Classification of Symmetrical Non-Overlapping Three-Phase Windings

Johannes J. Germishuizen and Maarten J. Kamper

Abstract—Concentrated windings are commonly associated with permanent magnet machines. However, it is the opinion of the authors that this name does not uniquely describe this winding type. The paper suggests a unique classification scheme which is based on classical winding properties. This paper points out that non-overlapping windings can either be concentrated or distributed.

Index Terms—Non-overlapping, concentrated winding, basic winding, classification

I. 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 investigated 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 just a few years ago. A typical example of how advances in other fields lead to new ideas in electrical engineering, and especially electrical machines, is permanent magnet motors with non-overlapping windings. Furthermore, this winding type is not uniquely defined and needs reformulation as mentioned by the authors in [1].

In recent years various authors have pointed out the advantages and explained the design of permanent magnet machines with non-overlapping end-windings e.g. as given in [2]. Fig. 1(a) shows a single layer non-overlapping winding (the end-windings do not overlap). In the drawing it is clear that each coil is wound around a stator tooth. Moreover, the coils do not overlap. Cros and Viarouge [3] certainly aroused interest in non-overlapping windings with their valuable paper entitled Synthesis of High Performance PM Motors With Concentrated Windings, since this is a paper which is very often used as a reference for these winding types. The authors use the term concentrated windings in the title and give examples of windings that are not in conformance with the classical definition of a concentrated winding. In their paper it becomes clear that coils wound around a stator tooth are meant. This could be a possible explanation for the use of the term “concentrated windings” rather than “tooth coil windings”. It is interesting to note that in German this winding type is known as Zahnspulen which translated means tooth windings.

Fig. 1(b) shows a classical double layer winding with a coil pitch greater than one. Some of the coils are removed which makes it easier to identify the two layers. In this winding it is evident that the coil end-windings do overlap.

The importance of the theory on stator windings can be traced back to the 1930’s. In the first of his two remarkable papers Vilém Klíma (Wilhelm Kauders) [4] explains the systematics of stator windings and the calculation of the winding factors. Also in this paper the induced voltage in the coil sides is already mentioned and represented as a vector. The resultant vector diagram was called the star of coil groups. Two years later, in the second paper by Klíma [5], the algebraic methods developed in the first paper were visualised by means of Tingley’s diagram. The latter could be referred to as a linear representation of the star of slots that it is now called. The latter is also used by various authors such as are listed in [6].

The authors in [7] mention that Klíma’s equation for the closed form of the distribution factor\(^1\) of fractional slot windings is not found in textbooks.

\(^1\) Also known as the breadth factor.

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This paper will show that the winding in Fig. 1(a) is commonly referred to as a concentrated winding. It is the opinion of the authors that this name does not uniquely describe this winding type. 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 is referred to as a full-pitch concentrated winding as explained in textbooks such as [8]. Therefore, the objective of this paper is to answer the following question:

*How can concentrated windings commonly associated with permanent magnet machines be classified in a unique way?*

In order to answer this question the paper suggests a unique classification scheme which is based on the classical winding properties, i.e. slots per pole and phase and coil pitch. In the first part of the paper the winding properties are explained, while the second part focuses on characteristics required in the winding design.

II. DEFINITIONS AND TERMINOLOGY

In order to classify symmetrical non-overlapping three-phase windings in a unique way 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 which are used to sort them. These properties are explained in this section. The characteristic numbers give useful information on the winding and will depend on the properties which are used to classify them. These properties are explained in this section. The characteristic numbers give useful information on the winding when they are written as a reduced improper fraction. Good references are given by Wach in [9] and [10].

A. Slots and coils per pole and phase

Any three-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 and $p$ pole pairs the following definition holds for the slots per pole and phase:

$$q = \frac{Q_s}{2p} = \frac{q_n}{q_d} \quad (m = 3)$$  \hspace{1cm} (1)

where $\frac{Q_s}{2p}$ is the reduced form of $q$. For the case where $q_d$ equals one, $q$ is an integer and the winding is called an integral slot winding. When $q_d$ is greater than one, it is called a fractional slot winding. The reduced form of $q$ can be interpreted as follows: Each phase has $q_n$ slots that are distributed over $q_d$ poles.

The second winding property used in the classification scheme is the number of coils per pole and phase (not commonly used in literature). The definition is:

$$q_c = \frac{Q_c}{2p} = \frac{q_{c_n}}{q_{c_d}} \quad (m = 3)$$  \hspace{1cm} (2)

where $\frac{Q_c}{2p}$ is the reduced form of $q_c$. If $q_{c_n}$ (in the reduced form of $q_c$) is greater than one, then it is called a distributed winding. If $q_{c_n}$ equals one then it is a concentrated winding. The reduced form of $q_c$ can be interpreted as follows: Each phase has $q_{c_n}$ coils distributed over $q_{c_d}$ poles.

B. 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. However, the average coil pitch can be a real number and is defined as:

$$y_p = \frac{Q_s}{2p} \quad (y_p \in \mathbb{R})$$  \hspace{1cm} (3)

In the case where the average coil pitch as expressed in (3) equals a real number, the actual (or practical) coils pitch $y_d$ must be an integer, i.e.

$$y_d = \text{int}(y_p) \pm k \quad \left\{ \begin{array}{l} k \in \mathbb{N} \\ y_d \geq 1 \end{array} \right.$$  \hspace{1cm} (4)

When $y_d = y_p$, it is a full-pitch winding and if $y_d \neq y_p$, it is called a fractional pitch winding, i.e. the winding is chorded. The properties of single and double layer\(^4\) windings are summarised in Table (1).

<table>
<thead>
<tr>
<th>TABLE I: Winding properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single layer</td>
</tr>
<tr>
<td>Double layer</td>
</tr>
<tr>
<td>Average coil pitch</td>
</tr>
<tr>
<td>Actual coil pitch</td>
</tr>
<tr>
<td>$Q_s$ – number of stator slots</td>
</tr>
<tr>
<td>$Q_c$ – number of winding coils</td>
</tr>
<tr>
<td>$q$ – number of slots per pole and phase, (1)</td>
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<tr>
<td>$q_n$ – numerator of $q$</td>
</tr>
<tr>
<td>$q_d$ – denominator of $q$</td>
</tr>
<tr>
<td>$q_{c_n}$ – number of coils per pole and phase, (2)</td>
</tr>
<tr>
<td>$q_{c_d}$ – denominator of $q_c$</td>
</tr>
</tbody>
</table>

C. Definition of the working harmonic

All harmonics are referred to in terms of the bore $2\pi$ 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 $\nu^{th}$ order will have $\nu$ pole pairs and spans a peripheral angle of $\frac{2\pi}{\nu}$ as explained in [13]. Often the harmonic orders are normalised with respect to the *working harmonic*, i.e. $\xi_{\nu/p}$. This then means that the *working harmonic* is written as $\xi_1$ and sub-harmonics will have a fraction as subscript.

\(^4\)A single and double layer winding have one and two coil sides per slot respectively.
D. Basic winding

The smallest repetitive segment is called the basic winding (as defined in [13]). 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.

\[
t = \begin{cases} \gcd(Q_s, p) & \text{for double layer} \\ \gcd(\frac{Q_s}{2}, p) & \text{for single layer} \end{cases}
\]  

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

\[
Q_b = \frac{Q_s}{t} \quad \text{and} \quad p_b = \frac{p}{t}
\]  

(6)

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.

\[
p_b = \begin{cases} \frac{1}{2} q_{c_d} & q_{c_d} \text{ even} \\ q_{c_d} & q_{c_d} \text{ odd} \end{cases}
\]  

(7)

which is independent of \( t \). Examining (5), it can be seen that \( t \) can be rewritten as the \( \gcd \) between the number of coils and the pole pairs, i.e.

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

(8)

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. Since the winding design is independent of time, it does not cause any confusion.

E. 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 (6). The symmetry condition can be expressed as

\[
\frac{Q_s}{t} = mk, \quad k \in \mathbb{N}
\]  

(9)

which refers to 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 determines the remainder after division, i.e. \( \mod(a, b) = a - \text{floor}(\frac{a}{b})^5 \). When using the modulo function it means that \( \mod(\frac{Q_s}{t}, m) \) must equal zero. There are different ways of deriving the constraints for the winding symmetry condition. Table II gives different variations found in literature to express the symmetry condition.

TABLE II: Constraints for winding symmetry

<table>
<thead>
<tr>
<th>Reference</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wach, [9]</td>
<td>( \gcd(q_{c_d}, m) = 1 )</td>
</tr>
<tr>
<td></td>
<td>( \mod(\frac{Q_s}{t}, q_{c_d}, m) = 0 )</td>
</tr>
<tr>
<td>Cross and Viarouge, [3]</td>
<td>( \mod(\frac{Q_c}{2}, \gcd(Q_c, 2q_d), m) = 0 )</td>
</tr>
<tr>
<td>Bianchi, [6]</td>
<td>( \mod(\frac{Q_c}{t}, m) = 0 )</td>
</tr>
</tbody>
</table>

F. 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 subharmonics which are summarised as follows:

\[
t = p \quad \text{the winding has no subharmonics} \\
t < p \quad \text{the winding has subharmonics}
\]  

(10)

The reduced number of pole pairs can be calculated in two different ways. Two greatest common divisors, i.e. \( \gcd(Q_c, 2mp) \) 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:

\[
\gcd(Q_c, p) = \gcd(\frac{Q_c}{m}, 2p) = \frac{r}{r} \begin{cases} m & q_{c_d} \text{ even} \\ 2m & q_{c_d} \text{ odd} \end{cases}
\]  

(11)

III. 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. 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.

Fig. 2 shows a possible way to classify symmetrical three-phase windings. The reason for choosing the average coil pitch as a 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:

- **Overlapping and non-overlapping**: In overlapping windings the coil end-windings overlap and the coil pitch \( y_d \) is greater than one. If the coil pitch \( y_d \) equals one, the coil end-windings do not overlap.

- **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.

- **Full-pitch and fractional pitch**: If the coil pitch \( y_d \) equals the average coil pitch it is called a full-pitch winding. If
$yd \neq yp$ the winding is chorded and is called a fractional
pitch winding. In the special case where the number of
slots per pole and phase equals one it is called a full-pitch
concentrated winding.

- **Integral and fractional slot**: If the denominator $q_d$ equals
one it means that $q$ is an integer and it is called an integral
slot winding. If $q_d$ is greater than one it means $q$ is a
fraction and hence a fractional slot winding. In addition,
the average coil pitch $yp$ is a fraction.

- **Distributed and concentrated windings**: 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 concen-
trated winding. In the case where $q_{cn}$ equals one, it is
called a concentrated winding.

Fig. 2 defines the concentrated windings commonly associated
with permanent magnet machines in a unique way, i.e. non-
overlapping. Furthermore, it is shown that it could be either
concentrated or distributed.

$$q = \frac{Q_s}{m2p} = \frac{q_n}{q_d} \quad \text{and} \quad q_c = \frac{Q_c}{m2p} = \frac{q_{cn}}{q_d}$$

$$yp = \frac{Q_s}{2p} \quad \text{and} \quad y_d = \text{int}(yp) \pm k \quad \{k \in \mathbb{N} \quad y_d \geq 1\}$$

**IV. NON-OVERLAPPING AND OVERLAPPING WINDINGS**

Fig. 3 summaries the four primary winding types. The
two main categories are overlapping and non-overlapping.
Each category can then be a single or double layer winding.
Especially the winding types in Fig. 3(a) and Fig. 3(b) are
commonly used in permanent magnet machines. However,
authors use different terminologies and this can often be
misleading. The most common terms found in literature for
non-overlapping windings are:

- concentrated windings [14];
- concentrated fractional pitch windings [15];
- fractional slot wound [16]; and
- fractional slot [17].

In each case non-overlapping windings are meant, i.e. the
winding type where the coils are wound around a stator tooth.

Table III gives a few examples where the classification
scheme that has been introduced is applied. Examples 1
through 3 are typical single and double layer windings and
clearly indicate the difference between integral and fractional
slot. Examples 4 through 6 are commonly referred to in the
literature as concentrated windings. It is the opinion of the
authors that the term concentrated winding already has a
clear meaning in electrical machines, i.e. a winding where the
number of slots per pole and phases equals one. Examples 3
and 6 are an overlapping concentrated and a non-overlapping
concentrated winding respectively.

<table>
<thead>
<tr>
<th>No.</th>
<th>$Q_s$</th>
<th>$Q_c$</th>
<th>2p</th>
<th>$q_{n}/q_d$</th>
<th>$q_{cn}/q_d$</th>
<th>$yp$, $yd$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>108</td>
<td>108</td>
<td>10</td>
<td>18/5</td>
<td>18/5</td>
<td>10.8, 10</td>
<td>Overlapping fractional pitch distributed</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>18</td>
<td>4</td>
<td>3/1</td>
<td>3/2</td>
<td>9, 9</td>
<td>Overlapping full-pitch integral slot distributed</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>27</td>
<td>18</td>
<td>1/1</td>
<td>1/2</td>
<td>3, 3</td>
<td>Overlapping full-pitch integral slot concentrated</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>21</td>
<td>26</td>
<td>7/26</td>
<td>7/26</td>
<td>0.81, 1</td>
<td>Non-overlapping fractional pitch fractional slot distributed</td>
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<tr>
<td>5</td>
<td>72</td>
<td>36</td>
<td>68</td>
<td>6/17</td>
<td>3/17</td>
<td>1, 0.6</td>
<td>Non-overlapping fractional-pitch fractional slot distributed</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>15</td>
<td>20</td>
<td>1/2</td>
<td>1/4</td>
<td>1.5, 1</td>
<td>Non-overlapping fractional-pitch fractional slot concentrated</td>
</tr>
</tbody>
</table>

**V. INTEGRAL AND FRACTIONAL COIL WINDINGS**

The authors conclude the paper with a new idea, which is
found to be useful when comparing non-overlapping windings.
According to the classification of the three-phase windings in
Fig. 2, non-overlapping windings are always fractional slot
Fig. 3: Winding types

windings, except in some rare, unused cases. Therefore, non-overlapping windings are practically never integral slot windings. However, when comparing layouts of non-overlapping and overlapping windings the authors found that it is very useful to define integral- and fractional coil windings as presented in [1]. This is explained in the following sections.

A. Definition

Equations (1) and (2) are used to define the number of coil phase groups \( q_{cb} \) in a coil phase belt. In this way, integral coil and fractional coil windings are defined as

\[
q_{cb} = \begin{cases} 
\frac{c}{m} & \text{integral coil} \\
\frac{c}{m} & \text{fractional coil} 
\end{cases} 
\]

where

\[
q_{cb} = \begin{cases} 
q_d & \text{for overlapping} \\
3q_{ca} & \frac{Q_c}{Q_s} - 2p & \text{for non-overlapping} 
\end{cases} 
\]

B. Number of coils in a phase group

The basic winding is the smallest repetitive winding segment. However, in FE-modelling the basic winding can in some cases be divided into smaller sections based on the symmetry conditions. The latter will depend on the number of coils in a phase group. This results in a smaller FE-model with a reduced solution time. The number of coils distributed in a phase group is the numerator \( q_{ca} \) as defined in (2). It can also be defined in terms of the number of sections in the basic winding \( W_s \), i.e.

\[
q_{ca} = \frac{Q_c}{mW_s} \begin{cases} 
\frac{W_s}{\gcd(2p, Q_c)} & m \text{ is the number of phases} \\
q_{ca} & q_{ca} \in \mathbb{N} 
\end{cases} 
\]

which must be an integer number for the winding to be valid. In the case of concentrated non-overlapping windings, there is only one coil in a coil phase group \( q_{ca} = 1 \). For distributed non-overlapping windings there are two or more coils \( q_{ca} = 2, 3, \ldots \) distributed and connected into series to form a coil phase group.

C. Examples

The definition of the number of coil groups in a coil phase belt is applied to some of the examples given in Table III. Let us take the examples of two double layer windings; one is an overlapping winding and the other a non-overlapping winding. The results are presented in Table IV as 1b (5 coil groupings and 18 coils) and 4b (5 coil groupings and 7 coils).

Let us consider two single layer windings; one is an overlapping winding and the other a non-overlapping winding. In Table IV these are denoted as 2b (1 coil group and 3 coils) and 5b (1 coil group and 3 coils).

Note that \( q_{cb} \) in the case of the non-overlapping winding gives more information about the non-overlapping winding layout, namely if \( q_{cb} = 1 \) then all the \( q_{ca} \) coils in a coil phase belt are grouped together, while if \( q_{cb} > 1 \) then all the \( q_{ca} \) coils are distributed in an unsymmetrical way in the coil phase belt; the former is a typical characteristic of a fractional slot winding.
TABLE IV: Winding examples – part 2

<table>
<thead>
<tr>
<th>No.</th>
<th>$q_s$</th>
<th>$q_c$</th>
<th>$2p$</th>
<th>$q_{cd}$</th>
<th>$q_{ae}$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>100</td>
<td>108</td>
<td>18</td>
<td>5</td>
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<td>integral coil</td>
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</tbody>
</table>

D. Periodical boundary conditions for FE modelling

Note that $q_{cd}$ from (2) gives the (minimum) number of poles necessary that have to be meshed in the FE modelling of the machine, and, as explained by [1], if $q_{cd}$ is uneven then negative periodical boundary conditions must be applied in the FE analysis. If this is not done, then if $q_{cd}$ is even then positive periodical boundary conditions must be used.

VI. CONCLUSION

The paper uses well-known winding definitions and terminology and from this presents a classification scheme to relate different winding types to each other. It is also a useful guideline to compare windings that belong to the same category. The unique contribution of the paper is to point out that non-overlapping windings can be concentrated or distributed. Furthermore, the authors introduce a new concept of integral- and fractional coil windings for better comparison of non-overlapping windings.

REFERENCES


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