A Repetitive Control Scheme for Harmonic Suppression of Circulating Current in Modular Multilevel Converters: Review

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Abstract - The widespread use of power electronics in industrial, commercial and even residential electrical equipments causes deterioration of the quality of the electric power supply with distortion of the supply voltage. This has led to the development of more stringent requirements regarding harmonic current generation. These harmonic currents will introduce extra power loss, increase current stress of power devices, and even cause instability during transients [1]. One of the challenging problems in repetitive control is to maintain the performance of the controller when the manipulated and/or state variables are hitting the constraints. This review incorporates the concept of repetitive control into the design of an MMC controller, occurrence and optimization of harmonics, so that the benefits of both controllers are combined, such as repetitiveness, constraints and multi-variable control.

Keywords - Repetitive Control Scheme, Modular Multilevel Converters (MMC) , Harmonic Suppression.

I. INTRODUCTION

Modular multilevel converters are an innovative technology that allows voltage source converters comprised of low voltage. There are several types of multilevel converter topologies and while the fundamental concepts are similar, there are differences in the control requirements across these various topologies. The various multilevel converter topologies include: Cascaded H-Bridge, Diode-Clamped, flying capacitor and modular multilevel converters. There has been substantial progress in the development of pulse-width modulation techniques, voltage balancing algorithms and conventional control approaches applicable to modular multilevel converters. As far as the current and voltage control, the same approach for a conventional voltage source converter can be used. This scheme uses PI controllers to control the current along with the active and reactive power.

The multicarrier modulation schemes used for modular multilevel converters dictate the number of submodules that need to be on in an arm. This generates a voltage level between zero and the maximum converter voltage amplitude for the upper arm of each phase unit. Two references are required per phase, one for each arm. This reference is then compared to the multiple carriers discussed and a reference is generated with an available range of values from zero to N. The PWM output value here dictates the number of connected submodules in an arm.

A key principle to be understood is that in an ideal situation, the capacitors across each submodule can be modeled as an ideal DC voltage source. Switching in and out these DC voltage sources allows us to generate various voltage levels on the AC side. These various voltage levels allow the capability of producing an AC waveform with the resolution being directly tied to the number of submodules used in the converter.

A submodule, shown in Figure 1.1, consists of two IGBTs connected in a half-bridge topology with a capacitor across the devices to be used as an energy storage and supply device.

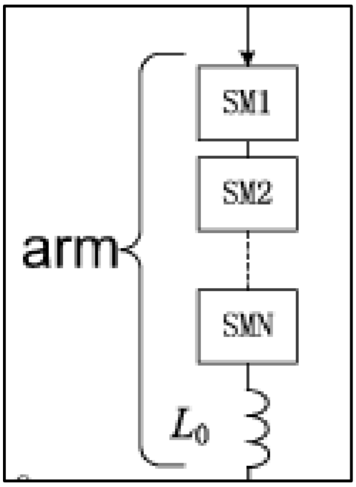

Figure: 1.1 Modular multilevel Converter Arm.

Other properties of the converter topology are that this sequence of submodules along with an arm inductor makes an arm of the converter as shown in Figure 1.2.

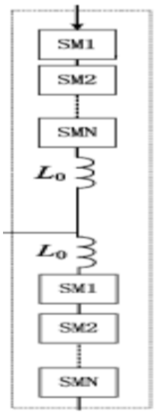

Figure 1.2 modular multilevel converter Phase units.

Two arms make up one phase of the converter, also called a phase unit, and this is shown in Figure 1.3.

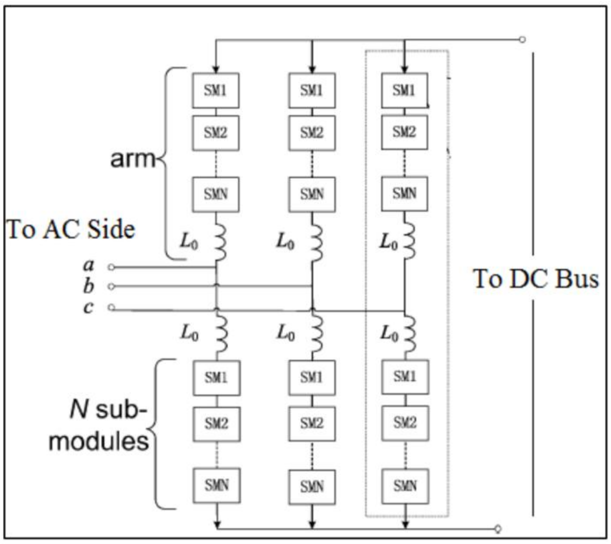

Figure 1.3 Full Modular multilevel Converter.

II. REPETITIVE CONTROL MODEL

A. Predictive Current Control of a PMSM

In this area, a new means to analyze and implement Space Vector Modulator (SVM) based on the introduction of Virtual Switching State (VSS). Further discovery includes the use of VSS to derive the equivalent pulse generation used in several PCC methods in the literatures. Finally, the synthesis of the algorithms for SVM and the pulse generation in PCC leads to a unified algorithm which is capable to implement many PWM techniques in a single scheme.

B. Model Predictive Control of a PMSM

The repetitive predictive controller for the speed and current regulation of a PMSM has been investigated under two different schemes based on the FOC. The first scheme employs the cascade structure but with MPC and RPC replacing the PI controllers for inner and outer-loop, respectively. The key contributions to the PMSM control is reflected by the effectiveness of Repetitive Predictive Control (RPC) in dealing with the sinusoidal disturbances and periodic position tracking with the RPC placed in the outer-loop. Another important contribution is credited to the formulation of the hexagonal voltage constraints for the

C. Repetitive-Predictive Control

The design of repetitive control using MPC contributes to the repetitive control society in several aspects. First of all, it provides a new means to tackle the repetitive control problem for MIMO systems in the presence of constraints, which is still a hurdle and lack of enough investigations in the repetitive control society. Secondly, the internal model used for MPC design is constructed by identifying the dominant frequency modes from the frequency sampling filter decomposition of the reference signal. The selection of only necessary frequency components into the design simplifies the design procedure and the resulting algorithm could be suited to the application that requires fast sampling time.

Repetitive control is concerned with the tracking of a periodic reference signal and has many applications. This requirement can be formulated by using the Internal Model Principle (IMP) (expressed in transfer-function terms) which states that to track a reference signal with zero error the generator polynomial of this signal must be included as part of the controller denominator. In principle, RC is perhaps very close to the Iterative Learning Control (ILC), since both of them target the control problem with repeating sweeps, passes or iterations. The key difference between them is the setting of initial conditions for each pass. One of the earliest work to realize the IMP was presented by S. Hara et. al. in the continuous time framework [38] where a delay is introduced into the positive feedback loop. At about the same time, the discrete version of internal model was studied and reported by M. Tomizuka et. al.. Similar to its continuous counterpart, the internal model in the discrete time domain is constructed by adding an M-sample delay to the positive feedback loop where M here indicates the period length of the exogenous signals, as shown in Figure 2.1. Consequently, the closed-loop representation of Figure 2.1(a) would lead to M poles that uniformly distribute on the unit circle as shown in Figure 2.1(b). In order to improve the robustness and stability issues caused by the internal model, some low pass filters are usually incorporated into the design as well.

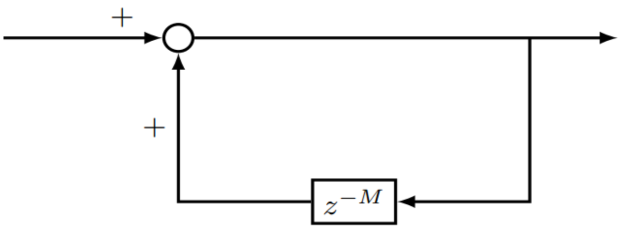

Figure 2.1 (a) Signal Generator

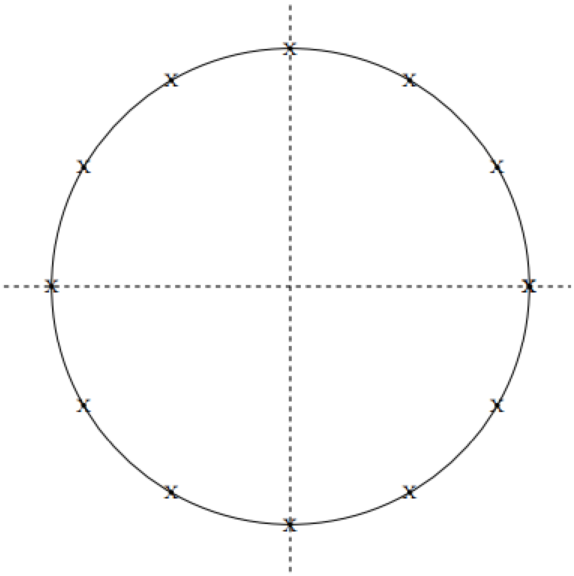

Figure 2.1 (b) Poles (M=12).

III. PREVIOUS WORK

L. He, K. Zhang, J. Xiong and S. Fan,[1] In a modular multilevel converter (MMC), the interaction between switching actions and fluctuating capacitor voltages of the submodules results in second- and other even-order harmonics in the circulating currents. These harmonic currents will introduce extra power loss, increase current stress of power devices, and even cause instability during transients. Traditional methods for circulating current harmonic suppression have problems such as limited harmonic rejection capability, limited application area, and complex implementation. This research work presents a plug-in repetitive control scheme to solve the problem. It combines the high dynamics of PI controller and good steady-state harmonic suppression of the repetitive controller, and minimizes the interference between the two controllers. It is suitable for multiple harmonic suppression, easy to implement, and applicable for both single-phase and three-phase MMCs. Simulation and experimental results on a single-phase MMC inverter proved the validity of the proposed control method.

M. Zhang, L. Huang, W. Yao and Z. Lu,[2] An improved circulating current control method by applying a digital plug-in repetitive controller is discussed for harmonic elimination of a carrier-phase-shift pulse-width-modulation (CPS-PWM)-based modular multilevel converter (MMC) in this research work. The performance of the controller is analyzed in detail based on an improved circulating current control model with the consideration of the submodule voltage disturbance. It is shown that the proposed control method has the merits of simplicity, versatility, and better performance of circulating harmonic current elimination than the traditional proportional integral controller. The stability analysis of the proposed method are also discussed in the research work as well as the design principles. Finally, the experimental results including the steady-state performance and the transient response are given, which validates the feasibility and excellent performance of the proposed control scheme.

Q. Song, W. Liu, X. Li, H. Rao, S. Xu and L. Li,[3] Modular multilevel converters (MMC) are considered a top converter alternative for voltage-source converter (VSC) high-voltage, direct current (HVDC) applications. Main circuit design and converter performance evaluation are always important issues to consider before installing a VSC-HVDC system. Investigation into a steady-state analysis method for an MMC-based VSC-HVDC system is necessary. This research work finds a circular interaction among the electrical quantities in an MMC. Through this circular interaction, a key equation can be established to solve the unknown circulating current. A new steady-state model is developed to simply and accurately describe the explicit analytical expressions for various voltage and current quantities in an MMC. The accuracy of the expressions is improved by the consideration of the circulating current when deriving all the analytical expressions. The model's simplicity is demonstrated by having only one key equation to solve. Based on the analytical expressions for the arm voltages, the equivalent circuits for MMC are proposed to improve the current understanding of the operation of MMC. The feasibility and accuracy of the proposed method are verified by comparing its results with the simulation and experimental results.

Y. Cho and J. S. Lai,[4] This research work investigates a plug-in repetitive control scheme for bridgeless power factor correction (PFC) converters to mitigate input current distortions under continuous conduction mode and discontinuous conduction mode operating conditions. From the PFC converter model and the fact that a type-II compensator is used, a design methodology to maximize the bandwidth of the feedback controller is suggested. After that, the error transfer function including the feedback controller is derived, and the stability of the repetitive control scheme is evaluated using the error transfer function. The implementation of the digital repetitive controller is also discussed. The simulation and experimental results show that the input current THD is significantly improved by using the proposed control scheme for a 1-kW single-phase bridgeless PFC converter prototype.

K. Ilves, A. Antonopoulos, S. Norrga and H. P. Nee,[5] The fundamental frequency component in the arm currents of a modular multilevel converter is a necessity for the operation of the converter, as is the connection and bypassing of the submodules. Inevitably, this will cause alternating components in the capacitor voltages. This research work investigates how the arm currents and capacitor voltages interact when the submodules are connected and bypassed in a sinusoidal manner. Equations that describe the circulating current that is caused by the variations in the total inserted voltage are derived. Resonant frequencies are identified and the resonant behaviour is verified by experimental results. It is also found that the effective values of the arm resistance and submodule capacitances can be extracted from the measurements by least square fitting of the analytical expressions to the measured values. Finally, the analytical expression for the arm currents is verified by experimental results.

K. Ilves, A. Antonopoulos, L. Harnefors, S. Norrga and H. P. Nee, [6] The modular multilevel converter is a suitable topology for high-voltage applications as it combines very low switching frequency and excellent harmonic performance. In fact, it has been shown that the modular multilevel converter can even be operated at the fundamental switching frequency. If the circulating current is not controlled, a second-order harmonic component will appear. This component increases the resistive losses and the capacitor voltage ripple. Different control methods have been developed for eliminating this component in the circulating current. These are, however, based on continuous representations of the system and no control method suitable for fundamental switching frequency has yet been proposed. This research work presents a control method that combines a fundamental switching frequency scheme with an active control of the circulating current. The controller is verified experimentally on a 10-kVA laboratory prototype with five submodules per arm. The experimental validation is performed in both inverter and rectifier modes.

IV. PROBLEM STATEMENT

One of the major issues namely harmonic distortions is not a new phenomenon in power system. At that time, the major sources of harmonics were the transformers and the main problem was inductive interference telephone systems. Harmonics are qualitatively defined as sinusoidal waveforms having frequencies that are integer multiples of the power line frequency. In power system engineering, the term harmonics is extensively used to define the distortion for voltage or current waveforms the power electronic converters inject nonsinusoidal (i.e., harmonic) currents into the AC utility grid and the harmonics injected into the power system cause line voltage distortions at the Point of Common Coupling (PCC) where the linear and nonlinear loads.

V. CONCLUSION

The objective of this revive is to investigate the application of model based on repetitive-predictive control to suppress harmonics in modular multilevel converter, along with study and analysis of the existing predictive current control methods and modular multilevel converter strategies in the literatures. To Minimizing capacitor voltage ripple, reducing converter power losses, reducing required switching frequency and converter voltage harmonic reduction several key metrics was performed. A key to modular multilevel converter operation is limiting the ripple of the capacitor voltages. This reduces the circulating current flowing within the converter.

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