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Characteristics analysis and improved arm control of modular multilevel converter under asymmetric operation conditions

Ziwen Liu, Shihong Miao*, Zhihua Fan, Kaiyun Chao, Yuliang Liu

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology (HUST), 430074 Wuhan, China

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ABSTRACT

This paper proposes a general analysis model and an improved arm control of modular multilevel converter (MMC) under asymmetric operation conditions. This general analysis model is established as the arm voltage equations with equivalent impedance parameters, and is applicable for characteristics analysis under both submodule (SM) fault condition and asymmetric arm parameter condition. Based on the analysis model, the equivalent circuits of the circulating current and the ac side current are obtained, and then the asymmetric characteristics are performed. According to the analysis results, an improved arm control of MMC is proposed, which is aimed at balancing the dc components in upper and lower arm currents, as well as suppressing the fundamental and double frequency circulating currents. Besides, the dynamic response of the proposed arm control is significantly improved by embedding an arm voltage inertial feedback control. Simulations on PSCAD/EMTDC verify the correctness of the theoretical analysis and the validity of the proposed control strategy.

1. Introduction

Modular multilevel converter (MMC) has attracted more and more attentions in the high/medium-voltage and high-power applications since it has significant advantages of outstanding output performance, superior harmonic characteristic, flexible scalability and fault processing ability [1,2]. The MMC related technologies have already been applied in engineering such as high voltage direct current transmission, high-power motor drives, flexible ac transmission systems, renewable energy generation, and so on [3–6].

Due to the broad application prospects and complicated characteristics of MMC, scholars have conducted plenty of researches including the operational issues [7], modeling analysis [8], modulation techniques [9] and control methods [10] of MMC. The operating characteristics of MMC system during asymmetric conditions differ a lot from that in normal conditions. In summary, there are three main asymmetric conditions that may happen on MMC system. First one is the unbalanced grid conditions. Under this unbalanced condition, there are positive-, negative- and zero-sequence circulating currents in MMC and the zero-sequence components flow into the dc side, which causes power ripples in the dc side [11]. But the upper and lower arms are still symmetric under this condition. This kind analysis and control are well discussed and processed (e.g. [12,13]).

The submodule (SM) fault is the second kind of asymmetric condition. Given large numbers of the SMs in each arm of MMC, fault tolerant control is one of the most significant challenges [14]. In practical engineering, some redundant SMs are always equipped in the arms of MMC. To make full use of the SMs, all SMs (including the redundant ones) can be used in normal operation and only the faulted SMs need to be bypassed from the arms under SM faults. This also ensures the uninterrupted operation of MMC under SM faults. But with this operation mode, the arms operate in asymmetric state since the number of SMs in each arm are inconformity, which brings challenge to the control system of the MMC. In [15], an energy-balancing control is proposed to keep the system operating normally under SM faults. In [16], an optimized control strategy based on the dynamic redundancy for the MMC is proposed. In [17], the energy reallocation control is proposed to manage the MMC with redundant SMs to suppress the circulating current. However, these above strategies need the information of exact number of the faulted SMs, which complicates the fault detection procedure. In [18], a fault-tolerant approach for the MMC under SM faults is proposed by improving the SMs utilization. This control needs three single-phase *dq* transformations for the three phases of MMC and the control parameters need to be adjusted properly.

The other kind of asymmetric situation is the unequal arm parameters. In actual engineering, certain difference may be existed in arm impedances of upper and lower arms, which will cause the deviation in

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* Corresponding author.
E-mail address: shmiao@hust.edu.cn (S. Miao).

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stored energy of the arms. In [19], the brief analysis indicates that asymmetric arm parameters have impact on the distribution of ac side current between upper and lower arms. In [20], detailed analysis based on the equivalent circuits and control scheme of MMC under asymmetric arm inductance conditions are presented.

Generally speaking, the SM fault condition and asymmetric arm parameters condition have characteristics in common since the arms of MMC operates asymmetrically under both the two conditions. However, there is few general analyses for these two conditions that can be available in the existing literatures. Therefore, an effective general analysis model and corresponding control scheme of MMC which is both applicable for SM fault condition and asymmetric arm parameter condition is necessary in particular. With this general analysis model and control strategy, the characteristics under asymmetric operation conditions of the arms should be revealed and the relevant asymmetric issues should be solved.

In this paper, the general analysis model and an improved arm control of MMC under asymmetric operation conditions is proposed. The main contributions of this paper can be drawn as:

1. The main causes of the asymmetric operation are firstly analyzed. It shows that under SM faults, the asymmetric average switching functions of SMs in upper and lower arms are the main cause, while under asymmetric arm parameter condition, the ac side current and the circulating current are not decoupled anymore and will cause the asymmetric operation of the arms.
2. The general analysis model is established for the characteristic analysis under both the SM fault and asymmetric arm parameter condition. Based on the analysis model, the equivalent circuits of the circulating current and ac side current are obtained, and then the asymmetric characteristics are performed.
3. According to the analysis results, an arm control of MMC is proposed, which is aimed at balancing the dc component currents in upper and lower arms, as well as suppressing the fundamental and double frequency circulating currents.
4. The dynamic stability of the proposed arm control is significantly improved by embedding the arm voltage inertial feedback control. Theoretical stability analysis is conducted to prove the efficiency of this control in improving the dynamic stability of the MMC system.

Simulations of a three-phase MMC system on PSCAD/EMTDC verify theoretical analysis and the validity of the proposed control strategy.

2. System configuration and modelling of MMC

2.1. System configuration of the MMC

The topological structure of the three-phase MMC is shown in Fig. 1 and each phase unit consists of two arms, namely upper arm and lower arm. Each arm contains N identical SMs, inductor and equivalent resistance. Generally, the inductors and resistances in each arm are symmetrically equal. The single SM adopts the half-bridge structure, and is composed of two complementary IGBT devices (T_1 and T_2), a dc capacitor and a bypass switch. By controlling the on-off state of T_1 and T_2, the output voltage of SMs can be zero or the capacitor voltage. When the SM is in fault, the bypass switch will be closed and short out the faulted module. The sorting algorithm of the capacitance voltage and the nearest-level modulation (NLM) strategy [21] is used in this paper, thus the upper and lower arms can output desired voltage waveform and can be equivalent as controlled voltage sources.

According to the Kirchhoff's law, the KVL equations of the upper and lower arm voltages are depicted by

$$\begin{cases} u_p = \frac{U_d}{2} - u_{on} - L_0\frac{di_p}{dt} - R_0 i_p - u_s \\ u_n = \frac{U_d}{2} + u_{on} - L_0\frac{di_n}{dt} - R_0 i_n + u_s \end{cases} \tag{1}$$

where u_p and u_n are the upper and lower arm voltages; i_p and i_n are the upper and lower arm currents; U_d is the dc side voltage; u_s is the ac side voltage. Based on the current component analysis [12], the upper and lower currents are obtained by

$$\begin{cases} i_p = I_{dc} + i_z + \frac{i_v}{2} \\ i_n = I_{dc} + i_z - \frac{i_v}{2} \end{cases} \tag{2}$$

where I_{dc} is the dc component of the arm current, i_v is the ac side current and i_z is the ac circulation in the arm current. Under normal conditions, the dominant component in i_z is the double frequency harmonic while higher harmonics are neglected since their amplitude is very small and has a very minor impact on the accuracy of the analysis results.

2.2. The mathematical model of MMC under asymmetric operation conditions

In order to realize fault-tolerant operation of the MMC under SM fault, the M redundant SMs are equipped in each arm to make the system operate redundantly, and these redundant SMs are operated as the N regular SMs. Under SM fault conditions, the actual numbers of the available SMs in upper and lower arms are n_1 and n_2. Let S_{pi} and S_{ni} represent the switching function of the single SM, where subscript p and n stand for upper and lower arms and i stands for the ith SM. Then it has

$$\begin{cases} S_{pi} = 1, & T_1 \text{ is on and } T_2 \text{ is off} \\ S_{pi} = 0, & T_1 \text{ is off and } T_2 \text{ is on} \end{cases}. \tag{3}$$

The upper arm reference voltage u_{p_ref} and lower arm reference voltage u_{n_ref} are set as

$$\begin{cases} u_{p\_ref} = \frac{U_d}{2} - \frac{mU_d}{2}\sin\omega t \\ u_{n\_ref} = \frac{U_d}{2} + \frac{mU_d}{2}\sin\omega t \end{cases} \tag{4}$$

where m is the modulation index and ω is the fundamental angular frequency. Based on the NLM strategy, the required SMs to be inserted in each arm is

$$\begin{cases} \sum_{i=1}^{n_1} S_{pi} = N_p = \frac{1 - m\sin(\omega t)}{2}N \\ \sum_{i=1}^{n_2} S_{ni} = N_n = \frac{1 + m\sin(\omega t)}{2}N \end{cases} \tag{5}$$

where N_p and N_n are the required SMs to be inserted in upper and lower arms.

Since the complete sorting algorithm of SM capacitance voltages is adopted, the probability that a single SM to be inserted at any moment is regarded as the same. This means the average switching functions of each SM are same in upper arm and in lower arm respectively, which are given by

$$\begin{cases} S_{pi\_av} = \frac{N_p}{n_1} = \frac{N}{n_1}\cdot\frac{1 - m\sin(\omega t)}{2} \\ S_{ni\_av} = \frac{N_n}{n_2} = \frac{N}{n_2}\cdot\frac{1 + m\sin(\omega t)}{2} \end{cases}. \tag{6}$$

According to (6), the average switching functions of the SMs S_{pi_av} and S_{ni_av} will be no more symmetrical when there are unequal faulted SMs in upper and lower arms (that is $n_1 \neq n_2$). Furtherly, the capacitor voltage of the SM is obtained by

$$\begin{cases} u_{cp} = \frac{1}{C}\int S_{pi\_av}\cdot i_p dt = \frac{1}{C}\int \frac{N}{n_1}\cdot\frac{1 - m\sin(\omega t)}{2}\cdot i_p dt \\ u_{cn} = \frac{1}{C}\int S_{ni\_av}\cdot i_n dt = \frac{1}{C}\int \frac{N}{n_2}\cdot\frac{1 + m\sin(\omega t)}{2}\cdot i_n dt \end{cases} \tag{7}$$

where u_{cp} and u_{cn} are the average capacitor voltages of single SM in upper and lower arms, respectively; C is the capacitor in SM. It can be seen from (7) that the SM capacitor voltages in upper and lower arms