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ELSYS Note

Winding axis

The magnetic winding axis is a fundamental reference quantity in electrical machine analysis and control. This note presents a simple method based on the working harmonic of the air gap vector potential. The method requires only a single finite-element solution, is independent of the winding topology, and is verified using the corresponding air gap flux density harmonic.

Introduction

The **magnetic winding axis** is a fundamental reference quantity in the analysis and control of electrical machines. It is required for the definition of current and flux space vectors, dq-transformations, rotor position references, and field-oriented control schemes.

In this note, the positive magnetic winding axis is defined as the angular position at which the fundamental air gap flux crosses the air gap from the rotor towards the stator for a given current excitation.

In FEA, the winding axis is often determined from winding functions, current-sheet distributions, magnetomotive force (MMF) waves, air gap flux density distributions, or space-vector representations. While all of these approaches are valid, they frequently require electrical-to-mechanical angle conversions and careful consideration of phase shifts and sign conventions. In particular, the well-known 90° electrical phase shift between the magnetic vector potential and the air gap flux density can complicate the interpretation of the results.

This note presents a simple alternative approach based on the working harmonic of the air gap vector potential. The method requires only a single finite-element solution and a harmonic analysis of the resulting vector potential distribution in the air gap.

Principle

A balanced three-phase current system is applied to the stator winding and the magnetic vector potential is sampled along the air gap boundary

$$A_z(\theta). \tag{1}$$

The working harmonic corresponding to the machine pole-pair number p is extracted using a DFT and can be written as

$$\hat{A}_p \cos\left(p \cdot \theta - \alpha_\mathrm{A}\right). \tag{2}$$

The phase angle α_A directly defines the spatial orientation of the stator excitation. In this note, the current system is initialised such that the phase-U current assumes its positive peak value,

$$i_\mathrm{U} = \hat{I},\ i_\mathrm{V} = -\frac{\hat{I}}{2},\ i_\mathrm{W} = -\frac{\hat{I}}{2}.$$

Consequently, the extracted phase angle is referenced to the positive phase-U excitation.

The magnetic vector potential is directly related to the current-sheet distribution and therefore provides a natural reference for the determination of the magnetic winding axis. The winding axis can consequently be obtained directly from the phase angle of its working harmonic.

4-Pole Induction Machine

The working harmonic of the air gap vector potential is extracted from the finite-element solution as shown in Fig. 2(a). The positive zero-crossing at $\theta = 150°$ identifies the positive magnetic winding axis.

Fig. 1 shows the negative winding axis obtained directly from the winding layout. For a machine with $p = 2$ pole pairs, the positive winding axis is located half a pole pitch away.

The winding axis obtained from the vector potential harmonic therefore agrees with the winding layout.

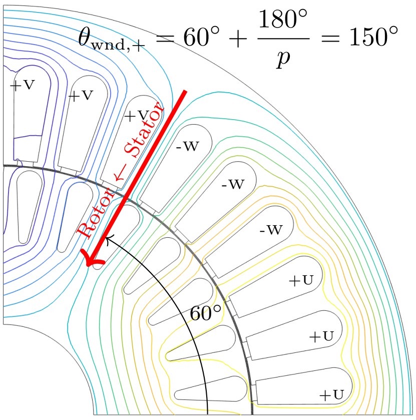
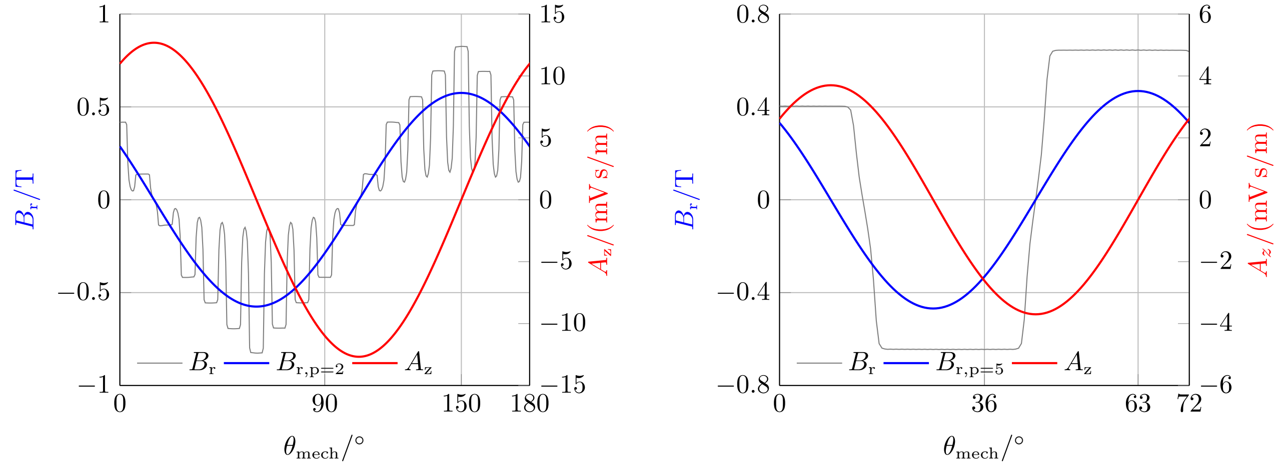


Fig. 1: 4-Pole induction motor



(a) Induction machine $Q_1 = 36$ and $p = 2$

(b) PMSM $Q_1 = 12$ and $p = 5$

Fig. 2: Air gap flux density and working harmonic of the vector potential.

12-Slot 10-Pole Machine

As a second example, the method is applied to a 12-slot 10-pole machine with a double-layer non-overlapping winding.

For this machine topology, the winding axis is considerably more difficult to determine directly from the winding layout. Traditional approaches based on winding functions, MMF distributions, current-sheet representations, or space-vector diagrams require several intermediate transformations and careful interpretation of phase conventions.

The determination of the winding axis is reduced to the following four steps:

1. Apply a balanced three-phase excitation.
2. Extract the air gap vector potential.
3. Determine the working harmonic using a DFT.
4. Obtain the winding axis from the harmonic phase angle.

The resulting winding axis is obtained directly from the finite-element solution without additional transformations. As shown in Fig. 2(b), the positive magnetic winding axis corresponds to the positive zero-crossing of the vector potential harmonic at 63°.

Fig. 3 illustrates the extracted harmonic for the 12-slot 10-pole machine. This example highlights the usefulness of the proposed method, since the winding-axis position is not readily identified from the winding layout or the magnetic field distribution.

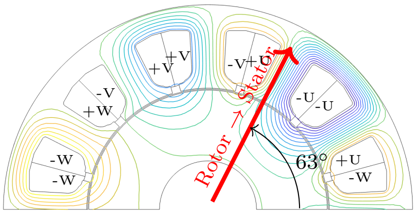


Fig. 3: 10-Pole PMSM

Air gap Flux Density

The air gap flux density may be used as an independent consistency check. In 2D finite-element formulations, the magnetic vector potential is the primary solution variable, while the flux density in the air gap is obtained from

$$\mathbf{B} = \nabla \times \mathbf{A} \implies B_r = \frac{1}{r}\frac{\partial A_z}{\partial \theta}.$$

The working harmonic of the flux density is therefore shifted by 90° electrical with respect to the vector potential harmonic. For both examples, the corresponding harmonics shown in Fig. 2 provide an independent verification of the extracted magnetic winding axis.

Conclusions

A simple method for determining the magnetic winding axis from finite-element simulations has been presented. The method is based on the working harmonic of the air gap vector potential and requires only a single finite-element solution.

The approach is independent of the winding topology and avoids repeated electrical-to-mechanical angle transformations as well as ambiguities caused by phase conventions. The resulting winding axis can be verified directly using the corresponding harmonic of the air gap flux density.

The method is particularly useful for fractional-slot and non-overlapping windings, where the magnetic winding axis is often difficult to identify directly from the winding layout.