Modeling, Switching Modulation Optimization, and Control of Multi-Active Bridge Converters

by

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ABSTRACT

Isolated multi-port converters (MPCs) realized through multi-active-bridge (MAB) topologies have recently attracted significant attention from power electronics researchers due to their applicability in renewable energy systems, microgrids, electric vehicles, solid-state transformers, energy storage, and space systems. However, widespread adoption of such MPCs is still hindered by key challenges, including increased switching losses at lighter load conditions and during non-unity gain voltage conversion, as well as cross-coupling between ports via the shared magnetic link.

This thesis presents a unified and generalized mathematical framework for modeling, circuit analysis, and loss-optimized modulation implementation for MAB-based DC-DC and DC-AC converters. The primary objective is to enhance system efficiency across a wide range of load conditions and voltage gain values by proposing an optimal phase–duty–frequency-controlled modulation strategy. The loss minimization approach consists of two key stages: (i) formulation of modulation-variable-dependent switching network loss objective functions using a proposed Generalized Harmonic Approximation (GHA) model, and (ii) application of a multivariable, multi-constrained optimization technique to minimize power loss across varying operating conditions. A universal zero-voltage switching (ZVS) criterion is also derived using a generalized port-equivalent circuit model.

The theoretical analysis and proposed modulation strategies are experimentally validated on various converter topologies within the MAB family, including DC-DC and DC-AC Dual-Active Bridge (DAB), and Triple-Active Bridge (TAB) converters. The proposed control methods significantly improve system efficiency, particularly under non-

unity gain and light-load conditions, when compared to conventional phase-shift modulation.

Expanding on this foundation, a parameter-adaptive modulation strategy is proposed for DAB converters. It employs a Physics-Informed Neural Network (PINN) to estimate circuit parameters (e.g., inductance and resistance) in real time from sensed data. This adaptive strategy enables dynamic modulation adjustment, ensuring improved soft-switching and efficiency. The method lays the groundwork for future exploration involving online-learning-capable ANN frameworks.

Additionally, the thesis introduces a GHA-based decoupling network that enables independent power control of coupled TAB load ports, resulting in faster transient response using simplified PI-based controllers.

Finally, a comprehensive analytical, simulation, and experimental investigation is conducted on realizable three-winding transformer configurations for TAB converters, focusing on controllable leakage inductance and its influence on soft-switching and power transfer capability.

DEDICATION

To my parents, my sister, and my younger self — who chose to become a professor without knowing what it truly takes.

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