Abstract

The integration of distributed energy resources (DER) such as photovoltaic (PV) systems and battery energy storage systems (BESS) into the power grid has led to the increasing adoption of high-power, multiport multilevel converter topologies like Modular Multilevel Converters (MMC) and Cascaded H-Bridge (CHB) converters. These converters offer scalability, modularity, and high-quality AC output, making them suitable for large-scale DER applications. However, a major challenge arises in maintaining power balance across converter arms or legs due to mismatch power generation and consumption in different DER units. This power mismatch can result from partial shading, dust accumulation, different PV panel ratings, and varying states of charge (SoC) in batteries, leading to high circulating current, submodule voltage imbalance, failing converter operating in linear modulation and unbalanced power injection into the AC grid.

This thesis investigates the energy balancing strategies in MMC and CHB converters under such mismatched conditions and proposes novel control methodologies to mitigate the adverse effects of power mismatch. The primary research gap addressed is the lack of robust techniques to manage leg-leg (horizontal) and arm-arm (vertical) power mismatches in DER-integrated modular multilevel converters, which are critical for ensuring grid compliance and converter performance. To address this, a novel two-fundamental frequency zero sequence voltage (Two-FFZSV) injection technique is developed to minimize the DC circulating current associated with leg-leg (horizontal) power mismatch in MMC. This is complemented by an independent arm power control technique to manage arm-arm (vertical) power mismatch and minimize the fundamental frequency circulating current (FFCC). This facilitates bidirectional power flow in individual arms, enabling seamless integration of PV and BESS units with different ratings and dynamic operating profiles in MMC.

The proposed control framework is further extended to MMC-based electric vehicle (EV) charging infrastructure, where the degree of power mismatch is extreme due to diverse loading combinations and the stochastic nature of EV arrival and departure. Under such conditions, conventional circulating current-based balancing methods suffer from extreme overcurrent, increased power losses majorly suffer from submodule voltage balancing. To overcome these limitations, a reactive power exchange method is introduced to manage submodule voltage balancing and maintain converter performance under highly unbalanced loading scenarios.

In addition, for the CHB converter-based DER systems, issue of overmodulation caused by FFZSV injection under high PV mismatch conditions is addressed. A strategy is developed to prevent over modulation by a control coordinating of PV and battery energy support at the submodule level. A

barycentric coordinate representation is introduced to determine the required battery support capacity for compensating unbalanced power generation. Furthermore, a topological reform is proposed for CHB-based BESS systems, where each cell is capable of generating a pure sinusoidal AC output voltage. This is achieved using a folding-unfolding circuit integrated with a dual active bridge (DAB), which produces a full-wave rectified (FWR) folded DC voltage that is subsequently unfolded into a sinusoidal AC waveform. This topology significantly improves the total harmonic distortion (THD) profile of AC output and operates at line frequency, thereby minimizing switching losses.

Overall, the proposed control methods and converter designs help maintain balanced power flow, reduce internal losses, and improve grid compatibility in systems using MMC and CHB converters with DER like PV and battery units. The effectiveness of these solutions is verified through MATLAB simulations and experimental prototypes.