Abstract

The increasing trend of electrical power demands in megacities, industries and transportation requires medium- or high-voltage power electronics devices to serve as the enabling components for high power conversion, due to design flexibility, better dynamic performance, energy efficiency and environment friendliness. Multilevel power converters, such as Neutral Point Clamped (NPC) Converters, Cascaded H-Bridge (CHB) Converters and Modular Multilevel Converters (MMCs), are popular commercialized candidates for such high power applications. Among them, the MMC possesses great performance in terms of functionality, hardware implementation, configuration complexity, output power quality, efficiency and reliability, and it shows considerable research potential in the academic world as well. This thesis aims to investigate the control and operation strategies that related to the efficiency, nonlinearity, modularity and reliability of MMCs.

At first, the configuration and operation principles of a three phase MMC is introduced. A comprehensive steady state analysis and the equivalent circuit model that are applicable to an MMC connected to either a DC or an AC bus are then presented in this thesis. In addition to better understanding of the MMC operation, the analysis and modeling of the MMC also suggest the conditions that ensure the stability operation of the MMC system. According to the aforementioned analysis and modeling, the control system of the MMC is introduced. The commonly used cascaded control strategy, including output and inner dynamics control loops, has been discussed. The existing modulation methods for MMCs have been summarized, and the phase-shifted pulse width modulation (PS-PWM) are detailed and adopted in this thesis.

The circulating current harmonics in each phase are expected to be suppressed in order to improve the performance and reduce the losses of MMCs. The characteristics of the circulating current harmonics are analyzed and it is revealed that the circulating current are dominated by even order harmonics. An even-

harmonic repetitive control scheme is proposed to eliminate the even harmonics in the differential current. The proposed repetitive controller has excellent harmonic elimination, with benefits of less memory occupation, less delay period, doubled low frequency gain, faster convergence rate and dynamic response and wider bandwidth at specific frequencies. The full design details of the even-harmonic repetitive control for an MMC system has been presented.

Moreover, the MMC is a multi-input multi-output bilinear system. A nonlinear control strategy is preferred for better control performance. The feedback linearization based current control for the MMC is proposed in this thesis to solve the bilinear control problem. The state function model of the MMC is linearized with the help of the feedback linearization technique. The output and inner differential current control loops are decoupled as two independent simple integrators. Classical linear control laws can be easily applied in the two current control loops. The control performance in steady state and during step changes is improved and the controller design process is facilitated.

The centralized control system will reduce the modularity of the MMC in terms of software implementation and is not practical in MMC systems with a large number of sub-modules. A distributed control strategy for MMCs is proposed in this thesis. The proposed control strategy is able to achieve all control objectives in conventional control strategies, with significantly reduced data exchanging among central and local controllers through a communication network.

The fault diagnosis and fault tolerant control for an MMC with redundant sub-modules significantly increases the system reliability. A real-time measurement based semiconductor device open-circuit fault diagnosis method has been proposed. This fault diagnosis is implemented in each local controller in the distributed control architecture with local information. It is capable of accurately identifying multiple faults within 3.5ms without false alarm. Based on the performance analysis of an MMC with bypassed faulty sub-modules, a fault tolerant control is accordingly proposed. The fault tolerant control guarantees the performance of the MMC to be the same as in normal operation. The fault tolerant control can be activated with 5ms after the fault occurrence. The MMC is able to seamlessly ride through the switching device open-circuit fault.

All the theoretical findings are verified in PLECS simulations. The effectiveness and practicalities of the control algorithms are confirmed on a scale down single-phase MMC prototype.