Rotor Insipient Fault Detection in Permanent Magnet Synchronous Motors.

By:

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(2009-MS-EE-147)

This thesis is submitted in partial fulfillment for the degree of Masters of Science in Electrical Engineering

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July 2013

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ACKNOWLEDGEMENTS

First of all Thanks to Allah. I would like to express my gratitude to all those who gave me the possibility to complete this thesis. I want to thank the Department of Electrical Engineering of UET for giving me permission to commence this thesis in the first instance, to do the necessary research work and to use departmental data.

I am deeply indebted to my supervisor Assistant Professor Syed Abul Rehman Kashif and Dr. Asghar Saqib from UET whose help, stimulating suggestions and encouragement helped me in all the time of research for and writing of this thesis.

My former colleagues from the Department of EE supported me in my research work. I want to thank them for all their help, support, interest and valuable hints. Especially I am obliged to my friends and family for their support.

Especially, I would like to give my special thanks to my mother whose patient love enabled me to complete this work.

Saad Saleem Khan

Abstract

The thesis work describes how an electrical engineer in the industry using permanent magnet synchronous motor (PMSM) should consider the presence of cracks in the rotor both in magnets and rotor body. These cracks have the common occurrence in the rotor of motor due to various reasons. We build the 3-D model of PMSM in Maxwell v 11 to study the effects of crack by using FEA (finite element analysis) to calculate the inductances of motor in one complete electrical cycle. After getting the values of inductances at different rotor angle in tabular form, we put these values in curve fitting tools of Matlab to get the function of inductance over time. Inductance functions before and after the cracks, will be used in current equation to get the current waveform before and after the crack. FFT analysis of current waveform shows the change in its spectrum i.e harmonics. Finally we examine the effects of cracks on harmonics and observe the pattern how harmonics will change as the crack widens over time. This will help us to detect the presence of cracks before they get too much wide with the passage of time and start affecting the performance of the system.

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1.1 Introduction

Permanent Magnet Synchronous Motor (PMSM) has found their applications in modern era industry because of its advantages over induction motors like its reduced copper losses, compactness, high output to volume ratio, high efficiency and very simple construction and maintenance as compared to induction motors. PMSM is useful in low and mid power applications such as speed drives, robotics and most importantly in electric vehicles and computer equipment. PMSM reliable operation has been demanded because of its growth in drive applications.

Faults in motors using Permanent Magnets are usually divided in three categories. Main category is electrical fault which is due to the faults in Stator Windings e.g. Short circuit fault, over current faults, ground faults etc. Mechanical faults of these motors are usually arises because of bearing faults which effects eccentricity, this fault is the second major fault in these type of motors. Third category of fault is magnetic faults which arise due to demagnetization of Permanent Magnets. Stator faults can be easily detected rather than mechanical or magnetic faults by using relays/fuses or by observing current and voltage waveforms. Different types of faults which are common have been shown in Figure 1.1 in the form of a chart.

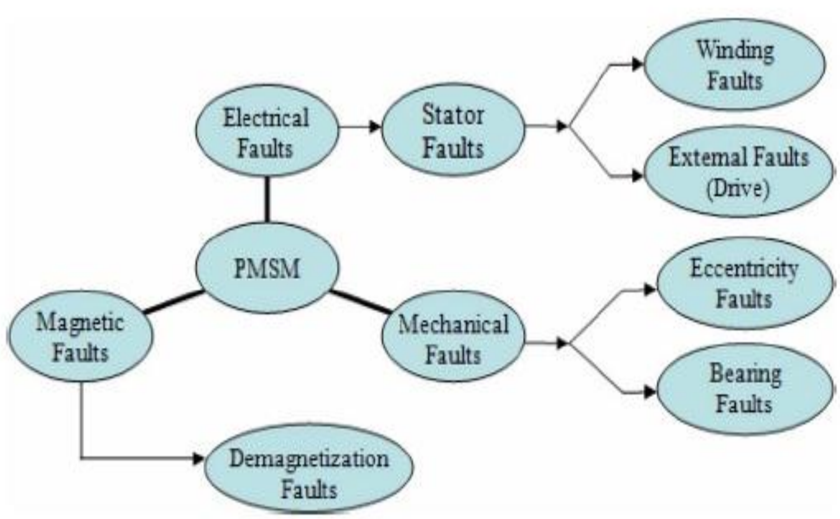

Figure 1.1 Permanent Magnet Motors fault categories [1]

Rotor faults such as cracks in the structure or magnets placed over the rotor structure, magnetic lines deviation, non-uniform flux distributions, are not easy to be detected by simply viewing the current and voltage waveform. However these faults can be detected by performing detailed analysis on current and voltage waveforms as these faults distorts the current waveforms by injecting harmonics. The effect of rotor magnetic and mechanical faults can be determined if spectrum pattern of these faults are already known and is compared with the spectrum of motor currents installed in application. Spectrum of currents and distribution of magnetic flux in three phase machines under healthy and faulty conditions can be studied by developing model of three machines in 3-D or 2-D Maxwell software. Complete model of a three phase permanent magnet synchronous motor was developed in 3-D Maxwell was developed and different faulty conditions were created. Motor currents spectrum and distribution of magnetic field lines were studied in detail. Rotor incipient faults were introduced in the model of machine and its effect on inductance or magnetic flux of the motor, which in turn affects the current waveform of PMSM, were observed.

In this work 3-D model of PMSM has been developed in Maxwell 3-D. The design involves the designing of surface mounted permanent magnet synchronous motor with double layer fractional slot concentrated winding. Maxwell model provides flexibility to study effects of different parameter variation on magnetic field distributions. This enables us to introduce cracks in the rotor magnets of motor and also widen them to check for the changes in the inductance waveform of permanent magnet synchronous motor. An analogy was developed for detection of insipient faults by studying the spectrum of currents in Maxwell. The frequency spectrum of current waveform has been studied as we widen the cracks. A comparative study of the frequency spectrum of current with magnets cracked and without cracks helps us to detect a pattern in current waveform and thus help us to detect the pattern when crack appears in the rotor.

Figure 1.2 shows the different winding structures used in three phase permanent magnet synchronous machines. Based on the configuration of how magnets are placed on the rotor of machine, permanent magnet synchronous machines are divided into two types:

1. Sinusoidal surface magnet PMSM
2. Sinusoidal interior magnet PMSM

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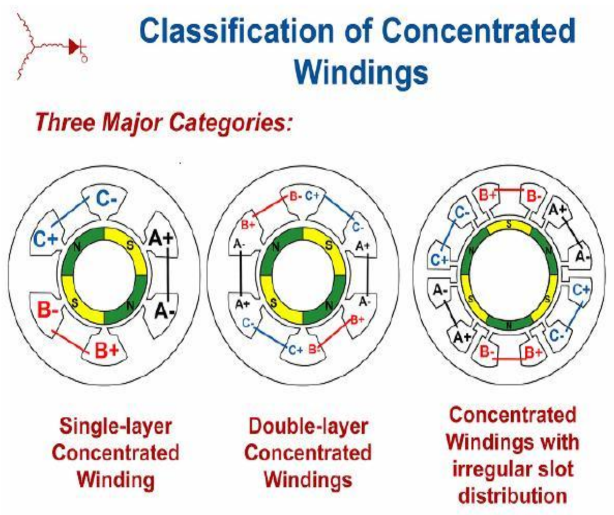

Figure 1.2 Different Configuration of Concentrated windings [2]

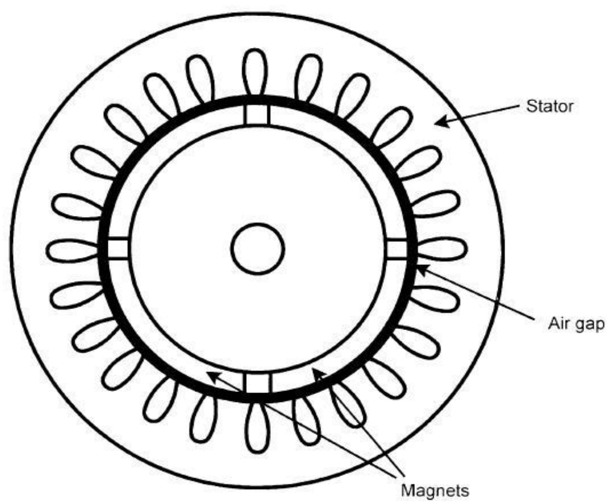

Figure 1.3 Sinusoidal surface magnets PMSM (SPMSM)[3]

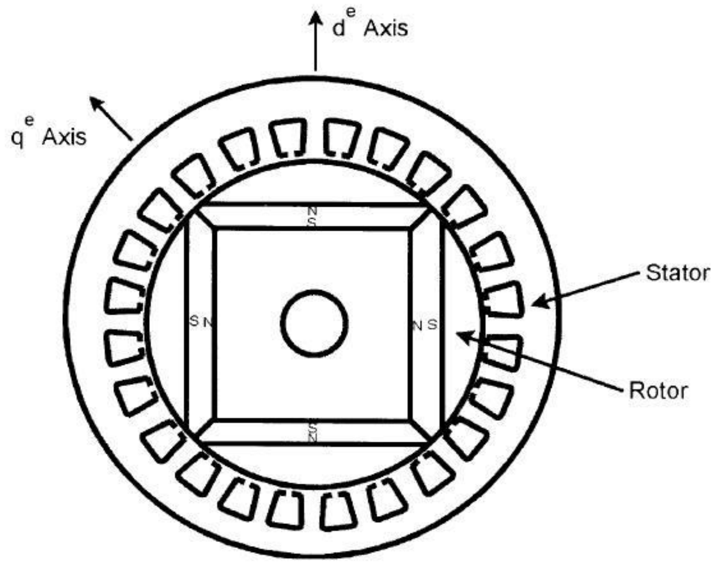

Fig 1.4 Sinusoidal interior surface magnet PMSM (IPMSM) [3]

1.2. Motivation

3-D Modeling and simulations are usually used in designing of permanent magnet machines compared to building system prototypes because of low cost. Having selected all components, the dynamic performance of PMSM has been analyzed using Maxwell model and cracks effect has been obtained like if it's done practically. This practice reduces time, cost of building prototypes and ensures that requirements are achieved.

In this ideal components have been assumed in the 3-D model of PMSM and simulations. The air gap between the rotor and the stator has been filled with air. The inductance calculations has been done by Maxwell v.11 using Finite Element Method (FEM) before and after the appearance of cracks and the tabular values obtained from Maxwell has been plotted in Matlab. Using variation in inductance values, variation in current waveforms was observed over one complete electrical cycle. After that with the help of Matlab function we plot the spectrum of current waveform in order to determine the pattern as crack appears and widens with time.

1.3. Literature Review

PM motor drives have been a topic of interest for the last twenty years. Different authors have carried out 2-D or 3-D modeling and simulation of such drives in order to solve the problem of detecting rotor faults of PMSM. Crack in rotor magnet is mechanical fault but it severely effects the distribution of magnetic fields and because of this it is sometime considered as a magnetic fault. Appearance of cracks change the distribution of magnet flux lines, some portion becomes less magnetized while the rest more magnetized. Sometimes crack creates demagnetizing effects in machine. Finite Element Method is used to study magnetic distribution behavior.

In 2008 J.A . Guemes, A.M.Iraolagoitia, M.P. Donsion, and J.I. Del Hoyo in [4] reviewed 2-D model of PMSM and analyzed the effectof cogging torque for different types of windings.

B.M. Ebrahimi, J. Faiz, and M.J.Roshtkhari in their paper [1] aimed at rotor faults i.e all eccentricity faults and designed the practical model for analysis and concluded that all eccentricity faults effects the harmonic components of line current of 3-phase PMSM and the harmonics which are effected due to eccentricity faults are given as:

$$f_{eccentricity} = \left[1 \pm \left(\frac{2k-1}{P}\right)\right] f_s \qquad \text{(With } k = 1,2,3\ldots\text{)} \qquad (1.1)$$

Thus this paper gives the pattern of frequency components which can be affected during eccentricity faults and can help us in the detection of these faults using spectrum analyzer of current waveform.

Z. Xiaochen, C. ShukangandL. Weiliin their paper [5] aimed to analyze the starting and operating performance by changing PMSM's load characteristics and used 2-D model of PMSM for finite element analysis.

Z.Xiaochen, L.Weili, C. Shukang, C. Junci, and Z.Chunboin their paper [6] aimed to analyze the heat transfer between stator and rotor and heat losses in rotor using 2-D model of PMSM using finite element analysis for starting motor at different loads. They also studied eddy losses in rotor related to thermal demagnetization of permanent magnets directly.

W. Roux, R.G. Harley, T.G. Habetler in [7] described the detection of rotor faults in PMSM. They discussed experimental methods for introducing rotor faults i.e eccentricity and broken magnets faults practically and to determine the effect of these faults on current spectrum in order to detect these faults from current and voltage waveforms.

D. Casadei, F. Filippetti, C. Rossi andA. Stefani in their paper [8] shows the characterization of rotor faults due to demagnetization of magnets by using 2-D model for finite element analysis. This paper concludes that these faults give rise to following harmonics.

$f_{dm} = \left[1 \pm \left(\frac{k}{p}\right)\right] f_s$ (With k = 1,2,3….) (1.2)

D.J.B. Smith, B.C.Mecrow, G.J. Atkinson, A.G. Jack, A. Mehna [9] in their paper observes shear stress concentration in PMSM which can lead to magnet cracking and rotor failure.

J. Wang, D.Howe, and Y.Amaran in their paper [10] describes an analytical approach to predict the armature reaction field of Permanent magnet motors along with the calculations of self and mutual inductances. It also facilitates the evaluation of any partial demagnetization.

Reference [11] develops and analyses an online methodology to detect demagnetization faults in SPMSM. The zero-sequence voltage component of the stator phase voltages has been monitored to detect demagnetization faults.

Reference [12] presents a time‑frequency method to detect and diagnose demagnetization faults in PMSMs such as cracks due to manufacturing faults using Hilbert Huang transform. The accuracy of the proposed method is proven by evaluating the experimental results of cracked PMSM in operation.

1.4. Outline of the Present Work

Sensors-less detection of cracks involves the detection of cracks without using sensors and to detect their presence just by harmonic analysis of current waveform and estimate the effects of cracks by observing the pattern of changing harmonics when the crack appears in the rotor and widens with the passage of time. The thesis work is divided in the following steps.

1. Modeling of three-phase permanent magnet synchronous motor in Maxwell is discussed in Chapter 3.
2. Detailed Survey of permanent magnet synchronous motor by using finite element

analysis method

3. Simulation of entire system using FFT analysis of current waveform when the faults occur in the rotor and its comparison with healthy system to detect the difference in the outputs of both systems.
4. Observing the pattern of change in the output of FFT analysis when cracks appear in PMSM and widens with time

Chapter 2: Effects and Detection of Magnet Cracks in PMSM

This chapter deals with the description of the effects and detection of cracks in the magnets of PMSM. A review of permanent magnet materials, inductance calculations through finite element method and analytical method for PMSM for both healthy and cracked magnets of rotor and various other techniques which helps in the detection of cracks is given in this chapter.

2.1 Permanent Magnet Synchronous Motor

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnetic coils in the rotor. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. The properties of different magnetic materials usually used over rotor of PMSM have been shown in Table 2.1

Table 2.1: Comparison of Permanent Magnet materials [12]

Material	Remanence B_r (T)	Intrinsic Coercivity jH_c(kA/m)	Curie Temp (^oC)	Temperature Coefficient Of B_r (%/^oC)	Temperature Coefficient Of jH_c(%/^oC)
AlNiCo	0.5 to1.35	40 to150	700 to 850	-0.01 to -0.02	-0.02 to -0.04
	low temp coefficient, very low intrinsic coercivity, non-linear behavior				
Hard Ferrites	0.15 to 0.43	150 to 350	450	-0.2	0.3 to 0.5
	low cost material, high electrical resistivity, linear quiet low Br				
SmCo	0.9 to 1.1	700 to 2400	500 to 850	-0.04	-0.2 to -0.3
	High magnetic properties, linear, high cost				
NdFeB	1.0 to 1.4	900 to 3200	310	-0.1	-0.4 to -0.8
	High magnetic properties, linear high temperature coefficient				
Bonded	**	**	**	**	**
	Complex shape, possible non-conductive -in many cases, non-linear				
** : Wide range based on the mixed and plastic magnetic materials					

A flux density versus magnetizing field for these magnets is illustrated in Figure 2.1

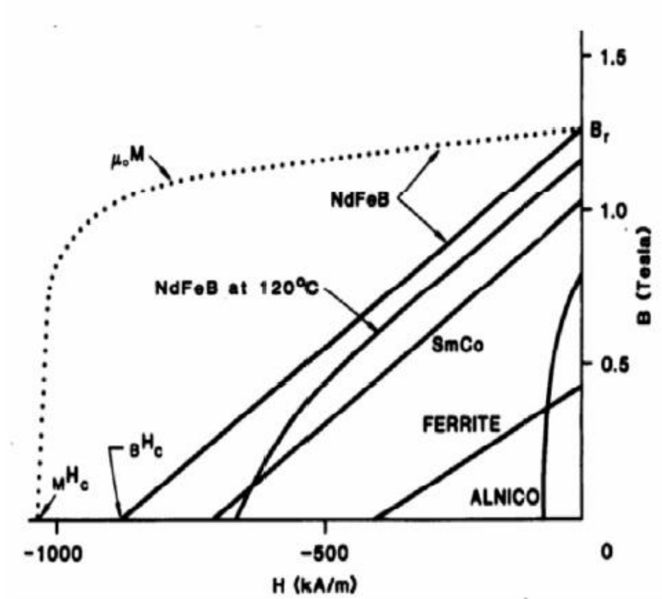

Figure 2.1 Flux density versus magnetizing field of permanent magnetic materials [13], [14]

2.2 Cracks in Permanent Magnet

Cracks in the permanent magnet have the common occurrence. These cracks arise in the rotor due to stresses, mishandling during manufacturing, corrosion of magnets [9].

Crack detection in the rotor using sensor-less technique is difficult. However there are methods such as inductance calculations through finite element method or by using zero sequence voltage component of the stator by considering the cracked magnet. Appearance of crack partially demagnetizes the magnet and changes the distribution of magnetic field. A cracked rotor has been shown in Figure 2.2. Both of above mentioned techniques use complex equations which are based on equations given by analytical techniques then by using finite element method we can solve these analytical equation for performing complex analysis on PMSM. Some practical model techniques are also discussed further in order to observe the pattern of disturbance in current and voltage spectrum by putting a crack in the rotor deliberately or by choosing an already cracked rotor motor.

Figure 2.2 Cracked rotor of PMSM. [11]

2.2.1 Inductance calculations through analytical techniques for healthy and partially demagnetized magnets [10]

A. Healthy Case

For the prediction of self and mutual inductances in closed forms the analytical technique has been used to facilitate the dynamic modeling used in FEM(Finite Element Method), this technique is also helpful for the evaluation of any irreversible demagnetization of magnets. The total self- and mutual inductances between phases i and j (where i and j are different phases) are given by

$L_{ps} = L_{as} + \ L_{sk}\ ,\ M_{ij} = M_{aij} + \ M_{sk}$

Where L_{as} is the air gap self inductance which is given as :

$$\mathrm{L_{as}} \ = \ \frac{8p\pi N_c^2 R_{se}}{\tau_p} \sum_{n=1,2\ldots}^{\infty} \frac{\left(K_{dmn}K_{pmn}\right)^2}{m_n \Delta_n} [c_{2n} B I_1(m_n R_{se}) + \ c_{1n} B K_1(m_n R_{se})]$$

And L_{sk} and M_{sk} is total slot self and mutual inductance, L_{sk} is given as:

$$L_{sk} = \ 4\pi p \mu_o N_{sp} N_c^2 \left[\frac{h}{S_w}\left(\frac{R_h}{3} - \frac{h}{4}\right) + \ (R_{se} + \ h_t)\left(\frac{h_t}{b_o} + \frac{S_w - b_o}{S_w + b_o}\ tan\alpha\right)\right]$$

M_{sk} can easily be determined from the same formula as for L_{sk}

The air-gap mutual inductance is given as:

$$M_{aij} = \frac{8p\pi N_c^2 R_{se}}{\tau_p} \sum_{n=1,2\ldots}^{\infty} \frac{\left(K_{dmn}K_{pmn}\right)^2}{m_n \Delta_n} [c_{2n} BI_1(m_n R_{se}) + c_{1n} BK_1(m_n R_{se})] \cos m_n \tau_{ij}$$

Where

$$K_{dmn} = \frac{sin\left(\frac{m_n b_o}{2}\right)}{\left(\frac{m_n}{\frac{b_o}{2}}\right)}$$

$$K_{pmn} = \frac{2\tau_p}{N_s \tau_s}\left[2sin\left(\frac{n\pi}{N_s}\right) - sin\left(\frac{3n\pi}{N_s}\right)\right]$$

$$m_n = \frac{2\pi n}{\tau_{mp}}$$

$$c_{1n} = BI_0(m_n R_0), c_{1n} = BK_0(m_n R_0)$$

BI_0 ( ) with order zero and BI_1( ) with order one are Bessel functions (modified) of 1st kind while BK_0( ) with order zero and BK_1( ) with order one are Bessel functions of 2nd kind. τ_p is the pole pitch, N_c is the number of coils, N_s is the number of slots over the modular pitch, R_{se} is the stator bore radius, S_w is slot width, the tooth tip height is denoted by h_t the angle at slot opening is denoted by α .Where N_{sp} is the number of slots per pole per phase. τ_{ij} is an axial displacement between two phases i and j.

B. Calculations for Partially demagnetized

The flux density component in the moving reference transformed by $z=z_r+vt$, where z is axial position with the reference of stationary position and I_m is the peak phase current is given as:

$$B_z(r, z_r, t) = \frac{3I_m}{2}\Big\{\sum_{n=3k+1}^{\infty}[a_n BI_o(m_n r) - b_n BK_o(m_n r)]\cos\left[m_n z_r + \frac{\pi(n-1)}{\tau_p}vt\right] - \sum_{n=3k+1}^{\infty}[a_n BI_o(m_n r) - b_n BK_o(m_n r)]\cos\left[m_n z_r + \frac{\pi(n+1)}{\tau_p}vt\right]\Big\} \quad , k = 0,1,2 \ldots \quad (2.1)$$

This equation (2.1) can be easily used to determine the extent of partial demagnetization (irreversible) of the magnets under consideration and help us to determine the inductance for cracked magnets using finite element analysis.

2.2.2 Experimental Demonstration of cracks

The experimental arrangement for cracked rotor of PMSM has been carried out in reference [12]. FFT stator current spectrum for a constant speed is shown in fig 2.3, this spectrum is compared with healthy system**.** The main faulty harmonics arise agrees with the equation 1.2. Demagnetization of the rotor magnets of PMSM was carried out during manufacture in this setup.

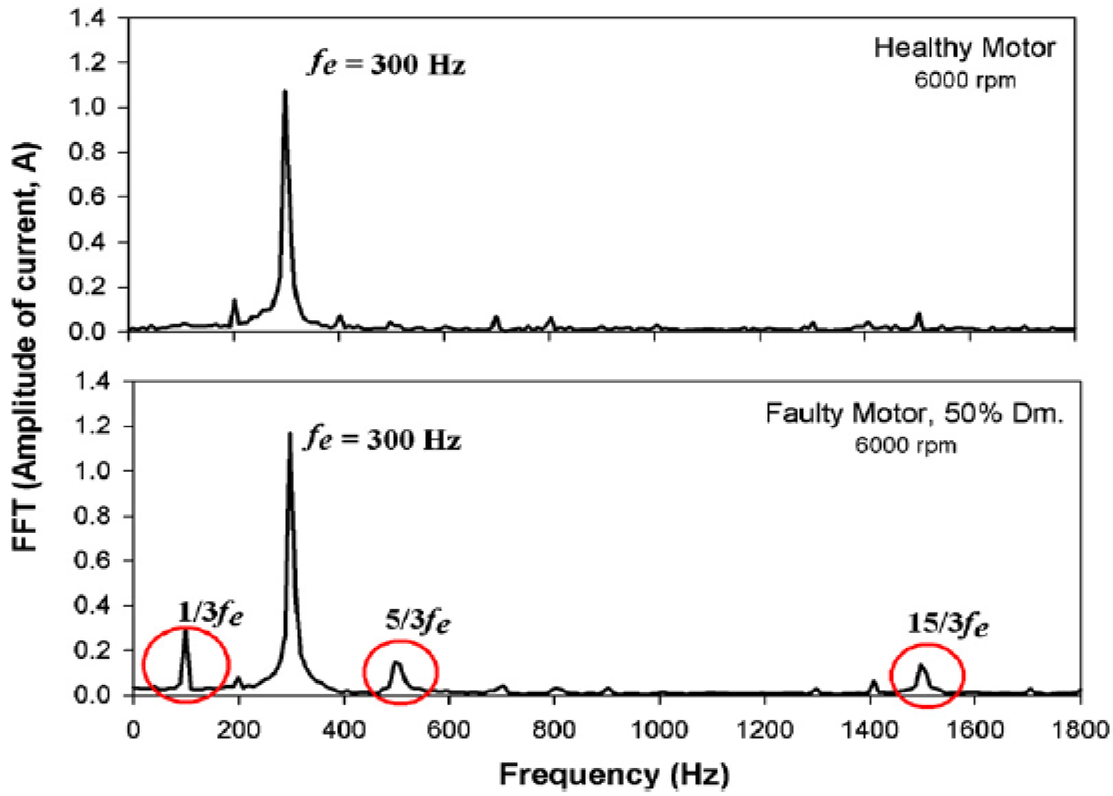

Figure 2.3 FFT stator current spectrum for a constant speed operating at rated load.[12]

2.2.3 Magnetic Flux Estimation [7]

In section 2.2.1 we have discussed the inductance calculation through analytical equations. Usually magnets with cracks are considered to be partially demagnetized magnets. These partially demagnetized magnets affect the flux linkages between rotor and stator. As in PMSM the rotor is excited because of its permanent magnets, in normal the case the flux linkages caused by rotor produces back emf in stator windings and by estimating the instantaneous value of this emf can help us to estimate the magnetic flux.

In order to estimate the magnetic flux new technique has been used in reference [7]. The d-axis stator winding flux is first estimated with the help of flux linking the stator winding in rotor reference frame which is denoted by $\lambda^{r}_{d(M)}$, subscript d and stands for d-axis and q-axis respectively, where as M stands for magnets where as superscript r stands for rotor frame, so $\lambda^{r}_{d(M)}$ is given as:

Where all values in the equation (2.2) are instantaneous. L, i , λ , ω, v, r and p stands for inductance, current, flux, rotational speed, voltage, resistance and differentiator operator respectively.

$$\lambda^{r}_{d(M)} = \lambda^{r}_{ds} - L^{r}_{ds} i^{r}_{ds}$$

$$\lambda^{r}_{d(M)} = \frac{v^{r}_{qs} - r_s i^{r}_{qs} - L^{r}_{ds} p i^{r}_{qs} - p\lambda^{r}_{q(M)}}{\omega_r} - L^{r}_{ds} i^{r}_{ds} \quad (2.2)$$

Usually in ideal case $\lambda^{r}_{q(M)}$ is zero and i^{r}_{qs} is constant so pi^{r}_{qs} term can be ignored. However in rotor faults and in non-ideal case $\lambda^{r}_{q(M)}$ is not zero and i^{r}_{qs} is not constant, but for the sake of simplicity we can average the right hand side over integral number periods of the frequency under discussion then the $\lambda^{r}_{q(M)}$ and i^{r}_{qs} can cancel each other and we get the average value of magnetic flux denoted by $\lambda^{r'}_{d(M)}$ is given in equation (2.3) .

$$\lambda^{r\prime}_{d(M)} = \frac{v^{r}_{qs} - r_s i^{r}_{qs}}{\omega_r} - L^{r}_{ds} i^{r}_{ds} \quad (2.3)$$

After averaging we can also take the constant value of inductance L^{r}_{ds}.

Because of rotor speed in equation (2.2) and (2.3), the variation in rotor speeds can be hard to tackle for estimating the flux also the rotor angle cannot be guessed at the time of calculating voltages and currents in rotor reference frame during rotation. That is why we use the synchronous reference frame for estimation. The average flux in synchronous reference frame $\lambda^{e'}_{d(M)}$ is given as :

$$\lambda^{e\prime}_{d(M)} = \frac{v^{e}_{qs} - r_s i^{e}_{qs}}{\omega_e} - L^{e}_{ds} i^{e}_{ds} \quad (2.4)$$

The flux weakening operation is given by the term $L^{e}_{ds} i^{e}_{ds}$. The value of L^{e}_{ds} is same as that of L^{r}_{ds}. The speed ω_e is same as that of reference speed under normal operating condition i.e. steady state condition.

The transformation matrix which transformed voltage and currents from abc-stationery reference to synchronous rotating reference is given in equation (2.5).

$$T_e = T(\theta_e)$$

$$T_e = \frac{2}{3}\begin{bmatrix} cos(\theta_e) & cos\left(\theta_e - \frac{2\pi}{3}\right) & cos\left(\theta_e + \frac{2\pi}{3}\right) \\ sin(\theta_e) & sin\left(\theta_e - \frac{2\pi}{3}\right) & cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} (2.5)$$

Where θ_e is the rotor angle and is given by:

$$\theta_e = \theta_{e0} + \omega_e t$$

The angle at t=0 is θe_0 i.e. when the magnetic flux aligns with d-axis. When the current and voltage of stator is measured we cannot guess the starting angle of the rotor.

We integrate the flux $\lambda^{e'}{}_{d(M)}$ over different periods at different starting angles θe_0 in order to transform quantities from stationary reference to synchronous reference and then get the maximum value of $\lambda^{e'}{}_{d(M)}$ that is aligned with d-axis of the rotor. This is usually done by trial and error method or by using brute force techniques in Finite Element Analysis. However if θe_0 is known we can easily estimate the value of flux $\lambda^{e'}{}_{d(M)}$ without any trouble, as flux $\lambda^{e'}{}_{d(M)}$ is proportional to θe_0, but this method is usually not feasible as the flux $\lambda^{e'}{}_{d(M)}$ is sinusoidal and inductance variations with respect to rotor position will affect the estimation by great deal.

The above method of estimating the magnetic flux can be implemented in Finite element method (FEM) to estimate flux for normal case when there is no crack in the rotor and also in faulty case when magnets bear cracks. Figure 2.4 shows that the magnetic flux values are different for cracked magnets from the values of flux in other rotor faults as compared to normal operating conditions, so from this method magnetic flux for cracked magnets can easily be detected with good precision as compared to other rotor faults.

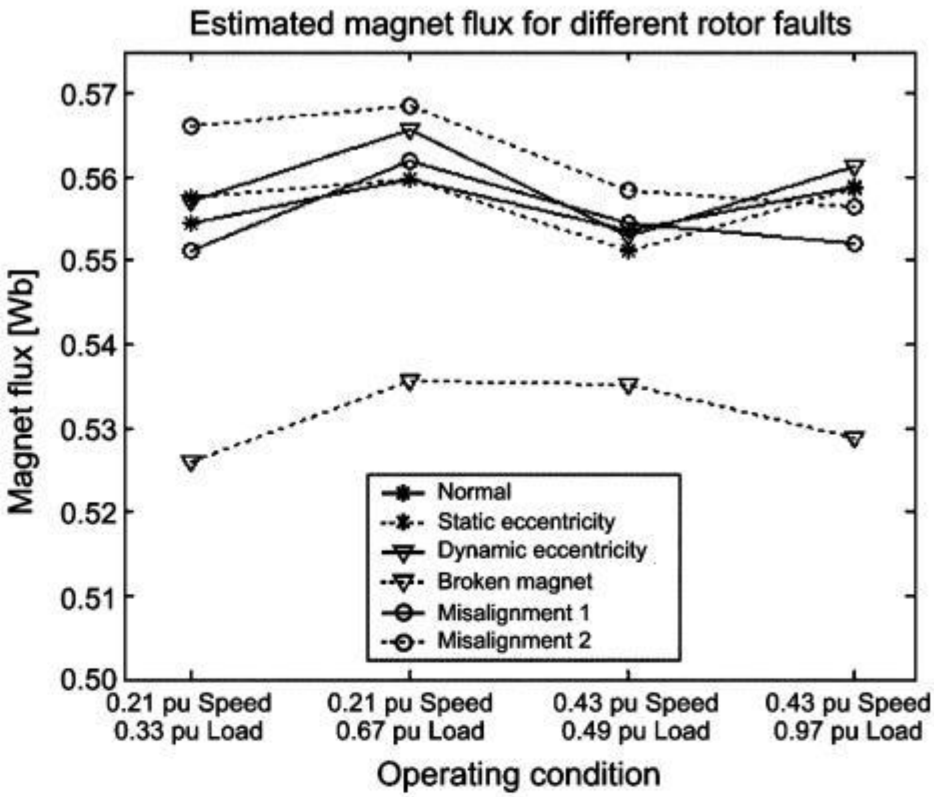

Figure 2.4 Magnetic flux at different operating conditions for various rotor faults [7]

Chapter 3

MODELING OF PMSM

3.1 Maxwell v11 Program

Maxwell is a computer operated interactive software that uses finite element analysis to solve 3D (3-dimensional) magneto static problem. For the purpose of designing and analyzing of electric machines model, Rotational Machine Expert (RMxprt) software is used [16].

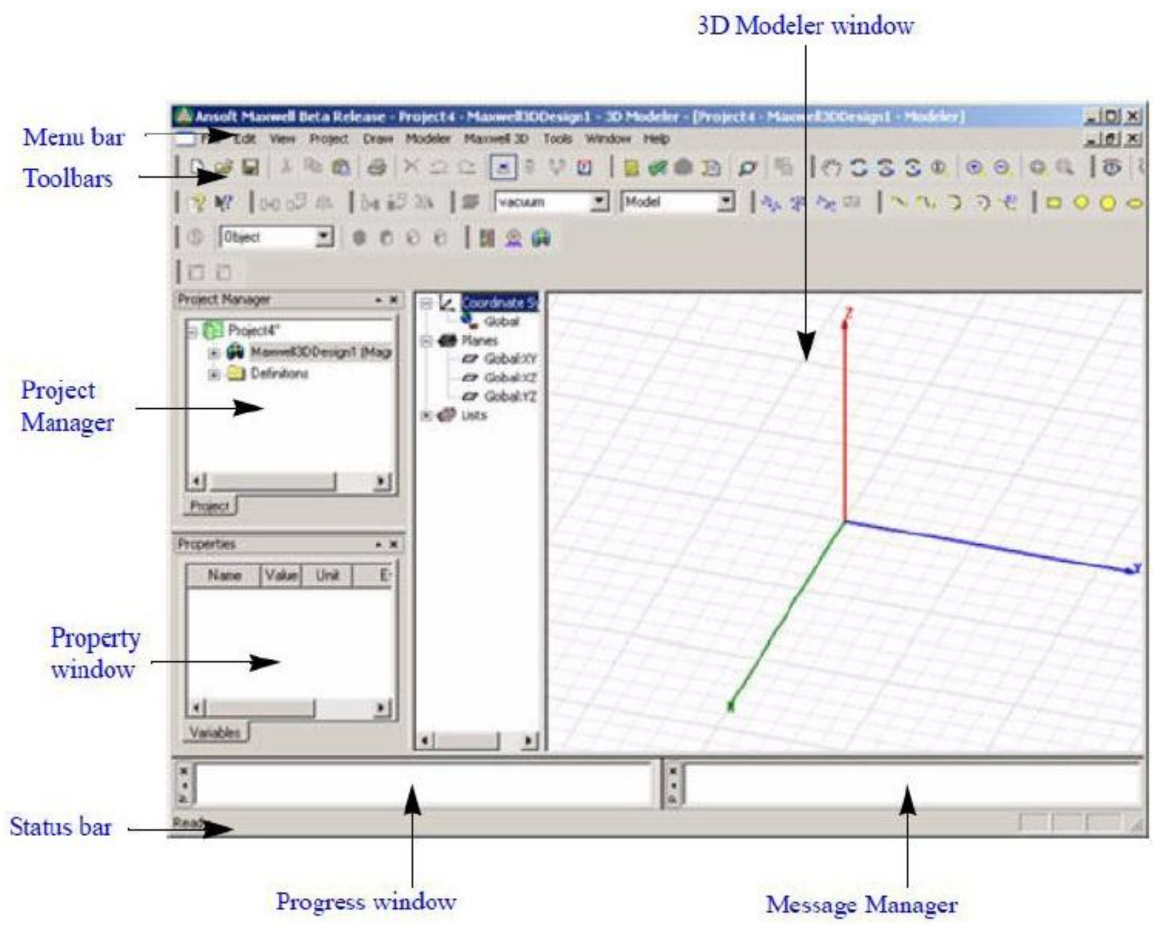

Figure 3.1 Maxwell Desktop Window [16]

It provides a very simple mean to solve complex equations involving systems under electromagnetic field lines.

Maxwell 3D offers four type of solutions:

1- Electric 3D fields which is further categorized into two types
   - Electrostatic 3D fields of voltages and charges given by the user’s distribution and other quantities that can be calculated are torque, force and capacitance.
   - Electric 3D fields in conductors given by spatial distribution of current density, electric field, voltage and power loss.
2- Magnetostatic 3D fields both linear and non-linear given by user’s distribution of DC current density and externally applied magnetic field. Additional quantities that can be manipulated are force, torque and self and mutual inductances.
3- Eddy current steady state magnetic fields with pulsation-induced eddy currents in solid conductors either caused by:
   - A user’s distribution of AC currents (with one single frequency but with different phases)
   - Application of externally applied magnetic fields
4- Transient magnetic fields caused by windings, conductors and magnets supplied by current or voltages over time. Motion effects are also included in simulations.

Steps to perform the analysis in Maxwell are:

- Making geometrical model
- Modification of design parameters
- Assign variables to the above parameters
- Assigning solution type
- Validate the design
- Simulating the design
- Plotting of field lines
- Parametric analysis

- Creation of animation of field lines [16]

3.2 PMSM Design

The design of PMSM in Maxwell v. 11 involves the following steps:

1- Set the solution type to eddy current as our concerned study is 3-phase AC current using double layer fractional concentrated winding.

2- First step is to create the geometry of stator by drawing two cylinders with outer cylinder diameter is 120 mm and inner cylinder diameter is 75 mm with height equal to 65 mm and subtract the inner cylinder from outer cylinder.

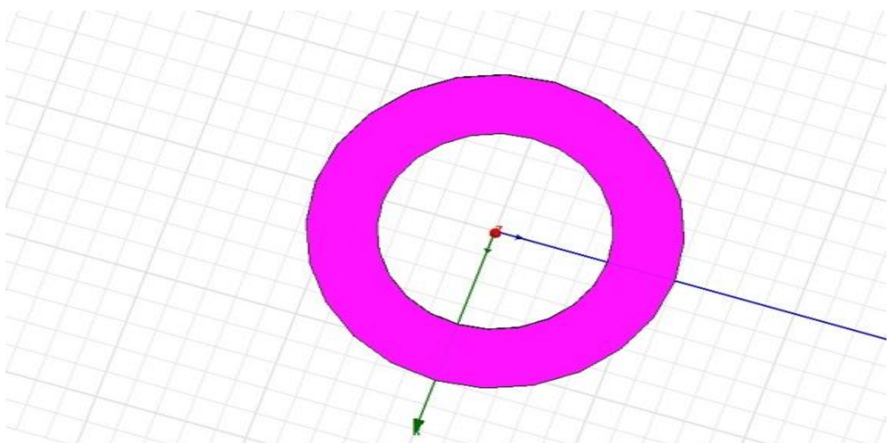

Fig 3.2 Stator Design

3- 2nd step is to put slot in the stator by inserting slot shaped body by keeping slot nozzle i.e Hs0 = 0.5mm and slot opening i.e Bs0= 2.5 mm in the stator and duplicate it to get 24 slots by and subtract them from stator body.

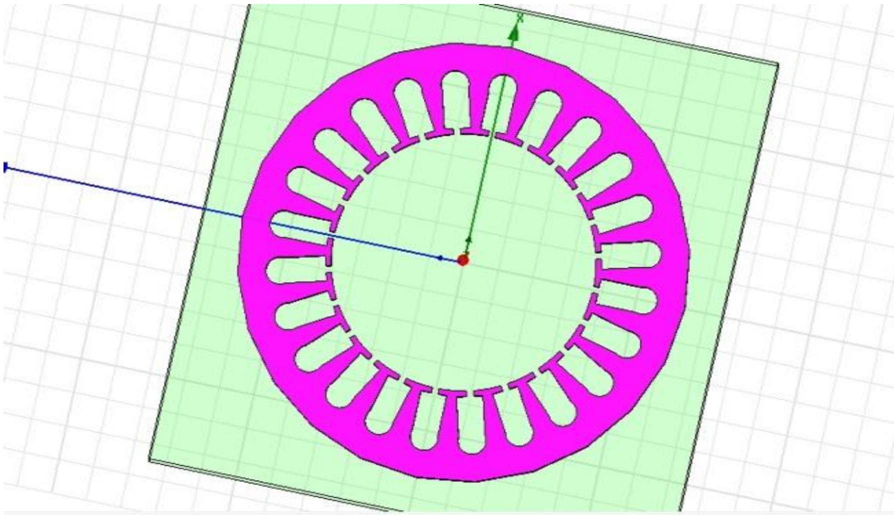

Fig 3.3 Slot Design

4- Now develop the rotor by inserting two cylinders one with outer one of 70.5mm diameter and inner one with 26 mm diameter with 65 mm height after that we subtract the inner cylinder from outer one.

5- Develop the shaft of 26 mm diameter with 65 mm height in the middle of the rotor.

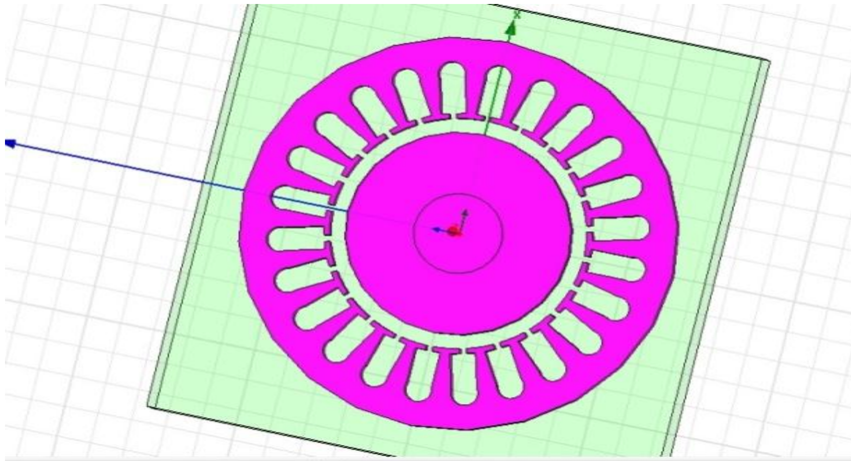

Fig 3.4 Rotor Design

6- Change the material type to NdFeB (only option available in eddy current solution type) and insert four magnets of 3.5 mm thickness stuck to rotor surface with 65 mm height.

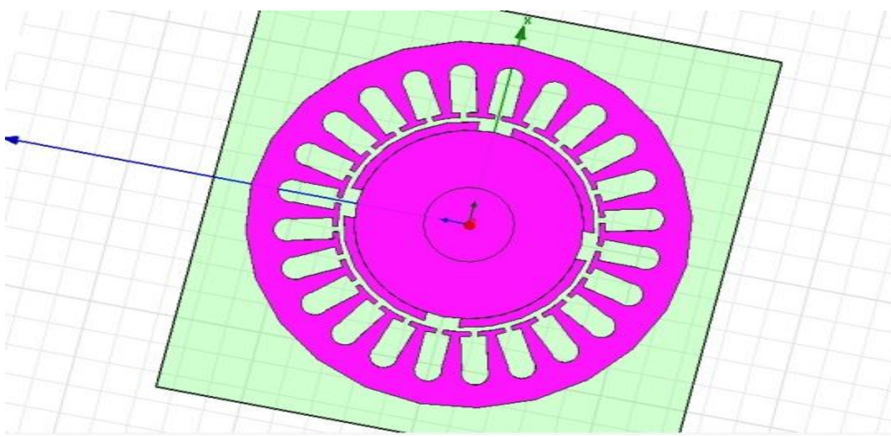

Fig 3.5 Magnets Design

7- After that insert the copper material windings in order to give FSCW(fractional slot concentrated winding) in the slots and give them the excitation values in ampere turns of 630 AT(calculated for cross-sectional area 24mm x 6mm = 144 mm^2 for 20 AWG) in 3-phase sinusoidal current excitation as given in fig 3.6.

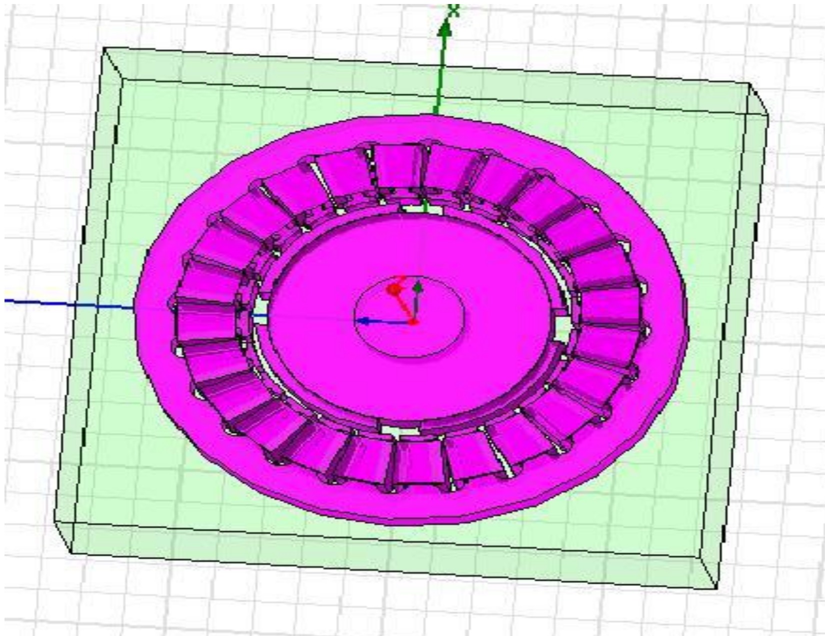

Fig 3.6 Windings Design

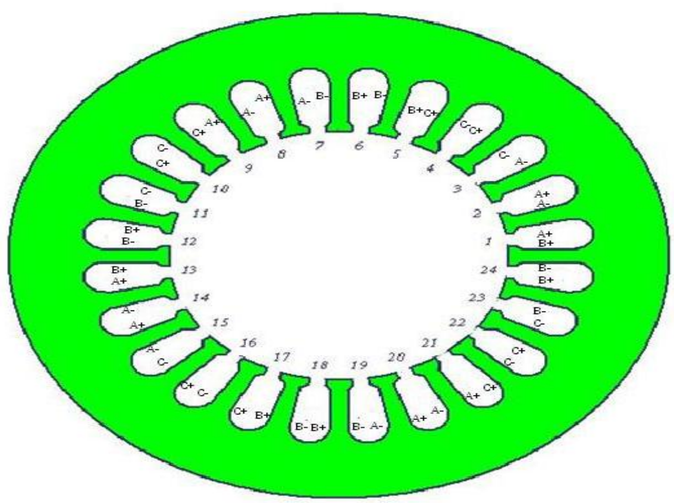

Fig 3.7 Double layer FSCW 4-pole for PMSM

8- The complete 3-D model of PMSM on Maxwell v.11 is shown in fig 3.8:

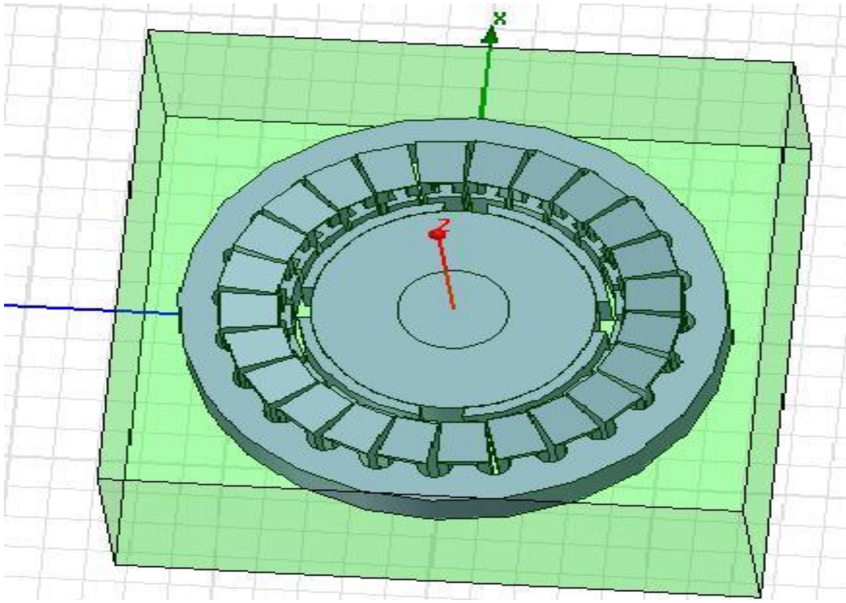

Fig 3.8 Complete 3-D PMSM Design

Chapter 4

RESULTS AND CONCLUSIONS

4.1 Parametric Analysis of Maxwell

After designing PMSM on Maxwell v.11 we perform the parametric analysis by changing the variable 'angle' i.e the angle of the rotor from 0 to 180 degree which is one complete electrical cycle as given by:

$$\theta_m = \frac{p}{2}\theta_p$$

θ_e = electrical angle

θ_p = mechanical angle

P= number of poles = 4

Then we get the value of inductance of all phase-A for one complete cycle in the form of graphical and tabular form.

Finite Element Analysis has been used for the computation of 3-phase uniform air gap PMSM inductance waveform over one complete electrical cycle. A non linear field analysis has been carried out for calculating the inductance of one of the three phases. The 3-D model of PMSM has been established.

Table 4.1

PMSM design specifications	
Power	550 W
Poles	4
Stator Outer Diameter	120mm
Stator Inner Diameter	75mm
Rotor Outer Diameter	64 mm
Rotor Inner Diameter	26 mm
Frequency	50 Hz
Magnetic Thickness	3 mm
Stack Length	35 mm
Winding type	Double Layer Fractional Slot Concentrated Winding

4.2 Results and Discussions

First of all inductance waveform taken after finite element analysis for one complete electrical cycle for phase-A without any crack then current waveform has been taken from this inductance waveform by applying the given formula:

$$i(t) = \frac{\phi(t)}{I(t)} \quad (4.1)$$

where i(t) = current over time, Φ(t) = flux over time, l(t) = inductance over time

After that fast fourier transform(FFT) has been performed on the current waveform in order to determine its frequency spectrum. After that we insert cracks of specific dimension and perform the same procedure discussed above, in order to review the clear effects of cracks on current spectrum we will widen the same cracks and again perform the above procedure to get the vivid pattern. In all previous research works discussed in chapter 1, analysis has been done with the help of 2-D model or with practical application of crack it was revealed that the frequency components revealed when rotor faults i.e magnetic or mechanical faults occur are given by the formula in equation 1.2.

we will see later what will be the effects of the two symmetrical cracks of specified dimension and how they will increase if these cracks widens with time.

4.2.2 Healthy Case

Simple Analysis involves the inductance calculations without any crack in the rotor. This analysis reveals that the inductance variation over one complete cycle is very minute which does not affect the current waveform and its frequency spectrum yields the high percentage of fundamental frequency component. Graphs revealing the above mentioned results are given below:

:

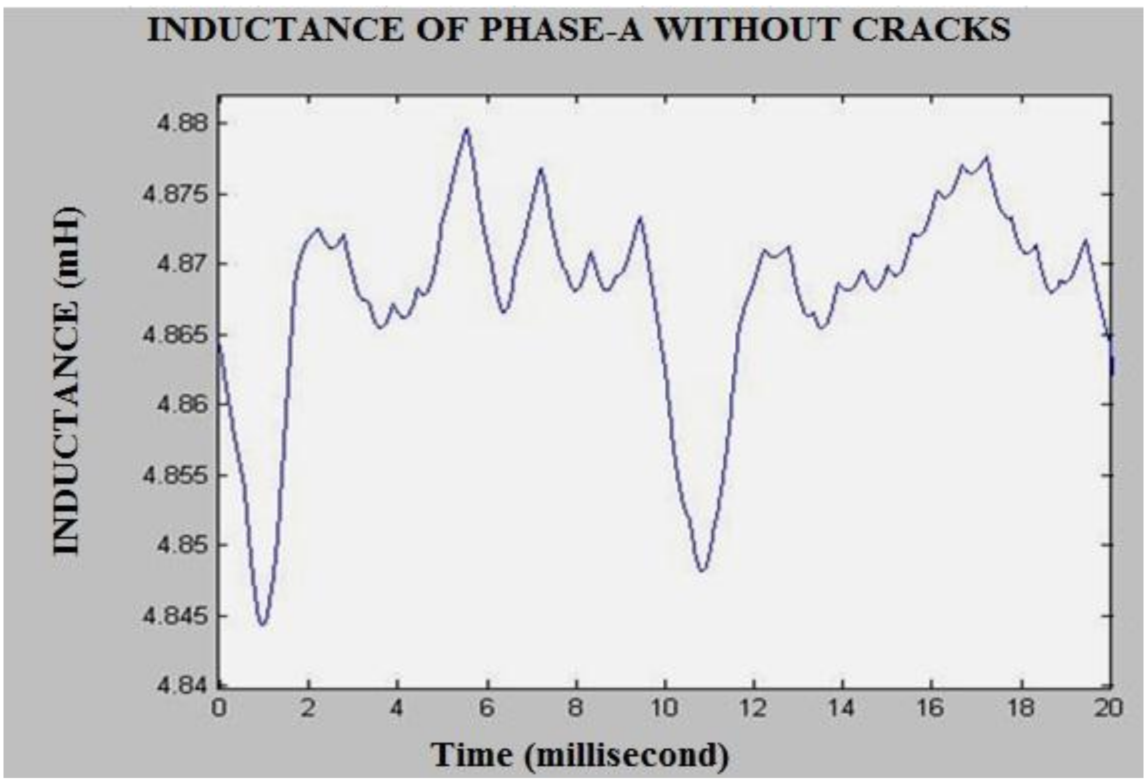

Fig 4.1 Inductance of phase-A without any crack

Here it is obvious that the inductance variation is very small i.e from 4.88 mH to 4.845 mH which does not affect the current waveform significantly as shown in figure below.

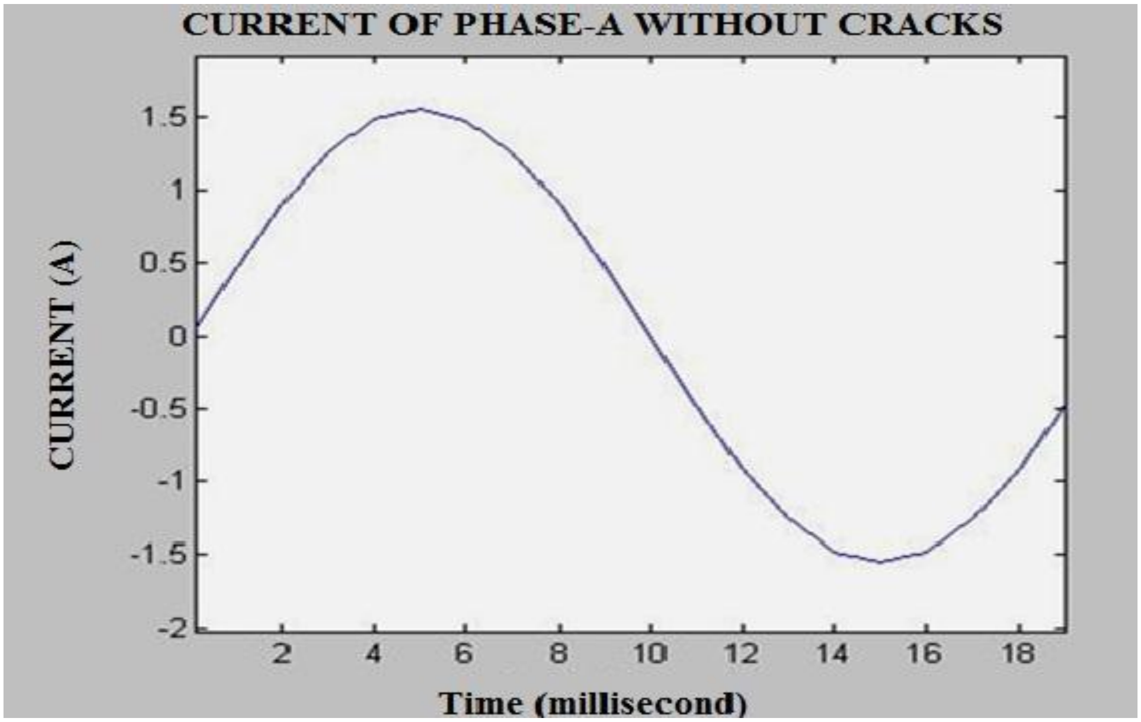

Fig 4.2 Current waveform of phase-A without any crack

As the current waveform has not been affected significantly so the current spectrum does not show any signs of harmonics as shown in figure below:

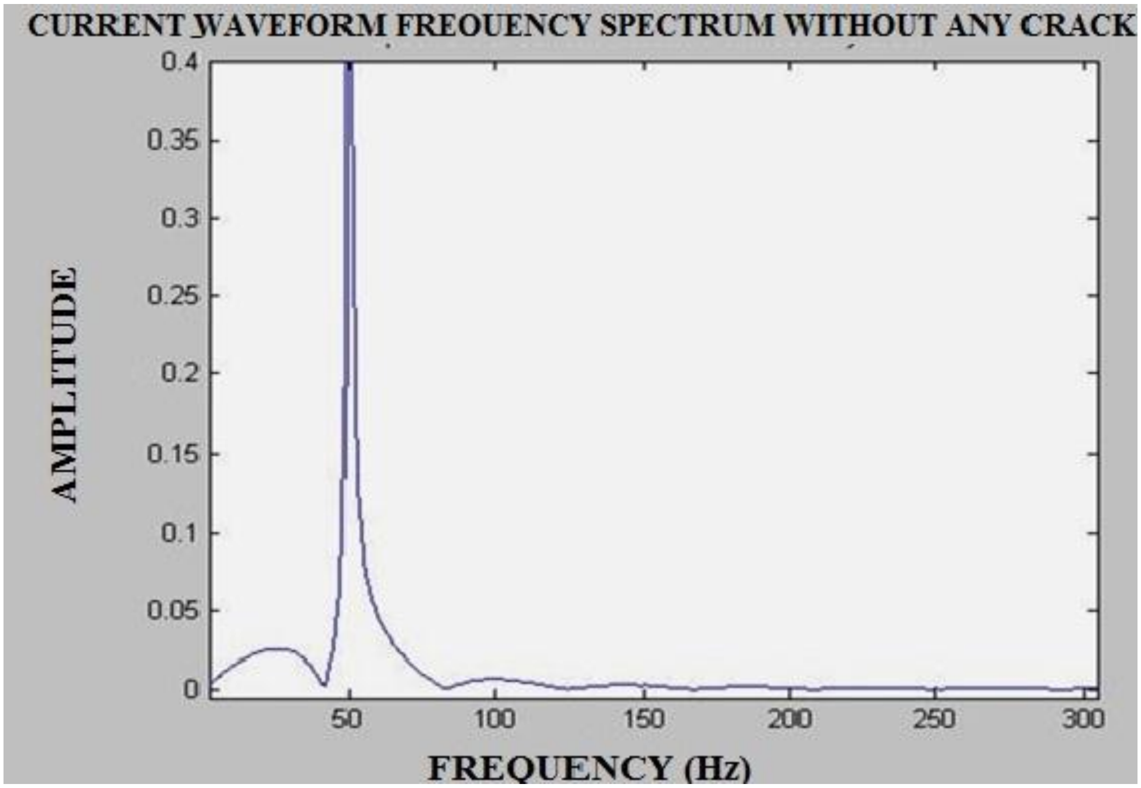

Fig 4.3 Frequency Spectrum of current waveform of phase-A without any crack

4.2.3 Faulty Case (with cracks)

The 2nd step involves the analysis of PMSM inductance and current waveform with the insertion of two cracks in the rotor magnets 180 degree apart so that symmetry of rotor remains the same. The dimensions of these crack inserted are dx = 14.5 mm ,dy= 3.5mm, dz = 28 mm approximately 5% of the rotor magnets. The cracks in the rotor are shown in fig 4.4 also the graphical representation of variation of inductance and current over one complete cycle alongwith the frequency spectrum of current waveform are given in figure:

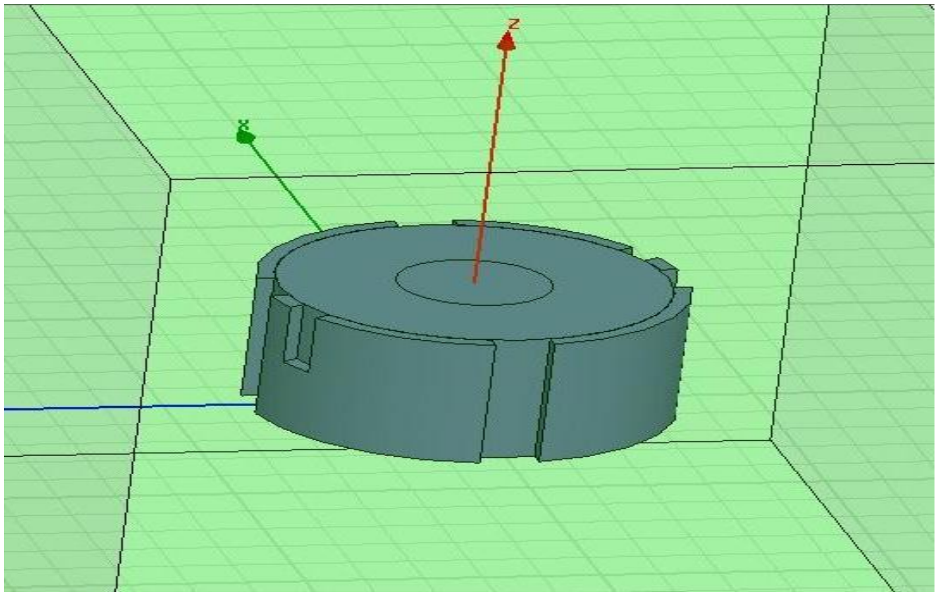

Fig 4.4 3-D model of PMSM rotor with approx 5% cracks in Magnets

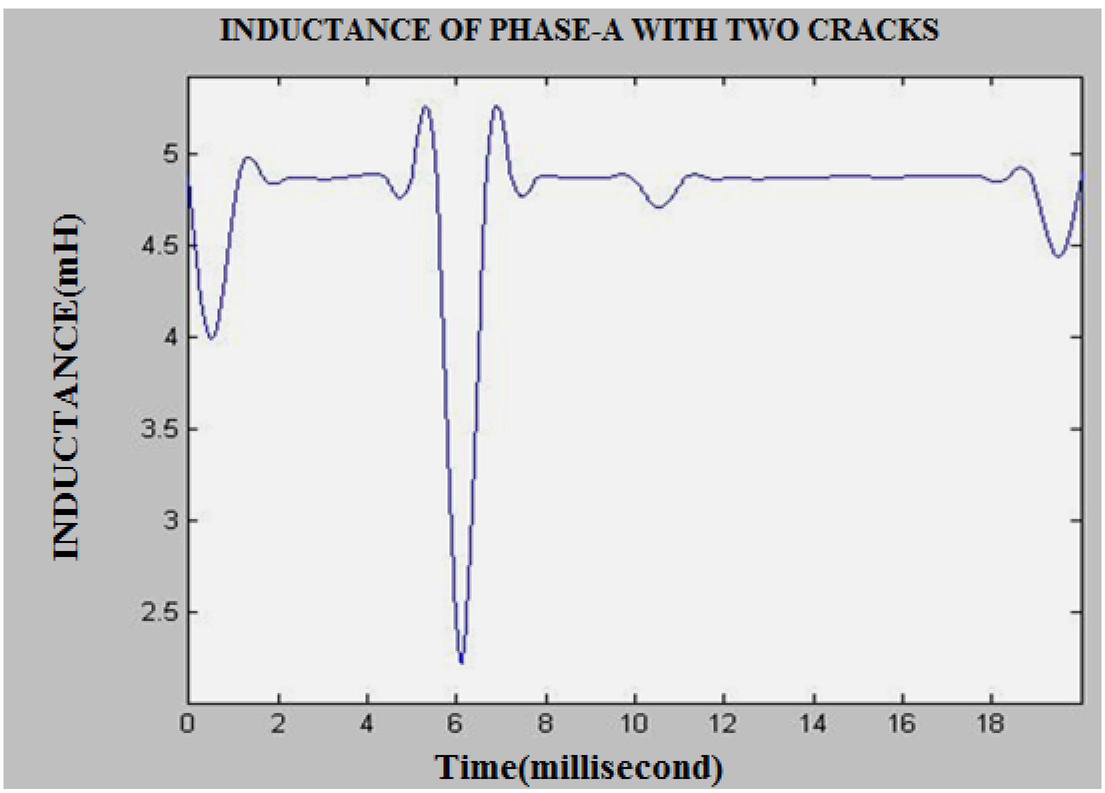

Fig 4.5 Inductance of phase-A with two approx 5% cracks in Magnets

Here it is obvious that the inductance variation has become significant i.e from 5.5 mH to 2 mH which affect the current waveform significantly as shown in figure below.

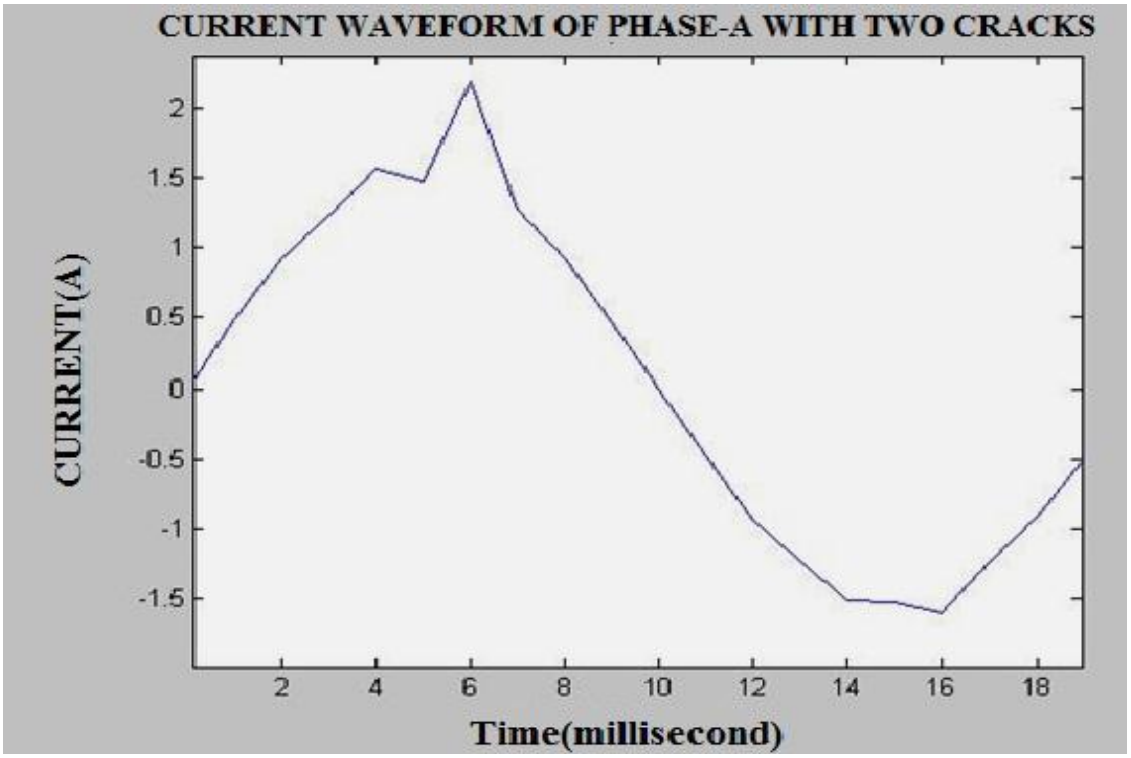

Fig 4.6 Current waveform of phase-A with two approx 5% cracks in Magnets

As the current waveform has been affected significantly so the current spectrum shows the signs of harmonics as shown in figure below:

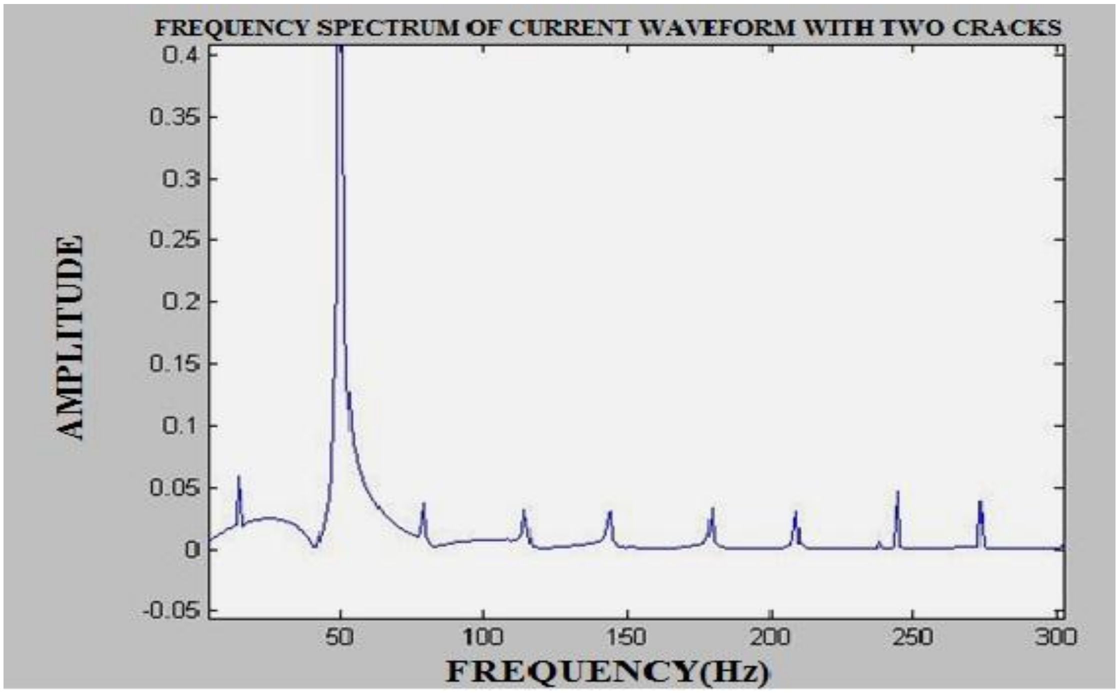

Fig 4.7 Frequency Spectrum of current waveform of phase-A with two approx 5% cracks in Magnets

Next step involves the widening of cracks and the new dimensions are dx = 15 mm ,dy= 3.5mm, dz = 30 mm approximately 10% of the rotor magnets, the graphical representation of inductance waveform and the current waveform alongwith its FFT analysis also with the representation of wider cracks are given below:

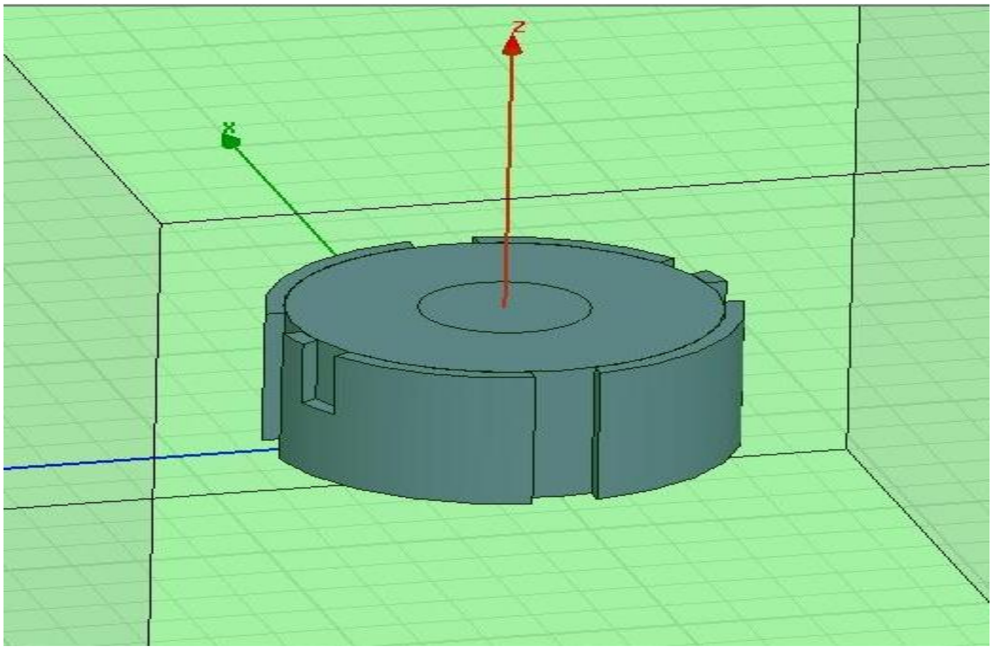

Fig 4.8 3-D model of PMSM rotor with approx 10% cracks in Magnets

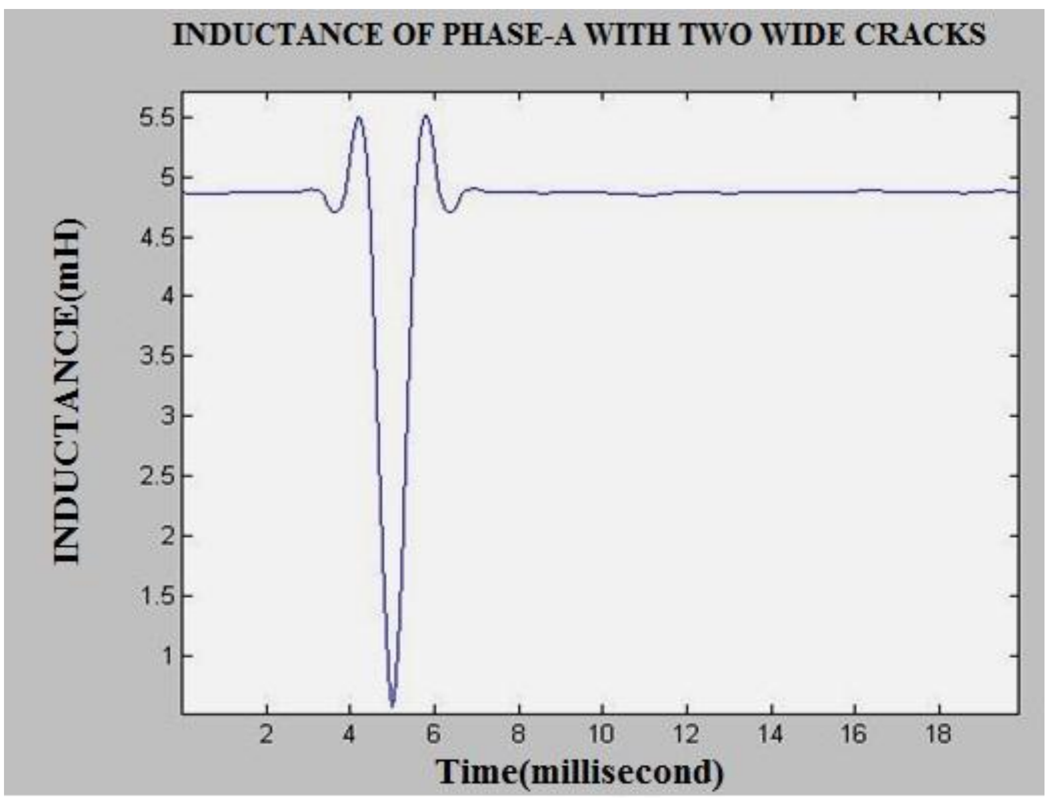

Fig 4.9 Inductance of phase-A with two approx 10% cracks in Magnets

Here it is obvious that the inductance variation has become more significant i.e from 5.5 mH to 0.5 mH which affect the current waveform even more significantly as shown in figure below.

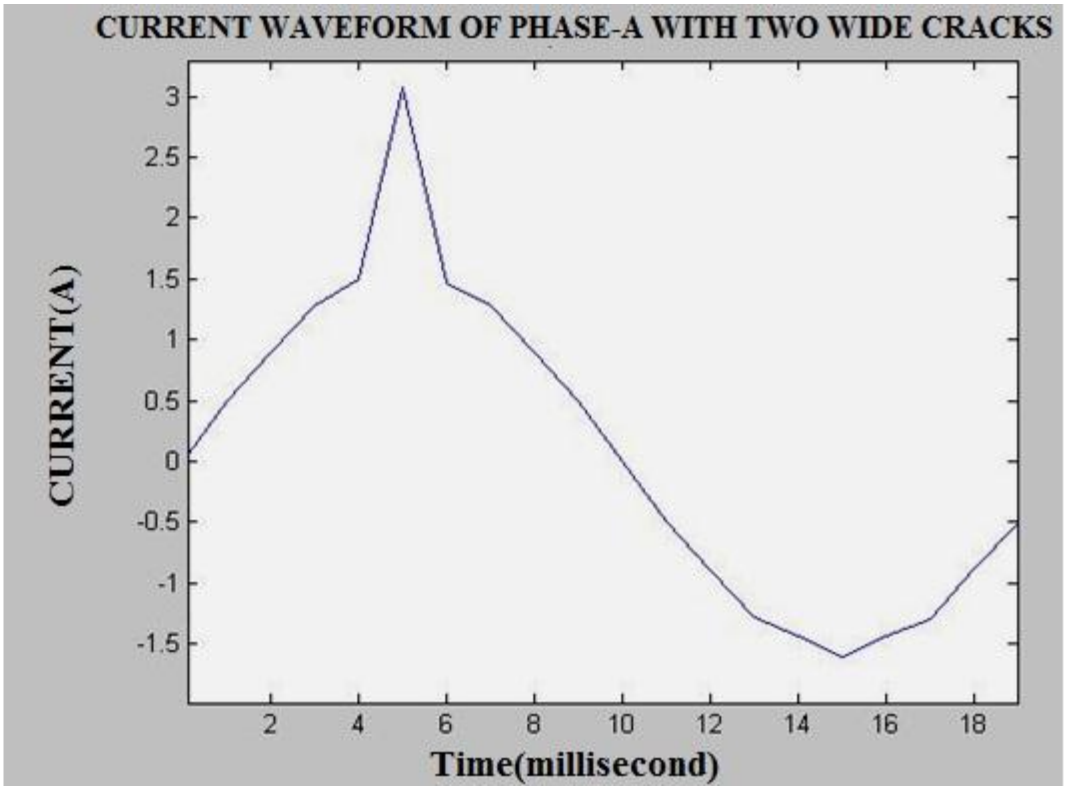

Fig 4.10 Current waveform of phase-A with two approx 10% cracks in Magnets

As the current waveform has been affected more significantly and the spics in current waveform has become more obvious so the current spectrum shows more signs of harmonics with greater amplitude as compared to 5% crack approx as shown in figure below.

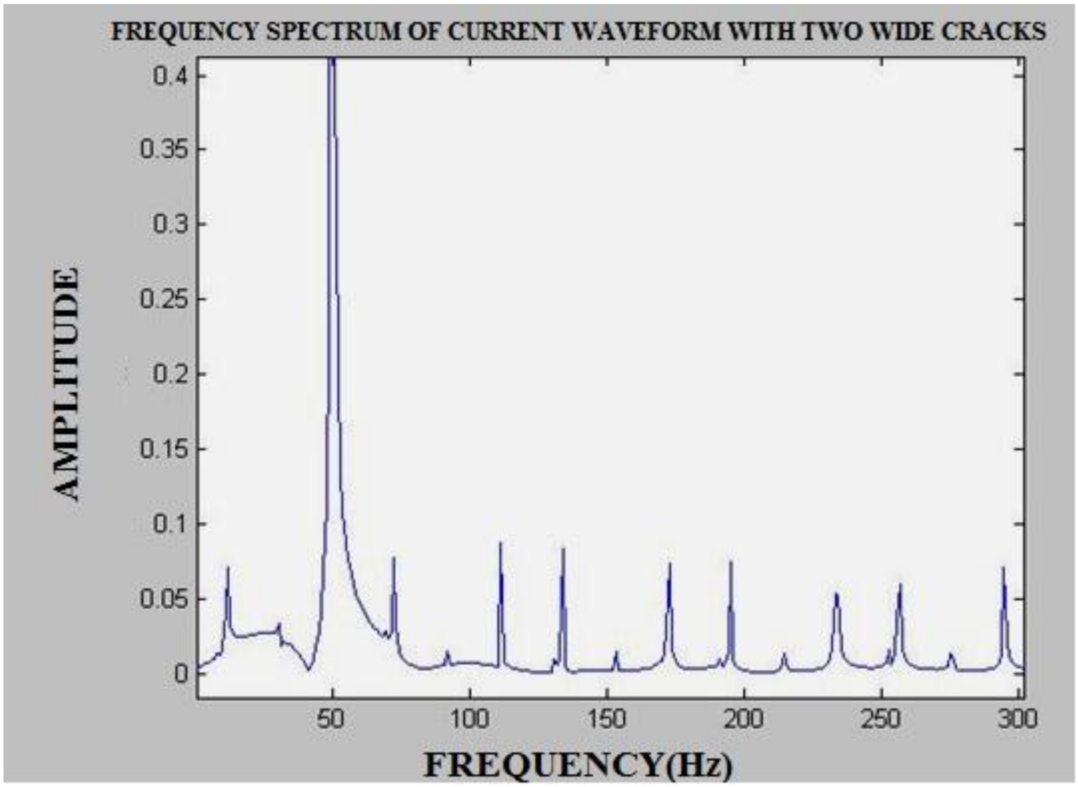

Fig 4.11 Current Spectrum of phase-A with two approx 10% cracks in Magnets

4.3 Conclusion

All the previous waveforms reveal that the sideband frequency components given in equation (1.2) for the value of k=1, 2, 3, 4… are observed in the current spectrum when cracks appear in the motor. Thus equation (1.2) gives the pattern and these frequency components can be utilized as a proper index for rotor faults i.e eccentricity of rotor, cracks in rotor and misalignment of rotor, however the eccentricity fault has affected a very large amount as compared to rotor faults as shown in fig 3.12 and the misalignment has the least effect.

Since the main field generates harmonic components at the value of k =0, 4, 8, 12 because of the associated rotating force wave, therefore these frequency components are not going to get effected by rotor faults. Thus it is not possible to recommend a frequency pattern which is based on these -value of k = 2,4,6,8. Therefore the frequency components at odd value of k =-3,-1, 1 , 3, 5…. are widely effected by rotor faults this has been very clear from frequency spectrum as well. These frequency components are greatly affected when the cracks appears and get wider with time are given by the value of odd multiples of k. Eccentricity faults and cracks in the rotor has same effects on odd multiples of k multiples given by equation (1.2), the eccentricity faults occur due to bearing faults and produce its effect immediately and does not increase significantly with time, however if the crack appears in the rotor it will progressively increase because of stresses, which affects the frequency components gradually with time until it rises to the some significant amount as shown in table 4.2.

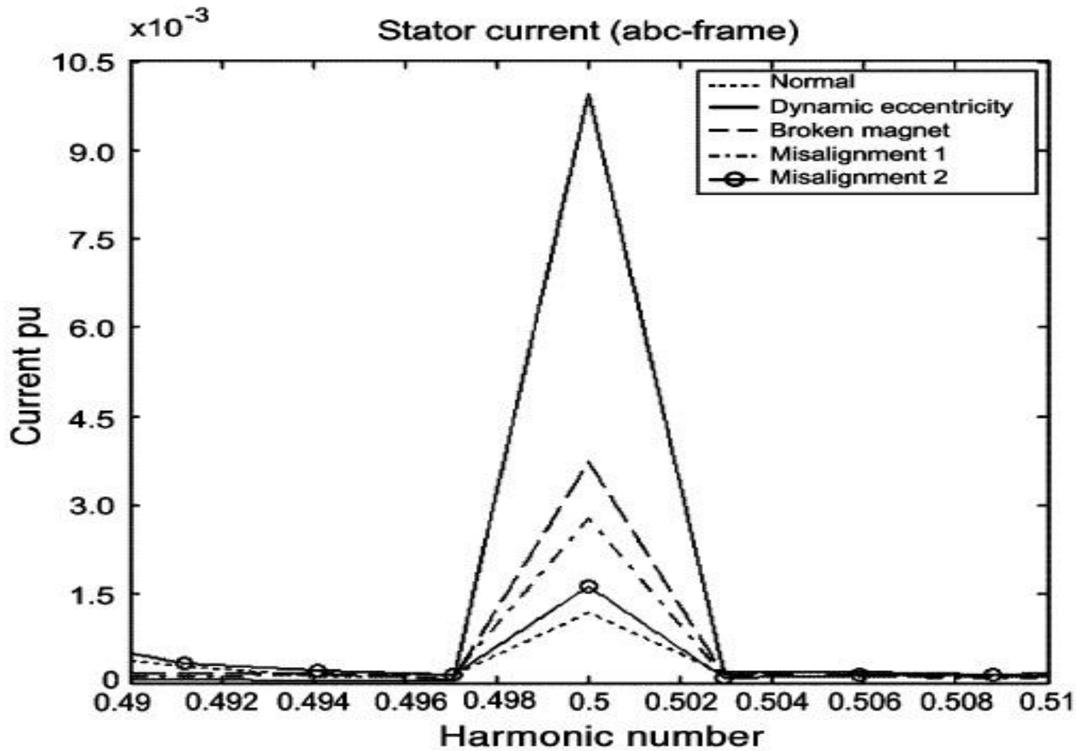

Fig 4.12 Harmonic components of the normal motor, a dynamic eccentricity, the broken magnet fault, a horizontal misalignment 1 and a slight vertical misalignment 2 [7]

Table 4.2

value of k	frequency component (Hz)	Amplitude value(with 5% cracks)	Amplitude value (with 10% cracks)
-3	12.5	0.06	0.08
-2	25	0.03	0.03
-1	37.5	0.02	0.03
1	62.5	0.05	0.07
2	75	0.02	0.02
3	87.5	0.02	0.025
4	100	0.01	0.01
5	112.5	0.04	0.09
6	125	0.01	0.01
7	137.5	0.04	0.08
8	150	0.01	0.01
9	162.5	0.01	0.015
10	175	0.01	0.06
11	187.5	0.04	0.07
12	200	0.01	0.01
13	212.5	0.025	0.025
14	225	0.01	0.01
15	237.5	0.02	0.06
16	250	0.01	0.01
17	262.5	0.01	0.05
18	275	0.03	0.03
19	287.5	0.01	0.06
20	300	0.01	0.01

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