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Three-Level Solid-State Transformer Architecture With Intelligent Fault-Tolerant Control for High-Density Data Centers

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ABSTRACT

High-performance computing data centers demand reliable and energy-efficient power delivery to manage rapid workload variations and high power density. Traditional transformer systems often show limited efficiency and weak adaptability under high performance computing (HPC) conditions. This study designed a three-level solid-state transformer with intelligent fault-tolerant control and workload-aware optimization. The architecture employed a neutral-point-clamped topology to reduce switching stress, a residual-based mechanism to sustain operation during device faults, and adaptive voltage regulation that tracked real-time workload changes. Experiments on a 50 kW prototype using HPC-oriented traces achieved 95.8–97.1% median efficiency, a 21% improvement in mean time between failures, and notable reductions in tracking error. The results demonstrate that combining multilevel conversion with intelligent control enhances efficiency, resilience, and workload responsiveness, providing a practical route to more scalable and stable HPC data center power delivery.

KEYWORDS

Three-Level Solid-State Transformer (SST), Fault-Tolerant Control, Workload-Aware Optimization, Data Center Power Delivery, Energy Efficiency and Reliability

INTRODUCTION

The rapid proliferation of cloud computing, artificial intelligence (AI), and big data analytics has driven an unprecedented demand for high-density data centers (George, 2025). These facilities are increasingly characterized by multi-megawatt power consumption, stringent efficiency requirements, and the necessity for uninterrupted service continuity (Kong et al., 2024). Traditional line-frequency transformers struggle to meet the scalability and efficiency expectations of next-generation data

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centers due to their bulky size, limited dynamic response, and lack of intelligent control features (Agarwala et al., 2024). Against this backdrop, solid-state transformers (SSTs) have emerged as a promising alternative, offering compact design, flexible voltage regulation, and seamless integration with renewable and storage resources (Cervero et al., 2023). In particular, the neutral-point clamped (NPC)-SST has attracted significant attention for its superior harmonic performance, higher efficiency, and better voltage stress distribution, making it highly suitable for mission-critical applications such as data centers (Wong, 2024).

Despite these advantages, conventional SST-based architectures face nontrivial challenges when deployed at scale in high-density data centers (Rahman et al., 2023). First, two-level or cascaded H-bridge designs exhibit limited efficiency under high-power, high-frequency operation, constraining their practical adoption (Bernet & Hiller, 2023). Second, existing fault-tolerant mechanisms are typically designed for distribution grids and do not adequately address the stringent reliability and latency requirements of data center workloads. Third, most recent studies have optimized for either efficiency or fault resilience but seldom achieved a balanced trade-off between the two (Xie et al., 2023). Moreover, many reported methods lack real-time adaptability, leading to performance degradation under dynamic workload fluctuations or partial device failures (Heydari et al., 2025). These gaps underscore the need for an architecture that not only improves efficiency and demonstrates potential for scalability but also embeds fault-tolerant mechanisms into the control layer, ensuring that high-density data centers can prevent costly downtime, safeguard service-level agreement compliance, and sustain performance under both device failures and workload bursts.

From a data center operations perspective, the performance of power delivery systems directly impacts higher-level computing outcomes. Specifically, voltage tracking accuracy is closely related to power capping and workload throttling behaviors at the rack level, while fault recovery latency determines the availability degradation window defined by Tier III/IV service standards. Similarly, long-term reliability metrics such as mean time between failures (MTBF) influence the probability of power-induced service interruptions. Although these computing-level outcomes are not always measured explicitly in power electronics studies, they are commonly inferred through electrical performance indicators that serve as practical and widely accepted proxies in data center environments.

Accordingly, this paper adopted such proxy-based evaluation to bridge power electronics design with high performance computing operational requirements, enabling quantitative assessment of how efficiency, fault tolerance, and workload-aware control jointly affect service continuity and scalability in high-density data centers. While these proxies do not replace direct information technology (IT)-level metrics, they provide a practical and widely adopted means to infer computing-level impacts from power-delivery behavior.

To address these issues, this paper introduced three key innovations. First, a three-level SST power architecture leveraging a NPC topology reduced switching losses and improved harmonic suppression. Second, an intelligent fault-tolerant control scheme based on adaptive reconfiguration and model-predictive decision-making enabled seamless operation during device faults without relying on hardware redundancy. Third, a workload-aware optimization layer dynamically adjusted voltage and current profiles in line with real-time computational demand, ensuring efficient resource utilization. Collectively, these modules form a unified solution that simultaneously improves efficiency, resilience, and adaptability.

To validate the approach, a 50 kW laboratory prototype was developed, incorporating realistic workload traces and representative hardware configurations. This setup captured the essential dynamics of high-density data center power delivery while remaining controllable and repeatable. The experimental study demonstrates measurable improvements over conventional baselines, with statistical tests confirming robustness across workloads and noise levels, though further validation on multi-megawatt prototypes remains necessary.

In summary, this study contributes by (1) integrating multi-level converter topology with intelligent fault-tolerant mechanisms, (2) demonstrating workload-aware adaptation that bridges power

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