

Analysis of harmonic field effects in
reluctance synchronous machines

Gideon Christiaan Heyns

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Analysis of harmonic field effects in reluctance synchronous machines

By

GIDEON CHRISTIAAN HEYNS

Submitted to the Department of Electrical Engineering in Fulfilment of the
Requirements for the Magister Technologiae in Electrical Engineering at the



SUPERVISOR: E. VOSS

DECEMBER 2011

Declaration

I, GIDEON CHRISTIAAN HEYNS, submit this thesis in fulfilment of the requirements for the degree of Magister Technologiae (MTech) in Electrical Engineering.

I claim that this is my own original work and that it has not been submitted in this or similar form for a degree at any other tertiary institution.



.....
Gideon Christiaan Heyns

Candidate

29/03/2012

.....
Date

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Synopsis

The reluctance synchronous machine (RSM) is a type of synchronous machine which has no windings in the rotor and can be referred to as a non-excited synchronous machine. The RSM can be classified as either single or double salient machine. The single salient machine refers to saliency in the rotor only and double saliency refers to saliency in the rotor and stator. The RSM is based on the principle of reluctance, where torque is produced due to different reluctance paths within the rotor of the machine. The term reluctance is referred to the resistance of a material towards the flow of magnetic field.

Since the invention of vector controlled drives, RSMs regained the popularity of researchers and are becoming a field of interest. The RSM have numerous advantages, besides being cheap, robust, and reliable, the stator part is exactly the same as an induction machine. This will enable easy and cost efficient upgrades. Furthermore due to the non existing rotor currents heat dissipation will be low. However the RSM has an inherently high torque ripple due to its rotor geometry. The torque ripple is defined as the difference between maximum and minimum deviation of the torque referred to the average torque. The torque ripple creates uneven pull on the rotor which creates deformation of the rotor and consequently uneven run. As a result the torque ripple indicates that the speed of the RSM changes permanently. The machines designers ultimate goal would be to design a machine with the lowest torque ripple combined with a maximum average torque. The aim of this thesis is to provide a detailed analysis on the field quantities and its harmonics of a RSM and to examine the effects which these harmonics have on the torque production. This analysis would give designers a better understanding of the principles of RSMs and help to obtain certain performance results. The research design and methodology will include the harmonic content of the flux density components in the center of the air gap. The flux density components will be analysed in terms of its harmonics and the torque produced by these flux density harmonics will also be investigated.

Table of Content

Declaration	ii
Acknowledgements	iii
Synopsis	iv
List of Figures and Tables	vii
List of Symbols and Abbreviations	x
1 Introduction	1
1.1 Previous research on RSMs	1
1.2 Problem statement	3
1.3 Problem approach	4
1.4 Outline of thesis	5
2 Overview of RSM model	6
2.1 Model of machine	6
2.1.1 <i>Flux density derived from the vector potential</i>	7
2.1.2 <i>Investigation of flux density distribution in the air gap</i>	8
2.1.3 <i>Torque calculation using Maxwell's stress tensor</i>	9
2.1.4 <i>Investigation of torque ripple</i>	11
3 Flux density analysis in the air gap	14
3.1 Analysing the flux density distribution	14
3.1.1 <i>Analysing the normal component</i>	16
3.1.2 <i>Analysing the normal component harmonics</i>	24
3.1.3 <i>Analysing the tangential component</i>	31
3.1.4 <i>Analysing the tangential component harmonics</i>	37
3.2 Summary of findings	43

4	Force distribution analysis in the air gap	44
4.1	Force distribution compared to flux density distribution	44
4.2	Force distribution compared to flux density harmonics	49
4.3	Force contributions of the two MSD sections	52
4.4	Summary of findings	53
5	Torque analysis in the air gap	54
5.1	Torque compared to force distribution	54
5.2	Torque harmonic analysis	56
5.3	Summary of findings	57
6	Conclusions and Recommendations	58
6.1	Conclusions	58
6.2	Recommendations	59
7	References	62
A	Flux linkage calculation from the vector potential	64
B	Calculation of the current angle	67
C	Degree of distortion calculation on B_n	68
D	Degree of distortion calculation on B_t	72
E	Machine Parameters	76

List of Figures and Tables

Fig.	Title	Page
1.2.1	Rotor structure of RSM subjected to analysis	3
2.1.1	RSM model with the path in the center of the air gap	6
2.1.2.1	Flux density calculation points within an air gap element	8
2.1.3.1	Contour Γ where torque will be calculated	10
2.1.4.1	Torque as a function of rotor position	11
2.1.4.2	Tangential force component as a function of rotor position	12
2.1.4.3	Normal force component as a function of rotor position	13
3.1.1	4 pole RSM with modelled pole in green	15
3.1.2	Tooth and slot sections of B_n and B_t for the reference position	15
3.1.1.1	B_n as a function of rotor position	17
3.1.1.2	D-axis shifted to the center of slot S4	18
3.1.1.3	D-axis shifted to the center of slot S5	18
3.1.1.4	B_n along the path in the center of the air gap as the d-axis moves through a slot pitch	19
3.1.1.5	B_n for d-axis position 1.5° mech.	20
3.1.1.6	B_n for d-axis position 11.5° mech.	21
3.1.1.7	Left flux barrier position for d-axis position 1.5° and 11.5°	22
3.1.1.8	Right flux barrier position for d-axis position 1.5° and 11.5°	22
3.1.1.9	B_n as a function of rotor position	23
3.1.2.1	B_n for the start position	24
3.1.2.2	Harmonic spectrum for d-axis start position 1.5°	25
3.1.2.3	B_n with and without dominant spatial harmonics	26
3.1.2.4	Harmonic spectrum for d-axis end position 11.5°	27
3.1.2.5	B_n with and without dominant spatial harmonics	28
3.1.2.6	Distortion of B_n of the original graph for all d-axis positions	29
3.1.2.7	Distortion of B_n without the 17 th for all d-axis positions	29

3.1.2.8	Distortion of B_n without the 19 th for all d-axis positions	30
3.1.2.9	Distortion of B_n without the combination for all d-axis positions	30
3.1.3.1	B_t as a function of rotor position	32
3.1.3.2	B_t along the path in the center of the air gap as the d-axis moves through a slot pitch	33
3.1.3.3	B_t for d-axis position 1.5° mech.	34
3.1.3.4	B_t for d-axis position 11.5° mech.	35
3.1.3.5	B_t as a function of rotor position	36
3.1.4.1	Harmonic spectrum for d-axis start position 1.5°	37
3.1.4.2	B_t without dominant spatial harmonics	38
3.1.4.3	Harmonic spectrum for d-axis end position 11.5°	39
3.1.4.4	B_t without dominant spatial harmonics	40
3.1.4.5	Distortion of B_t of the original graph for all d-axis positions	41
3.1.4.6	Distortion of B_t without the 17 th for all d-axis positions	41
3.1.4.7	Distortion of B_t without the 19 th for all d-axis positions	42
3.1.4.8	Distortion of B_t without the combination for all d-axis positions	42
4.1.1	B_n and B_t for the start position	44
4.1.2	Contour Γ in the center of the air gap	45
4.1.3	F_t for the start position	45
4.1.4	B_n and B_t for the end position	46
4.1.5	F_t for the end position	47
4.1.6	F_t along the path in the center of the air gap as the d-axis moves through a slot pitch	48
4.2.1	F_t without 19 th spatial harmonic for the start position	49
4.2.2	F_t without 19 th spatial harmonic for the end position	50
4.1.2.3	F_t along the path in the center of the air gap without the presents of the 19 th spatial harmonic	51
4.3.1	MSD force contributions for all d-axis positions	52

5.1.1	T_i as a function of rotor position	54
5.1.2	T_i without the 19 th harmonic as a function of rotor position	55
5.1.3	Torque harmonic spectrum	56

Table	Title	Page
3.1.2.1	Degree of distortion for each MSD section at the start position	25
3.1.2.2	Comparison between the degree of distortion for each MSD section	26
3.1.2.3	Degree of distortion for each MSD section at the end position	27
3.1.2.4	Comparison between the degree of distortion for each MSD section	28

List of Symbols and Abbreviations

Roman Alphabet

$\vec{A}$	vector potential (Vs/m)
A	cross-sectional area of circuit (m ²)
A_{avg+}	average magnetic vector potential at the enter side of a coil (Vs/m)
A_{avg-}	average magnetic vector potential at the return side of a coil (Vs/m)
A_{mi}	vector potential of element m at node i (Vs/m)
$A_{(GoR1+,GoR2+,GoR3+)}$	average magnetic vector potential at enter side of phase R (Vs/m)
$A_{(GoY1+,GoY2+,GoY3+)}$	average magnetic vector potential at enter side of phase Y (Vs/m)
$A_{(ReB1+,ReB2+,ReB3+)}$	average magnetic vector potential at enter side of phase B (Vs/m)
$A_{(GoR1-,GoR2-,GoR3-)}$	average magnetic vector potential at return side of phase R (Vs/m)
$A_{(GoY1-,GoY2-,GoY3-)}$	average magnetic vector potential at return side of phase Y (Vs/m)
$A_{(ReB1-,ReB2-,ReB3-)}$	average magnetic vector potential at return side of phase B (Vs/m)
A_z	z-component of vector potential (Vs/m)
$A_{z(n)}$	z-component of vector potential at node (n) (Vs/m)
$A_{z(n+1)}$	z-component of vector potential at node $(n+1)$ (Vs/m)
$A_{z(t)}$	z-component of vector potential at node (t) (Vs/m)
$A_{z(t+1)}$	z-component of vector potential at node $(t+1)$ (Vs/m)
$\vec{B}$	flux density vector (Vs/m ²)
B_n	normal component of flux density (Vs/m ²)
B_t	tangential component of flux density (Vs/m ²)
B_x	x-component of flux density (Vs/m ²)
B_y	y-component of flux density (Vs/m ²)
D_{T3}	degree of distortion along section T3
D_{T4}	degree of distortion along section T4

D_{T6}	degree of distortion along section T6
F_n	normal component of force (N)
F_t	tangential component of force (N)
$\vec{H}$	magnetic field strength vector (A/m)
i	point on node (where $i = 1, 2$ or 3) of element m
I_S	current space phasor (A $\angle$ deg)
$\vec{J}$	current density vector (A/m ²)
ℓ	effective winding length in the z direction (m)
ℓ_{mi}	effective length of winding filament at element m and node i (m)
ℓ_s	effective rotor stack length (m)
M	number of elements in meshed region of slot
m	corresponding element
N	number of turns per slot winding
N_{ph}	number of turns per phase
r	radius of the air-gap (m)
r_{mi}	radius of location of node i at element m (m)
S	area of integration (m ²)
S_m	sum of all elements
T_n	normal component of torque (Nm)
T_t	tangential component of torque (Nm)
T_s	resultant component of torque (Nm)
T_{avg}	average torque (Nm)
T_{max}	maximum instantaneous torque (Nm)
T_{min}	minimum instantaneous torque (Nm)
T_{ripple}	torque ripple (%)

Greek Alphabet

Γ	contour of integration (m)
Δ_m	cross-sectional area of element m (m ²)
Δn	distance between node (n) and node ($n+1$) (m)
Δt	distance between node (t) and node ($t+1$) (m)
ΔB_{T3}	difference in flux density at the sides of section T3
ΔT_3	length of section T3
μ_0	permeability of free space (Vs/Am)
μ	permeability (Vs/Am)
σ_n	normal stress component (N/m ²)
σ_t	tangential stress component (N/m ²)
φ	current angle (° el.)
Φ_n	normal flux component (Vs)
Φ_t	tangential flux component (Vs)
Φ_m	average flux of element m (Vs)
Φ_{mi}	flux of winding filament to node i at element m (Vs)
λ	flux linkage of a given coil (Vs)
λ_R	instantaneous flux linkage in phase R (Vs)
λ_Y	instantaneous flux linkage in phase Y (Vs)
λ_B	instantaneous flux linkage in phase B (Vs)
λ_m	flux linkage of element m (Vs)

Abbreviations:

MST	Maxwell's Stress Tensor
RSM	Reluctance Synchronous Machine
MSD	Most Significant Distorted

1. Introduction

1.1 Previous research on RSMs

One of the first discoveries made in the area of RSMs was in 1874, where Carl Wilhelm Siemens, brother of the more famous Ernest Werner von Siemens, discovered that he could suppress the excitation field of a single phase synchronous machine without stopping the machine (Blondel, 1913). Blondel (1913) stated that a reaction motor (motor with no excitation field in rotor) should have a very small air gap to decrease the reluctance. He also stated that the armature reaction on the field will influence the inductance of the armature, which has an effect on the power factor. Thompson (1902) also experimented with a salient-type rotor with slitted field poles to decrease the armature reaction.

Kostko (1923) moved away from the salient-type rotor, due to the limit reached in development and focused on round rotors with flux barriers. For the next 35 years authors like (Trickey 1933, 1946; Taalat 1951; Lin 1951; Douglas 1956) concentrated on the performance calculations using different rotor structures.

From the 1960's up to 1970's stability analysis was of main concern where the leaders in this field were Lawrenson and Gupta (1964, 1967) with their research on segmental-rotor reluctance motors. Cruickshank and Anderson (1971) were the first to investigate axially laminated rotors. Lipo and Krause (1967) used Nyquist stability criterion to analyze the stability of an RSM. At this point in time the models were all time consuming, due to finite element software not being commercially available.

Honsinger (1971) focused on a two flux barrier per pole rotor with cut outs which created much interest and later a study on the effect of changing its rotor dimensions and cross magnetization between L_d and L_q inductances was conducted by Kamper (1994).

From the 1970's up to the late 1990's the single-salient RSM regained popularity. During this time Krause (1969) and Ong (1977) used power electronically controlled devices which enabled to change the frequency which controlled the open loop operation of the single salient RSM. Closed loop control for single salient RSMs received further attention when Weh and Schroder (1985) investigated an axially laminated rotor with a multi-phase reluctance machine controlled by a static inverter, while El-Antably and Hudson (1985) focused on fiber glass insulation between the rotor laminations. Fratta (1987) applied the first full vector control scheme to a RSM.

With the help of Weh and Schroder (1985) he discovered for the first time that the single salient RSM during closed loop operation is capable of producing high power density.

From the 1990's until present, considerable research has been done on the single- and double salient reluctance machine. (Vagati et al. 1992) changed their focus from axially laminated rotors to transverse laminated rotors, due to increased iron losses. Lipo (1991) explained that with precise current control the torque per copper loss of an RSM could be improved above that of an induction motor provided that saturation was taken into account. (Toliyat et al. 1992) experimented with a five phase single salient reluctance machine. This machine produced 10% more torque per rms current due to a better switch utilization factor compared to the conventional three phase six transistor bridge. This resulted in a smoother MMF wave in the air gap which contributed to a reduced torque ripple. Takayoshi (1994) examined the ratio between the iron width and the insulation width of the laminations in an axial laminated rotor. The results showed that a ratio of 0.5 produces a high saliency with a competitive power factor. From 1995 onwards considerable research was conducted on the flux barrier arrangements in transverse laminated rotors. Parasiliti and Villani (1995) experimented with the flux barrier widths of a conventional two flux barrier per pole rotor. The overall design indicated an increase of 33% in the torque production and 11% in the power factor compared to a standard design. (Vagati et al. 1998) analyzed a transverse laminated rotor constructed of iron segments which were held together by iron ribs. The design was optimized in terms of the number of segments, their widths and the number of iron ribs. The results indicated a reduction of the torque ripple and pointed out that the difference in torque ripple between fully pitched windings and windings short pitched by 2 slots is 0.43%, therefore indicating that chording has a minimal influence on the torque ripple. Bomela and Kamper (2002) conducted further experiments on stator chording and rotor skewing and concluded that for low torque ripple and minimal effect on the torque rating of a RSM, it should have full pitched stator windings, the rotor should be skewed by a stator slot and a high number of stator slots should be used.

(Bianchi et al. 2009) experimented with two different flux barrier arrangements in one rotor which are designed to cancel a torque harmonic of a certain order and to compensate those of other orders to obtain an overall smoother torque.

To summarise, the above mentioned authors mainly concentrated their research on different rotor geometries in single and double salient machines and the performance of these rotors during open loop and closed loop control.

1.2 Problem statement

The focus of this thesis is on the single salient vector controlled RSM with an unskewed transverse laminated rotor with two flux barriers per pole, similar to what was used by Honsinger (1971) except having no sector or segmental cut outs. Refer to Fig. 1.2.1.

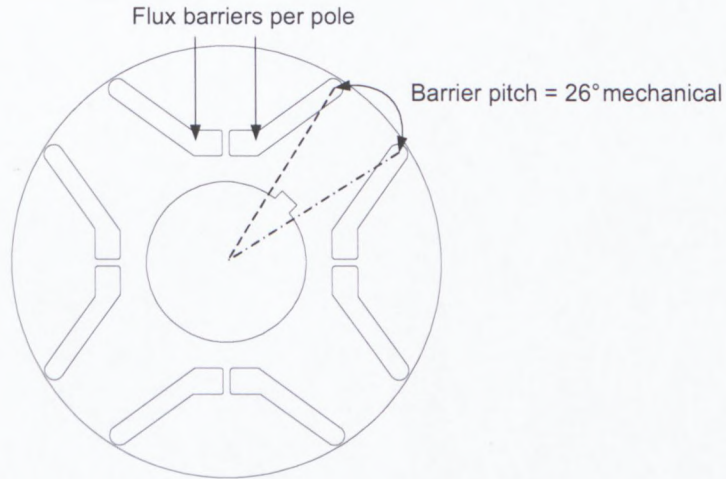


Fig. 1.2.1 Rotor structure of RSM subjected to analysis

This rotor structure, having a barrier pitch of 26° mech. produced a decrease in torque ripple based on previous research done by Hanekom (2006). Previous research by (Vagati et al. 1998), (Bomela & Kamper 2002) and (Bianchi et al. 2009), which contributed to improved torque quality of RSMs, mainly focused on the changes in rotor geometry and alterations to the winding layout and geometry of the stator. While authors like (Lin 1951; Moreira 1992; Kocabas 2009) focused on the harmonic content of the MMF wave form and how it is affected by rotor and stator geometry changes and saturation effects. These authors' contributions enhanced development of RSMs over the years. However, very little research actually provides a full analysis on the field quantities and its harmonics in an RSMs air gap and compares the individual relationships between their harmonics which would provide a deeper insight into this area of research. Therefore the idea behind this research is to analyse the field quantities and its harmonic effects on the torque production of the RSM.

This would give designers a better understanding of the field principles of RSMs and would help to obtain certain performance results which may lead to new designs or discoveries.

The problem statement therefore is: "What flux density harmonic produces what torque and why and how does it influence the total torque developed at different rotor positions?"

1.3 Problem approach

The approach to the problem in section 1.2 will be based on a steady state analysis. The machine used in the analysis is a three phase, 7.5 kW, 4 pole, 36 slot RSM with full pitched windings and 35 turns per coil per slot. The fully pitched windings were chosen to model the simplest machine and a reference for further research. One pole pitch of the machine was modelled using a 2D finite element program, therefore neglecting end effects. The pole pitch is divided in 180 steps measured in mech. degrees, therefore the model consist of 180 magneto static studies which were solved by the time stepping method used by the program. According to literature data acquisition should take place along a path which is on the rotor surface. Previous studies have shown that the change in data acquisition in the center of the air gap is minute compared to the rotor surface. Therefore the path of data acquisition will be in the center of the air gap.

The flux density components obtained at each rotor position will be analysed to provide an overall picture of how it changes and what creates these changes. The normal and tangential components of the flux density are then subjected to a Fourier analysis. Only the flux density harmonics of the normal and tangential components of the same frequencies will be used to calculate the torque. This information will provide which flux density harmonic relates to which torque harmonic.

The aim of this study is to find if and how torque harmonics relate to each other and to those of the flux density harmonics.

1.4 Outline of thesis

The layout of the remaining part of the thesis is as follows:

- Chapter 2: This section will explain the RSM model subject to analysis and how the flux density distribution is derived from the vector potential. An investigation of the flux density distribution will be done followed by a detailed explanation of torque calculation and torque ripple.
- Chapter 3: In this chapter the machine model will be described. The flux density components will be obtained in the centre of the air gap and will be analysed. The flux density components will also be subjected to a Fourier analysis. The dominant spatial harmonics will be determined and its effect on the flux density components will also be analysed. At the end of the section a summary of important findings is given.
- Chapter 4: This chapter will calculate the force distribution along the path using the flux density data from chapter 3. The force distribution will then be analysed in-depth. The force distribution will be determined without the presence of the dominant flux density harmonics in order to determine their effect. At the end of the section a summary of important findings is given.
- Chapter 5: This chapter will calculate the torque for each rotor position using the force distribution data from chapter 4. The torque ripple and average torque will be calculated. The torque is then determined without the presence of the dominant flux density harmonics. The torque ripple and average torque will be calculated on this graph and compared to the original torque graph. These two torque graphs will then be Fourier analysed where the dominant harmonics will be determined and compared.
- Chapter 6: This chapter will provide conclusions and recommendations regarding all findings. Areas not covered by this work will be highlighted and future research will be indicated.

2. Overview of RSM model

This chapter shows the physical geometry of the RSM modelled with finite element software. The model consists of a rotor structure similar to what was used by Honsinger (1971) except having no sector or segmental cut outs. The rotor has two air openings per pole which is defined as flux barriers. The flux density distribution and torque calculation using Maxwell's Stress Tensor (MST) will also be discussed in this section.

2.1 Model of machine

Fig. 2.1.1 illustrates a refined mesh of the RSM model. Due to its periodicity the behaviour of a full machine can always be derived from one pole pitch. Therefore only one pole pitch of the machine is needed for analysis. A dense mesh is created in the center of the air gap to ensure accurate data acquisition. The stator consists of a single layer winding with open slots and is fed by a full load sinusoidal current of 16A rms. The rotor section is initially shifted 56.5° mech. mathematically positive from the x-axis which in turn represents the 0° mech. position, which will be the reference rotor position in the analysis. The rotor is then shifted 90° mech. mathematical negative in increments of 0.5° mech.

A time stepping analysis will be performed at each rotor position and the flux density would be obtained along each segment of the path in the center of the air gap.

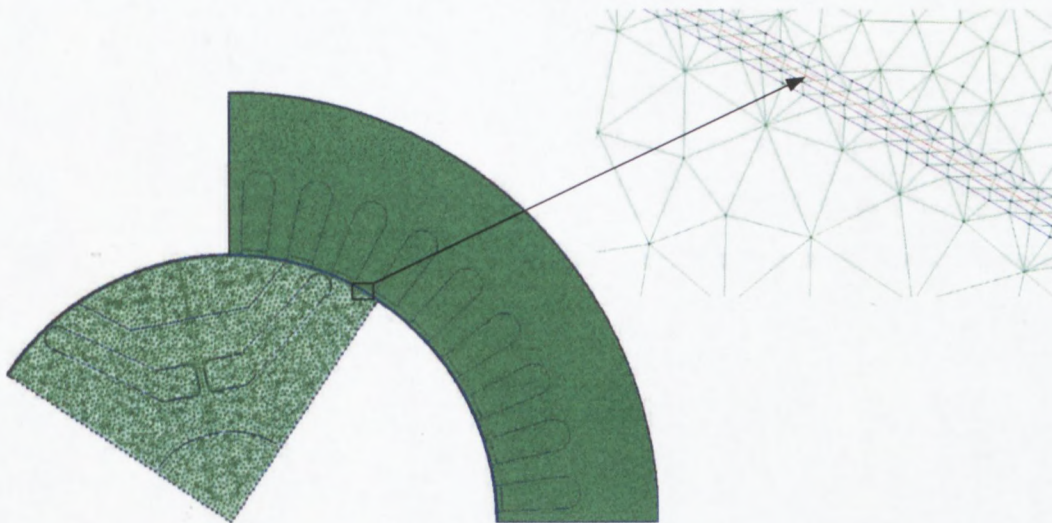


Fig. 2.1.1 RSM model with the path in the center of the air gap

2.1.1 Flux density derived from the vector potential

This thesis will deal with steady-state machine operation only. From Ampère's law one obtains

$$\text{curl} \vec{H} = \vec{J} \quad (2.1.1.1)$$

which is of general nature and holds true for any current carrying region of the RSM model. The left hand side of (2.1.1.1) can be written as

$$\text{curl} \vec{H} = \text{curl} \left(\frac{\text{curl} \vec{B}}{\mu} \right) \quad (2.1.1.2)$$

which yields that

$$\vec{B} = \text{curl} \vec{A} \quad (2.1.1.3)$$

Because this thesis investigates a 2D problem the vector potential has only a z-component which is a function of the coordinates x and y. As a result the 2D flux density in the center of the air gap is calculated according to (2.1.1.3) and yields (2.1.1.4), (2.1.1.5) and (2.1.1.6).

$$\vec{B} = \begin{vmatrix} \vec{e}_x & \vec{e}_y & \vec{e}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ 0 & 0 & A_z \end{vmatrix} = \left(\frac{\partial A_z}{\partial y} \right) \vec{e}_x - \left(\frac{\partial A_z}{\partial x} \right) \vec{e}_y = B_x \vec{e}_x + B_y \vec{e}_y \quad (2.1.1.4)$$

$$B_x = \frac{\partial A_z}{\partial y} \quad (2.1.1.5)$$

$$B_y = -\frac{\partial A_z}{\partial x} \quad (2.1.1.6)$$

2.1.2 Investigation of flux density distribution in the air gap

The RSM model contains several elements in the air gap as shown in section 2.1 Fig. 2.1.1. Data acquisition occurs along a path in the center of the air gap which cuts through each element as shown in Fig. 2.1.2.1. The flux density derived in section 2.1.1 is calculated according to (2.1.2.1) and (2.1.2.2), where (2.1.2.1) is the tangential component of the flux density to the path in the center of the air gap and (2.1.2.2) is the normal component of the flux density to the path in the center of the air gap as shown in Fig. 2.1.2.1 (Bomela and Kamper 2002, p.4).

$$B_t = \frac{A_{z(n+1)} - A_{z(n)}}{\Delta n} \quad (2.1.2.1)$$

$$B_n = \frac{A_{z(t+1)} - A_{z(t)}}{\Delta t} \quad (2.1.2.2)$$

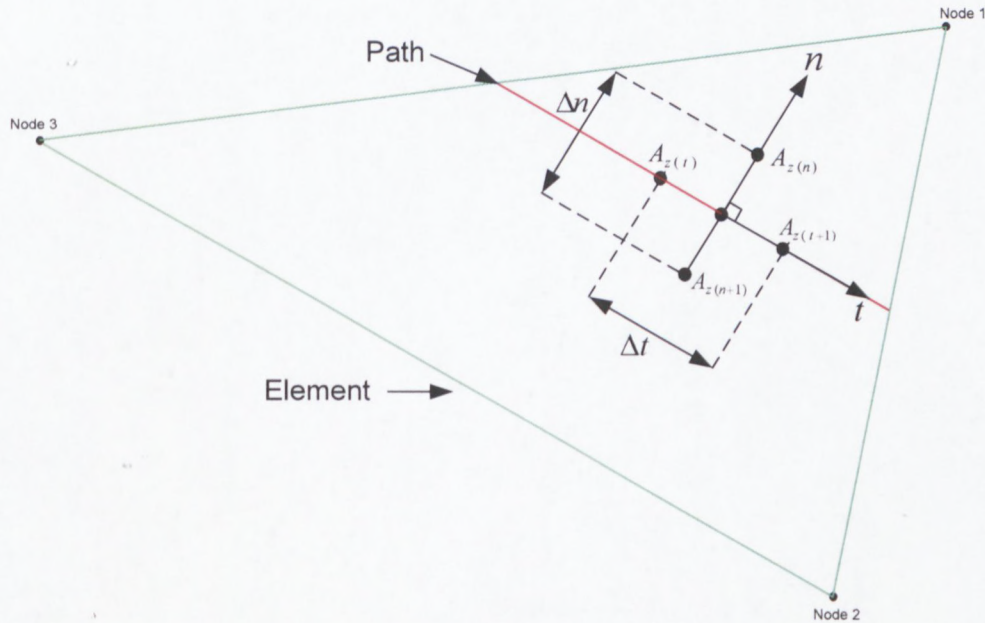


Fig. 2.1.2.1 Flux density calculation points within an air gap element

The flux density having the unit $\frac{Vs}{m^2}$, is constant within an element because the vector potential is assumed to vary linearly across the element.

The flux is obtained from (2.1.2.3) and (2.1.2.4).

$$\Phi_t = A_{z(n+1)} - A_{z(n)} \quad (2.1.2.3)$$

which is the tangential component of the flux and

$$\Phi_n = A_{z(t+1)} - A_{z(t)} \quad (2.1.2.4)$$

which is the normal component of the flux both having the unit $\frac{Vs}{m}$. The vector potentials in (2.1.2.3) and (2.1.2.4) are then multiplied with the length $2\pi r_{mi}$, where r_{mi} is the radius of the location of node i of element m as explained in Appendix A. Therefore the flux has the unit Vs . The flux linkage per pole phase group is also derived according to Appendix A.

2.1.3 Torque calculation using Maxwell's stress tensor

The stresses proposed by Maxwell to explain magnetic phenomena consist of a longitudinal stress acting along a flux line and a transverse pressure. He also stated that the total force on a group of field sources may be calculated by forming a closed surface around them and integrating the stresses along this surface (Wignall et al. 1988). Therefore the stress on a segment can be separated into the normal and tangential component which are calculated from:

$$\sigma_n = \frac{B_n^2 - B_t^2}{2\mu_0} \quad (2.1.3.1)$$

$$\sigma_t = \frac{B_n B_t}{\mu_0} \quad (2.1.3.2)$$

where B_n and B_t are the normal and tangential flux density components, μ_0 is the permeability of free space. As a result the normal and tangential force component and tangential torque component are calculated from (2.1.3.1) and (2.1.3.2) according to a closed contour integral along the center of the air gap shown in Fig. 2.1.3.1 resulting in (2.1.3.3), (2.1.3.4) and (2.1.3.5) respectively.

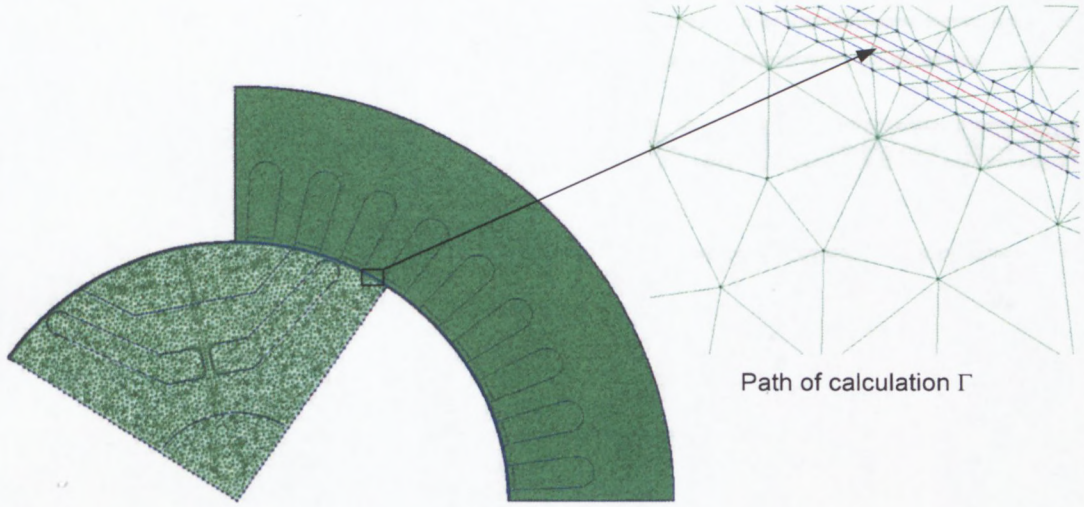


Fig. 2.1.3.1 Contour Γ where torque will be calculated

$$F_n = \frac{1}{2\mu_0} \oint_{\Gamma} (B_n^2 - B_t^2) d\Gamma \times l_s \quad (2.1.3.3)$$

$$F_t = \frac{1}{\mu_0} \oint_{\Gamma} B_n B_t d\Gamma \times l_s \quad (2.1.3.4)$$

$$T_t = \frac{1}{\mu_0} \oint_{\Gamma} r B_t B_n d\Gamma \times \ell_s \quad (2.1.3.5)$$

where F_n and F_t are the instantaneous normal and tangential component of the force, T_t the tangential torque component, ℓ_s is the effective stack length of the rotor and r the radius between the centre of the shaft and contour Γ . T_t is the only torque component responsible for rotor movement therefore being the subject of the analysis.

2.1.4 Investigation of torque ripple

Since the adoption of vector controlled drives, RSMs regained the popularity of researchers and became a field of interest. The RSM has a robust rotor construction which is relative cheap compared to that of an induction motor due to the rotor being constructed using steel laminations only. Nevertheless, the RSM has a very high torque ripple. Torque ripple is defined as the deviation of the minimum and maximum torque from the average value as given in (2.1.4.1).

$$T_{ripple} = \frac{T_{max} - T_{min}}{T_{avg}} \times 100 \% \quad (2.1.4.1)$$

where T_{max} , T_{min} and T_{avg} are defined as the maximum-, minimum- and average torque respectively as shown in Fig. 2.1.4.1.

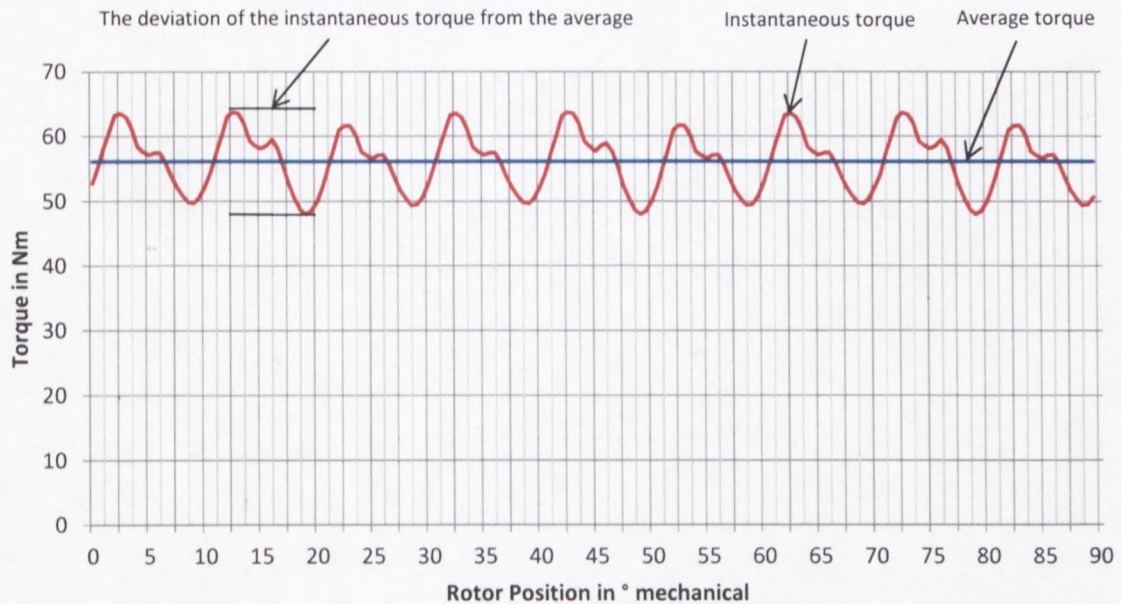


Fig. 2.1.4.1 Torque as a function of rotor position

This fluctuating torque is unwanted since it creates uneven pull on the rotor which causes its deformation (Güemes et al. 2011). The fluctuating torque is easiest explained by referring to a stator tooth of the RSM. As a rotor pole approaches alignment with a stator tooth, the rotor is accelerated due to the alignment being the point of minimum energy. As the rotor pole continues past the alignment point it is decelerated. It is important to notice that this effect applies to all stator teeth and poles simultaneously and will further investigated in chapter 4.

The two force components namely F_t and F_n are responsible for creating deformation on the rotor surface and stator surface respectively. The instantaneous force creating rotor movement is proportional to the sum of the stresses acting on all segments along the rotor surface. These two force components as a function of rotor position are shown in Fig.'s 2.1.4.2 and 2.1.4.3.

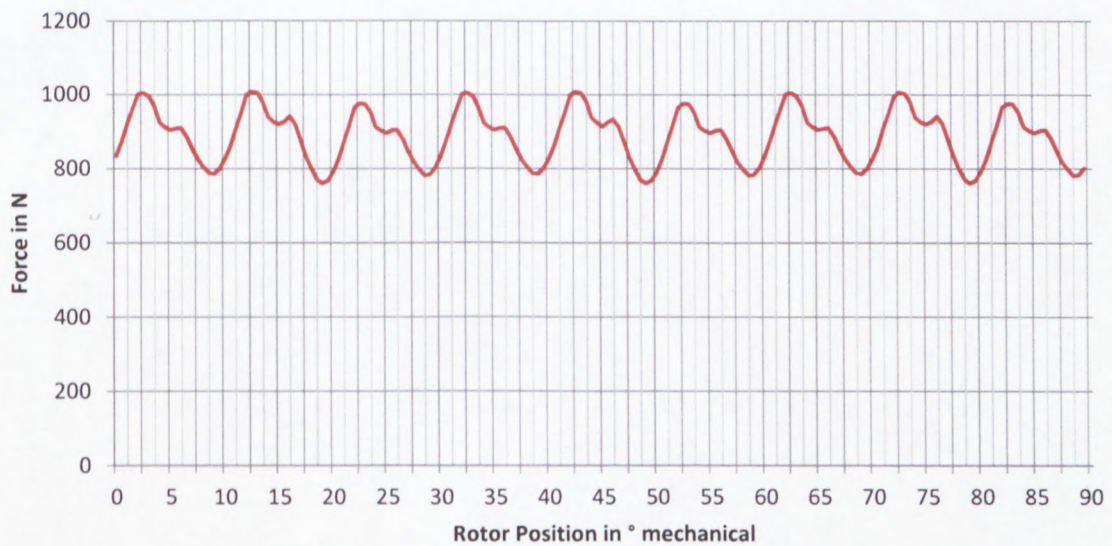


Fig. 2.1.4.2 Tangential force component as a function of rotor position

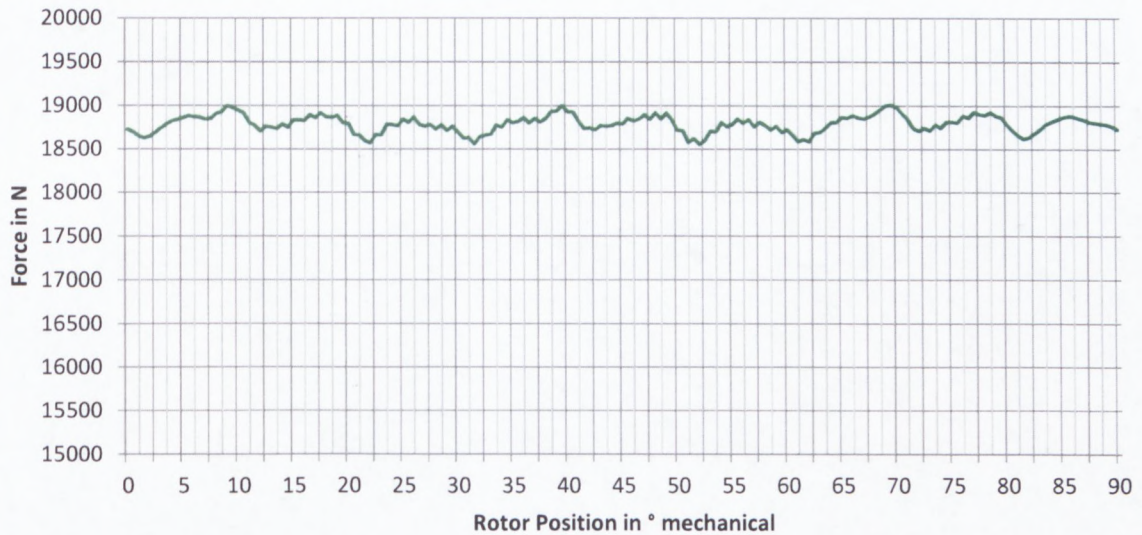


Fig. 2.1.4.3 Normal force component as a function of rotor position

According to (2.1.3.5), it is clear that if the fluctuation in B_n and B_t could be reduced, the torque ripple as well as the mechanical vibration will reduce. An interesting aspect is that the normal force component varies from being 19 to 24 times larger compared to the tangential force component. For example if the maximum and minimum instantaneous rotational force of the machine is 790 and 316 N respectively, the instantaneous force created by the normal force which acts on the stator teeth area facing the rotor, would be 15010 and 7584 N respectively. This emphasises the importance of the mechanical strength of the stator core, especially the stator teeth and machine housing (Delaere, 1999).

3. Flux Density analysis in the air gap

In this chapter the 2D RSM will be modelled using finite element software. Data acquisition will take place along a specified path which cuts a fine mesh discretization in the center of the air gap. The flux density distribution will be obtained on each segment of the path for each rotor position. A detailed analysis will describe the particular change in waveform along the path in the center of the air gap as the rotor rotates. A Fourier analysis will be performed on the flux density distribution to determine its spatial harmonic content. The spatial harmonic content will then be analysed in terms of the original flux density wave. At the end of the chapter all findings will be summarised.

3.1 Analysing the flux density distribution

In this section the d-axis of the 2D RSM model is initially shifted mathematically positive by 56.5° mech. from the x-axis which represents the 0° mech. reference position as shown in Fig. 3.1.1. It is a representation of the 4 pole RSM with the pole modelled shown in green. This rotor shift creates a current angle of 53° el. as explained in Appendix C, which produced the lowest torque ripple and highest average torque. From this reference position the rotor is shifted mathematically negative through a pole pitch of 90° mech. in steps of 0.5° . The normal component B_n and tangential component B_t are obtained per segment of the path in the center of the air gap for each rotor position. The emphasis will be on how B_n and B_t are influenced as the rotor rotates through a pole pitch. Therefore B_n and B_t along the path will be divided in teeth sections, ranging from tooth 1 (T1) to tooth 10 (T10) and slot sections, ranging from slot 1 (S1) to slot 9 (S9) as shown in Fig.'s 3.1.1 and 3.1.2.

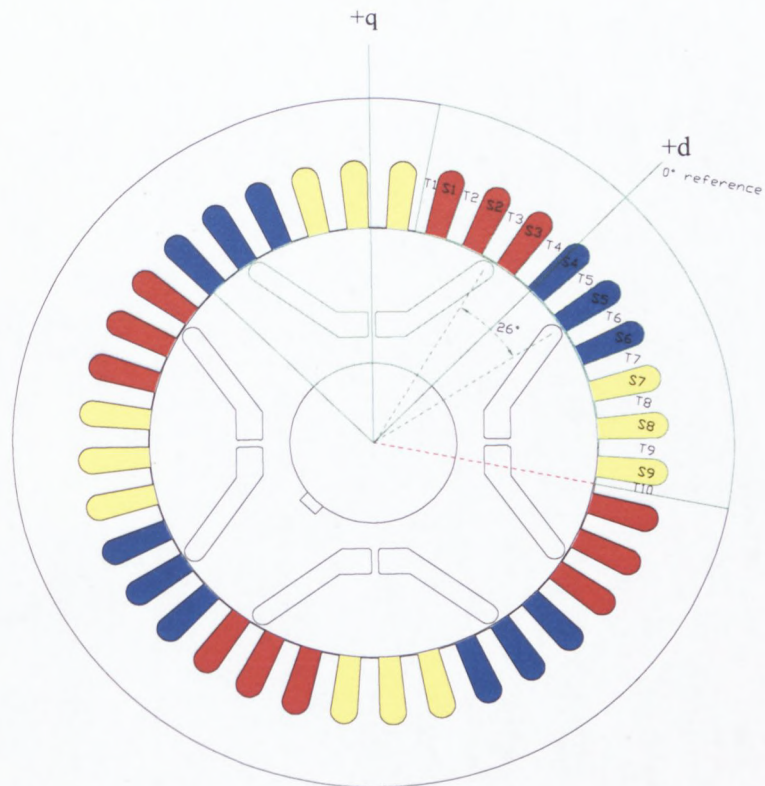


Fig. 3.1.1 4 pole RSM with modelled pole in green

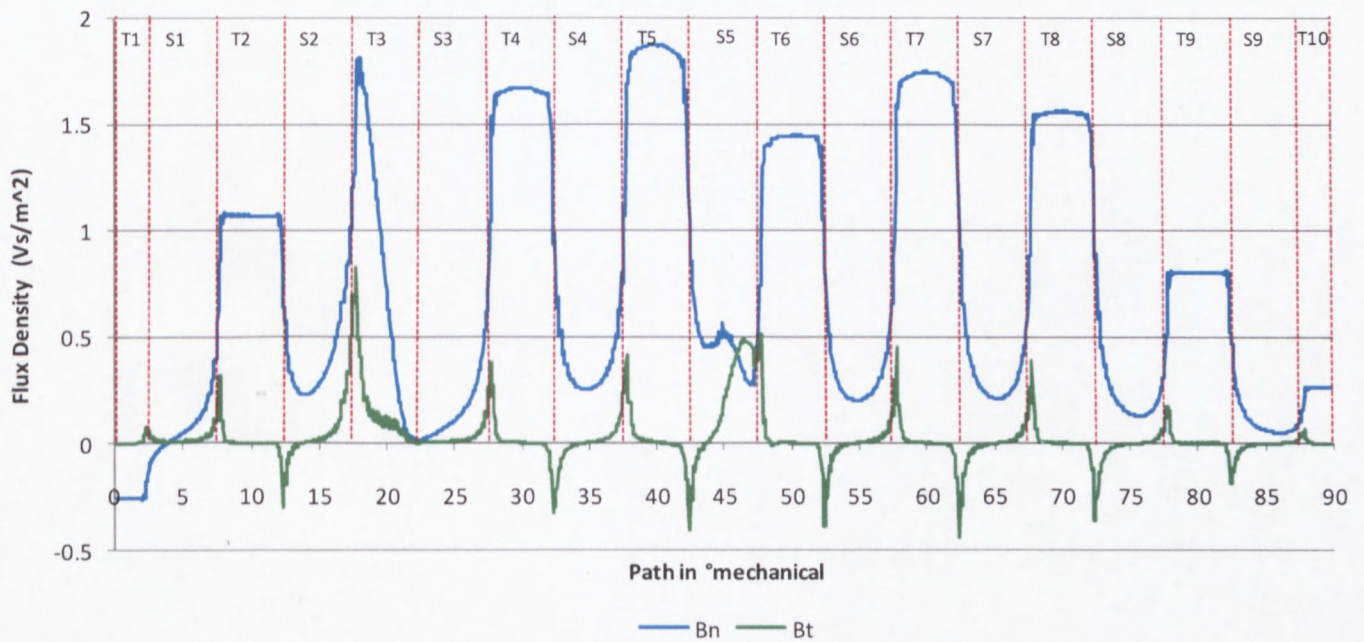


Fig. 3.1.2 Tooth and slot sections of B_n and B_t for the reference position

3.1.1 Analysing the normal component

Fig. 3.1.1.1 shows B_n along the center of the air gap as the d-axis moves from the 0° mech. reference position through the pole pitch. From this Fig. it is evident that the boundary conditions are met which is set to be the same in magnitude but opposite in polarity. The analyses will consist of a study explained as follows:

- This study will shift the rotor by 1.5° mech. mathematically negative in order for the d-axis to be in the center of slot section (S4). B_n along the path in the center of the air gap will then be analysed as the d-axis shifts mathematically negative from position 1.5° , which is the center of slot section (S4), to position 11.5° , which is the center of slot section (S5).

This study will provide a detailed analysis of B_n as the d-axis moves through a slot pitch of 10° mech. These steps were chosen because the significant pattern repeats itself for every slot pitch which allows us to simplify the analysis.

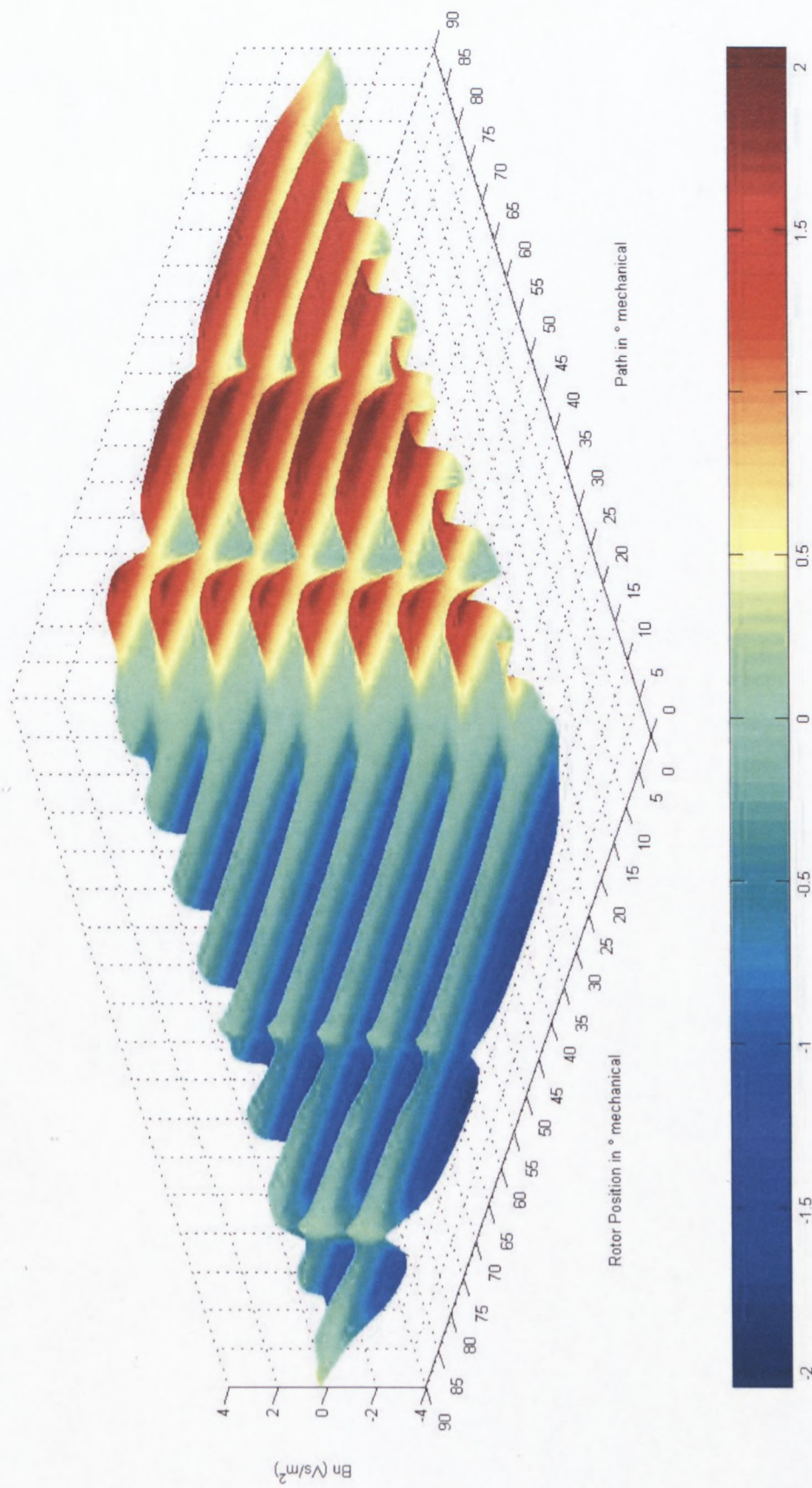


Fig. 3.1.1.1 B_n as a function of rotor position

The d-axis is shifted 10° mech. in steps of 0.5° from slot S4 to slot S5 as shown in Fig.'s 3.1.1.2 and 3.1.1.3. B_n along the path of the center of the air gap is obtained for each d-axis position.

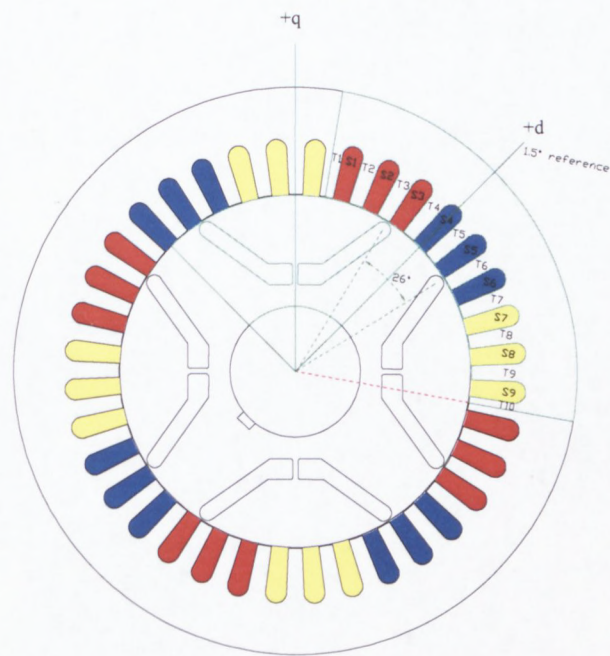


Fig. 3.1.1.2 D-axis shifted to the center of slot S4

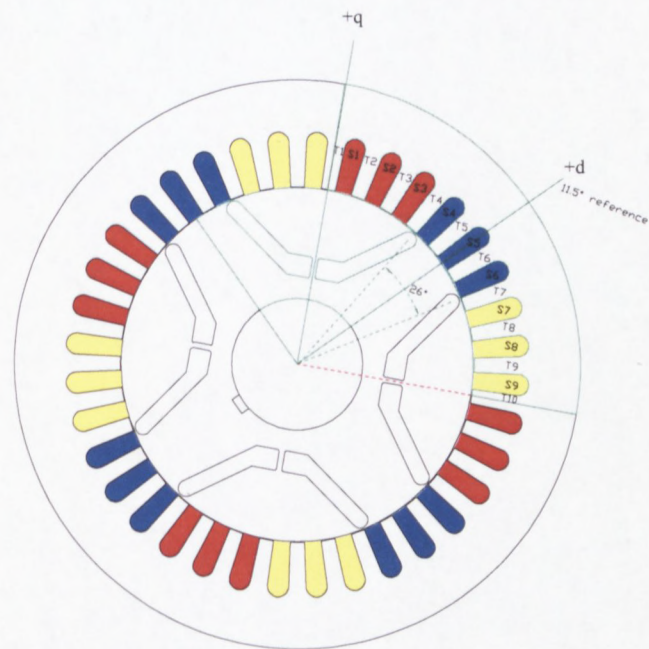


Fig. 3.1.1.3 D-axis shifted to the center of slot S5

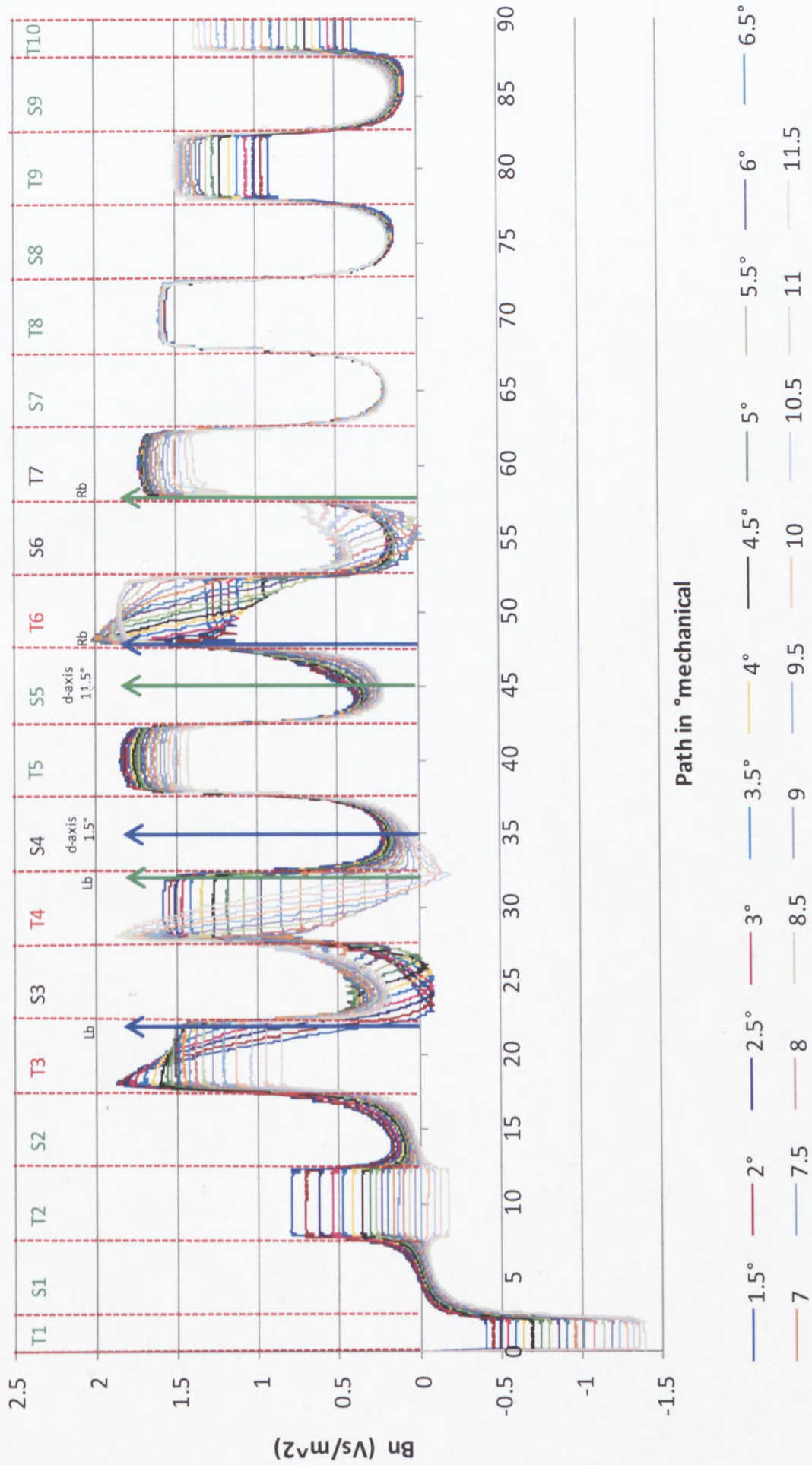


Fig. 3.1.1.4 B_n along the path in the center of the air gap as the d-axis moves through a slot pitch

According to Fig. 3.1.1.4 B_n along the centers of the slot sections is significantly lower in magnitude than in the centers of the tooth sections, which is expected and according to theory. The graph also shows that sections T3, T4 and T6 contain significantly higher distortions than the remaining sections which are therefore referred to as the most significant distorted (MSD) sections by the author.

In the following the MSD sections will be analysed by referring to Fig.'s 3.1.1.5 and 3.1.1.6.

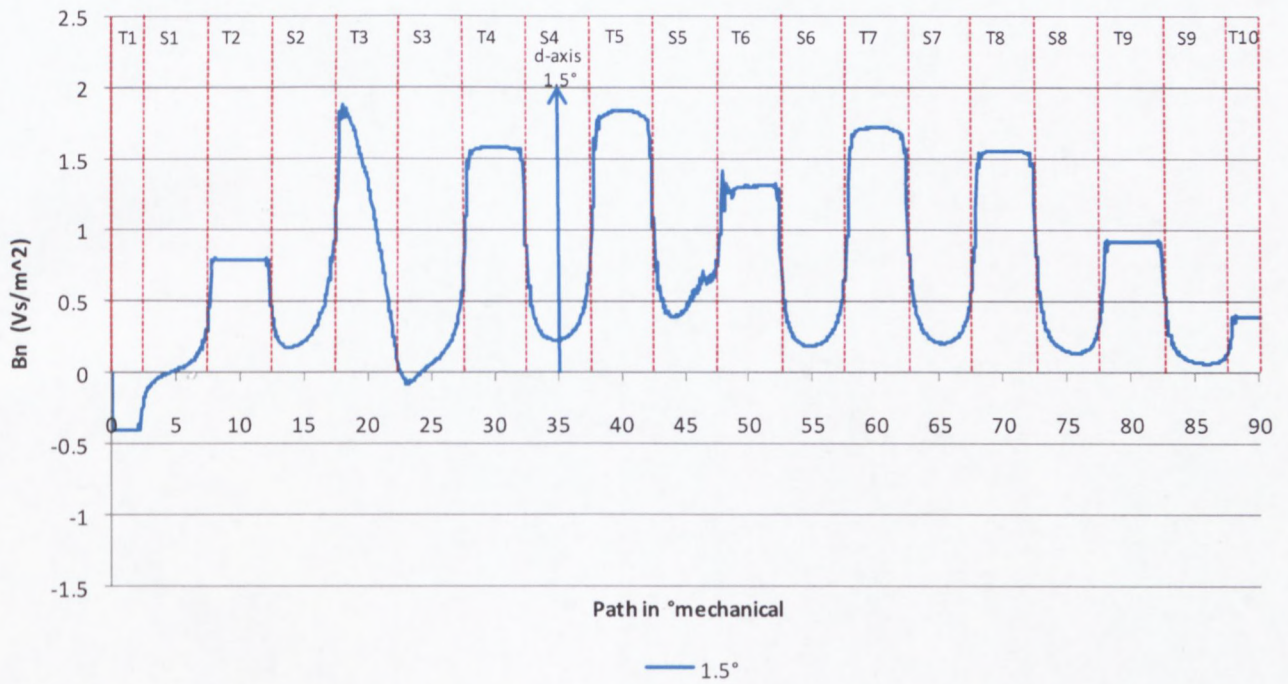


Fig. 3.1.1.5 B_n for d-axis position 1.5° mech.

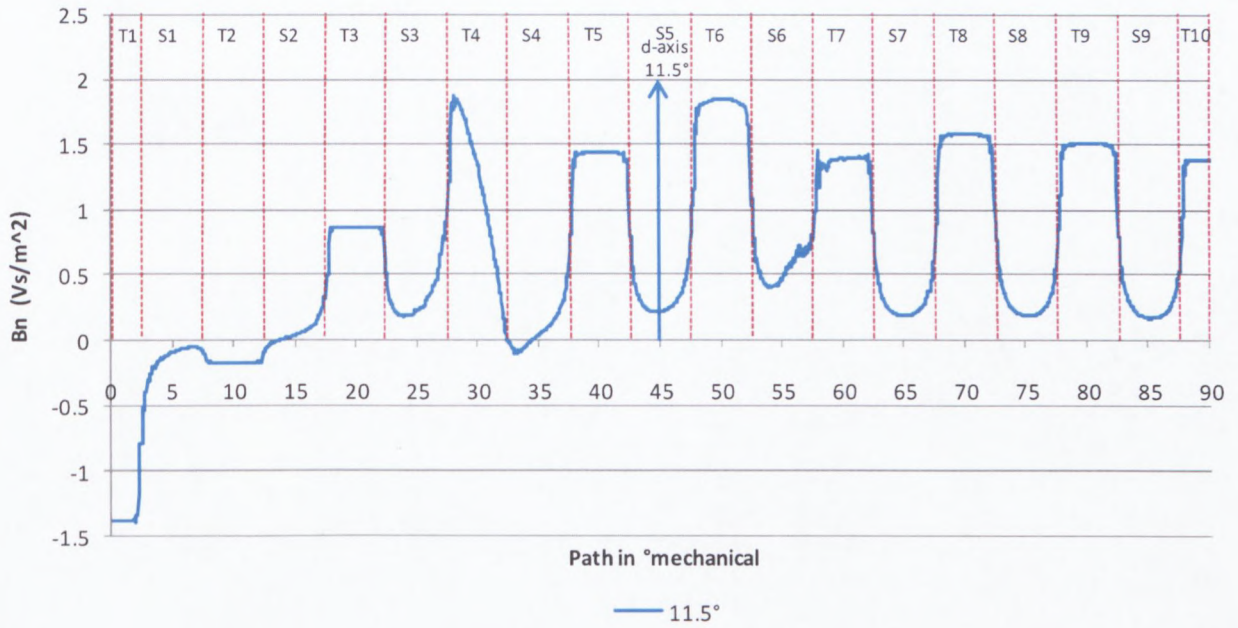


Fig. 3.1.1.6 B_n for d-axis position 11.5° mech.

According to Fig. 3.1.1.5 the flux density is high at the left hand side of section T3 which is explained by looking at the field pictures shown in Fig.'s 3.1.1.7 and 3.1.1.8. The same can be said for section T6, while section T4 is undistorted on the left. Moving on to Fig. 3.1.1.6 the flux density is high at the left hand side of section T4 which is also explained by looking at the field pictures shown in Fig.'s 3.1.1.7 and 3.1.1.8. The same can also be said for section T7, while section T3 is undistorted on the left.

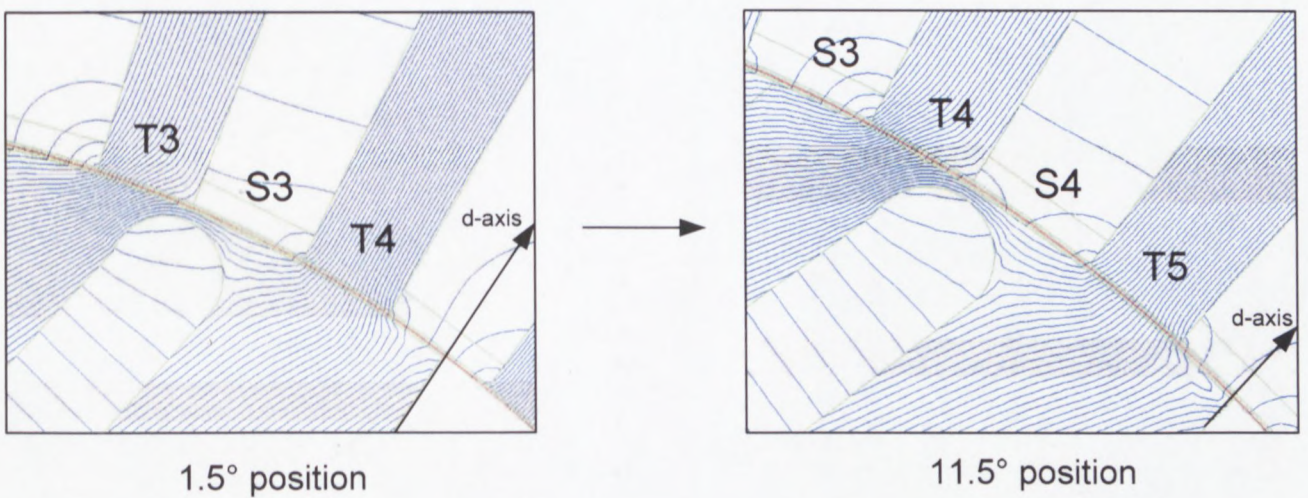


Fig. 3.1.1.7 Left flux barrier position for d-axis position 1.5° and 11.5°

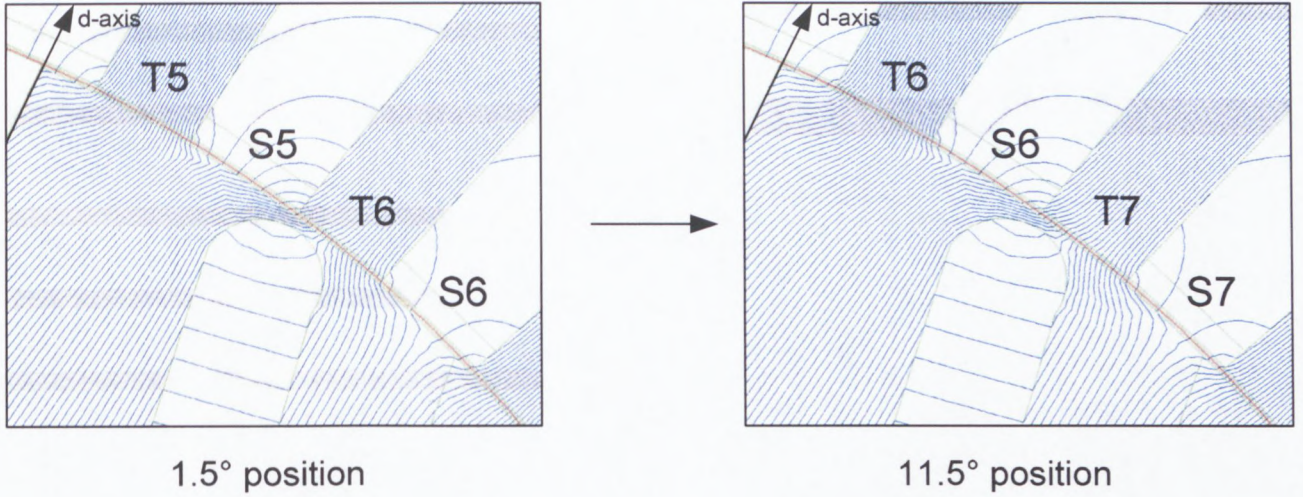


Fig. 3.1.1.8 Right flux barrier position for d-axis position 1.5° and 11.5°

These two analyses explain the MSD sections for the start and end position outlining the slot pitch. The positions in between change accordingly and can be viewed in Fig. 3.1.1.4. An interesting observation is that the left flux barrier has a more significant effect on MSD sections T3 and T4 respectively, while the right flux barrier has a less significant effect on T6. This is quite interesting because it raises the question whether asymmetrical flux barrier arrangements may be well worth investigating in future research. So far the MSD sections were analysed from d-axis position 1.5° to 11.5°. These results for a pole pitch are shown in Fig. 3.1.1.9.

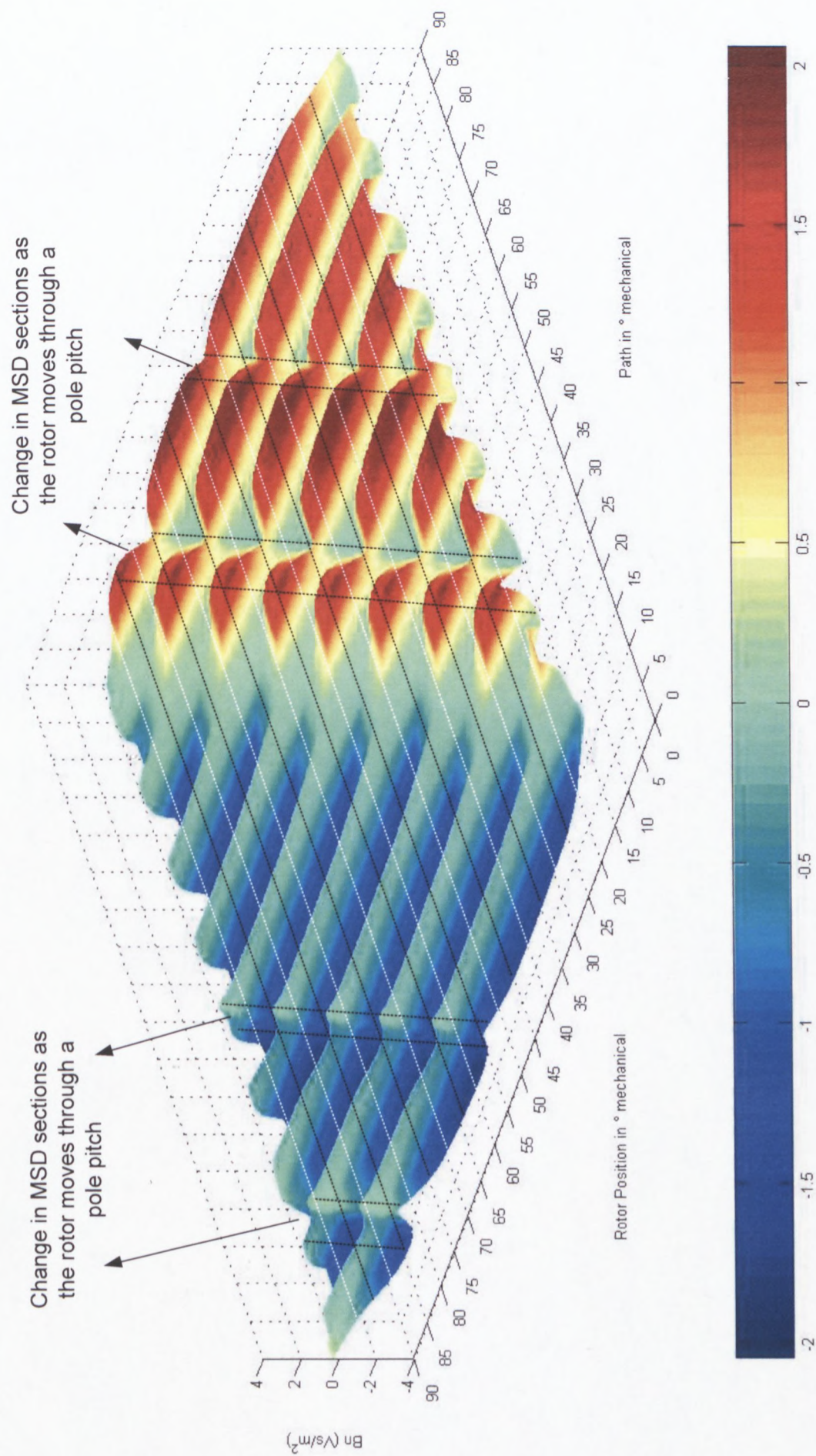


Fig. 3.1.1.9 MSD sections as a function of rotor position

3.1.2 Analysing the normal component harmonics

In this section B_n under the slot pitch will be subjected to a Fourier analysis and the effect of the dominant spatial harmonics on the MSD sections will be determined. In order to quantify the amount of distortion in the MSD sections the slope between the left and right side is calculated according to

$$D_{T3} = \frac{\Delta B_{T3}}{\Delta T_3} \quad (3.1.2.1)$$

where D_{T3} is the degree of distortion along section T3, ΔB_{T3} is the difference of B_n at the beginning and end side of section T3 and ΔT_3 the length of section T3, which if applied to Fig. 3.1.1.5 results in Fig. 3.1.2.1.

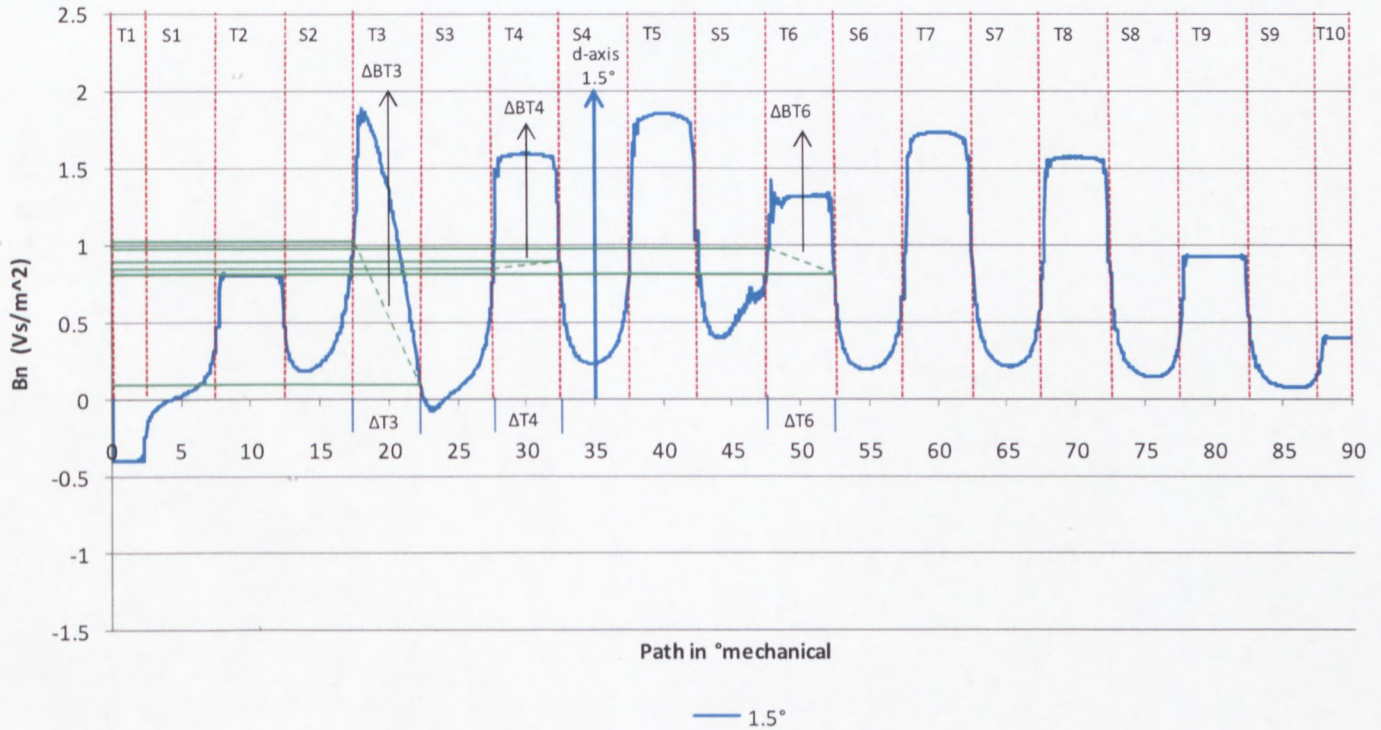


Fig. 3.1.2.1 B_n for the start position

The results for the three MSD sections at the start position are shown in table 3.1.2.1.

Table 3.1.2.1 Degree of distortion for each MSD section at d-axis start position 1.5°

D-axis position	D_{T3}	D_{T4}	D_{T6}
1.5°	6.61	-0.69	2.07

If Fig. 3.1.2.1 is Fourier analysed the results is shown in Fig. 3.1.2.2.

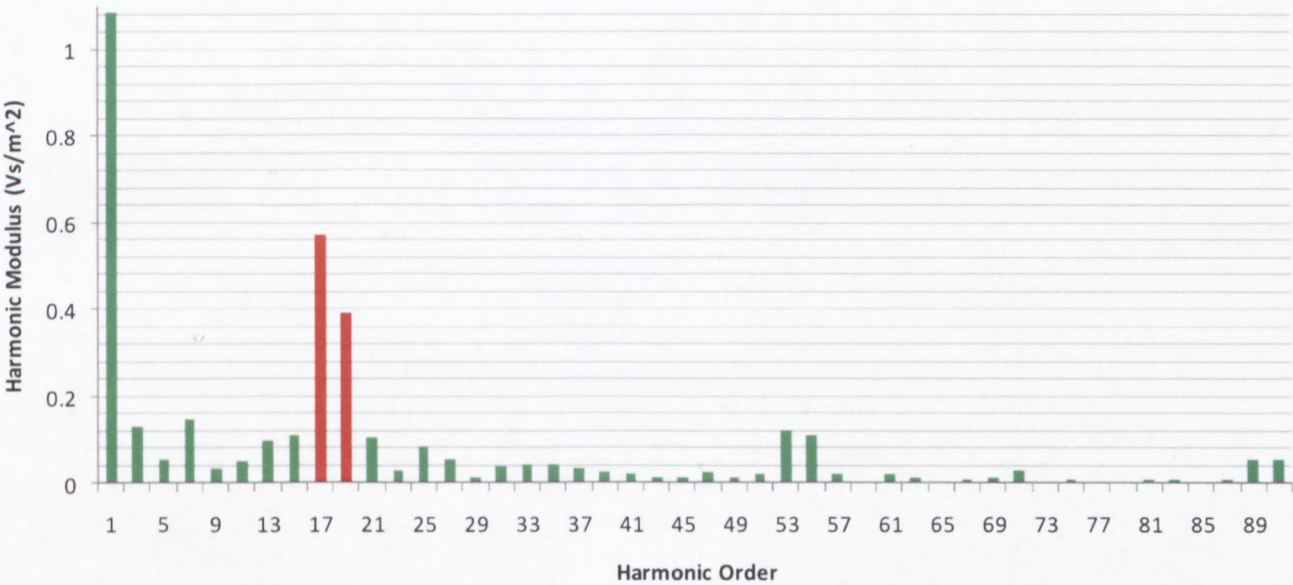


Fig. 3.1.2.2 Harmonic spectrum for d-axis start position 1.5°

According to Fig. 3.1.2.2 B_n contains odd harmonics only due to B_n being an odd function. It is also evident that the dominant spatial harmonics are the 17th and the 19th harmonic. Fig. 3.1.2.3 shows B_n for the start position were all possible combinations of these dominant spatial harmonics are removed.

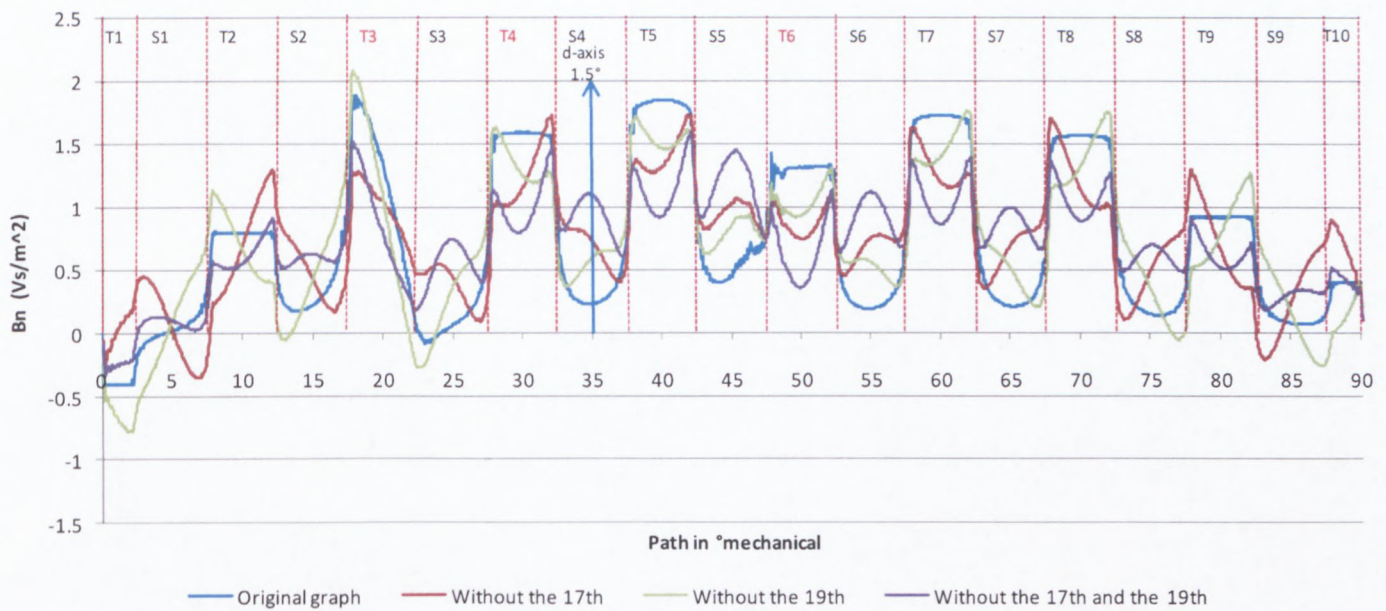


Fig. 3.1.2.3 B_n with and without dominant spatial harmonics

The table below shows the distortion of the MSD sections.

Table 3.1.2.2 Comparison between the degree of distortion for each MSD section

B_n	D_{T3}	D_{T4}	D_{T6}
Original graph	6.61	-0.69	2.07
Without the 17th	0.68	-4.25	1.21
Without the 19th	9.71	1.84	0.4
Without the 17th and the 19th	4	-2.24	0.4

From table 3.1.2.2 it can be seen that without the presence of the 19th spatial harmonic two MSD sections, namely T3 and T4 experience a significant increase in distortion compared to the original graph. Without the presence of the 17th or the combination of them results only in one MSD section, namely T4 to increase in distortion. As a result the 19th spatial harmonic has the most significant effect on B_n for the start position.

Moving on to the end position table 3.1.2.3 shows the results for the three MSD sections.

Table 3.1.2.3 Degree of distortion for each MSD section at d-axis end position 11.5°

D-axis position	D_{T3}	D_{T4}	D_{T6}
11.5°	0.46	6.72	0.51

If Fig. 3.1.1.6 is Fourier analysed the results is shown in Fig. 3.1.2.4.

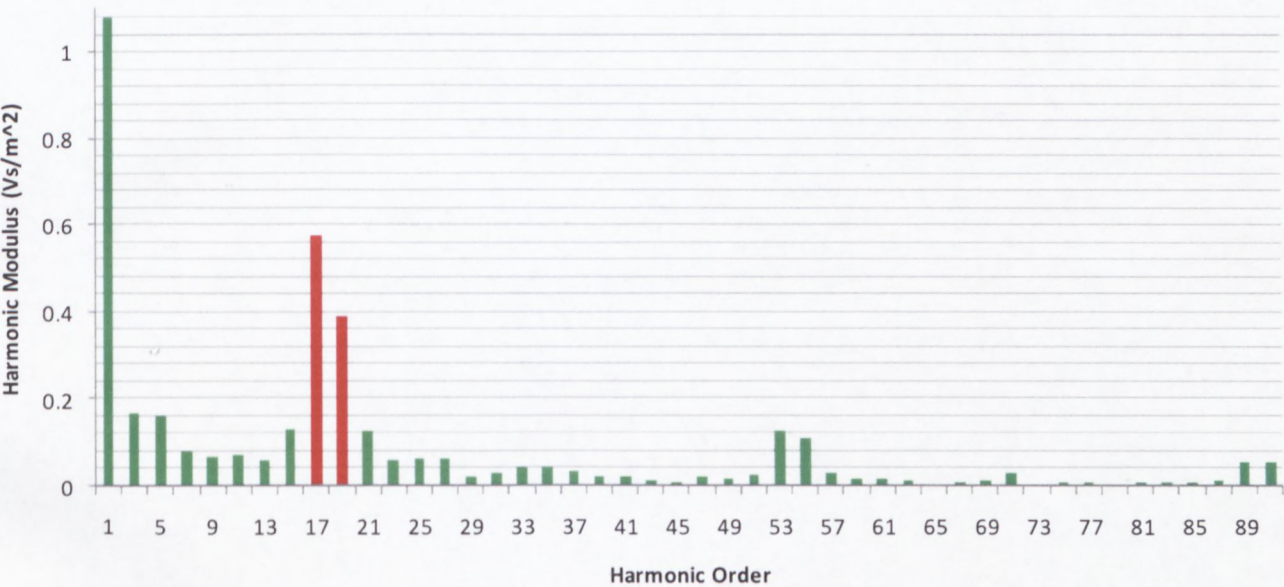


Fig. 3.1.2.4 Harmonic spectrum for d-axis end position 11.5°

According to Fig. 3.1.2.4 it is also evident that the dominant spatial harmonics are the 17th and the 19th harmonic, the same as for the start position. Fig. 3.1.2.5 shows B_n for the end position were all possible combinations of these dominant spatial harmonics are removed.

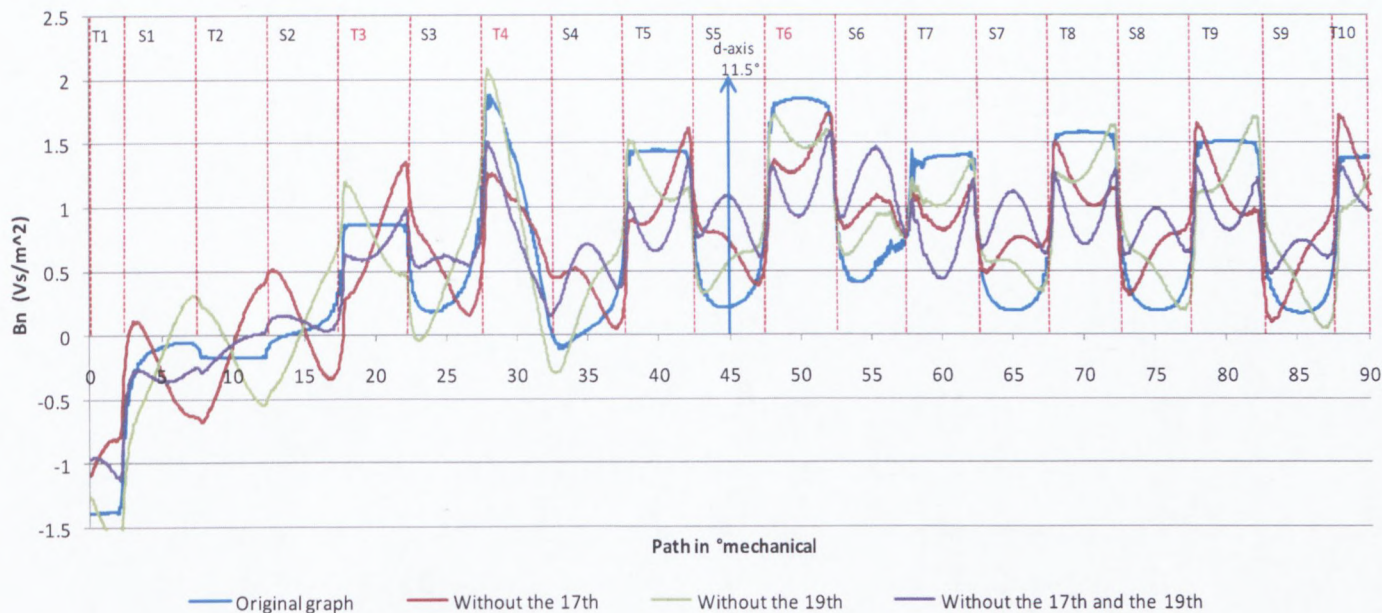


Fig. 3.1.2.5 B_n with and without dominant spatial harmonics

The table below shows the distortion of the MSD sections.

Table 3.1.2.4 Comparison between the degree of distortion for each MSD section

B_n	D_{T3}	D_{T4}	D_{T6}
Original graph	0.46	6.72	0.51
Without the 17th	-6.44	0.74	-2.47
Without the 19th	4.2	9.89	0.63
Without the 17th and the 19th	-2.3	4.08	-1.67

From table 3.1.2.4 it can be seen that without the presence of the 19th spatial harmonic three MSD sections namely T3, T4 and T6 experience a significant increase in distortion compared to the original graph. Without the presence of the 17th or the combination of them results in two MSD section namely T3 and T4 to increase in distortion. As a result the 19th spatial harmonic has the most significant effect on B_n for the end position.

The same procedure has been carried out for all d-axis positions, shown in Fig.'s 3.1.2.6-3.1.2.9 and Appendix D, which revealed that the 19th spatial harmonic also have the most significant effect for all positions. Overall it is concluded that the 19th spatial harmonic has the most significant effect for each d-axis position.

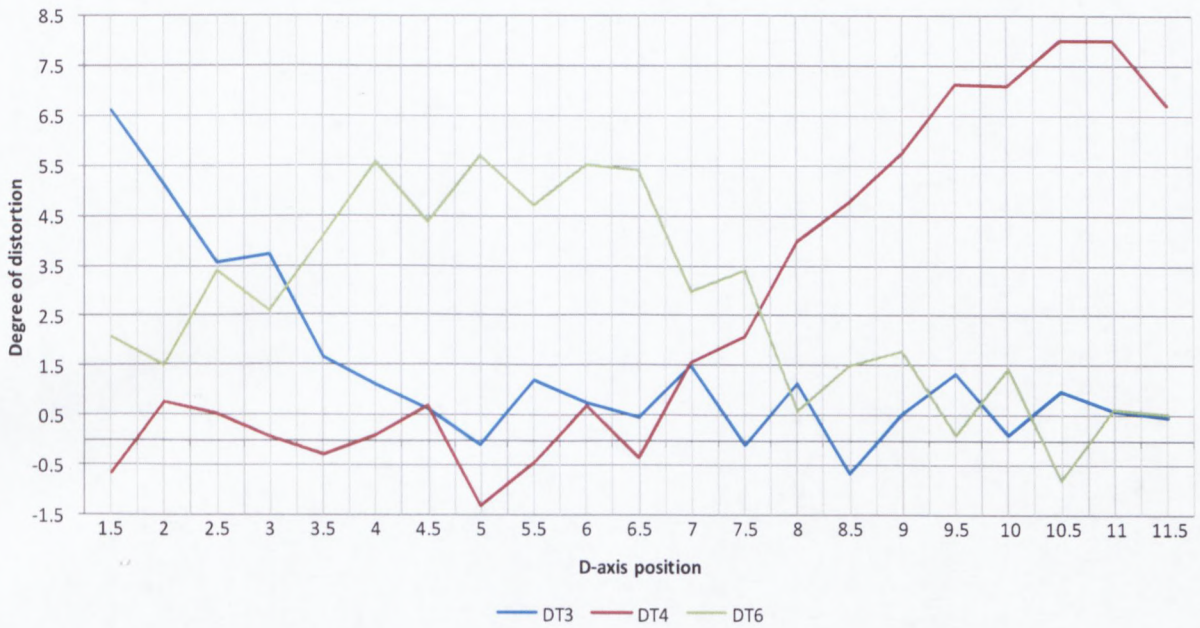


Fig. 3.1.2.6 Distortion of B_n of the original graph for all d-axis positions

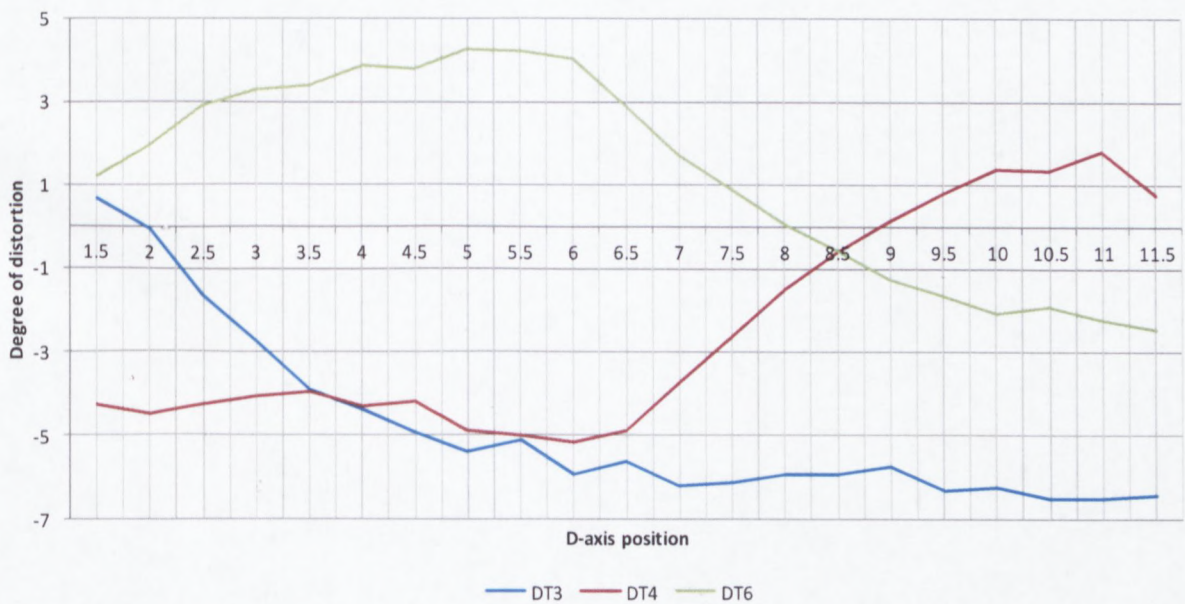


Fig. 3.1.2.7 Distortion of B_n without the 17th for all d-axis positions

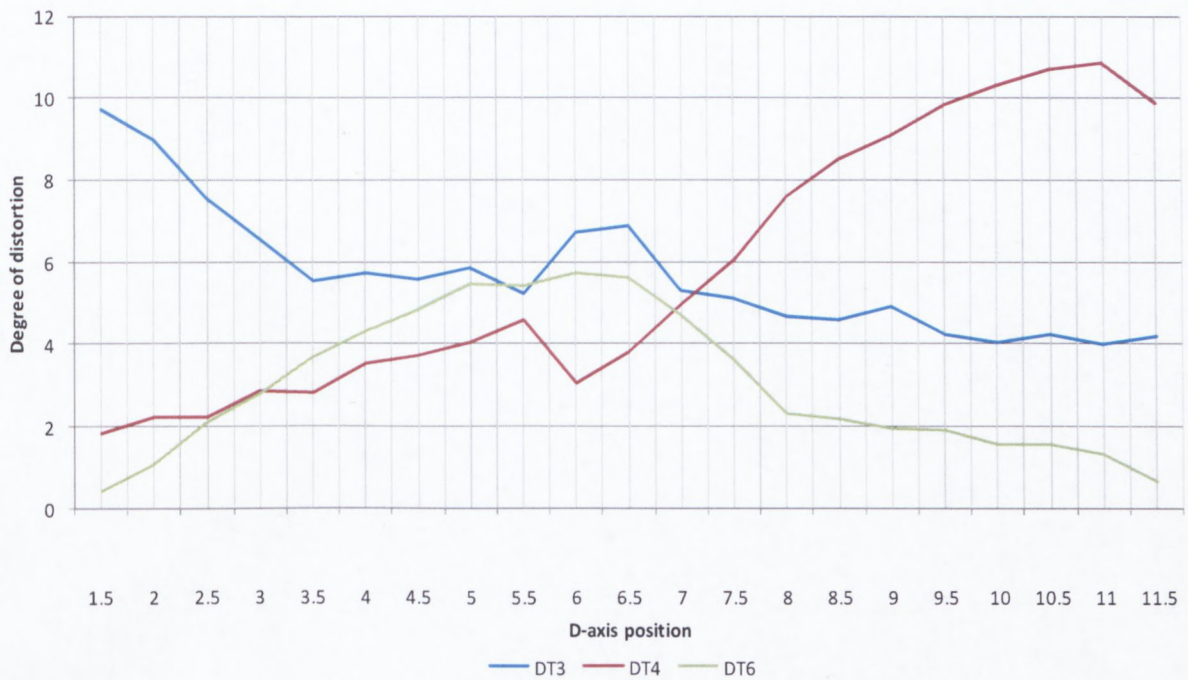


Fig. 3.1.2.8 Distortion of B_n without the 19th for all d-axis positions

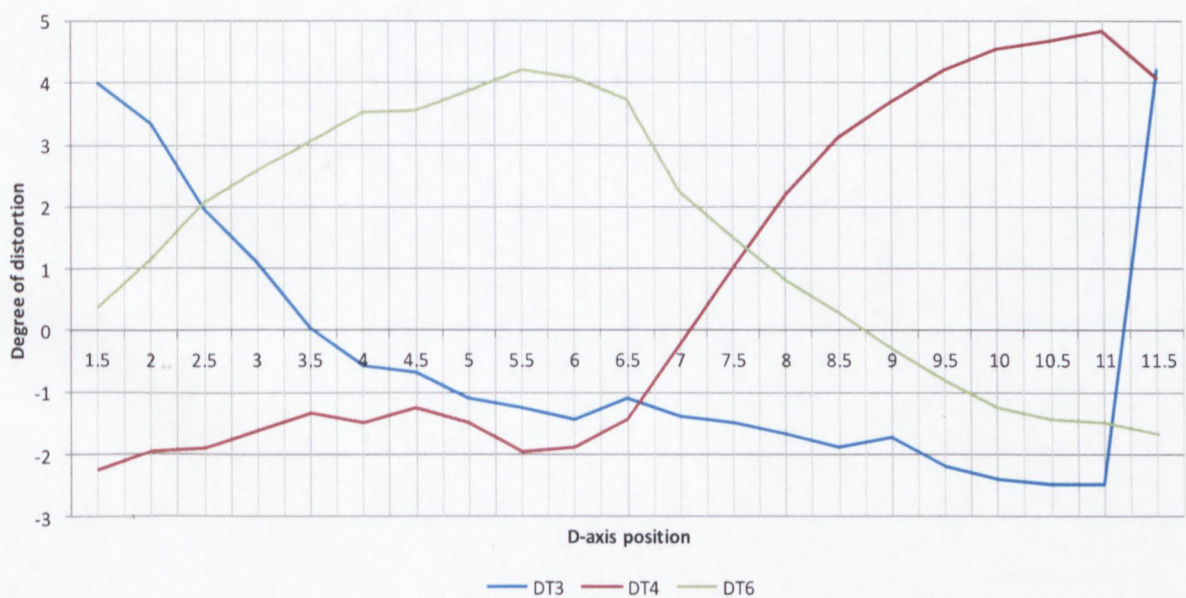


Fig. 3.1.2.9 Distortion of B_n without the combination for all d-axis positions

3.1.3 *Analysing the tangential component*

In this section B_t will be analysed in the same way as B_n . Therefore Fig. 3.1.3.1 shows B_t along the path as the d-axis moves from the 0° mech. reference position through the pole pitch. The d-axis is shifted 10° mech. in steps of 0.5° from slot S4 to slot S5 as shown in Fig.'s 3.1.1.2 and 3.1.1.3 in section 3.1.1. B_t along the path is obtained for each d-axis position shown in Fig. 3.1.3.2.

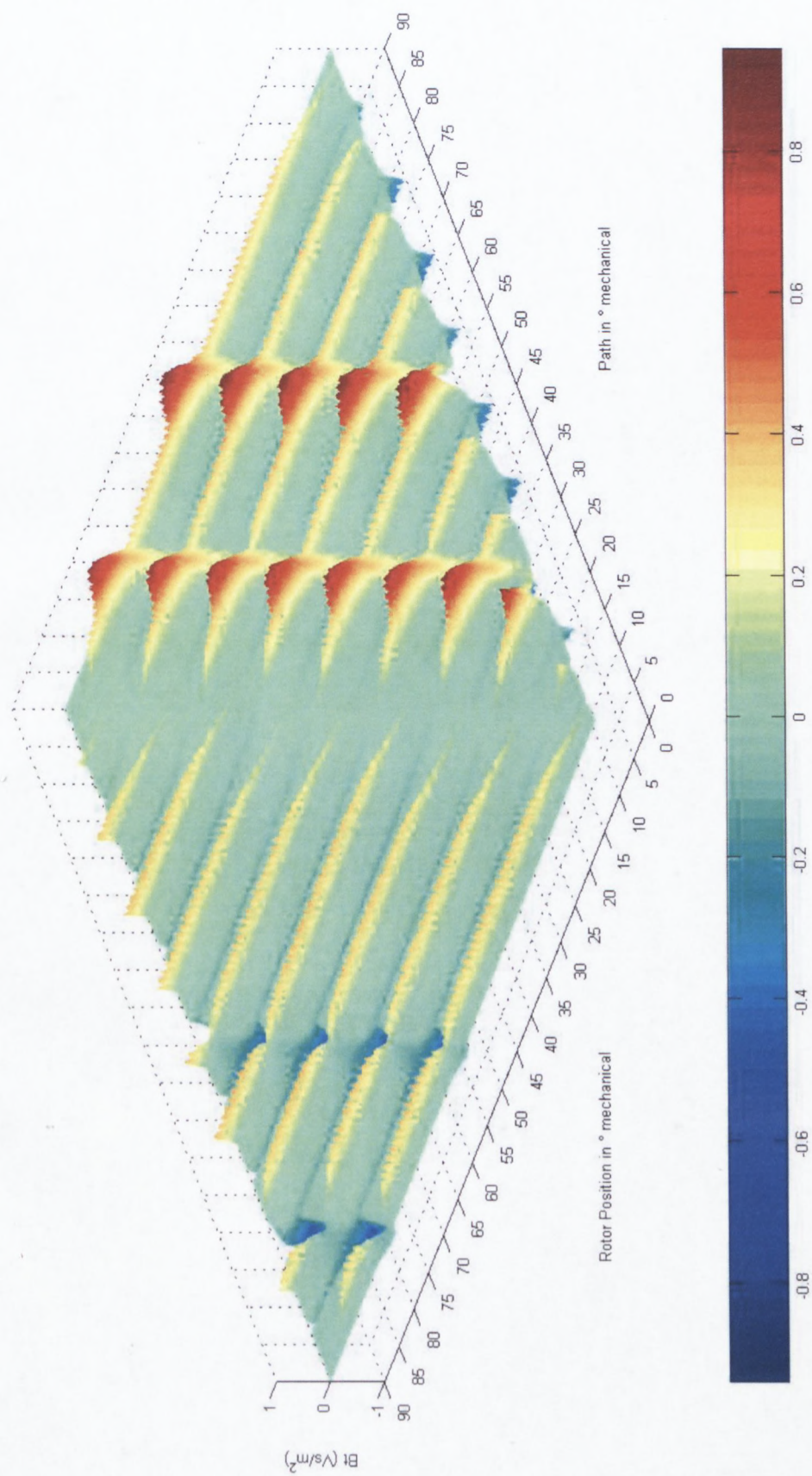


Fig. 3.1.3.1 B_t as a function of rotor position

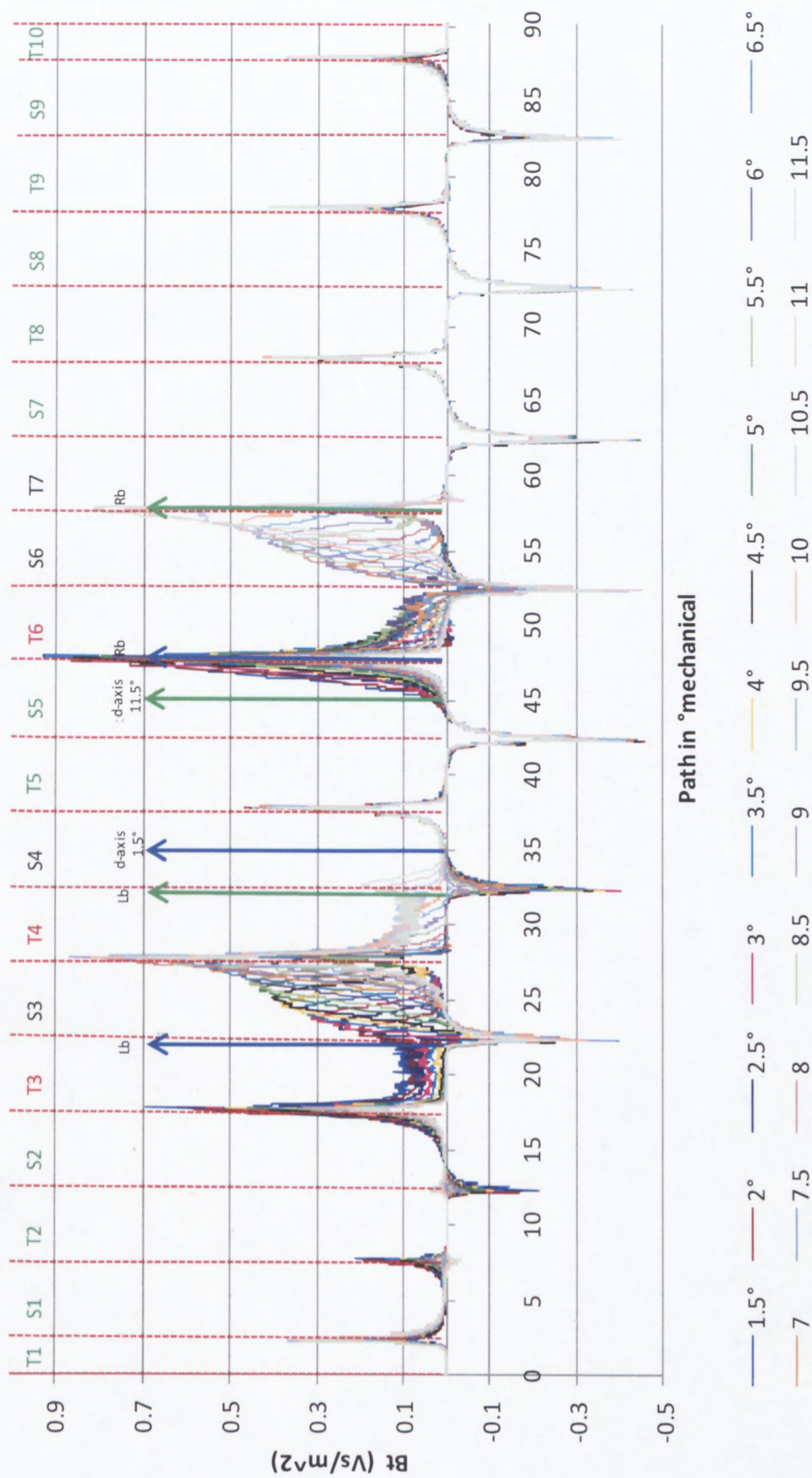


Fig. 3.1.3.2 B_t along the path in the center of the air gap as the d-axis moves through a slot pitch

According to Fig. 3.1.3.2 B_t mostly exists along the edges of the tooth sections, which is expected and according to theory. The graph also shows that sections T3, T4 and T6 contain significantly higher distortions than the remaining sections which are therefore referred to as the most significant distorted (MSD) sections by the author.

In the following the MSD sections will be analysed by referring to Fig.'s 3.1.3.3 and 3.1.3.4.

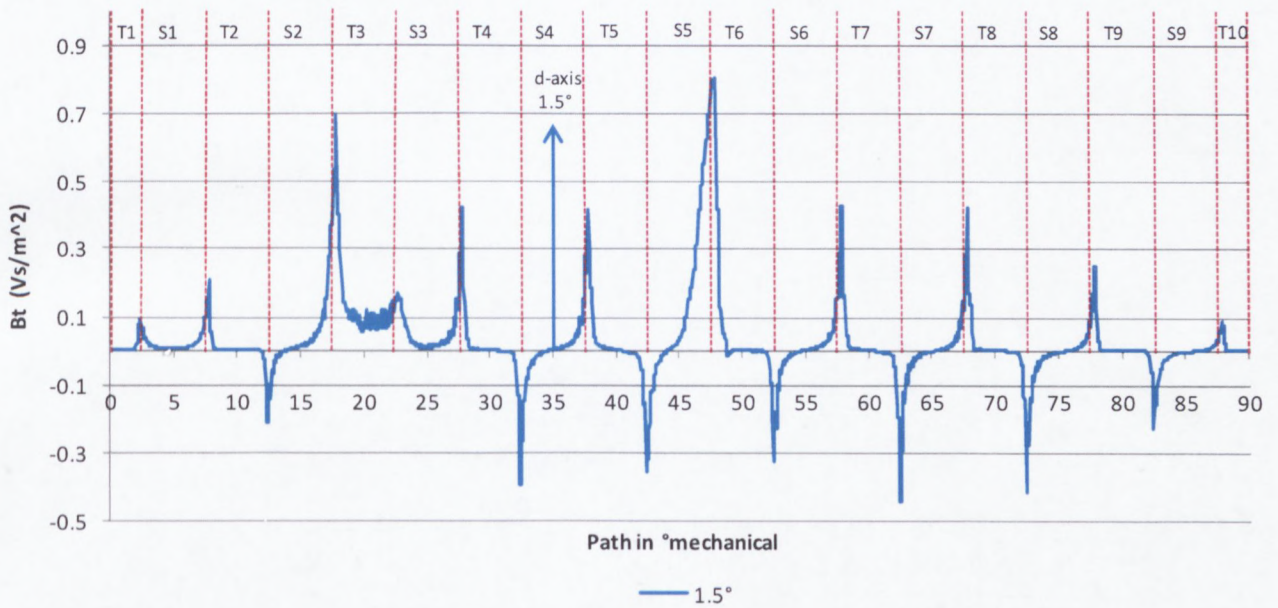


Fig. 3.1.3.3 B_t for d-axis position 1.5° mech.

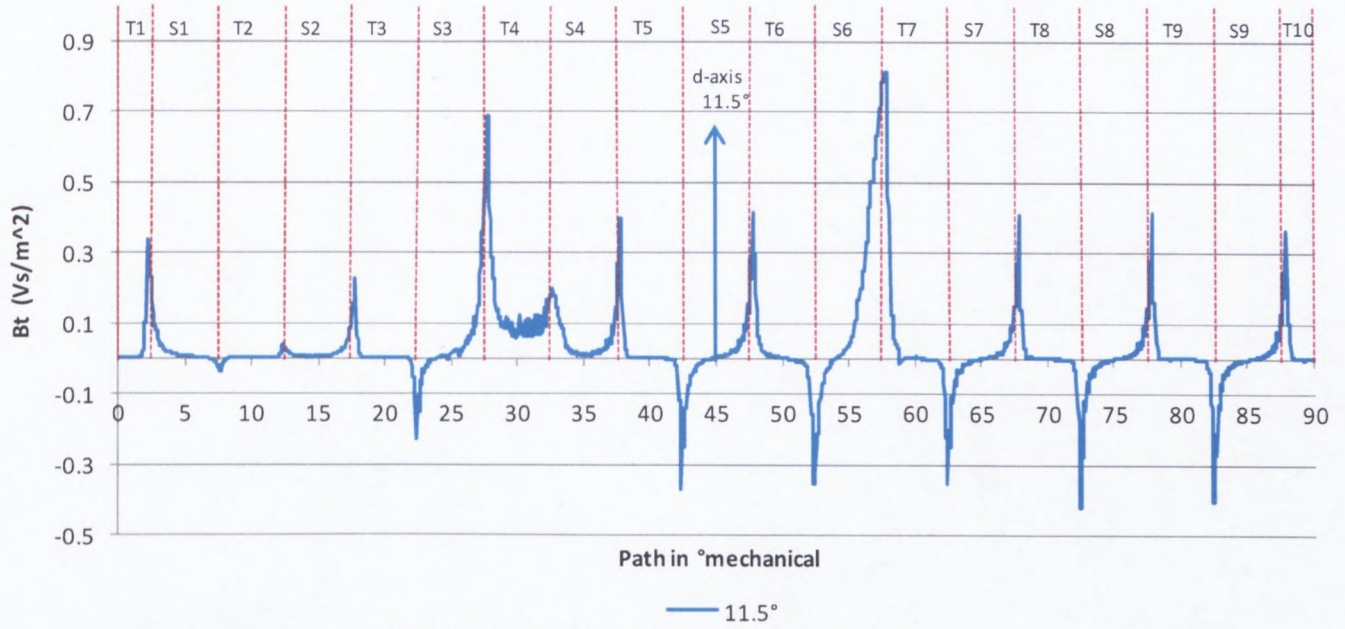


Fig. 3.1.3.4 B_t for d-axis position 11.5° mech.

According to Fig. 3.1.3.3 the flux density is high at the left hand side of section T3 which is explained by looking at the field pictures shown in Fig.'s 3.1.1.7 and 3.1.1.8 in section 3.1.1. The same can be said for section T6, while section T4 is undistorted on the left. Moving on to Fig. 3.1.3.4 the flux density is high at the left hand side of section T4 which is also explained by looking at the field pictures shown in Fig.'s 3.1.1.7 and 3.1.1.8. The same can also be said for section T7, while section T3 is undistorted on the left.

These two analyses explain the MSD sections for the start and end position outlining the slot pitch. The positions in between change accordingly and can be viewed in Fig. 3.1.3.2. An interesting observation the same as in B_n is that the left flux barrier has a more significant effect on MSD sections T3 and T4 respectively, while the right flux barrier has a less significant effect on T6. This yet again raises the question whether asymmetrical flux barrier arrangements may be well worth investigating in future research. So far the MSD sections were analysed from d-axis position 1.5° to 11.5°. These results for a pole pitch are shown in Fig. 3.1.3.5.

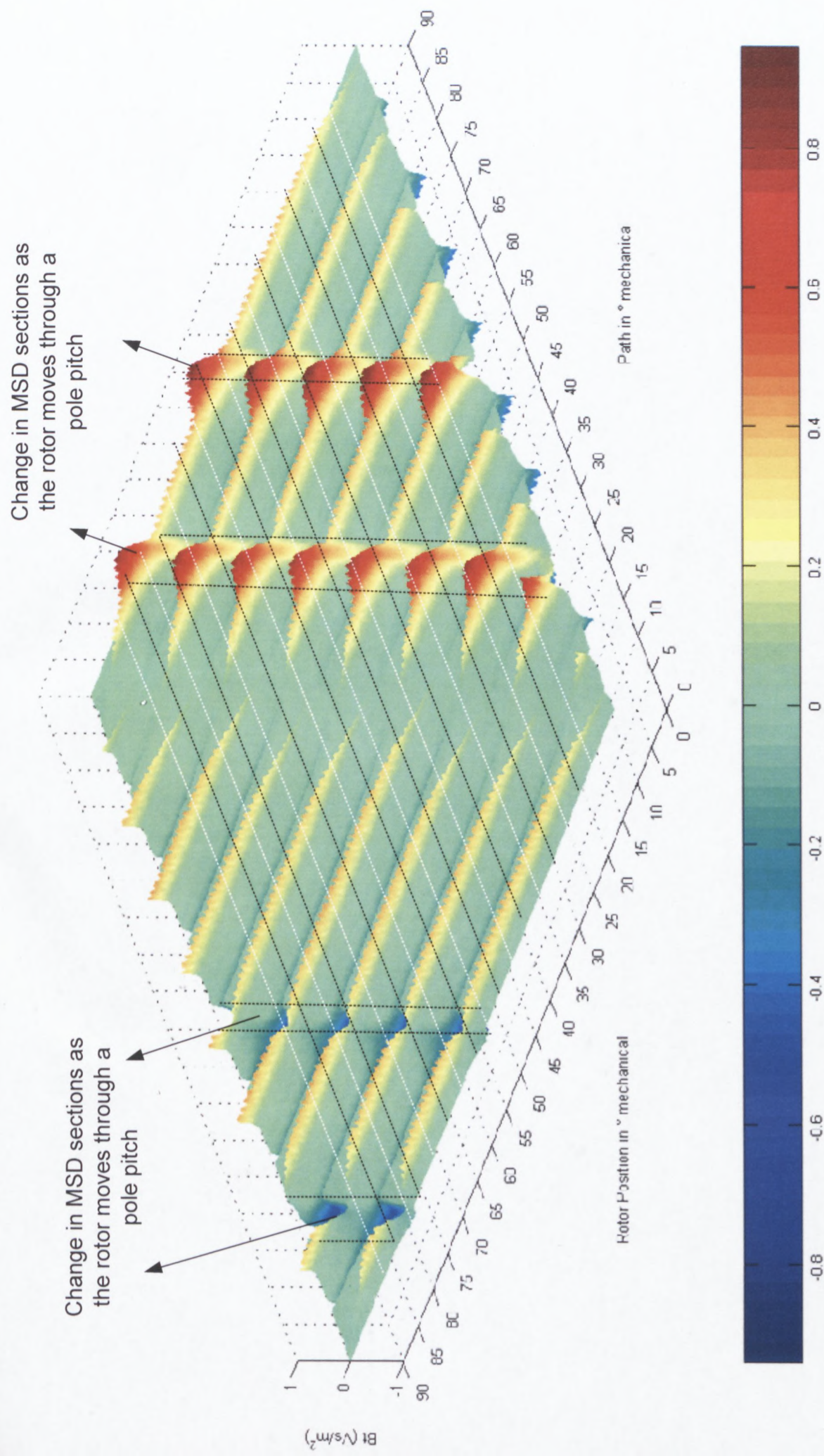


Fig. 3.1.3.5 B_z as a function of rotor position

3.1.4 Analysing the tangential component harmonics

In this section B_t under the slot pitch will be subjected to a Fourier analysis and the effect of the dominant spatial harmonics on the MSD sections will be determined.

First the degree of distortion for each MSD section of the start position is determined the same as in the case of B_n and is given in table 3.1.4.1.

Table 3.1.4.1 Degree of distortion for each MSD section at d-axis start position 1.5°

D-axis position	D_{T3}	D_{T4}	D_{T6}
1.5°	2.07	3.22	5.92

If Fig. 3.1.3.5 is Fourier analysed the results is shown in Fig. 3.1.4.1.

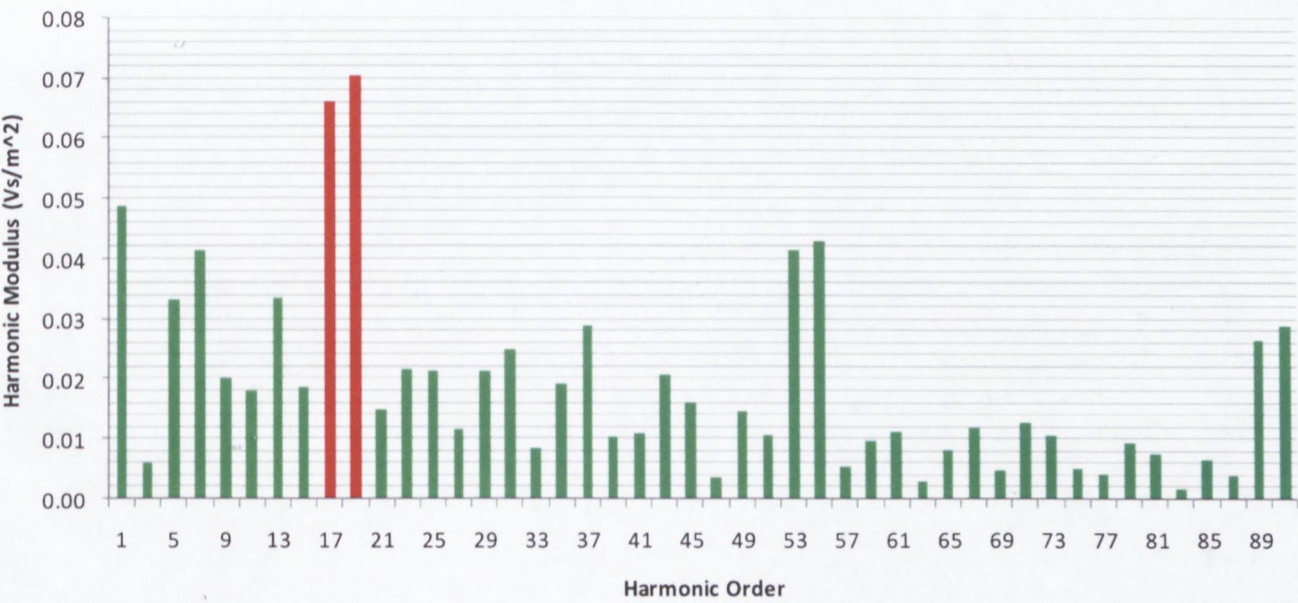


Fig. 3.1.4.1 Harmonic spectrum for d-axis start position 1.5°

According to Fig. 3.1.4.1 B_t also contains odd harmonics only due to B_t being an odd function. It is also evident that the dominant spatial harmonics are the 17th and the 19th harmonic. Fig. 3.1.4.2 shows B_t for the start position were all possible combinations of these dominant spatial harmonics are removed.

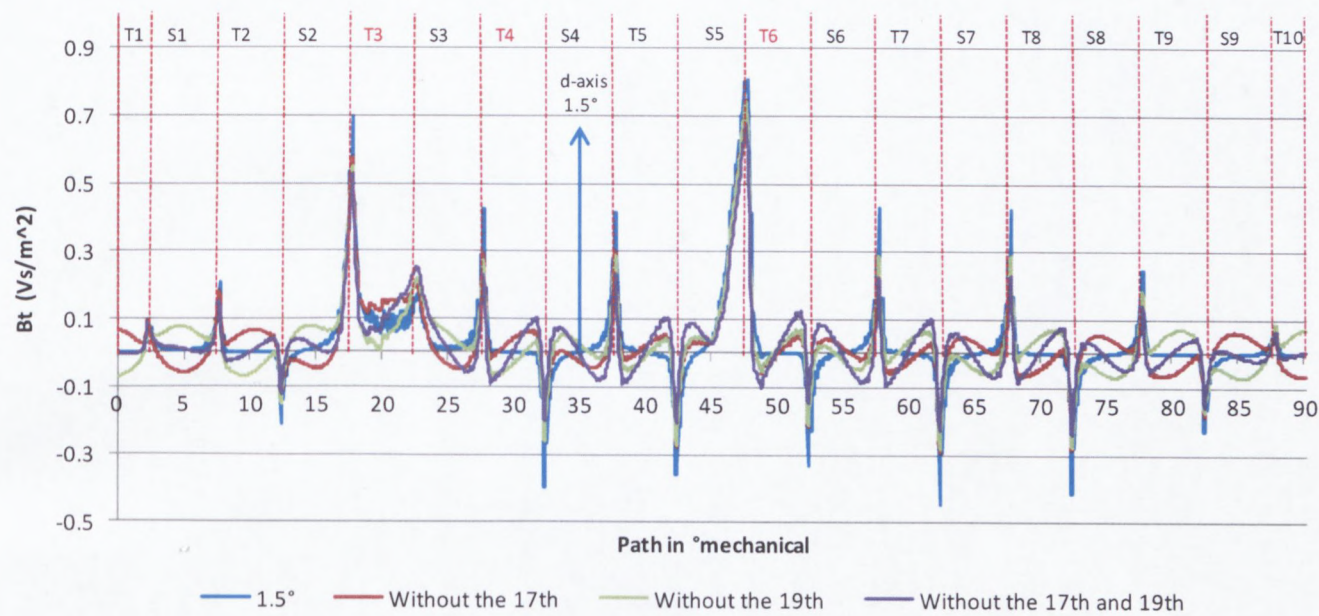


Fig. 3.1.4.2 B_t without dominant spatial harmonics

The table below shows the distortion of the MSD sections.

Table 3.1.4.2 Comparison between the degree of distortion for each MSD section

B_t	D_{T3}	D_{T4}	D_{T6}
Original graph	2.07	3.22	5.92
Without the 17 th	1.44	1.67	4.88
Without the 19 th	1.32	1.61	4.71
Without the 17 th and the 19 th	1.44	1.84	4.77

From table 3.1.4.2 it can be seen that without the presence of the 19th spatial harmonic the MSD sections experiences a more significant decrease in distortion, compared to those of the 17th or the combination of them. As a result the **19th** spatial harmonic has the most significant effect on the start position.

Moving on to the end position table 3.1.4.3 shows the results for the three MSD sections.

Table 3.1.4.3 Degree of distortion for each MSD section at d-axis end position 11.5°

D-axis position	D_{T3}	D_{T4}	D_{T6}
11.5°	1.78	4.13	2.93

If Fig. 3.1.3.6 is Fourier analysed the results is shown in Fig. 3.1.4.3.

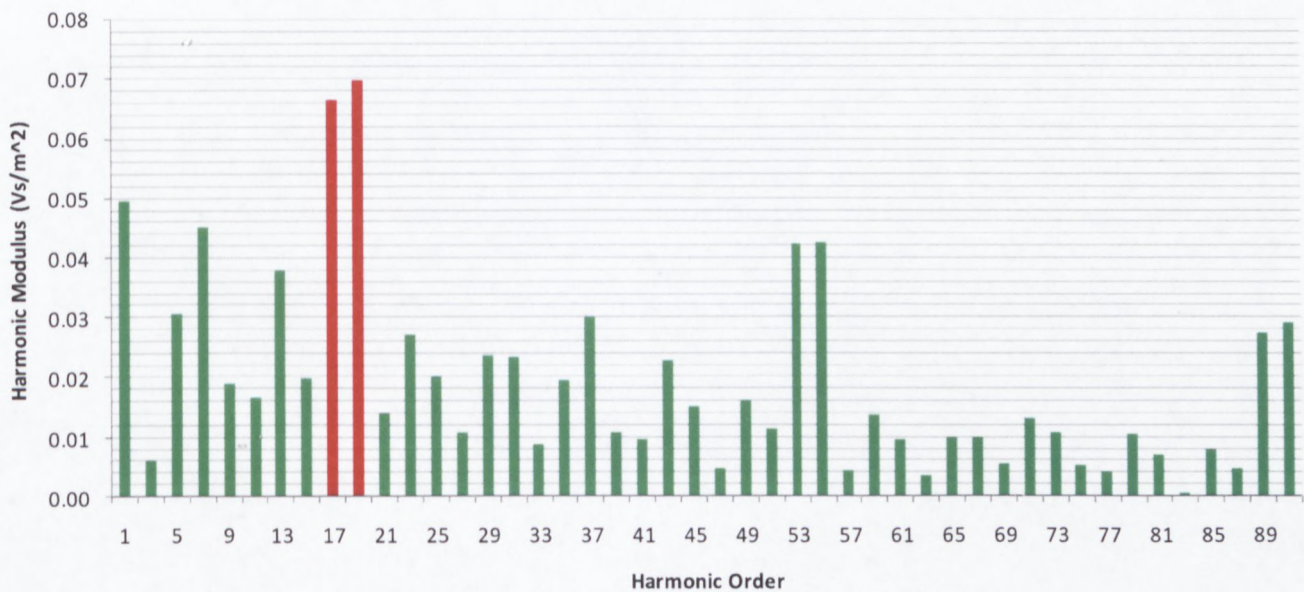


Fig. 3.1.4.3 Harmonic spectrum for d-axis end position 11.5°

According to Fig. 3.1.4.3 it is also evident that the dominant spatial harmonics are the 17th and the 19th harmonic, the same as for the start position. Fig. 3.1.4.4 shows B_r along the path for the end position were all possible combinations of these dominant spatial harmonics are removed.

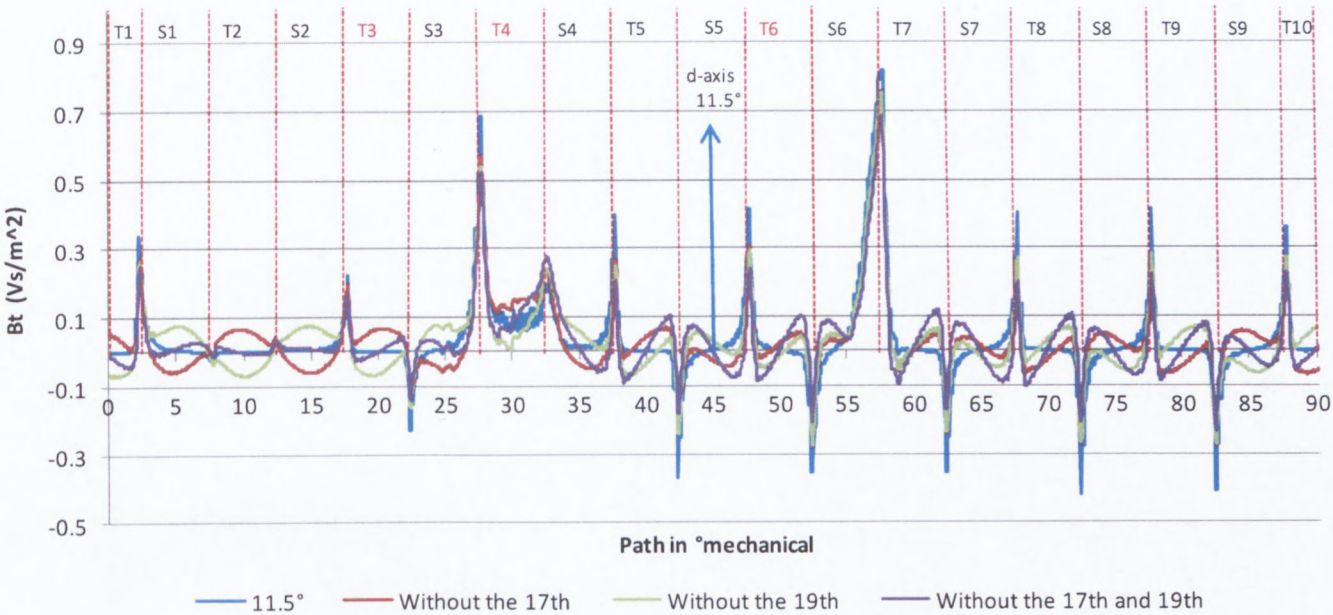


Fig. 3.1.4.4 B_t without dominant spatial harmonics

The table below shows the distortion of the MSD sections.

Table 3.1.4.4 Comparison between the degree of distortion for each MSD section

B_t	D_{T3}	D_{T4}	D_{T6}
Original graph	1.78	4.13	2.93
Without the 17th	1.44	1.26	2.41
Without the 19th	1.09	1.15	1.89
Without the 17th and the 19th	1.26	1.43	2.01

From table 3.1.4.4 it can be seen that that without the presence of the 19th spatial harmonic the MSD sections experiences a more significant decrease in distortion, compared to those of the 17th or the combination of them. As a result the 19th spatial harmonic has the most significant effect on B_t for the end position.

The same procedure has been carried out for all d-axis positions shown in Fig.'s 3.1.4.5-3.1.4.8 and Appendix E, which revealed that the 19th spatial harmonic also have the most significant effect for all positions. Overall it is concluded that the 19th spatial harmonic has the most significant effect for each d-axis position.

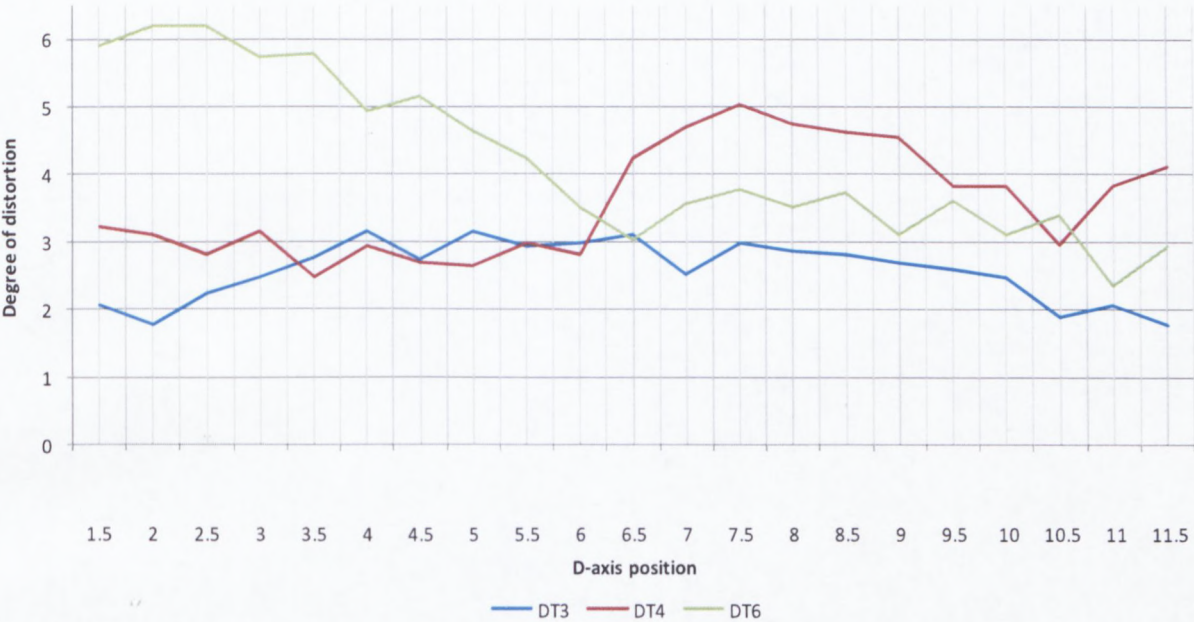


Fig. 3.1.4.5 Distortion of B_l of the original graph for all d-axis positions



Fig. 3.1.4.6 Distortion of B_l without the 17th for all d-axis positions

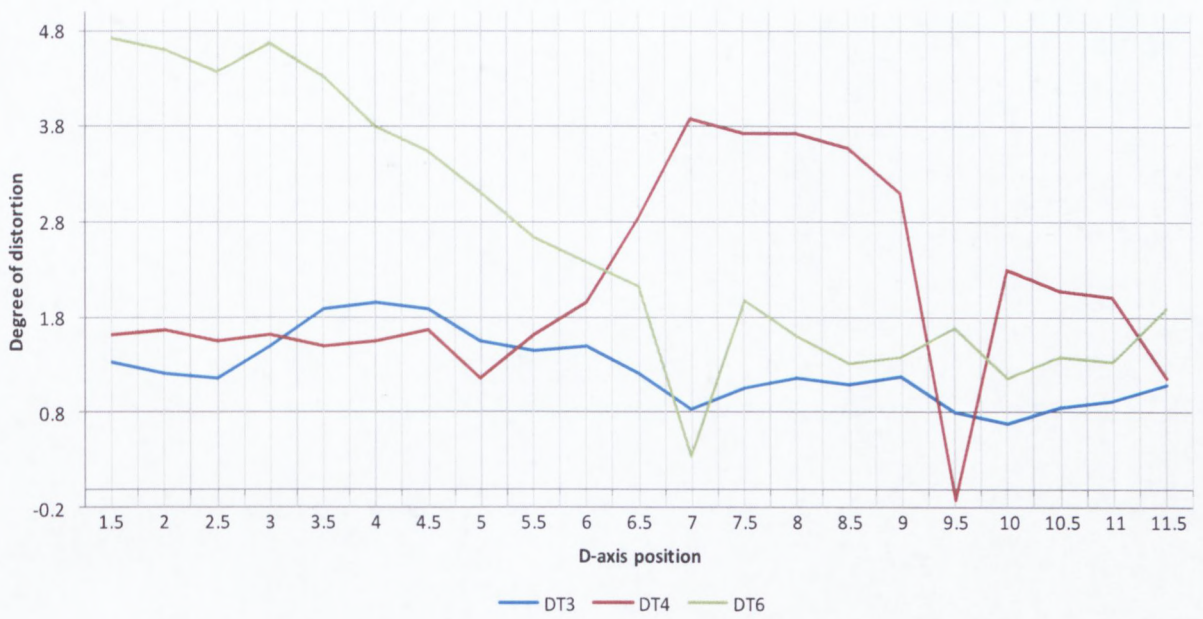


Fig. 3.1.4.7 Distortion of B_i without the 19th for all d-axis positions

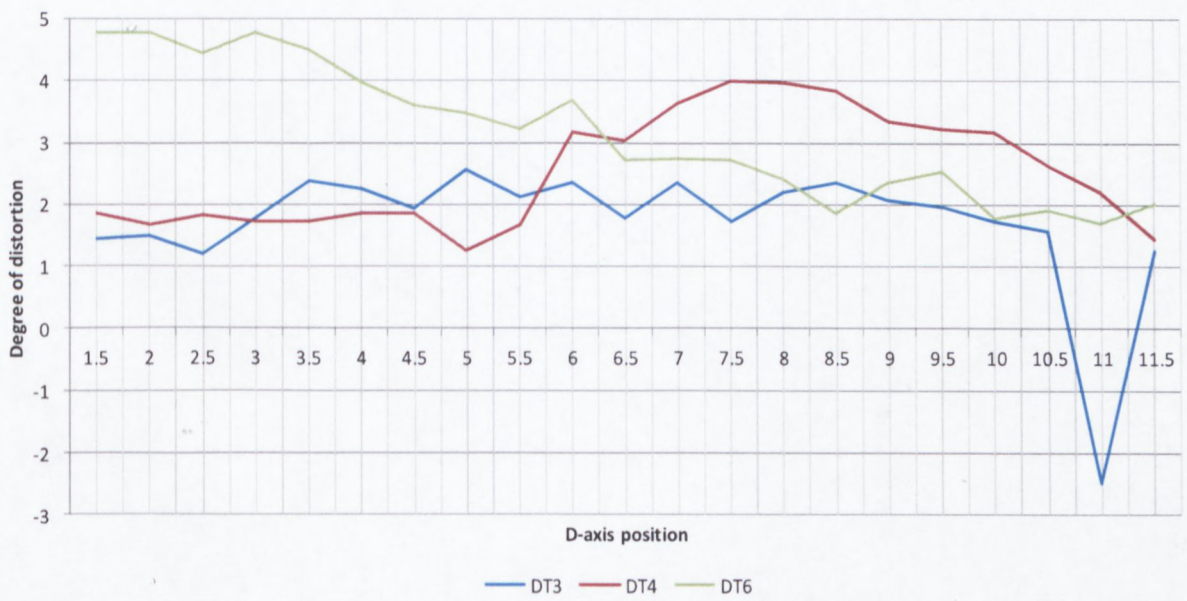


Fig. 3.1.4.8 Distortion of B_i without the combination for all d-axis positions

3.2 Summary of findings

The findings of chapter 3 are summarised as follow:

- MSD sections for B_n and B_t were identified for the slot pitch (S4-S5) which holds the significance of being the most significantly distorted by the flux barriers.
- These MSD sections repeat itself for each slot pitch and shifts along the path. Therefore only one slot pitch is necessary to be analysed.
- The left flux barrier has a more significant effect on MSD sections T3 and T4 respectively, compared to the effect the right flux barrier has on MSD section T6. Therefore it might be well worth investigating asymmetrical flux barrier arrangements in future research.
- The Fourier analysis on B_n and B_t revealed the 17th and 19th dominant spatial harmonics. The 19th spatial harmonic has the biggest influence on the distortion of B_n and B_t .

4. Force distribution analysis in the air gap

In this chapter B_n and B_t along the slot pitch as discussed in chapter 3, will be used to calculate the tangential force distribution. This force component is responsible for rotor motion only therefore it is the only component regarded. The effect of the most significant flux density harmonic on the tangential force distribution will also be analysed for which the data from chapter 3 are used.

4.1 Force distribution compared to flux density distribution

The tangential stress distribution can be calculated according to MST from

$$\sigma_t = \frac{B_n B_t}{\mu_0} \quad (4.1.1)$$

where, B_n and B_t are the normal and tangential flux density components as shown in Fig.

4.1.1 below and μ_0 is the permeability of free space.

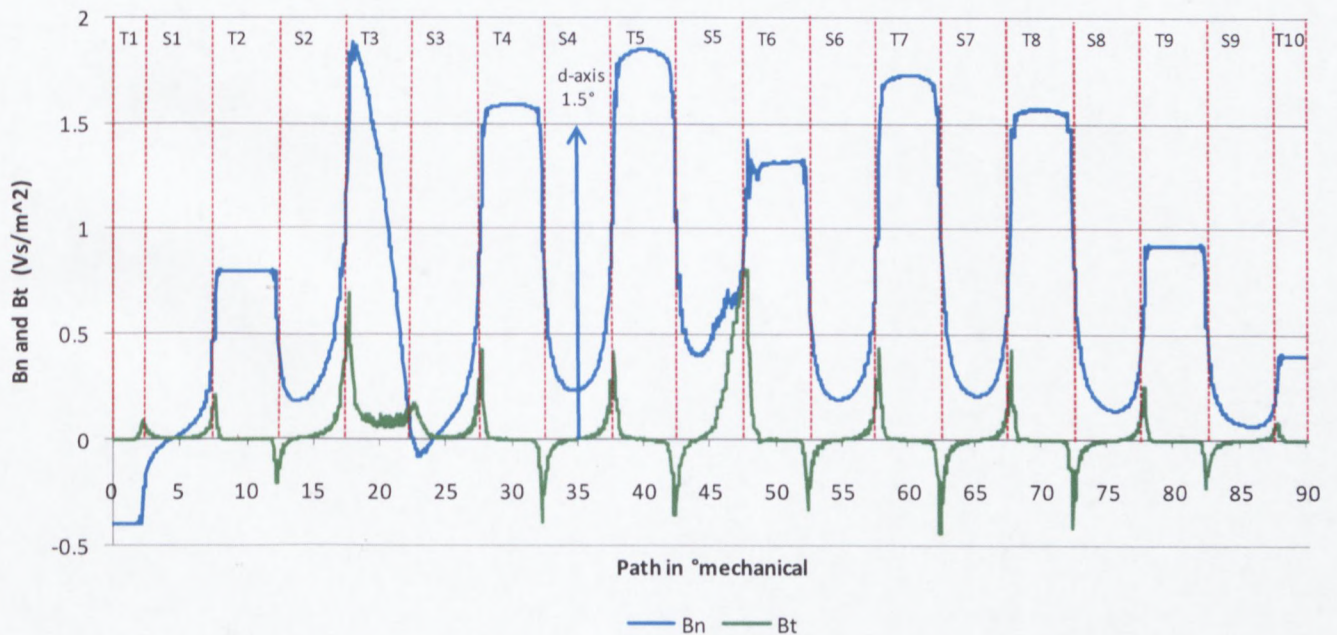


Fig. 4.1.1 B_n and B_t for the start position

The tangential force (F_t) distribution is then calculated from

$$F_t = \sigma_t \cdot d\Gamma \tag{4.1.2}$$

where $d\Gamma$ is the segment length of the path shown in Fig. 4.1.2 which is repeated from chapter 2 for easy reference. F_t is shown in Fig. 4.1.3.

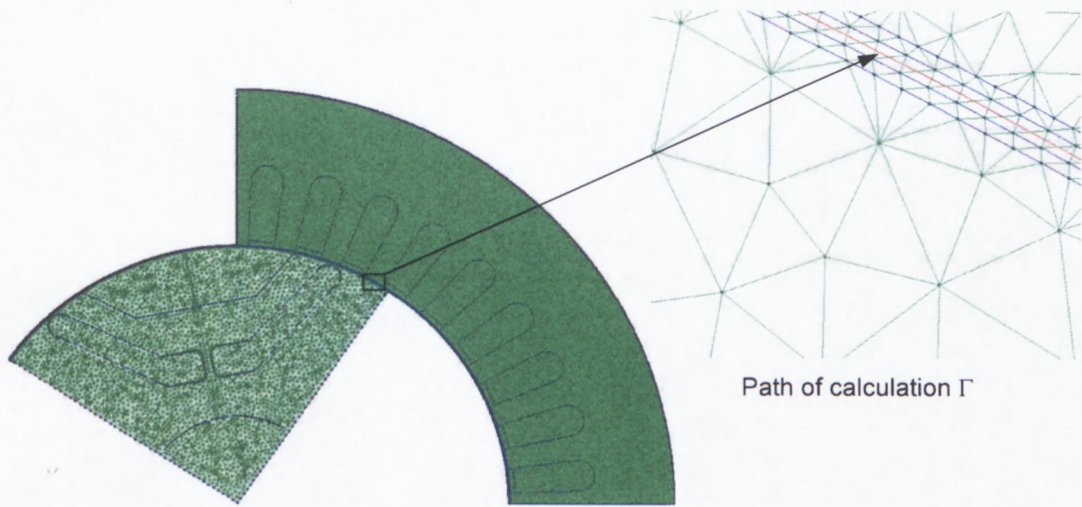


Fig. 4.1.2 Contour Γ in the center of the air gap

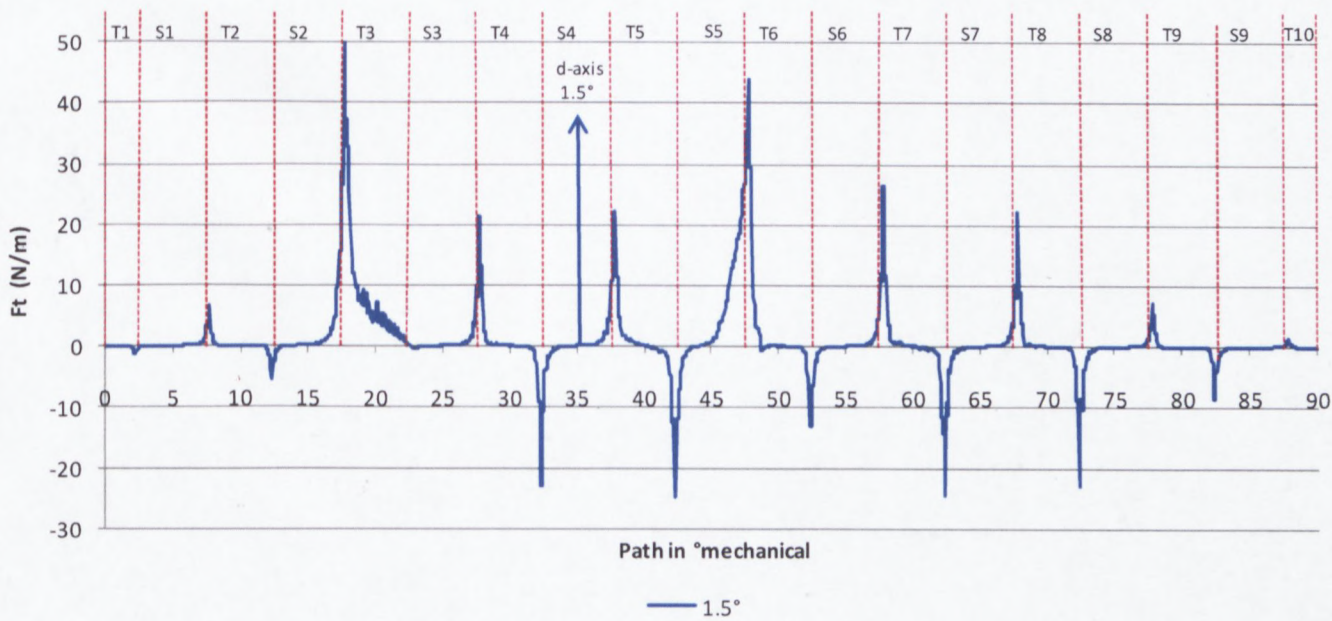


Fig. 4.1.3 F_t for the start position

Comparing Fig. 4.1.1 to 4.1.3 it is evident that B_n primarily contributes to the magnitude of F_t , while B_t primarily contributes to the shape. This is also discovered by (Salon et al. 1997). Furthermore F_t mostly exists on the sides of the teeth sections which oppose each other. An interesting aspect is that F_t at the left hand side of MSD sections T3 and T6 are significantly higher than the right hand side. Comparing this to the undistorted sections where F_t is the same in magnitude leads to the conclusion that F_t created at the left side of T3 and T6 produces the primary rotational force. This motivates the significance of the MSD sections.

For the end position, Fig.'s 4.1.4 and 4.1.5 shows B_n and B_t and F_t .

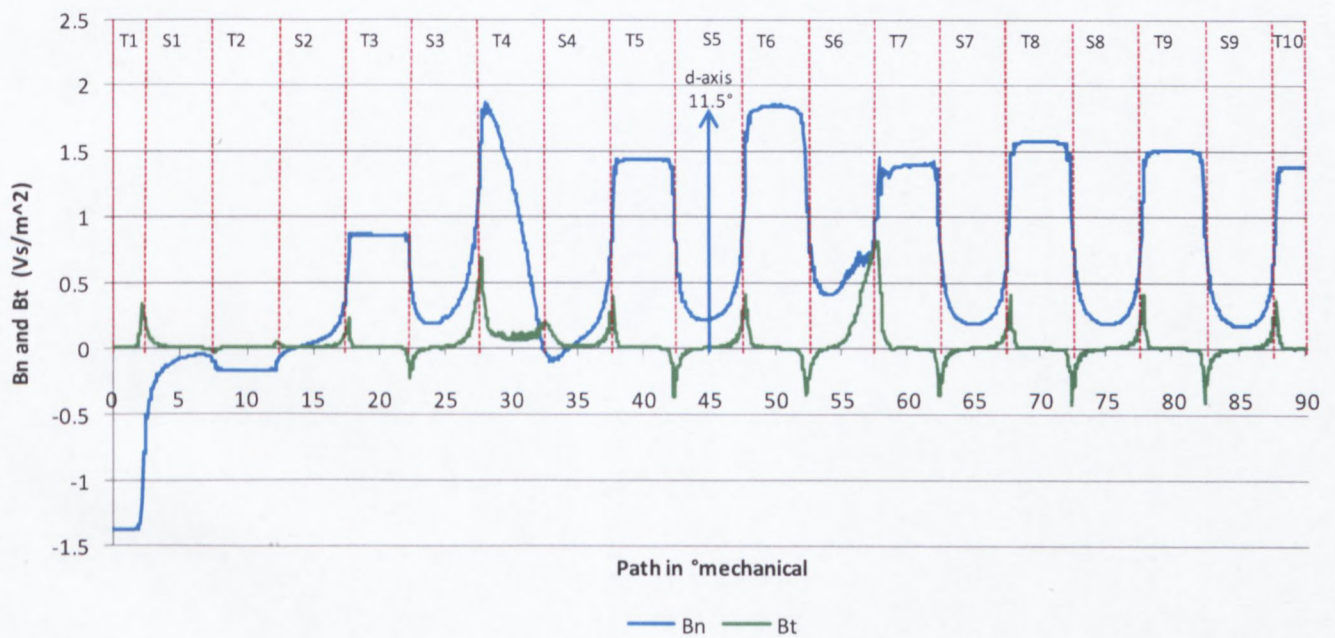


Fig. 4.1.4 B_n and B_t for the end position

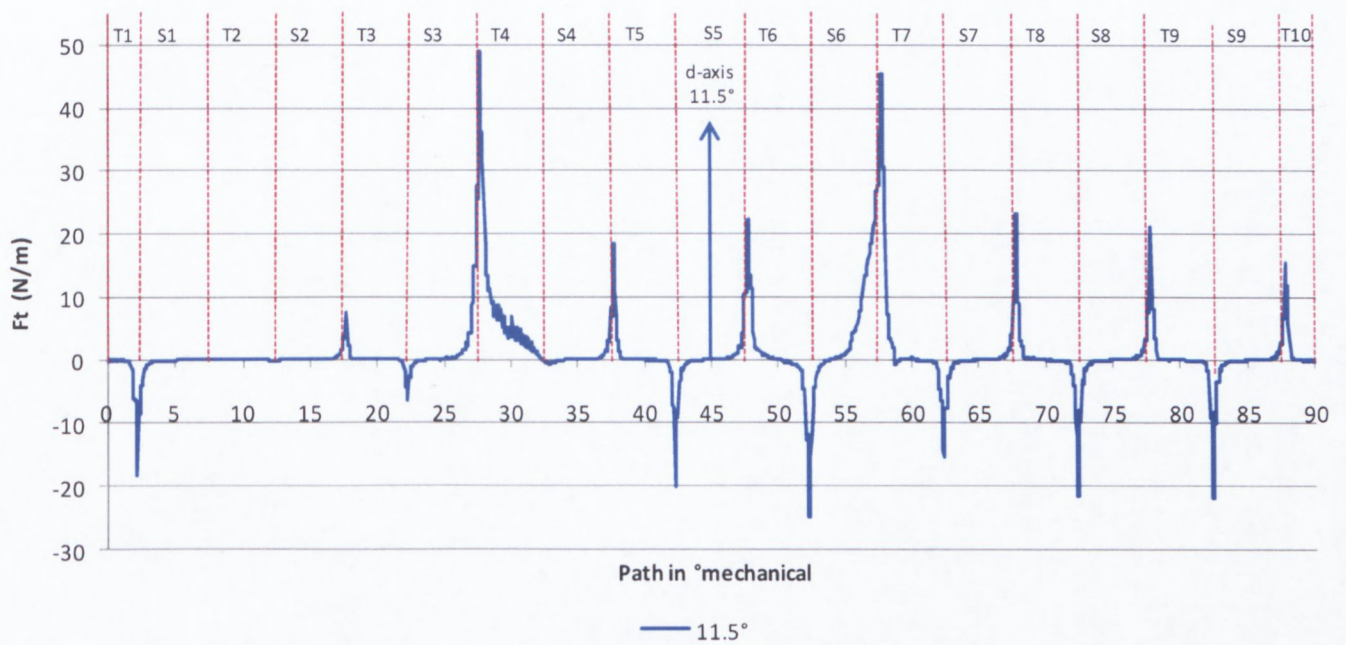


Fig. 4.1.5 F_t for the end position

Sections T4 and T7 produce the primary rotational force and this conclusion also applies to the positions in between as shown in Fig. 4.1.6.

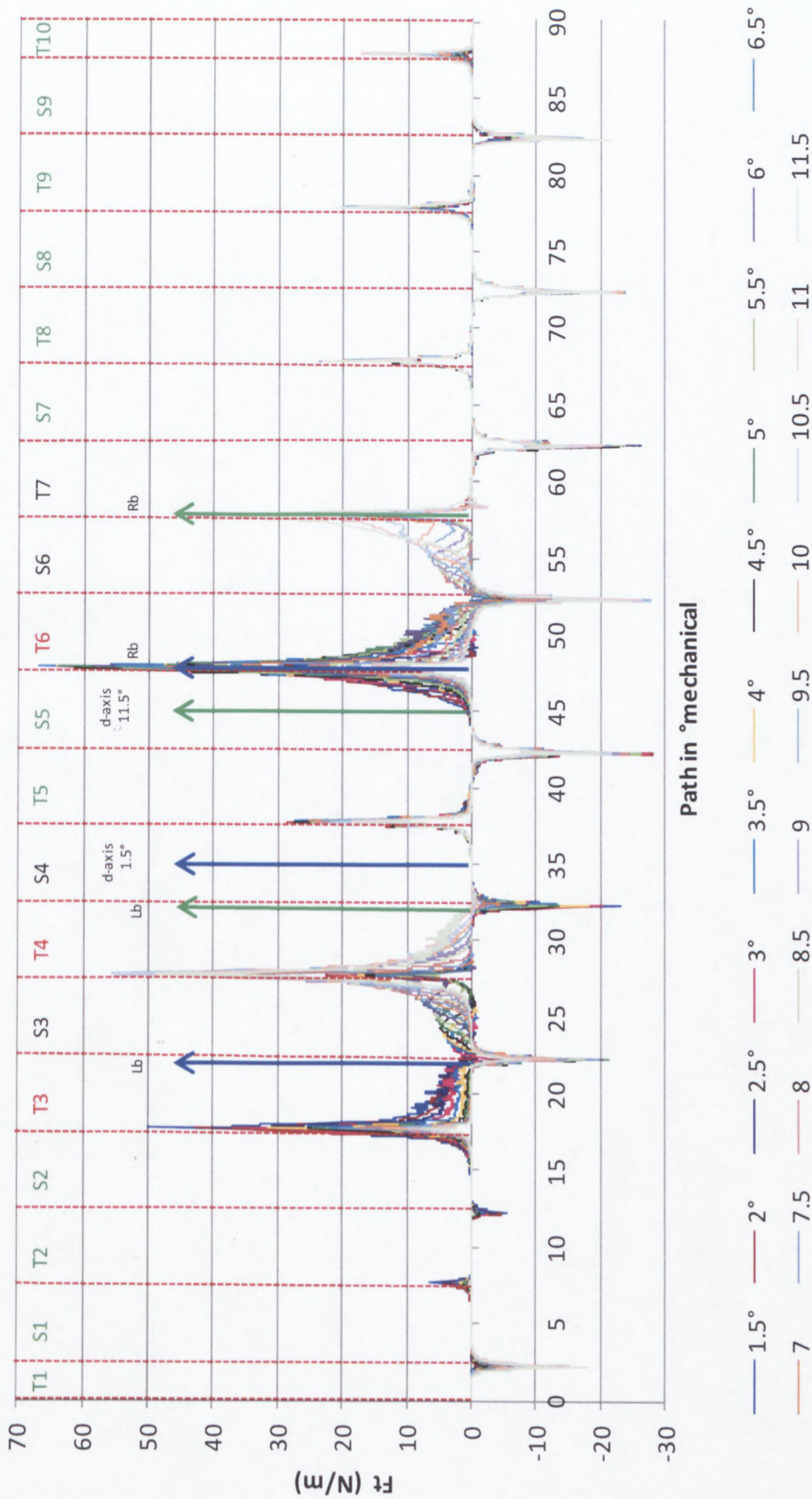


Fig. 4.1.6 F_t along the path in the center of the air gap as the d-axis moves through a slot pitch

Overall it can be said that the primary rotational force created on the rotor exists on the left side of the MSD sections. This then highlights the significance of the number of flux barriers and their arrangement as this determines the significance and the number of MSD sections respectively.

4.2 Force distribution compared to flux density harmonics

In this section F_t is determined without the 19th harmonic and shown in Fig. 4.2.1 for the start position and Fig. 4.2.2 for the end position.

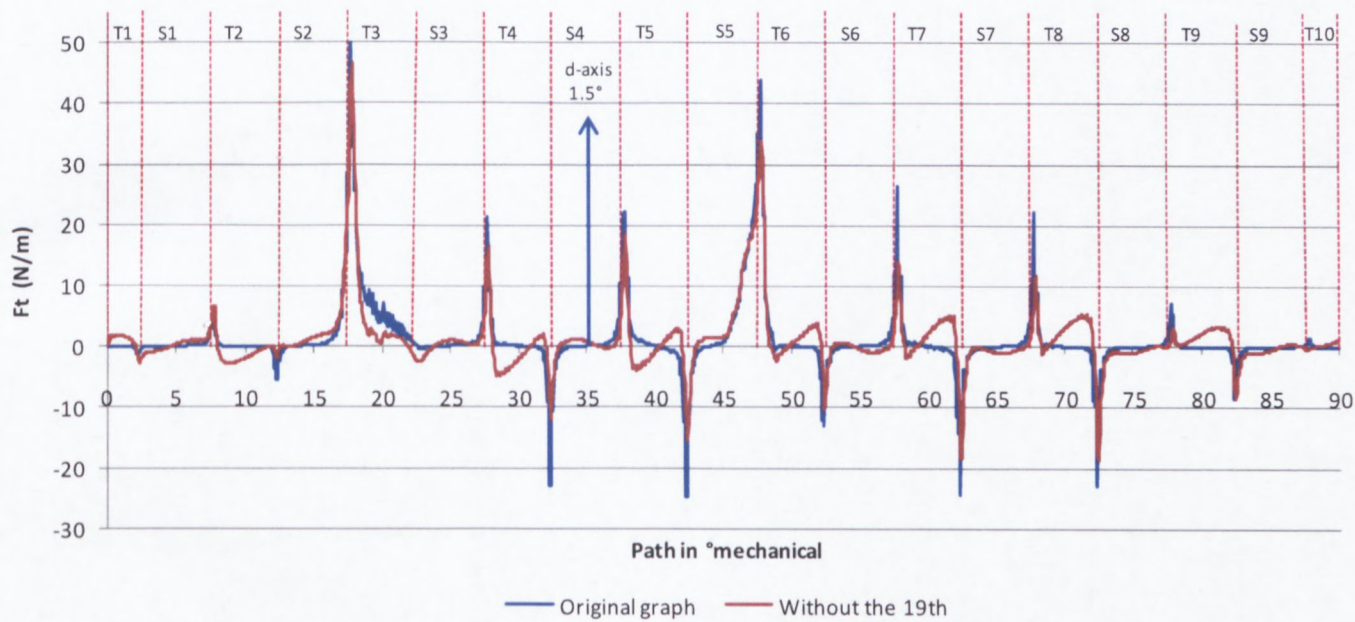


Fig. 4.2.1 F_t without 19th spatial harmonic for the start position

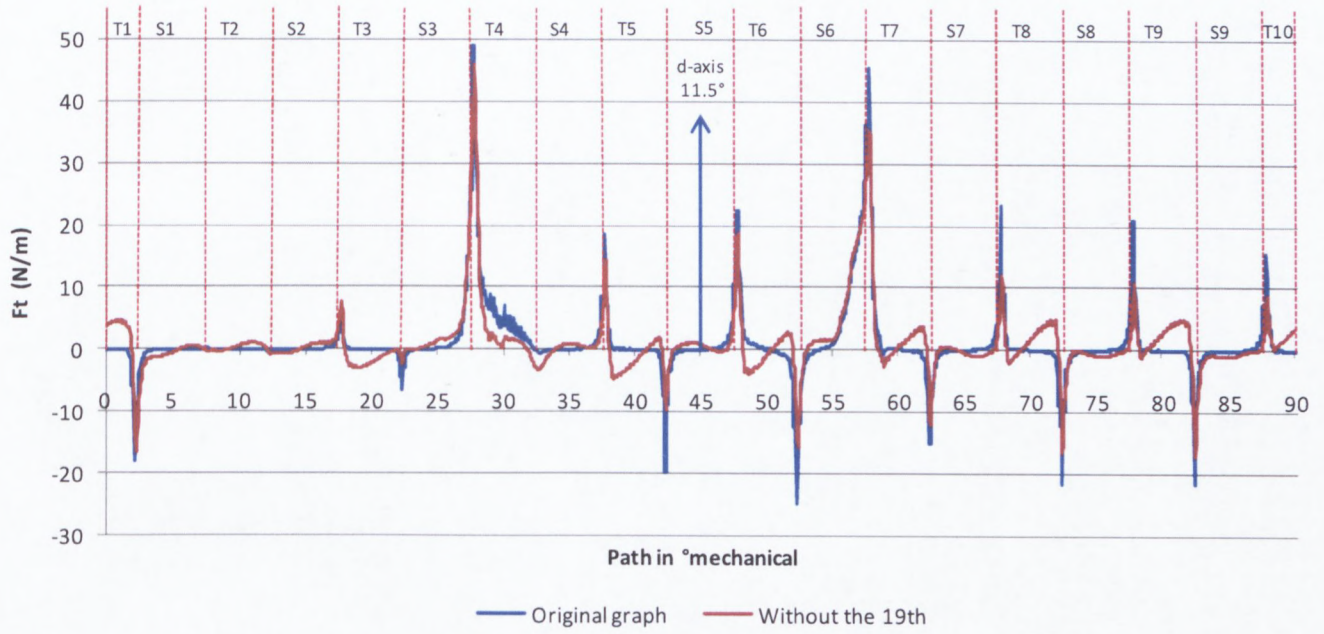


Fig. 4.2.2 F_t without 19th spatial harmonic for the end position

Both graphs show that without the 19th harmonic F_t is reduced in magnitude at the sides of the MSD sections. Overall it can be said that the positions of the dominant forces are determined by the position of the flux barriers and is independent of the harmonics. The same conclusion holds for the positions in between as shown in Fig.4.2.3.

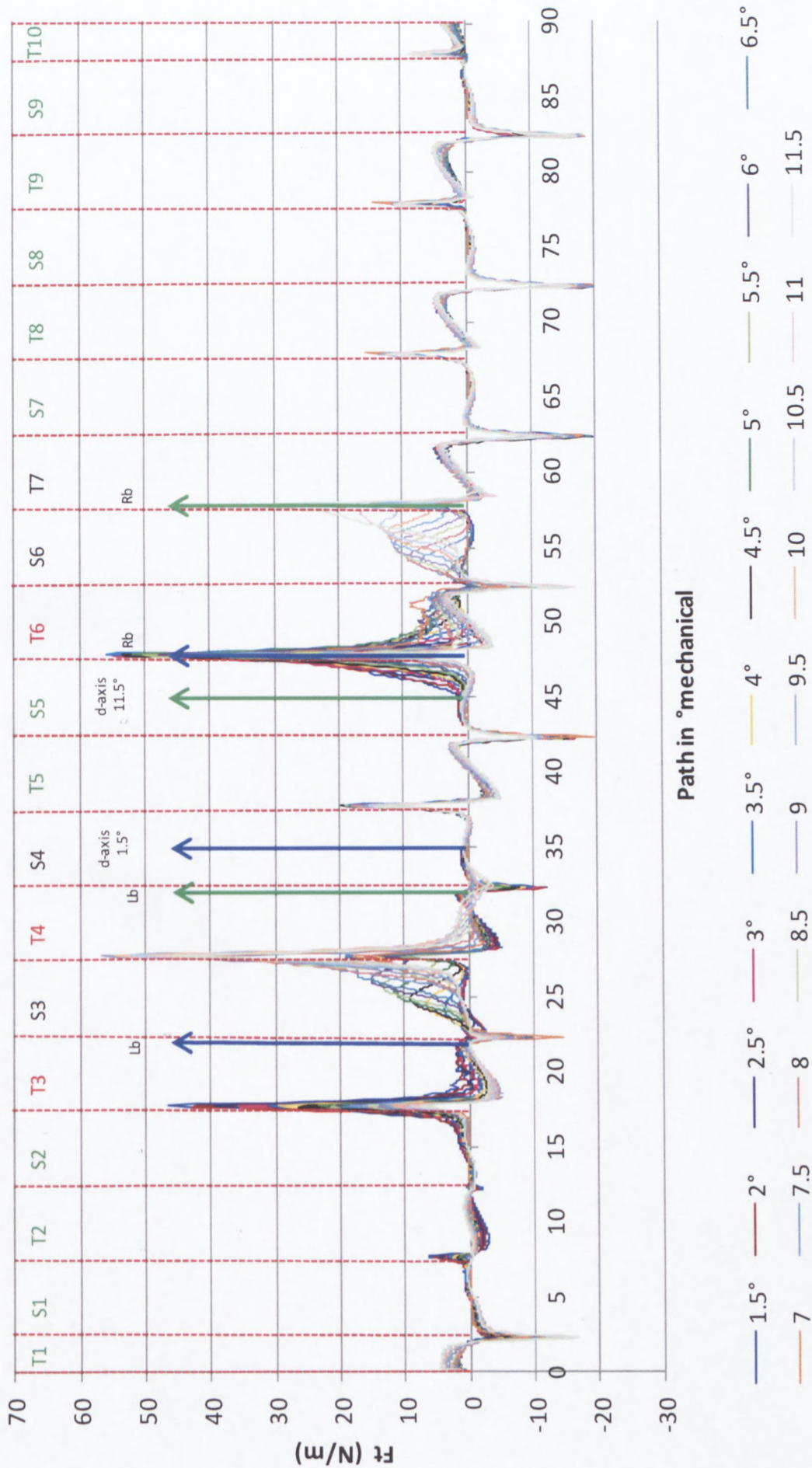


Fig. 4.1.2.3 F_t along the path in the center of the air gap without the presents of the 19th spatial harmonic

4.3 Force contributions of the two MSD sections

For each d-axis position in the slot pitch two MSD sections exist. In this section the force distribution along the two MSD sections are summated and compared to the total summation of the force along the whole path. The contribution in (%) of the two MSD section to the total will be determined for all positions and is shown in Fig. 4.3.1.

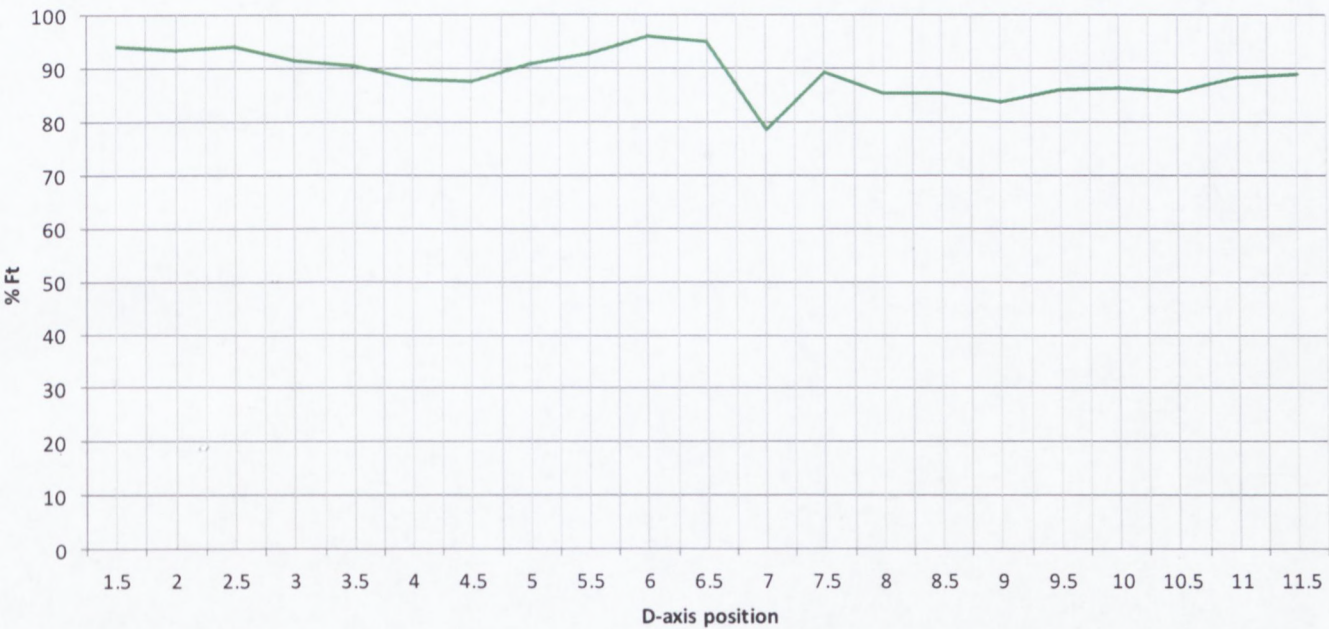


Fig. 4.3.1 MSD force contributions for all d-axis positions

4.4 Summary of findings

The findings of chapter 4 are summarised as follow:

- B_n primarily determines the magnitude of F_t , while B_t determines its shape.
- F_t primarily exists on the edges of the teeth with no or little along the face.
- The instantaneous rotational force on the rotor is only created at the sides of two teeth (two MSD sections) created by the flux barriers.
- Different flux barrier arrangements and the number of flux barriers determine the significance and the number of MSD sections respectively, which in this case produce an average value of 89.1% of the rotational force.

5. Torque analysis in the air gap

In this chapter F_t for each d-axis position within the pole pitch, will be used to calculate the torque at the shaft of the motor. The same calculations will be repeated with the absence of the 19th flux density harmonic. These two output torque graphs will be compared to each other and then be subjected to a Fourier analysis.

5.1 Torque compared to force distribution

The magnitude of the instantaneous tangential torque can be calculated using F_t as obtained from chapter 4 using

$$T_t = r \sum F_t \ell_s \quad (5.1.1)$$

where ℓ_s is the effective stack length and r the radius between the centre of the shaft and the path. Fig. 5.1.1 shows the torque as a function of rotor position.

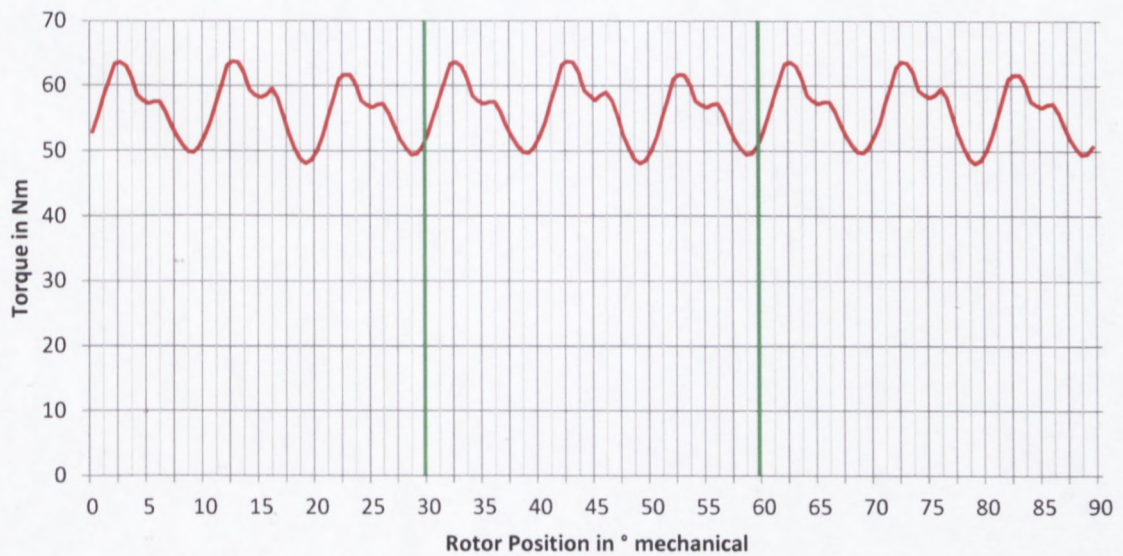


Fig. 5.1.1 T_t as a function of rotor position

According to Fig. 5.1.1 the torque has a periodicity of 30° mech. The torque ripple is equal to 27.92% which is calculated according to (2.1.4.1) in chapter 2. The average torque is equal to 56.11 Nm. From these results it can be seen that the torque ripple is high and is the main disadvantage of the RSM. The torque without the 19th flux density harmonic is shown in Fig. 5.1.2.

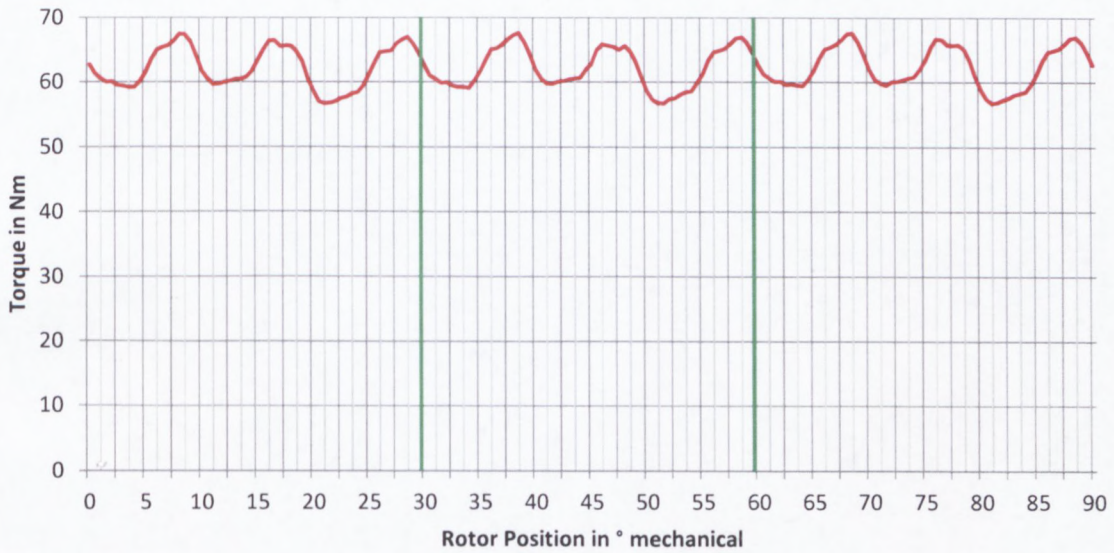


Fig. 5.1.2 T_e without the 19th harmonic as a function of rotor position

The graph has also a periodicity of 30° mech. and a torque ripple of 17.49% and an average torque of 62.21 Nm. Without the 19th flux density harmonic the torque ripple is reduced by 37.36% and the average torque increased by 9.8%. These results pose a significant improvement in the performance of the RSM. However the question is how does this improvement affect the torque harmonics and how can it be implemented practically? The following section will deal with these questions.

5.2 Torque harmonic analysis

In this section the two torque graphs are subjected to a Fourier analysis and shown in Fig. 5.1.3.

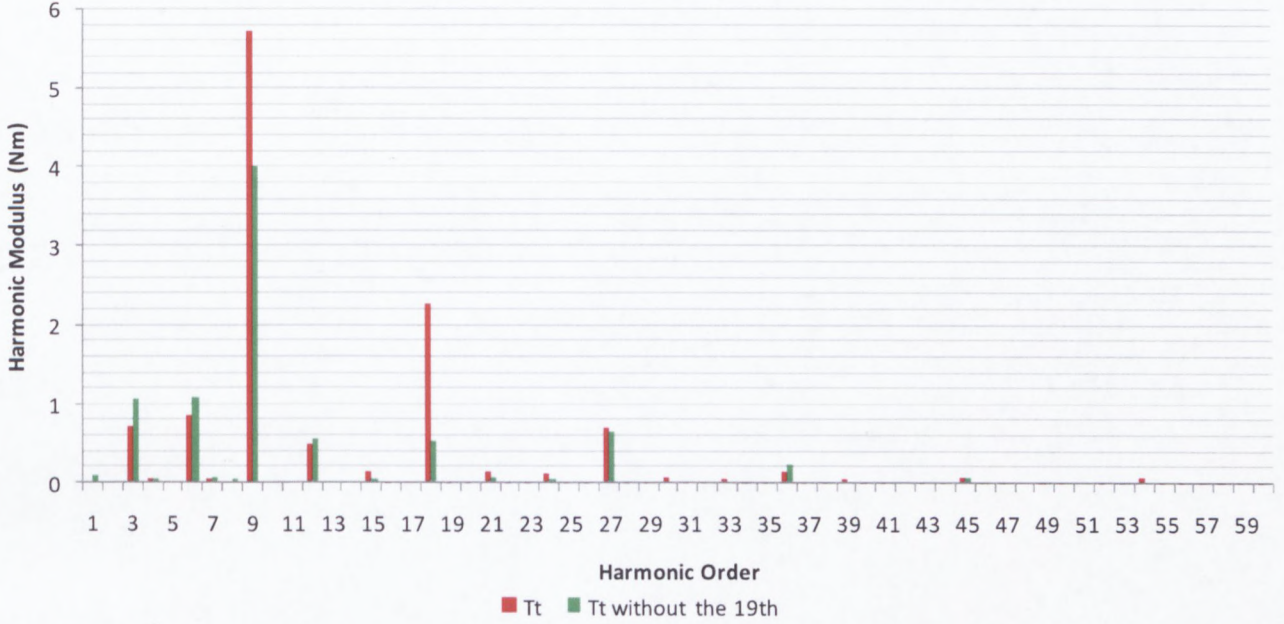


Fig. 5.1.3 Torque harmonic spectrum

It is evident that the dominant torque harmonics are the 9th and 18th harmonic with the 9th being the larger. The reason for this is that a pole pitch of the RSM consists of 9 slots, therefore the 9th and a multiple thereof are the dominant harmonics (Hanekom, 2004). Without the 19th flux density harmonic the 9th torque harmonic is reduced by 30.2% and the 18th by 76.39%.

This is significant improvements and indicates that in order to achieve similar results modifications to the stator will be a good start point. The aim will be to “smoothen” the air gap flux density in order to compensate for the 19th flux density harmonic which has an influence on the 9th torque harmonic which in turn is closely linked to the number of slots. Overall this can be achieved by inserting magnetic wedges in the stator slots as proven by Smith (2010), to change the flux barrier pitch as proven by Hanekom (2006) and to use asymmetrical flux barrier arrangements.

5.3 Summary of findings

The findings of chapter 5 are summarised as follow:

- T_i has an average value of 56 Nm and a torque ripple of 27.92 %.
- T_i determined with the absence of the 19th flux density harmonic has a 9.8 % increase in average torque and a 37.36 % reduction in torque ripple.
- The Fourier analysis on T_i revealed that the dominant harmonics are the 9th and 18th where the 9th is significantly larger than the 18th.
- T_i determined without the 19th flux density harmonic produced a 30.2 % reduction in the 9th torque harmonic and a 76.39 % reduction in the 18th torque harmonic.
- Overall the absence of the 19th flux density harmonic improves the performance of the RSM by reducing the torque ripple and increasing the average torque.

6. Conclusions and Recommendations

In this section all findings from chapter's 3 to 5 will be summarised and recommendations with respect to future research be given.

6.1 Conclusions

The aim of this thesis was to analyse the flux density in the air gap and what effect its harmonics have on the torque produced. The findings of chapter 3 revealed that the flux barriers over the slot pitch distort the flux density in three teeth more than in others which were called the most significant distorted (MSD) sections. These three MSD sections repeat themselves for each slot pitch while shifting through the pole pitch. From Fig.'s 3.1.1.4 and 3.1.3.2 on page 19 and 33 respectively, the left flux barrier has a more significant effect on MSD sections T3 and T4 respectively, while the right flux barrier has a less significant effect on T6, both for normal and tangential components. This indicates that future research into asymmetrical flux barrier arrangements should be done, were asymmetry in the sense of this thesis means that the distances of the flux barriers from the d-axis differ.

Analysing the harmonic content of the flux density revealed that the 19th harmonic had the most significant effect on the MSD sections. The findings of chapter 4 showed that the instantaneous force is created at the sides of two MSD sections and contribute 89.1% to the rotational force and is independent of the harmonic content. Therefore it can be said that the significance of the MSD sections and the number of MSD sections are directly proportional to the average torque of the RSM.

The findings of chapter 5 showed that the torque of the RSM has a high ripple. Without the 19th flux density harmonic the torque ripple was reduced by 37.36 % and the average torque increase by 9.8 %. Without the 19th flux density harmonic the dominant torque harmonics namely the 9th and 18th are reduced by 30.2 % and 76.39 % respectively.

Overall these results indicate that the presence of the 19th flux density harmonic should be eliminated in order to improve average torque and torque ripple of the RSM.

6.2 Recommendations

This thesis revealed that asymmetrical flux barrier arrangements lead to future research. The aim could be to determine the significance of the MSD sections as a function of the degree of asymmetry. The number of flux barriers per pole could also be increased which may increase the number of MSD sections.

This thesis investigated the tangential force component only, i.e. (the normal component which is responsible for noise is neglected). Therefore future research could be done on how the number of MSD sections and flux barriers influence this component.

This thesis showed that the main forces are being created at the edges of the stator teeth (MSD sections). It is therefore recommended to investigate the influence of the slot width to tooth width ratio on the forces created at the sides of the teeth.

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Appendix A

Flux linkage calculation from the vector potential

The vector potential is determined at each node of the RSM model and assumed to vary linearly across each element resulting in constant flux density within each element.

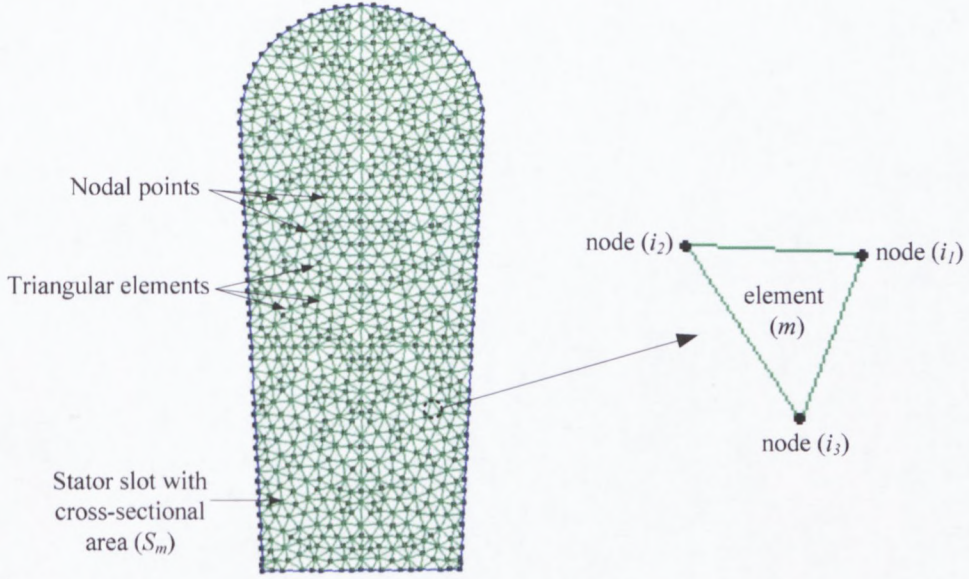


Fig. A.1 Cross-sectional view of a meshed stator slot in the RSM model

Consider the stator slot in Fig. A.1 consisting of a coil with N turns. Let each node in the slot's cross-sectional area S_m be represented as a winding filament. The flux Φ_{mi} , where $i = 1, 2$ or 3 , corresponding to node i of element m is calculated from the product of the vector potential A_{mi} and the effective length ℓ_{mi} of the current filament. Due to the geometry of the RSM model being cylindrical the flux Φ_{mi} is calculated according to (A.1.1)

$$\Phi_{mi} = A_{mi} \cdot 2\pi \cdot r_{mi} \quad (\text{A.1.1})$$

where r_{mi} is the radius of the location of node i of element m . As a result the total flux within element m is calculated by taking the average of the fluxes calculated at the nodal points as shown in (A.1.2).

$$\Phi_m = \frac{1}{3} \sum_{i=1}^3 A_{mi} \cdot 2\pi \cdot r_{mi} \quad (\text{A.1.2})$$

In order to calculate the actual flux linkage of each element the number of turns presented by each element must be known. The number of turns per element is determined from the ratio between the cross-sectional area of the slot S_m , which is described as the sum of all elements, and the element Δ_m itself. Therefore the flux linkage of element m is calculated according to (A.1.3).

$$\lambda_m = N\Phi_m \frac{\Delta_m}{S_m} = N\Phi_m \Delta_m \left/ \sum_{m=1}^M \Delta_m \right. \quad (\text{A.1.3})$$

where M is the number of elements in the mesh region of the slot. From (A.1.2) and (A.1.3) the total flux linkage of the slot region can be calculated according to (A.1.4).

$$\lambda = \sum_{m=1}^M \lambda_m = 2\pi N \left[\left(\sum_{m=1}^M \frac{\Delta_m}{3} \sum_{i=1}^3 A_{mi} r_{mi} \right) \right/ \sum_{m=1}^M \Delta_m \right] \quad (\text{A.1.4})$$

In cylindrical studies the solution potential includes the nodal radius which refers to the part in square brackets and is calculated by the post-processor of the finite element software. This solution is then represented as the total weighted average solution potential (A_{avg}) over the whole slot region shown in (A.1.5).

$$\lambda = 2\pi N A_{avg} \quad (\text{A.1.5})$$

In Cartesian coordinates the flux linkage is expressed as the difference in weighted average vector potential on the "Go" side of the coil (A_{avg+}) and the weighted average vector potential on the "Return" side of the coil (A_{avg-}). The resulting expression for coil to coil flux linkage becomes

$$\lambda = N\ell(A_{avg+} - A_{avg-}) \quad (\text{A.1.6})$$

which is used to calculate a pole phase group of each phase accordingly

$$\lambda_R = N_{ph}\ell[(A_{GoR1+} - A_{GoR1-}) + (A_{GoR2+} - A_{GoR2-}) + (A_{GoR3+} - A_{GoR3-})] \quad (\text{A.1.7})$$

$$\lambda_Y = N_{ph}\ell[(A_{GoY1+} - A_{GoY1-}) + (A_{GoY2+} - A_{GoY2-}) + (A_{GoY3+} - A_{GoY3-})] \quad (\text{A.1.8})$$

$$\lambda_B = -N_{ph}\ell[(A_{ReB1+} - A_{ReB1-}) + (A_{ReB2+} - A_{ReB2-}) + (A_{ReB3+} - A_{ReB3-})] \quad (\text{A.1.9})$$

where N_{ph} is the number of turns per coil, $A_{(GoR1+,GoR2+,GoR3+)}$, $A_{(GoY1+,GoY2+,GoY3+)}$ and $A_{(ReB1+,ReB2+,ReB3+)}$ are the weighted average vector potentials on the “Go” side of the red, yellow and blue phase and, $A_{(GoR1-,GoR2-,GoR3-)}$, $A_{(GoY1-,GoY2-,GoY3-)}$ and $A_{(ReB1-,ReB2-,ReB3-)}$ are weighted average vector potentials on the “Return” side of the red, yellow and blue phase.

Appendix B

Calculation of the current angle

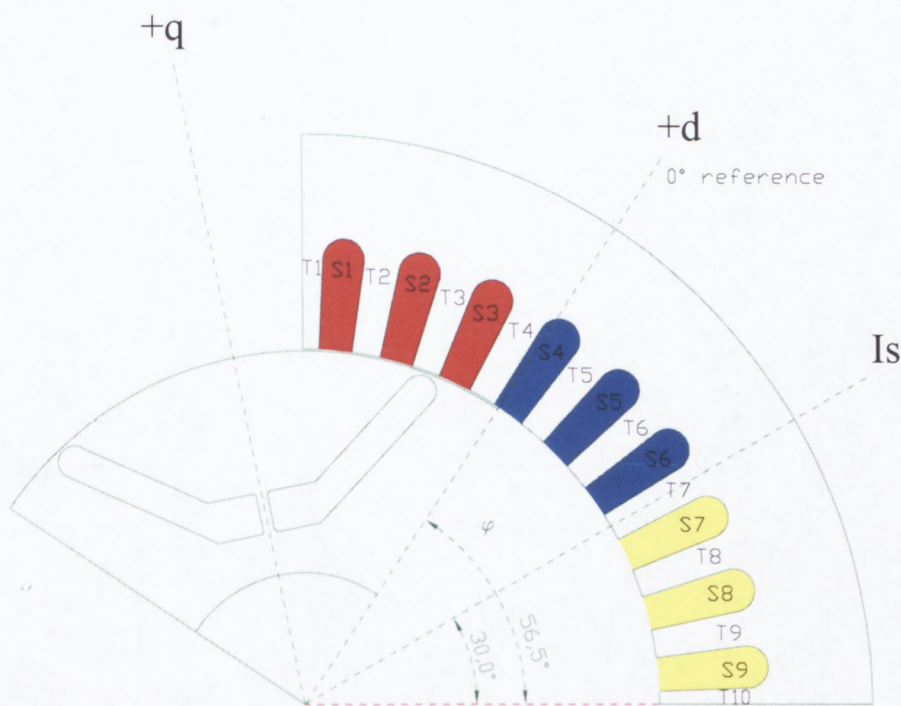


Fig. B.1 Current angle calculation

The rotor of the RSM model is initially shifted by 56.5° mech. mathematically positive from the x-axis as shown in Fig. B.1. At this point in time the current space phasor (Is) is shifted by 30° mech. from the x-axis in the same direction. The current angle (φ) shown in figure B.1 is defined by theory as being the angle between the d-axis of the rotor and Is in ° el. Therefore $\varphi = 56.5^\circ - 30^\circ = 26.5^\circ$ mech. which results in $\varphi = 53^\circ$ el. due to the machine having four poles.

Appendix C

Degree of distortion calculation of B_n

The table C.1 below indicates the degree of distortion of each MSD section for all d-axis position between the start and finish position within a slot pitch.

Table C.1 Distortion calculation of B_n

D-axis position 2°	D_{T3}	D_{T4}	D_{T6}
Original graph	5.12	0.75	1.49
Without the 17 th	-0.06	-4.48	1.95
Without the 19 th	8.97	2.24	1.09
Without the 17 th and the 19 th	3.33	-1.95	1.15
D-axis position 2.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	3.56	0.52	3.39
Without the 17 th	-1.67	-4.25	2.87
Without the 19 th	7.53	2.24	2.12
Without the 17 th and the 19 th	1.95	-1.9	2.07
D-axis position 3°	D_{T3}	D_{T4}	D_{T6}
Original graph	3.74	0.06	2.59
Without the 17 th	-2.76	-4.08	3.28
Without the 19 th	6.55	2.87	2.76
Without the 17 th and the 19 th	1.09	-1.61	2.59
D-axis position 3.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.67	-0.29	4.08
Without the 17 th	-3.91	-3.97	3.39
Without the 19 th	5.52	2.82	3.68
Without the 17 th and the 19 th	0.02	-1.32	3.04

D-axis position 4°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.09	0.11	5.57
Without the 17th	-4.37	-4.31	3.85
Without the 19th	5.75	3.51	4.31
Without the 17th and the 19th	-0.57	-1.49	3.51
D-axis position 4.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.63	0.69	4.37
Without the 17th	-4.94	-4.2	3.79
Without the 19th	5.57	3.74	4.83
Without the 17th and the 19th	-0.69	-1.26	3.56
D-axis position 5°	D_{T3}	D_{T4}	D_{T6}
Original graph	-0.11	-1.32	5.69
Without the 17th	-5.4	-4.9	4.25
Without the 19th	5.86	4.02	5.46
Without the 17th and the 19th	-1.09	-1.49	3.85
D-axis position 5.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.21	-0.46	4.71
Without the 17th	-5.11	-5.02	4.19
Without the 19th	5.23	4.6	5.4
Without the 17th and the 19th	-1.26	-1.95	4.2
D-axis position 6°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.75	0.69	5.5
Without the 17th	-5.92	-5.17	4.02
Without the 19th	6.72	3.05	5.75
Without the 17th and the 19th	-1.44	-1.89	4.08
D-axis position 6.5°	D_{T3}	D_{T4}	D_{T6}

Original graph	0.46	-0.34	5.4
Without the 17 th	-5.63	-4.89	2.87
Without the 19 th	6.89	3.8	5.63
Without the 17 th and the 19 th	-1.09	-1.44	3.73
D-axis position 7°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.49	1.55	2.99
Without the 17 th	-6.21	-3.74	1.72
Without the 19 th	5.29	4.94	4.71
Without the 17 th and the 19 th	-1.38	-0.23	2.24
D-axis position 7.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	-0.11	2.07	3.4
Without the 17 th	-6.11	-2.64	0.86
Without the 19 th	5.10	6.05	3.62
Without the 17 th and the 19 th	-1.49	1.03	1.49
D-axis position 8°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.15	3.97	0.57
Without the 17 th	-5.92	-1.49	0.06
Without the 19 th	4.66	7.59	2.3
Without the 17 th and the 19 th	-1.67	2.18	0.8
D-axis position 8.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	-0.69	4.77	1.49
Without the 17 th	-5.92	-0.63	-0.57
Without the 19 th	4.6	8.51	2.18
Without the 17 th and the 19 th	-1.89	3.1	0.28
D-axis position 9°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.52	5.75	1.78

Without the 17 th	-5.75	0.11	-1.26
Without the 19 th	4.89	9.08	1.95
Without the 17 th and the 19 th	-1.72	3.68	-0.28
D-axis position 9.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.32	7.13	0.11
Without the 17 th	-6.32	0.8	-1.67
Without the 19 th	4.25	9.82	1.89
Without the 17 th and the 19 th	-2.18	4.2	-0.8
D-axis position 10°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.11	7.09	1.44
Without the 17 th	-6.26	1.38	-2.07
Without the 19 th	4.02	10.29	1.55
Without the 17 th and the 19 th	-2.41	4.54	-1.26
D-axis position 10.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.98	7.99	-0.8
Without the 17 th	-6.5	1.32	-1.95
Without the 19 th	4.25	10.69	1.55
Without the 17 th and the 19 th	-2.47	4.66	-1.44
D-axis position 11°	D_{T3}	D_{T4}	D_{T6}
Original graph	0.57	7.99	0.63
Without the 17 th	-6.53	1.78	-2.24
Without the 19 th	3.98	10.86	1.32
Without the 17 th and the 19 th	-2.47	4.83	-1.49

Appendix D

Degree of distortion calculation for B_t

The table D.1 below indicates the degree of distortion of each MSD section for all d-axis position between the start and finish position within a slot pitch.

Table D.1 Distortion calculation of B_t

D-axis position 2°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.78	3.1	6.2
Without the 17 th	1.38	1.89	4.89
Without the 19 th	1.21	1.67	4.6
Without the 17 th and the 19 th	1.49	1.67	4.77
D-axis position 2.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.24	2.82	6.21
Without the 17 th	1.32	1.84	4.77
Without the 19 th	1.15	1.55	4.36
Without the 17 th and the 19 th	1.21	1.83	4.43
D-axis position 3°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.47	3.16	5.75
Without the 17 th	1.84	1.83	4.77
Without the 19 th	1.49	1.61	4.66
Without the 17 th and the 19 th	1.78	1.72	4.77
D-axis position 3.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.76	2.47	5.8
Without the 17 th	2.01	1.72	4.48
Without the 19 th	1.89	1.49	4.31
Without the 17 th and the 19 th	2.38	1.72	4.48

D-axis position 4°	D_{T3}	D_{T4}	D_{T6}
Original graph	3.16	2.93	4.94
Without the 17th	2.3	1.67	3.9
Without the 19th	1.96	1.55	3.79
Without the 17th and the 19th	2.24	1.84	3.97
D-axis position 4.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.75	2.7	5.17
Without the 17th	2.18	1.72	3.68
Without the 19th	1.89	1.67	3.53
Without the 17th and the 19th	1.94	1.84	3.59
D-axis position 5°	D_{T3}	D_{T4}	D_{T6}
Original graph	3.16	2.64	4.66
Without the 17th	2.53	1.69	3.73
Without the 19th	1.55	1.15	3.1
Without the 17th and the 19th	2.55	1.25	3.48
D-axis position 5.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.93	2.99	4.25
Without the 17th	2.75	1.72	3.56
Without the 19th	1.44	1.61	2.64
Without the 17th and the 19th	2.12	1.66	3.22
D-axis position 6°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.99	2.82	3.51
Without the 17th	2.18	2.41	3.39
Without the 19th	1.49	1.95	2.38
Without the 17th and the 19th	2.36	3.16	3.68
D-axis position 6.5°	D_{T3}	D_{T4}	D_{T6}

Original graph	3.1	4.25	3.04
Without the 17th	2.64	3.22	3.1
Without the 19th	1.21	2.84	2.12
Without the 17th and the 19th	1.78	3.03	2.72
D-axis position 7°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.53	4.71	3.56
Without the 17th	2.52	4.09	2.49
Without the 19th	0.83	3.87	0.34
Without the 17th and the 19th	2.35	3.62	2.73
D-axis position 7.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.99	5.05	3.79
Without the 17th	2.75	4.59	3.05
Without the 19th	1.06	3.71	1.97
Without the 17th and the 19th	1.73	4	2.71
D-axis position 8°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.87	4.74	3.51
Without the 17th	2.64	4.28	2.76
Without the 19th	1.15	3.71	1.6
Without the 17th and the 19th	2.18	3.97	2.39
D-axis position 8.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.81	4.64	3.74
Without the 17th	2.3	4.48	3.1
Without the 19th	1.09	3.56	1.31
Without the 17th and the 19th	2.35	3.84	1.86
D-axis position 9°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.7	4.56	3.1

Without the 17th	2.47	4.26	2.54
Without the 19th	1.18	3.09	1.38
Without the 17th and the 19th	2.06	3.33	2.36
D-axis position 9.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.59	3.82	3.62
Without the 17th	2.24	3.64	2.36
Without the 19th	0.8	-0.11	1.69
Without the 17th and the 19th	1.95	3.22	2.53
D-axis position 10°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.47	3.82	3.1
Without the 17th	2.41	3.68	2.59
Without the 19th	0.68	2.29	1.15
Without the 17th and the 19th	1.71	3.16	1.78
D-axis position 10.5°	D_{T3}	D_{T4}	D_{T6}
Original graph	1.89	2.97	3.39
Without the 17th	1.95	2.82	2.07
Without the 19th	0.85	2.07	1.38
Without the 17th and the 19th	1.57	2.64	1.91
D-axis position 11°	D_{T3}	D_{T4}	D_{T6}
Original graph	2.07	3.83	2.35
Without the 17th	1.72	2.39	2.7
Without the 19th	0.92	2.01	1.32
Without the 17th and the 19th	1.89	2.18	1.69

Appendix E

Machine Parameters

The table E.1 below shows the machine parameters of the modelled RSM.

Table E.1 Machine Parameters

Frame	D 132S
Class Insulation	B
Power Rating	7.5 kW
Current	16A full load
Phases	3
Poles	4
Frequency	50Hz
Number of slots	36
Pole pitch	9 slots
Winding	Concentric
No. of coils	18
Connection	Delta
Chording factor	1
Slots per pole phase group	3
Stator iron O/D	203.2mm
Stator I/D	126.98mm
Rotor D	126.3mm
Stack length	133.4mm
Air gap	0.34mm
Skew	None

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