Winding Analysis of Six Phase Induction Motor

A Project Report

Submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **WINDING ANALYSIS OF SIX PHASE INDUCTION MOTOR** Submitted by Sandeep Kumar Chaurasia, to the Indian Institute of Technology, Madras, for the award of the dual degree, **Bachelor of Technology in Electrical Engineering and Master of Technology in Power System and Power Electronics,** is a bona fide record of the research work done by him under my supervision.

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ABSTRACT

Industries have been adopting the technology of Multi-Phase Induction motor, replacing the traditional three phase induction motor because of several benefits in term of performance and in faulty situations. In this thesis multiple analysis are performed for the comparison of performance of six phase induction machine over most conventional three phase machine. Different types of windings are implemented on stator of induction machine designed in Ansys Maxwell. Winding design for three phase and six phase were implemented in same size of machine core to see the possible benefit of applying six phase winding over three phase winding. Six phase Induction machine is excited from Ansys Simplorer using six phase voltage source inverter. Lap, Wave, Concentric type of windings are implemented with integral or fractional type of winding for six phase winding. Most popular type of winding which is adopted by many industries to design six phase induction motor is two group of three phase winding with the angular shift of 30 degree in between them, implemented in this paper. Harmonic analysis has been performed for finding the advantage of using two-group of three phase winding. Radial magnetic flux density curves are plotted and analysed for different type of windings.

Faults analysis have been performed for three phase induction machine with single phase missing and six phase induction machine with one or multiple phase missing. Three phase and six phase Machines are analysed for a broad range of speed from low speed 55 RPM to high speed 3000 RPM and relative improvement in torque and efficiency have been studied. Finite element analysis is performed on the design of machine in Ansys Maxwell.

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ABBREVIATIONS

EMF	Electromotive force
MMF	Magneto motive force
IM	Induction motor
THD	Total Harmonic distortion
FEM	Finite Elements Method
VSI	Voltage Source Inverter
DC	Direct Current
AC	Alternating Current
RPS	Radian per second
RPM	Rotation per minute

NOTATION

m	Number of phase
P	Number of Poles
Ns	Number of Slots in one Layer
S	Total Number of Slots
q	Number of Slots per Pole per Phase
K_w	Winding Factor
α_s	Slot angle in Electrical Radian
β	Angle of Coil Pitch in Electrical Angle
γ'	Phase Spread in Radian
y_b	Back Pitch in Number of Slots
y_f	Forward Pitch in Number of Slots
L1	Layer 1 (Upper Layer)
L2	Layer 2 (Bottom Layer)
d	Number of Poles in a Unit
t	Time
V	Voltage
I	Current
ω_s	Synchronous Speed
Vdc	DC Voltage
n_m	Winding Function
θ	Rotational Angle
R_b	DC Value of Complete Winding Resistance
L_b	Lumped value of Inductance
T	Torque
Hs0	Slot opening height.
Hs01	Slot closed bridge height.
Hs1	Wedge height.

Hs2	Slot body height.
Bs0	Slot opening width.
Bs1	Slot wedge maximum width.
Bs2	Slot body bottom width, 0 for parallel teeth.
H	Magnetic Field
J	Current Distribution
B	Magnetic Flux Density
R_e	End Resistance
L_e	End Inductance
μ	Magnetic permeability of material
γ	Magnetic reluctivity of the material
σ	Electrical conductivity of conductor
$\overline{D}$	Electric Flux Density

CHAPTER 1

INTRODUCTION

Amongst many types of electrical motors, induction motor is used by many industries for a long time. Several factors which include robustness, low cost and low maintenance have made them popular for industrial applications when compared to dc and other ac motors. Power ratings of these machines varies from fraction of horsepower to thousands of horsepower. Induction motors can run approximately at constant speed depend on the motor slip at no-load and full load. Now a days, research interest has been shifting towards multiphase Induction machine design due to the new technologies coming in power electronics which is providing various control techniques for the stable operation of the machine. Multiphase Induction machine can be of any number of phase but more than one. Multi-phase machines are used in many fields, namely ship propulsion, aircraft and electric vehicle. Normally motors are designed for the applications which include constant or varied speed, constant torque, continues or intermediate duty, steep or sudden starts, and frequent start and stop operations in any industry. Hence suitable type of motor is to be selected for the specific application. Because advancement in converter topologies, multiphase induction machine operation can be implemented easily for the desired operation.
Many aspects are considered for the designing of an Induction motor. Winding Pattern is an important concern to check out. Performance of the motor can be altered by choosing the different types of Winding patterns for both stator and rotor. Winding distribution may affect the motor MMF space harmonics, which led to change in the performance of the motor. The advantage of using multiphase Induction motor is that the distribution of winding will be more viable because of increase in winding factor. Many types of winding patterns are practised by the researchers for improving the torque profile and efficiency of the induction machine. Six Phase induction motors have one more advantage which is to device ratings can be reduced by sharing the load across more half bridge sections and in terms of motor magnetics, they can increase the winding factor slightly.

The primary objective of this project is to determine the benefits of using six phase induction motor over three phase induction motor. Winding of three phase induction motor has given on a pre designed stator core and squirrel-cage rotor with six number of poles. Six phase winding pattern is designed by keeping the same stator and rotor core materials considering the same number of poles and same number of slots as that of the three phase machine. Two major category of winding patterns, integral and Fractional type of winding are analysed in this report. The performance of the six phase machine is analysed from low speed to high speed range. For the constant speed of operation, comparison is done for steady state torque, torque ripple, phase currents and efficiency developed by the six phase induction motor to that of three phase induction motor. Fault tolerance analysis is done for both three phase and six phase induction motor under loss of phase condition for comparing the torque ripple content.

Ansys Maxwell/Rmxprt tool is used for developing the machine model. All the machine design related parameters such as coils connections for a winding, number of poles, number of slots, stator and rotor diameters, conductor size and material etc. are defined in Rmxprt. All the equivalent parameters and the machine model are exported from Rmxprt to Ansys Maxwell 2D/3D model, which is then analysed by Finite Element method. Using Ansys Circuit Editor or Ansys Simplorer, Excitations are given to the windings of the machine.

1.1Advantages of Multi-Phase Induction Motor

- Multi-phase induction motor produce less pulsating torque because of more sinusoidal nature of MMF produced.[1]
- During phase loss, Multi-phase IM works very well.
- High power handling capability
- Increase in power factor due to more copper loss

Some of the disadvantages of Multi-phase IM are cost increments in production of inverter because of increase in IGBT. More number of phases makes winding alignment more complex because of requirement of extra connectors, which give difficulties during modelling of the machine.

1.2 Motivation for the Project

This project covers the studies of winding design developed in few literature. Project requirement and motivation were to check out the benefits of using multi-phase induction motor instead of typical three phase induction motor for the industrial purpose. Machine used for analysis is high voltage and high power rating Induction motor with squirrel cage rotor which is analysed for different type of windings and performance under faulty condition which can be single or multiple phase loss. Finite Element Analysis is done on Ansys Maxwell software with excitation from direct sinusoidal input or from the voltage source inverter using Ansys Simplorer. Biggest disadvantage of using Multi-phase induction motor is to design costly VSI. Hence it is required to check if the improved performance of induction motor can compensate the extra cost accumulated by the inverter. Several studies have been conducted and reported in this report for implementing the six phase winding design and the cancellation of non-required harmonics from the windings.

1.3Organization of the Report

This report consists of 5 chapters. The content of each of the chapters is as discussed here.

Chapter 1 - It gives the basic introduction on High power machine which are currently used in industries. It also provide the advantages of using Multi-phase (six phase) induction motors.

Chapter 2 – This chapter explains type of windings and the reason of using particular winding. Integral to Fractional winding patters are shown with their phasor diagram. While machines Air gap magnetic flux density has been studied.

Chapter 3 – It shows the idea of implementing the six phase winding using two group three phase winding. Harmonic analysis has been performed for this type of winding. Harmonics in current because of voltage source inverter also studied.

Chapter 4 – This chapter basically covers the software works. Setting the coils connection, method of designing of motor in Ansys and working principal of software.

Chapter 5 - Simulation results are shown in this chapter. Simulation of three phase and six phase motor for different speed range are shown and performance differences are analysed. It also cover the fault analysis of motor under one or more phase missing.

Conclusion is derived based on the results from the simulation and future work which can be done, represented in this section.

CHAPTER 2

WINDING LAYOUTS FOR MACHINE

2.1 Designing of Multi-Phase Induction Motor

For designing of AC windings some procedures are carried out which are assigning coils in the slots to the various phases, assigning the direction of currents in coil sides, coils connection per phase, coils connection in between phases and the size of the conductor. The objective of these windings are to produce a pure sinusoidal distributed and rotating mmf, through proper feeding of various phases with sinusoidal time-varying symmetrical currents. All these are in order to produce constant torque which is free from ripple, under steady state operating conditions.

2.2 Design of Three Phase Winding

Three-phase winding is placed in one or two-layers of the stator slots, which is single or double-layer winding. For single-layer configurations a total number of coils are equals to half of the number of stator slots and for double-layer configurations it is equal to the number of stator slots. Full-pitched or short-pitched coil is used for requirement of different performance. Mostly, windings for induction machines are built with integer slots per pole per phase. For improvement of starting torque or reduction of cogging we normally use fractional slots per pole per phase. These windings are characterized by their mmf fundamental amplitude and the space Harmonic contents, (the lower the amplitudes of the higher harmonics, the better the peak mmf). The winding factor K_w, characterizes their fundamental harmonic content in terms of the peak mmf value of the entire waveform. Another main concern is to produce balanced resistance and leakage inductance per phase.

2.3 Rules for Designing AC Winding

1. Two Coil sides (Conductor) makes one coil. So basically two slots filled by one coil. One slot contain positive side of conductor and another slot contain negative side of conductor.
2. The number of slots per pole is usually integer whereas number of slots per pole per phase could be fractional or integral.
3. In double layer winding there is an advantage of using full pitch or short pitch winding whereas single layer winding not affected by pitch factor.
4. Angle between two slots can be measured in term of electrical radian.
   Emf induced in stator winding due to travelling mmf. The emfs induced in coil sides placed in nearby slots have some phase shift which can be represent as α_s in electrical radian. Fig 2.1 showing the coil pitch angle andα_s.

$$\alpha_s = \frac{\pi P}{N_s} \tag{1}$$

P = Number of poles *Ns* = Number of stator slots.

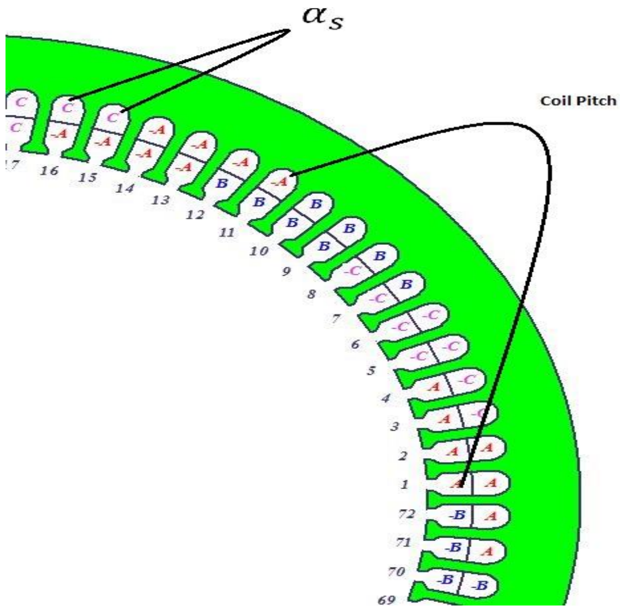


Fig. 2.1 Electrical angle of Coil pitch and consecutive Slot angle α_s

Figure 2.1 representing the coil made by positive side from slot 1 inner layer and negative side from slot 11 upper layer. Total number of slots covered by this coil is 10 slots, hence coil pitch is 10. Angle between two adjacent slots isα_s.

5. Single-layer windings:

   The slots per pole per phase form a phase belt of coil sides. These coil sides return in another phase belt which is π radians moved from the original phase belt.

6. Double Layer windings:

   The slot per pole per phase form a phase belt of coil sides in upper layer. These phase belt have all the terminals in same polarity. The coil sides of this phase belt return in another phase belt in bottom layer which have all coil sides of negative polarity. The slots covered by these two phase belt is called coil pitch which have electrical angle of β.

   Number of coils per phase is, $\frac{N_s}{m}$

$$\beta = \frac{N_s}{m} \times \alpha_s \tag{2}$$

7. Connection of coils per phase:
   Connections of coils made on the basis of type of winding pattern. There are variety of winding available as lap winding, wave winding or concentric winding.
8. If the number of poles *P*, the number of slots per pole per phase *q*, and number of phases for such a design is known then the number of slots *Ns*, is calculated as :

$$N_s = P \times q \times m$$

9. Whenever number of slots per pole per phase q is integer, integral winding is suppose to implement. If *q* is fractional then fractional winding is only possibilty.

Some Basic definition of the most frequently used words,

Pole pitch:
It is the Peripheral distance between identical points on the two adjacent poles. It is always equal to 180^o electrical.
Coil pitch:
It is the distance between two coil sides of a Coil. It is usually measured in terms of teeth, slots or electrical degrees.
Full Pitch:
When coil pitch is same as pole pitch. In term of slots coil pitch is equal to number of slots in stator divided by number of poles.
Short Pitch:
When coil pitch is shorter than pole pitch.
Phase belt:
The group of adjacent slots belonging to one phase under one pole-pair.
Phase spread:
The angle subtended by one Phase belt is called Phase spread.

Table 2.1 shows represent the possible slot combinations for a 3-phase induction motors which can be readily reconfigured into 6-phase induction motor. NA represent that Integral winding not possible because of fractional value of Number of slots per pole per phase.

No. of slots	No. of poles	No. of phases / No. of slots per pole per phase	No. of phases / No. of slots per pole per phase
12	2	3 / 2	6 / 1
	4	3 / 1	6 / Fraction ($1/2$) NA
	6	3 / Fraction ($2/3$) NA	6 / Fraction ($1/3$) NA
24	2	3 / 4	6 / 2
	4	3 / 2	6 / 1
	6	3 / Fraction ($4/3$) NA	6 / Fraction ($2/3$) NA
36	2	3 / 6	6 / 3
	4	3 / 3	6 / Fraction ($3/2$)NA
	6	3 / 2	6 / 1
48	2	3 / 8	6 / 4
	4	3 / 4	6 / 2
	6	3 / Fraction ($8/3$) NA	6 / Fraction ($4/3$) NA
60	2	3 / 10	6 / 5
	4	3 / 5	6 / Fraction ($5/2$)NA
	6	3 / Fraction ($10/3$) NA	6 / Fraction ($5/3$) NA
72	2	3 / 12	6 / 6
	4	3 / 6	6 / 3
	6	3 / 4	6 / 2

Table 2.1 Possible slot combination for 3 phase and 6 phase

2.4 Implementation of Armature Winding

Different types of windings are implemented on squirrel cage induction machine with double layer stator and 72 slots in each layer. Some of the steps are performed to know the possible winding design which are possible to implement.

Number of slots per layer N_s = 72

Number of layers a = 2

Total Number of slots S = 144

Number of poles P = 6

Number of phase m = 6

Difference of electrical angle between two slots,

$$\alpha_s = \frac{\pi P}{N_s} = \frac{\pi}{12}$$

Number of slots per pole per phase *q,*

$$q = \frac{S}{m \times P} = 4 \qquad (3)$$

Phase spread γ',

$$\gamma' = \frac{2\pi}{m}\ or\ \frac{2\pi}{2m} = \frac{\pi}{3}\ or\ \frac{\pi}{6}$$

2.4.1 Lap Winding

Number of slots per pole per phase is integer. Lap winding is the winding in which successive coils overlap each other. Lap winding is also known as parallel windings. The number of parallel path is equal to the number of poles. Lap windings are used for low voltage and high current application of IM. Integral Lap winding is designed in following ways.

Considering phase spread of 60^o :

Four slots which are per pole per phase will occupy adjacent slots to make it 60^o phase spread.

Pole pitch = $\frac{N_S}{P} = 12$

Selecting coil pitch = 10 (Short pitch winding)

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
L1	+A	+A	+A	+A	-C	-C	-C	-C	+B	+B	+B	+B	-A1	-A1	-A1	-A1	+C1	+C1	+C1	+C1	-B1	-B1	-B1	-B1
L2	+A1	+A1	-C1	-C1	-C1	-C1	+B1	+B1	+B1	+B1	-A	-A	-A	-A	+C	+C	+C	+C	-B	-B	-B	-B	+A1	+A1

Table 2.2 60^o phase spread lap winding pattern

Table2.2 represents the 1/3rd fraction of stator of IM. The coil sides distribution in slots for 6 phases A, B, C, A1, B1, and C1 are done in the described manner. Where L1 is upper layer and L2 is inner layer. Distribution of coil sides in upper layer L1 is depend on values of number of phase, number of poles and number of slots in armature but distribution of coil sides in inner layer L2 will also depend on coil pitch of the winding. Upper and inner layers are identical but only shift of number of slots in coil pitch.

Figure 2.2 showing the star of slot emf for upper layer. 1 to 72 numbers are representing upper layer slots. Inner layer slots can be decided on the basis of coil pitch which is taken ten.

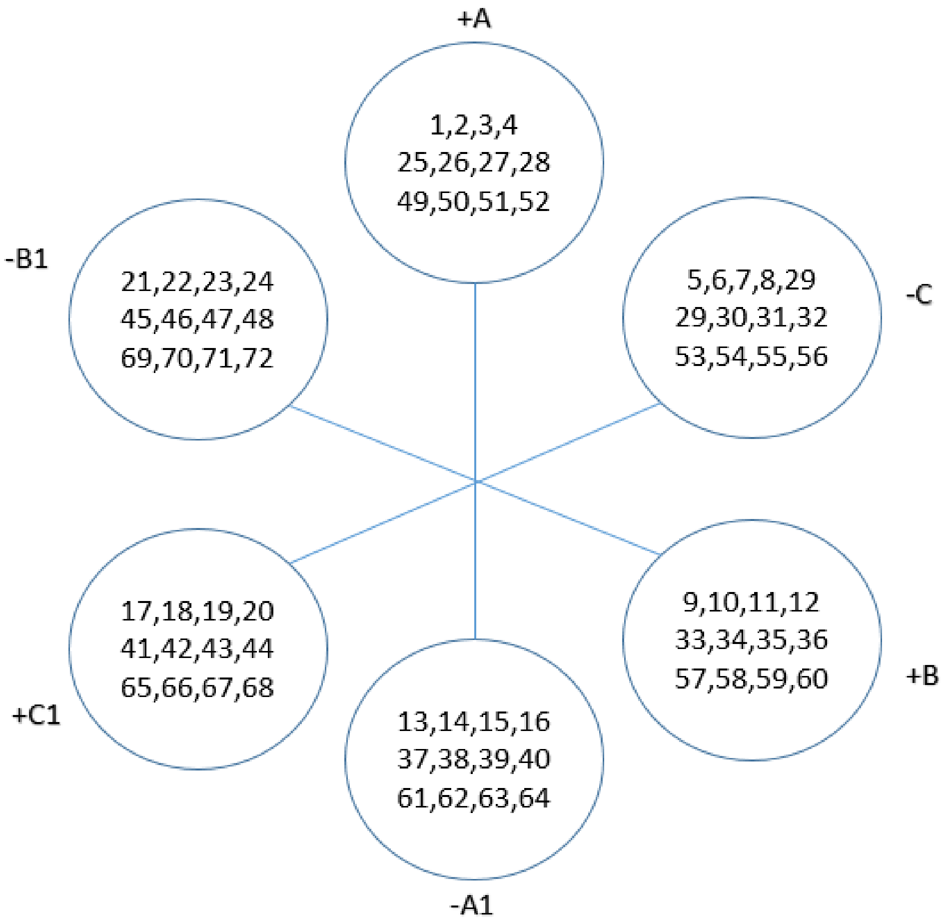


Fig. 2.2 The star of slot emf phasors for a double layer, 60^o phase spread winding (One layer shown) with 6 poles and 4 slots per pole per phase.

Fig. 2.3 showing the Lap winding connection for phase A in Maxwell Circuit Editor. 3 parallel paths are taken into account which is showing below in Fig. 2.3.

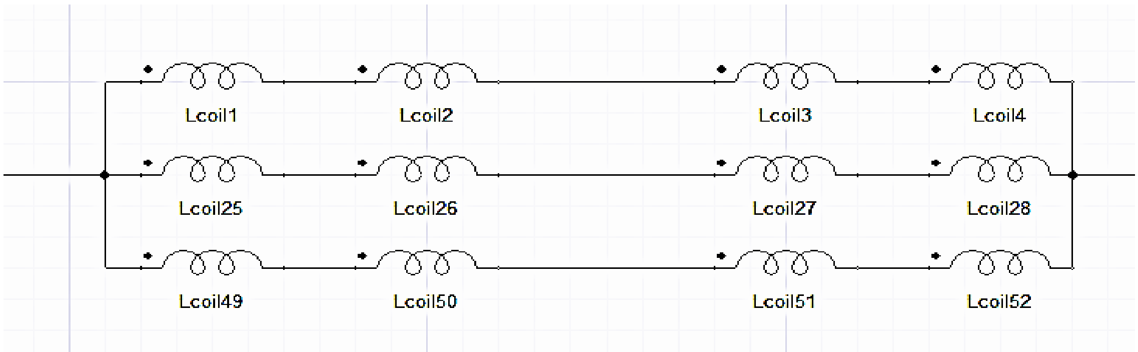


Fig. 2.3 Coils Connection for Phase A

Fig. 2.4 (a) showing the phasor diagram of symmetrical spatial distribution of voltage by six phase windings. Fig. 2.4 (b) shows, equivalent phasor diagram for six phase winding. Phasor diagram (a) to (b) can be achieved when winding of phases C, A1 and B1 are inverted for the voltage excitation.

This process is done for achieving maximum flux linkage, which is explained in section 2.4.2.

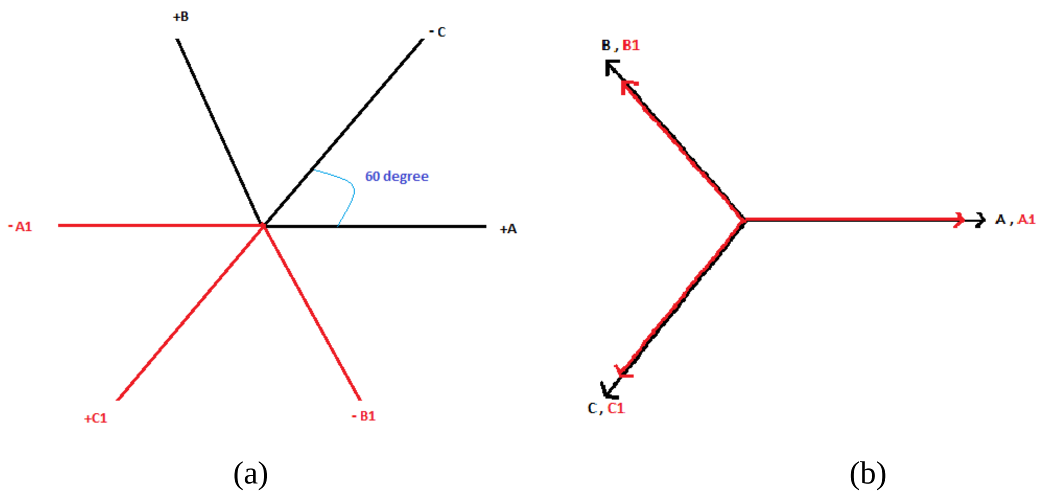


Fig. 2.4 Spatial distribution of voltage phasors in six phase IM

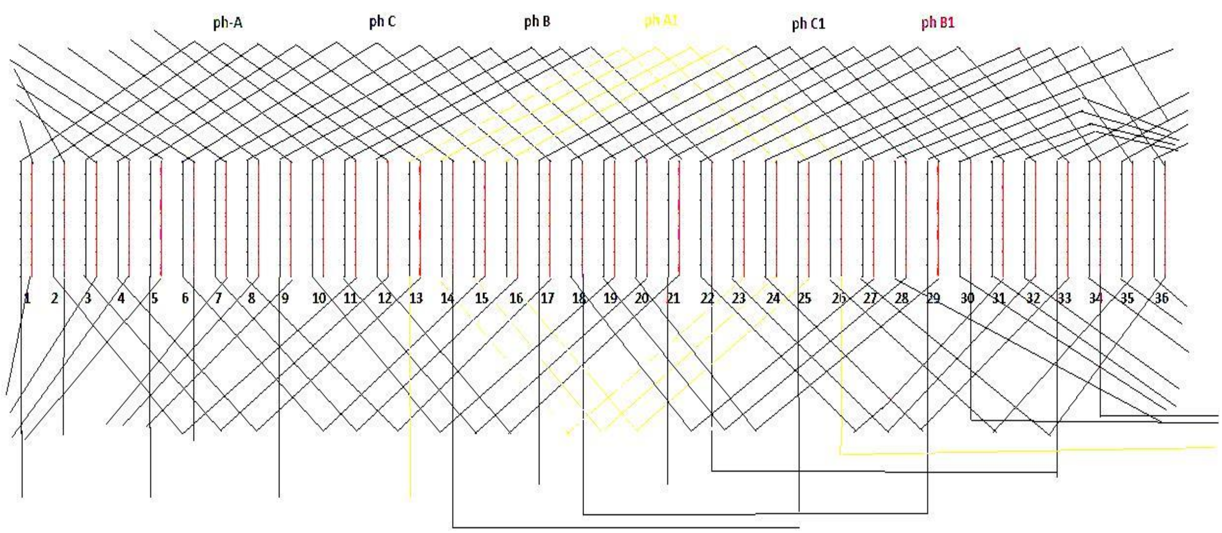


Fig. 2.5 Lap winding for six phase

Figure 2.5 shows the complete coils connection for lap winding in stator of the half of the six phase induction machine.

2.4.2 Calculation of Air Gap Radial Flux Density:

In Maxwell2D, Field calculator is used to plot the Flux density graph in air gap. A semicircle curve plotted in air gap to calculate the radial magnetic flux density B on this curve. Using inbuilt variable Magnetic flux density B and Function PHI, B radial in air gap is plotted.

Equation used is,

$$B_{radial} = B_x \times \cos(PHI) + B_y \times \sin(PHI) \quad (4)$$

Plots of B_{radial} in air gap semicircle which covers the 36 slots of the stator given in fig. 2.6 and fig. 2.7. Fig. 2.6 represent Radial magnetic flux density plot in air gap for ABC winding and fig2.7 represent radial magnetic flux density plot in air gap for A1B1C1 winding. For plotting Fig2.6 Phase A, B and C are excited form voltage source. Slip value is taken zero for the synchronous speed of 610 RPM. Voltage given for excitation was 885V peak value and 120^o phase shift for consecutive phases. Winding A1, B1 and C1 are left open without any connection. Same procedure is followed for plotting Fig. 2.7 with voltage excitation in A1B1C1 windings. In these two plots total number of peaks is 36. Each peak represents one slot of the stator. If we compare these two plots it is concluded that these two plots are identical which means if we excite these two groups from two three phase simultaneously, we can achieve the maximum flux linkage because there is 0 degree phase shift between these two radial magnetic flux density plots.

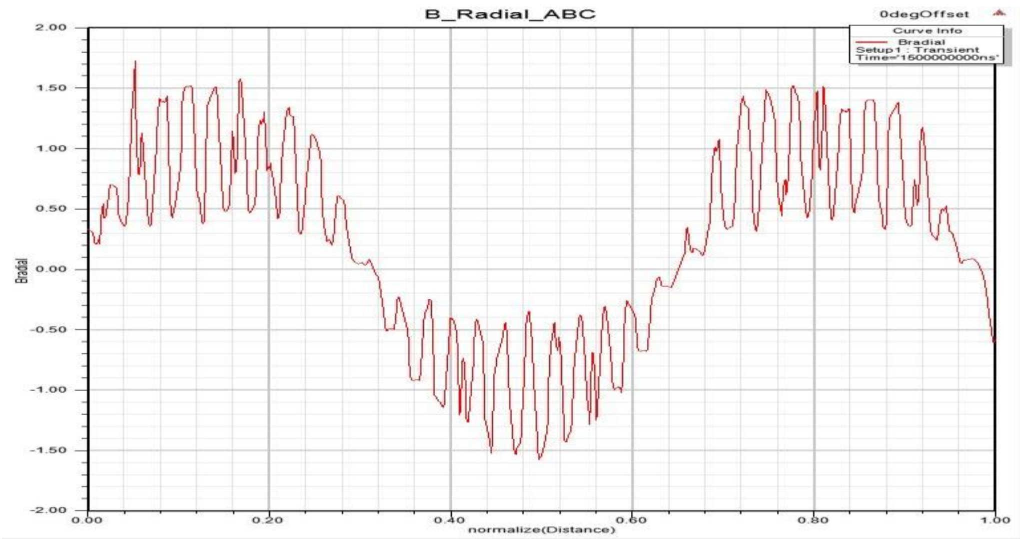


Fig. 2.6 Radial magnetic flux density plot in air gap for ABC winding

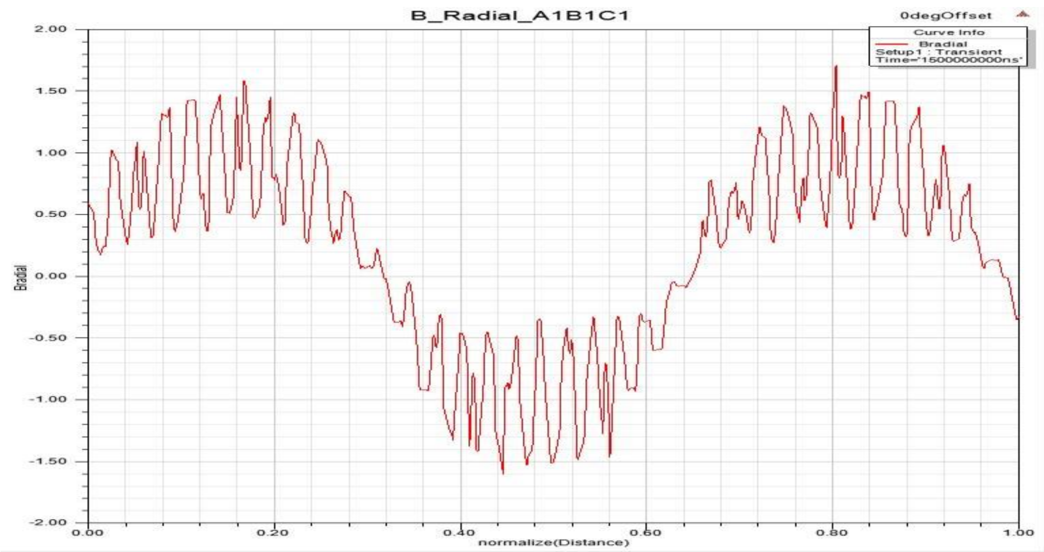


Fig. 2.7 Radial magnetic flux density plot in air gap for A1B1C1 winding

Considering the Phase spread of 30^o:

Four slots which are per pole per phase will occupy two adjacent slots to make it 30^o phase spread. Basically two coil sides are occupied by two slots from upper layer and other two coil sides are occupied by two slots of inner layer just below the upper layer.

Pole pitch = $\frac{N_S}{P} = 12$, Selecting coil pitch = 12 (full pitch winding, since short pitch winding is not possible.)

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
L1	+A	+A	+A1	+A1	-C	-C	-C1	-C1	+B	+B	+B1	+B1	-A	-A	-A1	-A1	+C	+C	+C1	+C1	-B	-B	-B1	-B1
L2	+A	+A	+A1	+A1	-C	-C	-C1	-C1	+B	+B	+B1	+B1	-A	-A	-A1	-A1	+C	+C	+C1	+C1	-B	-B	-B1	-B1

Table 2.3 30^o phase spread lap winding pattern

Table2.3 shows six phases A, B, C, A1, B1, C1 coil side's distribution in slots in described manner. One Phase pitch is two consecutive slots which make it 30^o phase spread. Coils connection for 4 slots per pole per phase is in series as given in Fig. 2.8

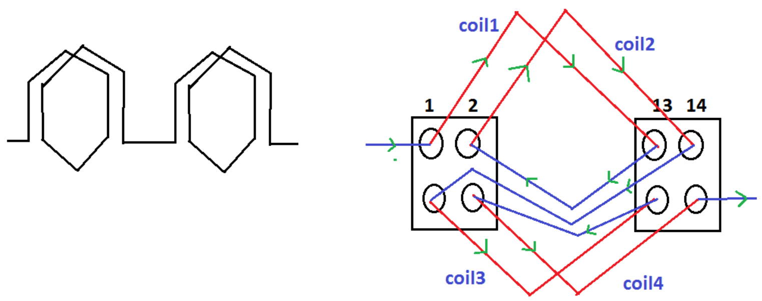


Fig. 2.8 Lap winding connection for slots in per pole per phase

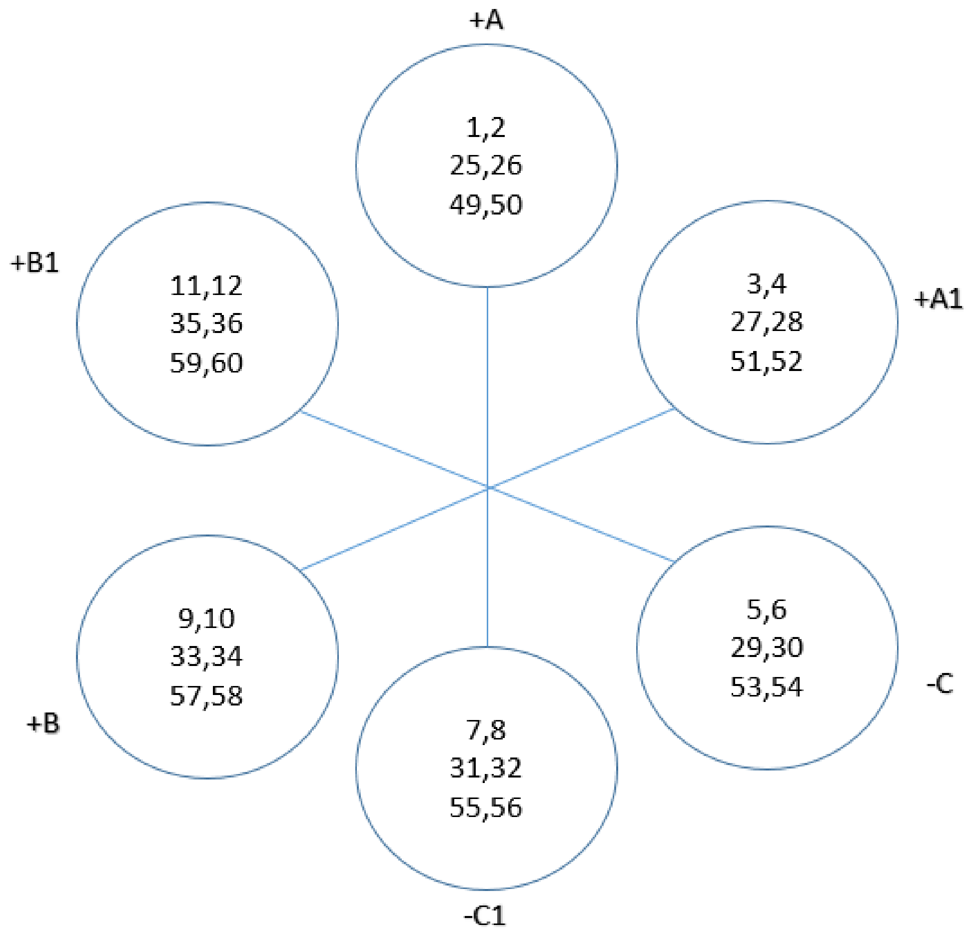


Fig. 2.9 The star of slot emf phasors for a double layer 30^o phase spread winding with 6 poles and 4 slots per pole per phase.

Figure 2.9 showing the star of slot emf for both layers. Numbers are representing both upper and inner layer slots. Here short pitch winding is not possible so the only option we left with 12 coil pitch. Missing numbers from diagram are actually representing the slots which are actually occupied by another side of the coils.

Fig. 2.10 showing the Lap winding connection for phase A in Maxwell Circuit Editor where 3 parallel paths are taken into account.

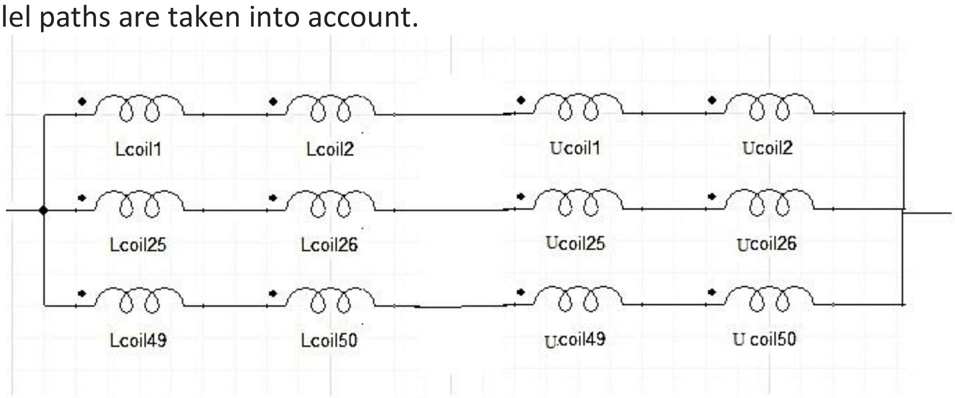
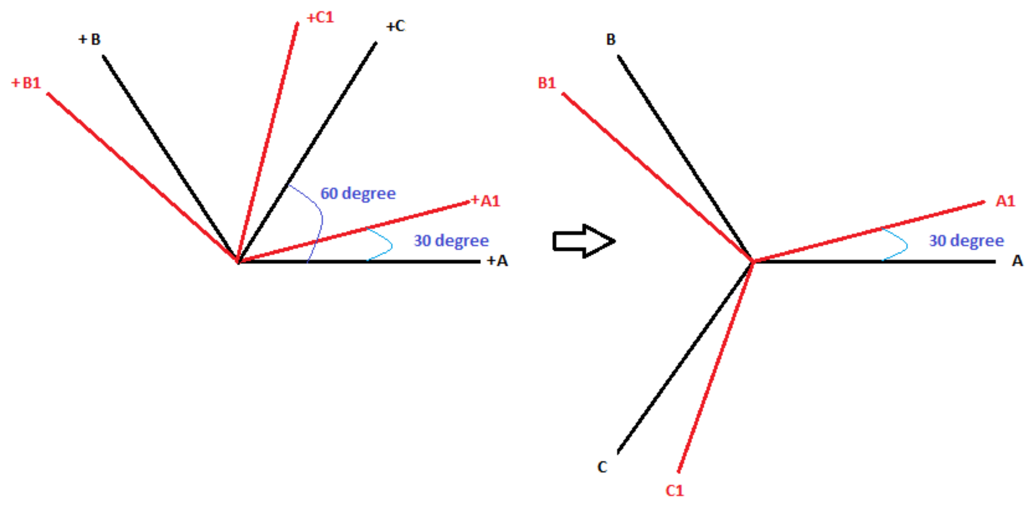


Fig. 2.10 Coils connection for Phase A

Fig.2.11 showing the phasor diagram of spatial distribution of voltage in 6phase winding. Six phase winding is equivalent to two sets of three phase winding ABC and A1B1C1. (a) Shows the winding phasor after coil sides distribution in slots. (b) Phasor diagram of winding after inverting phase C and C1. The dual three-phase windings are excited by dual three phase voltage source which have 30 degree phase shift[12].



(a) (b)

Fig. 2.11 Asymmetric spatial distribution of voltage phasors in six phase IM

Plot of B_{radial} in air gap semicircle which covers the 36 slots of the stator, given in Fig2.12 to 2.14. When ABC is exited form the voltage source and A1B1C1 is opened, slip is taken zero for the synchronous speed operation. Voltage 885V peak value applied. A total number of 36 peaks can be observed from the plots.

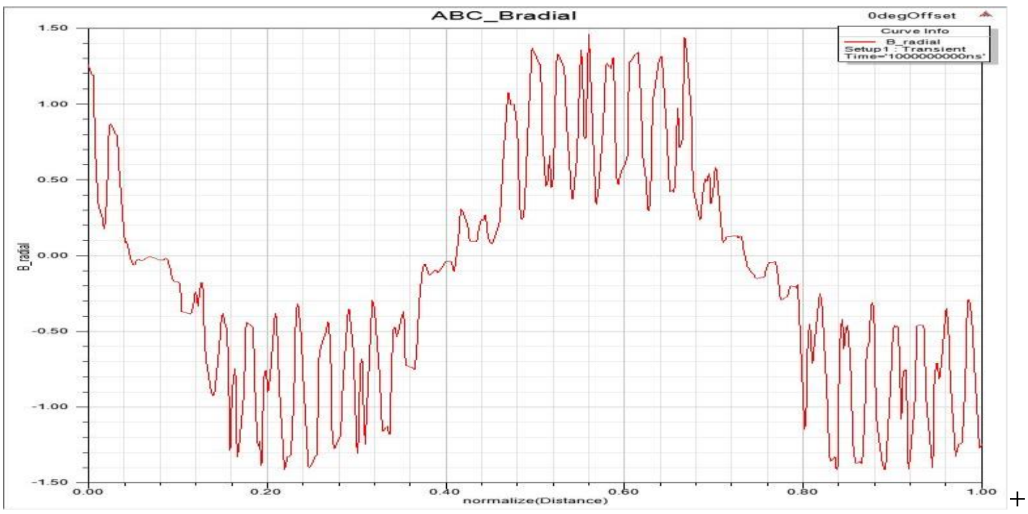


Fig. 2.12 Radial magnetic flux density plot in air gap for ABC winding

When A1B1C1 is excited 0^o offset to ABC, fig. 2.13 showing the plot of B radial.

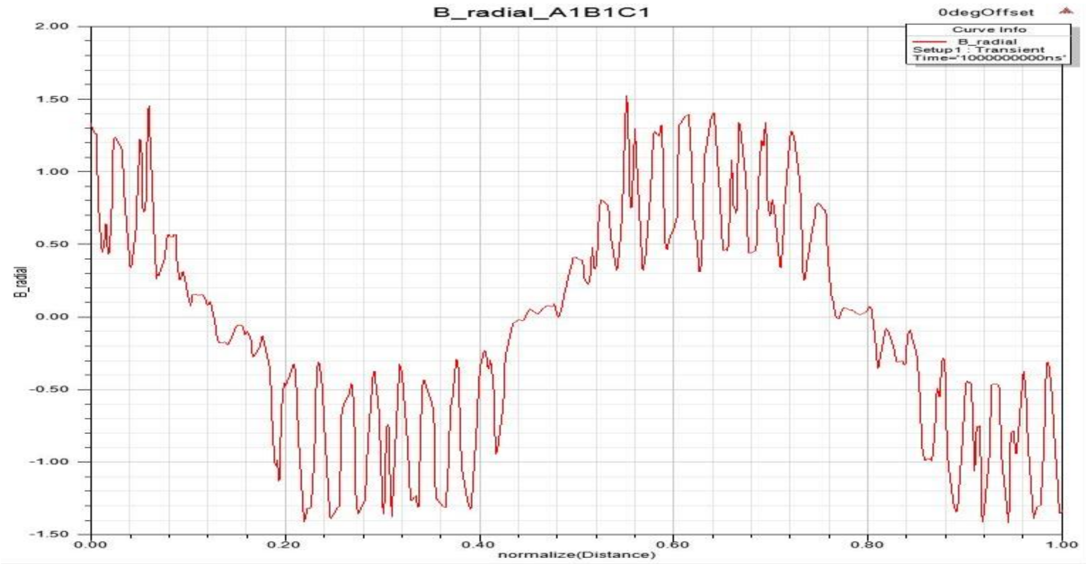


Fig. 2.13 Radial magnetic flux density plot in air gap for A1B1C1 winding with 0^o offset

A1B1C1 is excited 30^o offset to ABC, Fig. 2.14 showing the plot of B radial.

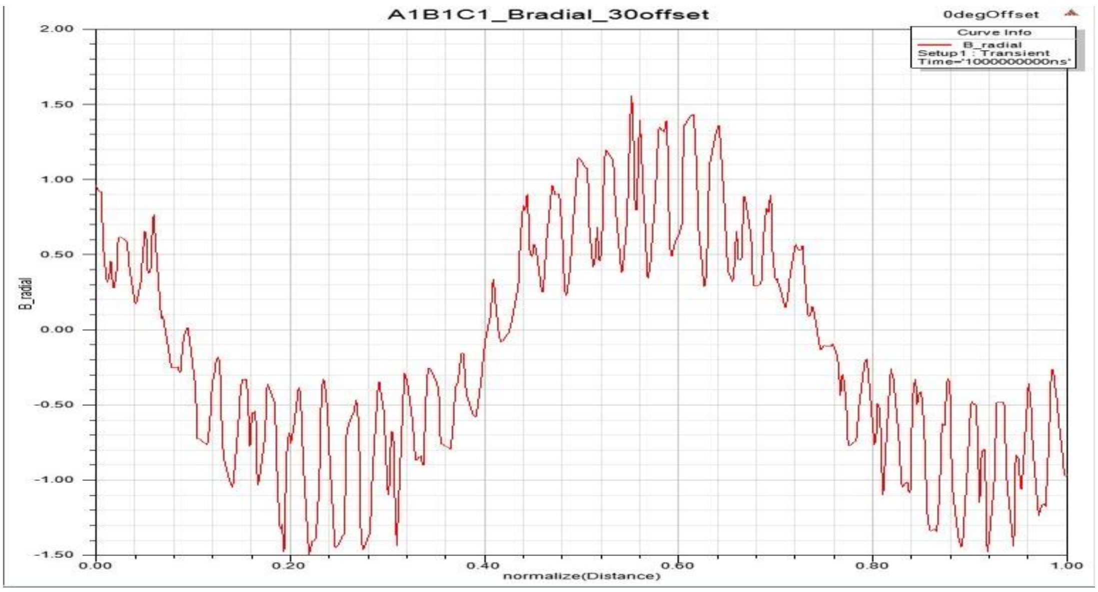


Fig. 2.14 Radial magnetic flux density plot in air gap for A1B1C1 winding with 30^o offset

From figure 2.12 and 2.14, it is clear that when excitation is same for both three phase model ABC and A1B1C1 or say phase offset is 0 degree, the air gap magnetic flux density for A1B1C1 is two peak shifted to right compare to air gap magnetic flux density for ABC. Since one peak is correspond to one slot of the stator core. So there will be a total of 30^o phase shift between ABC and A1B1C1. When A1B1C1 is excited by 30^o offset the peak shift will be nullified which can be observed by comparing peak shift from Fig2.12 and Fig.2.14. Since there is no peak shift between these two plots means they are perfectly overlapping to each other.

2.4.3 Wave Winding

This winding forms a wave with its coil that is why it is named as wave winding. It is also called series winding because its coils are connected in series. Wave windings have only two parallel paths. For a given number of poles and armature conductors it gives more emf than that of lap winding. Hence wave winding is used in high voltage and low current machines application. In lap winding special connectors are needed to connect the individual coils but in wave winding there is no need of special connectors. This saves large additional expenses on copper.

In AC winding, with integral number of slots per pole per phase, the winding would close after completing one trip around the armature. To prevent closing of the winding after one trip, we have to an abnormal step. After having complete half winding, it is necessary to reverse the direction of turns around the machine.

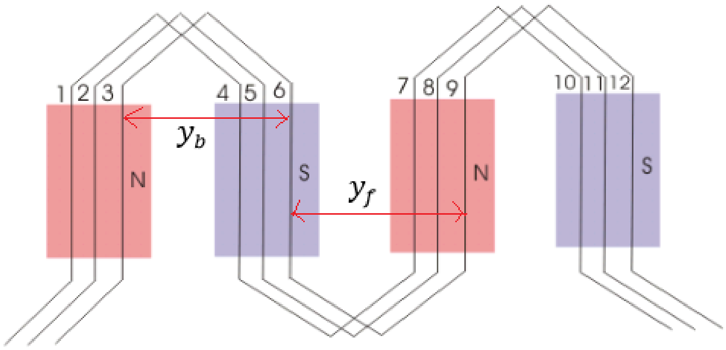


Fig. 2.15 y_b is back pitch and y_f is front pitch

Slots per pole per phase q' = 4

Total winding pitch Y = $y_b + y_f$

$$Y = \frac{2 \times 6pq}{\frac{p}{2}} = 96 \qquad (5)$$

Where Y is an even Integer. y_b Is back pitch and y_f is front pitch.

Since y_b is larger than y_f and the difference of y_b and y_f should be 2. So the solution is y_b = 49 and y_f =47.

The distributions of Coil sides for six phases are shown in table 2.4

Phase A	1,2,3,4	25,26,27,28	49,50,51,52	73,74,75,76	97,98,99,100	121,122,123,124
Phase B	9,10,11,12	33,34,35,36	57,58,59,60	81,82,83,84	105,106,107,108	129,130,131,132
Phase C	5,6,7,8	29,30,31,32	53,54,55,56	77,78,79,80	101,102,103,104	125,126,127,128
Phase A1	13,14,15,16	37,38,39,40	61,62,63,64	85,86,87,88	109,110,111,112	133,134,135,136

Phase B1	21,22,23,24	45,46,47,48	69,70,71,72	93,94,95,96	117,118,119,120	141,142,143,144
Phase C1	17,18,19,20	41,42,43,44	65,66,67,68	89,90,91,92	113,114,115,116	137,138,139,140

Table 2.4 Coil distribution of 60^o phase spread Wave winding

Considering Winding pattern for phase A, procedures for wave winding pattern in one of the parallel path.

Clockwise procedure:

1. Coil side 1 of layer L1 in slot 1 is connected at the back side to coil side (1+49) = 50 of layer L2 in slot 25.
2. Coil side 50 of layer L2 in slot 25 is connected at the front side to coil side (50+47) =97 of layer L1 in slot 49.
3. Coil side 97 of layer L1 in slot 49 is connected at the back side to coil side (97+49) = 146 -144 = 2 of layer L2 in slot 1.
4. Coil side 2 of layer L2 in slot 1 is connected at the front side to coil side (2+47) = 49 of layer L1 in slot 25.
5. Coil side 49 of layer L1 in slot 25 is connected at the back side to coil side (49+49) = 98 of layer L2 in slot 49.
6. Coil side 98 of layer L2 in slot 49 is connected at the front side to coil side (98+47) =145-144=1 of layer L1 in slot 1. <Stop>
   Notice – If we make connection given in point 6, the winding closes and so coil side 98 will be connected to coil side 3 in slot 2 instead of coil side 1.

7. Coil side 3 of layer L1 in slot 2 is connected at the back side to coil side (3+49) = 52 of layer L2 in slot 26.
8. Coil side 52 of layer L2 in slot 26 is connected at the front side to coil side (52+47) =99 of layer L1 in slot 50.
9. Coil side 99 of layer L1 in slot 50 is connected at the back side to coil side (99+49) = 148 -144 = 4 of layer L2 in slot 2.
10. Coil side 4 of layer L2 in slot 2 is connected at the front side to coil side (4+47) = 51 of layer L1 in slot 26.
11. Coil side 51 of layer L1 in slot 26 is connected at the back side to coil side (51+49) = 100 of layer L2 in slot 50.
12. Coil side 100 of layer L2 in slot 50 is connected at the front side to coil side (100+47) =147-144=3 of layer L1 in slot 1. <Stop>
    Notice – Again If we make connection given in point 6, the winding closes and so coil side 100 will be connected to coil side 4 in slot 2 instead of coil side 3.

For another parallel path winding is repeated in anti-clockwise. After having complete half the winding, it is necessary to reverse the direction of turns around the machine. Table 2.5 shows the slots filling by the coil sides.

Slot	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30	31 32	33 34	35 36	37 38	39 40	41 42	43 44	45 46	47 48
L1	+A	+A	+A1	+A1	-C	-C	-C1	-C1	+B	+B	+B1	+B1	-A	-A	-A1	-A1	+C	+C	+C1	+C1	-B	-B	-B1	-B1
L2	+A	+A	+A1	+A1	-C	-C	-C1	-C1	+B	+B	+B1	+B1	-A	-A	-A1	-A1	+C	+C	+C1	+C1	-B	-B	-B1	-B1

Table 2.5 30^o phase spread Wave winding pattern

2.4.4 Fractional Winding

2.4.4.1 Advantages of Applying Fractional Winding

1. Number of poles is large for the AC machine operating for low speed, so if number of slots per pole per phase becomes really small (q=1 to 3), it would give rise to large content of harmonics in the EMF induced. The large value of harmonic content in integral slot windings is due to the fact that corresponding winding elements of each phase, under different poles, occupy similar position with respect to pole to pole axis and so the harmonics add algebraically. If winding is wound fractional winding, the corresponding winding elements of a phase under different poles, may occupy dissimilar positions with respect to pole axis. The displacement of these winding elements with respect to magnetic field is so selective that the higher harmonics are decreased without significantly affecting the fundamental.

2. The leakage reactance of the winding is reduced.

3. For implementing Fractional winding, chording is required hence the amount of copper requirement will reduce since end connection will become shorter.

In the integral slot windings every pole phase group have all coils connected in series. But in fractional slot winding there will be different number of slots in pole phase group. Fractional winding may create non-uniform flux density around the air gap but the machine operation would be satisfactory if the phase group are arranged around the stator core in a certain degree of uniformity.

2.4.4.2 Implementation of Fractional Winding

Considering ten pole, six phase fractional slot windings for double layer stator with total of 144 slots. –

Electrical angle between two slots,

$$\alpha_s = \frac{180 \times 10}{72} = 25^0$$

Number of slots per pole per phase,

$$q = \frac{72 \times 2}{10 \times 6} = \frac{12}{5} = 2\frac{2}{5}$$

$2\frac{2}{5}$ represents hidden values of the variable require for designing fractional winding.

Number of units = 2

Number of poles in a unit = *d* = 5

Number of slots per phase in one unit *M*= *q*×*d* = 12

So each phase in a single unit contains 3 group of 2 coils and 2 group of 3 coils.

Number of total slots in each unit = *m*×*M* = 72

The simplest approach of filling the slots is to calculate the value of integer D.

Where D is difference between two slots which correspond to two consecutive pastors of slot star.

$$D = \frac{1 + mMQ}{d} \quad (6)$$

Putting all the known variables in equation we get,

$$D = \frac{1 + 72Q}{5}$$

For D should be integer the smallest value of Q will be 2, hence D = 29.

Now using layout series we can easily fill all the phase.

$$1, (1 + D), (1 + 2D), \dots \dots \dots, (1 + (mM - 1)D - xmM)$$

For phaseA slots will be,

1, 1+D = 30, 1+2D = 59, 1+3D-mM = 88-72 = 16, 1+4D-mM = 45 and so on.

This series sequentially calculates the slots for all six phase to fill in layer 1. Depending on coil pitch value we can fill the layer 2.

Phase Poles	Phase A	Phase B	Phase C	Phase D	Phase E	Phase F
Pole_1 (+coil side) Upper Layer L1	1, 2, 3	4, 5	6, 7, 8	9, 10	11, 12	13, 14, 15
Pole_2 (+coil side) Upper Layer L1	16, 17	18, 19, 20	21, 22	23, 24	25, 26,27	28, 29
Pole_3 (+coil side) Upper Layer L1	30, 31, 32	33, 34	35, 36	37, 38, 39	40, 41	42, 43, 44
Pole_4 (+coil side) Upper Layer L1	45, 46	47, 48	49, 50, 51	52, 53	54, 55,56	57, 58
Pole_5 (+coil side) Upper Layer L1	59, 60	61, 62, 63	64, 65	66, 67, 68	69, 70	71, 72

Table 2.6 Fractional winding, slots distribution in 6 phases for positive polarity

CHAPTER 3

STUDY ON HARMONICS OF WINDINGS

3.1 Two Sets of Three Phase Group for Modelling of Six Phase Winding

Designing of six phase winding can be symmetrical or asymmetrical. 60^0 Phase shifts between consecutive phases which make it symmetrical design have disadvantage of circulating currents[1][12]. So the six phase winding is designed using two sets of three phase winding with 30^0 phase shift, which eliminates $(6n \pm 1)$ order harmonics, where n = 1, 3, 5…[7][8]. We can choose any arbitrary phase shift. This configuration is referred to in literature having different names, for example split-phase[7], dual three-phase (DTP)[8], double-star or dual-stator. For verification we have analysed the two set of three phase winding with some arbitrary phase shifts, which gave non-sinusoidal radial magnetic flux in the air gap and produced rippled torque. Taking 30^0 phase shift it is concluded that there will be no circulating current because of 30° space shift between two winding sets and with the same electrical phase shift between the supplies voltages, many harmonics are eliminated from the air gap flux. Actually, the excitation voltage time harmonics such as 5th, 7th, 17th, 19th, …, etc. are prevented from contributing to the air gap flux and torque pulsation, while they are contributing in the supply input current[2][3]. Fig. 3.1 shows the Asymmetrical six phase winding.

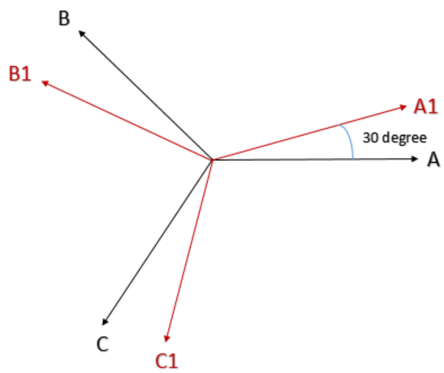


Fig. 3.1 Phasor Diagram of six phase winding diagram

The two group of three phase are ABC and A1B1C1 in given Fig.3.1 which have an angular displacement of30^0.

3.2 Analysis of Harmonics

There are two type of harmonics make impact on the performance of the motor. Voltage time harmonics because of six-pulse excitation from inverter side and winding harmonics because of non-sinusoidal nature of windings.

3.2.1 Voltage Harmonics

If the connection of the winding is star connection then the Fourier decomposition of voltage across one of the phase of motor will be represented as,

$$(V_k)^{Group\ 1}_{Phase\ A}(t) = \frac{2\,Vdc}{\pi(-1)^n(1 \pm 6n)} \cos\big((6n \pm 1)\omega_s t\big) \tag{7}$$

Now the total voltage for Phase A will be,

$$V^{Set\ 1}_{Phase\ A}(t) = Re \sum_{k=1}^{\infty} V_k\, e^{jk\omega_s t} \tag{8}$$

For other Voltages B and C in the same three phase group (Group1) will be,

$$V^{Set\ 1}_{Phase\ B}(t) \ = \ Re \sum_{k=1}^{\infty} V_k\, e^{jk\omega_s t} e^{-jk\frac{2\pi}{3}}$$

$$= Re \sum_{k=1}^{\infty} V_k\, e^{jk\omega_s t}\ a^{-k} \tag{9}$$

$$V^{Set\ 1}_{Phase\ C}(t) \ = \ Re \sum_{k=1}^{\infty} V_k\, e^{jk\omega_s t}\ \ e^{jk\frac{2\pi}{3}}$$

$$= Re \sum_{k=1}^{\infty} V_k\, e^{jk\omega_s t}\ a \tag{10}$$

Where a =$e^{j\frac{2\pi}{3}}$.

If$a^k \ = \ e^{j\frac{2\pi}{3}}$, then the values of k will give harmonics which will support the fundamental harmonic and it will support the rotation in forward direction.

If$a^k = e^{-j\frac{2\pi}{3}}$, it will support the backward rotation.

If $a^k = 1$, there will be cancellation of harmonics.Net harmonic of k order will be zero.

It is clear form equation (8), (9) and (10) that forward-rotating harmonics will be for *k* = 1, 7, 13, 19, 25, 31….etc. Backward-rotating harmonics will be for *k* = 5, 11, 17, 23…etc. For *k* = 3, 9, 15… etc. no current harmonic produce.

The other three phase winding which is Group2, A1B1C1 is rotated 30^0 electrical angle from Group1. So the voltage equations for A1, B1, C1 will be multiplied by a factor *b* =$e^{j\frac{\pi}{6}}$ to the voltage equations for A, B, C.

3.2.2 Winding Harmonics

The winding function n_m of phase A of a three phase winding harmonic can be denoted as,

$$n_m^{\substack{Phase\ A\\Group1}} = N_m \cos(m\theta)$$

$$n_m^{\substack{Phase\ B\\Group1}} = N_m \cos(m(\theta - \frac{2\pi}{3}))$$

$$n_m^{\substack{Phase\ C\\Group1}} = N_m \cos(m(\theta + \frac{2\pi}{3}))$$

Where $\theta$the electrical angle, m is is the space harmonic and $N_m$is the winding coefficient.

For other group2 A1B1C1 of six phase winding, phase shift will be $\frac{\pi}{12}$ and hence the equation,

$$n_m^{\substack{Phase\ A\\Group2}} = N_m \cos(m(\theta - \frac{\pi}{12}))$$

$$n_m^{\substack{Phase\ A\\Group2}} = N_m \cos(m(\theta - \frac{9\pi}{12}))$$

$$n_m^{\substack{Phase\ A\\Group2}} = N_m \cos(m(\theta + \frac{7\pi}{12}))$$

For Six phase winding the MMF generated will be

$$\text{MMF}\ (\theta, \text{t}) = \text{Re} \sum_{Group1}^{Group2} \sum_{Phase1}^{Phase3} n_{set}^{Phase}(\theta) i_{set}^{Phase}\ (t)$$

$$\text{MMF}(\theta,t) = \text{Re}\sum_{m'=-\infty}^{\infty}\sum_{k=1}^{\infty}\left(\frac{N_m}{2}\left(\left(1+b^{m'}b^{-k}\right)+a^{m'}a^{-k}\left(1+b^{m'}b^{-k}\right)\right.\right.$$
$$\left.\left.+\,a^{-m'}a^{k}\left(1+b^{m'}b^{-k}\right)\right)\overline{I_k}e^{j(kw_st-m'\theta)}\right) \qquad (11)$$

If $(m'-k) = \pm 6n$, where n is an integer.

$$\left(1+b^{m'}b^{-k}\right) = \begin{Bmatrix} 0, if\ n\ is\ odd \\ 2, if\ n\ is\ even \end{Bmatrix}$$

If $\left(1+b^{m'}b^{-k}\right)$ = 0 then the magnetizing reactance for space-time harmonic is short circuited.

If $k = 1$, 13, 25…etc., then $m' = 1$,-5, 7,-11, 13…etc. In which case, the value of $\left(1+b^{m'}b^{-k}\right)$ will be zero. When m'= -5, 7,-17, 19 etc. If k = 7, 19, etc., then the same series of m' exists but this time $\left(1+b^{m'}b^{-k}\right)$ will be not zero. For making it zero m'should be 1, -11, 13,-23…etc. In this simulation, it will be assumed that the only space harmonics of any significance are the 5th, 7th, 11th, 13th, 23rd, and 25th [3].
Hence from the analysis if using six-phase machine with two groups of three phase winding some of the non-required harmonics will be eliminated.

CHAPTER 4

MACHINE DIMENSIONS AND SETUP IN ANSYS

4.1 Machine Dimensions and Connections

Stator and rotor were designed by giving pre-calculated parameter to Ansys Maxwell RMxprt. Machine dimensions are given in an annexure, while the description is given here.

Stator Parameters,

Outer Diameter	The outer diameter of the stator core.
Inner Diameter	The inner diameter of the stator core.
Length	The length of the stator core.
Stacking Factor	The stacking factor of the stator core.
Steel Type	The steel type of the stator core.
Number of Slots	The number of slots the stator core contains.
Slot Type	The type of slots in the stator core
Lamination Sectors	The number of lamination sectors.
Pressboard Thickness	The magnetic press board thickness (0 for a non-magnetic press board).
Skew Width	The skew width measured in slot number.

Table 4.1

For defining slot type we need to choose the shape of the slot and then give inner dimension of the slot.

Hs0	Slot opening height.
Hs01	Slot closed bridge height.
Hs1	Wedge height.
Hs2	Slot body height.
Bs0	Slot opening width.
Bs1	Slot wedge maximum width.
Bs2	Slot body bottom width, 0 for parallel teeth.

Table 4.2

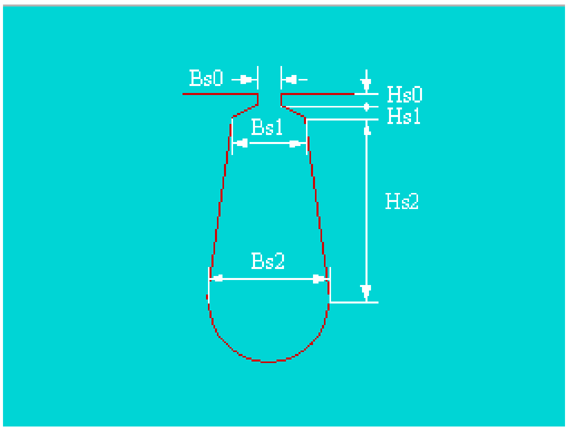


Fig. 4.1 Slot Dimensions

Rotor parameters,
Squirrel cage rotor is used for modelling of the machine. Slot type is defined in the same way as for stator. Values provided for End length, end ring height and end ring width. Types are defined for slot, bar conductor type and End ring conductor type.

For setup of the machine some of the quantities user have to define. Operation type, Load type, Rated Output type, Rated speed, Rated Voltage, Rated speed and operating temperature.

After designing the model we can validate the model for possible mistakes in Design setting or Analysis setup then analyse the model. Further for finite element analysis model can be exported to 2D or 3D model. Fig.4.2 shows the basic model of rotor and stator in Rmxprt. Fig. 4.3 shows stator design after assigning double layer and winding type.

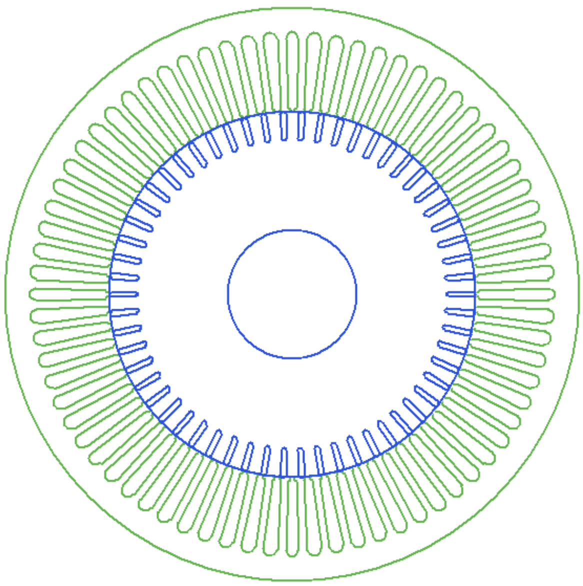


Fig. 4.2 Stator and Rotor design in Rmxprt

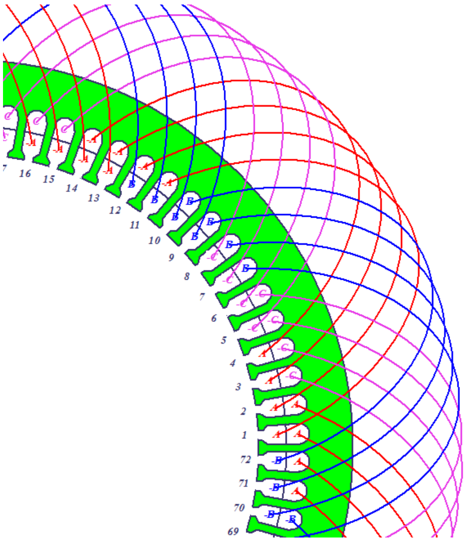


Fig. 4.3 Coils Connection in Rmxprt

While exporting from RMxprt to Maxwell2D, Rmxprt calculate equivalent resistance and lumped inductance. Stranded type of conductors used for windings. For a stranded winding, the resistance term is the complete DC resistance of the winding (since the solver does not determine resistance of a stranded winding) as well as the resistance of the end-effects, leads, source, etc. For both solid and stranded windings, the inductance term can represent: the extra inductance for a portion of the winding which is not modelled (for instance, end-effects), the leads connecting the winding to the source, or the source inductance. (The main winding inductance itself is calculated directly by the solver because Conductor's inductance varies as FE analysing proceed in machine model)

Maxwell2D model then excited by using Maxwell Circuit Editor. In our analysis we have choose the voltage type of excitation. All the coils are connected in Maxwell Circuit editor and then excited.

Simulation time given is 1 second and step time used is 0.002 sec. It takes approximately 3 hour to run the analysis complete. Transient solver used for analysis. Geometry mode is Cartesian XY.

The transient field simulator computes the time-domain magnetic fields in 2D or 3D. The source of the magnetic fields can be:

• Moving or non-moving time varying currents and voltages.

• Moving or non-moving permanent magnets and/or coils.

• Moving or non-moving external circuit coupling.

The quantities magnetic field, **H**, and the current distribution, **J**; the magnetic flux density, **B**, solved by the transient field simulator. Derived quantities such as forces, energy, torques, speed, position, winding flux linkage, and winding induced voltage may be calculated from these basic field quantities.

End connections are primarily used in passive conductors (with no source current assigned) when modelling cylindrical squirrel cage induction motors.

For evenly distributed conductors, the End Resistance, R_e, and the End Inductance, L_e, are assigned between the ends of each conductor pair.

Boundary Setup

1. Vector Potential Boundary
2. Master Boundary
3. Slave Boundary

Matching boundaries have an advantage of periodicity in a structure. Assigning the correct boundary condition allows us to make Finite Element analysis for a fraction of design to get the output in less time. Matching boundaries force the magnetic field at each point on one boundary (Slave boundary) to match the magnetic field at each corresponding point on the other surface (Master boundary). Use Vector Potential boundaries to set the magnetic vector potential to a constant value on a boundary.

Mesh Operation

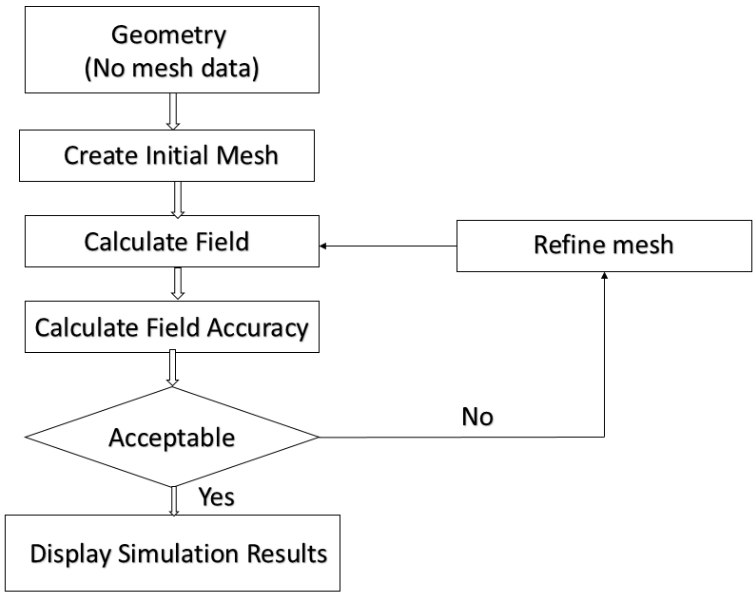


Fig. 4.4 Mesh operation

Maxwell2D mesh maker can create meshes on designed geometry according to predefined mesh operations. A mesh operation defines one or more conditions for some selected objects for mesh maker to create meshes that satisfy the conditions. RMxprt automatically sets up some mesh operations for different machine parts based on geometry sizes.

Figure 4.5 shows the mesh plot for half part of the machine. From figure, it is clearly visible that at corners mesh plot is denser and this is why while designing slots, one need to calculate more accurate dimension on corners.

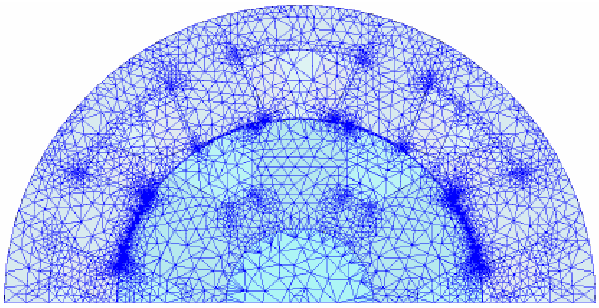


Fig. 4.5 Finite Element Mesh Plot

4.2 Finite Element Method

For designing of motor, flux path and empirical factors are unknown. Calculating these values with accurately is difficult process for humankind. For little change in geometry, there is a need of evaluate the accurate changes in performance parameters related to the magnetic field. “Ansys” Software comes with exclusive package for performing finite element analysis. Ansys Software accurately calculates magnetic fields and the related design parameters for motor of any 2D or 3D geometry with or without eddy currents and with accurate armature reaction.

4.2.1 Working Principal of FEM

Finite element method works on principal of energy conservation. The law of energy conservation in electric machine can be derived from Maxwell’s equations.
Flux density $\bar{B}$, field intensity$\bar{H}$, current density $\bar{J}$ and the electrical field $\bar{E}$ are related equations,

$$\bar{B} = \mu . \bar{H} \tag{12}$$

$$\bar{H} = \gamma . \bar{B} \tag{13}$$

$$\bar{J} = \sigma . \bar{E} \tag{14}$$

Where,
μ => Magnetic permeability of material
γ => Magnetic reluctivity of the material
σ => Electrical conductivity of conductor

The Maxwell's equations,

$$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \tag{15}$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{16}$$

$$\nabla . \bar{B} = 0 \tag{17}$$

Where,
$\bar{D}$ is the electric flux density / displacement vector.

CHAPTER 5

FE ANALYSIS AND SIMULATION RESULTS

The simulation results of various topologies designed for comparison between three phase and six phase machine has been presented in this chapter. Aim of this project is to compare the performance of six phase winding to three phase winding, keeping certain desired parameter constant. Finite element analysis is done on 2D machine model using the software Ansys Maxwell for very low speed to High speed range of operations. Faults analysis is also presented in this chapter. Torque at steady state, torque ripple, Currents in phases and efficiency of the motor analysed for speed range of 55 rpm to 3000 rpm. Driver for this motor is already designed which provide different voltage based on the speed application. Varies Slip is adjusted from drive side to feed require frequency for the voltage excitation.

5.1 Three Phase Machine

Lap winding is implemented in stator core for the three phase machine. Keeping six pole in the machine, double layer winding is implemented with chorded pitch. Number of slots per pole per phase is eight for three phase machine. Since six poles are there so six parallel paths are introduce in single phase. Connections of coils and excitation is given in given figure. 5.1.

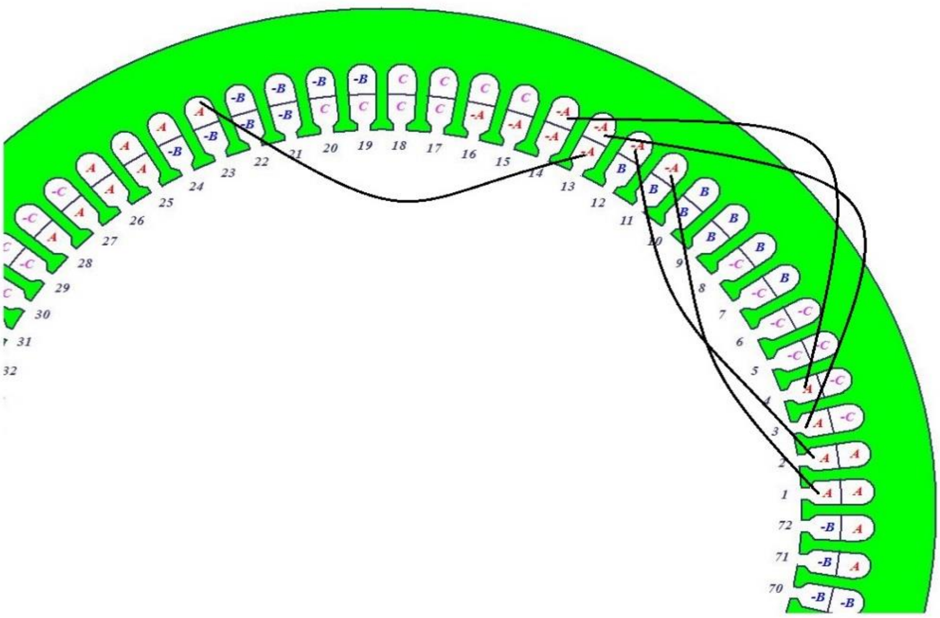


Fig 5.1 Three phase winding in Rmxprt

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
L1	+A	+A	+A	+A	-C	-C	-C	-C	+B	+B	+B	+B	-A	-A	-A	-A	+C	+C	+C	+C	-B	-B	-B	-B
L2	-B	-B	+A	+A	+A	+A	-C	-C	-C	-C	+B	+B	+B	+B	-A	-A	-A	-A	+C	+C	+C	+C	-B	-B

Table 5.1 Three phase lap winding pattern

Machine with3 phase and 72 coils will be having 24 coils per phase. Since six pole is there, hence these 24 coils are divided in 6 parallel paths such that each parallel path must have identical flux linkage which will generate same emf. Same emf because if emf is different for every parallel path then there will be a circulating current in winding, which actually destroy the flux generated in air gap. For generating same emf all parallel path should have same resistance and inductance value. Because of this coils are arranged in such way that all parallel path should have same emf generated. For example, take two parallel paths from phase A, in Fig 5.2.

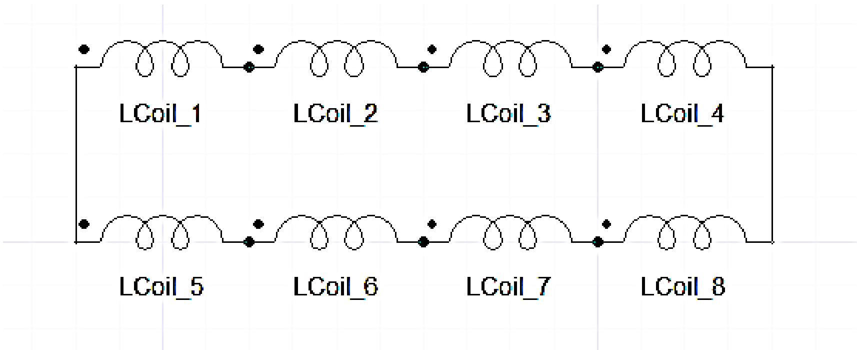


Fig. 5.2 Two parallel paths of Phase A winding

Some coils are given below by taking two coil sides from the given table 5.1, keeping coil pitch value 10.

Coil_1 => L2_S3 to L1_S13 (Coil side of layer 2(L2) and slot 3(S3) is connected to coil side of layer 1(L1) and slot 13(S13))

Coil_2 => L2_S4 to L1_S14

Coil_3 => L2_S5 to L1_S15

Coil_4 => L2_S6 to L1_S16

Coil_5 => L1_S25 to L2_S15

Coil_6 => L1_S26 to L2_S16

Coil_7 => L1_S27 to L2_S17

Coil_8 => L1_S28 to L2_S18 etc.

We can see from fig. 5.2 that the Coil_1 and Coil_5 are in same phase because difference of slots between slot 3 and slot 15 is 12.

Electrical angle of one slot is15^0 . For 12 slots it will be $15^0 \times 12$ =180^0. Since Coils 5, 6,7 and 8 are inverted with respect to Coils 1, 2,3 and 4, hence there will be another 180^0 phase difference which will make $180^0 + 180^0$ = 360^0 phase difference between the two parallel paths. Hence there will be no circulating current because of same emf will produce in these parallel paths. Apart from this number of conductors in single coil is taken 9.

For case study, three phase induction machine ran at constant speed of 1400 RPM. Voltages given for excitation are,

	Peak Voltage	Slip	Frequency	Phase Shift	R_{Dc} Ohm	L_{Lumped} (Henry)
Phase A	1531.3104	0.002	70.18247443	0	0.017559	5.13736e-005
Phase B	1531.3104	0.002	70.18247443	-120	0.017559	5.13736e-005
Phase C	1531.3104	0.002	70.18247443	-240	0.017559	5.13736e-005

Table 5.2 Three phase voltage excitation

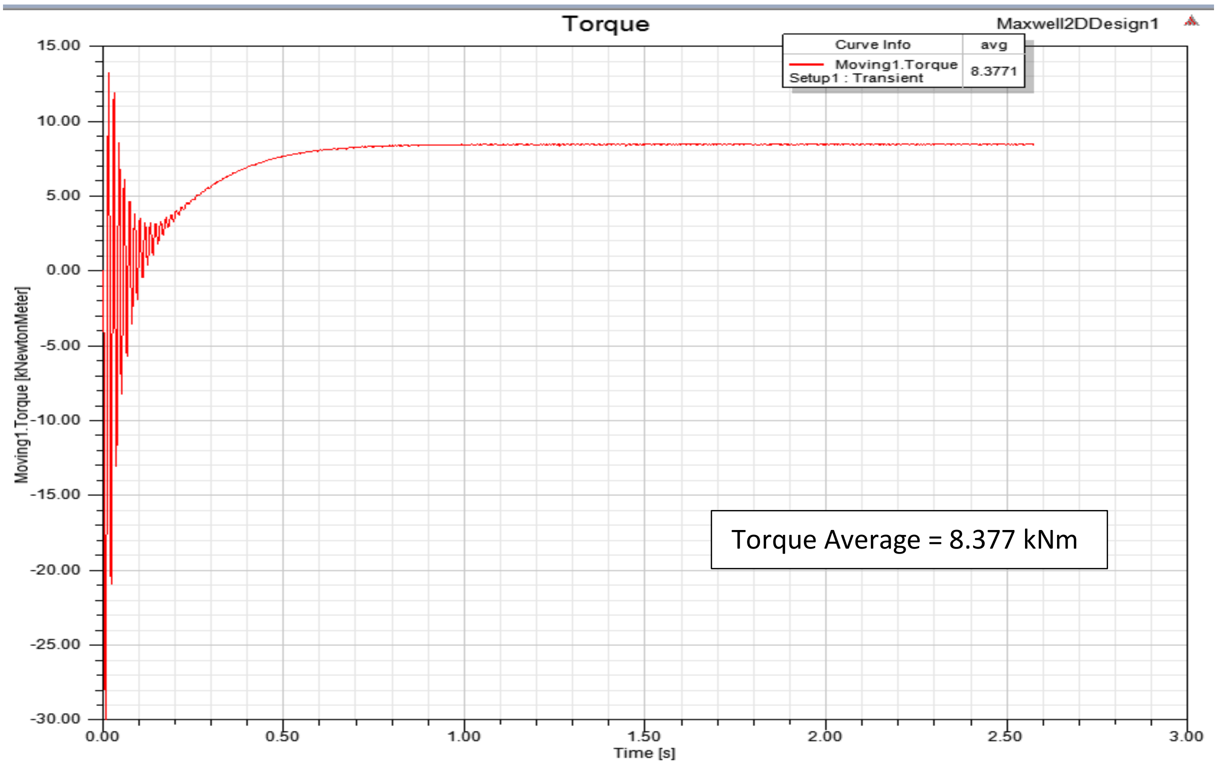


Fig. 5.3 Torque of three phase induction motor at 1400 RPM

Solution type transient solver is used. In figure 5.3, Torque settled after 0.65 second. Average torque is calculated for the steady state time period from 1 second to 2.5 second which is 8.377 kNm.

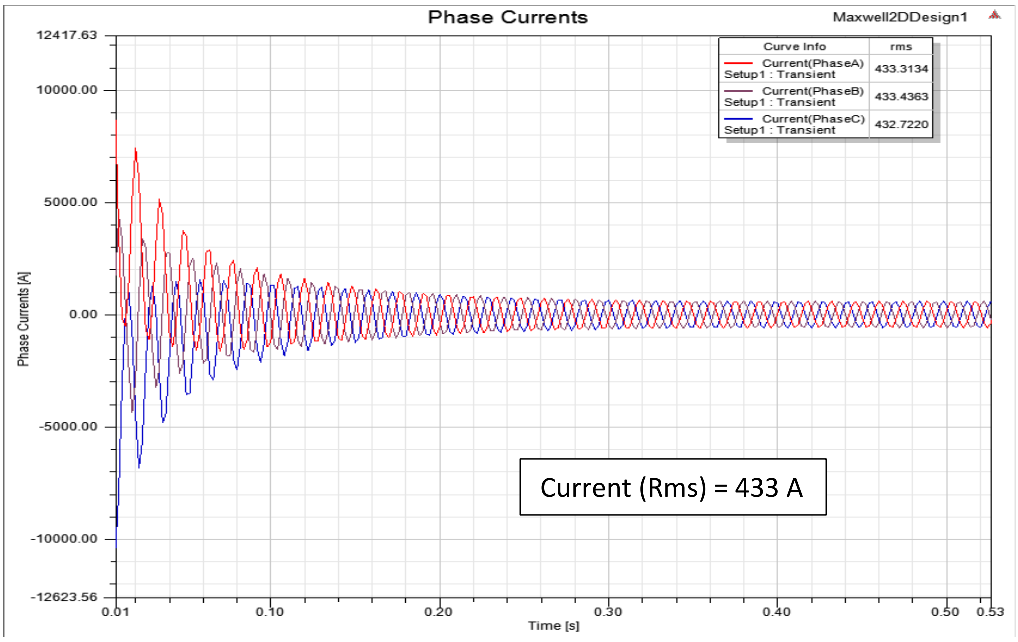


Fig. 5.4 Currents of three phase induction motor at 1400 RPM

In figure 5.4 RMS currents are calculated after settlement of the all three phase currents. Time period of 1 Second to 2.5 second is taken for calculating RMS Currents. Currents are found 433 Ampere for all three phases.

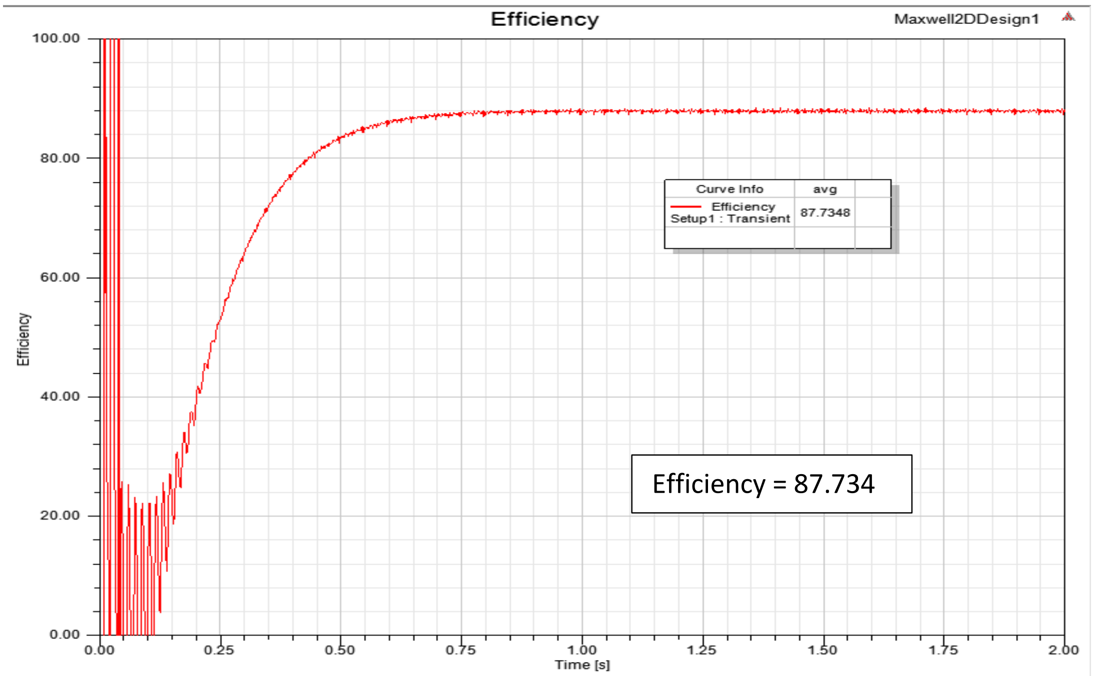


Fig. 5.5 Efficiency of three phase induction motor at 1400 RPM

Figure 5.5 shows that initially, efficiency shoot-up very high and then it settled on value of 87.73 percent.

5.2 Six Phase Machine Simulation Results

Three phase machine winding splits into six phase winding because of benefit of operating the machine in dual mode.

Lap winding results

Excitation for six phase induction motor is given in table 5.3. Finite element analysis has been performed. Number for parallel paths are reduced to three for this winding. So lumped inductance L_{Lumped} and DC resistance R_{Dc} for six phase was adjusted from the three phase data given in table 5.5.

	Peak Voltage (V)	Slip	Frequency	Phase Shift	R_{Dc} (ohm)	L_{Lumped} (Henry)
Phase A	1531.3104	0.003	70.2106319	0	0.017559*2	5.13736e-005*2
Phase B	1531.3104	0.003	70.2106319	-120	0.017559*2	5.13736e-005*2
Phase C	1531.3104	0.003	70.2106319	-240	0.017559*2	5.13736e-005*2
Phase A1	1531.3104	0.003	70.2106319	-30	0.017559*2	5.13736e-005*2
Phase B1	1531.3104	0.003	70.2106319	-150	0.017559*2	5.13736e-005*2
Phase C1	1531.3104	0.003	70.2106319	-270	0.017559*2	5.13736e-005*2

Table 5.3 Six phase voltage excitation

Taking 30^0 phase spread, 6 pole lap winding is designed for six phase machine. Coil pitch = 12 (Full pitch winding)

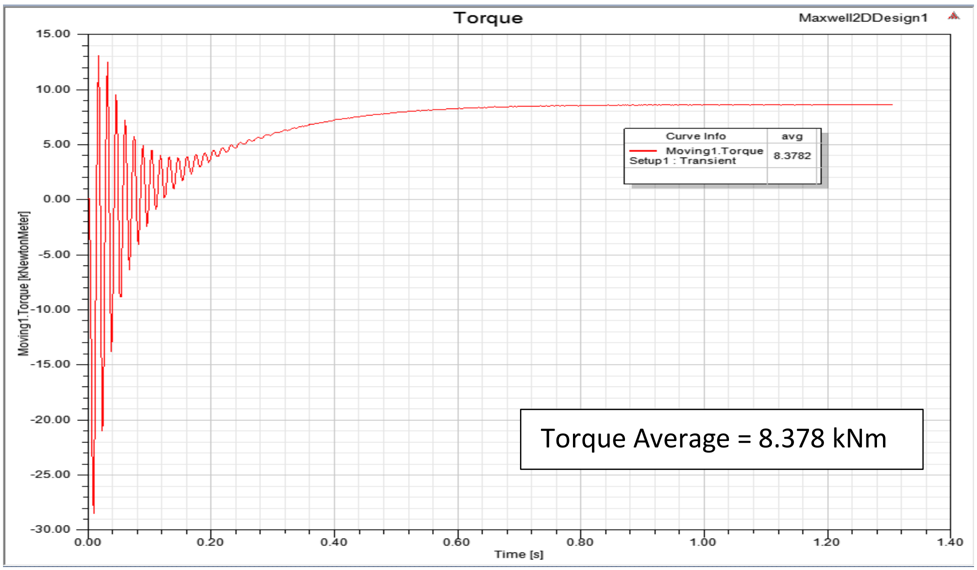


Fig. 5.6 Torque of six phase induction motor at 1400 RPM

Solution type transient solver is used. Slip varied for achieving the same torque which was produced by 3 phase induction machine. Varying the slip constrain to change the supply frequency for 6 phase induction motor. In figure 5.6 Since Torque settled after 0.65 second, Average torque is calculated for the steady state time period from 0.65 second to 1.2 second which is 8.377 kNm.

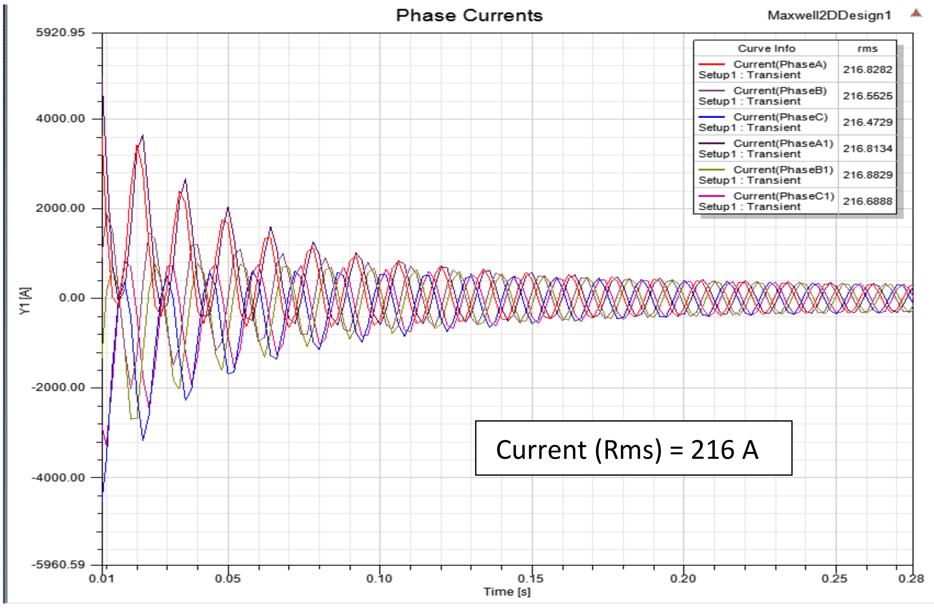


Fig. 5.7 Currents of three phase induction motor at 1400 RPM

Time period from 0.65 Second to 1 second is taken for calculating RMS Currents. From figure5.7 it is clear that currents for all phases are 216 Ampere which is almost half of the current of three phase induction motor. In term of improvement in torque for using six phase induction motor over three phase induction motor is very negligible if currents are keep half of the full currents in three phase motor.

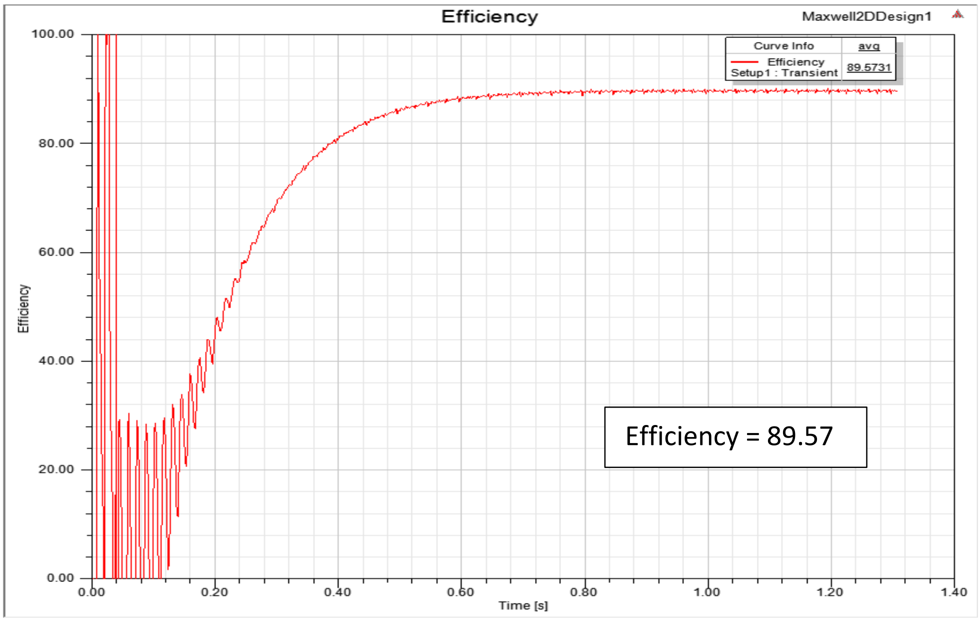


Fig. 5.8 Efficiency of six phase induction motor at 1400 RPM

In figure 5.8 Efficiency obtain is 89.57 percent which is Approx. 1.9 percent more than that of three phase induction motor.

5.3 Case study for different speed of operation:

Figure 5.9 and figure 5.10 are the results obtained from low speed to high speed operation of the machine. Comparisons are performed for three phase machine to six phase machine for different types of windings which are already discussed in chapter 2. For low speed operation 55, 75, 150 and 300 RPM are taken and for high speed operation 600, 800, 1000, 1400, 1600, 2100, 2400, 3000, 3180 RPM are taken for analysis. Induction motor ran maintaining constant speed, for various winding problem slip values adjusted to get the same value of torque for a particular speed of operation. Getting same values of torque make it comfortable to compare their currents in order to see the possible benefit of particular winding. Benefit is measured on the basis that, for producing same torque which model is pumping less currents.

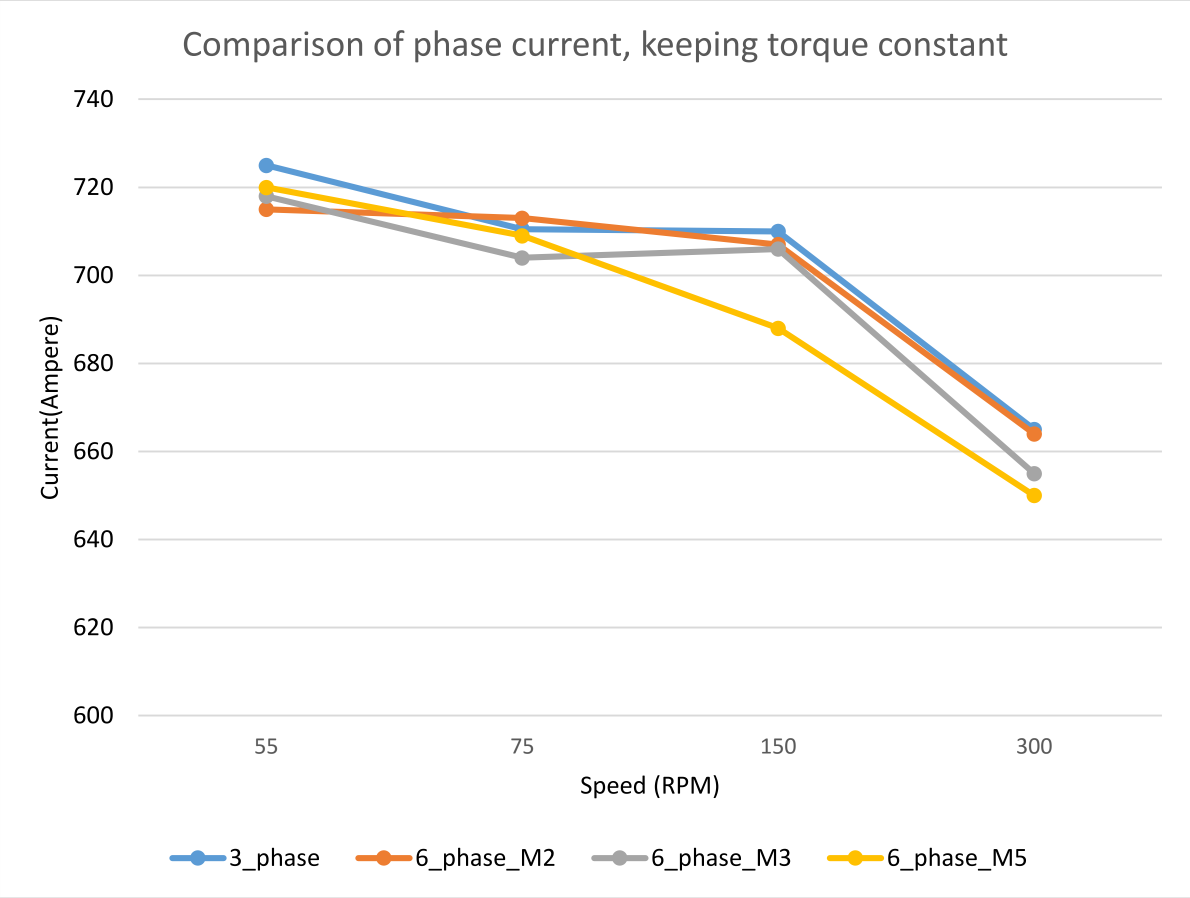


Fig. 5.9 Low speed performance

From Figure 5.9 and figure 5.10 it is clear that keeping same power input and Steady state torque, currents withdrawn from voltage sources are almost same. This result is obtained from finite element analysis of the machine in Maxwell2D.

Models for 6 phase M2, M3 and M4 are given in as,

6_phase_M2 => 6 phase Lap winding keeping 30^ophase spread with full pitch winding.

6_phase_M3 => 6 phase Lap winding keeping 45^o phase spread with full pitch winding.

6_phase_M4 => 6 phase Lap winding keeping 60^o phase spread with chorded coil pitch 10.

Apart from these three models some other type of model designed for analysis, which is Lap winding keeping 60^o phase spread with different coil pitch, because of their less efficiency compares to 10 coil pitch winding they are not considered for study.

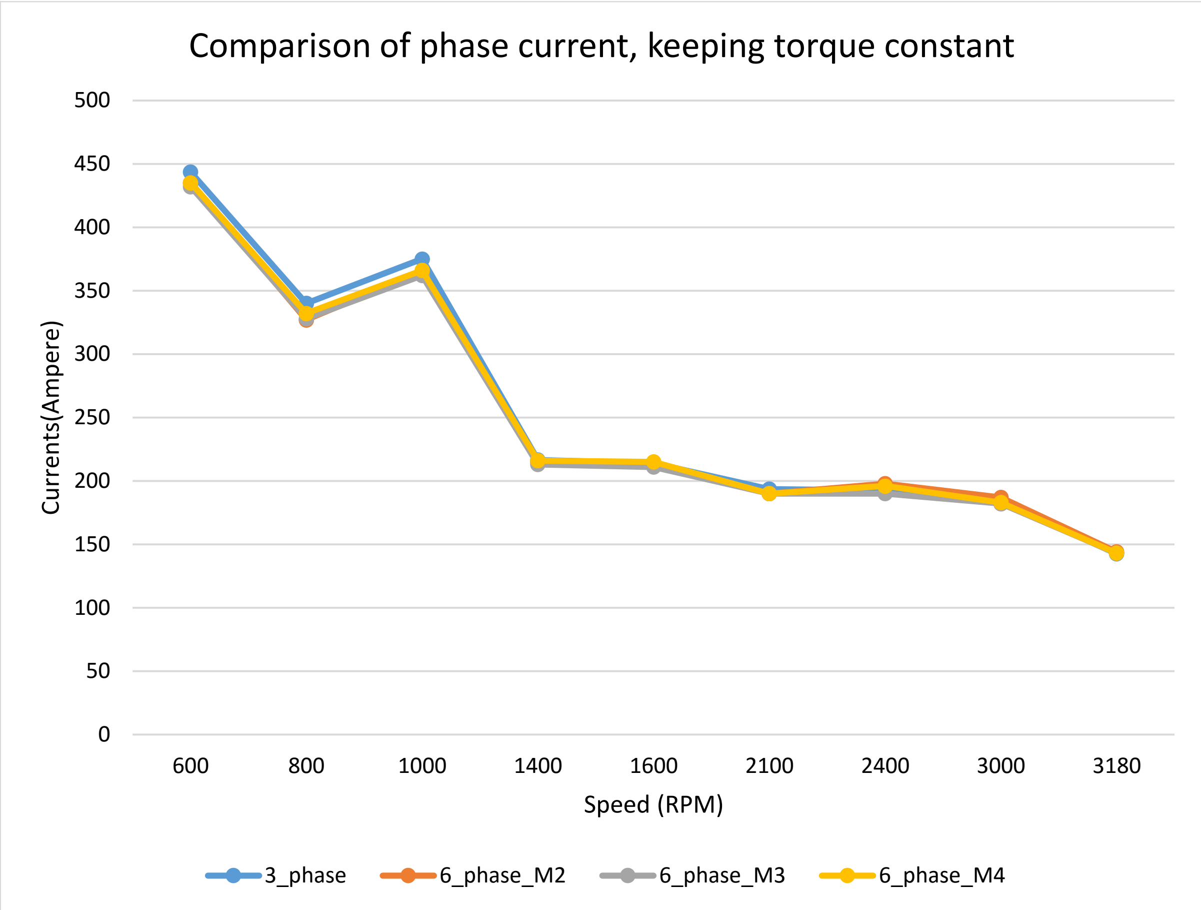


Fig. 5.10 High speed performance

Slip values used for various speeds are given in table 5.4 for low speed operations.

Speed (RPM)	3 Phase	6_Phase_M2	6_Phase_M3	6_Phase_M4
55	0.15	0.16	0.175	0.163
75	0.11	0.136	0.13	0.13
150	0.06	0.0715	0.075	0.063
300	0.03	0.036	0.04	0.032

Table 5.4 Slip used for different model

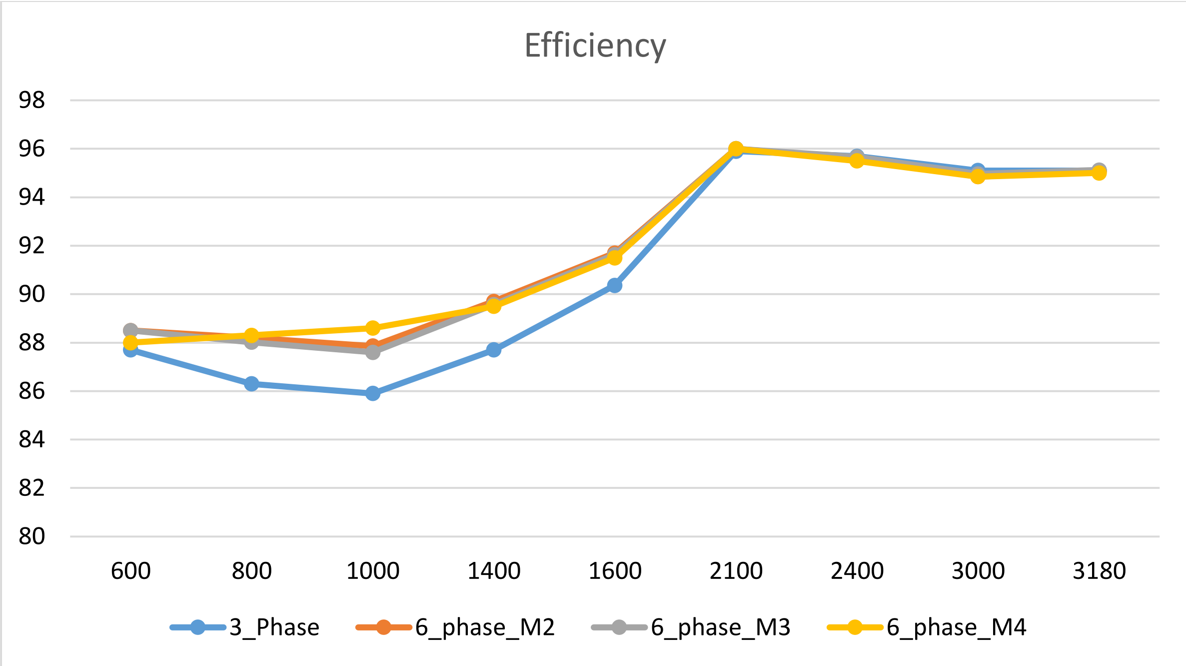


Fig. 5.11 Efficiency at high speed operation

Figure 5.11 indicates, from efficiency point of view there are 2 to 3 % more efficiency at higher speed for six phase induction machine compare to that of the three phase induction machine. Efficiency for low speed operation is almost same for 3 phase and 6 phase IM. After 600 RPM efficiency improved by a factor of 2 to 3 %. Efficiency after reaching 96 % at a speed of 2100 RPM it became almost constant for higher speeds.

No.	Model	Winding Type	Phase Voltage (V)	Phase Spread	R_{Dc} (Ohm)	L_{lumped} (Henry)	T_{avg} (kNm)	I_{rms} (Amp)
1	3 Parallel paths	Lap	V	30^o	$2R_b$	$2L_b$	16.45	332
2	3 Parallel paths	Concentric	V	30^o	$2R_b$	$2L_b$	16.30	331
3	6 parallel paths	Lap	$\frac{V}{2}$	30^o	$\frac{R_b}{2}$	$\frac{L_b}{2}$	16.76	671
4	2 parallel paths	Wave	$\frac{3V}{2}$	30^o	$\frac{9R_b}{2}$	$\frac{9R_b}{2}$	16.76	227

Table. 5.5 Simulation results for different winding patterns

Table 5.5 shows the results of simulation carried out on 6phase induction motor with 30^0 phase spread winding for different number of parallel paths which make it either lap or wave winding. DC Resistance R_{Dc} and lumped inductance L_{lumped} of the winding adjusted from value of R_b and L_b. R_b is 0.017559 ohm and L_b is 5.13736e-005 Henry. Average torque is calculated for the period when steady state reached to the end of the simulation time. Time step taken for simulation is 0.002 sec and end time of the simulation is 1 second. Voltage is adjusted keeping voltage excitation per coil same for all windings.

It is concluded that for almost same torque and same input power, model can be chosen on the basis of high voltage and low current application or low voltage and high current application without even disturbing the output torque and speed of the machine.

If we choose to go for 60^o phase spread winding from 30^o phase spread, one factor is needed to adjust for voltage excitation, keeping the same voltage per coil. Figure 5.12 shows that vector A is formed by emf induced in 30^o phase spread winding from one of the layer since two slots will be in sequence, After considering both layer the total emf generated in one phase spread will be “2A”. For 60^o phase spread winding all four slots are in consecutive order which made a vector “R” from its emf generated. So as we move from 30^o phase spread to 60^o phase spread a fraction need to multiply in voltage value.

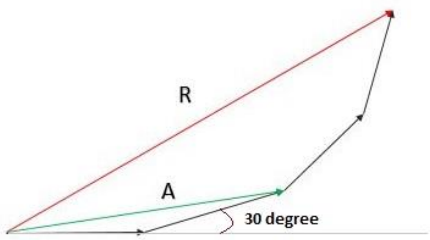


Fig. 5.12 Vector diagram of emf phasor

Figure 5.12 shows that if 4 coils which make number of slots per pole per phase are in 60^o phase spread the resultant emf generated will be R. If these 4 coils are in 30^o phase spread the resulting emf will be 2A.

Values of R is 3.83063 and A is 1.98288. So,

$$Fraction = \frac{R}{2A} = 1.03528$$

5.4 Faults Analysis

One of the main advantages of a multiphase motor over a conventional three-phase motor is the improved reliability due to its fault tolerance features. A comparative analysis is performed between six phase induction motor to three phase induction motor. Various phase loss conditions are applied on six phase configuration and same task performed for three phase machine. In results, it is found that the ripple content in the torque for three phase is much more than the six phase toque ripple. So it is clear that the six phase provides significant output torque to run the system even when such a machine loses one or more phases. Phase missing implies that in excitation circuit, voltage source will be opened.

Three phase induction machine analysis on loss of single phase C with Phase A and B are healthy.

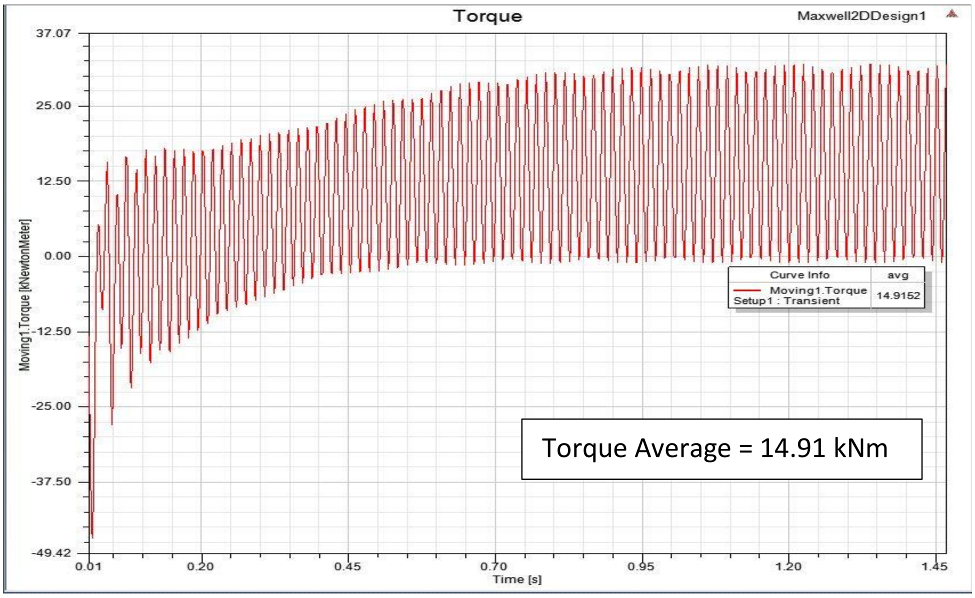


Fig. 5.13 Torque of 3 phase machine under single phase loss

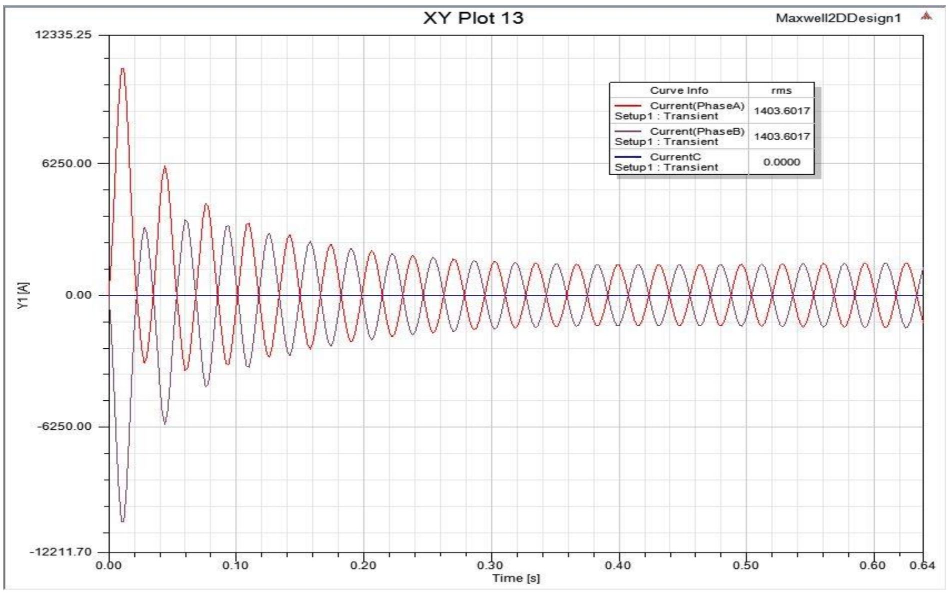


Fig. 5.14 Currents of 3 phase machine under single phase loss

Figure 5.13 shows really high ripple in torque under single phase loss. Ripple was around 112% of the average torque taken for the time period 0.75 sec to 1.25 sec. Currents drawn by single phase is 1403 ampere (rms). Figure 5.15 shows six phase induction machine torque under single phase loss. Ripple in torque is really less compare to that of the three phase torque. So ripple is approx. 9 % of the average torque. Currents drawn from five phases are given in table 5.6.

Fig. 5.15 to 5.16 shows the six phase induction machine analysis results, on loss of single phase C1 with Phase A, B, C, A1 and B1 are healthy.

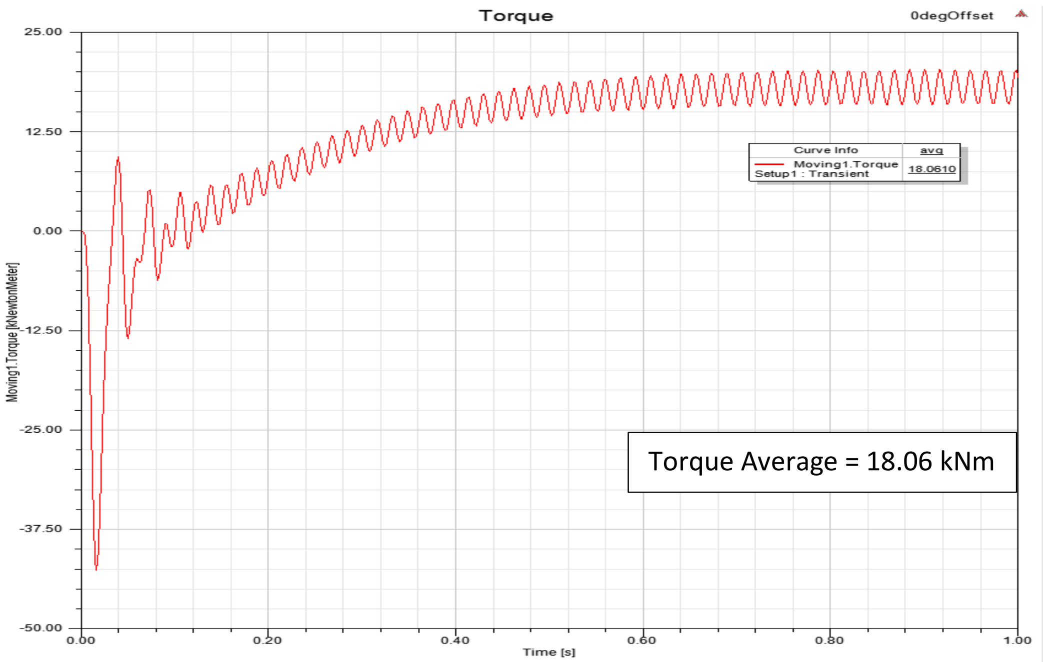


Fig. 5.15 Torque of 6 phase machine under single phase loss

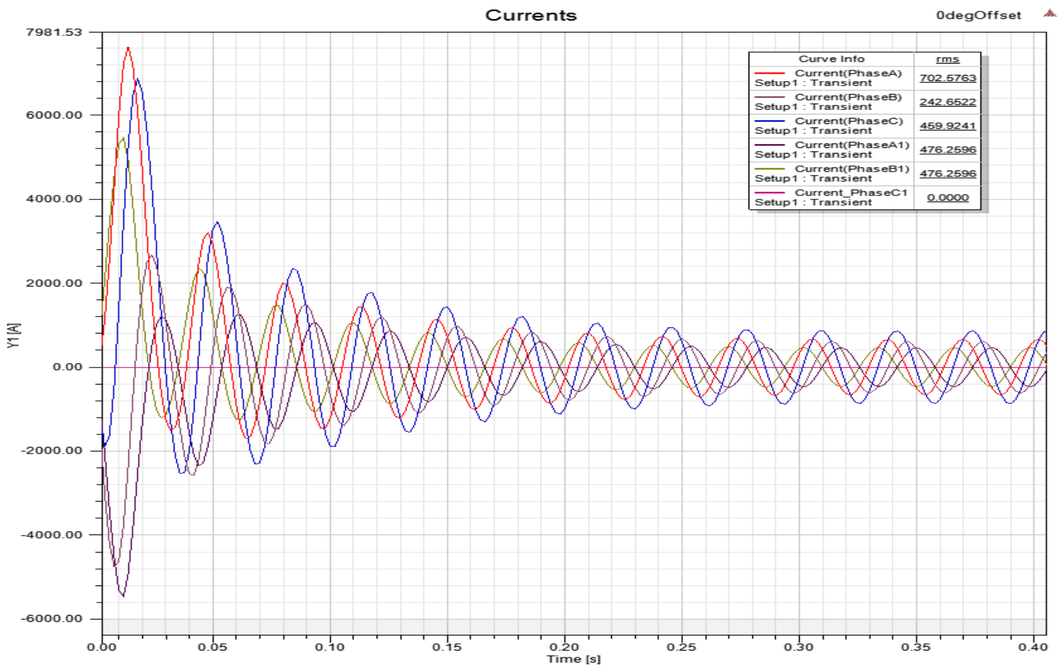


Fig. 5.16 Currents of 6 phase machine under single phase loss

Complete analysis results on faults tolerance of six phase machine as compared to three phase machine shown in the table 5.6. Some other faults analysis performed on six phase under two phase loss. Simulations are performed for two near phase loss which is B1&C1 and Two far phases from different set of three phase excitation which is B&C1 in one case and C&C1 in another case. From phase loss C & C1 it can be seen that ripple is 108.5% which is almost equal to the single phase C loss in three phase machine but the current withdrawn is different (Phase A current in 3Phase case is 1403 and phase A current in 6phase machine is 585 ampere which is less than the half of the current 1403). Under loss of two near phases B1 and C1 the ripple in torque is very less which is 16.2% only.

Connection	Condition	Torque Ripple	Torque Average (kNm)	I_{rms} (Ampere)	
3 Phase	A, B phase healthy Phase loss of phase C	112%	14.79	Phase A	1403
				Phase B	1403
				Phase C	0
6 Phase	A, B, C, A1and B1 phase healthy Phase loss of phase C1	9.08%	18.06	Phase A	702
				Phase B	242
				Phase C	459
				Phase A1	476
				Phase B1	476
				Phase C1	0
6 Phase	A, B, C and A1 phase healthy Phase loss of phase B1 and C1	16.2%	16.97	Phase A	719
				Phase B	703
				Phase C	786
				Phase A1	0
				Phase B1	0
				Phase C1	0
6 Phase	A, C, A1and B1 phase healthy Phase loss of phase B and C1	45.01%	16.60	Phase A	684
				Phase B	0
				Phase C	684
				Phase A1	589
				Phase B1	589
				Phase C1	0
6 Phase	A, B, A1and B1 phase healthy Phase loss of phase C and C1	108.5%	14.83	Phase A	585
				Phase B	585
				Phase C	0
				Phase A1	585
				Phase B1	585
				Phase C1	0

Table. 5.6 Faults Analysis results

CONCLUSION

A broad comparison between six phase and three phase winding have been studied. Constant speed performance from low to high speed range have been analysed for many type of winding pattern, from results of comparison of six phase and three phase, there is not much difference in half of the current of three phase machine to six phase machine current for producing same steady state torque value. Slips have very slight variations for producing same torque for different type of windings. Faults analysis have been done for six phase and three phase machine and it has been observed that for six phase really less ripple in case of one phase missing so the average torque produced by six phase machine is higher than three phase machine. There is advantage of using fractional winding for reducing of some of the harmonics but fractional winding was not implemented in this project work because of number of poles and slots are fixed for the designed machine.

Future work:

For this project, analysis has been performed considering six phase inverter for fixed voltage supply. Inverter can be model for some particular type of winding on basis the requirement of maximum current in one phase, power and voltage application. Here winding is designed considering the fact that phase changing is suitable from three phase to six phase. We can further implement pole changing winding or phase-pole changing winding for multipurpose behaviour of the motor. For improving the steady state torque of induction motor we can implement injection of third harmonic current technique, which is completely different field of study.

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