Mission-Profile-Based Testing Scheme for Sub-Modules in Modular Multilevel Converter

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Modular multilevel converter (MMC) has been widely used in medium/high-voltage direct current transmission, motor drive, and renewable energy power generation. The reliability requirements of the MMC system, which is composed of numerous sub-modules (SMs) as building blocks, are getting crucial. However, the testing for reliability of SMs in a full MMC system is time-consuming and costly. In this paper, a mission profile emulator for SMs in the MMC system is therefore focused; by using this mission profile emulator, the SMs can be tested individually without building a full MMC system. Simulation results have shown that arm current and capacitor voltage of the SM under test agree well with the SM in a complete MMC system. A scaled-down experimental platform is built and experimental results have proved the validity of this emulator.

Keywords: mission profile emulator, modular multilevel converter, sub-modules, carrier phase-shift pulse width modulation

1. Introduction

Modular Multilevel Converter (MMC), is being widely used and has shown significant engineering prospects in multiple applications, such as Medium to High-voltage Direct Current Distribution/Transmission Systems. Compared with traditional voltage source converters, MMC offers a series of merits, especially the easily-scalable voltage and power levels, improved reliability and cost reduction (1–5). It is known that reliability performance is particularly essential for MMC system, where a significant number of Sub-Modules (SMs) are employed (6). Therefore, attention should be paid to the SMs of MMC (6–9). However, due to the high number of components and the complicated working conditions, building a complete MMC system for such kind of testing is time-consuming and costly, and the reliability performance of SMs is difficult to be tested considering the realistic loading conditions in a complete MMC system (10). As a solution, mission profile emulator for SMs was proposed to reduce the testing costs and can facilitate the analysis and design of the reliability performances.

There are several studies to emulate the working conditions of power electronic converters. Opposition method is generally applied to test power electronic converters under different working conditions (10). However, the steady-state arm current of MMC is relatively complicated to be emulated, which mainly consists of fundamental AC waveform, circulating current with low-order harmonics (depending on the control strategies) and a DC bias. In (10)–(12), testing schemes for MMC SM have been proposed, but they can only emulate sinusoidal arm current, and the switching frequency of SM is much higher than that in actual working condition. As a result, the reliability performance of SM under test, which is highly dependent on the switching frequency, would deviate from practical situation. A modified testing scheme by adding an external AC voltage source is proposed in (13). The switching frequency of SM is closer to practical frequency, but it cannot successfully deal with the DC bias in arm current, either. The testing scheme proposed in (14) emulates the arm current well by using hysteresis control, using offline simulation results of MMC system to provide arm current reference of converter and switching sequence of SM under test. However, the switching frequency is not constant by hysteresis control, and will result in more harmonics and complicates the emulator design. An equivalent circuit of MMC phase leg is proposed in (15), however, in the case of rectifying mode, the electrical stress of SM cannot be emulated equivalently. In (16), a novel SM-based mission profile emulator is proposed, and the requirement for DC power is significantly reduced, however, the capacitor voltage is controlled to keep constant, which ignoring the voltage fluctuation of actual capacitor voltage.

In this paper, a mission profile emulator for SMs in MMC is analyzed, the SMs under test is designed to behave similarly to the practical operation of SMs in a complete MMC system, in terms of electrical loading behaviors. A proportion-integration-resonance (PIR) controller is proposed and adopted to improve the tracking accuracy of the arm current which consists of DC and fundamental components, second-order harmonic in some mission profiles. The capacitor voltage balancing control for Carrier Phase-Shift Pulse Width Modulation (CPS-PWM) proposed in (17) is employed, to regulate the SM capacitor voltage. Simulation results are presented to verify the validity and accuracy of the proposed mission profile emulator, and both in the rectifying and inverting mode, the mission profile emulator is capable of...
emulating the electrical behaviors of SM. In the end, a scaled-down experimental setup based on the proposed design and control methods is built. Experimental results demonstrate the ability of the emulator to recreate the basic mission profiles of SM in MMC system.

2. Key Electrical Characteristics of Sub-Module in MMC for Emulation

A typical configuration of a three-phase MMC system with half-bridge SMs is shown in Fig. 1. CPS-PWM is selected to be the modulation method for MMC, and the SM voltage balancing control strategy in (17), (18) are used in this paper. The selected mission profiles of SMs include the arm current and capacitor voltage. The analytical expressions of arm current and capacitor voltage, which would be the references for the emulator controller, can be obtained by MMC mathematical model. The steady-state arm current mainly consists of DC, fundamental and second-order components (19), as is expressed in (1).

\[
\begin{align*}
    i_{\text{arm}_2}(t) &= \frac{i_2(t)}{2} + \frac{1}{3} i_{dc} + i_{\text{circ}_2}(t) \\
    i_{\text{arm}_1}(t) &= \frac{i_1(t)}{2} + \frac{1}{3} i_{dc} + i_{\text{circ}_1}(t)
\end{align*}
\]

where \(i_{\text{arm}_2}(t)\) and \(i_{\text{arm}_1}(t)\) are arm current of MMC upper arm and lower arm respectively. \(i_2(t)\) is the fundamental current, \(i_{dc}\) is DC bus current, and \(i_{\text{circ}}\) is low-order harmonics mainly including second-order component. \(j\) represents the index of one of the three phases, (A, B or C). Ignoring the MMC power losses and considering power conservation \(P_{ac} = P_{dc}\), the DC bus current can be derived as:

\[
\begin{align*}
    V_{dc} I_{dc} &= \frac{3}{2} I_g U_g \cos \varphi \\
    U_g &= V_{dc} \times \frac{m}{2} \\
    I_{dc} &= \frac{3 m I_g \cos \varphi}{4}
\end{align*}
\]

Where \(I_g\) and \(U_g\) are amplitude of grid current and grid voltage respectively, \(m\) is the modulation index of MMC system. Providing that the operating conditions are determined, \(I_g\), \(U_g\), \(m\) and \(\varphi\) can be considered known variables. In (19), the steady-state of MMC system is analyzed, and the analytical expression of low-order harmonics is also involved, substituting the expression of \(I_{dc}\) and \(i_{\text{circ}}\) into Equation (1), then the arm current can be obtained.

Owing to the charging and discharging of submodule capacitors, each individual capacitor voltage includes a ripple component in addition to its DC component \(c\), as is shown in Equation (4).

\[
u_{csm}(t) = u_{csm} + u_{cak}(t) + u_{cak}(t)
\]

Where \(u_{csm}(t)\) is the capacitor voltage of SM. \(u_{cak}(t)\) and \(u_{cak}(t)\) are AC component and DC component of SM capacitor voltage respectively.

The series connected SMs in each arm of MMC can be equivalent to the controlled voltage source, a simplified structure of MMC is shown in Fig. 2, \(L_f\) and \(R_f\) denote the equivalent inductance and resistance respectively, as expressed in

\[
\begin{align*}
    L_f &= L_{arm} + L_g \\
    R_f &= R_{arm} + R_g
\end{align*}
\]

Where, \(L_{arm}\) denotes the grid inductance of MMC system, \(L_g\) denotes MMC arm inductance. Based on the MMC equivalent model, the arm voltage can be solved according to Kirchhoff law. Equation (6) shows the expressions of MMC arm voltage and SM duty ratio, the upper arm is selected as an example.

\[
\begin{align*}
    U_{g1}(t) &= \frac{V_{dc}}{2} - u_{g2}(t) - R_f \frac{d}{dt} i_{g1}(t) \\
    D_{sm}(t) &= U_{g1}(t) / V_{dc}
\end{align*}
\]

Where, \(u_{g1}(t)\) denotes the grid voltage of MMC system, \(D_{sm}(t)\) denotes the duty ratio of SM. The time-averaged current flowing into the capacitor \(i_{arm}(t)\) is expressed in (7), therefore, the capacitor voltage ripple can be obtained, as expressed in (8).

\[
\begin{align*}
    i_{arm}(t) &= D_{sm}(t) i_{arm}(t) + u_{csm}(t) X_C \\
    u_{csm}(t) &= u_{cak}(t) + u_{cak}(t) + X_c
\end{align*}
\]

Where \(X_c\) denotes the corresponding capacitor impedance for different frequencies. \(u_{csm}(t)\) denotes the reference of SM capacitor voltage. Based on the analysis above, the arm current and capacitor voltage can be obtained by theoretical analysis, and the expressions of arm current and capacitor voltage have to be applied to the SM under test as the voltage/current control references in the mission profile emulator.
3. Principle and Design of the Sub-Module Mission Profile Emulator for MMC

The configuration of single SM mission profile emulator is shown in Fig. 3. The emulator mainly consists of the device under test (DUT), MMC model, current controller and capacitor voltage balancing controller.

As can be seen in Fig. 3, DUT is a half-bridge SM in MMC system and the other parts are used to simulate the voltage and current loading behaviors of the DUT in the practical MMC system. In this paper, a half-bridge converter together with an inductor is employed to generate the required arm current of SM under test. The emulator arm current and capacitor voltage are sampled, and then used to compare with references generated by the MMC model. The switching signals of the half-bridge and SM under test are then determined by the current error and capacitor voltage error respectively.

The control diagram of MMC model is shown in Fig. 4. The inputs of MMC model are mission profiles of MMC system, including operating parameters and MMC system parameters, then the arm current reference, voltage reference and SM duty ratio are generated and output to the controller. For the SM under test, if the arm current and the capacitor voltage stressed on the SMs are consistent with those in a practical MMC system, then the loading behaviors of SM under test should be the same with the SMs in a practical MMC system. In this paper, CPS-PWM is adopted. As is shown in Fig. 5, By applying CPS-PWM, each arm with \( n \) SMs in MMC system requires \( n \) triangular carrier waves, and each carrier wave is phase shifted by a fixed angle of \( 360^\circ/n \). Therefore, by selecting and configuring the carrier wave phase angle, the corresponding SM in MMC can be selected as the target SM under test.

The current controller regulates the DC-AC converter according to the arm current reference. In this paper, a proportion-integration-resonance (PIR) controller is used to track the arm current reference with multiple components. The block diagram of the current controller for half-bridge converter is shown in Fig. 6. The PIR controller is...
constructed by connecting the resonance controller in parallel with a PI controller. The PI controller determines the dynamic performance of the emulator and produces dc control output. The resonant terms can deal with fundamental and second-order components in the arm current of MMC.

In practice, the voltage distribution among SMs will be subjected to a significant degree of imbalance. In order to keep the safe and reliable operation of MMCs, voltage balancing control is needed to eliminate the voltage imbalance between SMs in the same arm. The capacitor voltage balancing must be taken into consideration in mission profile emulator as well.

As is mentioned above, a half-bridge converter is adopted to generate the arm current, when the carrier waves of half-bridge converter and SM under test are in the same frequency and aligned phase angle, the arm current ripple can be minimum, and the interface inductance can be designed in a much lower value.

The voltage balancing controller in Fig. 3 aims at balancing the capacitor voltage of SM under test with the capacitor voltages generated by MMC model. The specific control diagram is shown in Fig. 7, a compensation voltage $\Delta u_{sm}$ used to regulate the SM under test capacitor voltage is generated by a PI controller, then the compensation voltage $\Delta u_{sm}$ is added to the Duty ratio of SM under test $D_{sm}$. By applying the control strategy shown in Fig. 6, the mission profile emulator is capable of emulating the electrical behaviors of multiple SMs. Each SM under test corresponding to a voltage balancing control. Another capacitor voltage balancing control method is shown in Fig. 8 in which the compensation signal $\Delta u_{sm}$ is added to the regulation signal of arm current, therefore this capacitor voltage control only can be applied to single SM test circuit.

4. Performance Validations

In this paper, the control strategy in Fig. 6 and Fig. 7 is adopted. Some validation for the single SM mission profile emulator is conducted by simulation (Plexim PLECS). A full scale MMC system parameters in simulation is shown in Table 1. The bode diagram of traditional PI controller is shown in Fig. 9, and Fig. 10 shows the bode diagram of current controller, as can be seen, for PIR controller, the phase margin is $63^\circ$, and the bandwidth is 1200 Hz. And the presence of two resonant peaks at 50 Hz and 100 Hz guarantee the effectiveness of current controller. The steady-state arm current and the steady-state SM capacitor voltage between emulator and MMC system with circulating current suppression are compared in Fig. 11(a) and Fig. 11(b) respectively. And Fig. 12 shows the electrical behaviors of emulator in rectifying mode. In order to improve the emulation accuracy, the MMC system without circulating current suppression control is also considered in this paper, as is shown in Fig. 13.

As can be seen, the arm current agrees well with the results from the MMC system. The capacitor voltage waveforms show that the capacitor voltage of SM under test is also close to the SM capacitor voltage in MMC system. By
applying the proposed control strategy, under the rectifying mode, both the arm current and the capacitor voltage can agree well with the reference without steady deviation Fig. 14 shows the steady-state error between MMC system with circulating current suppression and emulator. Both the steady-state arm current error and steady-state capacitor voltage error are remarkably small compared to the arm current and capacitor voltage, and the current ripple level can be accurately restrained which means the PIR controller and capacitor voltage balancing strategy work well. The simulation results have demonstrated that the current and voltage behaviors in MMC system can be accurately achieved by the MMC.
SMs mission profile emulator proposed in this paper. A scaled-down experiment platform for a single SM has been built up, as shown in Fig. 15, the peak value of arm current is set to 16-A and the rated average DC voltage of SM is set at 200 V. With 1.5 mF SM capacitance, the voltage ripple is around 5% DC voltage of SM, and the interface inductance is chosen to be 1.8 mH, which could limit the Maximum ripple current less than 1A. The design parameters for the experiment platform are concluded in Table 2. Some experimental measurements related to the mission profile emulator are conducted on the given experimental setup.

The current reference and voltage reference are calculated in the Digital Signal Processor (DSP) according to the analysis in section 2, and both the half-bridge converter and SM under test are controlled. In Fig. 16(a) and Fig. 16(b), the emulated arm current and capacitor voltage with circulating current suppression is presented respectively, and Fig. 17(a) and Fig. 17(b) present the emulated arm current and capacitor voltage without circulating current suppression. As can be seen, the DC bias, fundamental and second-order components of SM under test arm current can be explicitly observed. When applying the MMC circulating current suppression, the second order component in Fig. 16 is eliminated. The capacitor voltage waveform accords well with the reference value listed in Table 2. The experiment results show the validity of the proposed mission profile emulator.

### 5. Conclusion

In this paper, a mission profile emulator for MMC is analyzed, the mission profiles of SM in a complete MMC system can be accurately achieved. The scheme of the mission
profile emulator is presented. PIR current controller is employed to control the compound arm current, and voltage balancing for CPS-PWM is specially considered in the MMC model. With this emulator, the testing for reliability performance of future HVDC SuperGrids with modular multilevel converters, in Proc. 14th EPE Birmingham, pp. 1–10 (2011).

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References


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