Abstract

Low-voltage direct current (LVDC) distribution systems are increasingly adopted in applications such as electric vehicle charging infrastructure, data centers, and DC microgrids. However, the absence of natural current zero crossings and the typically low inductance of LVDC networks make fault current interruption particularly challenging, requiring protection devices capable of operating on a sub-millisecond timescale. While solid-state and hybrid circuit breakers offer fast response, they suffer from high losses, limited galvanic isolation, and unfavorable failure modes. Mechanical circuit breakers remain the most robust and efficient solution, but their performance is fundamentally constrained by the speed of the contact actuation mechanism.

This thesis investigates the modeling and design of a railgun-driven electromagnetic actuator for ultrafast mechanical LVDC circuit breakers. The proposed actuation concept leverages the extremely low inductance and high force density of railgun systems to achieve very high acceleration and contact separation speeds. A hierarchical modeling framework is developed, ranging from analytical formulations to quasistatic and fully transient multiphysics simulations, enabling an in-depth analysis of electromagnetic forces, mechanical dynamics, thermal effects, and friction phenomena. In parallel, a dedicated pulse-power electric drive is designed to supply the railgun actuator, capable of delivering peak currents exceeding 165 kA within 22 µs.

System-level simulations are used to assess breaker performance under realistic LVDC fault conditions and to quantify the impact of system inductance and actuator dynamics on current interruption. The results demonstrate that higher actuation speeds lead to faster current extinction, lower peak fault currents, and significantly reduced energy dissipation in the breaker. Experimental validation of the railgun actuator confirms excellent agreement with the proposed models, achieving a contact displacement of 15 mm in 300 µs and peak velocities above 100 m/s. When integrated into a system-level protection scenario, the measured actuator dynamics enable current interruption within 420 µs to 700 µs for system inductances between 10 µH and 100 µH.

The achieved performance significantly exceeds that of state-of-the-art single-use protection devices such as pyrofuses and provides a markedly faster response than Thomson-coil–based actuators commonly employed in ultrafast circuit breakers. The results demonstrate that railgun-based actuation constitutes a viable and high-performance solution for next-generation ultrafast mechanical LVDC circuit breakers, bridging the gap between conventional mechanical and solid-state protection technologies.