

# Abstract

Variable Flux Machines (VFMs) are a promising solution for improving the sustainability and operating flexibility of electric drives, particularly in traction applications. By exploiting low-coercivity permanent magnets, VFMs allow their magnetization state ( $MS$ ) to be intentionally adjusted during operation, enabling adaption of the PM flux linkage according to torque and speed requirement. This feature can extend the operating speed range, improve efficiency over the driving cycle and reduce the dependence on heavy rare earth permanent magnets. However, these advantages are accompanied by significant challenges in machine design, electromagnetic modeling and control, mainly due to the irreversible demagnetization and remagnetization behavior of low-coercivity magnets and the high-amplitude current pulses required for  $MS$  manipulation.

This dissertation addresses these challenges through a framework covering machine geometry selection, control-oriented modeling, optimal strategy for  $MS$  regulation while maintaining smooth torque control and operating range evaluation under inverter voltage constraints. First, different rotor topologies for VFMs employing only low-coercivity magnets are comparatively analyzed. The results show that the Surface Permanent Magnet (SPM) topology provides the best compromise in terms of remagnetization current demand, robustness against unintended demagnetization, and torque controllability during  $MS$  variation transients. Based on this outcome, an SPM Proof-of-Concept (POC) machine is designed as the main reference case, and a traction-oriented VFM using FeN magnets is also developed for traction application case analysis.

The development of VFM control strategies requires extensive simulation stages. Compared to standard PMSMs, the VFM models inherently need to dynamically account for PM demagnetization. This is traditionally achieved by co-simulation merging Finite Element Analysis (FEA) software into the simulation environment, with significant computational burden, time and storage demand, incompatible with control development and calibration purposes. To this end, a control-oriented electromagnetic model of the VFM is proposed. A baseline formulation is first developed to represent irreversible demagnetization and remagnetization through the use of magnetization maps, flux maps, and an  $MS$  updating mechanism. The model is subsequently extended to include asymmetric magnetization under load by introducing the complex magnetization state, an armature-flux formulation, and a two-virtual-magnet representation. [The proposed modeling methodologies are validated against FEA-based simulations and implemented in a real-time Hardware-in-the-Loop \(HiL\) environment, showing high accuracy together with a significantly improved computational effort.](#)

On the control side, two dedicated strategies are proposed to mitigate torque pulsation during  $MS$  variation under load. The first one is developed within Direct Flux Vector Control framework, while the second one is based on a modified Field Oriented Control structure, referred to as the  $i_d - T$  strategy. Both approaches avoid the explicit estimation of the full current trajectory through intermediate magnetization states and proved to achieve smooth torque transitions during demagnetization and remagnetization processes.

Finally, the dissertation addresses the inverter voltage limit during remagnetization transient, which strongly constrains the feasible operating range of VFM under load. A computationally efficient method is proposed to determine the remagnetization feasibility boundary in the torque-speed plane by combining pre-calculated flux maps and magnetization maps. The

analysis shows that remagnetization introduces a hysteresis effect in the practically accessible operating region and that multi-step remagnetization can mitigate this limitation.

This dissertation provides a coherent framework for the design, modeling and control of VFMs, and contributes practical methods for enabling their adoption in high-performance and more sustainable electric drive applications.