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Performance evaluation of three and multi-three-phase electrical machines using off-line mapping

A sustainable and green future requires an effective energy transition towards more efficient and carbon-free solutions. The electrification of various applications, e.g., automotive, naval, aircraft, wind energy, etc., is an effective tool for these aims. Electrified systems include different engineering areas, i.e., electrical machines, battery systems, power converters, etc. A reliable design and analysis of the system components require more efficient approaches to minimize costs and time-to-market. Nowadays, it is evident that we need new intelligent methods to emulate the whole system's behavior.

The virtualization of the electric components in an electrified system is a method with excellent potential to assess the system design goodness in terms of efficiency and operational limits. The core of electrified systems is the electrical machine, which must be designed to target the maximum possible efficiency and fault-tolerant operation. New solutions such as multiphase electrical machines fulfill these goals. The main advantage of multiphase drives is reducing the current per phase without increasing the phase voltage. Moreover, multiphase drives are intrinsically fault-tolerant. The latter two characteristics make multiphase machines more attractive for the future of electrified systems. Indeed, the higher number of phases improves the system reliability using redundancy from both power converter and electrical machine points of view. However, multiphase drives are still limited to high power and safety-critical application due to the historical evolution of the three-phase drives, which have reached more maturity only in the last few years.

The main goal of the dissertation is to develop a straightforward methodology for computing the efficiency and loss mapping of three-phase and multi-three-phase electrical machines. The proposed method allows a quick and accurate energetic assessment and machine virtualization. The method does not require expensive test rigs to manage demanding speed and torque, but it is based on an equivalent circuit/analytical model accurately evaluated. Therefore, the proposed procedures represent an effective solution to avoid the burden of FEA analyses and expensive experimental mapping procedures. Moreover, the proposed method allows the reconstruction of all electrical variables of the machine (i.e., currents, voltages, fluxes), representing the first step toward accurate virtualization of electrical machines operated in wide torque-speed ranges. Last but not least, the mapping output can achieve the maximum efficiency control strategy and avoid the maximum torque per ampere that is usually implemented in machine control.

The dissertation develops as follows:

- The procedure is developed to quickly compute the efficiency maps of three-phase induction motors (IMs) operated in wide torque-speed ranges. The efficiency, losses, currents, voltages, fluxes, maps of the machine (both in motoring and generator operation), were obtained considering different operating temperatures and dc-link voltages. All electromechanical variables are reconstructed, replacing a machine control strategy. The input of the methodology consists of the standard test procedure results like dc, no-load, and locked-rotor tests performed at different voltage and frequency levels. All machine’s nonlinearities, e.g., magnetic saturation, skin effect, and iron losses, are strictly considered. The proposed methodology was validated on a 10 kW, 4 poles, 100 Hz IM prototype. Computed and experimental efficiency maps for different operating conditions are in very good agreement, confirming the validity of the proposed methodology.

- The mapping for the three-phase synchronous internal permanent magnets (IPM) is developed based on the same methodology proposed for three-phase IMs. However, in this case, the input variables of the mapping algorithm, i.e., magnetic characterization, core, and PM losses, were not measured on a prototype but obtained by 2D Finite Element Analysis (FEA). An accurate mapping is obtained, considering all the nonlinearities of the machine. The effectiveness of the procedure was validated through an FEA comparison.

- In the continuous need for energy saving, requiring more efficient electrical drives, the mapping for multi-three-phase IM is developed. A novel mapping algorithm is proposed considering healthy and open-winding faulty conditions. The procedure is based on the results of standard test procedures like dc, no-load, and locked-rotor tests performed at different voltage and frequency levels under a sinusoidal supply. Note that the standard tests still need to be consolidated for multi-three-phase IM and are not easy to perform due to the unavailability of sinusoidal multiphase sources. Based on the test results performed under inverter supply, the mapping was developed using all mathematical methods available in the literature, obtaining the same results for all machine conditions and confirming the algorithm's robustness. Moreover, the simplicity of the mapping algorithm is preserved. The mapping code replaces control strategies, i.e., maximum efficiency, minimum stator Joule losses, and minimum stator flux.

The experimental validation was carried out on 12-phase asymmetrical IM 10~kW, 4~poles, 6000~rpm, implementing a sophisticated machine control, a complex test rig, and an advanced measurement system. The open-winding faulty conditions were emulated, turning off the power module, and the corresponding unit, i.e., winding set plus inverter, was disconnected from the dc-link. The experimental results demonstrate the effectiveness and feasibility of the proposed mapping algorithm, providing all necessary data for the multi-three-phase IM virtualization in both conditions and the reference values for control implementation, i.e., stator flux, *dq* stator currents.