Port-Hamiltonian Modeling of a Synchronous Reluctance Machine for Structure-Preserving Model Reduction

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Electric motors are key components in industrial production and electrified powertrains. Their design involves competing objectives such as efficiency, power density, material use, acoustic behavior, and cost, creating a demand for simulation models that combine physical fidelity with computational efficiency. The synchronous reluctance machine (SynRM) considered here is a representative multiphysical system in which electromagnetic and mechanical dynamics are coupled through the air gap; see Figure 1.

Port-Hamiltonian (pH) systems provide an energy-based framework for coupled multiphysical systems. Energy storage, dissipation, and power transfer are represented explicitly, while physical subsystems are interconnected through power-conjugate variables, preserving important system-theoretic properties such as passivity.

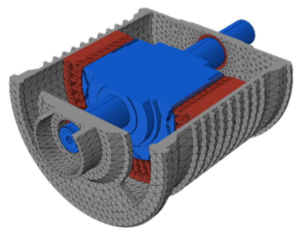

Abbildung 1: Synchronous reluctance machine as a multiphysical benchmark coupling electromagnetic and mechanical dynamics; model geometry based on [1].

For the SynRM, a modular pH model has been developed [2]. A three-dimensional finite-element model of the elastic mechanical components is coupled to a one-dimensional electromagnetic reluctance model through discrete interaction points at the air gap. A particular feature is the variable air gap: mechanical deformation changes the magnetic reluctance and therefore the electromagnetic energy which in turn affects the deformation of the air-gap. By incorporating the configuration-dependent reluctance directly into the Hamiltonian, electromagnetic forces and structural deformation arise consistently from the same energy formulation. Numerical simulations verify the expected energy balance and demonstrate the applicability of the approach to an engineering-scale multiphysical model. The resulting FE-based formulation is, however, high-dimensional. This creates a conflict between physical fidelity and the computational efficiency required for repeated simulation, optimization, and control-oriented applications. Moreover, conventional model order reduction (MOR) may destroy the energetic structure and passivity of the original pH system. Structure-preserving MOR is therefore not merely a computational acceleration, but an integral part of the modeling concept.

The modular formulation raises an additional methodological question: should the complete coupled model be reduced, or should the physical subsystems be reduced individually before interconnection? The latter retains the possibility of adapting the approximation space to the dynamics of each physical domain while maintaining an energy-consistent coupling, as illustrated in Figure 2. For the present SynRM demonstrator, first reduction studies focus on the mechanical subsystem using linear Krylov- and spectral-based approaches. Certified a-posteriori error bounds for reduced pH systems provide a systematic basis for assessing the approximation quality and, in future, for selecting suitable reduced dimensions before subsystem interconnection [3, 4].

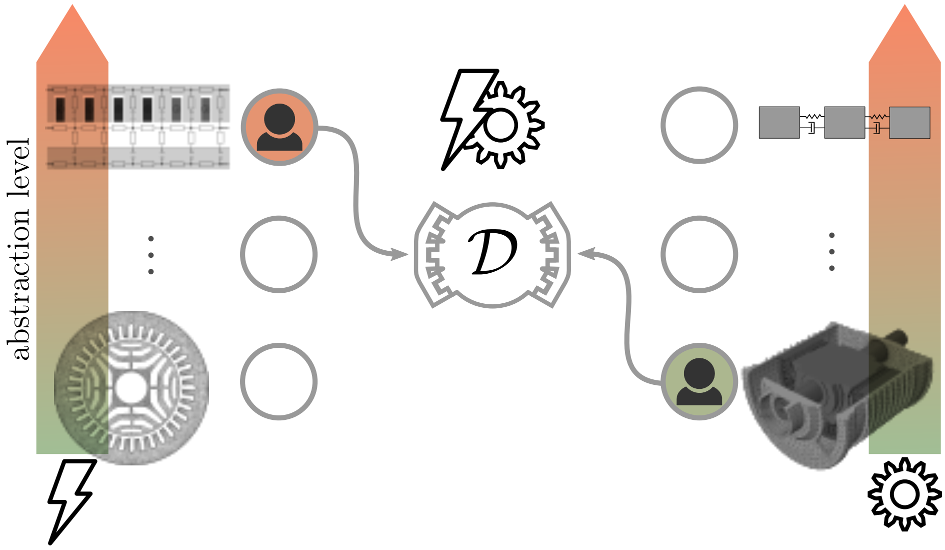

Abbildung 2: Modular port-Hamiltonian representation of the electromagnetic (left) and mechanical (right) SynRM subsystems. Their interconnection is power-conserving and preserves the overall energy balance.

The present demonstrator deliberately isolates the coupling problem: the rotor is treated as rigid and non-rotating, while the electromagnetic domain is represented by a simplified reluctance network. This allows the energy-consistent coupling, the influence of the variable air gap, and the consequences for structure-preserving reduction to be studied separately before extending the model towards rotor rotation and more detailed electromagnetic descriptions.

The SynRM thus serves as a representative engineering benchmark for combining energy-based multiphysics modeling with structure-preserving model reduction as a basis for efficient simulation and design optimization.

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Literatur

[1] Hermle, M.; Kesten, J.; Doppelbauer, M.; Eberhard, P.: Dynamic Modeling of a Synchronous Reluctance Machine for Transient Simulation of Vibrations under Variable Rotor Magnetization. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, Vol. 238, No. 1, pp. 52–63, 2024. doi: 10.1177/14644193241259984

[2] Seibert, J.F.: Modular modeling and simulation of a synchronous reluctance machine in port-Hamiltonian representation. Master Thesis MSC-356, Institute of Engineering and Computational Mechanics, University of Stuttgart, 2025.

[3] Rettberg, J.; Wittwar, D.; Buchfink, P.; Herkert, R.; Fehr, J.; Haasdonk, B.: Improved a posteriori error bounds for reduced port-Hamiltonian systems. Advances in Computational Mathematics, Vol. 50, No. 5, p. 100, 2024. doi: 10.1007/s10444-024-10195-8

[4] Rettberg, J.: Data-driven Modeling and Certified Model Order Reduction of Port-Hamiltonian Systems. Dissertation, Schriften aus dem Institut für Technische und Numerische Mechanik der Universität Stuttgart, (submitted) Aachen: Shaker Verlag, 2026.