

Modelling of space harmonics in AC machines for real-time applications

Context

Electric machines are ubiquitous in modern society, with applications across the residential, industrial, and transportation sectors. Simultaneously, current concerns about climate change and the need for a more responsible use of energy motivate the development of more efficient electric drives and control strategies for their operation. For example, in numerous industrial applications, higher efficiency could be achieved by feeding electric machines using power converters rather than connecting them directly to the mains. Moreover, power electronics has enabled meeting a fundamental demand of the manufacturing industry for highly accurate, dynamic speed or position control.

Although permanent magnet machines offer the best potential for efficiency and dynamics, the induction machine remains the most widely used motor type in industry, mainly for economic reasons. Its robustness, simple design, and minimal wear allow significant reductions in manufacturing costs and maintenance effort, making it well-suited for low-cost applications and harsh operating conditions.

Low-power applications up to a few tens of kilowatts typically use off-the-shelf machines that can be easily operated using well-established schemes such as field-oriented or direct torque control. These control techniques assume a sinusoidally distributed radial magnetic field in the air-gap between the stator and the rotor. However, the air-gap field distribution of low-power induction machines typically exhibits high levels of harmonics, leading to unwanted stator current components, torque oscillations, and increased losses. Simultaneously, these field harmonics, commonly referred to as “space harmonics”, provide helpful information for monitoring machine condition or estimating rotor speed.

The consideration of space harmonics requires more precise machine models than those used in traditional electric drive control. While finite element analysis is an appropriate response to this need in machine design, it is not suitable for control applications involving unknown internal machine structures and magnetic properties, a typical situation with off-the-shelf machines. Moreover, the machine models must remain simple enough to execute in real time on drive controllers with modest computational power, such as microcontrollers.

The study published in [1] describes a modelling strategy that addresses these requirements in the special case of linear magnetic properties, a constant air-gap length, and space harmonics arising from the non-sinusoidal distribution of the electric conductors along the air-gap circumference. The approach relies on the winding function theory and key mathematical properties of Fourier series to derive simple analytical relations between currents and flux linkages under the influence of the field harmonics. A mathematical transformation based on Fourier matrices was proposed to obtain efficient state-space models for specific machines.

Research focus

The modelling approach in [1] is expected to benefit model-based drive control applications by:

- allowing for current and torque waveforms with reduced harmonic content in steady state;
- providing new insights into the modelling of AC machines;
- bridging the gap between mathematics and the practical field of electric drives with a physically meaningful interpretation of the model's mathematical equations.

In this context, our ongoing research activities focus on the following lines of inquiry:

- Applying the approach to multi-phase induction machines;
- Examining the concrete benefits of the approach for closed-loop control (e.g. predictive or encoderless control);
- Extending the theory in [1] to machines with variable air-gap length (e.g. reluctance synchronous machines) and magnetic non-linearities;
- Comparing the strategy to Kron's modelling of space harmonics based on virtual machines;

From a research perspective, the following aspects are particularly interesting:

- machines with variable air-gap length:
 - The model equations are more complex, and additional dependences on the rotor angle arise;
 - The strategy developed so far does not yield the desired simplifications of the model equations.
- machines with pronounced non-linear magnetic behaviour:
 - The magnetic relations are tremendously more complicated;
 - There are no such handy mathematical tools as in the linear case;
 - The influence of space harmonics on the current waveforms is blurred and therefore difficult to make sense of.

Contact

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Selected publications

[1] Julien Cordier. *Modelling space harmonics in induction machines for real-time applications*, doctoral thesis, Technical University of Munich, 2020.

[2] J. Cordier, S. Klass, and R. Kennel. A comparison of three state-space models of an induction machine derived from the same set of conductor distribution harmonics. In *2021 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2021 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, pages 451–460, 2021. DOI: 10.1109/OPTIM-ACEMP50812.2021.9590035