Title:

"Numerical modeling and optimization of the magnetic coupler for high-power induction charging systems"

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Summary:

The objective of the thesis is to develop a digital tool for multiphysics modeling and optimization of the magnetic coupler for high-power inductive charging on the order of MW (megawatts). Optimization of this component is carried out on the geometry, dimensions, and arrangement of coils and magnetic field concentrators. Its design is subject to numerous constraints related to size, mass, heating, technological limits of associated electronic components, and restrictions on electromagnetic exposure. For high-power systems, components are subjected to significant constraints related to strong electromagnetic and thermal fields. In this environment, parametric variations due to nonlinearities in material properties would have a considerable effect on the overall system performance. In the optimization process, the aim is to maximize tolerance to material property variations, air gap variations, and misalignments between coils of the coupler performance. For modeling, to reduce computation time, an optimized multi-model coupling (FEM, BEM, PEEC, SIBC, degenerate elements, etc.) will be implemented and integrated into the optimization approach. The thesis work will also contribute to the development of open-source calculation codes.

Numerical modeling and optimization of the magnetic coupler for high-power induction charging systems

Inductive charging systems offer increased convenience by eliminating connections between the charger and the vehicle's battery. This can simplify the charging process, especially in situations where physical connectivity may be difficult or inconvenient, such as marine environments, underwater environments, public spaces, or construction zones. Although inductive charging for electric vehicles is still in the development phase, it represents a promising direction for the future of electric mobility. Technologies continue to improve to increase the efficiency of energy transmission by induction and make wireless charging more competitive compared to wired methods.

In this thesis, we focus on statically high-power inductive charging systems in the range of MW. These systems find application for large-scale maritime or terrestrial electric/hybrid vehicles, such as ferries, underwater drones, heavy-duty trucks, or construction machinery. Recent studies and developments have demonstrated their interest and feasibility (Kim et al. 2015) (Guidi, Suul, and Jenset 2017) (Chalmers 2023) (WAVE 2023).

The magnetic coupler is the central element enabling energy transfer through magnetic coupling between transmitting and receiving coils. It is subject to numerous constraints related to size, mass, heating, technological limits of associated electronic components, and electromagnetic exposure restrictions. An optimal design of this component maximizes the transmitted power and energy efficiency (Budhia, Covic, and Boys 2011) (Bosshard et al. 2015).

The optimization of this component involves geometry, dimensions, and arrangement of coils and magnetic field concentrators. In the literature, several coupler structures have been proposed (Patil et al. 2017) (Feng et al. 2020). Recent works include studies on topology optimization (Otomo and Igarashi 2022) (Pei et al. 2023), meta-model-based optimization (Pei 2022), and parametric optimization (Bensetti et al. 2023). These works primarily aimed at automotive applications where the target power is in the range of tens of kW. The modeling is generally based on the finite element method, allowing for the consideration of the complex three-dimensional geometry of the system. Variation in material properties with magnetic field and temperature is neglected.

For systems with multi-MW power, the components are subjected to greater constraints related to strong electromagnetic and thermal fields. In this environment, parametric variations due to material property nonlinearities would have a significant effect on the overall system performance. At high powers, it is desirable for maximum coupling to be achieved with high tolerance to material property variations, air gap variations, and coil misalignments to avoid excessive over-sizing of the electronic converter and compensation circuit, which can lead to significant system cost overruns. Therefore, it is important for material property nonlinearities to be considered in the optimization approach.

The objective of the thesis is to develop a numerical tool for modeling and optimizing the magnetic coupler for high-power inductive charging. Variations in coupler performance are to be minimized under different operating conditions. This approach requires the development of a reduced computation time multi-physics 3D model. The classical finite element modeling approach (FEM) is relevant for 3D simulations with magnetic and nonlinear materials but is computationally expensive. Indeed, the need to mesh air regions leads to large matrix systems. Additionally, to account for the pronounced skin effect at typical operating frequencies of charging systems, conductive regions must be finely meshed. Furthermore, the presence of thin regions such as shielding screens requires fine or deformed meshing, leading to poorly conditioned matrix systems.

In the literature, various coupled hybrid methods have been proposed to reduce simulation time. Coupling finite elements with integral methods such as BEM and PEEC is feasible, allowing for the elimination of air meshing (Tran et al. 2008) (Rüberg, Kielhorn, and Zechner 2021). The pronounced skin effect can be addressed by the FEM-SIBC method without meshing highly conductive regions (Desmoort et al. 2017) (Ba et al. 2020). Thin regions can be modeled using degenerate element methods (Ren 1998) (Bui et al. 2016b). A multi-physics electromagnetic and thermal model is also possible with coupled methods (Ba et al. 2020) (Bui et al. 2016a). In this thesis, an optimized multi-model coupling will be implemented and integrated into the optimization approach. The thesis work will also contribute to the development of open-source calculation codes.

Keywords: Inductive Charging, High Power, Electromagnetic Thermal Coupling, Optimization, 3D Finite Elements, Boundary Elements, PEEC, Coupled Methods.

General Information:

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- Duration: 3 years
- Start Date: October 2024
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- Qualifications: Engineer/Master 2 in Electrical Engineering, Applied Mathematics
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Planning:

$T_0 + n$ mois →	+06	+12	+18	+24	+30	+36
State of the Art	■	■	■	■	■	■
• High-power Inductive Charging	■	■	■	■	■	■
• Numerical Modeling of Coupler	■	■				
• Optimization Method for Coupler	■	■				
Implementation of Coupled Methods + Validation		■	■	■		
Coupler Optimization + Validation			■	■	■	
Conferences + Article Writing			■	■	■	
Thesis Manuscript Writing	■	■	■	■	■	■
Finalization + Thesis Manuscript Submission					■	■
Preparation for Defense						■

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