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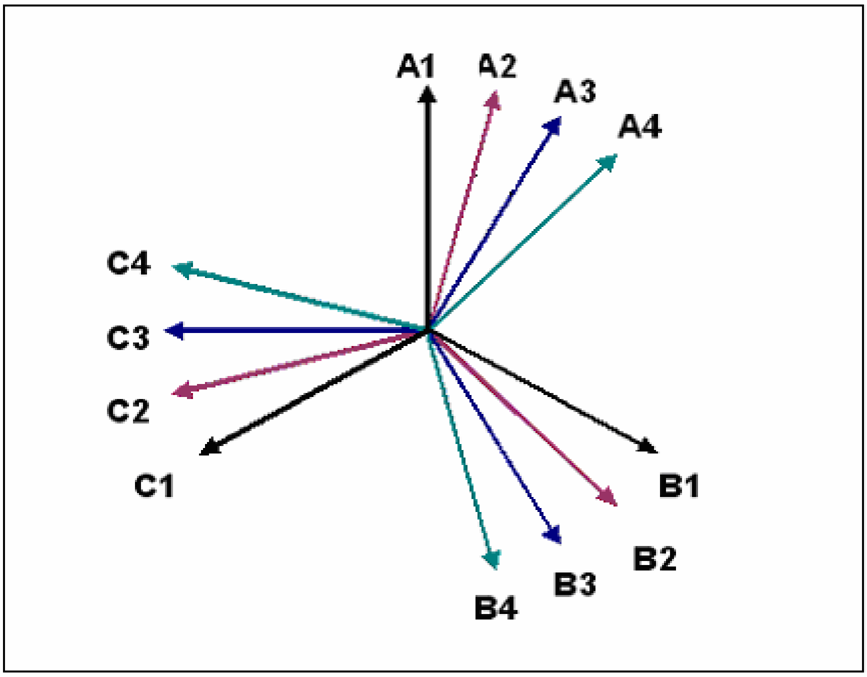

Comparative analysis of multiphase machines

Master's Thesis in the International Master's programme in Electric Power Engineering

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To

My parents

My children Muqeet and Izan

Summary:

This report describes performance analysis of multiphase machines. There has been a growing interest in multiphase machines due to their fault tolerant feature which is suitable for reliability sensitive applications like aerospace, hybrid vehicles and traction. There is a need to study different aspects of these machines in further detail for commercial realization. In this report, FEM simulation results of multiphase machines are presented with focus on the 6-phase machines.

A comprehensive comparison of multiphase machines in general and the 6-phase machine in particular has been presented. In the 6-phase machines, there are no contributions of the 5^{th}, 7^{th}, 17^{th} and 19^{th} harmonics from the stator. This feature eliminates 6^{th} and 18^{th} torque pulsations and rotor surface losses are reduced. Total losses of the 6-phase machines are usually lower. However amount of loss reduction is topology dependant. In induction machines, loss reduction can be variable depending upon star or delta connection. Loss reduction in PM machines is rotor design dependant. Low order MMF harmonics from the stator are further eliminated with increasing phase number. The value of THD drops when going from a 3-phase to a 12-phase machine. The 6-phase synchronous machine is evaluated in further depth which shows drop in damper bar losses for sinusoidal supply when analyzing affects of possible supply angle mismatch from the converter. It is shown that the 6-phase machine is sensitive to supply angle mismatch. Total losses of the machine increase with increase of deviation from 30 degrees supply angle.

A comprehensive study is made on the influences of parameters, such as winding layout, wedge material properties and rotor pole shape of a 3-phase synchronous machine and results are compared with the 6-phase machine. Both machines are already well optimized for individual parameters. However, from space harmonics point of view, use of short pitch, magnetic wedge and arched pole is helpful to reduce rotor surface losses with a slight increase of total losses. The 6-phase machine is more suited to these changes. Although, total losses of the machine are slightly higher, yet there is a decrease of rotor surface losses. A detailed study of the induction and the PM machine is suggested as future work.

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1 INTRODUCTION

1.1 Purpose

The purpose of the report is to compare the performance of multiphase machines with conventional three phase machines. The study also includes the influences of supply angle of multiphase machines on the air gap harmonics and total losses of 6-phase salient pole synchronous machines by using FEM simulations. Besides, parametric and material sensitivity in a 3-phase machine is also studied.

1.2 Scope

The target of the report is to build a better understanding of multiphase machines in general and the 6-phase machines specifically. Performance of multiphase machines with different topologies and winding layouts have been investigated and a comprehensive comparison with existing three phase machine has been reported. For further understanding of the 6-phase machines, salient pole synchronous machine is investigated for supply angle influences on losses and space harmonics in order to visualize affects of mismatch in inverter supply. The report gives an evaluation of parametric sensitivity of 3-phase machines and compares results with 6-phase synchronous machines. This report also gives an overview of reported concepts about multiphase machines in literature review and patents survey. This report is based on FEM simulations and no experiment has been performed.

1.3 Structure

This report has the following structure.

Section 1 Introduction (this section) describes the purpose and scope for this report as well as terms, abbreviations and acronyms used.

Section 2 Literature review and patents survey, exhibits the relevant works reported in recognized literature resources. Methodology describes the used methods, nature of obtained results and simulation limitations.

Section 3 investigates the performance of six phase synchronous machine in a situation when there is mismatch in the inverter supply angle of the machine.

Section 4 sensitivity study of 3-phase synchronous machine to design parameters compares the results with the default design.

Section 5 compares the performance of full pitch 3-phase and 6-phase salient pole synchronous machines. Sensitivity of these machines to design parameters is also compared.

Section 6 describes the harmonic analysis of the 9 and 12-phase synchronous machines by differentiating the stator MMF harmonics patterns.

Section 7 investigates the performance of six phase induction machine and results are compared with 3-phase full pitch and short pitch cases. The machines are simulated in both star and delta configurations and results are compared.

Section 8 covers performance comparison of six phase permanent magnet synchronous machine with the 3-phase permanent magnet synchronous machine.

Section 9 Conclusions and future work lists the conclusions extracted from this work and propose some ideas for future work.

2 BACKGROUND

2.1 Literature review

Three phase machines have been in use more frequently for last century. However, there has been a growing interest in multiphase machines in application areas where reliability is a prime target. Development of application areas like traction and aerospace has provided the motivation for research in multiphase machines. Although, higher reliability in multiphase machines is the major area of attraction, there are some additional benefits also which include reduced torque pulsations, less acoustic noise, reduced total losses and reduced rating of drive circuits.

In this section, a literature survey on work accomplished in the field of multiphase machines is presented. Toliyat [1] presented an analysis of the multiphase induction machine describing the flux linkages in the machine. The model is restricted to full pitch concentrated windings but both transient and steady state behavior were simulated. Toliyat [2] also presents the analysis of a five phase machine and compares its results with three phase machine. In [3] Vetter has analyzed the damper winding currents of a synchronous machine with a solid iron rotor based on the self and mutual inductance modeling technique. Theoretical results are compared with measured damper bar currents of a six phase synchronous machine fed by two six pulse converters.

Zamani [4] has developed a complete model of a six phase self commutated synchronous machine considering effects of both time and space harmonics. Equations for calculation of machine inductances are developed. Simulation results of uniform and salient pole six phase machine are compared which conclude that the air gap flux density distribution is non uniform and torque pulsation is higher in the salient pole machine due to space harmonics.

Lipo [5] developed a closed loop current control scheme for a multiphase induction drive to maintain a smooth torque following the loss of one phase. The method used an asymmetrical current pattern on the remaining phases to maintain pre-fault rotating MMF. Zhao and Lipo [6] investigated field oriented control methods for a six phase loss. A d-q dynamic model was developed and verified on an experimental machine.

Yuriy [7] has discussed adjustable speed drives with multiphase machines. The theoretical model takes into account all current and space harmonics of the MMF. It concludes that multiphase machines should have a full pitch winding with rectangular space distribution of the phase MMF. Terrien [8] has modeled and simulated high power electrical drives using a double star synchronous motor. Effects of winding displacement angle on torque ripple and harmonics have been explored. Two configurations of current and voltage supply have been investigated. Comparisons show that with current supply torque ripple depends on the physical winding displacement angle. However, in the case of voltage supply torque ripple depends on the physical winding displacement angle as well as on leakage inductance.

Schulte [9] has discussed noise reduction using multi-phase windings for synchronous machine. The paper emphasizes that variation of winding arrangement based on mutual displacement of two winding systems allows for the reduction of body sound at reasonable out put power forfeits. Mcmohan [10] and Dorell [11] believe that cost effective integrated drives with good performance can be designed using square wave excited multiphase motors. Lipo [12] describes a technique of injecting third harmonic zero sequence current components in the phase current which greatly improves the machine torque density. Singh [13] provides a useful survey of developments in multiphase induction machine drives, highlighting issues such as fault tolerance and reliability. Williamson [14] reviews the current trend for multiphase machine in propulsion applications and discusses issue of fault tolerance in multiphase drives. Possible post-fault control strategies have been discussed which minimizes motor losses and torque pulsation due to the electrical imbalance following loss of one or more phases. Smith and Williamson [15] explain losses and torque pulsations in multiphase induction machines. The paper provides comprehensive fundamentals of multiphase machines developing basic equations and understanding.

Lin [16] develops an equivalent circuit model of a cycloconverter fed multiphase synchronous machine. Simulations of a 12-phase synchronous machine have been taken as an example. An approach has been proposed which decomposes d and q- axis variables of multiphase synchronous machine into low and high frequency components. The paper concludes that simulation results are correct for steady and quasi steady state analysis.

Parsa [17] has summarized the work done by various researchers on multiphase machines outlining advantages of multiphase machines. It is concluded that besides reducing torque pulsations, multiphase machines offer additional degrees of freedom to improve overall performance and reliability of the system. Dorell [18] has implemented a model for a 6-phase induction machine driven by an inverter, operating in 6-pulse modes. Results have been verified experimentally and it is illustrated that the improvement in inverter efficiency when operating in six pulse mode may improve the performance of the overall system.

Apsley [19] presents induction motor performance as function of phase number. The paper has developed a model for multiphase machines using the technique of generalized harmonic analysis and has validated it by comparison with experimental data. A detailed technology status review of multiphase induction motor drives is presented in [20] by Levi which covers all aspects of multiphase motor drives. The paper describes characteristics, modeling, control schemes and advantages of multiphase machines while referring to all reported concepts till date. The issue of fault tolerance has also been discussed in detail.

2.2 Patent survey

A comprehensive patent survey of multiphase machines is discussed in this section. Multiphase machines is a very general term which covers many aspects like machine topologies, winding layouts, number of phases, supply and drive circuits. Some related aspects like torque improvement and fault detection are also addressed here. A search criteria is based on key words and their combinations like Multiphase drives/ machines, dual the stator machine, spilt phase machines, synchronous, induction/asynchronous machines, PM machines, reluctance and stepper motors/machines. This survey covers many of the reported patents irrespective of their validity. However results have been arranged in chronological manner starting with older filed patents up till today. Results are categorized as follows:

1. Machine topology
2. Winding layout/ connection
3. Drive circuit

2.2.1 Machine topology

Multiphase machines have been implemented in different number of phases and topologies like induction, permanent magnet claw pole and stepper motors:

1. Takahashi (JP60009536 19850118) had patents of 5 phase brushless DC motor with improved efficiency and reduced torque ripple.
2. MINEBEA KK (KR200169497Y 20000325) owns the patents of 5 phase hybrid type stepping motor.
3. Japan Servo Co., Ltd (6,153,953 20001128) the patent claims a multiphase permanent magnet type stepper motor comprising of n, number of excitation coils in the stator cores where ''n'' is odd and not smaller than 5.
4. Lipo (US 6,242,884 B1 20010605) claims the patents of a dual stator induction machine drives. The induction machine has two stator windings which are supplied from two separate sources. The two stator windings have different number of poles to essentially eliminate magnetic coupling between the two windings and to decouple torque developed by each set of winding. Power is supplied to the two winding sets by two separate frequency invertors.
5. Bradfield (US 2005/0006973 A1 20050113) covers a twin coil claw pole rotor with a five phase stator winding. The rotor consists of two segments where each segment has P/2 claw poles while ‘P’ is an even number.

2.2.2 Multiphase winding

1. Khtutoretsky (4,132,914 19790102) claims an arrangement in multiphase electrical machines in which a six phase winding is provided with reduced maximum voltage between terminals in the end portion. Two sets of three phase windings are wound in opposite directions which help to reduce the highest possible voltage in the phase zone junction.
2. GE Canada Inc. (2,086,185 19921223) suggests a dynamoelectric machine with a dual stator winding. Two three-phase sets of windings are 30 degrees displaced and connected in star configuration. The patent suggests a connection of winding in a way that it can be connected to a 12 pulse LCI source. Alternatively, the winding can be connected in a way to be supplied by a conventional power source.
3. Akhunov (RU2227357 20040220) and (RU2227358 20040220) discuss nine and twelve-phase fractional windings of the machines to reduce dominant harmonics in MMF waveforms in order to decrease differential dissipation.

2.2.3 Drive circuit

1. Electric Power Research Institute Inc. (WO 97/12438 19970403) discloses an inverter controlled induction machine with extended speed range. A four pole induction machine with extended speed range includes six independent stator windings. The stator winding is supplied by two current regulated inverters. The machine operates in two modes: a four pole machine, when both inverters supply current with the same polarity, and as a two pole machine, when current supplied from one inverter has reversed polarity compared to the other inverter supplied current.
2. Texas A&M University (US 6,426,605 B1 20020713) has the patents of a five phase induction machine system and its operating method. The machine is controlled by a processor and for each phase, the machine receives a command current. It is claimed that the method helps to improve the machines power density.
3. MELEC CC (JP 2004023991 20040122) has the patents for the driving method of a 5 phase stepping motor. It is claimed that the method has higher accuracy, resolution and helps to reduce the size of the stepping motor.

4. Coverteam Ltd (GB 2,436927A 20071010) discloses a drive circuit for a machine with a dual stator winding. Two 3-phase winding sets are supplied by two PWM inverter sets. Stator coils in the first and second winding sets are connected in such a way that their vector sum of voltages across the stator coils is the same for each set of winding.
5. Westinghouse (4,952,915 19900828) has the patents of failed electrical component detector for multiphase electric machines.
6. Lipo (US 2003/0085627 A1 20030508) claims a multiphase electric motor with third harmonic current injection. The motor comprises of a stator with a dual three phase winding which is displaced 30 degrees. Power is supplied to the motor by two sources at the same fundamental frequency and a component of the third harmonic. The additional third harmonic component reduces peak flux density allowing an increase in effective torque.

2.3 Methodology

The studied machines are simulated using FEM. All work has been done in three application modes:

- Magneto static
- Harmonic mode
- Time stepping

2.3.1 Magneto static mode

Flux density of machine is a function of space and time. Thus the air gap of an electric machine has a complicated flux picture containing time and space harmonics which are difficult to distinguish. Magneto static application is a helpful tool as time is static at a particular instant. Only space harmonics are present in the picture. Quantities which are of interest in this application mode are:

- Flux density
- Load angle
- Field current

One limitation of this application mode is that it does not give any information of induced quantities as time is constant.

2.3.2 Harmonic Mode

This application mode has been used for induction machines only. Harmonic mode simulations of machines give satisfactory results for the following:

- Torque – speed curves
- Nominal operation point
- Single slip

The rotor of the machine in this application mode is stationary. Analysis of the machine is carried out by assuming fields with slip frequency. This puts a limitation on accuracy of losses obtained from this mode. This limitation provides a necessary motivation for time dependant simulations of the machine.

2.3.3 Time stepping mode

Simulations in this application mode are time dependant and results have been computed by calculating all time dependant parameters of the machine. It is a more practical mode giving detailed information of induced quantities and losses in all components of a machine. Quantities which are of interest are:

- Induced currents
- Induced emf
- Torque fluctuations
- Time harmonics
- Losses

Time steps are user defined and different mesh density and accuracy can be requested. However, high number of steps per period is required for accurate harmonic analysis of the machine which requires long time simulations.

3 THE SIX PHASE SYNCHRONOUS MACHINE ANALYSIS

3.1 Introduction

The studied machine in this particular case is a six phase salient pole synchronous machine. It has a full pitch winding and uses two sets of the 3-phase windings that are displaced 30 degrees in space, as shown in Figure 3.1. Redundancy is the basic motivation for use of full pitch windings in the 6-phase machines. The idea is to make two 3-phase systems electrically and magnetically independent so that a fault in one system should not affect the other system.

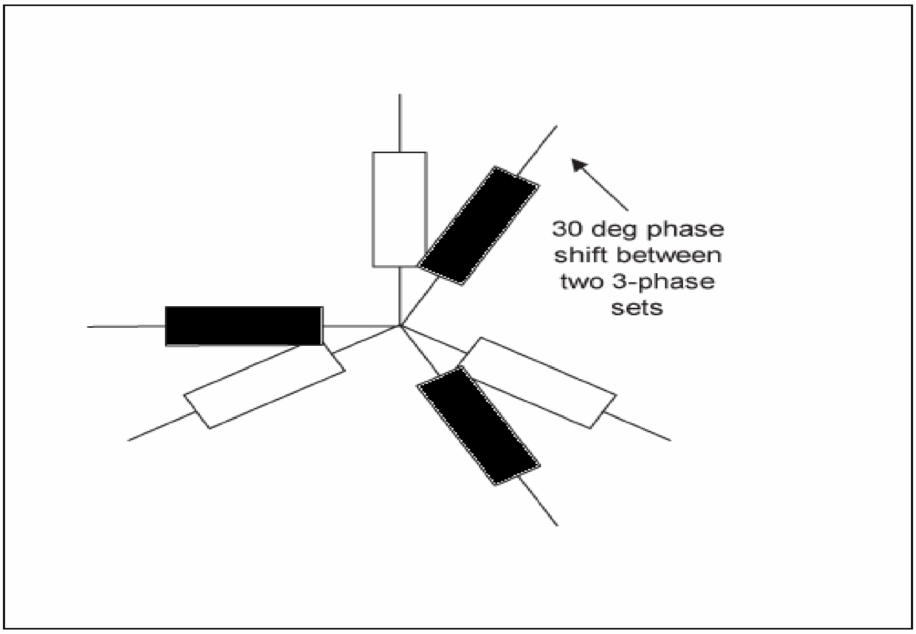

Figure 3.1: Winding arrangement in six phase synchronous machine

3.2 Supply angle study

The 6-phase machines have two independent sets of 3-phase windings which are supplied from independent converters. It is quite obvious to expect some mismatch in supply of the two converters. In this task, machine performance has been investigated under the conditions when there is a mismatch in the supply angle of two sets of windings from 30 degrees original supply angle shift. Studied range of supply angle is 10 degrees to 45 degrees as shown in Figure 3.2. However, 30 degrees space shift between two sets of 3-phase windings is constant in all cases.

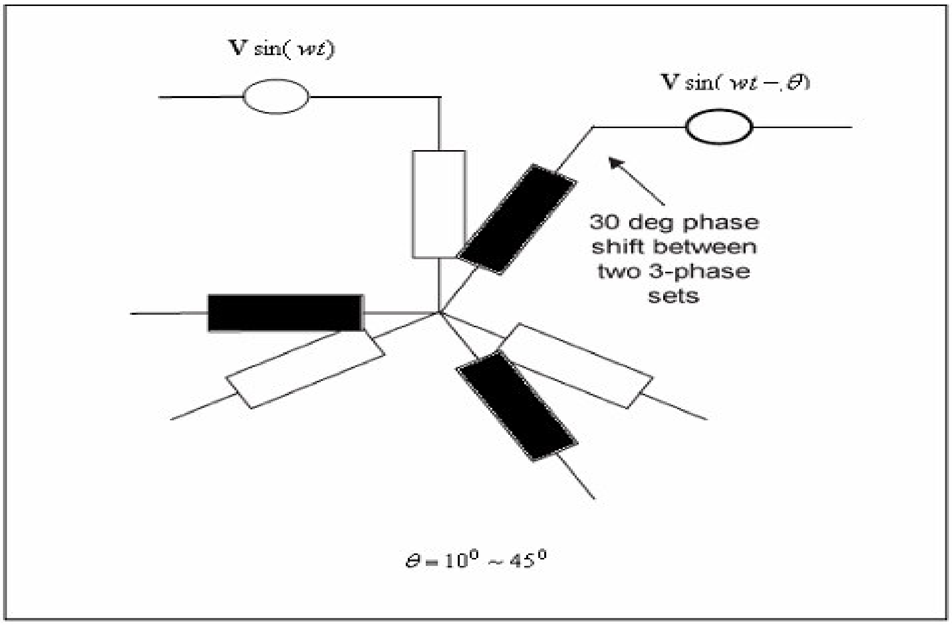

Figure 3.2: Supply arrangement of 6-phase synchronous machine

3.2.1 Space harmonic analysis

The air gap MMF is a combination of both rotor and stator MMF whereas the stator MMF in 6-phase machines is due to two sets of windings. MMF harmonics due to these sets are given as

$$F_{set1}(k') = \hat{F}_k \cos(k'(wt - p\theta) \qquad (2.1)$$

$$F_{set2}(k') = \hat{F}_{k'} \cos(k'(wt - \alpha) - p\theta + \beta) \qquad (2.2)$$

Where MMF is represented here as 'F'

k'=1, 5, 7, 11, etc are the time harmonics

α Is the time shift in the supply of the second system

β Is the space displacement of the second set of winding

p Is the number of poles

For supply angle study, only α will be changed but β is kept constant at 30 degrees in all simulated cases. Replacing the supply angle to 30 degrees and adding the two equations reveal that the 5th, 7th, 17th and 19th harmonics of the two systems add to zero. So, the first non-zero harmonics for the 30 degrees case are the 11th and 13th but it is not true for other studied supply angles. Flux density in the air gap is a function of permeance and MMF where as MMF is generated by the stator and rotor currents. Space harmonics can exist due to the winding distribution in slots and a salient the air gap. Rotor saliency and saturation also play their role which makes it difficult to get ideal results of equations 2.1 and 2.2. A series of simulations are performed to verify the affect of supply angle on harmonics in the air gap. A comparison of flux density spectrums of 6-phase synchronous machine with different supply angles is shown in Figure 3.3 taking the 30 degrees as a reference case. Values are given in per unit taking the 30 degrees case values as base for each individual harmonic of the spectrum. The 17th and 19th harmonics are the only note able harmonics which are higher than the 30 degrees base case. THD has been calculated only for the harmonics which have been shown in the spectrum given below. It may not be accurate but gives sufficient information to compare different cases in the spectrum. Comparison of values yields that 30 degrees supply angle gives a more smooth the air gap field.

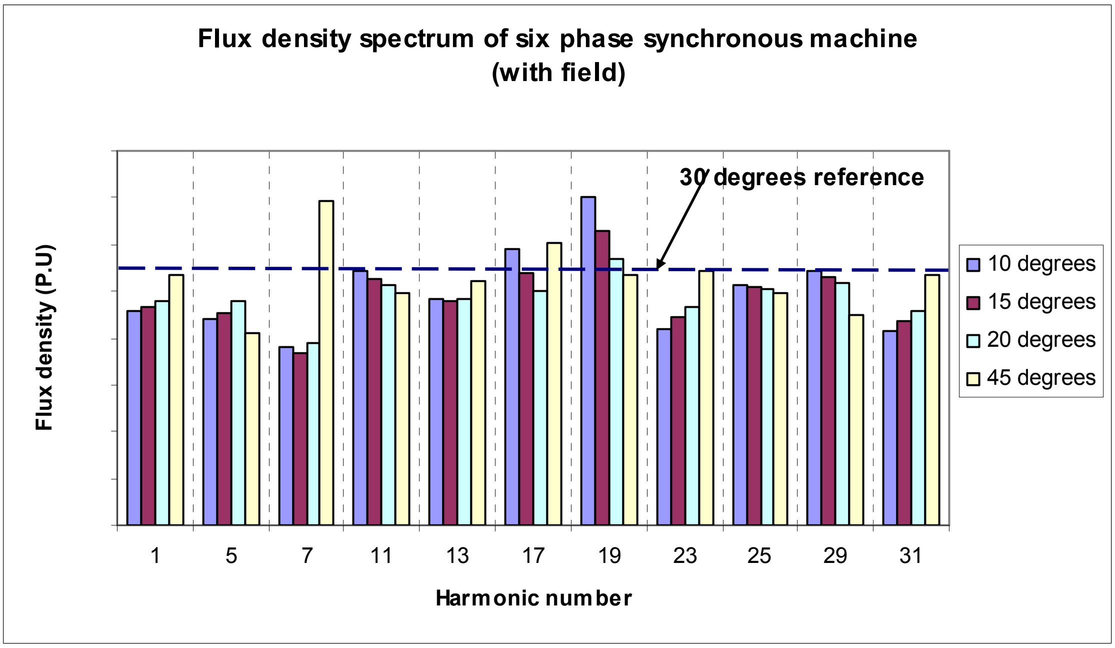

Figure 3.3: Flux density spectrum of the six phase synchronous machine with different supply angle

3.2.2 The stator field contribution

The machine is simulated further without any field supply to investigate contribution of harmonics from the stator fields. All the cases have been simulated with sinusoidal supply and contain no time harmonics. The field current is no more influencing harmonics in the air gap. Flux density in the air gap is now only influenced by the stator and rotor permeance as saliency effect is still there. Flux density spectrum comparison of all the cases under no field condition is given in Figure 3.4 Analyzing Figure 3.3 and Figure 3.4 yields that rotor field suppresses most harmonics at the expense of the 13^{th}, 17^{th}, 29^{th} and 31^{st} harmonic. However the 5^{th}, 7^{th} and 11^{th} harmonics are high magnitude harmonics in all cases compared to the 30 degrees case as shown in Figure 3.4 . This explains that the low 5^{th} and 7^{th} harmonics which are an inherent feature of the 6-phase machines start to increase with mismatch of winding displacement angle and supply angle.

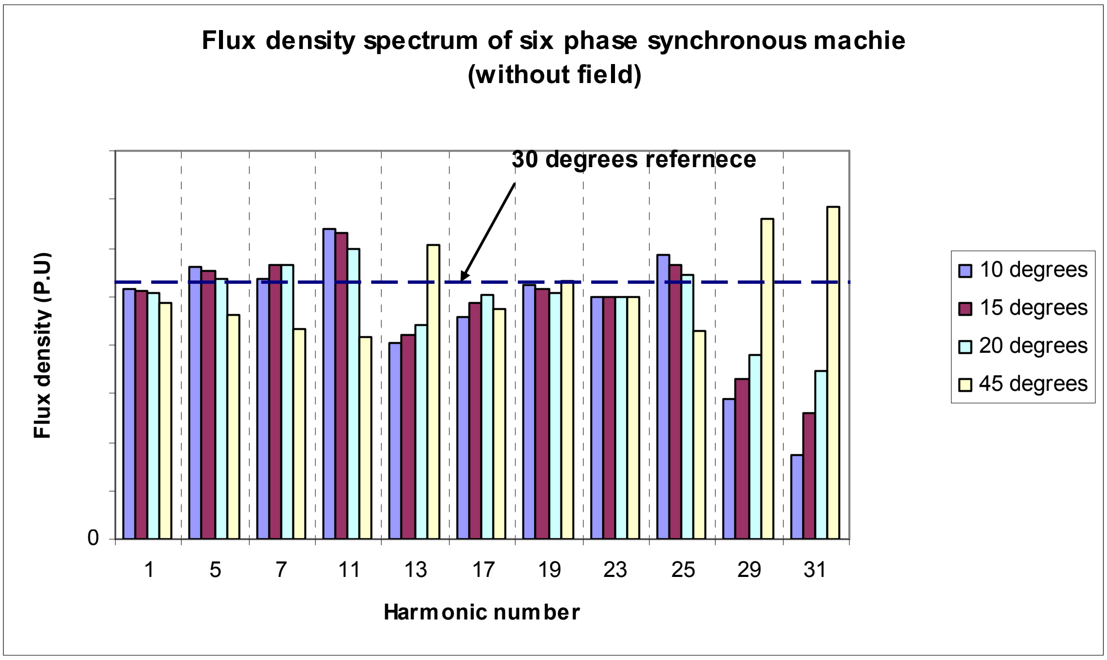

Figure 3.4: Flux density spectrum of the six phase synchronous machine with different supply angle

The variation trend of the 5^{th} and 7^{th} harmonics is shown in Figure 3.5. The rotor field suppresses the 5^{th} harmonic curve. The peak of the curve occurs at 30 degrees. While the 7^{th} harmonic curve shifts up with rotor current supply with peak at 45 degrees (but still the 30 degrees case has higher value than the other three cases.)

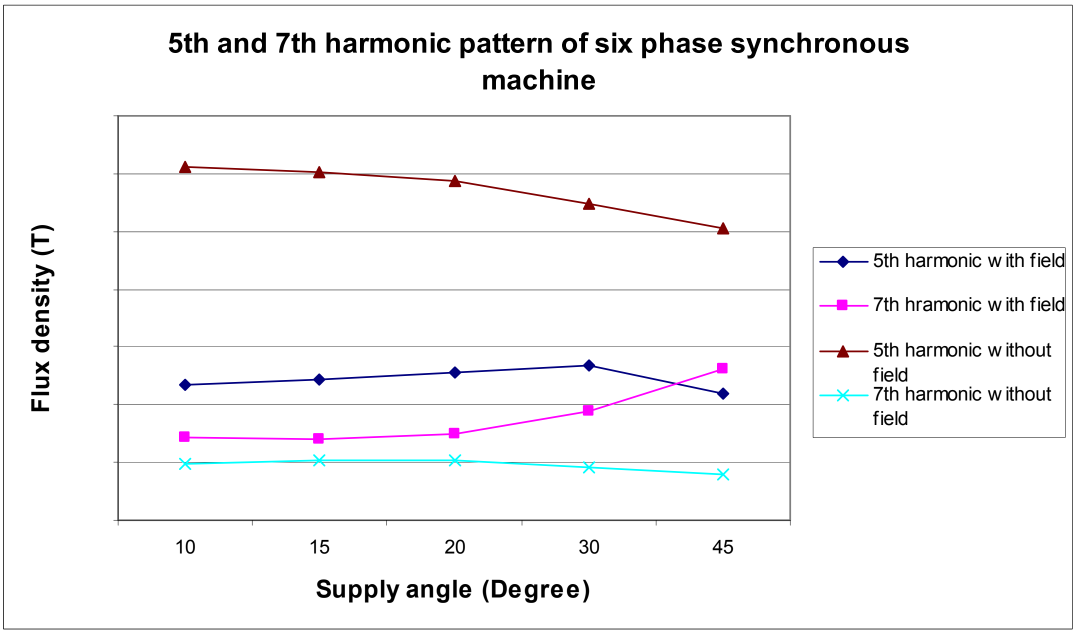

Figure 3.5: Variation trend of 5^{th} and 7^{th} space harmonic with and without field supply in six phase synchronous machines for different supply angles

3.2.3 Cylindrical Rotor Case

It is a special case in which the salient poles have been replaced with a cylindrical rotor. All the materials of the machine components are replaced with ideal iron to avoid saliency and saturation affects. Results of this case satisfy the equation 2.1 and 2.2. It can be seen in Figure 3.6 that 30 degrees case in which two winding sets are 30 degrees displaced in space and supply is displaced 30 degrees in time shows that the 5th and 7th harmonics are totally eliminated while the stator slot harmonics, i.e. the 23rd and 25th, are unaffected by a supply angle change. It can be concluded that the 5th and 7th harmonics can be eliminated with proper selection of winding layout and supply angle in cylindrical rotor machines but not in salient pole machines.

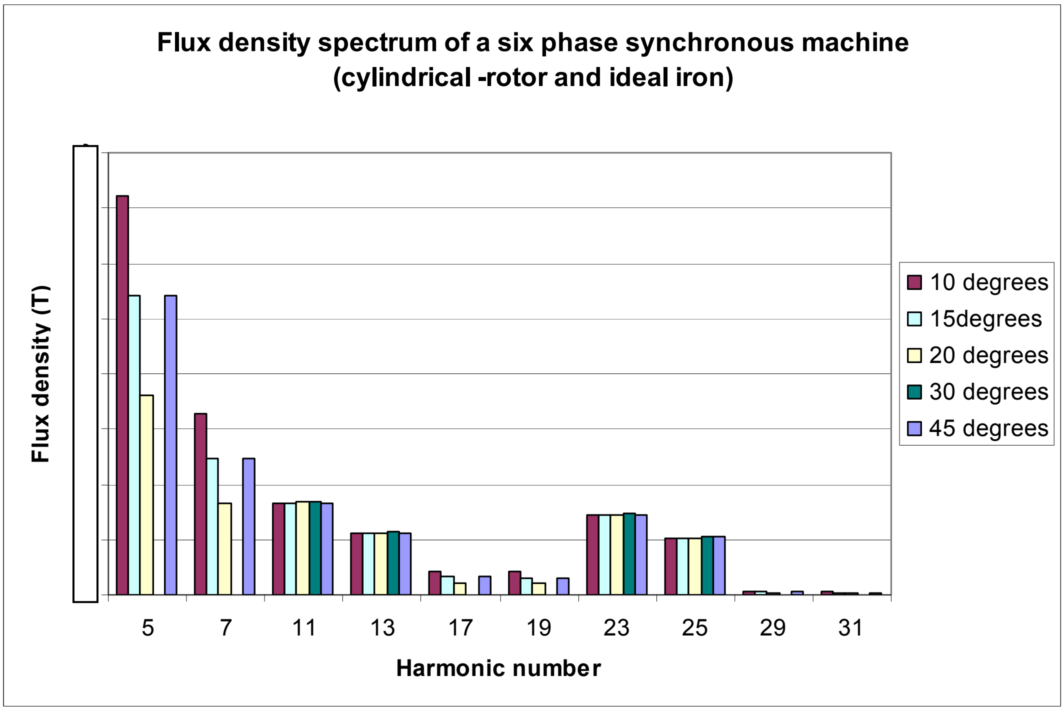

Figure 3.6: Flux density spectrum of six phase synchronous machine with cylindrical rotor and ideal iron under different supply angle condition

3.2.4 Performance analysis

Time dependant simulations of the machine enable comparison of losses and induced currents of distinct cases. Significant affect of supply angle change is evident in damper bar currents. The air gap harmonics induce currents in damper bars. In Figure 3.7, the harmonic spectrum of averaged damper bar currents is shown. It is shown that the 30 degrees case in which the 5th, 7th, 17th and 19th harmonics add to zero has no 6th and 18th harmonics in damper bar currents. The first significant harmonic in the 30 degrees case is the 12th in the spectrum. The 6-phase machine with the 30 degrees supply angle had high 11th. 13th, 23rd and 25th harmonics in the air gap fields; therefore it has higher magnitude of the 12th and 24th induced harmonics in damper bar currents. In other supply angle cases the 6th harmonic is high but the 12th and 24th harmonics are lower.

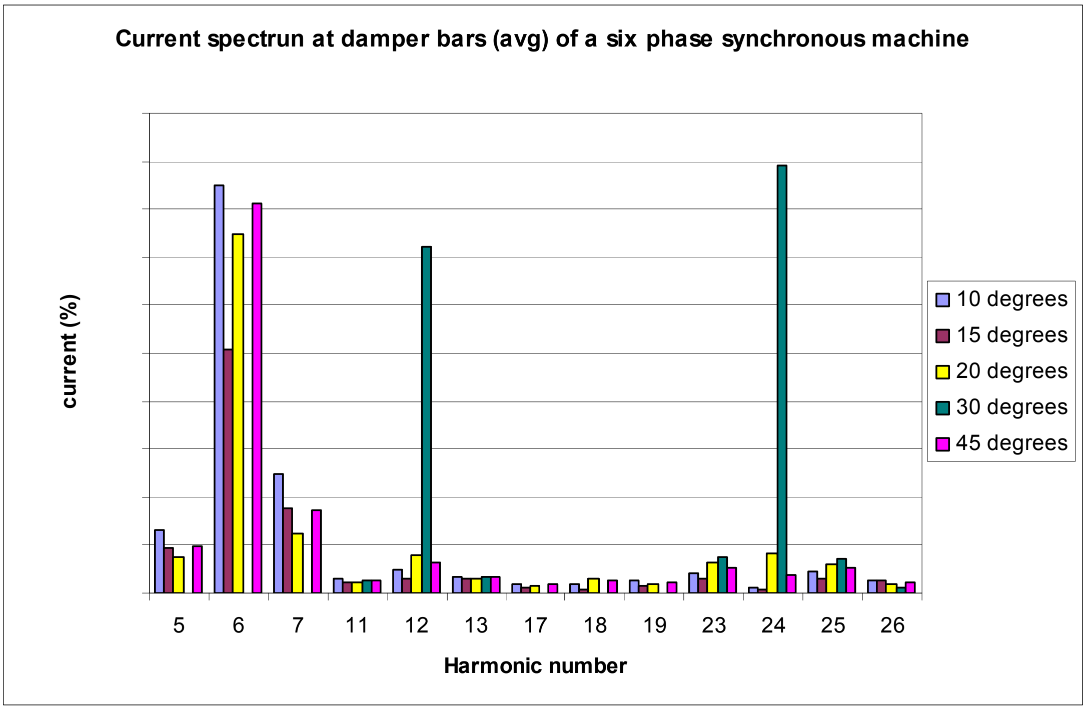

Figure 3.7: Frequency spectrum of averaged damper bar currents

Similar pattern is present in machine torque as shown in Figure 3.8. The 6-phase machine with 30 degrees supply angle has shown negligible 6^{th} and 18^{th} harmonics while these harmonics are present in all the cases with supply angle other than 30 degrees.

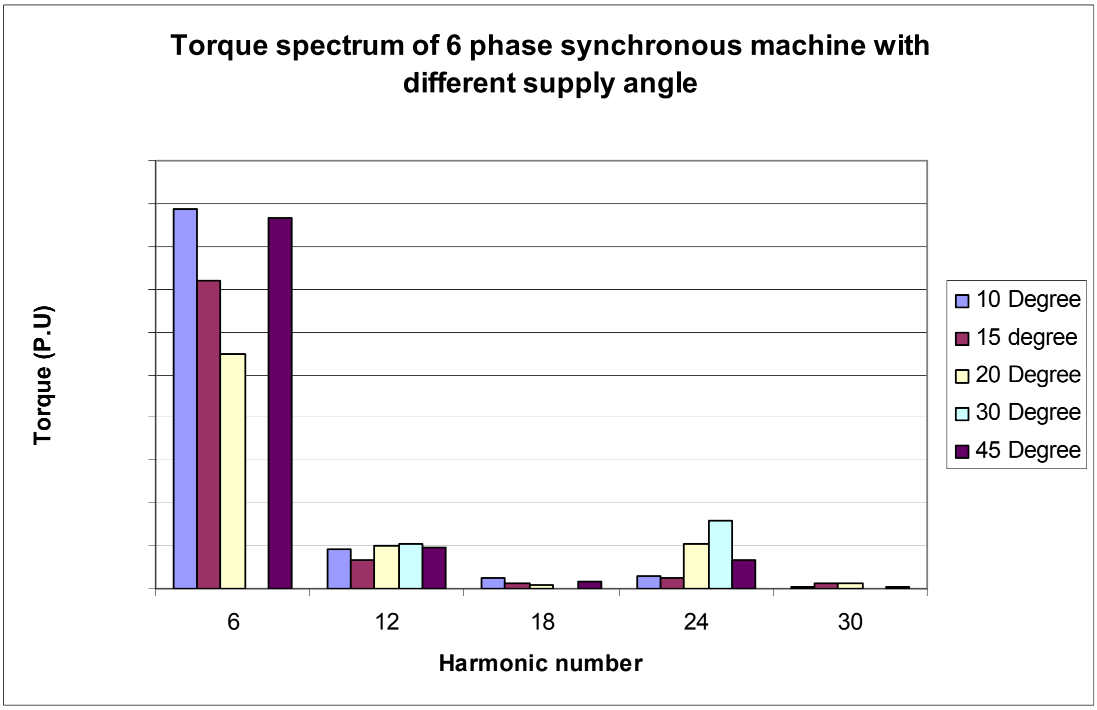

Figure 3.8: Torque spectrum of 6-phase machine with different supply angle

This reduced 6^{th} harmonic pulsation in machine torque is a major advantage of the 6-phase machine but the spectrum above suggests that in order to benefit from this feature the supply and displacement angle of winding should be exactly 30 degrees. These high harmonics in the air gap and damper bar currents for other cases obviously have their influences on machine losses. The electro magnetic torque equation of a multiphase machine is given as:

$$T_e(t) = \frac{1}{w(t)} \sum_{m=1}^{n} e_m(t) * i_m(t)$$

Where m, represents number of phases in motor, $i_m(t)$ is the phase current, $e_m(t)$ is the phase back EMF and $T_e(t)$ is total torque developed by the machine. If emf and current are in phase as they are in the 30 degrees case then torque will sum up to n times for n phase machine. In the 30 degrees case emf for second system is displaced 30 degrees due to winding displacement and supply has the same shift as well. So, torque from two systems will add to 2 per unit. For example, in case of a 10 degrees supply angle there is a shift in phase emf and supply angle of the second system which will cause reduction in torque. In an effort to keep this machine torque at its level, machine phase current will rise to a higher value. This explains the highest stator current in the 10 degrees supply angle simulations while the 30 degrees case has minimum stator current requirement.

It can be summarized here that supply angle other than 30 degrees causes more losses and 6^{th} harmonic ripple in torque. Efficiency of the machine is also not as good due to increase of rotor and stator currents for the same torque requirement.

3.2.5 Time Harmonic Study

Target of this exercise is to locate patterns in time harmonics which have the same influence on space harmonics for different supply angles. In these simulations the machine is supplied with forced harmonic currents in supply in magneto-static mode and coefficients of the resulting harmonic components in the air gap flux are calculated. Harmonic currents are calculated according to the formula

$$i(t) = q * n * \sqrt{2} * \frac{I_{rms}}{a} * \sin(kwt + \theta)$$

Where 'q' is number of slots per phase, n is number of conductors in each slot, a is number of parallel paths in the circuit, k is order of the time harmonic

The machine is supplied with 100% desired harmonic current and resulting space harmonics are recorded. Input currents were calculated for different angles and different harmonic numbers. Study is limited up to the 31^{st} harmonic. It is very interesting to know that each angle has a different pattern. For instance in the 30 degrees case there are four distinct set of currents which are first, 5^{th} , 7^{th} and 11th harmonic and pattern starts repeating itself from 13th harmonic and onwards. It is observed that the number of sets of similar harmonics increases when going from the 30 degrees case down to the 10 degrees case. Table 3.1 enlists the similar sets of time harmonics in each case. The 10 degrees case is not shown in the table as it is not repeating itself in the studied harmonic index.

Table 3.1: Set of time harmonics with the same influences on space harmonics related to supply angle of the machine

	30 Degrees	20 Degrees	15 Degrees
Set 1	1, 13, 25th	1, 19th	1,25th
Set 2	5, 17, 29th	5, 23rd	5, 29th
Set 3	7, 19, 31st	7, 25th	7, 31st
Set 4	11, 23rd	11, 29th	11
Set 5	-	13, 31st	13
Set 6	-	-	17
Set 7	-	-	19
Set 8	-	-	23

In order to quantify affect of time harmonics in supply on the air gap harmonics a series of magneto static simulations is performed. It is justified to claim that 10 degrees case is good from a control point of view as lower order harmonics are independent of each other and it is easy to control machine loss distribution by injecting any desired time harmonic. Low order time harmonics in the supply should be avoided as they have significant effect on the air gap space harmonics and resulting in higher losses of the machine.

4 PARAMETRIC SENSITIVITY ANALYSIS OF 3-PHASE SYNCHRONOUS MACHINES

In this task effort has been made to study the design parameters sensitivity of a three phase machine. Three parameters which have been studied are

- Winding layout
- Wedge material
- Rotor pole shape

4.1 Winding layout

The machine winding pitch has an effect on space harmonics of the machine. These variations of harmonics influence losses and efficiency of the machine. The Machine is simulated for different cases of short pitch winding and results have been compared with the full pitch winding case. The fundamental component of the flux density increases with a decreasing winding pitch. In simulated cases, 8/12 has maximum value of the fundamental component of flux density in the air gap. Flux density spectrums of all five cases have been compared in Figure 4.1. It is interesting to note that 5th and 7th harmonics decrease while 11th and 13th harmonics increase with a decreasing winding pitch.

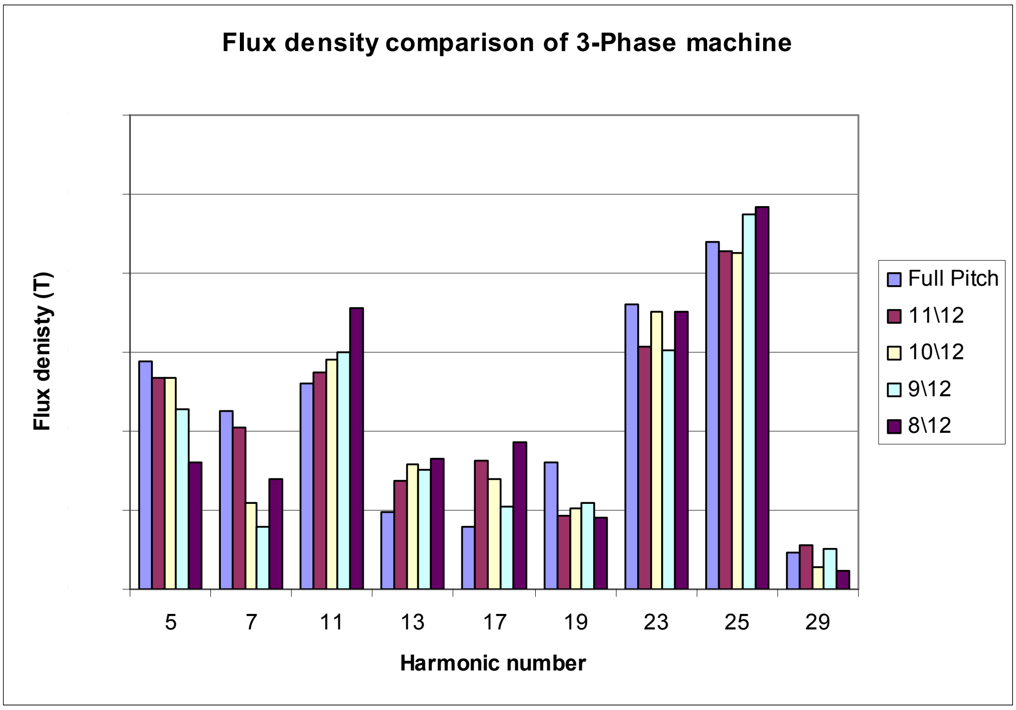

Figure 4.1: Flux density spectrum in the air gap of the 3-phase synchronous machine for different winding layouts (Time stepping)

These harmonics have an obvious influence on machine damper bar currents and torque which subsequently affects machine losses and efficiency. Frequency spectrum of averaged damper bar currents is shown in Figure 4.2. The three phase machine with full pitch winding has high magnitude of the 6th harmonic while the 10/12 case has minimum 6th and 18th harmonics in damper bar currents. The magnitude of the 12th

harmonic is reduced for the 11/12 case. Other significant harmonic is the 24th which is due to stator slots and is not affected much by reducing the winding pitch.

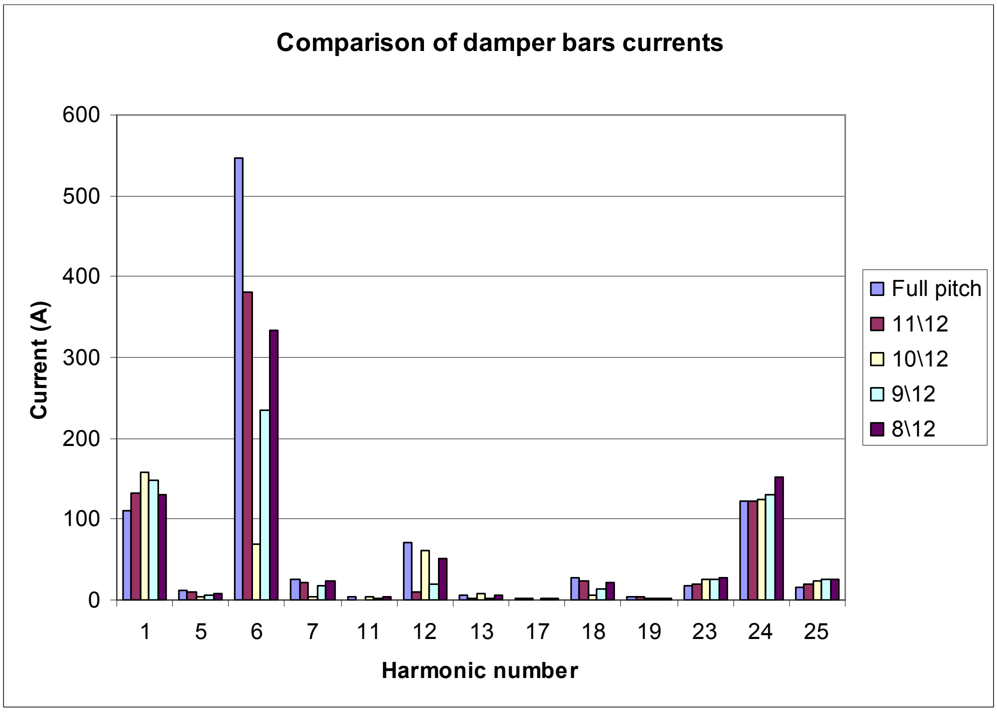

Figure 4.2 comparison of averaged damper bar currents spectrum of the 3-phase synchronous machine with different winding layouts

Total losses of the machine are significantly higher in the 9/12 and 8/12 cases and efficiency is also poor in these cases whereas the 10/12 case has slightly higher total losses than the full pitch winding case but efficiency is almost the same. However the 10/12 case has reduced rotor surface losses and 6th harmonic pulsation in torque which is quite beneficial.

4.2 Wedge material study

The main function of the wedge is to keep away the coils from the air gap. In some cases they help to reduce the variations in magnetic permeance caused by stator slots. Use of magnetic wedges helps in reducing space harmonic losses in rotor. Two cases with different wedge materials have been simulated to exploit magnetic influences of wedges:

1. Air wedge
2. Magnetic wedge

In the first case material of the wedge has the same properties as air while in the second case wedge material has the same magnetic properties as the stator tooth tip. This leads to magnetic short circuits of the stator teeth and slot wedges as shown in Figure 4.3.

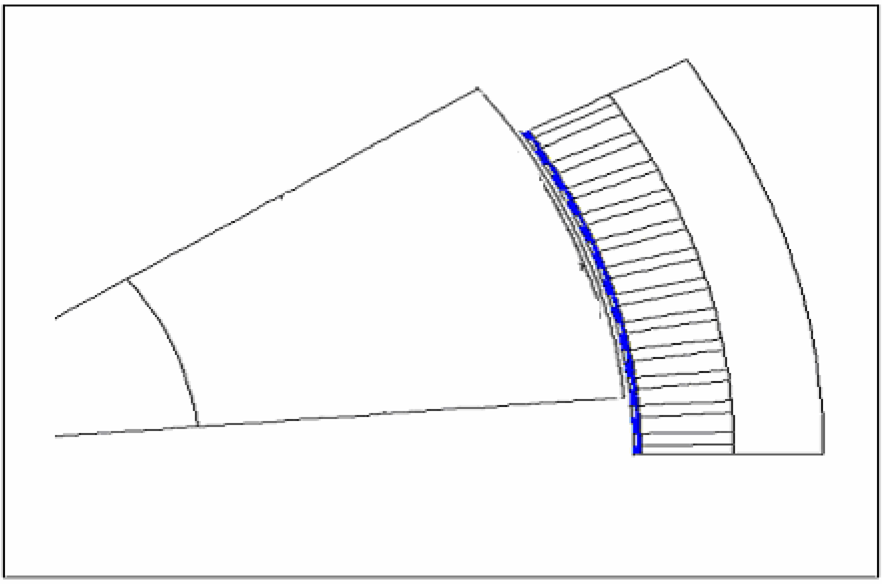

Figure 4.3: Magnetic short circuit in the stator teeth tips of a 3-phase synchronous machine due to use of magnetic wedges

Now comparing flux density spectrums in the air gap for both cases shown in Figure 4.4 reveals that magnetic wedges help to reduce the slot harmonics which are 23rd and 25th. However there is an increase in other low order harmonics like the 7th, 11th and 17th which expose themselves in machine losses and induced currents.

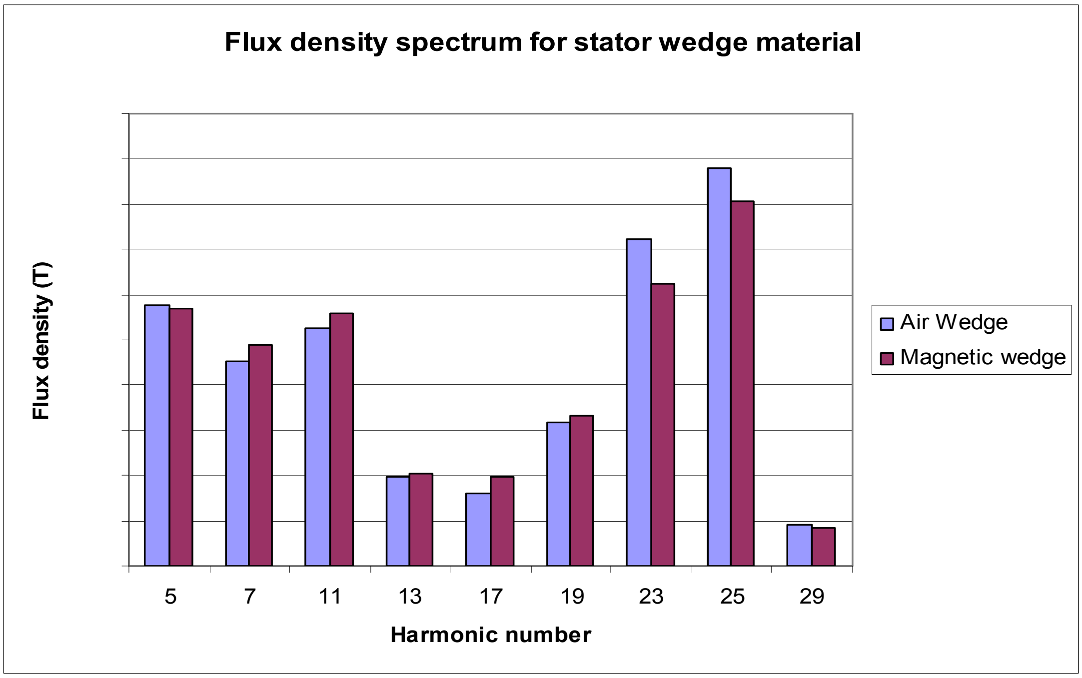

Figure 4.4: Flux density spectrum in the air gap of the 3-phase synchronous machines with different wedge materials

Torque and damper bar currents (which are averaged here) exhibit similar pattern with high 6th and 12th pulsations in the magnetic wedge case. As expected, low order harmonics in the air gap are higher compared to the air wedge case. The 24th harmonic pulsation has decreased in the magnetic wedge case as shown in Figure 4.5.

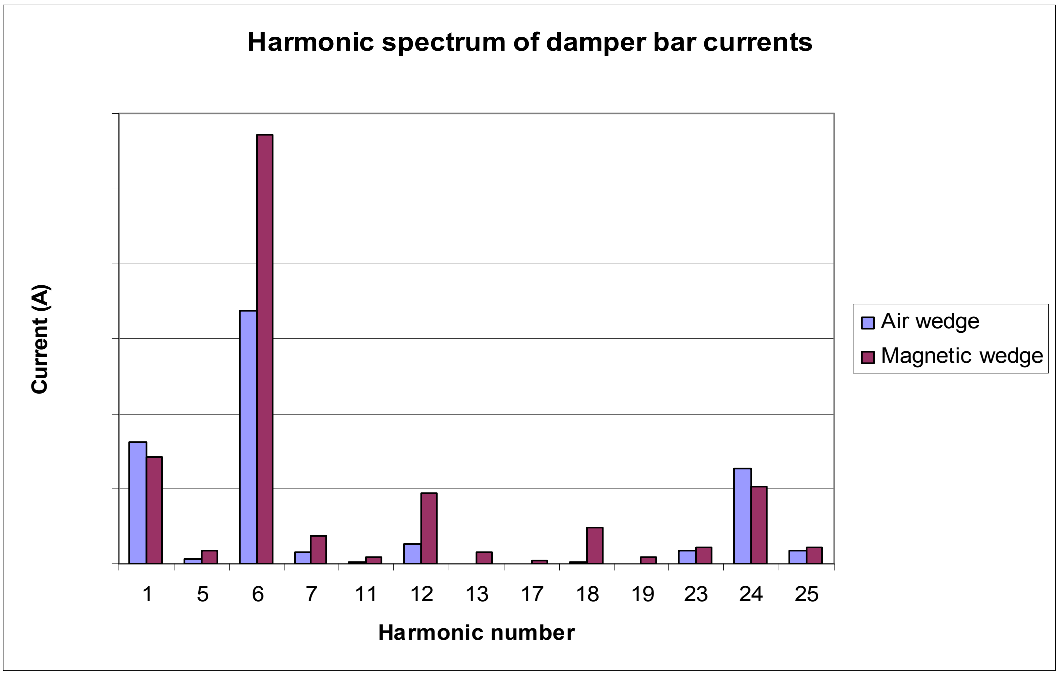

Figure 4.5: Spectrum of averaged damper bar currents of a 3-phase synchronous machine for different wedge materials

The torque spectrum also follows the same pattern as damper bar currents with higher 6th and 12th pulsations. One distinction here is the 18th harmonic which is significant in the magnetic wedge case while it is almost zero in the air wedge case.

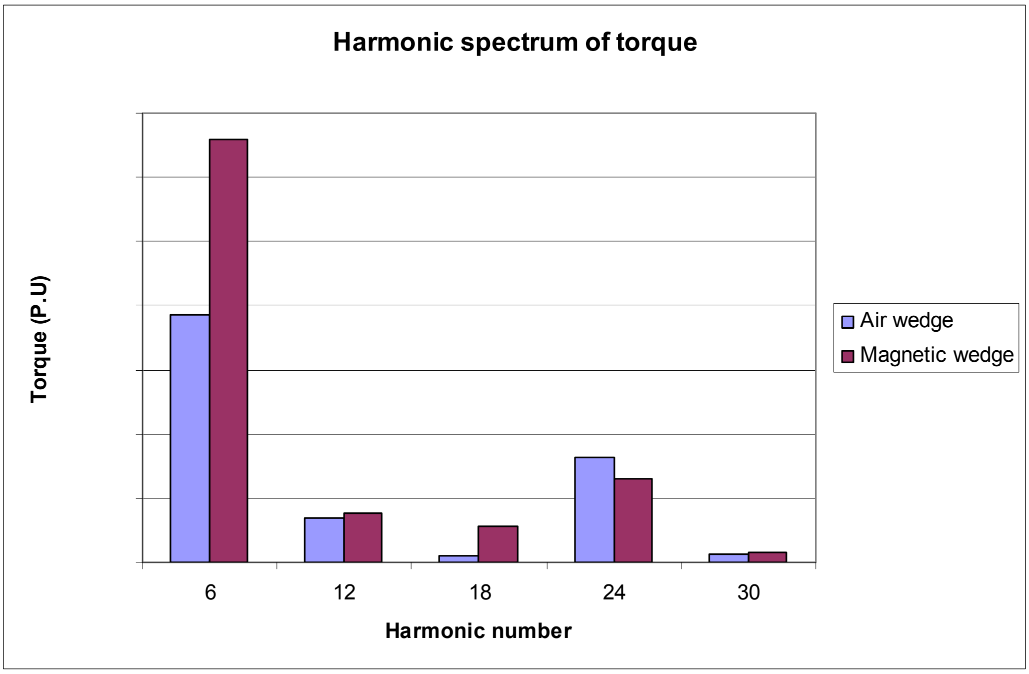

Figure 4.6: Torque spectrum of a 3-phase synchronous machine with different wedge materials

Developed torque and efficiency is almost the same in both cases. Stator current remains constant which leads to almost constant copper losses of the machine. However rotor copper losses has increased in the magnetic wedge case due to an increased field current.

4.3 Rotor pole shape

In salient pole synchronous machines rotor saliency has its influences on the air gap flux density. To quantify sensitivity of harmonics to rotor pole saliency, a parametric study of a 3-phase synchronous machine is carried out in the magneto-static application mode of FEM simulations.

4.3.1 Parametric study of the rotor pole

In this task, rotor pole width and height is varied with the help of design parameters as shown in Figure 4.7. Pole parameters are changed in such a way that the air gap length, pole body width and field winding area remains constant. These constraints are placed by magnetization, mechanical strength and heat dissipation factors. The flux density spectrum is drawn in the air gap for each case and results are compared with the original existing case.

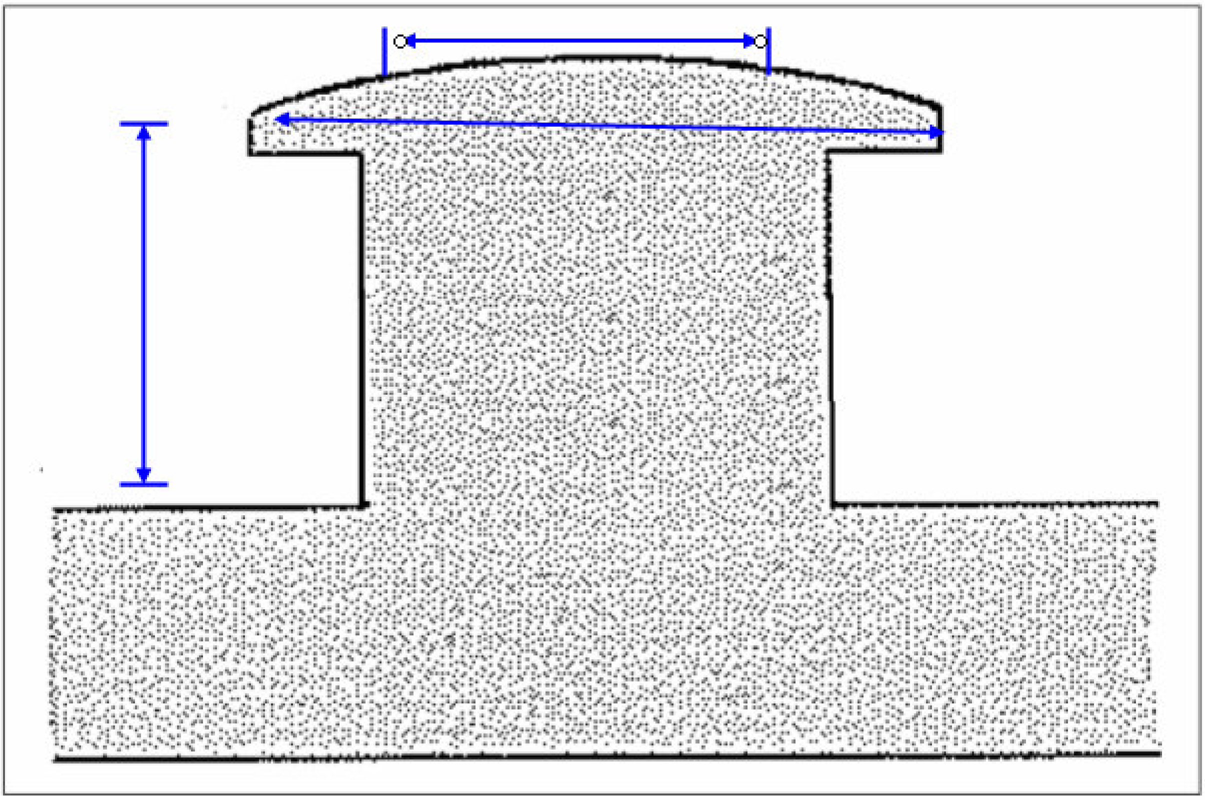

Figure 4.7: Cross sectional view of the rotor pole with parametric description [25]

4.3.1.1 Height of pole

Changes in pole height are constrained by the air gap length. The air gap length has been kept constant as in the original case to keep the generality of the comparison. Rotor pole height is basically a combination of pole shoe height and pole body height. In this task, changes in pole shoe height and pole body height has been made in such a way that the total pole height is constant. Harmonic spectrums of these cases reveal that the fundamental component is not influenced with the pole shoe height. However increasing the height of the pole shoe has positive affect on the harmonic spectrum

4.3.1.2 Pole width

Variation in pole shoe width is constrained by specified adjacent pole distance and field winding width respectively. Pole shoe width has already reached its minimum optimal point; further reducing the pole shoe width will expose the field winding to stator fields. This will cause increase of leakage flux and face some mechanical constraints. Only increase of pole shoe width has been investigated in this section. Width of rotor pole body has been kept constant as shown in figure to keep the same mechanical robustness in all machines. The fundamental component of the air gap flux density is almost the same in all these cases whilst the 5^{th} and 7^{th} harmonics increase with increase of rotor pole width. The original case is decently well optimized.

4.3.1.3 Central pole shoe width

Varying the width of the centre part of pole shoe does not bring significant changes in harmonic spectrum of the air gap flux density. In this task only the width of pole centre is varied while all other design parameters are kept constant. Width is increased in three steps and results are stored. Field winding width and height have been kept constant in all cases in order to keep the same thermal situation of the machine. There are no significant variations in harmonics pattern of flux density for the simulated cases. Thus, original design is already well optimized.

4.3.1.4 Conclusions

It can be concluded after parametric study that increasing the pole shoe height compared to the pole body height brings improvement in harmonic spectrum. On the other hand, increasing the pole shoe width increases the magnitude of space harmonics.

4.3.2 Pole face topology

In this exercise two pole shapes which differ in pole shoe configuration have been simulated and compared with the original machine in aspects of losses, harmonics and efficiency. Two simulated cases are the wide pole and the arched pole shaped machines where the wide pole shape is relatively flat at the centre of the pole shoe. One care which should be taken in case of the arched pole topology is that the arch should not be steep enough to make a sharp tip in the pole shoe. This tip can be saturated and lead to high local losses and hot spots.

Flux density spectrums for all three cases are compared. Analysis implies that the wide pole structure increases harmonics in the air gap. The fundamental component of the flux density is not influenced by pole shape change. The arched pole shape has shown a reduction of harmonics compared to the original existing case. It has the minimum value of THD. A similar kind of pattern is observed when comparing induced currents in damper bars. The system has significant 6^{th}, 12^{th}, 18^{th} and 24^{th} harmonics but these harmonics are suppressed in case of the arched pole. The wide pole shape has higher induced harmonics in damper bars due to high harmonics in the air gap flux. Total losses are higher in the wide pole case compared to the original existing case. The arched pole has slightly increased total losses compared to the original case but the efficiency of the machine is almost the same as the original case. However, the arched pole has an additional benefit of reduced pulsation in the machine torque.

5 COMPARISON OF 3 AND 6-PHASE SYNCHRONOUS MACHINES

5.1 Comparison of full pitch 3 and 6-phase synchronous machines

In this chapter, simulation results for three and six phase full pitch machines have been compared. The 6-phase machines are believed to have low torque fluctuations, better performance and reliability. The 6-phase machine has 30 degrees displaced windings and has the same shift in supply angle of two 3-phase systems. The 6-phase machine is a modified version of the three phase machine with winding split into two 3-phase winding sets. Quantities that have been compared are

- The air gap flux
- Induced currents
- Torque fluctuations
- Losses
- Parametric sensitivity

Both 3 and 6-phase machines have also been compared for parametric sensitivity and rotor pole shape topologies. Parametric sensitivity analysis results of the 6-phase machine have been discussed in [24].

Figure 5.1 compares the flux density spectrum in the air gap for 3 and 6-phase synchronous machines. It shows that the 6-phase machine successfully reduces the 5th and 7th harmonics and even slot harmonics. However the 11th, 13th and 17th harmonics are higher in the 6-phase machines.

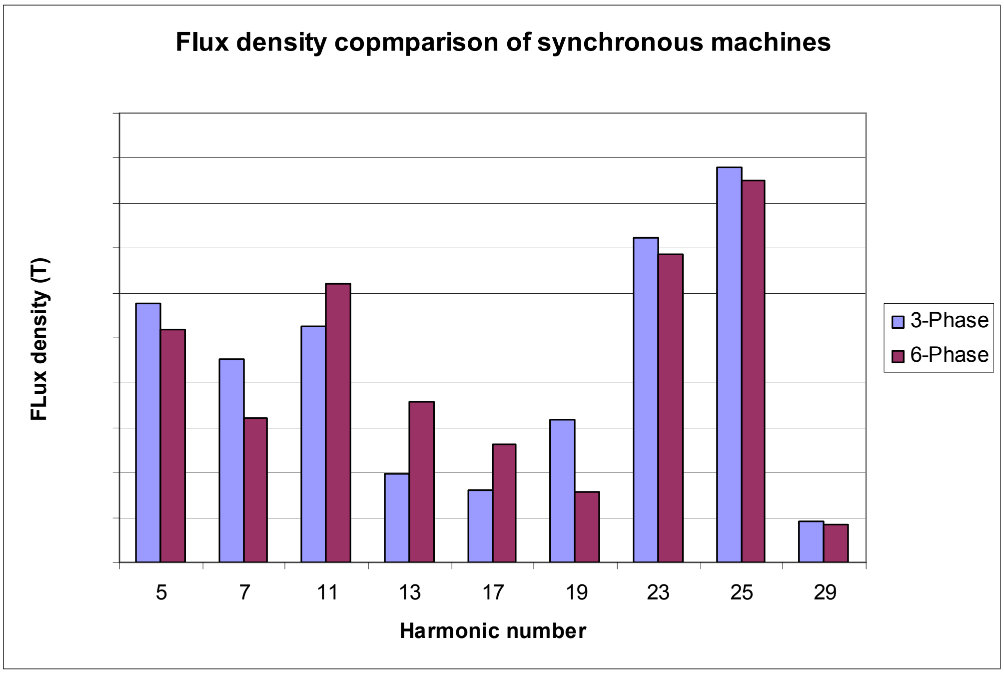

Figure 5.1: Space harmonics comparison of 3 and 6-phase synchronous machines

One of the interesting features of the 6-phase machines is the lower fluctuation in damper bar currents and torque as shown in Figure 5.2 and Figure 5.3. Reduced 5th and 7th the air gap harmonics, which is due to displacement of two winding sets, is the main cause of this beneficial feature. Whereas high 11th and 13th the air gap harmonics of the flux density explains increased 12th torque pulsation. On other hand 3-phase full pitch machine has high 6th and 18th harmonics which are non existent in the 6-phase machine.

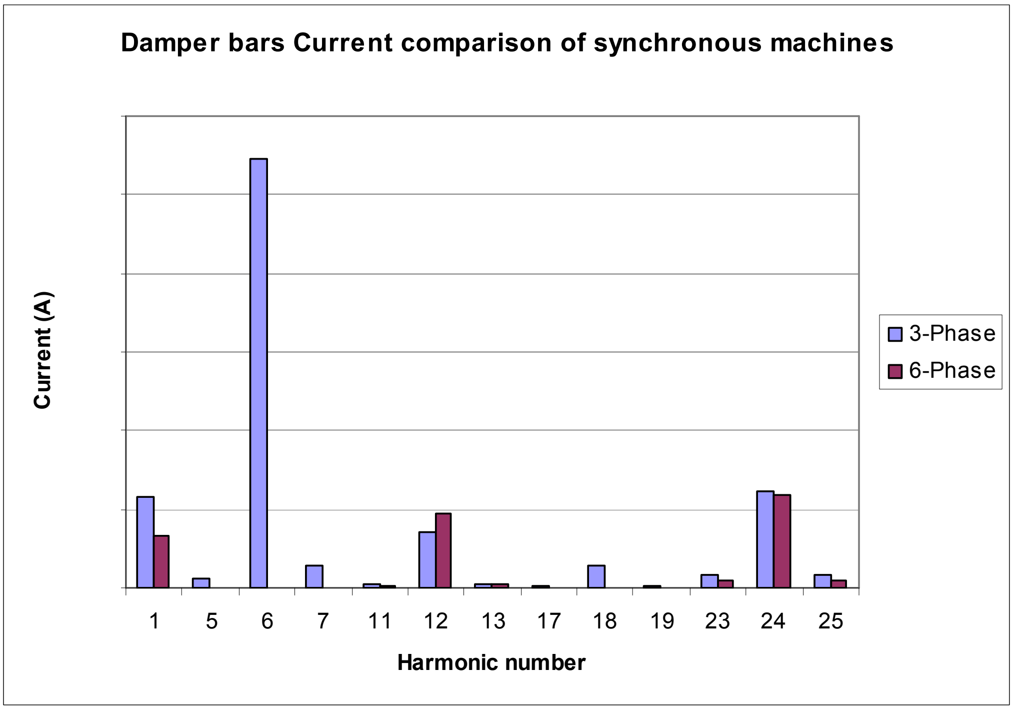

Figure 5.2: Comparison of damper bar currents harmonics of 3 and 6-phase full pitch synchronous machines

Interaction of the fundamental, 5^{th} and 7^{th} the air gap harmonics generate the sixth harmonic torque pulsation. In the 6-phase machine, the sixth harmonic torque pulsation generated by two sets of windings cancel each other. Frequency of the first significant torque pulsation is 12 times of the fundamental frequency which is induced due to the 11^{th} and 13^{th} harmonics.

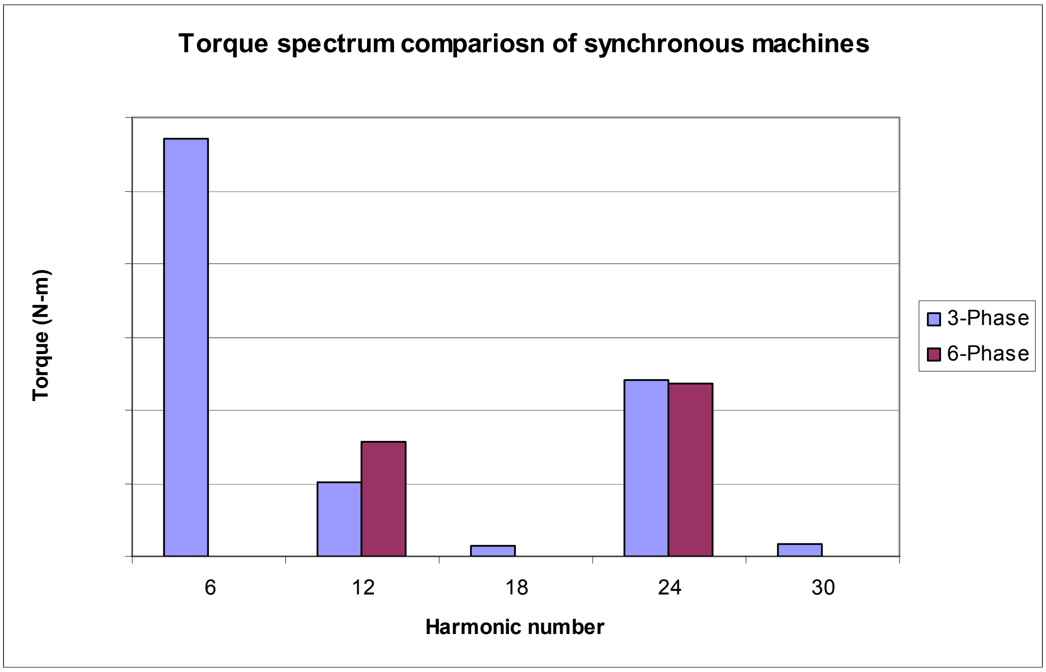

Figure 5.3: Torque spectrum comparison of 3 and 6-phase synchronous machines

Speed of the machine is almost constant with small fluctuations. Motor inertia damps out the speed fluctuations but still the 6^{th} and 12^{th} are significant harmonics in 3 and 6-phase machines, respectively as can be seen in Figure 5.4.

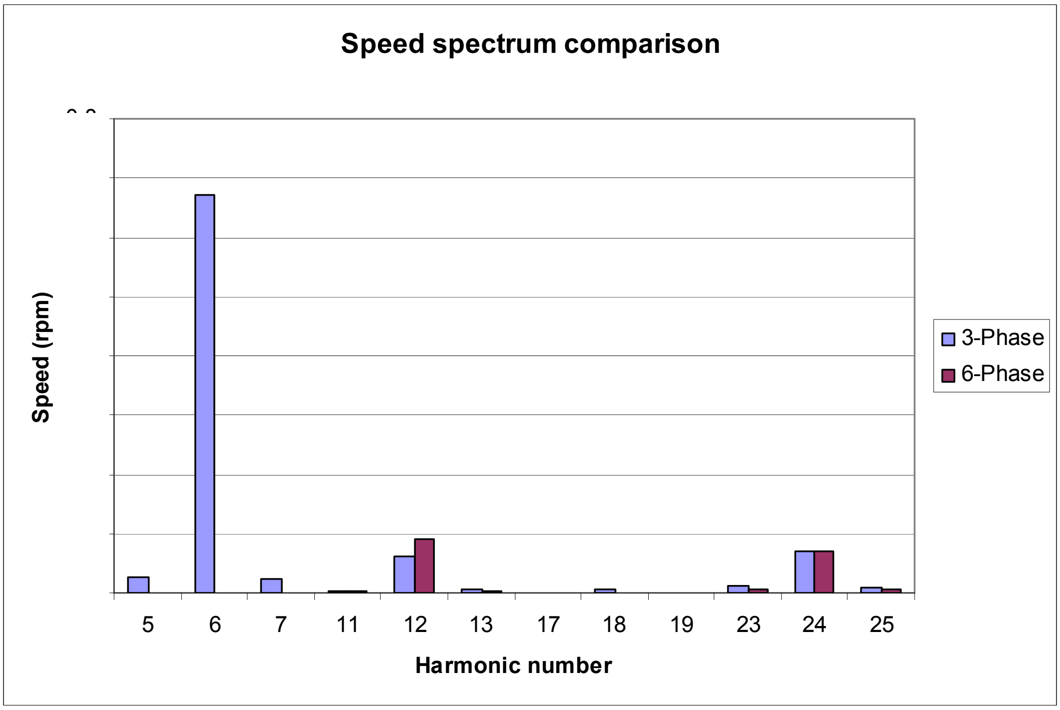

Figure 5.4: Speed spectrum comparison of 3 and 6-phase synchronous machines

These harmonic trends clearly influence the machine losses. The 6-phase machine which has negligible 6th harmonic ripple in damper bar currents has significantly decreased bar losses. Iron losses and rotor copper losses have decreased with the decrease of field current requirement. Stator copper losses of the machine have increased in case of the 6-phase machine which affect efficiency of the machine slightly.

It can be concluded that for the same torque requirement the 6-phase machine gives less fluctuating toque and speed. Total losses have decreased in case of the 6-phase machine compared to the 3-phase machine. In addition the 6-phase machine also offers redundancy and reduced stator currents.

5.2 Parametric sensitivity comparison

Both machines have been simulated for the same changes in design parameters. Affect of these changes on machine losses is recorded and then compared to its respective original existing design. Parameters studied are:

- Coil pitch
- Wedge material
- Rotor pole shape

The emphasis has been on comparing trends or response of the machine to these changes. The parametric study of the 6-phase machine has been discussed in [24]. Results of that study are used here for comparison with the three phase machine.

5.2.1 Coil pitch sensitivity comparison

For the coil pitch study three configurations, 11/12, 10/12 and 9/12 have been simulated for both 3 and 6-phase machines. The fundamental component of flux density is higher for short pitch cases in both 3 and 6-phase machines. Field current of the short pitch cases in both the machines is also higher for given the torque requirement.

Losses of the 3 and 6-phase machines with different winding layout are compared to observe different variation trends in rotor iron and bar losses. The 3-phase machine has shown a decreasing trend of said losses with an acceptable value for the 10/12 case which explains its wide acceptance. On the other hand, the 6-phase machine shows an increasing trend of losses for each simulated case.

5.2.2 Wedge material change

Another studied parameter is the material of the slot wedge. Mechanical functionality of the wedge is to keep winding from falling. In addition, it affects space harmonic losses in the rotor. The wedge material is changed to a material with the magnetic properties the same as the stator tooth tip for the both machines and results are compared to the original case for which the wedge material is the same as air. Changing the wedge material to magnetic with properties the same as the stator tooth tip causes a magnetic short circuit on the stator side. This short circuit causes more flux in the stator magnetic circuit and causes more iron losses in the stator. For the same reason, rotor circuit has less contribution of MMF and experiences reduced iron losses. Performance of both the 3 and 6-phase machines with the magnetic wedge material is compared. In the 6-phase machine, rotor iron losses have decreased along with the rotor bar losses. In the three phase machine only rotor iron losses have decreased. Both 3 and 6-phase machines have the same response to wedge material change other than for machine bar losses. Reduced bar losses in 6-phase machines compared to the 3-phase machines are due to absence of low order harmonics induced in the damper bar currents.

5.2.3 Pole shape comparison

In rotor pole shape study, two pole faces named wide and arched pole are simulated. The wide pole has increased pole shoe width which means more iron and arched pole has arched pole face giving a smoother pole surface. Performance parameters of both 3 and 6-phase machines for wide and arched pole are studied along with their original values. The fundamental component of flux density is not affected by the change of pole face configuration in any machine. However in both 3 and 6-phase machines, the wide pole case has increased the field current and lead to poor efficiency. Both machines exhibit that arched pole shape has only slightly higher losses. While the wide pole configuration has significantly high rotor iron losses and field current. The increased rotor iron losses are due to increased amount of iron in the rotor pole. Field current increase causes high field winding loss.

6 ANALYSIS OF 9 AND 12-PHASE SYNCHRONOUS MACHINES

6.1 The 12-phase synchronous machine

An attempt has been made to visualize the behavior of a 12-phase salient pole synchronous machine using the same implementation principle as the 6-phase machine. The 12-phase machine has four sets of 3-phase windings which are displaced 15 degrees from each other in space as shown in Figure 6.1. The 12-phase machine is supplied from four independent sources with supply angle shift of 15 degrees from each other. In this case the 6 and 12-phase machines have been modified from the same 3-phase machine where as slots per pole per phase are four, two and one in the 3, 6 and 12-phase machines respectively. In the 3-phase machine there is a single supply while in the higher phase machines each set of a three phase winding is supplied from an independent source.

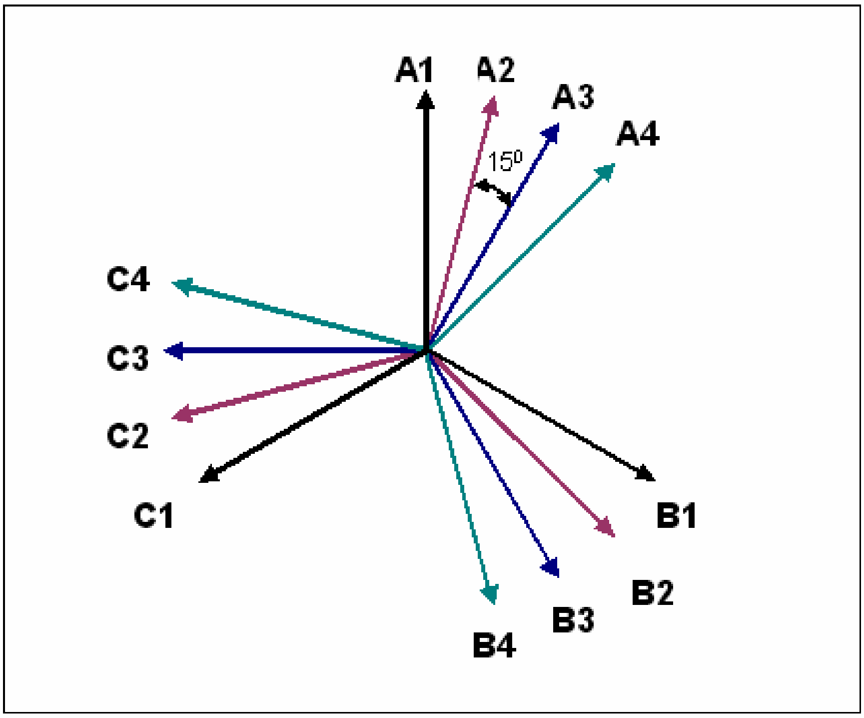

Figure 6.1: Winding arrangement of the 12-phase synchronous machine

For all machines, a torque curve in the air gap (for the same field current) is obtained by changing the rotor position in the magneto static application mode. For the same load torque requirement, a comparison of torque curves for different machines is presented in Figure 6.2.

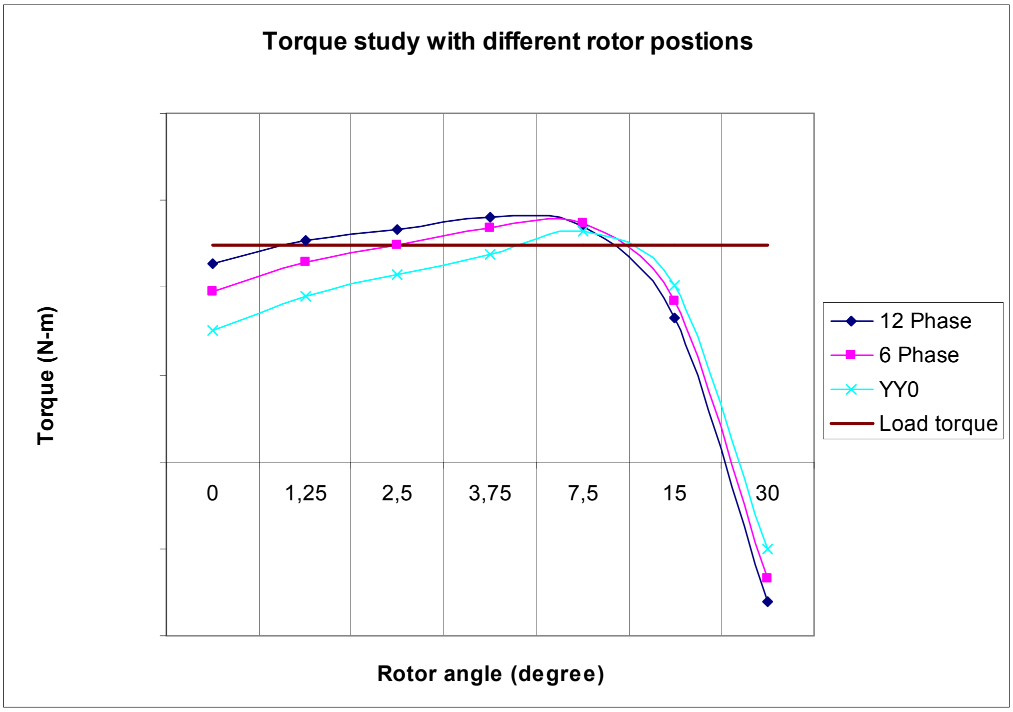

Figure 6.2: Torque curves of salient pole multiphase synchronous machines developed by changing the rotor position and using the magneto static simulation

The torque of the machine improves in the 12-phase case and the machine can produce the required load torque for smaller rotor angles which is a reflection of machine load angle. In figure above, the required load torque has been displayed as a straight line. Whereas x-intercept (on the left side, lower valued) of machine torque curve and load torque defines the operating point of that machine. Load torque line is intercepting each machine curve at two points. This means the 12-phase machine is capable of delivering the same power and load torque at a reduced load angle and is operating at a more stable point than the other compared machines. It can also be assumed that it will have less loss compared to other machines for the smaller load angle case.

In order to compare the air gap fluxes, the machines are simulated for rotor angles where the load torque condition is fulfilled. Harmonic spectrum comparison of these machines is presented in Figure 6.3.

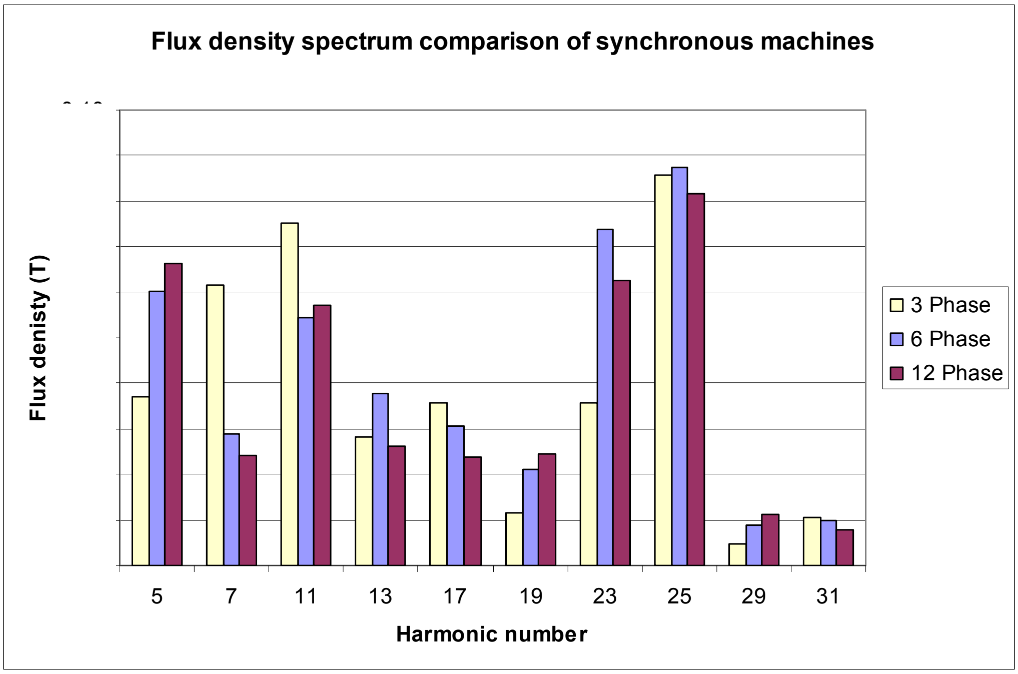

Figure 6.3: Flux density spectrum comparison of a 12-phase synchronous machine with 3 and 6-phase synchronous machines

An ideal case of a cylindrical rotor is simulated in order to get a better view of the air gap flux harmonics independent of saliency, rotor field and saturation affects. The cylindrical rotor case has no field supply and ideal iron is used in all components of the machine. This helps to remove saturation and saliency affects from the picture. The harmonic spectrum for the cylindrical rotor case is shown in Figure 6.4.

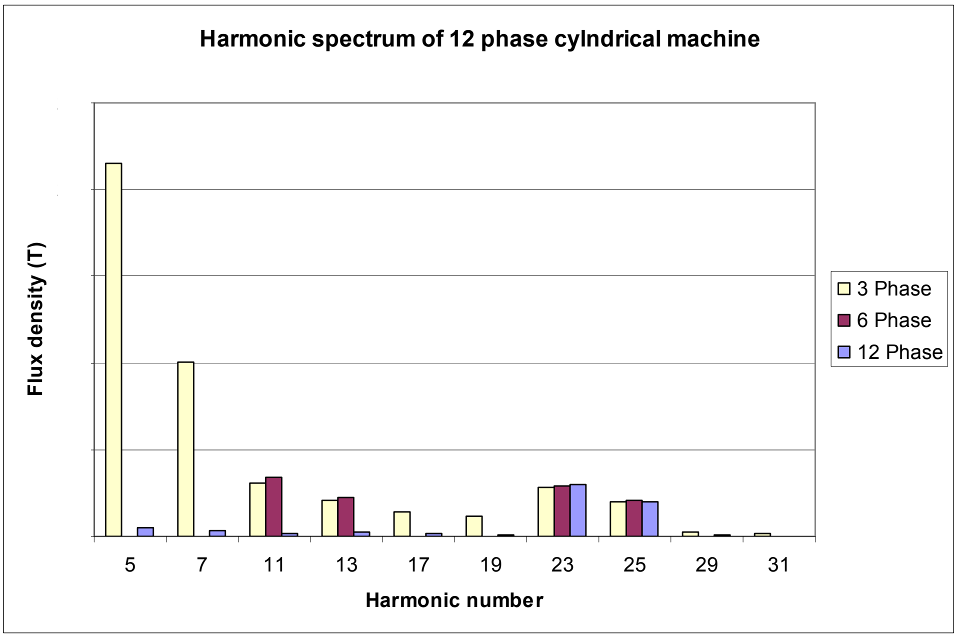

Figure 6.4: Flux density spectrum of 12-phase cylindrical rotor machine without field supply and employing ideal iron

The 12-phase machine in general has an almost negligible magnitude of low order harmonics. The first significant harmonics in the spectrum for the 12-phase machine are the 23rd and 25th. Even in the actual case in which field and saliency affects are playing their role 12-phase machine has a better spectrum. It has reduced the 7th, 13th, 17th, 19th, 23rd and 25th harmonics at the expanse of the highest 5th and 19th harmonic among all. In general it can be concluded that the 12-phase machine has a better harmonic spectrum than the 6-phase machine.

6.2 The 9-phase synchronous machine

The 9-phase machine has three sets of 3-phase windings which are displaced by 20 degrees from each other as shown in Figure 6.5. The machine is supplied from three independent power sources which are 20 degrees displaced in time from each other. The 3-phase machine has been modified to higher phase machines. Slots per pole per phase are six, three and two for the 3, 6, and 9-phase machines.

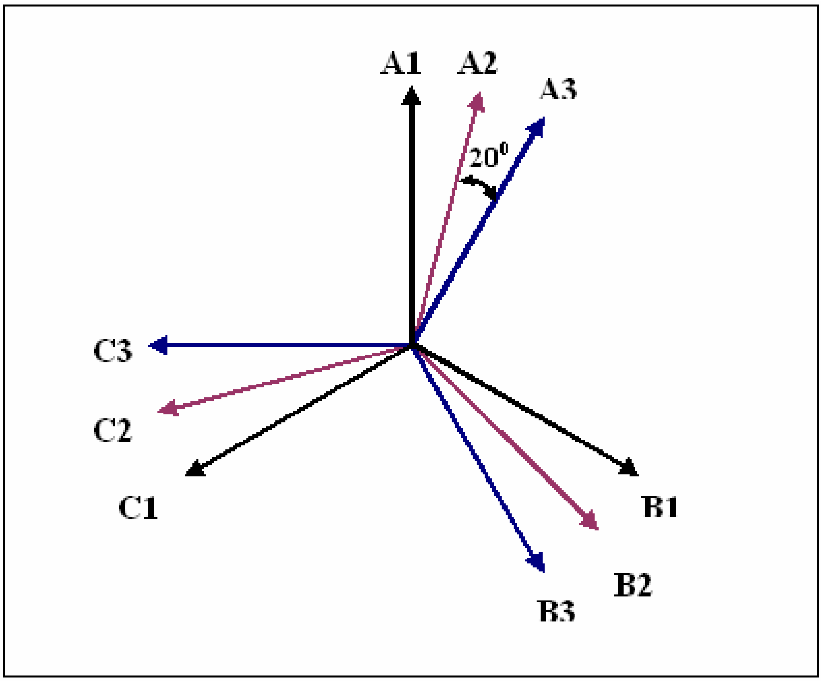

Figure 6.5: Winding arrangement of a 9-phase synchronous machine

The torque curves of all these machines with the same field excitation, in magneto static mode are given in Figure 6.6. It shows that the 9-phase machine is capable of delivering more torque even at lower load angles.

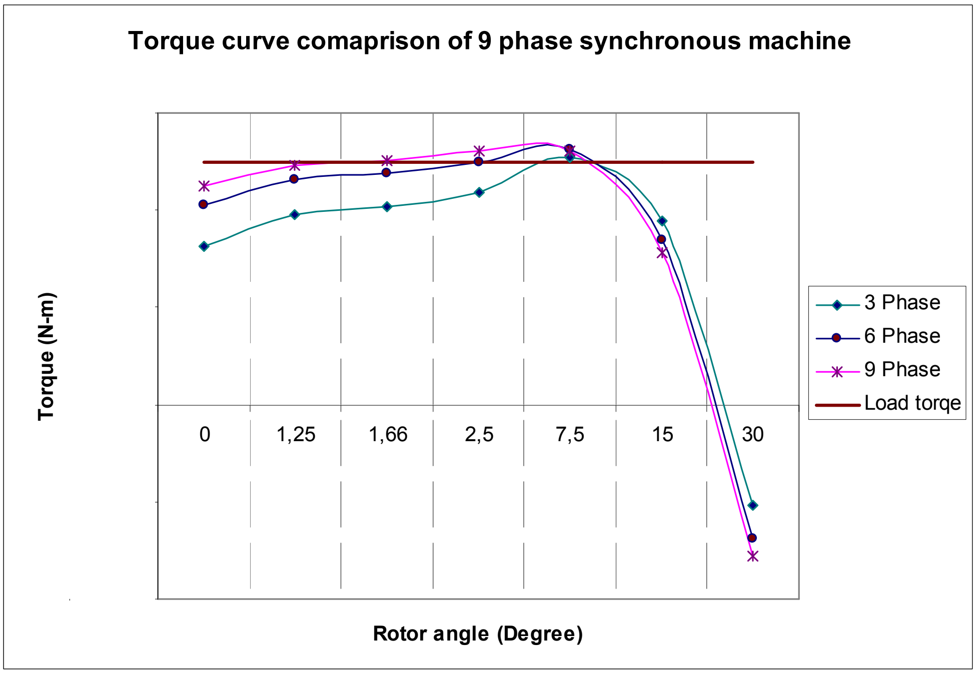

Figure 6.6: Torque curve comparison of the 9-phase salient pole synchronous machine developed by changing rotor position and using the magneto static simulation

Flux density spectrum of the 9-phase cylindrical rotor machine is compared with the 3 and 6-phase cylindrical rotor machines are given in Figure 6.7 . In the cylindrical rotor case, there is no field supply to the machines and the whole machine has been filled with ideal iron. The harmonics in the figure below are due to the winding arrangement and it shows that the 9-phase machine has 17th and 19th harmonics. All other low order harmonics are cancelled due to the mutual affect of the three winding sets.

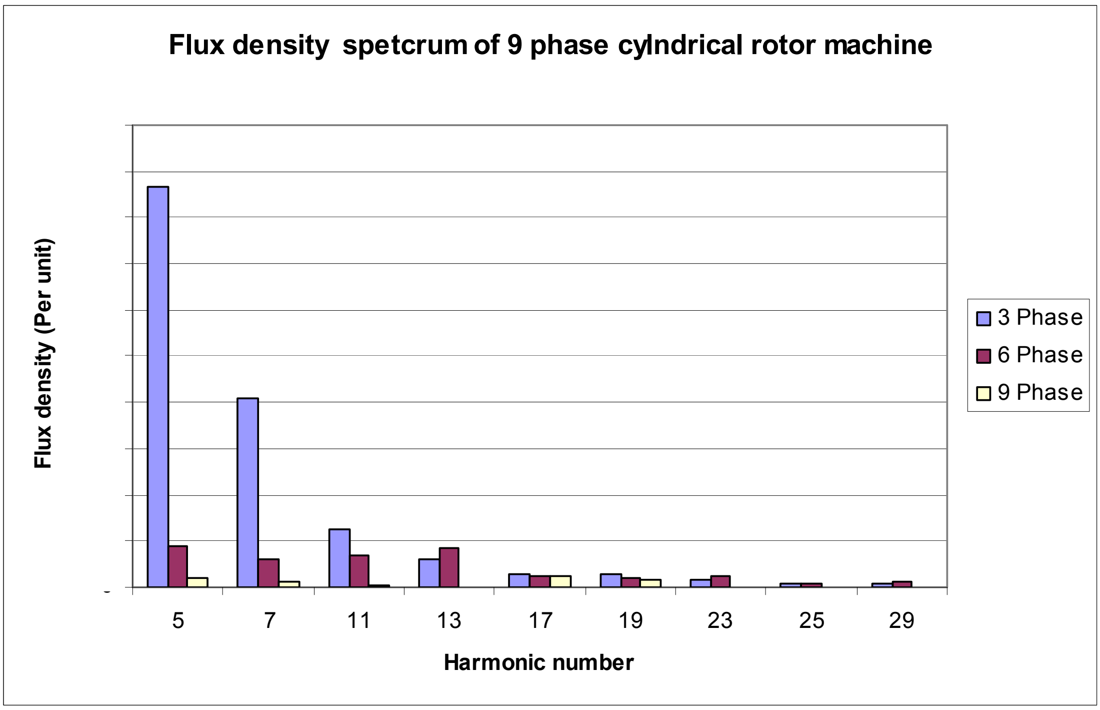

Figure 6.7: flux density spectrum of 9-phase cylindrical rotor machine without field supply and using ideal iron

It can be concluded that the order of first space harmonics increases with increasing phase numbers. Table 6.1 summarizes the order of harmonics which appear in multiphase machines. Positive sign donates that the direction of rotation is the same as the fundamental component of rotating field.

Table 6.1: Order of space harmonic in multiphase cylindrical rotor machines

Number of Phases	Space Harmonic order							
	5	7	11	13	17	19	23	25
3	-	+	-	+	-	+	-	+
6			-	+			-	+
9					-	+		
12							-	+

7 INDUCTION MACHINE ANALYSIS

In this chapter, the 6-phase full pitch induction machine has been analyzed and compared with the 3-phase full pitch and short pitch counter parts. In order to make a valid comparison, the basic design is the same for all cases. The winding displacement between 2 sets of the 3-phase winding is 30 degrees in all simulated cases. The replacement of the 3-phase winding by a multiphase winding brings the advantage of redundancy. The machines have been analyzed for both star and delta connections. Aim of this analysis is not to compare two connections quantitatively but to observe any varying trends as a function of the phase number.

7.1 The Double star connected 6-phase induction machine

7.1.1 Harmonic FEM analysis

7.1.1.1 Torque-slip curves comparison

For the same output power and speed requirement torque-slip curves of these machines have been compared. The machines are connected in star and the 6-phase machine has half the rated voltage of the three phase machine. Figure 7.1 gives the torque-slip curve of the all three machines. It can be observed easily that the torque-slip curve of the 6-phase machine is slightly lower than its 3-phase counter parts. Lipo [23] explains this loss due to the increased stator leakage inductance in the 6-phase machine which comprises of two three phase winding sets displaced from each other.

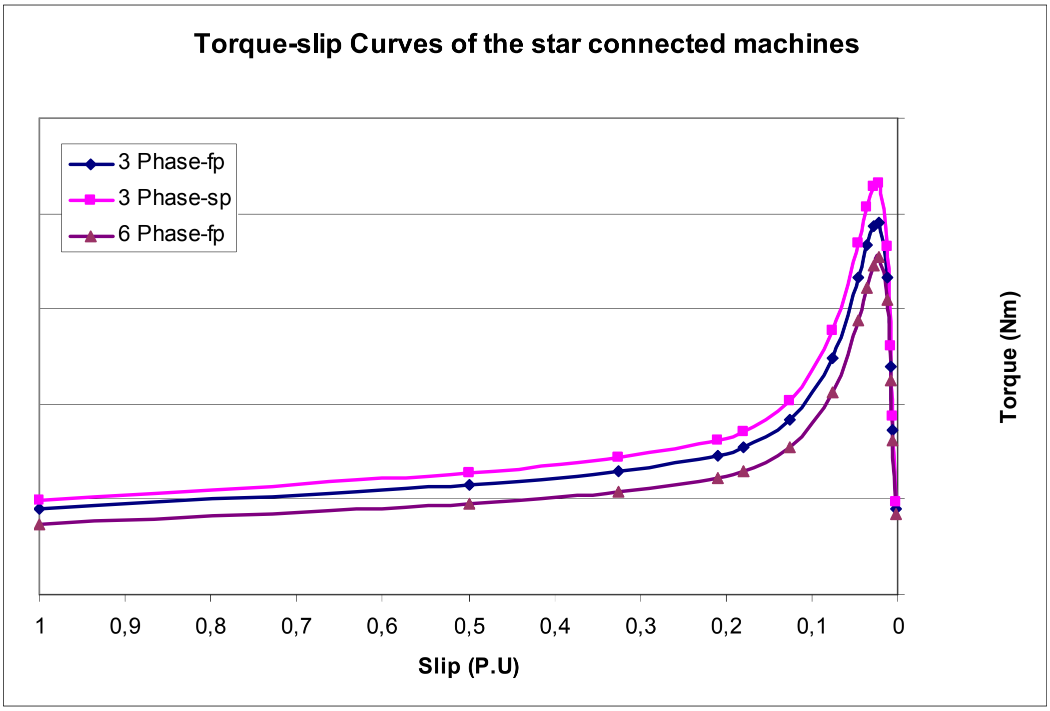

Figure 7.1: Torque-slip curves of induction machines (Harmonic FEM analysis)

The effect of end winding inductance has also been investigated. It can be stated that the end winding inductance has no significant influences on the machine nominal operation point and it will not change the torque speed relationship of the 3 and 6-phase machines given in Figure 7.1.

7.1.1.2 Current – slip curves comparison

A similar pattern is observed if current slip curves of these machines are compared due to the same reasons mentioned above. Figure 7.2 below shows comparison of these cases. The 6-phase machine has a lower starting current compared to the 3-phase short pitch and full pitch cases which is an additional advantage of the 6-phase machine.

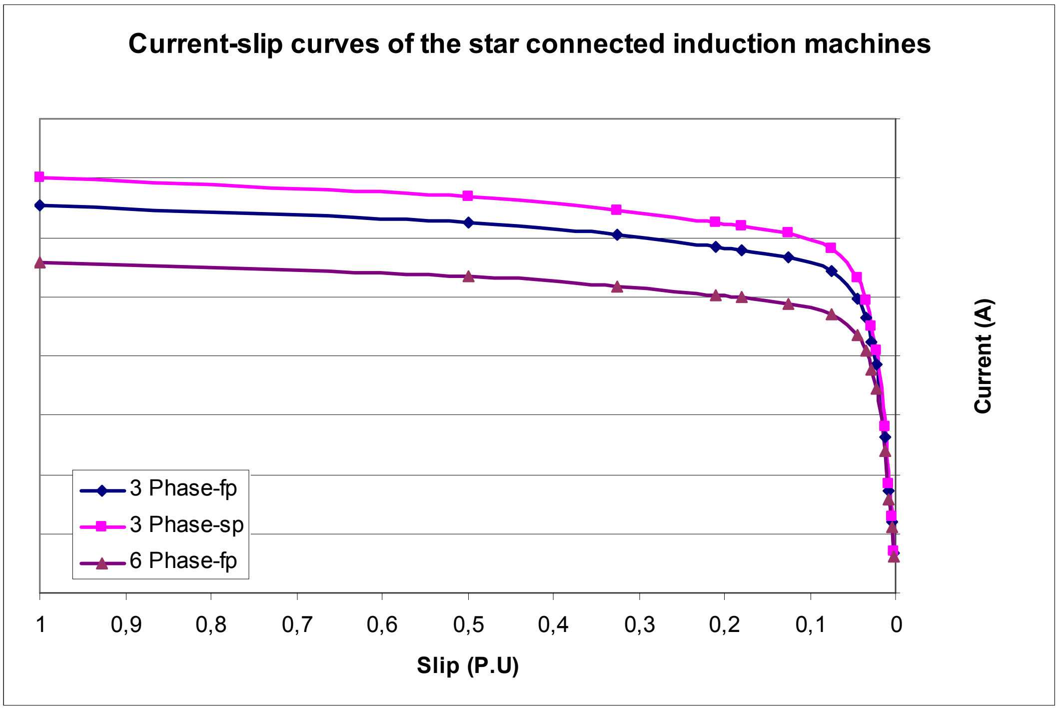

Figure 7.2: Current slip curves of star connected induction machines (Harmonic FEM analysis)

7.1.1.3 Nominal point operation

Nominal operating points of all three machines which differ only in number of phases and winding layout have been determined. The machines are connected in star. Slip, currents and torque developed by the machines have been compared. All three machines are operating in close proximity with the same output torque, power and speed. The 6-phase machine is operating at a slightly higher slip than the other two simulated cases. All other performance parameters in the 6-phase machine case are relatively higher except the power factor which is slightly lower than the 3-phase short pitch case.

Stator copper losses of the machine depend upon its current loading and (for two machines with the same base design and output requirement) are given as [15]:

$$\frac{P_{S,cu}^{m1}}{P_{S,Cu}^{m2}} = \left[\frac{k_{d1}^{m2} k_{p1}^{m2}}{k_{d1}^{m1} k_{p1}^{m1}}\right]^2 \qquad \text{(Equation 5.1)}$$

According to equation 5.1 the stator copper losses can be reduced by using a 6-phase winding compared to the same machine with a 3-phase winding of the same pitch, as distribution factor of the 6-phase machine will be slightly higher than the 3-phase machine. Rotor copper losses depend upon the magnitude of the fundamental component of the air gap field and induced currents in the rotor cage. Harmonics other than fundamental also contribute to these losses. The rotor impedance is slip dependant. As mentioned earlier, the 6-phase machine is slightly degraded and working at a higher slip. This causes increased induced currents in rotor (and rotor copper losses) of the 6-phase machine. Although iron losses are not a function of its phase number yet they are influenced by the harmonics distribution of the increased phases.

7.1.2 Constant speed time stepping simulations

The following simulations are time dependant in which the speed has been kept constant. The nominal slip which was determined in the pervious section using harmonic FEM simulation is used as input parameter in this operation mode. The machines are star connected and output power requirement is the same for all simulated machines. Comparison of the air gap field harmonics, losses and torque pulsations are discussed in this section. Rotor currents are pulsating at a frequency which is a multiple of slip and line frequency. As the machine is operating in the low slip range therefore frequency of rotor currents is quite low. For a valid harmonic analysis of the rotor bar currents, the machines have to be simulated for longer durations with increased number of steps per period of slip frequency subsequently, the harmonic analysis is not considered in this discussion.

The air gap field harmonics are influenced by the stator and rotor MMF. Time harmonics in the supply also have their influences. Generally speaking time and space harmonics in the air gap field are related according to equation 5.2:

$$v = p(q - 2Nm) \qquad N = 0, \pm 1, \pm 2, \pm 3, ... \qquad \text{(Equation 5.2)}$$

Where v is space harmonic, q is time harmonic, p is number of poles and m describes the number of phases. In all considered cases, supply is sinusoidal and contains no time harmonics. Only the fundamental component of excitation is of interest in this situation. So, setting the value of q=1 in the above equation yields the pattern of the air gap space harmonics. It can be concluded from the outcome of this equation that ideally there will be only 11^{th}, 13^{th}, 23^{rd}, 25^{th}, 35^{th} and 37^{th} harmonics in the air gap for the 6-phase machine. The magnitude of these higher order space harmonics in the 6-phase machine is also lower as the winding factor decreases more sharply with an increase of the order of space harmonics compared to the 3-phase full pitch case [15]. Figure 7.3 contains comparison of the air gap flux density harmonics.

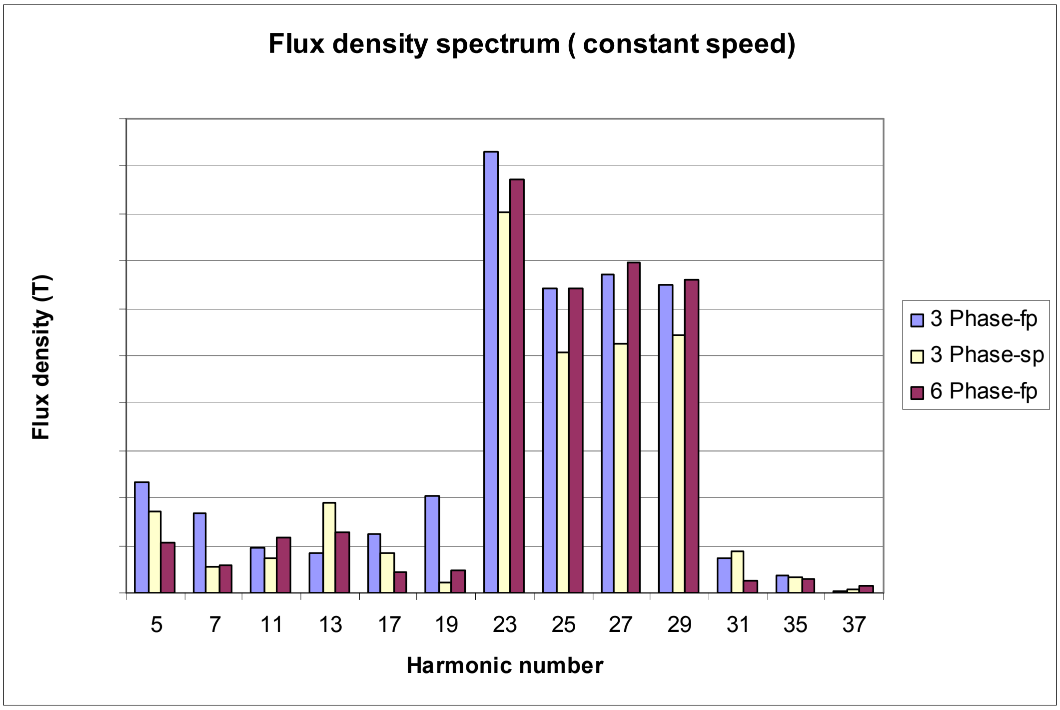

Figure 7.3: Flux density spectrum in the air gap of induction machines (constant speed simulations).

The harmonic index is considered for the first 40 harmonics. Deviation of results from the ideal case is due to saturation and slot permeance which have not been considered in equation 5.2. Anyhow low order harmonics are still quite minimal in the 6-phase machine.

7.1.3 Performance comparison

The air gap harmonics cause torque pulsations. Magnitude of these pulsations depends on the product of the magnitudes of two interacting fields. Low order harmonics are minimal in the 6-phase and the 3-phase short pitch cases as witnessed in Figure 7.3. This ensures smaller ripple at low frequencies especially the 6th harmonic pulsation of torque which is zero in the 6-phase machines and is considered as a major benefit of multiphase machines. Figure 7.4 shows a comparison of torque pulsations in all three cases. Significant ripple in the torque is the 24th harmonic pulsation which is high for all cases but the 3-phase full pitch machine has an exception at 30th harmonic pulsation in torque which is significantly higher than any other case. The 6-phase machine does not have this ripple. This explains machine improved losses. All other pulsations are quite small. Even the 36th harmonic which lies in high frequency range is small.

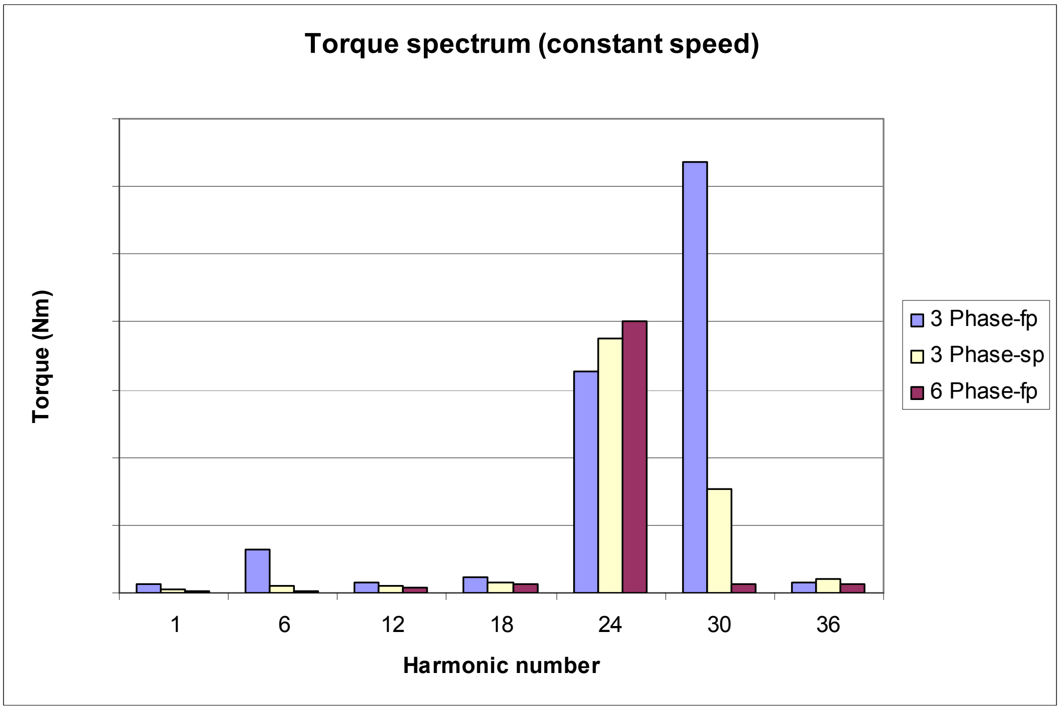

Figure 7.4: Torque pulsations of induction machines (constant speed simulations)

Performance of all these cases at their respective nominal operation points will be compared now. Output power is the same in all the cases. The 6-phase machine is slightly degraded due to increased leakage inductance and is operating at a slightly higher slip. Speed and torque developed by all machines are the same in general. Rotor currents are induced by the stator and their magnitude is slip dependant. The 3-phase short pitch case has minimum slip and therefore has minimum induced currents where as the 6-phase machine has higher amplitude currents due to its higher slip. Also the 6-phase machine has slightly lower power factor which explains its higher stator current than the other two cases.

7.1.4 Loss comparison

The stator copper losses of the 6-phase machine are higher than the 3-phase full pitch case, as expected due to the higher stator current. There is a decrease in rotor copper losses although the rotor design is the same in all cases and the fundamental the air gap field is also approximately the same. So, under these conditions the rotor copper losses should not depend on the machine phase number but the reduction in rotor copper losses we witness here is due to the improved harmonic spectrum in the air gap which have lower magnitudes for higher harmonics. Similarly, iron losses of the machine do not depend on the stator phase number but the harmonic spectrum improvement gained in the 6-phase machine definitely helps to improve the losses.

It can be concluded from this study that the 6-phase machine will have lower magnitude of the harmonic fields in the air gap compared to the 3-phase case. Torque pulsation will also be reduced except those pulsations which are due to slot permeance effects. The machine iron and rotor copper losses have decreased while there is a marginal increase in the stator copper losses in the 6-phase machine causing minimal decrease in efficiency compared to the 3-phase full pitch case.

7.2 Double delta connected 6-phase induction machine

Multiple sets of the 3-phase windings in multiphase machines gives an option of phase interconnection as required by the user. In this section of report the 6-phase machine with double delta phase connections is studied and its results are compared with the 3-phase full pitch and short pitch cases of the same connection configuration. A small modification has been made in the base design of machine for delta connections. The number of conductors in the stator slots has been increased to bring down the flux density in the air gap. However, this change of conductors in the stator slot is the same for all cases and does not challenge the validity of the comparison.

7.2.1 Harmonic FEM analysis

7.2.1.1 Torque – slip curves comparison

Torque-slip curve of the double delta connected machines is compared with the 3-phase short pitch and the 3-phase full pitch cases as seen in Figure 7.5. The relative variation of torque-slip curves of the said machines in delta configuration is the same as the result of the star configuration which was shown in Figure 7.1

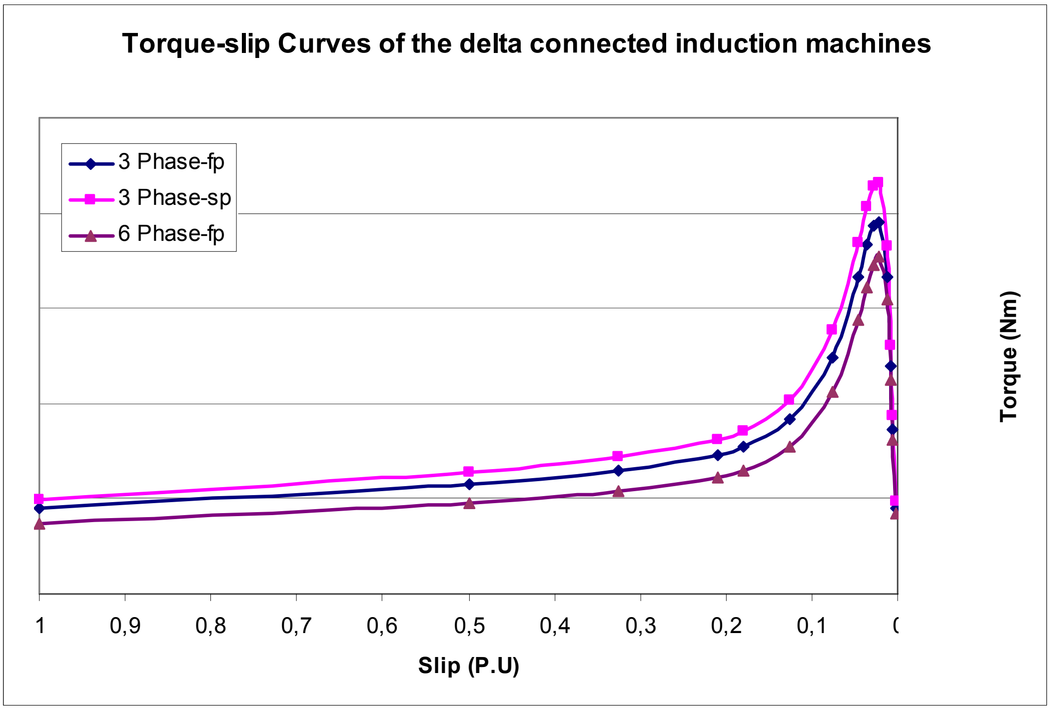

Figure 7.5: Torque-slip curves of delta connected induction machines from harmonic FEM analysis

7.2.1.2 Current-slip comparison of delta connected induction machines

Figure 7.6 shows that the 6-phase double delta machine has a lower starting current compared to the other two shown cases. The relation of these curves with respect to each other is the same as the star connected induction machines shown in Figure 7.2.

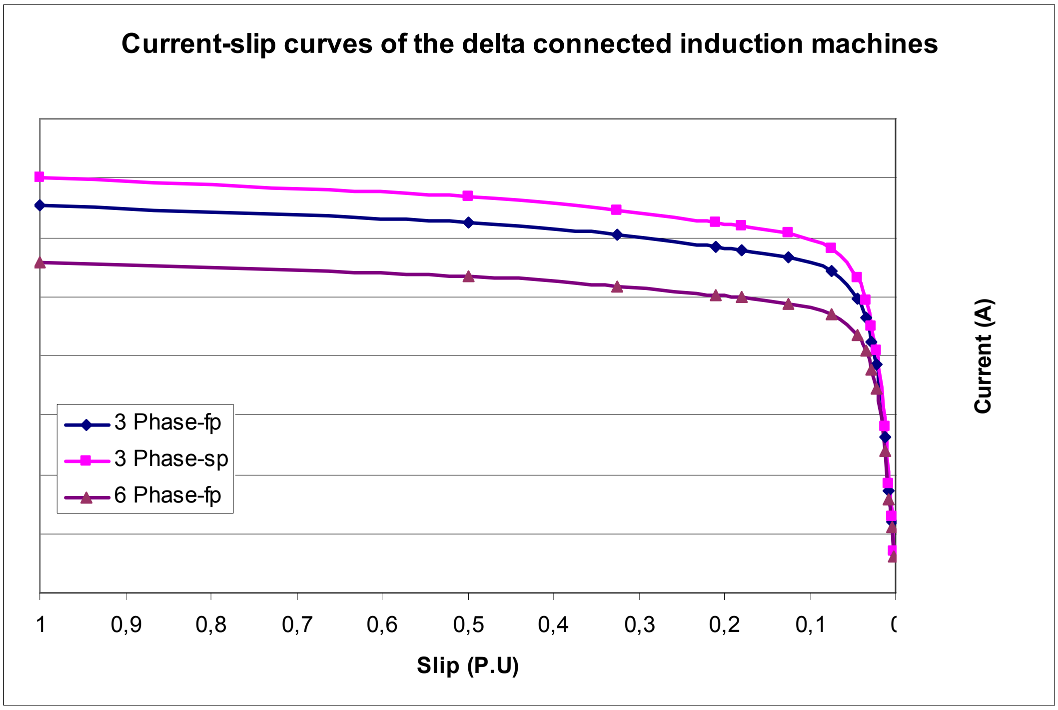

Figure 7.6: Current-slip curves of delta connected induction machines from Harmonic FEM analysis

7.2.1.3 Nominal point

Comparison of performance parameters reveal that the nominal point for these delta connected machines are higher than the same star connected machines but the pattern is the same in both connection types with the 6-phase machine having a higher operation point than the other two discussed cases. Efficiency of all the machines is still high as it was for the star connected machines.

7.2.2 Constant speed time stepping simulation

Time dependant simulations results of the 6-phase double delta machine have been compared with delta connected 3-phase full pitch and short pitch cases. Constant speed application mode analyses the machine at a given operation point. Comparison criterions are space harmonics, torque pulsations and losses of the machines.

Flux density spectrums in the air gap for the delta connected machines are shown in Figure 7.7. It is evident in the Figure below that the 5^{th} and 7^{th} harmonics in the 6-phase machine are smaller than the 3-phase full pitch cases as expected while the 11^{th} and 13^{th} harmonics in the 6-phase machine are high. However amplitude variation range of all low order harmonics is low and significant harmonics in the spectrum are slot permeance harmonics. If only slot permeance harmonics are compared in Figure 7.3 and Figure 7.7 (which are star and delta connected configurations respectively) then both the 3-phase full pitch and short pitch machines show an increase in the 25^{th}, 27^{th} and 29^{th} harmonics.

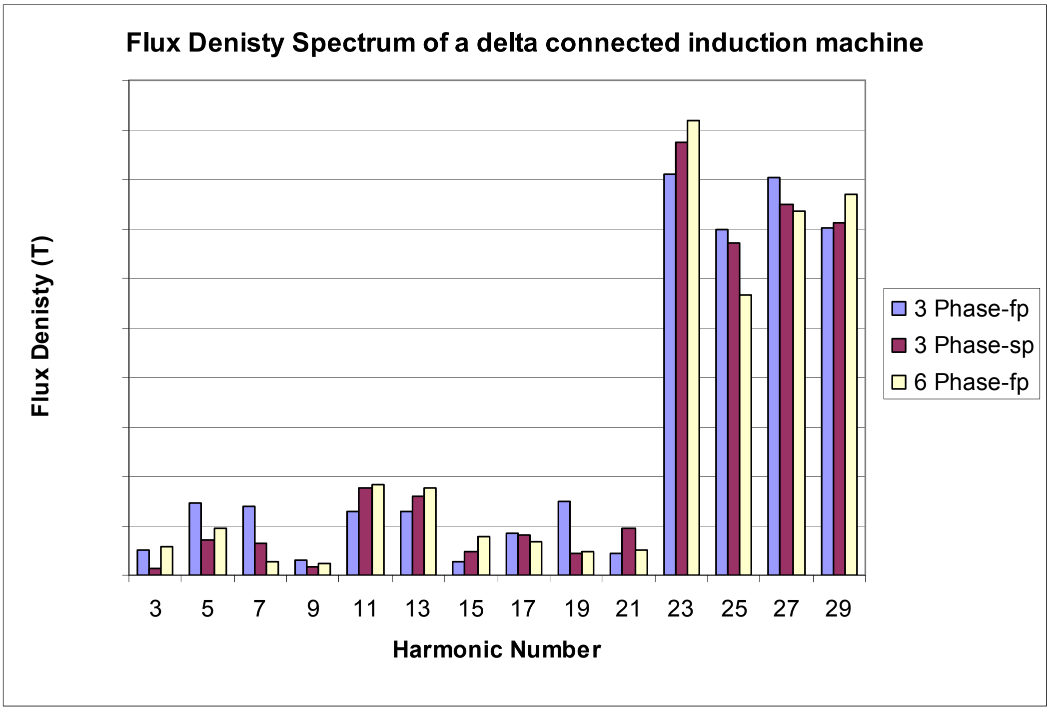

Figure 7.7: Flux density spectrum in the air gap of delta connected induction machines using constant speed time stepping mode

7.2.3 Performance comparison

Performance comparison of all three machines in delta configurations includes developed torque and pulsation in torques. Operating slip, power factor and the stator currents drawn from mains to develop the torque are also compared.

Torque pulsations of the machine are independent of connection configuration as shown in the following Figure 7.8. Significant pulsation in torque is the 24^{th} harmonic in case of the 6-phase machine while both 3-phase cases also have higher 30^{th} harmonic pulsation. The 6^{th} harmonic torque pulsation is only evident in the 3-phase full pitch case. Pattern of pulsations in the torque is the same for both connection configurations as there are no significant variations in the air gap field harmonics as well while switching from star to delta configurations as discussed in the previous section.

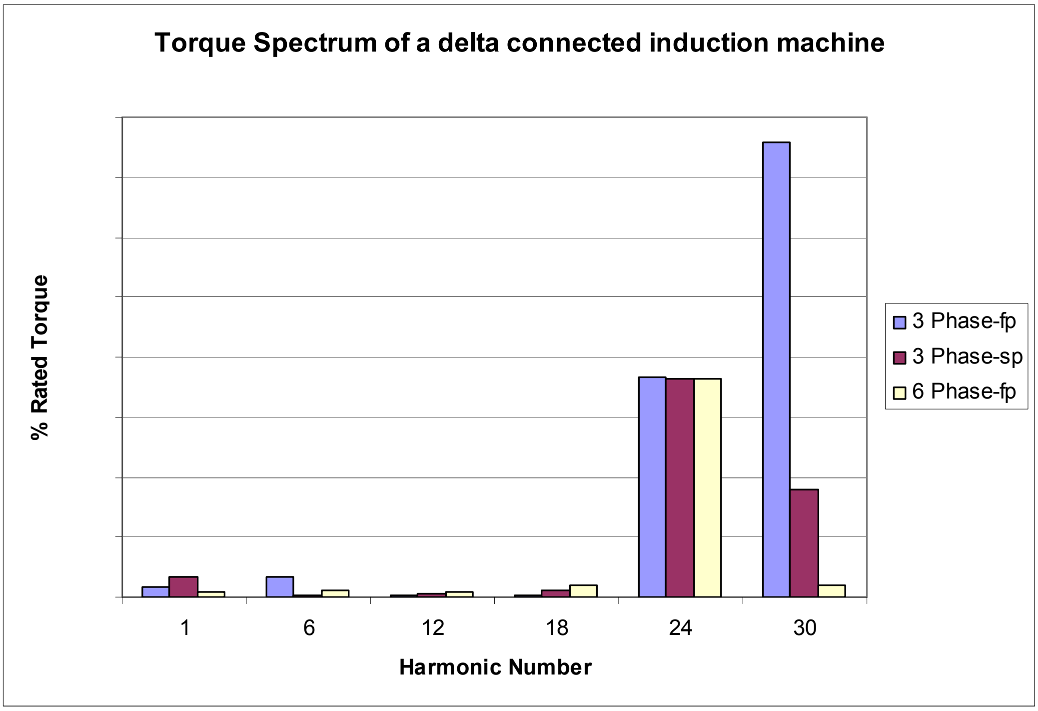

Figure 7.8: Torque pulsations comparison of delta connected induction machines

Further in this section, performance parameters are compared. Comparing performance parameters of these delta connected machines show that the 6-phase machine has increased the stator and rotor bar currents due to a poor power factor and an increased slip. However, overall efficiency of the three machines is the same. Comparison of results for delta connected machines with star connected machines show that operation points of all the delta connected machines have moved to an upper value in torque-slip curves yet variation pattern of parameters is the same as for star connected machines.

7.2.4 Loss comparison

Losses comparisons of all three machines in delta configurations reveal that total losses of the 6-phase machine are lower than the 3-phase full pitch case.

7.3 Comparison of star and delta connected machines

In this section of the report the 6-phase machine with double star and double delta phase connections is compared with the 3-phase full pitch and short pitch cases of the same connection configuration. Target of this comparison is to compare the variation trends. It can be concluded that delta connected machines are operating at a slightly higher nominal slip. The torque pulsation pattern is the same in star and delta connected machines. Reduction of total losses compared to the 3-phase full pitch case is higher in the 6-phase double delta machine compared to the 6-phase double star machine. It can be concluded that the 6-phase induction machine is capable of delivering the same torque and power at reduced total losses. There is a marginal increase in the stator copper losses but the rotor copper loss and the iron losses will decrease due to improved the air gap harmonic fields. Secondly these benefits are not linked with any connection type. Both double star and double delta will benefit from these improvements.

8 PM MACHINE ANALYSIS

In this chapter the 6-phase permanent magnet machine has been compared with the 3-phase counter part. There are four surface mounted magnets in both machines. The only difference in both machines is the number of phases and both have full pitch winding. The machines are supplied with sinusoidal voltages. In the 6-phase machine two the 3-phase winding sets are 30 degrees displaced. Comparison criteria are losses, induced voltages and the air gap harmonics under the same load.

8.1 Magneto static analysis

In a magneto static study, flux density spectrums of the 3 and 6-phase machines are compared and are shown in Figure 8.1, where ''FL'' denotes the full load case.

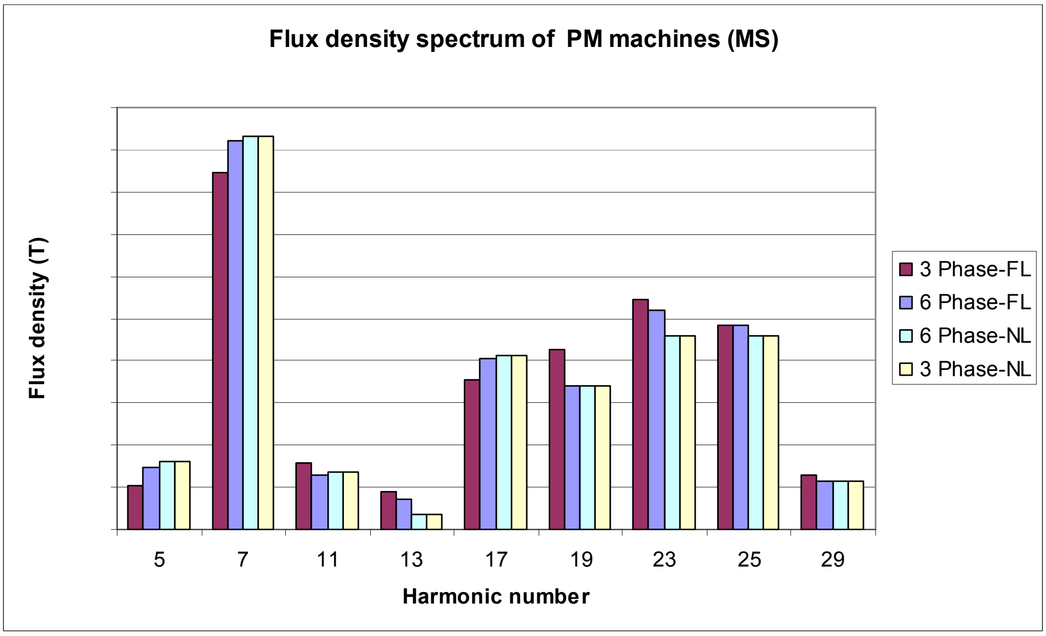

Figure 8.1: Flux density spectrum in the air gap of 3 and 6-phase PM machines at full load and no load conditions (Magneto static simulations)

The figure above shows that some harmonics like the 7th, 17th, 19th, 23rd and 25th are relatively higher than the other harmonics in the spectrum. The spectrum shown in Figure 8.1 is a common picture of the stator and rotor MMF influences. A special case has been simulated in order to locate the harmonics which are under individual rotor or stator influences. In this case the machine has been simulated under no load condition. Materials of all the stator components, rotor rim and shaft have been replaced with ideal iron with high permeability. Under no load condition the 3-phase and 6-phase machine are practically the same machines as there is no the stator supply and rotor parameters are the same in both cases. Under this scenario, the flux density spectrum in the air gap contains only rotor generated harmonics. Ideal iron in the machine takes away any saturation affects. The flux density spectrums of this special case are compared with normal no-load and full-load cases of the 3 and 6-phase machines in Figure 8.2. In the Figure 8.2, ''FL'' and ''NL'' represent full-load and no-load cases. The ''Real iron-NL'' case gives the result of both the 3 and 6-phase machines as there is no difference between a 3 and 6-phase machine under no-load conditions.

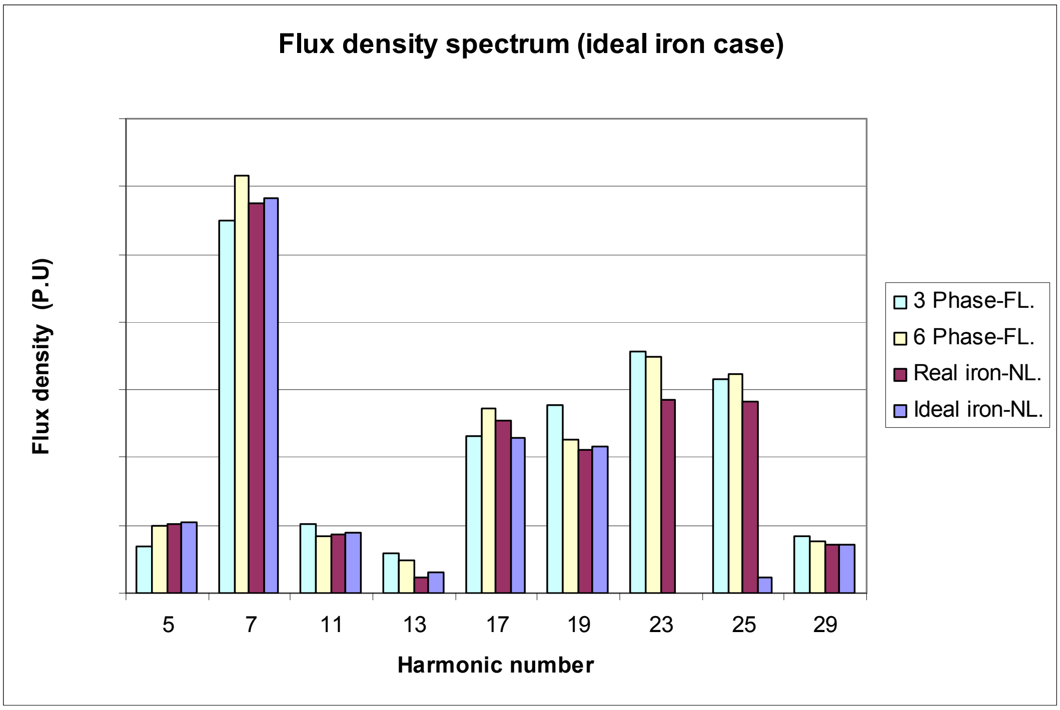

Figure 8.2: Flux density spectrum comparison of PM machines at full load with no load real iron and ideal iron case (Magneto static simulations)

Study of the spectrum above confirms that the 23rd and 25th harmonics which are due to the stator slots have vanished. While the 7th, 17th and 19th harmonics which are dominant in the 3 and 6-phase machines full-load spectrum are due to rotor MMF. Circumferential space in between magnets acts as slots and reacts with the stator MMF to give these high harmonics.

8.2 Time stepping analysis

Both 3 and 6-phase machines have been simulated and studied under no load and full load conditions.

8.2.1 No-load simulations

No load simulation is good to visualize the rotor MMF influences on the machine as there is no stator field anymore. Quantities of interest in no load simulations are flux density in the air gap and induced voltages in the stator winding. Space harmonics in the air gap field are solely due to rotor magnetization field and are influenced by the magnets position and spacing at the pole surface. Flux density spectrums of 3 and 6-phase machines are shown in Figure 8.3.

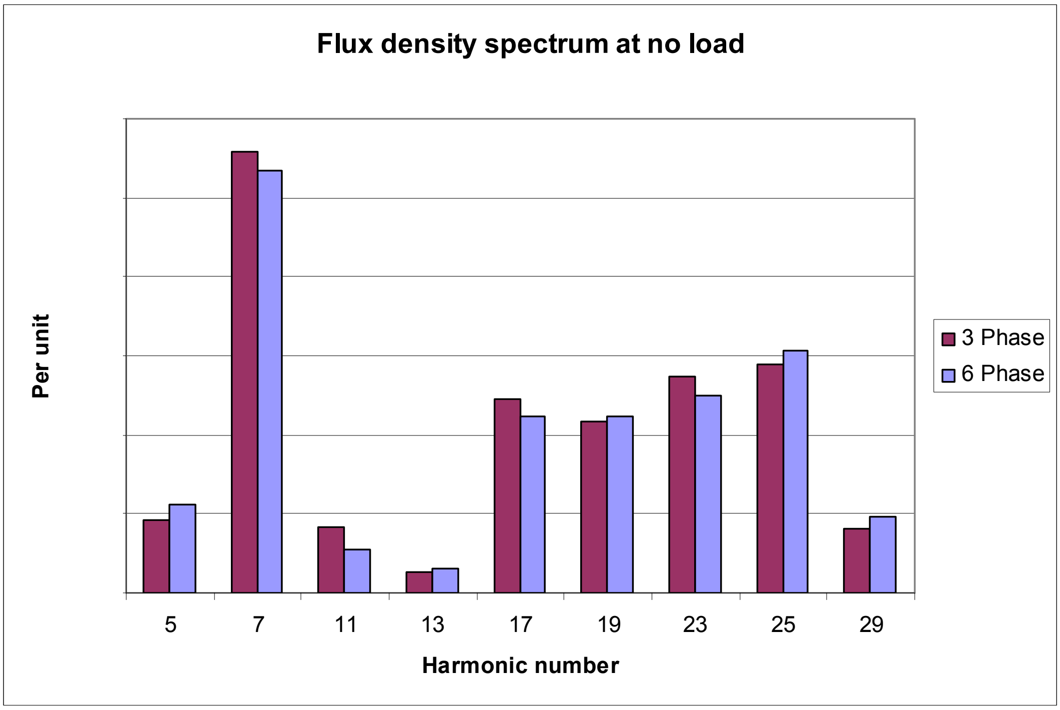

Figure 8.3: Comparison of flux density spectrum of PM machines under no load condition (Time stepping)

Induced voltage in the stator under no load condition identifies all the rotor generated harmonics as the stator field is not present in the picture. Back emf spectrums for both machines are compared in Figure 8.4. However, values are in per unit of their respective fundamental.

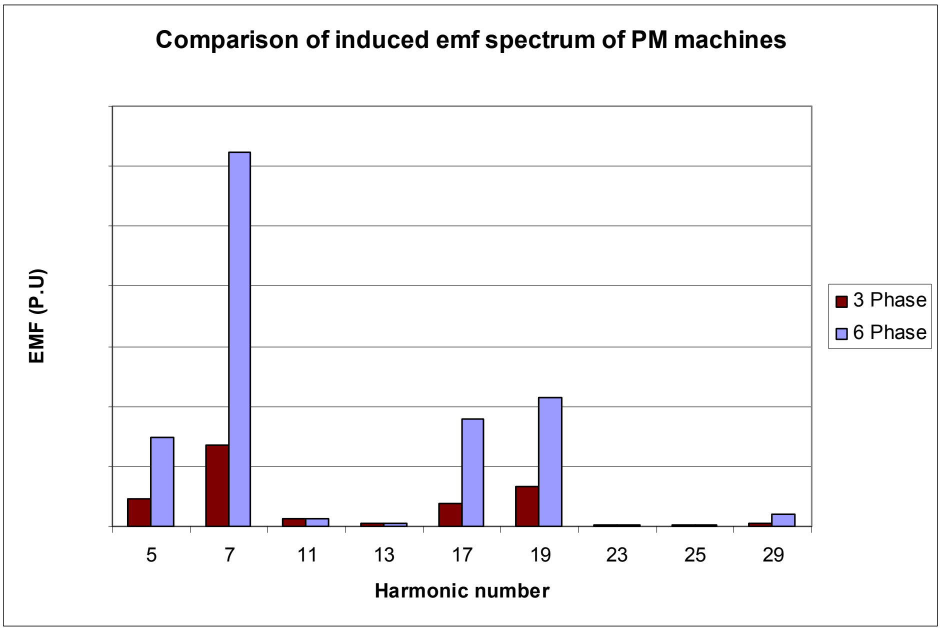

Figure 8.4: Harmonic spectrum comparison of induced voltages of PM machines

The spectrums above reveal that the rotor is inducing 5^{th}, 7^{th}, 17^{th} and 19^{th} harmonics which are also dominant harmonics in the machine flux density spectrum. While the 23^{rd} and 25^{th} harmonics have vanished from spectrum. Results in Figure 8.4 are matching with the claims made in Figure 8.2 in which ideal iron is used to take away saturation affects and remove the 23rd and 25th harmonics while above mentioned harmonics (which are due to the rotor field) are present in both figures.

The torque pulsation spectrum at no load is given in Figure 8.5. The torque spectrum has only one high frequency 24th harmonic pulsation which is due to the stator slotting affects.

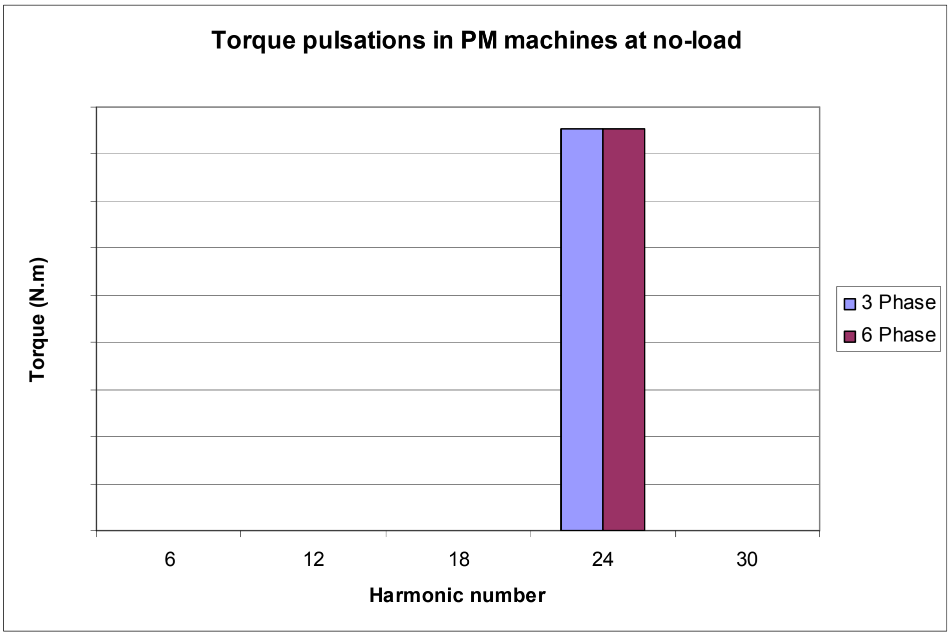

Figure 8.5: Torque pulsations in PM machines at no-load condition

8.2.2 Full load simulations

Both 3 and 6-phase machines are simulated for the same output power and speed requirement. Load torque applied to both machines is the same and constant. Performances of both machines have been compared under steady state and full load conditions. The flux density spectrum for 3 and 6-phase machines is compared in Figure 8.6.

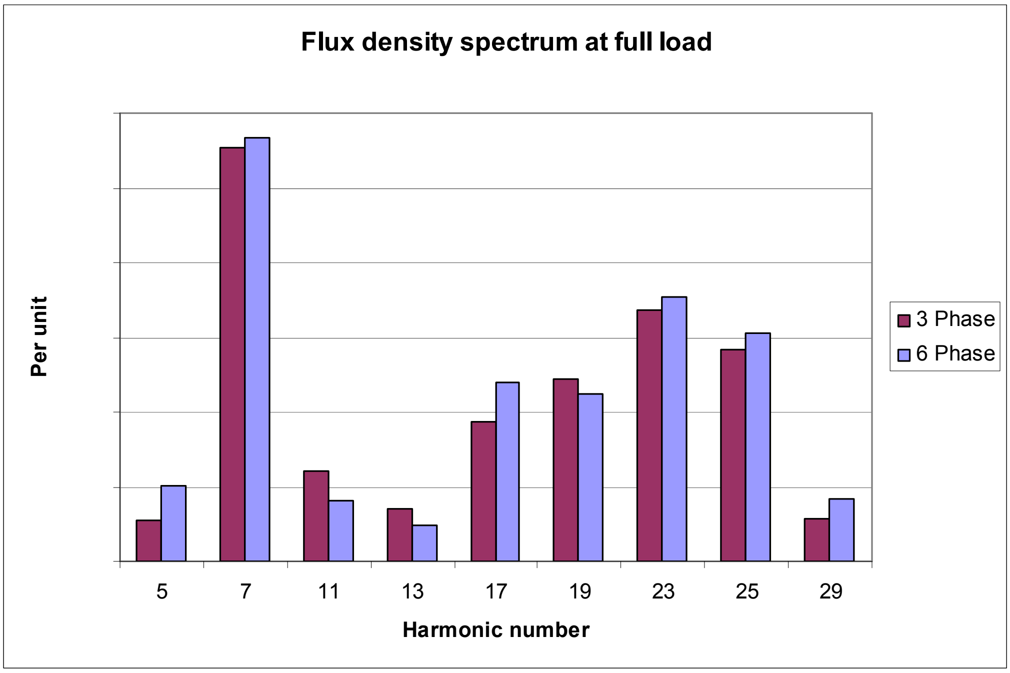

Figure 8.6: Flux density comparison of PM machines at full load (Time stepping)

The flux density spectrum at full load with time stepping analysis is the same as shown in Figure 8.1 for magneto static analysis. The 6-phase machine has slightly higher harmonics than the 3-phase machine. However, as mentioned earlier these harmonic contributions are mainly from the rotor side. Figure 8.2 verifies this claim as the 23rd and 25th harmonics have vanished while the rotor mainly produces 5th, 7th, 17th and 19th harmonics.

The stator currents spectrum of the 3 and 6-phase machines are compared in Figure 8.7. The harmonics and their respective variation trend with respect to 3 and 6-phase machines are the same as induced voltages which are shown in Figure 8.4. Values of the stator current spectrum are in per unit and the 6-phase machine has higher magnitude of these harmonics compared to the 3-phase machine.

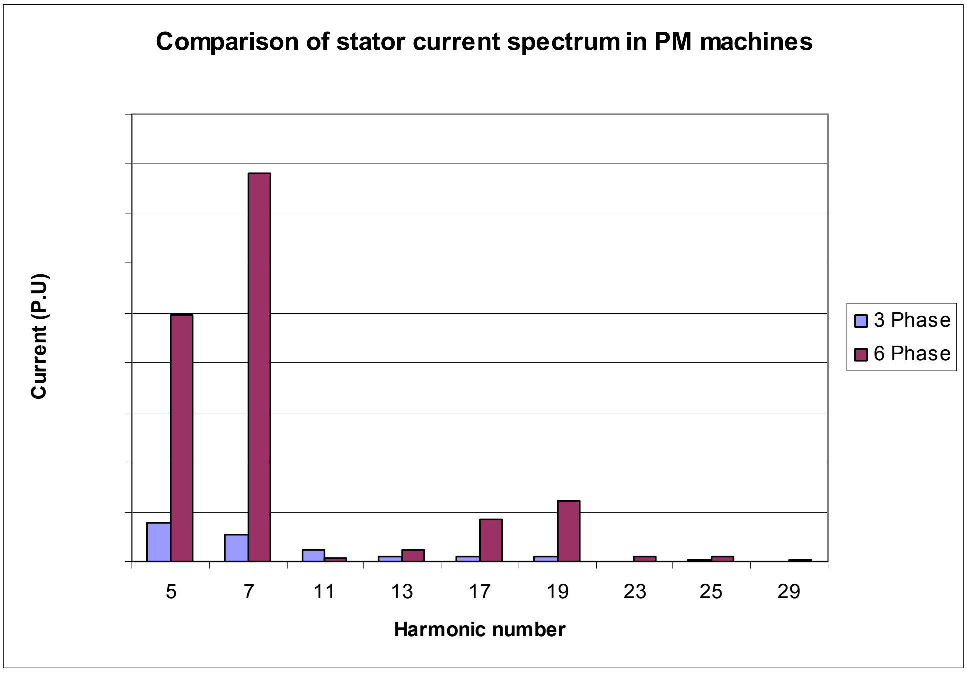

Figure 8.7: Comparison of the stator current spectrums in PM machines at full load

Torque pulsations of the machine are influenced by both the stator and rotor fields. Time and space harmonics which are present in these fields also interact to create pulsations in the developed torque. The torque spectrum of the 3 and 6-phase machines are compared in Figure 8.8. The 6-phase machine has lower 6th and 18th harmonic pulsation in the torque which is an inherent feature of all the 6-phase machines with 30 degrees displaced winding sets.

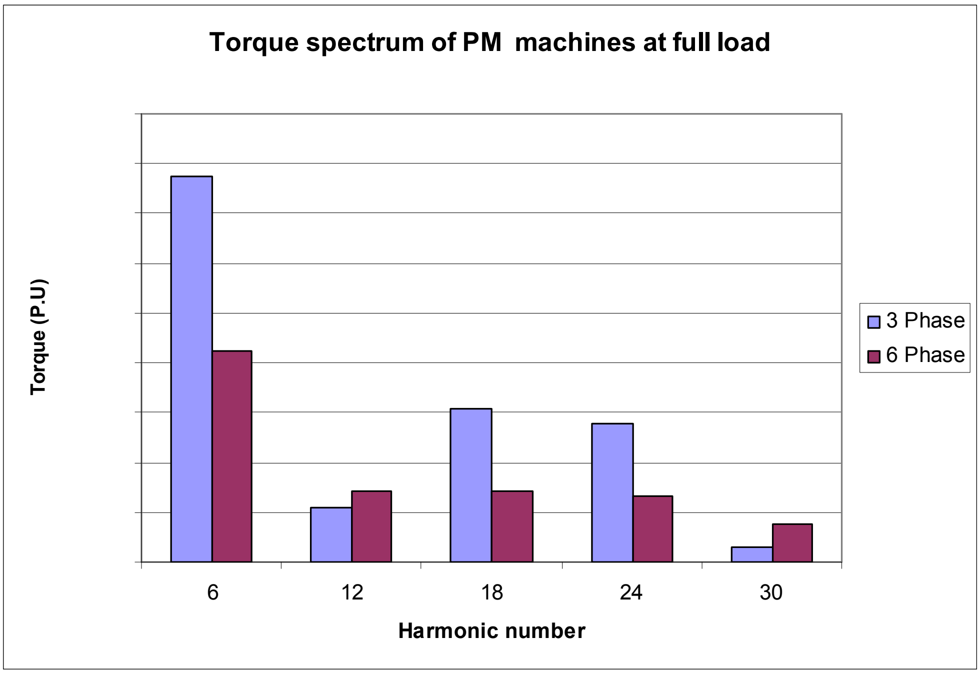

Figure 8.8: Torque pulsations in PM machines at full load

The performance of the 3 and 6-phase permanent magnet machines is compared. There is a nominal increase of torque in the 6-phase machine compared to the 3-phase machine while the power factor and efficiency have decreased.

Losses of the machine are occurring only on the stator side. Rotor conducting losses are zero due to the use of non conducting magnets. Although there are some conducting losses in magnets in reality but limitations imposed by the working tool did not allow calculation of these losses in the studied cases. Similarly, iron losses are also very low on the rotor side as the stator field links minimally to the rotor of machine due to low permeability of air and magnets. The stator copper and iron losses constitute the main losses of the machine. Both the 3 and 6-phase machines have the same trend of losses on the rotor side. The rotor losses in the 6-phase machine are lower than the 3-phase machine although rotor losses are minimal in both machines of values around 1.64 Watts. The 6-phase machine has higher copper losses due to the presence of the 5th and 7th harmonics in the stator currents compared to the 3-phase machine. The iron losses in both the 3 and 6-phase machines are almost the same as dominant harmonics in the MMF are due to the rotor magnets and are not influenced by the number of machine phases. The total losses in the 6-phase machine are then higher compared to the 3-phase machine.

9 CONCLUSIONS

9.1 Supply angle study of the 6-phase synchronous machine

For the 6-phase machine with the two winding sets displaced by 30 degrees in space, the 5^{th}, 7^{th}, 17^{th}, and 19^{th} harmonics are not cancelled if supply angle deviates from 30 degrees shift between two systems. The sixth harmonic pulsation in torque increases with increase of deviation from 30 degrees supply angle. The stator current requirement increases sharply with deviation angle increase for the same torque requirement. There is an increase of stator current for 20 degrees mismatch from the 30 degrees supply angle. The total losses of the machine are very high in case of 20 degrees deviation from the 30 degrees supply angle.

9.2 Parametric sensitivity analysis of the 3-phase synchronous machine

The short pitch winding cases have reduced space harmonics compared to the 3-phase full pitch winding case. The total losses have slightly increased while the rotor surface losses have decreased in the short pitch winding cases compared to the 3-phase full pitch case. The short pitch case of the 10/12 configuration has reduced bar losses whereas the total losses are higher compared to the 3-phase full pitch winding case.

Use of the magnetic wedge material in place of the air wedge in stator slots helps to reduce the rotor surface losses however the stator iron losses increase by almost the same amount. Total losses are higher in the magnetic wedge case thus efficiency is lower.

The rotor pole shape study reveals that the arched pole shape, due to reduced harmonic distortion, is better than the original design shape which is somewhat flat. The rotor iron and bar losses decrease while the field winding loss increases in case of the arched pole shape, compared to the original design. The torque pulsation is lower and total losses are higher with almost the same efficiency.

9.3 Comparison of 3 and 6-phase synchronous machines

In the 6-phase machine there are no 5^{th}, 7^{th}, 17^{th}, and 19^{th} space harmonics from the stator side. Rotor saliency contributes to these space harmonics but still magnitude is smaller compared to the 3-phase machine. There are no 6^{th} and 18^{th} torque pulsations in the 6-phase machine while the 12^{th} and 24^{th} harmonic pulsation are higher in the 6-phase machine compared to the 3-phase machine. The damper bar losses have decreased in the 6-phase machine compared to the 3-phase machine. Total losses of the 6-phase machine are lower than of the 3-phase machine.

Parametric sensitivity comparison of the 3 and 6-phase synchronous machines reveals that for the 3-phase machine rotor surface losses decrease in case of the short pitch winding, whereas in the 6-phase machine these losses are higher for all short pitch cases, except the 11/12 compared to the 6-phase full pitch.

The magnetic wedge is more suited in the 6-phase machine compared to the 3-phase machine as it reduces rotor iron losses as well as bar losses. Whereas the magnetic wedge in the 3-phase machine reduces only rotor iron losses while its bar losses are higher compared to its air wedge case.

The arched pole shape is more favorable to the 6-phase machine compared to the 3-phase machine as the increase of total losses in the 6-phase machine is lower compared to the 3-phase machine.

9.4 Comparison of 3 and 6-phase induction machines

The 6-phase machines are more useful in induction machine topology as loss reduction can be higher compared to the other studied topologies. The 6-phase induction machine has lower losses, reduced torque pulsation and better air gap flux waveform, compared to the 3-phase induction machine.

9.5 Comparison of 3 and 6-phase PM machines

The 6-phase PM machines are rotor design sensitive and need a careful consideration. The spacing between magnets generates space harmonics in the air gap field. The stator copper losses are higher in the 6-phase machine compared to the 3-phase machine. The losses are higher due to increased induced harmonics in the stator currents in case of the 6-phase machine.

In the calculations, the magnets are assumed to be non conducting and thus rotor conducting losses are zero. However, in reality there are losses in magnets and consideration of these losses can change the loss comparison of these machines.

9.6 Harmonic analysis of 9 and 12-phase machines

The order of the stator MMF harmonics increases with increasing phase number as shown in Table 6.1. The value of THD drops while shifting from a 3-phase to a 12-phase machine.

10 FUTURE WORK

Performance of the 6-phase machine with sinusoidal supply has been investigated in this report while an investigation with time harmonics can be performed in the future. Fault and redundancy analysis can be performed on the 6-phase machines. The PM machines should be investigated in more detail considering magnet losses as well which were ignored during this study. The space harmonic analysis of the 9 and 12-phase machines has been performed in this report while a more detailed performance analysis of these machines using time stepping simulations can be a topic of interest for future work.

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