

Symmetrical windings

Design and analysis of stator windings

Version 0.0.1

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Chapter 1

Introduction

Analysis of electrical machines is a very well-known subject in electrical engineering and at a first glance one might think that this field cannot be embarked on any further. However, this is not the case, since advances in materials such as permanent magnets offer new possibilities which might not have been economical a few years ago. In addition to the development of the materials used in electrical machines, the mathematical and physics software tools for solving complex problems and the visualisation of the results have also improved. Furthermore, the technologies driving the microprocessors and storage devices used in personal computers have contributed to solve difficult mathematical functions by means of numerical methods. All these factors have influenced the way electrical machines are designed and will be designed in the future. The research presented in this book is a typical example of how advances in other fields can lead to new ideas in electrical engineering, and especially electrical machines.

1.1 Problem statement

Designing the winding is from an electromagnetic point of view the most important part in machine design. In this step the coil sides of the phases need to be assigned to an appropriate stator slot which allows a rotating magnetic field when phase displaced currents are applied to the winding. Once the assignment is done, adjacent coil sides belonging to the same phase are called a phase belt. This is the definition used in modern textbooks such as that written by [1] and was already in use in early papers by [2].

In order to design symmetrical windings, it is necessary to have a systematic algorithm to allocate the slots. Then, after doing this, the coils can be inserted in the appropriate slots. The immediate and essential main question that first needs to be answered is:

What is the mathematical expression to allocate the stator slots belonging to a phase belt?

Another sub-question arises from the requirement to allocate the slots that belong to a phase belt. Especially when using FEM to analyse machines, the entering of the winding arrangement is a

complex process. The problem is exacerbated if different winding types are to be analysed. Furthermore, in the conceptual design phase a compact representation of the winding could simplify the choice of the initial geometrical parameters. Therefore the sub-question is:

How can a winding layout be represented in a compact form?

1.2 Overlapping and non-overlapping windings

Fig. 1.1(a) shows a double layer overlapping winding. In the drawing some of the coils are removed which makes it easier to identify the two layers. In (b) a non-overlapping single layer winding is shown. Only each second stator tooth has a coil wound around it.

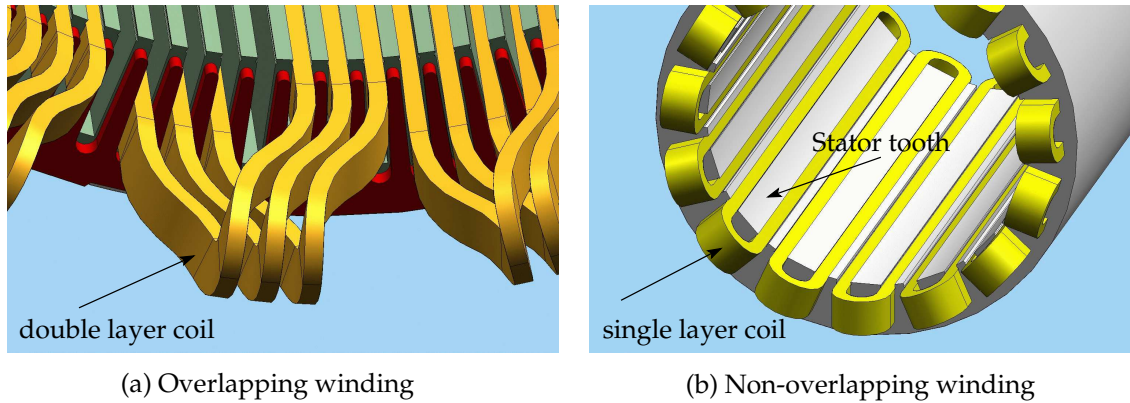


Figure 1.1: Double layer overlapping and single layer non-overlapping windings

Non-overlapping windings are a sub-set of fractional slot windings and need some extra discussion. It is often categorised as concentrated. This is not necessarily wrong but is incongruent with the formal definition. The opposite of a concentrated winding is a distributed winding. In the latter case a the coils of a given phase are distributed in several slots. When referring to overlapping and non-overlapping windings a concentrated winding could be defined as follows:

1. Formally a concentrated winding is one where the number of slots per pole and phase equals one. In this case the coil pitch equals the pole pitch and it is categorised as overlapping. This means that each coil side of the winding is placed in a single slot. If the coil spans a pole pitch, it is called a full-pitch concentrated winding.
2. Non-overlapping could also be classified as concentrated, but then it is not done in terms of the formal definition. Concentrated in this case means that a coil is concentrated around a stator tooth as shown in Fig. 1.1(b).

A simplified illustration of single and double layer non-overlapping windings¹ is shown in Fig. 1.2 and the difference between them is given in Tab. 1.1. For the purposes of the present dissertation a double layer winding is defined as follows:

¹In German these winding types are commonly referred to as “Zahnspulen” which means “tooth coils”. Although tooth coils seem to be a very descriptive name for these windings, it is often called “concentrated coils” in the literature.

Definition 1.2.1. A double layer winding has two coil sides per stator slot. “Double layer” in the case of overlapping windings means that the coil sides in a slot are placed radially in two layers. In the case of non-overlapping windings a “double layer” winding has two coil sides side by side.

Table 1.1: Difference between single and double layer windings

Single layer	Double layer
In the case of the single layer winding each stator slot has only one coil side assigned to it as shown in Fig. 1.2(a).	A double layer winding has two coil sides assigned to a stator slot as shown in Fig. 1.2(b).

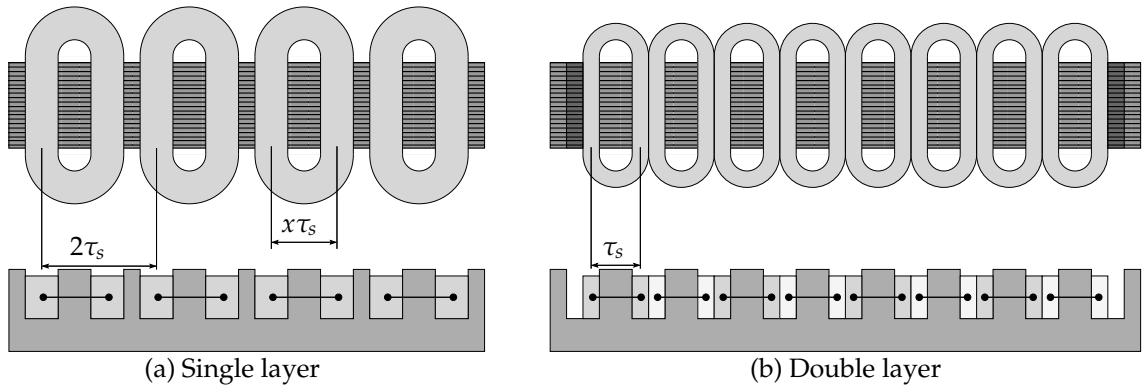


Figure 1.2: Double and single layer non-overlapping windings

In the literature different definitions of terms are in use for non-overlapping concentrated windings. The most common of them are:

- [3]: concentrated windings;
- [4]: concentrated fractional pitch windings;
- [5]: fractional slot wound; and
- [6]: fractional slot.

If the coils are to be equally in shape, which simplifies manufacturing, it is recognised that a single layer could easily have a variable slot pitch². Furthermore, the coils could be implemented as either form-wound or round-wound. Returning to the variable coil pitch of the single layer, it is important to mention that this is an extra degree of freedom that offers to be an attractive design parameter. The air gap flux that links the coil could thus be increased and torque ripple can be improved.

It is therefore helpful to classify a concentrated winding either as an overlapping or non-overlapping concentrated winding. [7] certainly aroused interest in non-overlapping concentrated windings with their paper entitled “Synthesis of High Performance PM Motors With Concentrated Windings”, since this is a paper which is very often used as a reference on these winding

²The concept of a variable coil pitch is explained in chapter ?? . Also refer to Fig. 3.1 for regular and irregular distributed slots.

types. This could be a possible explanation for the use of the term “concentrated windings” rather than “tooth coil windings”.

The expansion of the classical winding types used in machines by non-overlapping windings offers new possibilities in especially traction machine design. The main research question in section 1.1 suggests a design algorithm that takes into account the non-overlapping type. Obviously a method that is valid for all types is required. In addition, it should be easy to integrate into whichever process is in use.

1.3 Notes to the reader

The work presented in this thesis was done in N  ijrnberg, Germany. Consequently many of the literature used were in German. To name only a few, books by [8], [9] and [10] are still commonly used in design offices. It is noticeable that even though there exists a list of symbols for various quantities, English and German have in some cases different symbols for the same quantity. This is mainly due to the fact that languages develop individual and of course colloquial language rules. Even a direct translation does not necessarily give the typical word used. An example is the German word *Felderregerkurve*. A direct translation would be “field excitation curve”, which of course is not wrong. However, the field excitation curve in electrical terms is usually known as the “magnetomotive force” (mmf). Tab. 1.2 gives some common electrical machine quantities in English and German, and the different symbols in use.

Table 1.2: Typical machine quantities, there German translation and counterpart symbols

Quantity	English	German	Unit
magnetomotive force (<i>Durchflutung</i>)	F	Θ	A
flux linkage (<i>Flussverkettung</i>)	λ	ψ	V·s
voltage (<i>Spannung</i>)	V	U	V
specific resistance (<i>spezifischer Widerstand</i>)	ρ	ϱ	$\Omega\cdot\text{m}$
specific weight (<i>spezifischer Masse</i>)	ρ	γ	$\text{kg}\cdot\text{m}^{-3}$
conductivity (<i>Leitf��higkeit</i>)	σ	κ	$\text{S}\cdot\text{m}^{-1}$
cross section area (<i>Querschnitt</i>)	A	Q	m^2
turn number (<i>Windungszahl</i>)	N	W	-

It is commendable that the German terminology on electrical machines allows a very precise description of almost all aspects related to the subject. In many cases it is difficult to find an equivalent technical term in English, because it simply does not exist. The problem of different terminologies even exists within a language: different “schools” use different terms which makes the study of machine related books not easy. Also historical changes need to be kept in mind.

The term “machine” as used in the present dissertation means it could be a machine that is operated either as a motor or as a generator. In the title the term “motor” is used, since only the measured results of motor operation are presented. However, in the theoretical sections, the word “machine” is preferred.

The document is optimised for a two-sided printout. A flip-book shows that the fundamental and fifth harmonic of the mmf rotate in the opposite direction.

1.4 Design program

A Matlab script that implements the algorithm in Fig. 3.2 is used to plot the examples given in Tab. 3.3. The complete program listings are given in A and B. Start the script by typing from the Matlab prompt:

```
wnd = arun(1);
```

The resulting plots are shown in Fig. B.1 and the Matlab code is provided in appendix B.

Chapter 2

Classification of symmetrical windings

This report¹ is devoted to a derivation of an algorithmic method to design m -phase symmetrical windings and a representation thereof in a compact form. The basic principle of the winding of an electrical machine is to obtain a rotating magnetic field in the stator (the stationary part) that interacts with the moving part (the rotor). This is achieved by arranging the coils of the winding in the stator slots around the air gap periphery in such a way that a rotating field is developed when applying currents. As a result the induced voltage, which arises from flux per pole $\hat{\Phi}$, is obtained from Faraday's law. In general the sinusoidally induced voltage for a winding having N_s series turns per phase is

$$U_i = \sqrt{2}\pi f_1 \zeta_p N_s \hat{\Phi}, \quad \zeta_p \leq 1 \quad (2.1)$$

where ζ_p is the winding factor of the *working harmonic*. The induced voltage in (2.1) brings the importance of the winding design to the fore. For a given design requirement, it is desirable to have ζ_p as high as possible.

2.1 Definition of the working harmonic

Throughout the analysis all harmonics are referred to in terms of the bore 2π of the machine, i.e. the *fundamental harmonic* has the order $\nu = 1$ and forms one pole pair. The harmonic that produces the magnetic field that interacts with the rotor poles $2p$ has the order $\nu = p$ and is called the *working harmonic*. Any other harmonic of the ν^{th} order will have ν pole pairs and spans a peripheral angle of $\frac{2\pi}{\nu}$.

Often the harmonic orders are normalised with respect to the *working harmonic*, i.e. $\zeta_{\nu/p}$. This then means that the *working harmonic* is written as ζ_1 and sub-harmonics will have a fraction as subscript. This notation will not be used in this report.

¹Text taken from [11].

2.2 Basic winding properties

The winding design can be quite a difficult task and at this point it is useful to have a coarse classification of symmetrical windings. Since symmetrical windings comprise such a great variety, an attempt to categorise them will depend on the properties by which they are to be sorted.

2.2.1 Slots and coils per pole and phase

Any m -phase winding could be characterised by its number of slots per pole and phase. However, when comparing different winding designs with each other this number alone is insufficient. It does not take into account the number of layers the winding has. In addition, the number of coils per pole and phase should be defined. For a machine with Q_s stator slots, p pole pairs and m phases the following definitions holds:

Definition 2.2.1. *Slots per pole and phase:*

$$q = \frac{Q_s}{m2p} = \frac{q_n}{q_d} \quad (2.2)$$

$\frac{q_n}{q_d}$ is the reduced form of q . Each phase has q_n slots that are distributed over q_d poles. In the case where q_d equals one, q is an integer and the winding is called an integer slot winding. When q_d is greater than one, it is called a fractional slot winding.

Definition 2.2.2. *Coils per pole and phase:*

$$q_c = \frac{Q_c}{m2p} = \frac{q_{c_n}}{q_{c_d}} \quad (2.3)$$

$\frac{q_{c_n}}{q_{c_d}}$ is the reduced form of q_c . Each phase has q_{c_n} coils distributed over q_{c_d} poles. If q_{c_n} is greater than one and q_c is not equal to one it is a distributed winding.

These characteristic numbers give useful information on the winding when they are written as a reduced improper fraction². Additionally, the properties of single and double layer windings are summarised in Tab. 2.1.

Table 2.1: Winding properties

single layer winding	double layer winding
$q = 2q_c$	$q = q_c$
$Q_s = 2Q_c$	$Q_s = Q_c$

2.2.2 Average coil pitch

The coil pitch is defined as the peripheral angle between the two coil sides. It is practical to express the coil pitch in terms of the number of slots. Therefore, it is an integer number.

²The reduced fraction could be either a proper or an improper fraction. An improper fraction has the numerator greater than the denominator.

Definition 2.2.3. *The average coil pitch is defined as*

$$y_p = \frac{Q_s}{2p} \quad (2.4)$$

and the implemented coil pitch is given by

$$y_d = \text{int}(y_p) \pm k \quad \begin{cases} k \in \mathbb{N} \\ y_d \geq 1 \end{cases} \quad (2.5)$$

In the case where $y_d = y_p$ it is a full-pitch winding. If $y_d \neq y_p$ it is called a fractional pitch winding.

2.2.3 Classification scheme

The aim of the classification scheme is to find a way to relate different winding types to each other. It is also a useful guideline to compare windings that belong to the same category. For the design methodology offered in this report, the following winding parameters are chosen for the classification:

1. the reduced form of the number of coils per pole per phase;
2. the average coil pitch; and
3. the number of layers.

Tab. 2.2 shows a possible way to classify symmetrical m -phase windings. The reason for choosing the average coil pitch as a second property arises from the construction of the coils and it is valid for all types of windings. It could be seen as the ideal coil pitch. Additionally, the number of layers is a key parameter since the technology for manufacturing and the material used in single layer windings are different from that used in double layer windings. Using this classification scheme, the following definitions are associated with windings:

Distributed winding: If the numerator q_{cn} of q_c is greater than one, the winding is distributed. This means that the coil sides are distributed over q_{cn} slots. The opposite of a distributed winding is a concentrated winding.

Concentrated winding: In the case where q_{cn} equals one, it is called a concentrated winding.

Concentrated coil: When y_d equals one, it is a concentrated coil. In this case the coil is concentrated around a stator tooth. a concentrated winding.

Single and double layer: These windings are differentiated by the number of coils compared to the number of stator slots. In single layer windings the number of coils equals half the number of stator slots, while for double layer windings the number of coils is equal to the number of stator slots. In the present dissertation a double layer winding has two coil sides per slot which could be placed radially in two layers or side by side.

Overlapping and non-overlapping: In overlapping windings the coils overlap and the coil pitch y_d is greater than one. If the coil pitch y_d equals one, the coils do not overlap.

Integral slot winding: If the denominator q_d equals one, the phase belt has q_n slots over one pole.

Fractional slot: The denominator of q is greater than one. This means that the q_n slots are distributed over q_d poles. In addition, the average coil pitch y_p is a fraction.

Table 2.2: Classification of symmetrical windings

Parameter	Constraint	Classification
Q_c	$\frac{1}{2}Q_s$	single layer
	Q_s	double layer
y_d	$= 1$	non-overlapping
	> 1	overlapping
y_d	$= y_p$	full-pitch
	$\neq y_p$	fractional pitch
q_d	$= 1$	integral slot
	> 1	fractional slot
q_{c_n}	$= 1$	concentrated
	> 1	distributed

It is important to distinguish between a concentrated winding and a concentrated coil. The classification scheme in Fig. 2.2 defines a concentrated winding in a unique way. Concentrated windings are defined differently in literature. [12] refers to it as a traditional single layer winding whereas [3] refers to it as distributed.

Particularly the windings defined as a fractional slot are very attractive for use in permanent magnet synchronous machines. Especially the single layer non-overlapping winding could be used to reduce

- manufacturing costs compared to overlapping windings;
- the end winding losses;
- torque ripple; and
- the mutual coupling between the phases.

2.3 Characteristics of symmetrical windings

This section contains the major properties by which symmetrical m -phase windings are characterised.

2.3.1 Basic winding

Definition 2.3.1. *The smallest repetitive segment is called the basic winding (German: “Urwicklung”).*

Due to symmetry only the basic winding needs to be determined. If q_d is less than p the winding is composed of t identical *basic windings*, i.e.

$$t = \begin{cases} \gcd(Q_s, p) & \text{for double layer} \\ \gcd\left(\frac{Q_s}{2}, p\right) & \text{for single layer} \end{cases} \quad (2.6)$$

and gcd is called the greatest common divisor. In the case where $t = 1$ the winding has no symmetry. Each of the t *basic windings* will have Q_b slots and p_b pole pairs, therefore

$$Q_b = \frac{Q_s}{t} \quad \text{and} \quad p_b = \frac{p}{t} \quad (2.7)$$

The number p_b is the reduced pole pair. Another way of obtaining this number is by means of the denominator of q_c , i.e.

$$p_b = \begin{cases} \frac{1}{2}q_{c_d} & q_{c_d} \text{ even} \\ q_{c_d} & q_{c_d} \text{ odd} \end{cases} \quad (2.8)$$

which is independent of t . Examining (2.6), it is recognised that t can be rewritten as the gcd between the number of coils and the pole pairs, i.e.

$$t = \gcd(Q_c, p) \quad \begin{cases} Q_c = Q_s & \text{double layer} \\ Q_c = \frac{1}{2}Q_s & \text{single layer} \end{cases} \quad (2.9)$$

which is valid for both single and double layer windings. Although t is usually used as a variable for time it is commonly found in literature and will be used in the same way throughout this chapter. Since the winding design is independent of time, it does not cause any confusion.

It is favourable to use the terms “in and out going coil sides”³. Only the in going coil side needs to be assigned⁴ since the out going coil side is given by the coil pitch and type of winding.

2.3.2 Winding symmetry

For a winding to be symmetrical the number of coils used in each of the phases must be equal. Therefore the quotient between Q_c and m must be an integer. A requirement for a winding to be symmetrical can be derived from (2.7). The symmetry condition can be expressed as

$$\frac{Q_s}{t} = mk, \quad k \in \mathbb{N} \quad (2.10)$$

which relates the pole number, number of stator slots and phase number to each other. A very useful function employed in the method is the modulo function which finds the remainder after division, i.e. $\text{mod}(a, b) = a - \text{floor}\left(\frac{a}{b}\right)b$ ⁵. When using the modulo function it means that $\text{mod}\left(\frac{Q_s}{t}, m\right)$ must equal zero. There are different ways of deriving the constraints for the winding symmetry condition. Tab. 2.3 gives different variations found in the literature to express the symmetry condition.

³This is similar to the current which is defined as into and out of the page.

⁴The use of coil sides are preferred above coils, since it is then independent whether the coil sides belong to the same coil or not.

⁵The floor function of a real number x , $\text{floor}(x)$, is a function whose value is the largest integer less than or equal to x .

Table 2.3: Constraints for symmetry

Reference	Constraint
[13]	$\gcd(q_{c_d}, m) = 1$ $\text{mod}(\frac{Q_c}{q_{c_n}} q_{c_d}, m) = 0$
[14]	$\text{mod}(\frac{Q_s}{\gcd(Q_s, 2p)}, m) = 0$
[15]	$\text{mod}(\frac{Q_s}{t}, m) = 0$

2.3.3 Reduced number of pole pairs

The lowest harmonic generated by a winding is given by $t = \gcd(Q_c, p)$ and the working harmonic equals p . The reduced pole number gives information on the sub-harmonics which are summarised as follows:

$$\begin{aligned} t &= p && \text{the winding has no sub-harmonics} \\ t &< p && \text{the winding has sub-harmonics} \end{aligned} \quad (2.11)$$

The reduced number of pole pairs can be calculated in two different ways. Two greatest common divisors, i.e. $\gcd(Q_c, 2m p)$ and $\gcd(Q_c, p)$, are used to get q_{c_d} and p_b respectively. The relationship between these two factors is as follows:

$$\gcd(Q_c, p) = \frac{\gcd(Q_c, 2m p)}{r} \quad \text{where} \quad r = \begin{cases} m & q_{c_d} \text{ even} \\ 2m & q_{c_d} \text{ odd} \end{cases} \quad (2.12)$$

2.4 Rotating mmf

Distributing the coils around the air gap periphery firstly requires the winding characteristic as explained in section 2.2.1 and secondly a constraint assuring that the coils are assigned uniquely to the stator slots. Deriving such a constraint is done by means of the magnetomotive force (mmf) produced by a winding.

In the theory of three-phase windings the rotating magnetic field is derived from a single coil with N_t -turns. The mmf produced by the coil is then written as a Fourier series which allows it to be decomposed in the *working harmonic*, higher order harmonics and sub-harmonics if applicable. A detailed mathematical derivation is given by [16]. It is also possible to explain the decomposition by means of visualisation as shown in [8], [10] and [1]. The visualisation method is preferred and is used in the next sections in order to define the mmf envelope functions. This is necessary to answer the research sub-question which is the mathematical expression that defines a phase belt.

2.4.1 The mmf of a single turn coil

Consider a single coil with N_t -turns carrying a current i placed in the stator of a machine with a uniform air gap as shown in Fig. 2.1(a). Assuming an infinite permeability in the laminated parts,

the mmf in the stator and rotor can be neglected. This means the mmf across the air gap will be equal to the total mmf.

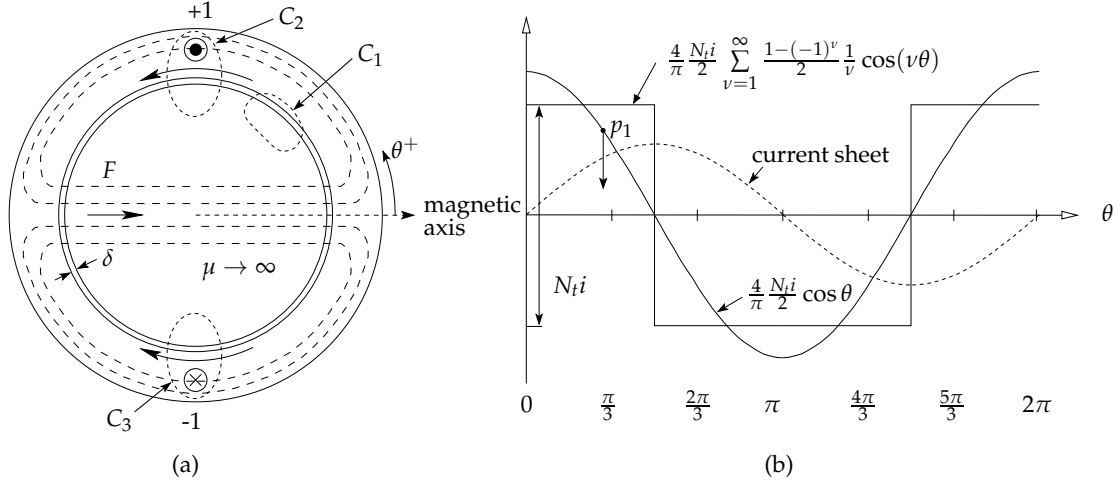


Figure 2.1: Spatial mmf distribution for a N_t -turn coil

The spatial mmf distribution around the air gap periphery is obtained by applying Ampère's law to the contours C_1 , C_2 and C_3 . The results of the integration are given in (2.13). The integral along C_1 is zero since the contour does not enclose any source. Contrary to this the integrals along C_2 and C_3 equal $N_t i$ and $-N_t i$ respectively. The current in coil side +1 is positive, and using the right hand rule, out of the page.

$$\oint \vec{H} \cdot d\vec{l} = \begin{cases} 0 & C_1 & 0 \leq \theta < \frac{\pi}{2} & \Rightarrow H(0) = H(\theta_1) \\ N_t i & C_2 & \frac{\pi}{2} \leq \theta < \frac{3\pi}{2} & \Rightarrow H(0) - H(\theta_2) = \frac{N_t i}{\delta} \\ -N_t i & C_3 & \frac{3\pi}{2} \leq \theta < \frac{5\pi}{2} & \Rightarrow H(0) - H(\theta_3) = \frac{N_t i}{\delta} \end{cases} \quad (2.13)$$

Since the flux to and from the rotor are equal, the air gap mmf will have an amplitude of $\frac{N_t i}{2}$. Fig. 2.1(b) shows the spatial of the single coil. This is a square wave and from the Fourier series the fundamental has an amplitude of $\frac{4}{\pi}$. The fundamental mmf can be seen as the result of a sinusoidally distributed current sheet on the stator inner diameter. When the coil is supplied by a current

$$i = \hat{I} \cos \omega t \quad (2.14)$$

any point on the mmf will have a vertical trajectory. For example, the point p_1 will start moving downward for t^+ until it reaches a minimum from where it will start to move upwards again. Applying a sinusoidal current to the coil results in a standing wave in the air gap. The spatial mmf distribution has the form

$$F(\theta, t) = \frac{4}{\pi} \frac{N_t}{2} \cos \theta (\hat{I} \cos \omega t) \quad (2.15)$$

and will have nodes at $\frac{\pi}{2}$ and $\frac{3\pi}{2}$ while the anti-nodes will be at 0 and π . Using a trigonometrical

identity⁶ (2.15) can be rewritten as the superposition of two rotating waves

$$\begin{aligned} F(\theta, t) &= \frac{1}{2} \frac{4}{\pi} \frac{N_t}{2} \hat{I} \cos(\theta - \omega t) + \frac{1}{2} \frac{4}{\pi} \frac{N_t}{2} \hat{I} \cos(\theta + \omega t) \\ &= F^+ + F^- \end{aligned} \quad (2.16)$$

The result in (2.16) means that a single coil produces two opposite rotating mmf waves in the air gap. In the next section this result is used to produce a single rotating mmf by displacing different coils in space.

2.4.2 The mmf of three single turn coils

Producing a single rotating mmf wave using three coils means that each of the spatial mmf distribution functions must have a displacement for both the spatial and time component. Using (2.16), the resultant mmf for three coils will have the following form, i.e.

$$\begin{aligned} F_R(\theta, t) &= (F_1^+ + F_1^-) + (F_2^+ + F_2^-) + (F_3^+ + F_3^-) \\ &= (F_1^+ + F_2^+ + F_3^+) + (F_1^- + F_2^- + F_3^-) \\ &= \sum_{n=1}^3 F_n^+ + \sum_{n=1}^3 F_n^- \end{aligned} \quad (2.17)$$

In general, choosing an angle of $\frac{2\pi}{m}$ between two adjacent positive coil sides will cause the negative waves to be cancelled. Thus, the positive waves are added together; this results in a single rotating wave. For m -phases the functions defined by

$$F_n(\theta, t) = \hat{F}_n \cos \left[\theta + \frac{2\pi(n-1)}{m} \right] \cos \left[\omega t + \frac{2\pi(n-1)}{m} \right], \quad 1 \leq n \leq m \quad (2.18)$$

will produce a rotating wave when supplied by three-phase currents that is phase shifted by $\frac{2\pi}{m}$ radians. Setting $m = 1$ in (2.18) will be the same as (2.15). The summation of m functions given in (2.18) simplifies to a single rotating mmf in the air gap. Using the trigonometric identity the resultant air gap mmf is

$$\begin{aligned} F_R(\theta, t) &= \sum_{n=1}^m \hat{F}_n \cos \left[\theta + \frac{2\pi(n-1)}{m} \right] \cos \left[\omega t + \frac{2\pi(n-1)}{m} \right] \\ &= \frac{1}{2} \sum_{n=1}^m \hat{F}_n \cos(\theta - \omega t) + \frac{1}{2} \sum_{n=1}^m \hat{F}_n \cos \left[\theta + \omega t + \frac{4\pi(n-1)}{m} \right] \\ &= \frac{m}{2} \hat{F}_1 \cos(\theta - \omega t) \end{aligned} \quad (2.19)$$

Therefore, the effect of displacing the positive coil sides of m -coils by $\frac{2\pi}{m}$ radians results in a single rotating mmf wave in the air gap which is $\frac{m}{2}$ times that of the first coil.

The preceding explanation of the rotating mmf wave is graphically shown in Fig. 2.2(a). Therefore, starting with a single coil as in Fig. 2.1(a) means it is necessary to add two more coils. Using the positive coil side of +1 as reference, the adjacent positive coil side +2 is placed at $-\frac{2\pi}{3}$ radians

⁶ $\cos A \cos B = \frac{1}{2} \cos(A - B) + \frac{1}{2} \cos(A + B)$

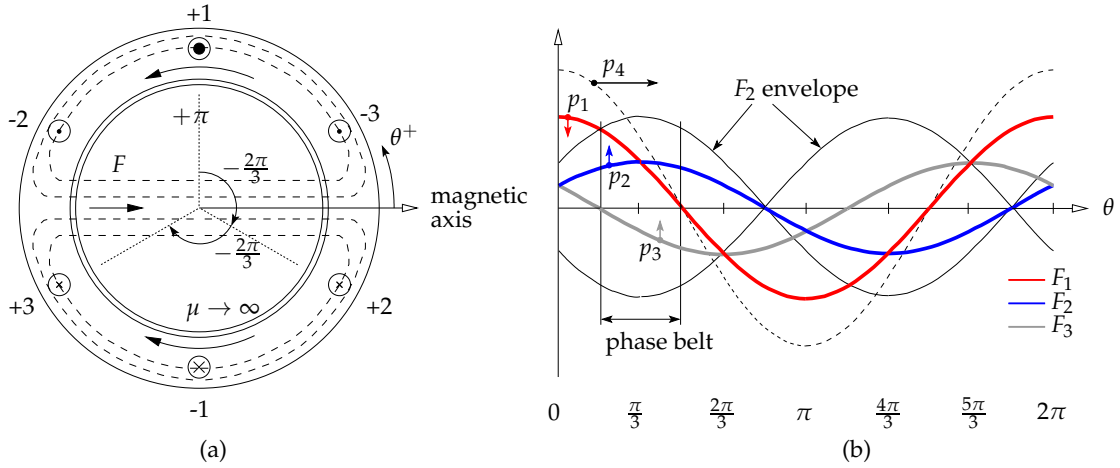


Figure 2.2: The fundamental spatial mmf distribution for a three-phase machine

clockwise from +1. Next, with +2 as reference the next adjacent positive coil side is $-\frac{2\pi}{3}$ radians clockwise from +2. The returning coil sides of both coils is displaced at $+\pi$ electrical radians in space. Since the resultant mmf wave is rotating in a positive direction the sequence⁷ will be

$$\{+1, -2, +3, -1, +2, -3\} \quad (2.20)$$

Fig. 2.2(b) shows graphically the mmf's of the three coils with N_t -turns. These are obtained by setting $m = 3$ and applying the following three-phase currents

$$\begin{aligned} i_1 &= \hat{I} \cos(\omega t) \\ i_2 &= \hat{I} \cos\left(\omega t + \frac{2\pi}{3}\right) \\ i_3 &= \hat{I} \cos\left(\omega t + \frac{4\pi}{3}\right) \end{aligned} \quad (2.21)$$

to the functions in (2.18). The resultant mmf will rotate in a counterclockwise direction. At $t = 0$ $i_2 = i_3 = -\frac{1}{2}i_1$, meaning the mmf of F_2 and F_3 will be half of F_1 . As time starts to increase, any point on F_1 will move downward while points on F_2 and F_3 will start moving in an upward direction. The points are marked p_1 through p_3 in the figure. Contrary to this, any point on the resultant mmf will start moving in the right direction (counter-clockwise) as indicated by point p_4 . As time increases the resultant mmf rotates as shown in Fig. 2.3. The fundamental mmf is shown at time equal to zero and a time instant $t = t_1$.

2.4.3 Definition of the mmf envelope functions

As time continues, any point on the standing wave will have a minimum and maximum value between which it oscillates. If p_2 is used as an example, it will be bounded as shown in Fig. 2.2(b),

⁷The direction of placing the positive coil sides and the returning coil sides is arbitrary. When the convention as explained is used, it simplifies the code which automatically does the coil assignment.

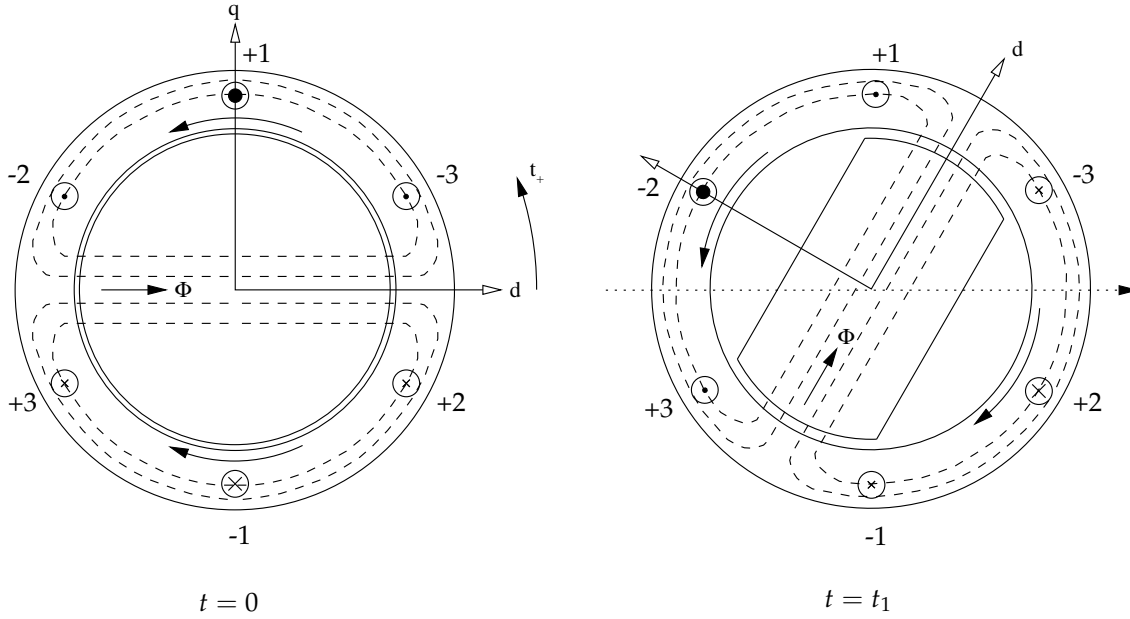


Figure 2.3: Rotation of the resultant mmf by displacing the three positive coil sides along the stator periphery

thus forming an envelope. Similarly, the remaining phases will each form envelope functions. The bounding functions for all the phases are given by

$$f_n(\theta) = \hat{F}_n \cos \left[\theta + \frac{2\pi}{m}(n-1) \right], \quad 1 \leq n \leq m \quad (2.22)$$

and the mmf of any of the phases will be bounded, i.e.

$$-|f_n(\theta)| \leq F_n(\theta, t) \leq |f_n(\theta)| \quad (2.23)$$

2.4.4 Phase belt definition

The mmf envelope functions in section 2.4.3 allow the definition of the phase belt in a unique way, which make it possible to allocate the stator slots that belong to a phase before the coil sides are assigned.

Definition 2.4.1. In general, the interval $\langle \theta_1, \theta_2 \rangle$ for which any of the m bounding functions in (2.22) is greater than the remaining $(m-1)$ functions is defined as a phase belt, i.e.

$$|f_i(\theta)| > |f_n(\theta)|, \quad \begin{cases} 1 \leq n \leq m \\ n \neq i \end{cases} \quad (2.24)$$

and the interval $\langle \theta_1, \theta_2 \rangle$ spans $\frac{2\pi}{2m}$ radians.

A useful parameter to define is the total number of phase belts around the air gap periphery, i.e.

$$N_p = \frac{2\pi p}{\left(\frac{2\pi}{2m}\right)} = p \cdot 2m \quad (2.25)$$

and means that the phase belt sequence (for three phases) given in (2.20) repeat itself p times around the air gap periphery.

2.4.5 Higher order harmonics

A similar procedure as for the working harmonic can be used to derive the direction of rotation for the higher order harmonics. The decomposition of the air gap mmf means that the resultant mmf is the sum of an infinite number of rotating waves. The general expression for harmonic order (for three phases and six phase belts) of the air gap mmf harmonics is

$$\nu = 1 + 6g \quad g = 0, \mp 1, \mp 2, \dots \quad (2.26)$$

and the speed of rotation is given by

$$\omega_\nu = \frac{\omega}{\nu} \quad (2.27)$$

A positive value of ν means that the harmonic is rotating counter-clockwise and a negative ν means it rotates clockwise. This convention is valid for the coil arrangement as given in Fig. 2.2(a) and the currents in (2.21). The rotation speed is proportional to the inverse of the harmonic order.

Chapter 3

Matrix representation of a winding

In this section it will be shown that the winding layouts can be represented by means of two matrices. The first matrix will contain information on the ingoing coil sides of the coils while the second matrix will be that of the outgoing coil sides. The matrices are referred to as \mathbf{M}_1 and \mathbf{M}_2 for the ingoing and outgoing coil sides respectively. Both matrices have n columns and m rows. In addition, the number of columns equals the number of stator slots and the rows are equal to the number of phases, thus $m = m^1$ and $n = Q_s$. The matrices can be expressed as

$$\mathbf{M}_1 = \begin{bmatrix} m_{11} & m_{12} & \dots & m_{1n} \\ m_{21} & m_{22} & \dots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{m1} & m_{m2} & \dots & m_{mn} \end{bmatrix} \quad \mathbf{M}_2 = \begin{bmatrix} m_{11} & m_{12} & \dots & m_{1n} \\ m_{21} & m_{22} & \dots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{m1} & m_{m2} & \dots & m_{mn} \end{bmatrix} \quad (3.1)$$

where

$$m_{ij} \in \{-1, 0, 1\} \quad (3.2)$$

and depends on the winding layout. In the rest of this section an algebraic method is derived to determine the matrix elements. The variables n_1 and n_2 are integers and will be used as loop variables later on in this chapter where the algorithm flowchart is explained. The subscripts 1 and 2 refer to the outer and inner loop respectively.

3.0.1 Slot vector

For assigning the Q_s slots to phase belts, the peripheral slot angle α needs to be defined in terms of the slot pitch τ_s . If the slots have a regular distribution the angle between any two adjacent slots equals τ_s . In the case of irregular distributed slots the average slot pitch will equal τ_s . A regular and irregular distribution are shown in Fig. 3.1. A vector is assigned to the centre of each stator slot. The exponential representation² of a vector is used, i.e.

$$e^{jv\alpha} = \cos(v\alpha) + j \sin(v\alpha) \quad (3.3)$$

¹It is typical in mathematics that the number of rows is represented by m . Equally the number of phases of an electrical machine is also represented by m . Furthermore, m_{11} is a matrix element while m is the number of phases.

²Also known as Euler's formula.

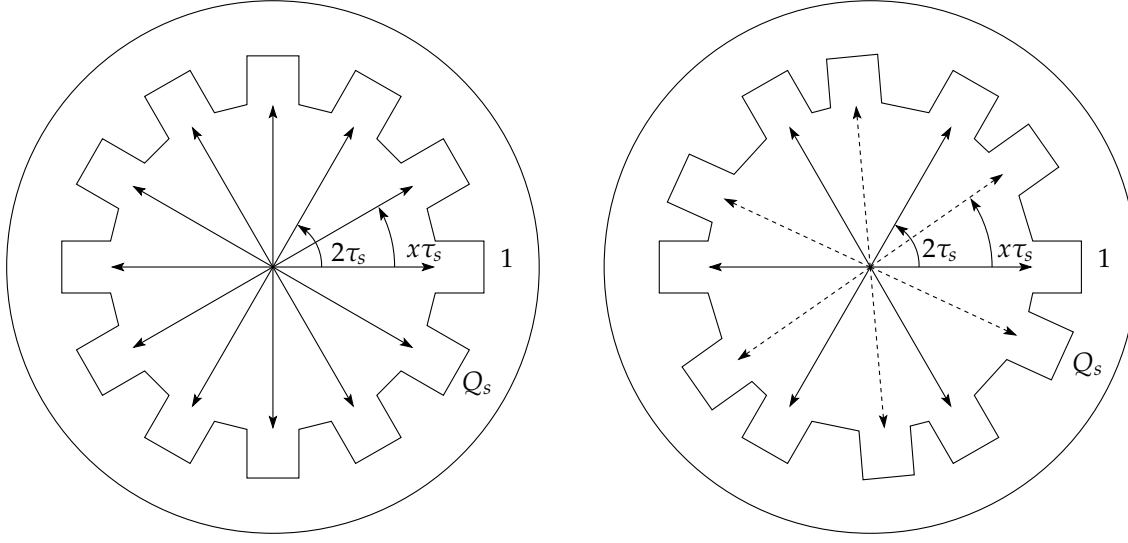
(a) Regular distribution $x = 1$ (b) Irregular distribution $0 < x < 2$

Figure 3.1: Star of slots

The variables ν and α are the harmonic order and slot peripheral angle respectively. All the vectors as shown in Fig. 3.1 are represented as a column matrix \mathbf{v}^* . The number of rows is equal to the number of slots, i.e.

$$\mathbf{v}^* = \left[e^{j\nu\alpha_1} e^{j\nu\alpha_{n_2}} \dots e^{j\nu\alpha_{Q_s}} \right]^T \quad 1 \leq n_2 \leq Q_s \quad (3.4)$$

where

$$\alpha_{n_2} = \begin{cases} \tau_s (n_2 - 1) & n_2 \text{ odd} \\ \alpha_{n_2-1} + x\tau_s & 0 < x < 2 \quad n_2 \text{ even} \end{cases} \quad 1 \leq n_2 \leq Q_s \quad (3.5)$$

where the α accounts for both regular and irregular distributed stator slots. Setting $\nu = p$ means that the electrical slot angles³ for the working harmonic are obtained.

3.0.2 Phase belt constraint

The phase belt constraint is used to determine the matrix elements m_{ij} in (3.1). From the slot angle α in (3.4) the corresponding electrical angle θ_e is obtained. A stator slot is assigned to the phase belt if the following constraint is true:

$$\theta_1 \leq \theta_e < \theta_2 \quad \left\{ \begin{array}{l} \theta_1 = \frac{2\pi}{2m} (n_1 - 1) \\ \theta_2 = \frac{2\pi}{2m} n_1 \\ 1 \leq n_1 \leq N_p \end{array} \right\} \quad \text{phase belt boundaries} \quad (3.6)$$

$$\left\{ \begin{array}{l} \theta_e = p\alpha_{n_2} \\ 1 \leq n_2 \leq Q_s \end{array} \right\} \quad \text{electrical slot angle}$$

³The electrical and mechanical slot have the following relationship: $\theta_e = p\theta_m$

The phase belt constraint as given in (3.6) is characterised by the phase belt boundaries and the electrical slot angle, which are summarised as follows:

Phase belt boundaries: The total number of phase belts around the air gap periphery is given by (2.25). Each of the phase belts is bounded by the angles θ_1 and θ_2 .

Electrical slot angle: The electrical slot angle is obtained by multiplying the peripheral slot angle in (3.5) by the pole pair number. If the electrical angle for a given slot lies within the phase belt boundaries, it belongs to that phase belt.

In order to assign the slot to a phase, it is necessary to know to which phase a given phase belt belongs. The phase can be determined in terms of the given phase belt number n_1 and the number of phases, i.e.

$$k = \text{mod}(n_1, 2m) \quad \begin{cases} 1 \leq n_1 \leq N_p \\ 2m \text{ if } \text{mod}(n_1, 2m) = 0 \end{cases} \quad 1 \leq k \leq 2m \quad (3.7)$$

The value of k as calculated in (3.7) corresponds to the phase belt number. Therefore, if the number of a given phase belt is known, the corresponding phase and its sign are calculated as follows:

$$\begin{aligned} \text{phase} &= \begin{cases} k & k \leq m \\ k - m & k > m \end{cases} \\ \text{sign} &= (-1)^{(k-1)} \end{aligned} \quad (3.8)$$

If $m = 3$ and $p = 1$ the number of phase belts equals 6. Applying (3.7) and (3.8) will result in the phase belt sequence as given in (2.20).

3.0.3 Algorithm flowchart

The explanation of the algorithm is accompanied by the flowchart in Fig. 3.2 and greatly simplifies the understanding. For convenience the relevant equations or tables are included which makes it easier to follow the description. The algorithm only applies to symmetrical windings and the three major parts are summarised as follows:

Outer loop: The outer loop of the flowchart is used for the total number of phase belts as given in (2.25). The loop index n_1 (in the range $1 \leq n_1 \leq N_p$) is used to calculate the given phase belt boundaries θ_1 and θ_2 as given in (3.6). Since the $2m$ phase belts repeat themselves along the air gap periphery, the actual phase belt number k in the phase belt sequence can be determined from n_1 as given in (3.7) and (3.8).

Inner loop: The inner loop has n_2 as index and is used to calculate the electrical angle for a given slot. If a slot is already assigned to a phase belt, the winding matrix will have an entry in the set $\{-1, 1\}$. In this case the loop is skipped.

Phase belt constraint: This is the key step to allocate a stator slot. If the electrical angle lies within the phase belt boundaries, it belongs to the given phase belt. The row and column number for the ingoing matrix \mathbf{M}_1 are determined from the inner loop index n_2 and the given phase belt number. The row number for \mathbf{M}_2 is the same as for \mathbf{M}_1 and the column number is obtained from the coil pitch y_d .

The assignment of the stator slots as offered in this dissertation is unique and not presented in this way by any of the references consulted.

3.0.4 Matrix element assignment

Once the phase belt constraint is fulfilled, the slot is allocated and the next step is to assign one of the values in the set given in (3.2). Actually only the sign needs to be determined. Since the phase belt sequence is alternating, the sign can be obtained from the phase belt itself. Following the flowchart through to the point where the test is performed, it is noticed that the matrix column number for \mathbf{M}_1 is given by the loop index variable n_2 . The entry has the value $(-1)^{(k-1)}$, where k is given in (3.7). The determination of the row, column and matrix element are summarised as follows⁴:

$$\begin{aligned} i &= \left\{ \begin{array}{ll} k & k \leq m \\ k - m & k > m \end{array} \right\} \text{ row number} \\ h &= (-1)^{(k-1)} \text{ matrix element sign} \\ j &= \left\{ \begin{array}{ll} n_2 + y_d & n_2 + y_d \leq Q_s \\ \text{mod}((n_2 + y_d), Q_s) & n_2 + y_d > Q_s \end{array} \right\} \text{ column number} \end{aligned} \quad (3.9)$$

3.1 Properties of the winding matrix

Presenting the winding in matrix form is very compact and has advantages in machine analysis. The matrix contains all the information of the winding arrangement in the stator slots. This allows the construction of the voltage phasor which is necessary to calculate the winding factor. In addition, the slot mmf can be obtained from the column data. The properties of the matrix are summarised as follows:

- if the winding is symmetrical, the number of assigned elements in all the rows are equal;
- the number of columns is equal to the number of stator slots;
- the number of rows is equal to the number of phases;
- for a single layer winding there is only one nonzero element in a column;
- a double layer winding has two nonzero elements in a row; and
- the matrix is valid for both a fixed and variable slot pitch.

In the rest of this section the winding matrix is used to calculate the winding factor and the slot mmf.

⁴The method was only tested for $m = 3, 5, 7, \dots$

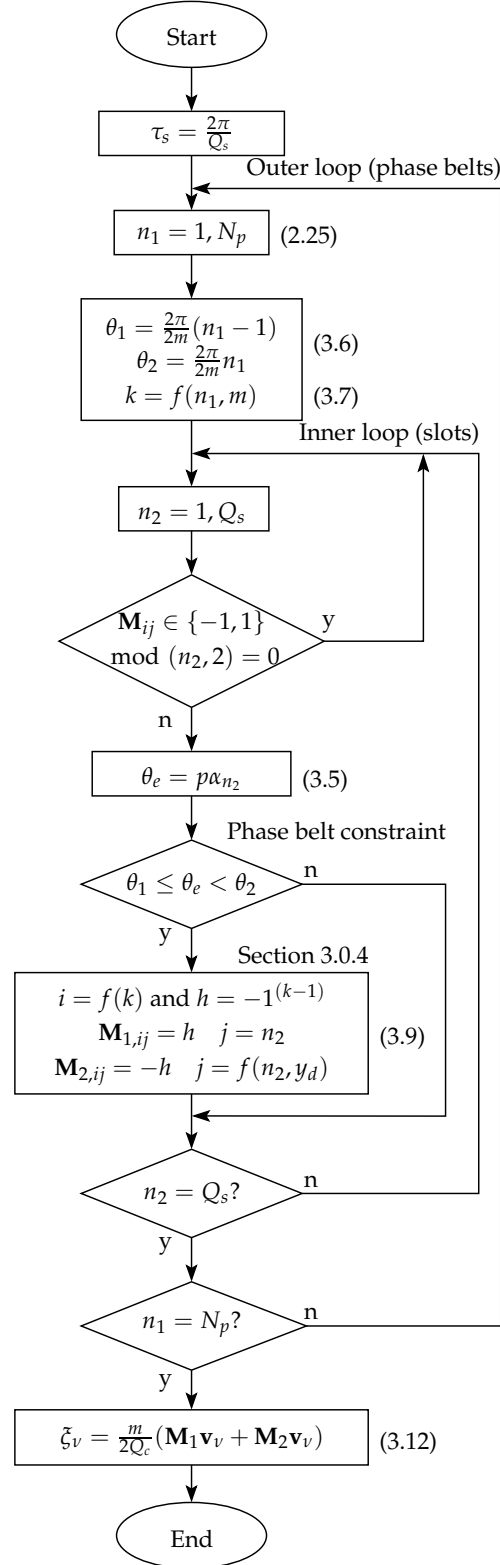


Figure 3.2: Flowchart to allocate the stator slots

3.1.1 Winding factor

With \mathbf{M}_1 and \mathbf{M}_2 assigned, the winding factor for any harmonic can be calculated as the product between the matrices and the slot vector as given in (3.4). This means that a row of the winding matrix is multiplied by the slot vector column matrix. The matrix product means that all the vectors belonging to the same phase are added and for the case $\nu = p$ equals

$$(m_{1,i1} + m_{2,i1})e^{jp\alpha_1} + (m_{1,i2} + m_{2,i2})e^{jp\alpha_2} + \dots + (m_{1,iQ_s} + m_{2,iQ_s})e^{jp\alpha_{Q_s}} \quad (3.10)$$

If the slot vector does not belong to the current phase, the coefficient

$$(m_{1,ij} + m_{2,ij}) \quad (3.11)$$

is zero. Furthermore, the product should be normalised. Since the total number of vectors is related to the coils per phase it should be multiplied by $\left(2\frac{Q_c}{m}\right)^{-1}$, i.e.

$$\zeta_\nu = \frac{m}{2Q_c} [\mathbf{M}_1 \mathbf{v}^\circ + \mathbf{M}_2 \mathbf{v}^\circ], \quad \in \mathbb{C} \quad (3.12)$$

The result (3.12) present the winding factor as a complex number and the absolute value is to be used as a reduction factor for the sinusoidally induced voltage in (2.1). Writing ζ_ν as

$$\zeta_\nu = a_\nu + jb_\nu \quad (3.13)$$

the phase angle is calculated as

$$\theta_\nu = \arctan\left(\frac{b_\nu}{a_\nu}\right) \quad (3.14)$$

The phase angle (in electrical radians) gives information on the position of the winding axes⁵ relative to the first slot. The two winding axes associated with each phase are called

- the current sheet anti-node axis and
- the magnetic axis

of the winding. A positive phase angle means that both winding axes have moved clockwise with respect to the first slot. The winding axes are a very import quantities in machine design. When the machine is supplied with a source, a rotating magnetic flux wave is generated. This reacts with the flux generated by the flux of the permanent magnets on the rotor. In order to control the resultant flux, it is necessary to know the exact position of the winding axes.

3.1.2 Current sheet anti-node axis

Equation (2.15) describes the space fundamental component of the mmf produced by the current in phase 1. It can be seen as the mmf wave produced by a finely divided sinusoidally distributed current sheet placed on the inner periphery of the stator. The position of the anti-node with

⁵The winding axes in the present dissertation refer to the current anti-node axis and the magnetic axis. This is shown in Fig. ??.

maximum deviation is given by θ_{an} . The relative position of θ_{an} with respect to the first slot is given by

$$\theta_{an_v} = -\frac{\theta_v}{p} \quad (3.15)$$

3.1.3 Magnetic axis

The axis along which the flux is directed when current is flowing in the coil, is defined as the magnetic axis. This is the same position where the current sheet has a node. The relative position of the magnetic axis θ_m with respect to the first slot is given by

$$\theta_{m_v} = -\frac{(\theta_v + \frac{\pi}{2})}{p} \quad (3.16)$$

The winding magnetic axis lags the current sheet anti-node axis by $\frac{\pi}{2}$ radians.

3.1.4 Slot mmf

The ampère-turns in each slot can be obtained from the matrix winding columns. Both the matrices \mathbf{M}_1 and \mathbf{M}_2 contain the coil side information for the ingoing and outgoing coil sides respectively. The total ampère-turns of a coil side is the product of its value in the winding matrix with the number of coil turns N_t . The direction of the current is given by the sign of the element. Therefore to get the total ampère-turns in the slot, the ampère-turns of the coil sides must be added. For a three-phase winding the slot mmf F_{slot} of the k^{th} slot is calculated as

$$\begin{aligned} F_{slot,k} &= N_t i_1 (m_{1,1k} + m_{2,1k}) + N_t i_2 (m_{1,2k} + m_{2,2k}) + N_t i_3 (m_{1,3k} + m_{2,3k}) \\ &= N_t \sum_{n=1}^3 i_n (m_{1,nk} + m_{2,nk}) \end{aligned} \quad (3.17)$$

3.2 Examples

The derived theory presented in this chapter is now illustrated by means of examples. The examples are summarised as follows:

Winding factor tables: The winding factors for different slot and pole pair combinations are calculated for single and double layer non-overlapping windings. The results presented are used to derive an expression to find the feasible range for the number of pole pairs, given the number of stator slots.

Slot mmf and current sheet: The prototype stator with 30 slots is used as an example. By choosing different pole pair numbers, it is shown how to obtain both a single and double layer winding. In each case a non-overlapping and overlapping winding are explained.

3.2.1 Winding factor table

The results are given in Tab. 3.1 Tab. 3.2 for single and double layer non-overlapping windings respectively. Only those slot and pole combinations for which the winding factor is greater than or equal to $\frac{\sqrt{3}}{2}$ are given. Those combinations that do not fulfill the condition in (2.10) are marked as not applicable. Presenting the winding factors in a table is helpful to identify the relationship between the number of stator slots and the number of poles which results in the best combinations. Only the winding factors for the working harmonic are presented.

The winding factors for single windings are calculated for pole pairs in the range from 4 to 28, whereas the number of stator slots range from 12 to 84. Although the focus in the present dissertation is on single layer non-overlapping windings, the winding factors for double layer windings are given as well. The winding factors are calculated for pole pairs in the range from 4 to 16, whereas the number of stator slots ranges from 12 to 48.

Table 3.1: $\xi_p \times 10^{-3}$ for single layer non-overlapping windings

p	Q_s												
	12	18	24	30	36	42	48	54	60	66	72	78	84
4	866												
5	966												
6	na	866											
7	966	902											
8	866	945	866										
9		na	na										
10		945	966	866									
11		902	958	874									
12		866	na	na	866								
13			958	940	870								
14			966	950	na	866							
15			na	na	966	na							
16			866	950	na	na	866						
17				940	956	na	859						
18				na	na	na	na	866					
19				866	956	na	907	na					
20				866	na	na	966	na	866				
21					966	na	na	na	na				
22					na	na	958	na	954	866			
23					870	na	956	na	893	na			
24					866	na	na	na	na	na	866		
25						na	956	na	966	na	848		
26						na	958	na	na	na	870	866	
27						na	na	na	na	na	na	na	
28						866	966	na	na	na	na	na	866

From the results in Tab. 3.1 and Tab. 3.2 the number of slots per pole and phase which results in a winding with suitable winding factors is given by

$$\frac{1}{4} \leq q \leq \frac{1}{2} \quad (3.18)$$

Table 3.2: $\xi_p \times 10^{-3}$ for double layer non-overlapping windings

p	Q_s												
	12	15	18	21	24	27	30	33	36	39	42	45	48
4	866												
5	930	866											
6	na	na	866										
7	930	950	900	866									
8	866	950	950	890	866								
9		na	na	na	na	866							
10		866	950	950	930	880	866						
11			900	950	950	920	870	866					
12			866	na	na	950	na	na	866				
13				890	950	950	940	900	870	866			
14				866	930	950	950	930	900	860	866		
15					na	950	na	na	930	na	na	866	
16					866	920	950	950	950	920	890	860	866

The result is the same as presented by [14] and [17]. Using this result, the range of pole pairs for a given number of slots can be expressed as follows:

$$\frac{Q_s}{m} \leq p \leq \frac{2Q_s}{m} \quad \left\{ \begin{array}{ll} Q_s \in \{6, 12, 18, \dots\} & \text{single layer} \\ Q_s \in \{3, 6, 9, \dots\} & \text{double layer} \end{array} \right. \quad (3.19)$$

3.2.2 Slot mmf and current sheet

This section entails examples of overlapping and non-overlapping windings with 30 stator slots. The classification parameters q , q_c and y_d (as given in Tab. 3.3) are used to classify the windings according to the scheme in Fig. 2.2. Additionally, for the selected number of pole pairs the winding factor, slot mmf and current sheet are calculated. It is important to mention that the choice of the position of the reference slot will determine the rotation direction of the resulting rotating field. It is desirable to have a field rotating in a counter-clockwise direction, since this is the positive direction in a polar coordinate system. To achieve this, the stator is rolled flat with the top part of the slots facing upwards.

Table 3.3: Different pole pair combinations with $Q_s = 30$

Q_s	p	Q_c	n_l	y_p	y_d	q	q_c	Q_b	t	ξ_p	ξ_{5p}	ξ_{7p}	Figure
30	10	15	1	$\frac{3}{2}$	1	$\frac{1}{2}$	$\frac{1}{4}$	6	5	0.866	0.866	0.866	3.3(b)
30	10	30	2	$\frac{3}{2}$	1	$\frac{1}{2}$	$\frac{1}{2}$	3	10	0.866	0.866	0.866	3.4(b)
30	5	15	1	3	3	1	$\frac{1}{2}$	6	5	1.0	1.0	1.0	3.5(b)
30	5	30	2	3	3	1	1	6	5	1.0	1.0	1.0	3.6(b)

Single layer non-overlapping

Fig. 3.3(a) shows an illustration of a single layer non-overlapping winding. There is only one coil side in each stator slot and the slot pitch could be either regular or irregular. An irregular slot pitch means that the coil pitch can be varied to improve the winding factor. Depending on the design criteria, it can also be used to improve the torque ripple. Since the outgoing coils are given by the coil pitch y_d , only every second slot needs to be assigned to a phase belt.

The example chosen is that of the prototype machine with 30 slots and 10 pole pairs. From Tab. 3.3 the values for q and q_c are $\frac{1}{2}$ and $\frac{1}{4}$ respectively. The basic winding is determined using q_c and has one coil per phase distributed over 4 poles. In total the basic winding has 6 slots. The winding has a sub-harmonic with 5 pole pairs. Since it is a single layer winding the number of coils is half the number of stator slots. The coil pitch equals one and this is a fractional slot winding. For convenience only the basic winding matrix elements for \mathbf{M}_1 and \mathbf{M}_2 are given as

$$\mathbf{M}_{1,b} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \quad \mathbf{M}_{2,b} = \begin{pmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{pmatrix} \quad (3.20)$$

To obtain the complete winding matrix, the matrix of the basic winding is repeated five times. For the ingoing coil side matrix this means

$$\mathbf{M}_1 = [\mathbf{M}_{1,b} \quad \mathbf{M}_{1,b} \quad \mathbf{M}_{1,b} \quad \mathbf{M}_{1,b} \quad \mathbf{M}_{1,b}] \quad (3.21)$$

The winding matrix is used to obtain the slot mmf F_{slot} from (3.17) as shown in the lower part of Fig. 3.3(b). The dashed line in the mmf plot is the current sheet. In the top part of the figure the winding factors are shown as well. From the figure it is clear that the winding factors are periodic with the number of stator slots. In the example the peripheral slot angle was calculated setting $x = 1$ in (3.5). Therefore, this is a regular distribution of the stator slots.

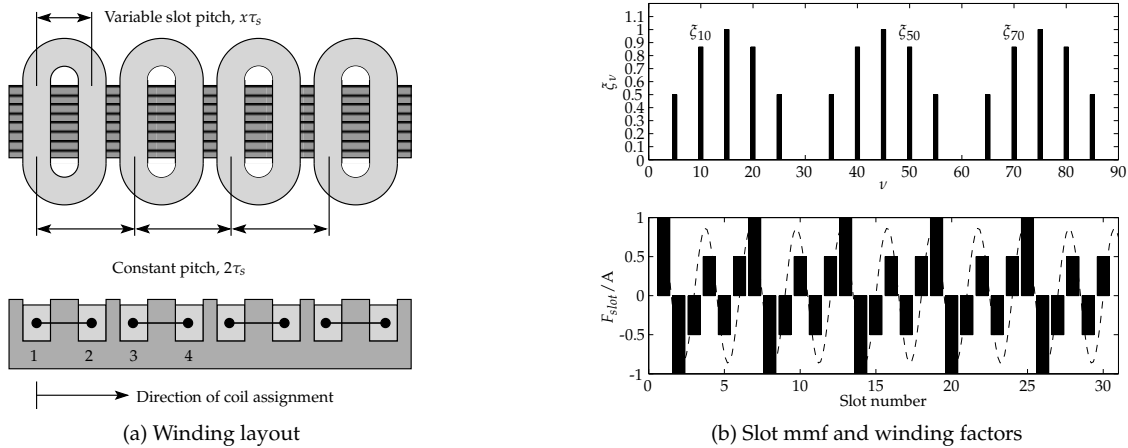


Figure 3.3: Non-overlapping single layer winding

Double layer non-overlapping

Fig. 3.4(a) shows a non-overlapping double layer winding. Each stator slot has two coil sides. Moreover, each slot needs to be assigned to a phase belt.

The prototype stator with 30 slots is used with 10 pole pairs. This is a double layer winding and the number of slots is equal to the number of coils. Both q and q_c and the basic winding has 3 slots. The lowest harmonic has 10 pole pairs which is the same as the working harmonic. Therefore, the winding has no sub-harmonics. The matrix elements of the basic winding are

$$\mathbf{M}_{1,b} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \mathbf{M}_{2,b} = \begin{pmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad (3.22)$$

The winding factors and slot mmf are directly obtained from the winding matrix as shown in Fig. 3.4(b). The current sheet that corresponds to the working harmonic is included.

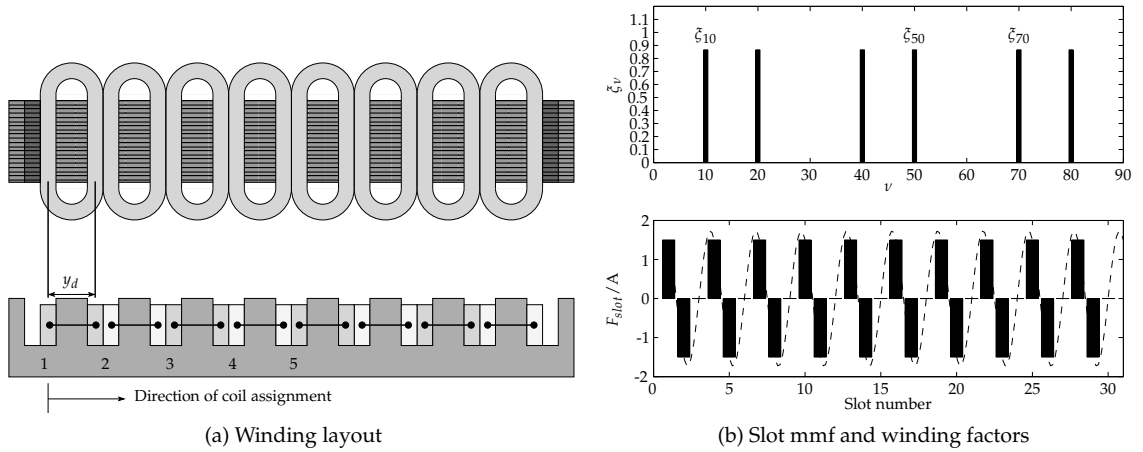


Figure 3.4: Non-overlapping double layer winding

Single layer overlapping

A general single layer overlapping winding is shown in Fig. 3.5(a). In this example the coil pitch equals 5. The ingoing coil side of the first coil is in slot 1 and the outgoing coil side in slot 6. It is clear from the figure that the coils overlap.

The example to illustrate the slot mmf and current sheet has 30 slots and a pole pair number equal to 5. In Tab. 3.3 the average pole pitch equals the pole pitch. Therefore this is called a concentrated winding as determined from Fig. 2.2. The basic winding matrix elements are given as

$$\mathbf{M}_{1,b} = \begin{pmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{pmatrix} \quad \mathbf{M}_{2,b} = \begin{pmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{pmatrix} \quad (3.23)$$

The calculated winding factor along with the slot mmf and current sheet are shown in Fig. 3.5(b). It is important to mention that the coil sides are distributed in such a way as to obtain a sinusoidal slot mmf distribution. The number of slots per pole and phase can be increased to obtain a better sinusoidal distribution. In doing so, the harmonic content will become less.

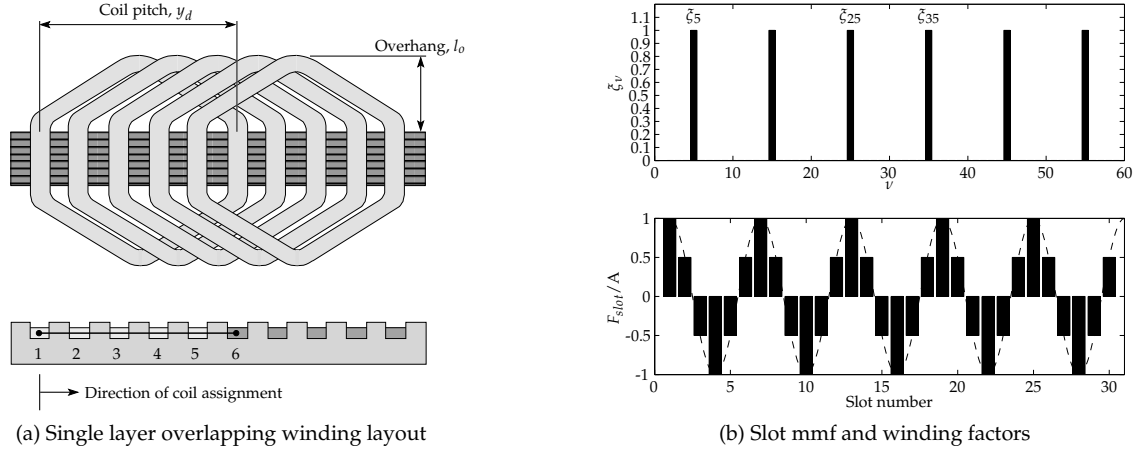


Figure 3.5: Single layer overlapping winding

Double layer overlapping

A double layer overlapping winding is commonly used in industrial machines. Overlapping double layer windings have a coil pitch greater than one, i.e. $y_d > 1$. Fig. 3.6a shows a double layer winding. Starting at the first slot, the coils are inserted in a counter-clockwise direction. The first coil has its ingoing coil side in the bottom part of slot 1 and the return coil side is in the top part of slot 6. The phase belt constraint in (3.6) is used to determine the phase of the coil side in the bottom part of the slot while the top coil sides are given by the coil pitch y_d .

Fig. 3.6b shows the slot mmf of a stator with $Q_s = 30$ slots and $p = 5$ pole pairs. Using the winding properties for this combination given in Tab. 3.3, it is a concentrated winding. The winding has no sub-harmonics.

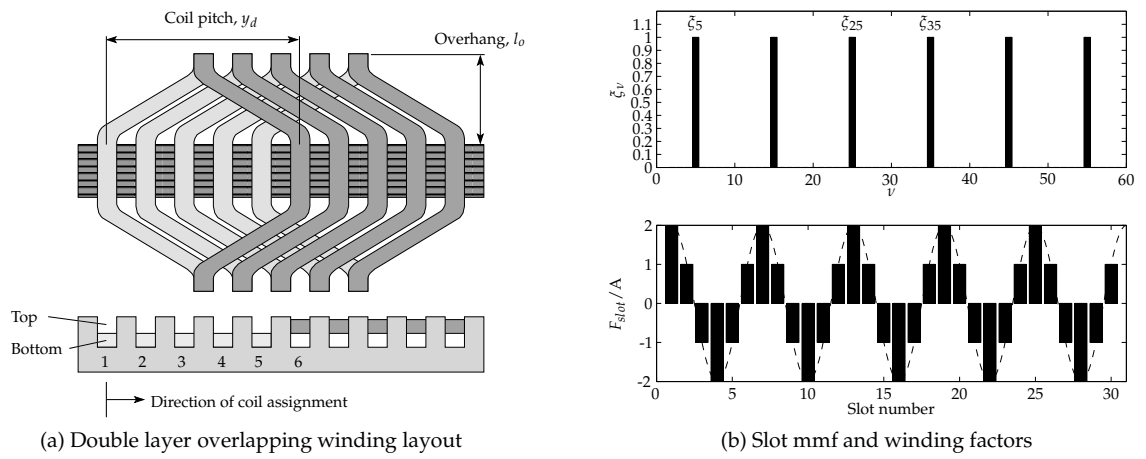


Figure 3.6: Double layer overlapping winding

3.3 Summary

In this report an algorithm was derived to present a winding in a matrix form. This compact form allows the calculation of the winding factors for all harmonics. The basis of the algorithm is the phase belt sequence and the phase belt constraint which are derived from the air gap mmf envelope functions.

Appendix A

Slot assignment CDesign.m

```
function Wnd = CDesign(varargin)

% CDesign('Qs',144,'p',20,'x',1,'nl',2,'yd',4,'m',3)
% CDesign('Qs',54,'p',6,'x',1,'nl',2,'yd',4,'m',3)
% [Xsi,C,CRe,theta_m,Coil_Data,Wnd] = CDesign(varargin)
%
% Calculate the winding properties and coil layout
%
% C and CRe
% thata_m
% Coil_Data
% Wnd
%
% Inputs:
% Qs, p, x, nl, yd, m
%
% The winding is uniquely specified by the following two numbers:
% 1. number of slots per pole and phase
% 2. number of coils per pole and phase
% When these numbers are written in its reduced form the following are
% used for the winding layout:
%
% qcn/qcd: The number of slots per phase of the basic winding to which a
% coil side must assigned to.
%
% J.J. Germishuizen 2007-2017

if (nargin < 12)
    error('Too few input arguments');
end

paramPairs = varargin(1:end);
```

```

[Qs,p,m,yd,nl,x] = input_parameter(paramPairs);

[Wnd] = properties(Qs,p,m,yd,nl,x);

[C,CRe,theta_m,Coil_Data] = coilassign(Wnd.Qs,Wnd.p, ...
    Wnd.m,Wnd.yd,Wnd.nl,Wnd.x);
Wnd.C = C;
Wnd.CRe = CRe;
Wnd.theta_m = theta_m;
Wnd.Coil_Data = Coil_Data;

% The winding factor properties depends wheter the denominator qcn
% is odd or even. the harmonic that corresponds to the working harmonic
% equals nu=p.

Xsi = [];
Xsi_m = [];
phase_axes = [];
fac = m/(2*Wnd.Qc);
for nu = 1:20*p
    A = C*exp(-i*nu*theta_m)'+CRe*exp(-i*nu*theta_m)';
    Xsi = [Xsi, fac*abs(A(1))];
    Xsi_m = [Xsi_m, fac*A];
    phase_axes = [phase_axes, angle(A)];
end
Wnd.Xsi = Xsi;
Wnd.Xsi_p = Xsi(p);
Wnd.Xsi_5p = Xsi(5*p);
Wnd.Xsi_7p = Xsi(7*p);

% Calculate the winding axis in degrees.
z = 0+i;
lo = 1;
hi = Wnd.Qbasic;
slot_angle_rad = theta_m(lo:hi);
M1 = abs(C(1,lo:hi));
M2 = abs(CRe(1,lo:hi));
tmpA = M1 * exp(z*slot_angle_rad)';
tmpB = M2 * exp(z*slot_angle_rad)';
Wnd.winding_axis = tmpA+tmpB;
tmpx = real(Wnd.winding_axis);
tmpy = imag(Wnd.winding_axis);
Wnd.winding_axis = -atan2(tmpy,tmpx)*180/pi + 180/Wnd.p + 360/(2*Wnd.Qs);

return;

function [Qs,p,m,yd,nl,x,plot] = input_parameter(paramPairs)

```

```

% Process param-value pairs
args = {};
for k = 1:2:length(paramPairs)
    param = lower(paramPairs{k});
    if (~ischar(param))
        error('Optional parameter names must be strings');
    end
    value = paramPairs{k+1};

    switch (param)
        case 'qs'
            Qs = value;
        case 'p'
            p = value;
        case 'm'
            m = value;
        case 'yd'
            yd = value;
        case 'nl'
            nl = value;
        case 'x'
            x = value;
        otherwise
            error(['Unrecognized option ' param '.']);
    end
end
return;

function [C,CRe,theta_m,Coil_Data] = coilassign(Qs,p,varargin)
% [Xsi,Coil_Data] = Coilassign(Qs,p,varargin)
%
% Input Qs : Number of stator slots
%       p  : Pole pairs
% Optional inputs
%       m  : Number of phases
%       cs : Coil span
%       nl : Double/Single layer
%       x  : Slot pitch (x*tau_s)
%
% The default output is the winding factor. The slot arrangement for
% a finite element analysis is an optional output.

if numel(varargin) == 0
    m = 3;
    yd = floor(Qs/(2*p));
    nl = 2;
    x = 1;
else

```

```

    m = varargin{1};
    yd = varargin{2};
    nl = varargin{3};
    x = varargin{4};
end

tau_s = 2*pi/Qs;
phase_belt = 2*pi/(2*m);
Coil_Names = cell(1,2*m);
n_phase_belts = 2*pi*p/phase_belt;
Np = n_phase_belts;
C = zeros(m,Qs);
CRe = zeros(m,Qs);
Coil_Data = cell(Qs,nl);
if nl == 2; x = 1; end;

for j = 1:2*m
    jj = mod(j,m);
    if jj == 0; jj = m; end;
    % Coil_Names = {A BRe ... ARe B ...}
    if -1*cos(mod(j,2)*pi) > 0
        Coil_Names{jj} = [char(64+jj)];
    else
        Coil_Names{jj} = [char(64+jj) 'Re'];
    end
end
Return_Path = [(m+1):2*m 1:m];
theta_m = [];

for n = 1:Qs
    if mod(n,2) == 1
        % odd slot numbers
        theta_m = [theta_m, tau_s*(n-1)];
    else
        % even slot numbers
        theta_m = [theta_m, theta_m(n-1)+tau_s*(x)];
    end
end

sumC = sum(abs(C));
sumCRe = sum(abs(CRe));
for n1 = 1:Np
    theta_1 = phase_belt*(n1-1);
    theta_2 = phase_belt*n1;
    % Determine the current phase belt
    k = mod(n1,2*m);
    if k == 0; k = 2*m; end;
    %

```

```

% Only consider the slot for which the phase belt is valid.
%
low = find(p*theta_m<=theta_1);
if isempty(low)
    lower_bound = 1;
else
    lower_bound = max(low);
end;
high = find(p*theta_m>=theta_2);
if isempty(high)
    high_bound = Qs;
else
    high_bound = min(high);
end;
%
for n2 = lower_bound:high_bound
    % Loop if theta_e is not in range
    theta_e = p*theta_m(n2);
    if theta_e > theta_2*1.05
        break;
    end;
    phase_interval = false;
    % Find the nonzero elements in column of ingoing matrix.
    % matrix is empty:    isempty(col_test_C) = 1
    % matrix not empty:  isempty(col_test_C) = 0
    if nl == 1
        %
        % Test if coil is already assigned to current slot. Find the
        % non-zero elements. If slot is not assigned yet, then col_test
        % is empty. Isempty returns 1 when col_test is empty. This only
        % holds for single layer. For double layer each slot must be
        % tested.
        %
        if sumC(n2)>=1 | sumCRe(n2)>=1
            continue;
        end
    else
        if sumC(n2)>=1
            continue;
        end
    end
    end
    %
    % Test if current slot is a multiple of the phase belt. Override
    % the value of k to assure correct coil assignment.
    %
    phase_test = zeros(1,2*m);
    for j = 1:2*m
        dmy = mod(theta_e,2*pi);

```

```

        epsilon = abs(dmy-(j-1)*phase_belt);
        if epsilon < 1e-10
            % override k
            k = j;
            if j==k
                phase_interval = true;
            end
        end
    end
end
if k <= m
    row = k;
else
    row = k-m;
end
%
% Slot found when slot angle within phase belt or phase interval.
%
if (theta_e >= theta_1) & (theta_e < theta_2) | phase_interval
    %
    % Assign the in-going coil side
    %  $(-1)^{(k-1)} = -1 \cdot \cos(\text{mod}(k,2) \cdot \pi)$ 
    %
    C(row,n2) = (-1)^(k-1);
    Coil_Data{n2,1} = [Coil_Names{k} num2str(n2)];
    %
    % Determine the return coil side -> first the slot number
    %
    if (n2+yd) <= Qs
        PhRe = n2+yd;
    else
        PhRe = mod(n2+yd,Qs);
    end
    CRe(row,PhRe) = -1*C(row,n2);
    kre = Return_Path(k);
    if nl == 2
        Coil_Data{PhRe,2} = [Coil_Names{kre} num2str(n2)];
    else
        Coil_Data{PhRe,1} = [Coil_Names{kre} num2str(n2)];
    end
    sumC = sum(abs(C));
    sumCRe = sum(abs(CRe));
end
end
end
return

function [Winding] = properties(Qs,p,m,yd,nl,x)

```

```

% Distinguish between following common divisors:
%
% 1. ts = gcd(Qs,p)
% 2. tc = gcd(Qc,p)
% 3. tq = gcd(Qs,2pm)

% Determine the coil sides per phase
% Wnd.cspp = Wnd.Qs/Wnd.m*Wnd.nl;

Winding = [];
Winding.Qs = Qs;
Winding.p = p;
Winding.m = m;
Winding.yd = yd;
Winding.nl = nl;
Winding.x = x;
if nl == 2
    Qc = Qs;
else
    Qc = Qs/2;
end

% Get the common divisors
ts = gcd(Qs,p);
tc = gcd(Qc,p);
tqs = gcd(Qs,2*p*m);
tqc = gcd(Qc,2*p*m);

% Get the number of coils per pole and phase
qcn = Qc/tqc;
qcd = (2*p*m)/tqc;

% Get the number of slots per pole and phase
qsn = Qs/tqs;
qsd = (2*p*m)/tqs;

% Average coil pitch
yp = Qs/(2*p);

% Calculate yd if the user specified yd = 0. Coil span should be at least
% one.
if yd == 0
    yd = floor(yp);
    if yd <= 0; yd = 1; end;
end

Winding.t = tc;
Winding.qsn = qsn;

```

```
Winding.qsd = qsd;
Winding.qcn = qcn;
Winding.qcd = qcd;
Winding.yp = yp;
Winding.yd = yd;
Winding.nl = nl;
Winding.Qbasic = Qs/tc;
Winding.pbasic = p/tc;
Winding.Qc = Qc;

if mod(qcd,2) == 0
    r = m;
else
    r = 2*m;
end

if ts<p
    Winding.subharmonic = true;
else
    Winding.subharmonic = false;
end

if mod(Winding.Qs/Winding.t,Winding.m)==0
    Winding.feasable = true;
else
    Winding.feasable = false;
end;
return;
```

Appendix B

Examples arun.m

```
function wdt = arun(val)
%
% This example m-file is a driver for main function CDesign.m. Test cases
% given here are for three phases. The test cases are defined as follows:
%
% 1. wdt = CDesign('Qs',30,'p',5, 'x',1,'nl',2,'yd',3,'m',3)
% 2. wdt = CDesign('Qs',54,'p',6, 'x',1,'nl',2,'yd',4,'m',3)
% 3. wdt = CDesign('Qs',30,'p',10,'x',1,'nl',1,'yd',1,'m',3)
% 4. wdt = CDesign('Qs',30,'p',10,'x',1,'nl',2,'yd',1,'m',3)
% 5. wdt = CDesign('Qs',30,'p',5, 'x',1,'nl',1,'yd',3,'m',3)
%
% To run the function:
%
% arun(3)
%
% to run test case number 3.
%
if nargin == 0
    fprintf('Type <%s\n%s\n', 'help arun>', 'for more information');
    return;
end
switch val
case 1
    wdt = CDesign('Qs',30,'p',10,'x',1,'nl',1,'yd',1,'m',3);
    filename = 'fig6b.tex';
case 2
    wdt = CDesign('Qs',30,'p',10,'x',1,'nl',2,'yd',1,'m',3);
    filename = 'fig7b.tex';
case 3
    wdt = CDesign('Qs',30,'p',5, 'x',1,'nl',1,'yd',3,'m',3);
    filename = 'fig8b.tex';
case 4
```

```

        wdt = CDesign('Qs',30,'p',5, 'x',1,'nl',2,'yd',3,'m',3);
        filename = 'fig9b.tex';
    case 5
        wdt = CDesign('Qs',54,'p',6, 'x',1,'nl',2,'yd',4,'m',3);
    otherwise
        disp('Invalid test case numer. Type help arun');
        wdt = NaN;
        return;
    end

% Qs          : number of stator slots
% p           : number of pole pairs
% m           : number of phases
% yd          : coil pitch
% nl          : number of layers
% x           : slot pitch (set default to 1)
% t           : symmetry factor
% qsn         : see definition 3.1
% qsd         : see definition 3.1
% qcn         : see definition 3.2
% qcd         : see definition 3.2
% yp          : average coil pitch
% Qbasic      : basic winding number of slots
% Qc          : number of coils
% C           : in-going coil sides
% CRe        : out-going coil sides

basic.m = wdt.m;
basic.Q = wdt.Qs;
basic.p = wdt.p;
basic.yd = wdt.yd;
basic.nl = wdt.nl;
basic.Qb = wdt.Qbasic;
basic.pb = wdt.p/wdt.t;

if basic.nl == 1
    bot = zeros(1,basic.Qb);
    mmf = zeros(1,basic.Qb);
    M1 = wdt.C;
    M2 = wdt.CRe;
    for i = 1:basic.Qb
        for ii = 1:wdt.m
            bot(i) = bot(i) + M1(ii,i)*ii + M2(ii,i)*ii;
            mmf(i) = mmf(i) + ...
                1/basic.nl*(M1(ii,i)*cos((ii-1)*2*pi/wdt.m) ...
                    + M2(ii,i)*cos((ii-1)*2*pi/wdt.m));
        end
    end
end
end

```

```

else
    bot = zeros(1,basic.Qb);
    top = zeros(1,basic.Qb);
    mmf = zeros(1,basic.Qb);
    M1 = wdt.C;
    M2 = wdt.CRe;
    for i = 1:basic.Qb
        for ii = 1:wdt.m
            bot(i) = bot(i) + M1(ii,i)*ii;
            top(i) = top(i) + M2(ii,i)*ii;
            mmf(i) = mmf(i) + ...
                1/basic.nl*(M1(ii,i)*cos((ii-1)*2*pi/wdt.m) ...
                + M2(ii,i)*cos((ii-1)*2*pi/wdt.m));
        end
    end
end
fac = 1/(4*basic.Q)*360;
x_str = {};
x_str(1) = ' ';
for i = 2:2*basic.Qb+1
    if mod(i,2) == 0
        x_str(i) = num2str(i/2);
    else
        x_str(i) = ' ';
    end
end
if basic.m == 3
    figure(1);
    clf;
    if ~ishold
        hold on;
    end
    for ii=1:basic.Qb
        [x,y] = slot(ii);
        plot(x*fac,y);
        if basic.nl == 1
            [x,y] = rect(ii,basic.nl,0,basic.yd);
            fill(x*fac,y,colour(bot(ii)));
        else
            [x,y] = rect(ii,basic.nl,0,basic.yd);
            fill(x*fac,y,colour(bot(ii)));
            [x,y] = rect(ii,basic.nl,1,basic.yd);
            fill(x*fac,y,colour(top(ii)));
        end
    end
end
x = [4:4:basic.Qb*4]-2;
bar(x*fac,mmf,0.5,'k');
% x-axis

```

```

set(gca,'xlim',[0 basic.Qb*4]*fac);
set(gca,'xtick',fac*[0:x(end)/(2*basic.Qb-1):x(end)]);
set(gca,'xticklabel',x_str)
% y-axis
set(gca,'ylim',[-1.75 1]);
set(gca,'ytick',[-1.75:0.25:1]);
set(gca,'yticklabel',{' ',' ',' ','-1.0', ' ','-0.5',...
    ' ',' ',' ','0.5', ' ','1.0'});
xlabel('Slot number')
%
% add the working harmonic. The calculated winding axis is in
% degrees and the half slot pitch is already accounted for.
%
wnd = [];
wnd.axis = wdt.winding_axis;
phi = wnd.axis*basic.p*pi/180+pi/2;
xw = linspace(0,basic.pb*2*pi,100*basic.pb);
kw = wdt.Xsi_p;
yw = kw*cos(xw-phi);
fac = 180/pi*basic.Qb/basic.Q/basic.pb;
plot(xw*fac,yw,'k--');
hold off;
grid on;
end
%matlab2tikz(filename,'width','\fwidth');
end

function col = colour(ph)

switch ph
case(1)
col = 'red';
case(-1)
col = 'red';
case(2)
col = 'blue';
case(-2)
col = 'blue';
case(3)
col = 'yellow';
case(-3)
col = 'yellow';
end
end

function [x,y] = slot(n)

offset = 1.75;

```

```
x = [0,1,1,3,3,4]+(n-1)*4;
y = [0,0,1,1,0,0]*0.5-offset;
end

function [x,y] = rect(n,nl,p,yd)

X = [1,1,3,3,1];
Y = [0,1,1,0,0]*0.5;
offset = 1.75;

if nl == 1
    x = X+(n-1)*4;
    y = Y-offset;
else
    if yd == 1
        if p == 0
            x = [2,2,3,3,2]+(n-1)*4;
            y = Y-offset;
        else
            x = [1,1,2,2,1]+(n-1)*4;
            y = Y-offset;
        end
    else
        if p == 0
            x = X+(n-1)*4;
            y = Y*0.5-offset+0.25;
        else
            x = X+(n-1)*4;
            y = Y*0.5-offset;
        end
    end
end
end
end
```

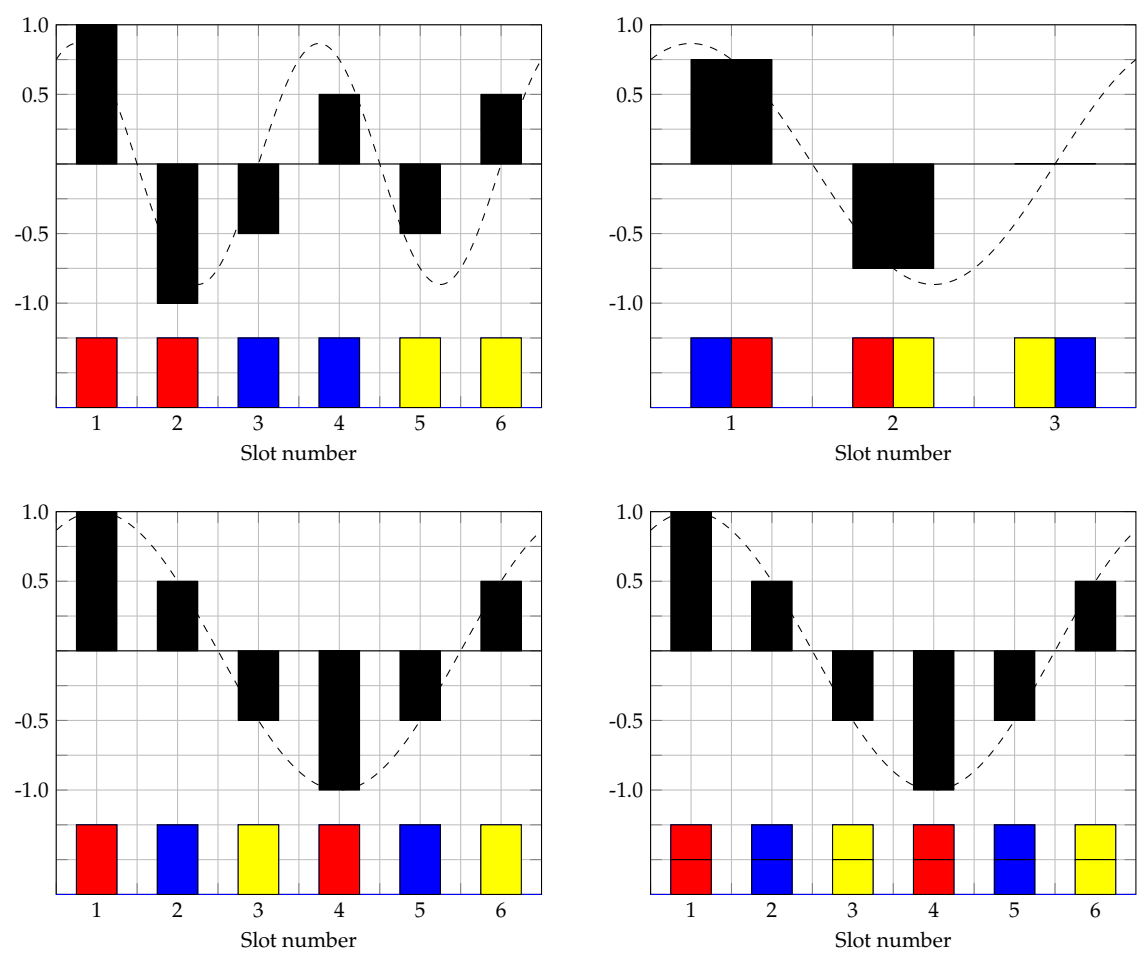


Figure B.1: Test results using `arun.m`

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