ELSYS Note

Unwinding the Basics of Machine Windings

This note provides a framework for classifying electrical machine windings based on key parameters like slots per pole per phase and coil pitch. The focus is on clarifying terminology and highlighting non-overlapping windings, which are widely used in modern machine designs. Clear classification aids in improving both design and analysis.

Introduction

The design of electrical machine windings has always been a key topic in engineering, with particular focus on their classification and terminology. The increasing popularity of non-overlapping windings, where coils are wound directly around individual stator teeth, has fueled this confusion. These windings are widely used in permanent magnet synchronous machines (PMSMs) due to their compact design and simplicity. Interest in this design was sparked by the work of a well-cited paper, [1]. While the paper specifies that the windings are placed around stator teeth, its title seems to refer to concentrated windings in general. This has led to confusion because, in the context of winding synthesis, "concentrated winding" already has a specific meaning: **a winding with one slot per pole per phase**.

The terminology introduced in the paper has been used inconsistently by many authors since then. A later study [2] attempted to clarify this by reintroducing the term "traditionally concentrated windings", but these efforts have not fully resolved the issue. Miscommunication often arises from unclear or overlapping definitions. Understanding the foundational terminology is crucial for accurate communication in the field and for promoting consistent practices in research and industry. This note explores a systematic approach to classify windings, offering a framework for both clarity and consistency in machine design. Furthermore, it emphasizes the importance of selecting terminology thoughtfully in research and avoiding unnecessary new terms unless absolutely essential.

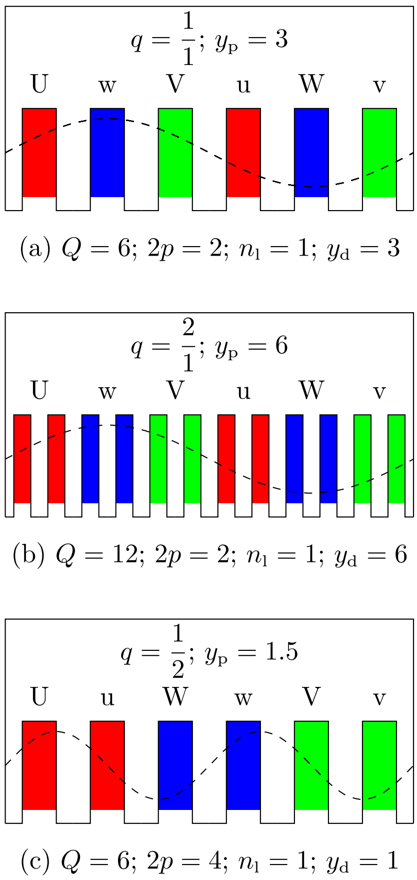
Winding classification

In this ELSYS Note, three winding layouts are presented to visually demonstrate the basic principles of machine winding classification. These layouts, illustrated in Fig. 1, serve as a starting point for understanding the structure and synthesis of windings. For a more comprehensive explanation and in-depth synthesis of windings, the reader is referred to [3].

Winding Configurations

The first configuration in Fig. 1(a) consists of 6 slots and 2 poles, forming a single-layer winding with a coil span of 3. While this arrangement is simple, it is less commonly used due to its generation of higher-order harmonics. Such configurations are typically reserved for specialized designs.

A more conventional approach is the distributed winding, where the coil sides are spread across multiple slots. In Fig. 1(b), the winding spans 2 slots per pole to reduce higher-order harmonics, improving performance in most applications.



(a) $Q = 6$; $2p = 2$; $n_l = 1$; $y_d = 3$

(b) $Q = 12$; $2p = 2$; $n_l = 1$; $y_d = 6$

(c) $Q = 6$; $2p = 4$; $n_l = 1$; $y_d = 1$

Fig. 1: Winding layouts

Table 1: Winding classification

Test	Classification Condition	
Distribution test	Concentrated	Distributed
	$q_n = q_d = 1$	$q \neq 1$
Integral slot	Integral slot	Fractional slot
	$q_d = 1$	$q_d \neq 1$
Layer	Single	Double
	$n_l = 1$	$n_l = 2$
Pitch	Full-pitch	Fractional pitch
	$y_d = y_p$	$y_d \neq y_p$
Overlapping	Non-overlapping	Overlapping
	$y_d = 1$	$y_d > 1$

Fractional vs. Integral

The classification of windings is often expressed using the term "slots per pole per phase" q, written in its "reduced form" form as:

$$q = \frac{q_n}{q_d} \quad (1)$$

where q_n and q_d are the integers Q/F and $(2p)/F$, F being the highest common factor (or "greatest common divisor") of Q and $(2p)$.

Single- vs. Double-Layer

A winding with two coil-sides per slot is defined as *double-layers*, while a *single-layer* winding has only one coil-side per slot. This distinction applies to both overlapping and non-overlapping windings, providing flexibilty in machine design.

Coil pitch

The *coil pitch* y_p is the peripheral angle between the two coil-sides of the same coil. In this note it is measured in mechanical radians. It is virtually the same as the span which is more usually measured in slots, i.e. in multiples of the slot-pitch. A full-pitch coil is one whose pitch is equal to the pole-pitch at the working harmonic; thus

$$y_p \begin{cases} = \dfrac{2\pi}{2p} \text{ mech. rad;} \\ = \dfrac{Q}{2p} \text{ slot span} \end{cases} \quad (2)$$

Note that although the span of a full-pitch coil is not an integer in a fractional-slot winding, the full-pitch coil is nevertheless an important reference concept.
The chosen coil span is necessarily an integer, giving rise to the actual pitch

$$y_d = \text{int}\,(y_p) \pm k \quad \begin{cases} k \in \mathbb{N}_0 \\ y_d \geq 1 \end{cases} \quad (3)$$

A full-pitch coil has $y_d = y_p$; otherwise the coil has fractional pitch.

The properties in (1)–(3) can be used to classify symmetrical windings according to Tab. 1.

Non-Overlapping

In the case where $y_d = 1$ the winding is non-overlapping, i.e. wound around the a stator tooth. Such a winding is shown in Fig. 1(c).

Conclusion

The classification of windings in electrical machines is essential for their design and performance. By defining parameters such as slots per pole per phase, coil pitch, and distinguishing overlapping from non-overlapping windings, a structured framework emerges. Key insights include the role of coil pitch in reducing harmonics and the growing use of non-overlapping windings, particularly in permanent magnet machines.

References

[1] Jérôme Cros and Philippe Viarouge. "Synthesis of High Performance PM Motors With Concentrated Windings". *IEEE Transactions on Energy Conversion* 17.2 (June 2002), pp. 248–253. DOI: 10.1109/TEC.2002.1009476.

[2] Florence Meier, Stephan Meier, and Juliette Soulard. "Emetor - An educational web-based design tool for permanent-magnet synchronous machines". *Proceedings of the 2008 International Conference on Electrical Machines.* 2008. DOI: 10.1109/ICELMACH.2008.4800232.

[3] Johannes Germishuizen and Andreas Kremser. "Algebraic Design of Symmetrical Windings for AC Machines". *IEEE Transactions on Industry Applications* 57.3 (2021), pp. 1928–1934. DOI: 10.1109/TIA.2021.3057607.