FAULT-TOLERANT CONTROL SCHEME OF MODULAR MULTILEVEL CONVERTER IN MEDIUM-VOLTAGE MOTOR DRIVE APPLICATIONS

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ABSTRACT

This paper proposes a fault-tolerant control scheme for a modular multilevel converter (MMC) in medium-voltage motor drives. The redundant submodules (SMs) are implemented in each converter arm to bring advantages during healthy and fault-tolerant operations. During the healthy operation, redundant SMs are controlled to function as a normal half-bridge SM, which helps reduce the SM capacitor voltages, improving the system's reliability and loss reduction. During the fault-tolerant operation, the failure SMs are only bypassed in one converter arm, and the other arm’s SMs keep functioning; thus, it utilizes redundant SMs for future failure SMs. The injected scheme is also performed to ensure low voltage ripples on the SM capacitors during the low-speed operation. The feasibility of the proposed control scheme has been verified by simulation results for the 4160-V/1-MW MMC-fed induction motor drive system.

Keywords: Fault-tolerant control, medium-voltage motor drive, modular multilevel converter, submodule capacitor voltage ripple.

1. INTRODUCTION

Modular multilevel converters (MMCs) have become a breakthrough topology for medium to high-voltage applications owing to their advantages such as low harmonic voltage, modularity, and scalability [1]. Therefore, MMCs have been developed in high-voltage direct current (HVDC) transmission systems [2], static synchronous compensators (STATCOMs) [3], and motor drives [4-9]. However, one of the main challenges of MMC is a large voltage ripple on the SM capacitor at a low fundamental frequency. It is derived that the SM capacitor voltage ripple is proportional to the output current level and inversely proportional to the fundamental frequency [4-6]. Therefore, it is challenging to maintain the SM capacitor voltage ripple within the allowable range for MMC in medium-voltage motor drive applications at low-speed operation.

Several studies have been presented to reduce the SM capacitor voltage ripple at low-speed operation [4-6]. One of the popular control methods is a sinusoidal-wave method, where the high-frequency common-mode voltage (CMV) and circulating current are injected into the converter in the low-speed range [4-7]. Studies on advanced control methods to reduce the circulating current and improve the converter efficiency also have been suggested [7-9]. They help to decrease the amplitude of the injected circulating current without affecting the output qualities.

The MMC with half-bridge SM, including two semiconductor switches and one capacitor, is widely used owing to its simple construction and easy control. Therefore, the MMC converter consists of numerous switching devices and one of them might become a potential failure point. Therefore, it is important to implement fault-tolerant strategies to avoid harmful accidents and to continuously operate the system without unplanned shutdown [10]. In literature review, there are two types of switch faults: short-circuit and open-circuit faults. Most of the industrial gate drivers can protect the IGBTs against short-circuit faults [11]. However, the open-circuit fault, which is caused by a failure in the gate-driver circuitry cannot be detected by the gate driver. It probably damages devices and deteriorates system performance.

Until now, a solution for riding through the open-circuit fault of switches in MMC-based motor drive applications has not been presented. In MMC-based HVDC applications, several fault-tolerant control methods have been suggested [12-14], which are classified into the cold reserve mode and hot reserve mode [12]. The difference between the two modes is the behavior of redundant SMs. In the cold reserve mode, the redundant SMs are normally bypassed and only activated once the fault occurs. Hence, this mode is suitable for HVDC applications, where numerous SMs have been employed [13]. On the other hand, in the hot reserve mode, the redundant SMs are controlled to operate as normal ones, which enhances the output voltage quality. Thus, this mode is preferable for medium-voltage applications due to the limited number of SMs per arm. In [12], the fault-tolerant control for MMC in medium-voltage applications is suggested, but SM capacitor voltage balancing should be taken into consideration to implement it in motor drive applications.

This paper proposes a fault-tolerant control scheme for a MMC in medium-voltage motor drives. During the healthy operation, the redundant SMs are controlled to function together with normal half-bridge SMs in each arm, which helps to reduce the SM capacitor voltages in the system. During the fault-tolerant operation, the failure SMs are only bypassed in one converter arm, and other arm's SMs keep running without any interruption. Therefore, the system performance is not deteriorated, and the reliability is improved.

2. MODULAR MULTILEVEL CONVERTER AND ITS OPERATING PRINCIPLE

2.1. Circuit structure

The circuit structure of the MMC is shown in Fig. 1. It consists of three legs (*x: a, b, c*), and one leg includes two arms (*g: U, L*). One arm comprises N_a healthy SMs and N_r redundant SMs. A half-bridge SM is used in this topology, including two switches, one capacitor, and one bypass switch *B*.

2.2. Basic operating principle

In MMC as shown in Fig. 1, the arm voltages and currents are expressed as:

$$v_{xU} = 0.5V_{dc} - V_o\cos(\omega t + \delta_x), \tag{1}$$

$$v_{xL} = 0.5V_{dc} + V_o\cos(\omega t + \delta_x), \tag{2}$$

$$i_{xU} = i_{circ,x} + 0.5i_x, \tag{3}$$

$$i_{xL} = i_{circ,x} - 0.5i_x, \tag{4}$$

where v_{xU} and v_{xL} represent the upper and lower arm voltage, i_{xU} and i_{xL} are the upper and lower arm current, and $i_{circ,x}$ is the circulating current within each leg. The AC output voltage and current are expressed as:

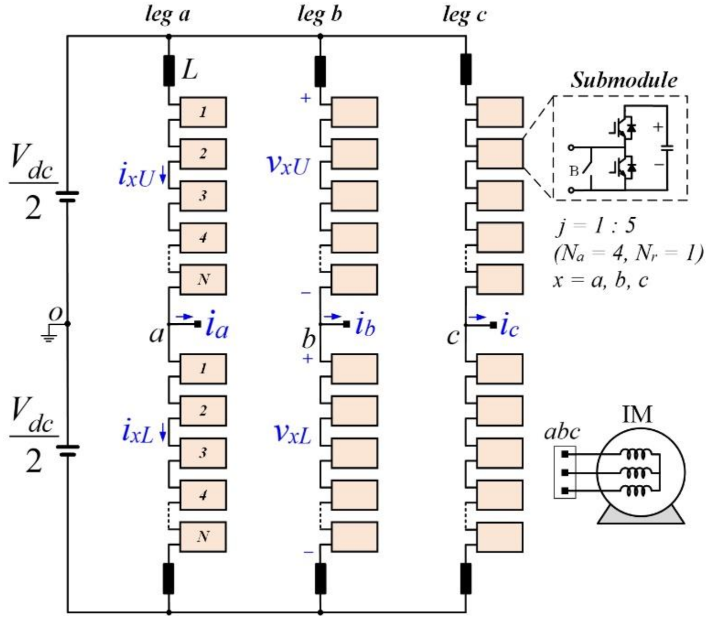

Fig. 1. Circuit structure of the MMC

$$v_x = V_o \cos(\omega t + \delta_x), \tag{5}$$

$$i_x = I_o \cos(\omega t + \delta_x - \phi), \tag{6}$$

where V_o and I_o are the voltage and current magnitudes, ω is the fundamental angular frequency, δ_x is the initial phase angle ($\delta_a = 0$, $\delta_b = 2\pi/3$ and $\delta_c = -2\pi/3$), and ϕ is the phase angle between voltage and current. In [xx], the SM capacitor voltage ripple, Δv_{c_pp}, is proportional to the output current value and inversely proportional to the fundamental frequency, which can be expressed as:

$$\Delta v_{c\_pp} = \frac{I_o}{2C\omega}, \tag{7}$$

where C is the SM capacitance. As a result, Δv_{c_pp} becomes larger in the low-speed range. It leads to the necessity of a mitigated method that should be integrated with the control method of motor drive. In this paper, the sinusoidal-wave method is employed to overcome that issue [4]; thus, the high-frequency CMV and circulating current are injected into each arm converter. The next section discusses the proposed fault-tolerant control.

3. THE PROPOSED FAULT-TOLERANT CONTROL SCHEME

Prior to a fault occurrence, N_r redundant SMs are utilized to decrease the voltage reference for SM capacitors, which is equal to $V_{dc}/(N_a + N_r)$. The SM voltage reference in the upper and lower arms are expressed as:

$$v_{xU}^{*} = \frac{1 - m\cos(\omega_o t + \varphi)}{2} \frac{V_{dc}}{N_a + N_r}, \tag{8}$$

$$v_{xL}^{*}=\frac{1+m\cos(\omega_o t+\varphi)}{2}\,\frac{V_{dc}}{N_a+N_r}\,, \tag{9}$$

where m is the modulation index.

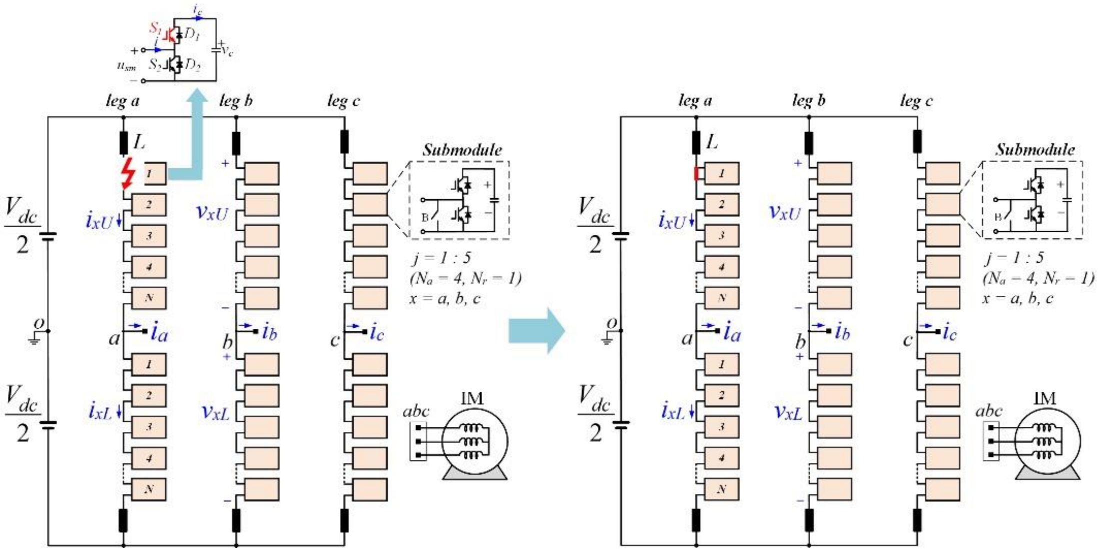

Fig. 2. Reconfiguration of MMC when an open fault occurs at the SM-1 in the upper arm of phase-a.

Fig. 2 illustrates the circuit reconfiguration of MMC when an open fault occurs at SM-1 in the upper arm of phase-*a*. To ensure the output voltage with low THD, the carrier frequencies of healthy SMs in the failure arm are updated to maintain the total equivalent switching frequency per arm to be the same as other arms. Therefore, the updated carrier frequency, f_c', of SMs in the upper arm of phase-*a* is expressed as:

$$f_c^{'}=\frac{N}{N^{'}}\,f_c\,, \tag{10}$$

where $N = N_a + N_r$ and N' is the remaining SMs in each arm. In addition, the SM capacitor voltage references in the failure arm are also updated as:

$$v_c^{*}=\frac{V_{dc}}{N^{'}}\,. \tag{11}$$

Next, the SM voltage references in the upper and lower arms are expressed as:

$$v_{xU}^{*}=\frac{1-m\cos(\omega_o t+\varphi)}{2}\,\frac{V_{dc}}{N^{'}}\,, \tag{12}$$

$$v_{xL}^{*}=\frac{1+m\cos(\omega_o t+\varphi)}{2}\,\frac{V_{dc}}{N}\,. \tag{13}$$

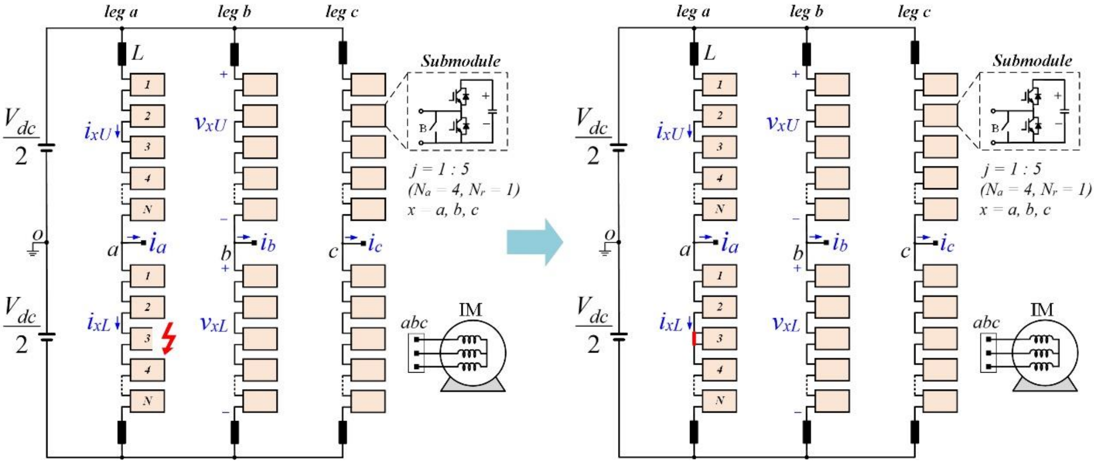

Fig. 3. Reconfiguration of MMC when an open fault occurs at the SM-3 in the lower arm of phase-a.

Similarly, if the failure SM belongs to the lower arm instead of upper arm, the carrier frequency and the SM capacitor voltage reference in the lower arm are updated. The SM voltage references in the upper and lower arms are given as:

$$v_{xU}^{*}=\frac{1-m\cos(\omega_o t+\varphi)}{2}\frac{V_{dc}}{N}, \tag{14}$$

$$v_{xL}^{*}=\frac{1+m\cos(\omega_o t+\varphi)}{2}\frac{V_{dc}}{N'}. \tag{15}$$

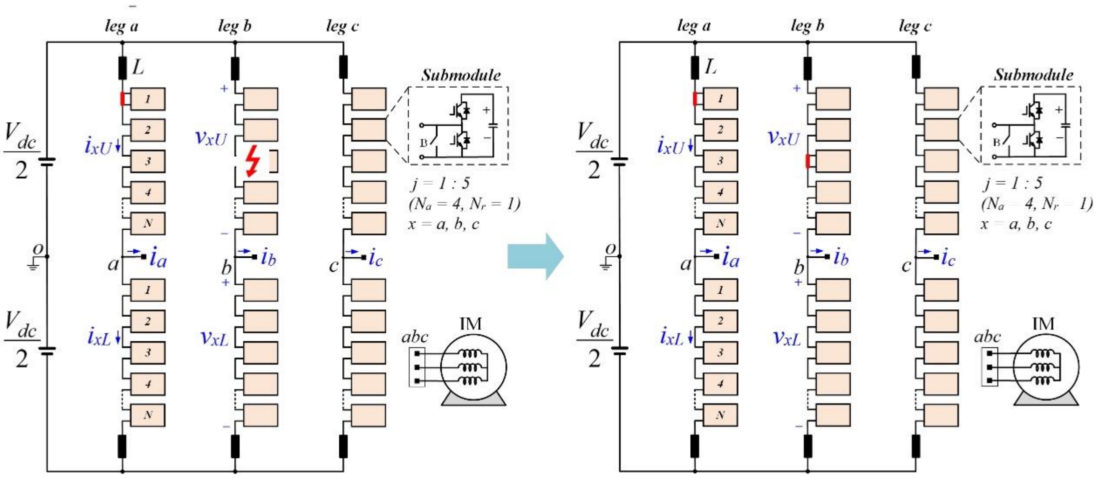

Fig. 4. Reconfiguration of MMC when an open fault occurs at the SM-3 in the lower arm of phase-a.

After recovery from the prior fault, another open-circuit fault may occur as shown in Fig. 4. Then, the carrier frequency and the SM capacitor voltage reference are updated based on the remaining SMs.

4. SIMULATION RESULTS

To validate the proposed control strategy, a 4160-V/1-MW simulation model of MMC in motor drive applications has been developed. The circuit parameters used for the simulation are listed in Table 1, in which four ordinary SMs and one redundant SM has been used per arm.

Table 1. Parameters used for simulation

Parameters	Symbol	Value
Converter (MMC)		
Apparent power (kVA)	S	1081
DC-link voltage (V)	V_{dc}	7000
Number of ordinary SMs per arm	N_a	4
Number of redundant SMs per arm	N_r	1
SM capacitor voltage reference (V)	v_c^*	1400
Arm inductance (mH)	L	1.5
SM capacitance (mF)	C	0.9
Carier frequency (Hz)	f_c	2000
Injected frequency (Hz)	f_h	200
Induction Motor (IM)		
Output power (hp)	P_o	1250
Rated voltage (V)	V_{LL}	4160
Rated current (A)	I_{rated}	150
Rated speed (rpm)	ω_{rm_rated}	1470
Rated torque (N.m)	T_{rated}	5970

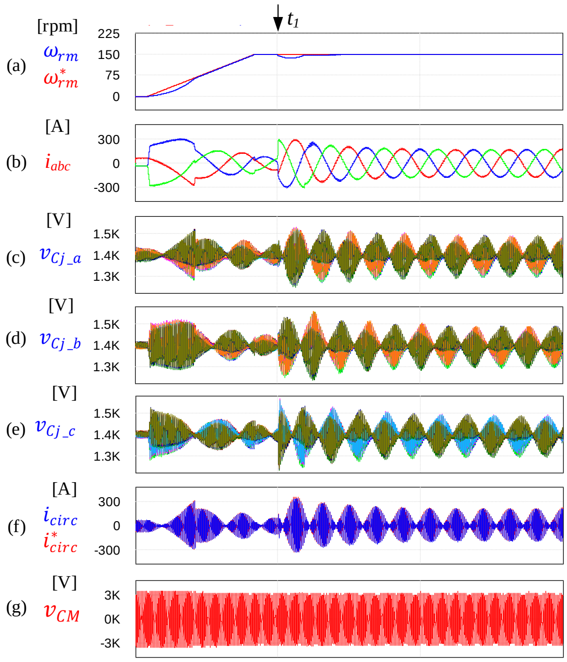

Fig. 5. Performance at low-speed operation (ω_{rm} = 150 rpm). (a) Motor speed. (b) Output current. (c) SM capacitor voltage in phase-a. (d) SM capacitor voltage in phase-b. (e) SM capacitor voltage in phase-c. (f) Circulating current. (g) Common-mode voltage.

Fig. 5 shows the performance of the normal operation of the MMC at ωrm = 150 rpm when the load torque is changed from no load to full load at t = t1. During the accelerating operation, the motor speed is increased from zero to 150 rpm as shown in Fig. 5(a). In Fig. 5(b), there is a high inrush current due to the startup of the motor. Fig. 5(c)-(e) demonstrates waveforms of the SM capacitor voltage in three phases, where their reference is 1400 V. As can be seen, the SM capacitor voltage is controlled to follow the reference well, and their ripples are within the allowable range. In Fig. 5(f), the circulating current is shown, where the high-frequency component is injected into each arm intentionally to mitigate the SM capacitor voltage ripple. Besides the injected circulating current, the injected CMV is also required as shown in Fig. 5(g).

Fig. 6 shows the performance of the proposed fault-tolerant control regarding S_1 open circuit fault of SM-2 in the upper arm of phase-*a*. At $t = t_1$, an open circuit fault occurs in SM-2, and its capacitor voltage will be zero. In addition, the reference for the SM capacitor voltage in the upper arm of the phase is updated to 1750 V because of the remaining four SMs. Also, the carrier frequency of those SMs is updated to 2.5 kHz from 2 kHz. As can be seen in Fig. 6(c), the SM capacitor voltages in the upper arm of phase-*a* follow well the reference of 1750 V. SM capacitor voltages in phase-*b* and phase-c are still balanced at 1400 V as shown in Fig. 6(d) and (e). The motor speed does not deteriorate during the fault-tolerant operation.

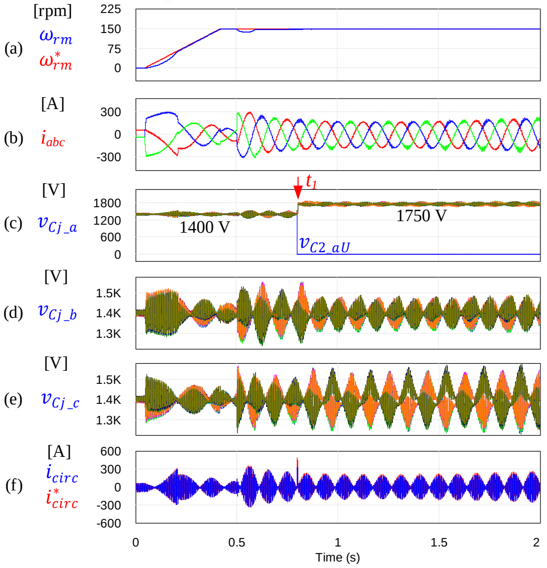

Fig. 6. Performance of the proposed fault-tolerant control regarding S_1 open circuit fault of SM-2 in the upper arm of phase-a. (a) Motor speed. (b) Output current. (c) SM capacitor voltage in phase-a. (d) SM capacitor voltage in phase-b. (e) SM capacitor voltage in phase-c. (f) Circulating current.

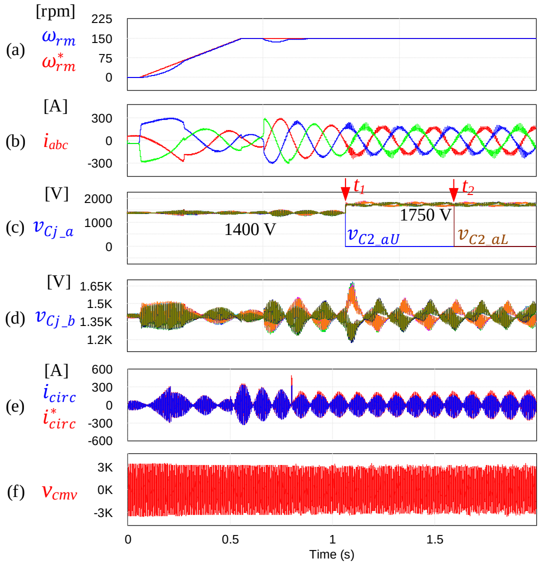

Fig. 7. Performance of the proposed fault-tolerant control regarding open circuit faults in the upper and lower arms of phase-a. (a) Motor speed. (b) Output current. (c) SM capacitor voltage in phase-a. (d) SM capacitor voltage in phase-b. (e) SM capacitor voltage in phase-c. (f) Circulating current.

Fig. 7 illustrates the performance of the proposed fault-tolerant control regarding open circuit faults in the upper and lower arms of phase-*a*. Open circuit faults occur in SM-2 in the upper lower arms at $t = t_1$ and $t = t_2$, respectively. Since there are four SMs in the lower arm after t_2, the SM capacitor voltage reference in the lower arm is updated to 1750 V shown in Fig. 7(c). Therefore, only eight healthy SMs function in phase-*a*. In Fig. 7(a), the motor speed follows its reference well. The SM capacitor voltages in other phases are also balanced at 1400 V.

5. CONCLUSION

This paper has proposed a fault-tolerant control scheme for the MMC in medium-voltage motor drives. In each converter arm, the redundant SMs are employed to bring benefits to healthy and fault-tolerant operations. The SM capacitor voltage reference can be decreased in healthy operation, which helps to reduce the voltage stress on switching devices. During the fault-tolerant operation, the failure SMs can be bypassed and the remaining SMs can be controlled with a higher voltage reference. Only the failure SMs are bypassed, and other healthy SMs in other arms still function normally. The validity of the proposed control strategy has been confirmed through the simulation results for the MMC-fed induction motor drive system.

REFERENCES

1. Lesnicar A. and Marquardt R. - An innovative modular multilevel converter topology suitable for a wide power range, in 2003 IEEE Bologna PowerTech **3** (2003) 272–277. https://doi.org/10.1109/PTC.2003.1304403
2. Allebrod S., Hamerski R., and Marquardt R. - New transformerless, scalable modular multilevel converters for HVDC-transmission, in Proceedings under Annual IEEE Conference on Power Electronics Specialists (PESC) (2008) 174–179. https://doi.org/10.1109/PESC.2008.4591920
3. Peng F. Z., Lai J., Mckeever J. W., and Vancoevering J. - A multilevel voltage-source inverter with separate DC sources for static var generation, IEEE Transactions on Industry Applications **32** (5) (1996) 1130-1138. https://doi.org/10.1109/IAS.1995.530626
4. Korn A. J., Winkelnkemper M., and Steimer P. - Low output frequency operation of the modular multi-level converter, in Proceedings *under* IEEE Energy Conversion Congress and Exposition (2010) 3993–3997. https://doi.org/10.1109/ECCE.2010.5617802
5. Hagiwara M., Hasegawa I., and Akagi H. -Start-up and low-speed operation of an electric motor driven by a modular multilevel cascade inverter, IEEE Transactions on Industry Applications **49** (4) (2013) 1473–1480. https://doi.org/10.1109/TIA.2013.2256331
6. Le D. D. and Lee D.-C. - A modular multilevel converter topology with novel middle submodules to reduce capacitor voltage fluctuations, IEEE Transactions on Power Electronics **37** (1) (2022) 70–75. https://doi.org/10.1109/TPEL.2021.3101884
7. Antonopoulos A., Ängquist L., Norrga S., Ilves K., Harnefors L., and Nee H. P. - Modular multilevel converter AC motor drives with constant torque from zero to nominal speed, IEEE Transactions on Industry Applications **50** (3) (2014) 1982–1993. https://doi.org/10.1109/TIA.2013.2286217
8. Le D. D. and Lee D.-C. - Current stress reduction and voltage THD improvement of FC-MMCs for AC machine drive applications, IEEE Transactions on Industrial Electronics **69** (1) (2022) 90–100. https://doi.org/10.1109/TIE.2021.3050394

9. Zhao F., Xiao G., Zhu T., Zheng X., Wu Z., and Zhao T., -A coordinated strategy of low-speed and start-up operation for medium-voltage variable-speed drives with a modular multilevel converter, IEEE Transactions on Power Electronics **35** (1) (2020) 709-724. https://doi.org/10.1109/TPEL.2019.2913696

10. Shao S., Wheeler P. W., Clare J. C., and Watson A. J. - Fault detection for modular multilevel converters based on sliding mode observer, IEEE Transaction on Power Electronics **28** (11) (2013) 4867–4872. https://doi.org/10.1109/TPEL.2013.2242093

11. Choi Ui.-M., Blaabjerg F., and Lee Kyo.-B. - Study and handling methods of power IGBT module failures in power electronic converter systems, IEEE Transactions on Power Electronics **30** (5) (2015) 2517–2533. https://doi.org/10.1109/TPEL.2014.2373390

12. Li B., Xu Z., Ding J., and Xu D. - Fault-tolerant control of medium-voltage modular multilevel converters with minimum performance degradation under submodule failures, IEEE Access **6** (2018) 11772–11781. https://doi.org/10.1109/ACCESS.2018.2811904

13. Wang J. and Tang Y. - A fault-tolerant operation method for medium voltage MMCs with phase-shifted carrier modulation, IEEE Transactions on Power Electronics **34** (10) (2019) 9459–9470. https://doi.org/10.1109/TPEL.2018.2890536

14. Yang S., Tang Y., and Wang P. - Seamless fault-tolerant operation of a modular multilevel converter with switch open-circuit fault diagnosis in a distributed control architecture, IEEE Transactions on Power Electronics **33** (8) (2018) 7058-7070. https://10.1109/TPEL.2017.2756849

TÓM TẮT

PHƯƠNG PHÁP HOẠT ĐỘNG VỚI KHẢ NĂNG CHỊU LỖI CHO BỘ BIẾN ĐỔI ĐA BẬC CẤU HÌNH MÔ-ĐUN TRONG TRUYỀN ĐỘNG ĐỘNG CƠ TRUNG THẾ

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Trong bài báo này, phương pháp hoạt động với khả năng chịu lỗi được đề xuất cho bộ biến đổi đa bậc cấu hình mô-đun (MMC) trong các bộ truyền động động cơ trung thế. Các mô-đun con dự phòng (SM) được triển khai trong mỗi nhánh để mang lại lợi ích trong quá trình vận hành bình thường và có khả năng chịu lỗi. Trong quá trình hoạt động bình thường, các SM dự phòng được điều khiển để hoạt động như một SM nửa cầu thông thường, giúp giảm điện áp của trên tụ của SM, từ đó cải thiện độ tin cậy của hệ thống và giảm tổn hao. Trong quá trình vận hành có khả năng chịu lỗi, các SM bị lỗi trong một nhánh được loại bỏ và các SM còn lại của nhánh khác vẫn tiếp tục hoạt động; do đó, các SM dự phòng có thể sử dụng cho các lỗi trong tương lai. Bên cạnh đó, giải thuật giảm dao động điện áp trên tụ của SM trong quá trình vận hành ở tốc độ thấp được áp dụng. Tính khả thi của phương pháp đề xuất đã được xác minh bằng kết quả mô phỏng cho hệ thống truyền động động cơ cảm ứng cấp nguồn MMC 4160-V/1-MW.

Từ khóa: Phương pháp hoạt động với khả năng chịu lỗi, bộ biến đổi đa bậc cấu hình mô-đun, dao động điện áp trên tụ của mô-đun.