR), Sinusoidal Pulse Width Modulation technique (SPWM), Variable frequency drive (VFD), Voltage/Frequency (V/F). Wavelet Transform (WT).

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1 INTRODUCTION

Implementation of Induction motor, in industries, is used for constant speed operations, but not for variable speed operations. It would be most helpful to industries, if the induction motor is used for variable speed operations, because of its low cost, consistent performance and robust nature. But, the less efficiency and high cost penalty due to low Power factor must be improved when it is used for variable speed operations. The innovative devices in power electronics made speed control of induction motor effective and now they are acceptable in industries for wide speed variation applications with lessen making and maintenance cost. The Inverter fed induction motor drive is used for applications, where the control of the speed or torque is required [1-2]. Inverter controls the speed of the motor by changing the frequency of the input to the machine, thus the Induction motor will run at demanded speed. Mainly, it allows transformation of power from one frequency to another. Also, output frequency can be varied from 10KHz to 30KHz to vary speed for wide range. In diverse applications, such as, mine mills, oxygenating of huge buildings, air blowers which save energy by allowing air volume to match the demand of the application, pumps, the Inverter fed Induction Motor Drive is used. Also, this drive is used in industrial air grade compressors to save the energy consumed [3].

2 VARIABLE FREQUENCY DRIVE OPERATION

The basic building block of Inverter fed Induction motor has AC-DC and DC to AC conversion and connected by DC bus. Whole unit displayed in fig.2.1, i.e. The three-phase full wave diode rectifier considered would convert 3- phase input AC supply into DC supply. The DC link connected at the output terminals of rectifier reduces the ripple contents in the DC output [4-5]. The three-phase inverter section consists of IGBT's where the filtered DC supply is being converted into stepped AC supply, fed to the induction motor. It is renowned that the synchronous speed (Ns) of an Induction motor is subjected to the supply frequency [6-7]. Therefore, the speed of the motor can be controlled using VFD is given by,

$$\text{Speed (rpm)}\, N_s = \frac{120f}{P} \qquad (1)$$

Where; f = Frequency in Hz,
p = Number of poles.

The Table. 2.1, shows the speed variation as frequency changes and it is represented as Frequency Vs speed curve in Fig.2.2, below.

Thus, speed of a motor can be conveniently adjusted widely with gradual change of frequency fed to the motor under the condition of constant poles. Pole changing method also gives speed change, but not in gradual change and it requires a physical change of poles to the motor. Therefore, the Inverter fed induction motor drive provides smooth and precise change in speed by changing in the frequency supplied to the motor through sinusoidal pulse width modulation technique (SPWM) implemented in the Inverter. By changing the frequency of the drive, the speed gets varied, so, the term VFD [8].

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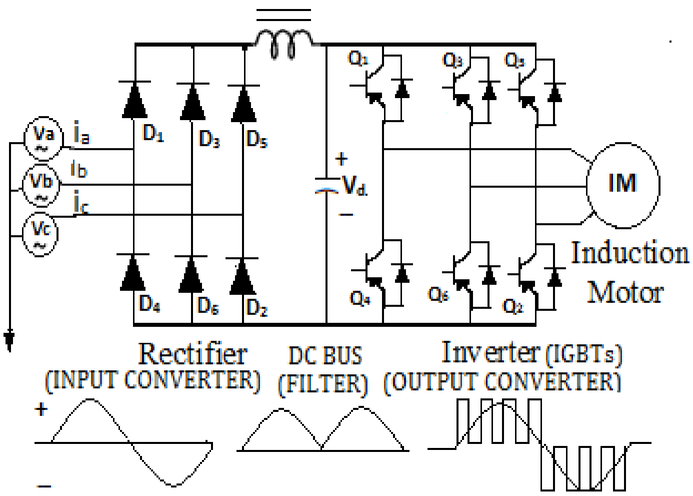

Fig2.1. *Circuit Diagram of inverter fed Induction Motor Drive.*

Frequency (Hz)	Speed(rpm) Theoretical	Speed(rpm) Simulated
20	600	496
25	750	615
30	900	735
35	1050	870
40	1200	1000
45	1350	1130
50	1500	1260

Table 2.1 *Frequency variation and corresponding rotor Speed*

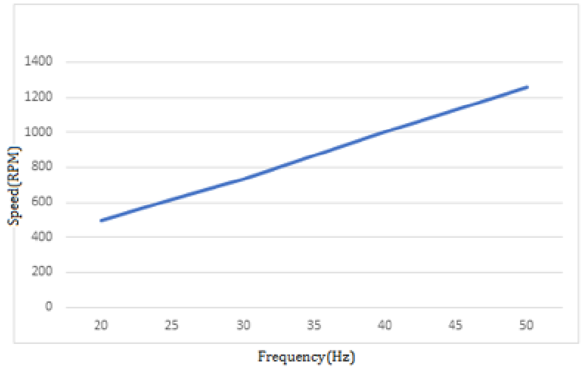

Fig.2.2*. The rotor speed Vs frequency curve.*

3. CONSTANT V/F RATIO OPERATION

Output voltage -to - frequency (V/f) ratio of all VFD maintains the constant, at all speeds to maintain magnetic flux not to get saturated.

The phase voltage V, frequency f and the magnetic flux Φ of the motor are related by the equation:

$V = 4.444\ f\ N\Phi_m$ or

$V/f = 4.444 N\Phi_m$

Where, N = number of stator turns per phase.

Φ_m = magnetic flux

If the input voltage fed is maintained constant as the frequency reduced, the magnetic flux would get saturated, which disturbs the motor performance. Therefore, to avoid the magnetic saturation the flux must be maintained fixed. Also, the torque of the motor is the interaction between stator flux and rotor flux, so, at variable speeds to maintain rated torque, the constant flux must be sustained at its rated value. This fundamental requirement is managed by keeping the (V/f) ratio unchanged, i.e. the voltage is reduced as the frequency is minimized to maintain the fixed (V/f) ratio, so that the magnetic core does not get saturated. A diode bridge and capacitor link is used to reduce the ripple content out of rectifier output, which, also to some extent eliminates harmonics. Due to PWM technique, output current waveform is closely matches with the source line current, which helps in minimizing the temperature. Fixed and closed to unity power factor will be maintained because of implementation of Sinusoidal pulse width modulation technique for reducing harmonics.

3.1. Variation OF Motor Speed

The bridge converter supplies DC power to the inverter drive, which is filtered by LC filters to get constant output waveform. Constant output waveform is essentially required for better performance of drive. Inverter output converts DC back to AC, and the inverter output voltage frequency and magnitude can be varied. This is done by using Insulated Gate Bipolar Transistor (IGBT).

3.2. Inverter with IGBTs

IGBTs are used for inverter control, i.e. at required specific intervals to switch the DC bus ON and OFF. The above operation produces variable AC voltage and frequency output, but output is not exactly pure sinusoidal in nature. So, IGBTs provide stepped AC output instead of sinusoidal waveform as shown in Fig.3.1. and in Fig.3. 2. If this supply is directly fed to the drive, it produces harmonics and drive performance gets degraded. This forces to use Pulse width modulation technique to reduce harmonics. It‘s important that it provides required variation of frequency and voltage to control the output parameters of motor. Pulse width modulation is most useful in varying the shape of non-sinusoidal waveform into approximately close to the sinusoidal waveform [8] as shown in Fig. 3.3.

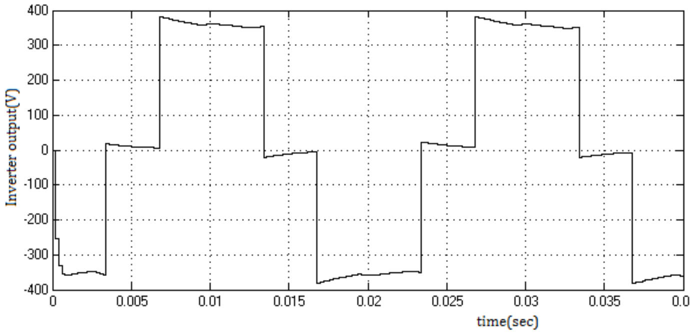

Fig3.1*. Single-phase Inverter Output Waveform*

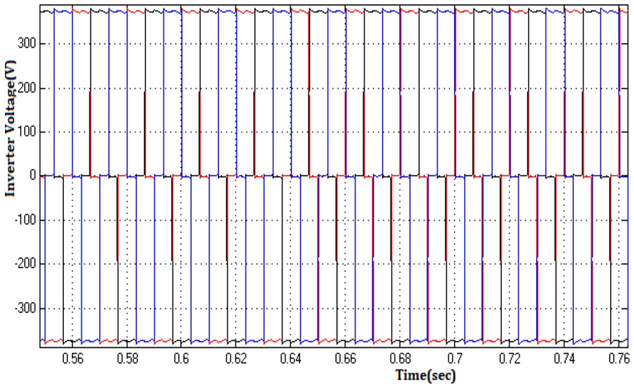

***Fig3.2**. Three-phase Inverter output waveforms*

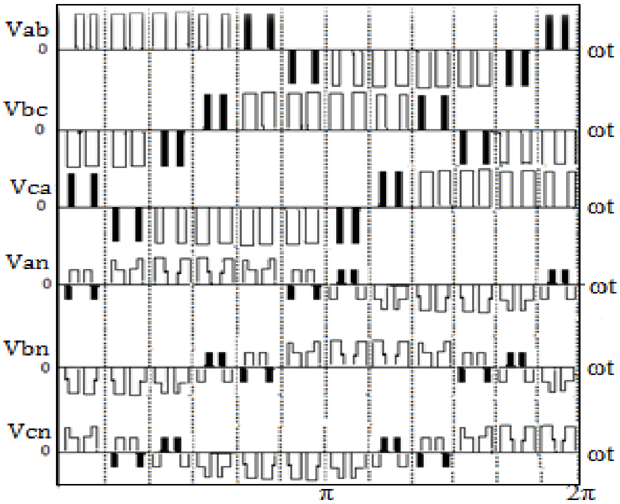

***Fig.3.3**. Inverter Output with SPWM*

Drive DC bus voltage is switched ON and OFF during the pulse width modulation is called switching frequency or carrier frequency. The switching frequency resolution must be high to keep the higher pulse width resolution. In modern variable frequency drive 4 to 16Khz or 4000 to 16000 switches on/off per second can be used for carrier frequency range. But for higher carrier frequency range the heat developed in the machine is higher due to harmonics developed, which could be balanced to decrease the heat level. The carrier frequency range in IGBT inverter can be higher compared to SCR frequency range.

4. MATHEMATICAL MODELLING OF A THREE-PHASE VOLTAGE SOURCE

AC 3-phase voltages with ω_e (constant frequency), which is filtered by LC filter and supplied to induction motor stator and is modelled using (2) to (4) as follows.

$$V_{as} = V_m cos\omega_e t \quad (2)$$

$$V_{bs} = V_m cos(\omega_e t + \theta) \quad (3)$$

$$V_{cs} = V_m cos(\omega_e t - \theta) \quad (4)$$

5. MODEL OF THE INDUCTION MOTOR

The induction motor is modeled using transformation of fixed a-b-c coordinates to rotating d-q-o coordinates. The equivalent circuit diagram of d-q-o coordination is shown in Fig.5.1. Formulated equations for 3-phase Induction Motor model has been given in the following equations [9].

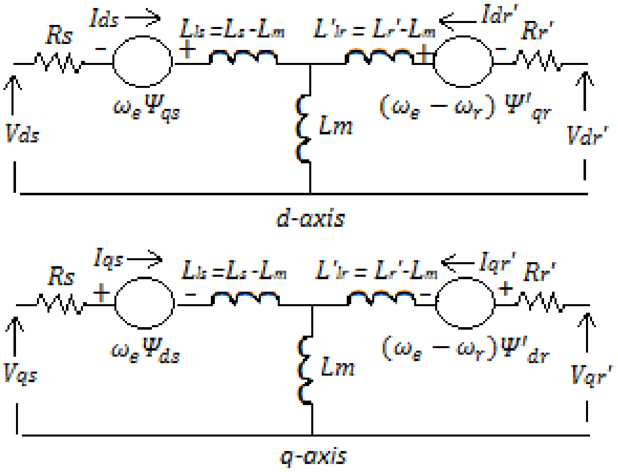

***Fig.5.1**. d-q-o model of Induction Motor*

From the above diagram, the following equations are obtained for the flux;

$$\varphi qs = Lsiqs + Lmiqr' \quad (5)$$

$$\varphi ds = Lsids + Lmidr' \quad (6)$$

$$\varphi qr' = Lr'iqr' + Lmiqs \quad (7)$$

$$\varphi dr' = Lr'idr + Lmids \quad (8)$$

where $Ls = Lis + Lm$ (9)

$$Lr' = Lir' + Lm \quad (10)$$

For the stator side,

$$Vqs = Rsiqs + (d/\,dt)\ \varphi qs + \omega e\varphi ds \quad (11)$$

$$Vds = Rsids + (d/\,dt)\ \varphi ds - \omega e\varphi qs \quad (12)$$

For the rotor side,

$$Vqr' = Rr'iqr' + (d\,/dt)\ \varphi qr' + \omega e - \omega r\varphi dr' \quad (13)$$

$$Vdr' = Rr'idr' + (d\,/dt)\ \varphi dr' - \omega e - \omega r\varphi qr \quad (14)$$

At this investigation, Vqr' and Vdr' are set to zero for a squirrel cage induction machine.

The generated electromagnetic torque is given as

$$Te = 3P/4\ Lm(idriqs - iqrids) \quad (15)$$

Where,

L_m	Mutual Inductance
L_{is}	Stator Leakage Inductance
L_{ir}	Rotor Leakage Inductance
I_{qs}	Q-axis component of the stator current
I_{ds}	D-axis component of the stator current
I_{qr}	Q-axis component of the rotor current
V_{ds}	D-axis component of the stator voltage
V_{dr}	D-axis component of the rotor voltage
ω_r	Rotating velocity of the Motor rotor in electrical degrees
R_r	Rotor resistance
I_{dr}	D-axis component of the rotor current
Φ_{qs}	Q-axis component of the stator flux

ϕ_{ds}	D-axis component of the stator flux
ϕ_{qr}	Q-axis component of the rotor flux
ϕ_{dr}	D-axis component of the rotor flux
V_{qs}	Q-axis component of the stator voltage
V_{qr}	Q-axis component of the rotor voltage
ω_e	Rotating velocity of the applied two-phase Q-D reference frame
R_s	Stator resistance

6. EFFECT OF CHANGE IN SUPPLY VOLTAGE ON STARTING TORQUE

$$T_{st} = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2} \quad (16)$$

Substituting E2 = supply voltage, V

Then, $T_{st} = \frac{K_1V^2R_2}{R_2^2+X_2^2} = \frac{K_1V^2R_2}{Z^2}$ (17)

Substituting, $K_3 = \frac{K_1R_2}{Z^2}$ then

$$T_{st} = K_3V^2 \quad (18)$$

7. INVERTER MODEL

Fig.7.1. DC supply of from rectifier imparted to the inverter and modulated inverter output will be fed to the motor. The inverter transistor states switching model has been shown in Table.7.1. And care must be taken not to get turn on simultaneously the transistors in any single leg at any time of operation of drive.

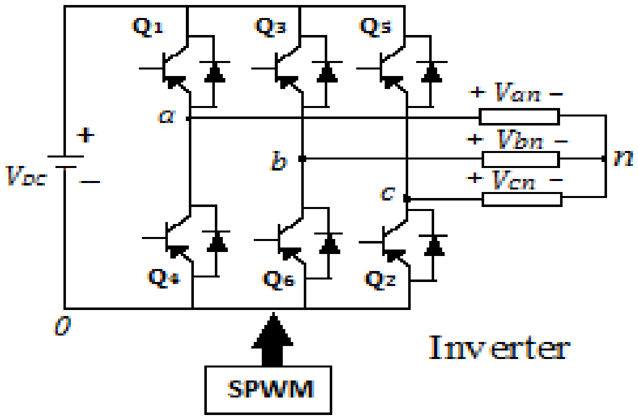

Fig. 7.1: *Three-phase Full–Bridge Inverter*

i.e.

$Q_1 + Q_2$ (19)

$Q_3 + Q_4$ (20)

$Q_5 + Q_6$ (21)

Modulating technique is used in a 3-phase inverter and valid transistor states will be selected in order to generate required waveform.

States	Q_1	Q_2	Q_5	V_{ab}	V_{bc}	V_{ca}
1	0	0	0	0	0	0
2	0	0	1	0	$-V_{dc}$	V_{dc}
3	0	1	0	$- V_{dc}$	V_{dc}	0
4	0	1	1	$- V_{dc}$	0	$- V_{dc}$
5	1	0	0	$- V_{dc}$	0	$- V_{dc}$
6	1	0	1	$- V_{dc}$	$- V_{dc}$	0
7	1	1	0	0	V_{dc}	$- V_{dc}$
8	1	1	1	0	0	0

Table.7.1. *The Transistor Switching States*

$$\frac{Vac}{2}(Q_1 - Q_2) = Van + Vno \quad (22)$$

$$\frac{Vac}{2}(Q_3 - Q_4) = Vbn + Vno \quad (23)$$

$$\frac{Vac}{2}(Q_5 - Q_6) = Vcn + Vno \quad (24)$$

Pulse width Modulating signals are; Equations (22) , (23) and (24).

By combining the Equations (22) , (23) , (24) and (17), (18), (19) the following equations obtained:

$$\frac{Vac}{2}(M_1) = Van + Vno \quad (25)$$

$$\frac{Vac}{2}(M_3) = Vbn + Vno \quad (26)$$

$$\frac{Vac}{2}(M_5) = Vcn + Vno \quad (27)$$

Adding Equations (25) to (27) to give Equation (28);

$$\frac{Vdc}{2}(Q_1 + Q_3 + Q_5 - Q_2 - Q_4 - Q_6) = Van + Vbn + Vcn + Vno \quad (28)$$

As we are dealing with balanced voltages, $Van + Vbn + Vcn = 0$, equation (28) becomes

$$\frac{Vac}{6}(2Q_1 + 2Q_3 + 2Q_5 - 3) = Vno \quad (29)$$

Substituting for Vno in Equations (22) to (24) gives:

$$\frac{Vac}{3}(2Q_1 - Q_3 - Q_5) = Van \quad (30)$$

$$\frac{Vac}{3}(2Q_3 - Q_3 - Q_5) = Vbn \quad (31)$$

$$\frac{Vac}{3}(2Q_5 - Q_3 - Q_1) = Vcn \quad (32)$$

8. COMPLETE MODEL OF INVERTER FED INDUCTION MOTOR DRIVE

The variable v/f obtained by simulated model of SPWM implemented inverter is utilized to control the output parameters of the motor. Figure 8.2, shows the Rotor speed. Figure 8.3 and 8.4, shows the simulated stator currents waveform. They initially get ramping waveforms before reaching normal values at 50 Hz. From the performance of the VFD, observed that, it is sensitive enough to reach its rated speed with rated frequency of 50Hz. Finally figure 8.5 shows the rotor torque of the model; initially it undergoes transient condition and then settles to a stable condition within few milliseconds.

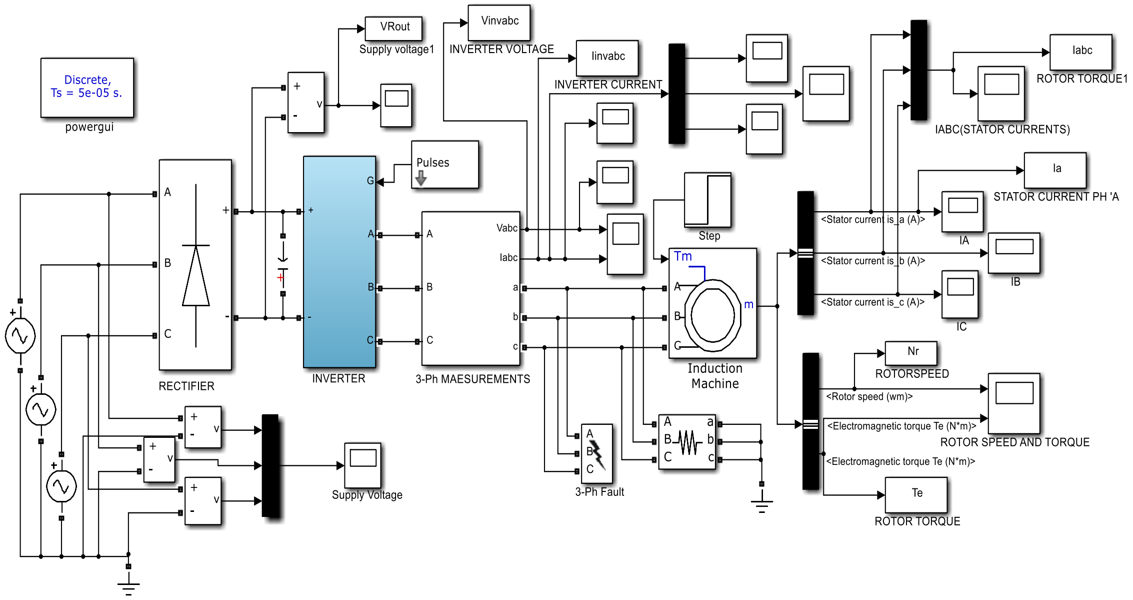

Fig.8.1. Simulation model of Three phase Rectifier Inverter- Induction motor drive

The Fig.8.1 shows the Simulink model. Values used in simulation are given in Table.8.1.

Parameter	Value
Supply Voltage 415volts (line)	Supply Frequency 50Hz
Rotor Type	Squirrel Cage Motor
Rating	3kW
Number of poles	4
Normal speed	1500rpm

***Table.8.1**. Simulation Parameters*

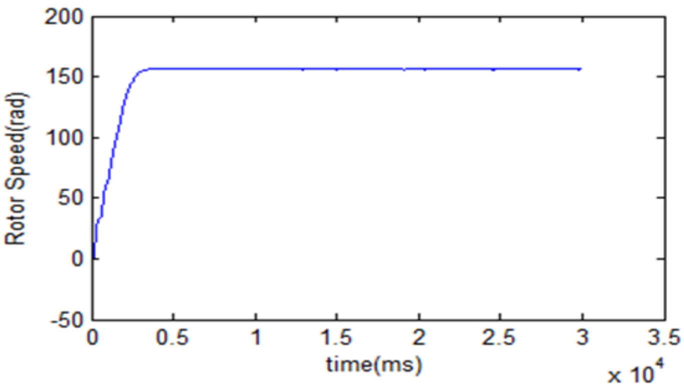

***Fig.8.2**. Rotor speed*

VFD have the following advantages;

i, saves the Energy,

ii, draws Less current at starting,

iii, minimizes thermal and mechanical stresses on Motor and belts during starting,

iv, Easy to retrofit, and

v, improved power factor.

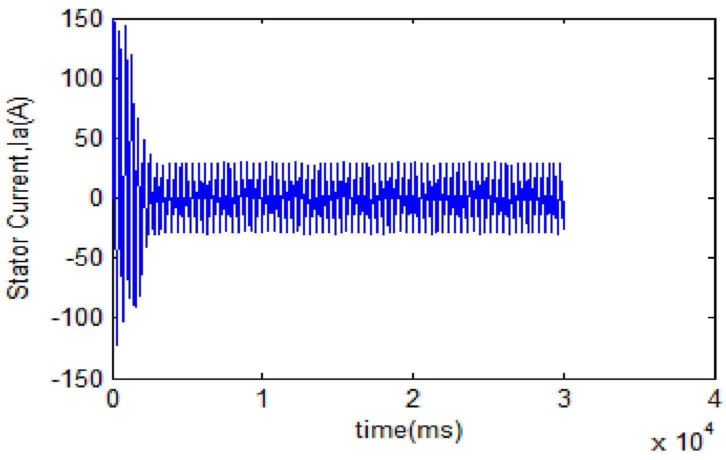

***Fig.8.3**. Statorcurren ‘a’phase.*

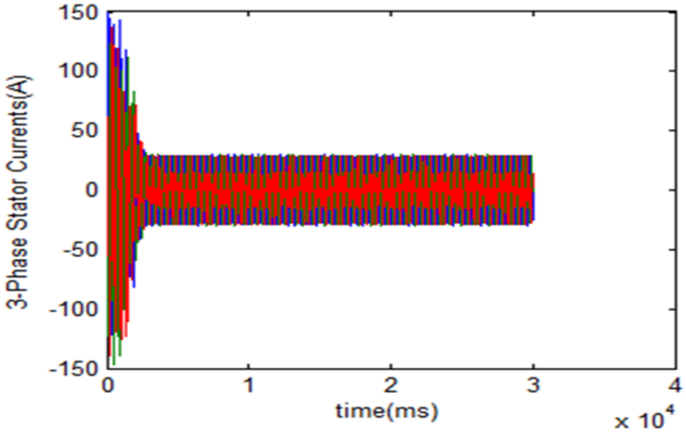

***FIG. 8.4.** THREE PHASE STATOR CURRENTS*

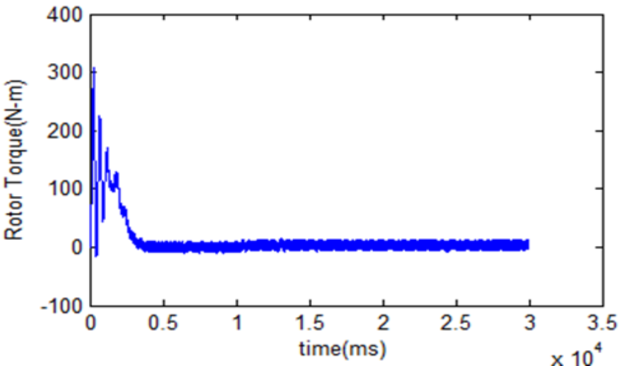

Fig.8.5. *Rotor torque*

9. FAULT DETECTION USING WAVELETS

[1] Finding fault signals using FFT may be most useful due to its functioning in the frequency domain only. But, in Dynamic conditions, i.e real time fault detection in the drive or parts of drive is most important when load is continuously varying. For non-periodic, non-stationary, short duration fault signal, which is of impulse nature can be super imposed by the wavelet transform to find fault in real time. For the analysis of current transient phenomena, Wavelet Transform (WT) is a suitable one due to its ability to extract information from transient signals simultaneously in the time and frequency domain [10-11].The analyzed signal from the wavelets has been displayed in Fig.9.1. The de-noised signal of original stator current of induction machine drive is showing the fault magnitude and time of fault occurrence at the fault period of 0.01secs. Which makes the digital signal processor to decide to reconfigure or shut down the drive, else it might become catastrophic fault by causing larger damages and losses.Noise removal from the faulty signal is essential to confirm the faulty signal compared to the healthy signal. Also, which helps diagnose the fault even under light load conditions. Wavelet Transform (WT) is a most suitable tool for reducing noise from faulty signals due to its perfect reconstruction (PR) filters [12-13].

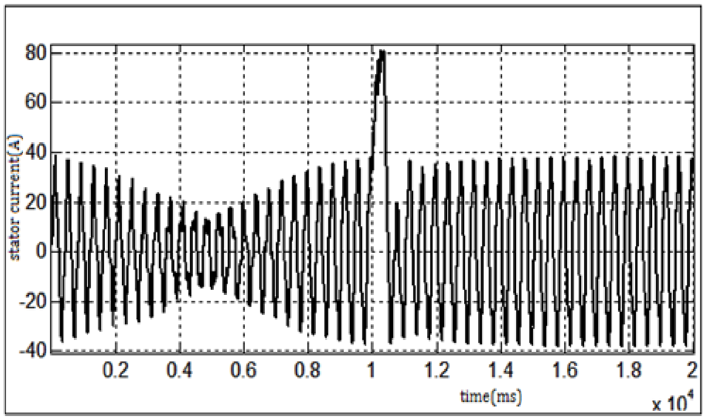

***Fig.9.1**. De-noised wavelet analysis for fault period 0.01s.*

10. CONCLUSION

In case of fault occurrence, identifying the fault is most important, for the wavelet is favorable option from the simulation study of this paper. This simulation model can be used for further research to study behavior of the drive under the inverter faults, diagnosing these faults using advanced monitoring techniques such as FFT and WTs and plan for necessary automatic control action. Also, can be investigated in detail for predicting the different faults at incipient level and by using the advanced signal processing techniques these faults can be diagnosed and the drive can be protected or reconfigured to avoid inadvertent shut down. This is an attempt to show that Wavelet detects the fault in shortest possible time duration.

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