A SVPWM-based fault-tolerance control method for three-level inverter under different working conditions

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Abstract: Aiming at the open-circuit fault of three-level NPC inverter used in traction system, the difference of current path at inverter legs before and after the fault is analyzed, and the change of space voltage vectors distribution is discussed. Then, based on the principle of Space Vector Pulse Width Modulation(SVPWM) and through the reconstruction of the basic voltage vectors, two fault-tolerant methods for different operating conditions of the train are proposed, and the idea of weak magnetism is innovatively proposed to realize fault-tolerant control at the condition on high speed. Simulation results show the effectiveness of the proposed methods.

Key Words: Fault-tolerant control, Three-lever Neutral Point Clamped (NPC) inverter, Open-switch fault

2021 33rd Chinese Control and Decision Conference (CCDC) | 978-1-6654-4089-9/21/$31.00 ©2021 IEEE | DOI: 10.1109/CCDC52312.2021.9602007

1 INTRODUCTION

Currently, three-level Neutral Point Clamped (NPC) inverter has been widely used in the traction drive control system of high-speed emu due to its advantages such as stable topology, high switching frequency and low output voltage harmonics[1-2].

However, high-speed trains often run under high load, and their operating environment is complex and changeable, which increases the possibility of the failure for the inverter used for traction system, seriously affecting the safety of train operation[3].

The power switching device is the weakest link in the traction inverter, and the open-circuit fault and short-circuit fault of switches are the main faults[4-5]. The fault diagnosis and fault tolerance of the power switching device for the inverter have gradually become the focus of research at home and abroad[6].

So far, the fault-tolerant control of three-level NPC inverter is mainly divided into hardware method and software method[7]. Among them, hardware method is mainly based on switch, leg, module or system-levels[8]. In [9-10], a three-level NPC inverter fault-tolerant topology based on transistor is proposed, when faults occur at a particular leg, shut off the fault leg consisting of four IGBT switches immediately and connect the fault leg to the zero potential point of the DC side directly, then use the three-phase voltage reconstructed by the remaining two phase voltage to drive the motor running. But this method may lead to the decrease of system output capacity and the imbalance of voltage in the DC link. [11] builds a fault-tolerant topology with a redundant leg beside the three-phase inverter legs. when a fault of one leg occurs, the fault leg is isolated immediately by fuse. Meanwhile, the fault leg is replaced by the redundant leg via a bidirectional thyristor, so that the system can continue to produce high quality three-phase voltage to drive the motor to continue to work. This fault-tolerant topology can almost restore the system to pre-fault performance, but it requires too many additional power switches and take up much space of the inverter.

The software method realizes fault-tolerant control through algorithm without changing the topology of the inverter, which can save the hardware cost and simplify the topology[12]. In [13], finite control set model predictive control (FCS-MPC) is proposed for a synchronous reluctance motor (SynRM) with a fault tolerance against an open-phase fault. After the fault occurs, the most appropriate switching state is selected for output by the finite set model predictive control algorithm, so as to optimize the system performance after the fault of the inverter. However, this method is sensitive to parameter variation, and each control period only acts on a single vector, resulting in large harmonics and voltage distortion for the system, besides, the switching frequency is not fixed due to irregular switching action.

Space Vector Pulse Width Modulation(SVPWM) technology is widely used in various inverters because of its small harmonic component of the current waveform and its ability to reduce the torque ripple of the motor[14]. In [15], a soft fault-tolerant control method based on the inherent redundancy voltage space vectors is proposed according to SVPWM principle, which can make the three-level inverter continue to operate after fault at one leg by reducing the modulation ratio. However, this method does not propose a fault-tolerant strategy to make the system run in the optimal state after failure, and the modulation ratio of inverter is greatly reduced so that the utilization rate of bus voltage decrease.

The authors are grateful for the support of the Natural Science Foundation of China (#61773407, #61621062, #61803390, #61490702), by the Key Laboratory of Energy Saving Control and Safety Monitoring for Rail Transportation (No. 2017TP1002), by Key Laboratory of High Performance Complex Manufacturing (#ZZYJKT2020-14), by the General Program of the Equipment Pre-research Field Foundation of China under Grant (No. 61400030501).

In this paper, based on SVPWM principle, the fault-tolerant control methods of traction inverter under different operating conditions for open-current fault at internal and external switches are discussed respectively. And different fault-tolerant control methods are proposed for different operating conditions of the train. When the train is running at low speed, the fault-tolerant control can be realized by using redundant voltage vectors. On the contraty, when the train is running at high speed, the idea of weak magnetism is creatively proposed to complete the fault-tolerance control for open-circuit fault of inverter, which makes the output current quality of the inverter significantly better than the method mentioned in [15]. Then the effectiveness of the proposed scheme is verified in the Matlab/Simulink environment.

2 Three-level NPC inverter for traction

If the three-phase asynchronous motor can realize M-T synchronous coordinate system in the system and make the M axis oriented in the direction of rotor flux, the independent control of magnetic field current i_M and torque current i_T can be realized, which is the basic idea of Field-Oriented Control (FOC). The control block diagram for traction system is shown in Fig 1.

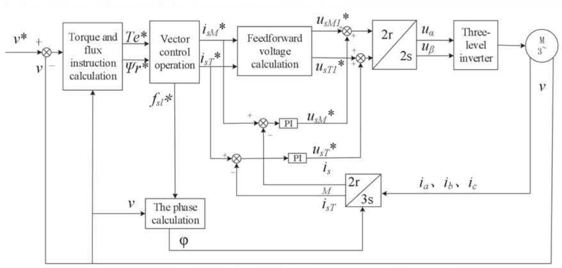


Fig 1. Field-Oriented Control block diagram

During the train traction operation, the intermediate DC link supplies the traction inverter with stable DC voltage. Then the inverter generates an alternating current with adjustable amplitude and frequency to drive the motor to work. The topology of three-lever NPC inverter is shown in Fig 2, which is composed of three legs, respectively output three-phase sinusoidal voltage to drive motor operation, each leg has four active switches IGBTs, named T_{x1}, T_{x2}, T_{x3}, T_{x4} (x means u、v、w). The DC input portion providing a DC voltage of U_{dc} size consists of two capacitors to provide zero potential point.

The four switches of each phase leg can form three different switching states, respectively named P, O, and N, as shown in Table 1.

Table1. Definition Of The Switching States

State of leg	State of IGBTs				Output phase voltage
	T_{x1}	T_{x2}	T_{x3}	T_{x4}	
[P]	ON	ON	OFF	OFF	$+U_{dc}/2$
[O]	OFF	ON	ON	OFF	0
[N]	OFF	OFF	ON	ON	$-U_{dc}/2$

The three-level NPC inverter can form a total of 27 switching state combinations. According to their magnitude, they can be divided into large vector, medium vector, small vector and zero vector. The length of the large vector is 2/3 U_{dc}, the length of the medium vector is $\sqrt{3}/3$ U_{dc}, the length of the small vector is 1/3 U_{dc} and the length of the zero vector is 0, whose distribution in space is shown in Fig 3.

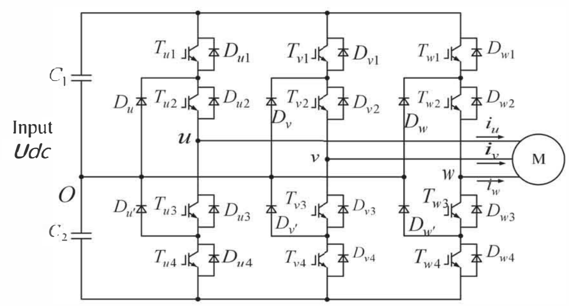


Fig 2. Topology diagram of three-level NPC inverter

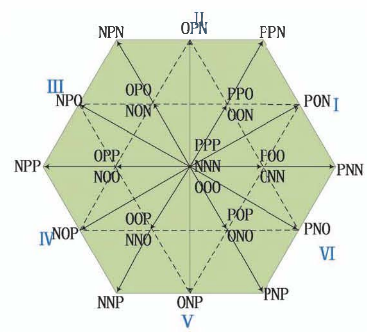


Fig 3. Space voltage vector distribution

According to the basic principle of SVPWM, when the three-phase stator phase voltages u_{aN} u_{bN} u_{cN} are respectively applied to the three-phase windings, three voltage space vectors $\boldsymbol{u}_{aN}$ $\boldsymbol{u}_{bN}$ $\boldsymbol{u}_{cN}$ that are 120 degrees out of phase in time each other can be defined, their direction is always on the axis of each phase, and the magnitude pulsates according to the sinusoidal law over time[16]. Then the synthetic space vector $\boldsymbol{U}_{ref}$ by the three-phase voltage space vectors is a rotating space vector whose amplitude is constant and rotates uniformly at the angular velocity w_s, which is shown in Fig 4, and their relationship can be represented by Formula (1).

$$\begin{cases} u_{aN} = U_m \sin wt \\ u_{bN} = U_m \sin\left(wt - \dfrac{2\pi}{3} \right) \\ u_{cN} = U_m \sin\left(wt - \dfrac{2\pi}{3} \right) \\ U_{ref} = \dfrac{2}{3}\left(u_{aN} + a u_{bN} + a^2 u_{cN} \right)\left(a = e^{j2\pi/3} \right) \\ w_s = 2\pi f_s \end{cases} \tag{1}$$

where, f_s represents the power supply angular frequency and U_m represents the amplitude of AC voltage.

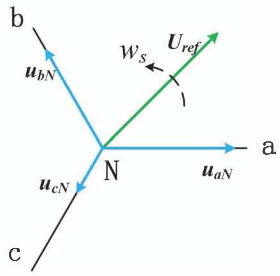


Fig 4. Voltage space vector

When the rotational speed is not very low, the voltage drop of the electronic resistance is small and negligible, then the approximate relationship between stator voltage $\boldsymbol{U_{ref}}$ and flux linkage ψ_s can be expressed by Formula (2).

$$\psi_s \approx \int u_{ref} dt \tag{2}$$

Therefore, when the space flux vector rotates once a circle, the voltage vector also continuously follows the tangent direction of the flux circle. Then, the shape problem of the rotating magnetic field of the motor can be transformed into the shape problem of the motion of the space voltage vector[17].

3 THE PROPOSED FAULT-TOLERANT METHODS FOR DIFFERENT WORKING CONDITIONS

To simplify the analysis, the u-phase leg is taken as an example. Different suitable fault-tolerant methods for the open-fault of IGBT switches are proposed respectively under low speed and high speed conditions.

3.1 Fault analysis

When an IGBT has an open fault, the IGBT will always be in the off state. At this point, the system will change the current direction, resulting in a change in the output voltage of the leg, and at the same time, the system will lose part of the basic voltage vectors.

A. Open-circuit fault at T_{u1}

The current direction from left to right is defined as positive direction. When an open-circuit fault occurs at T_{u1}, if $i_u > 0$ and the pulse control signal of u-phase leg is [1100] (1 represents IGBT on; 0 represents IGBT off), under normal circumstances, the current flows through T_{u1} and T_{u2}, at this time, the output voltage of u-phase is $U_{dc}/2$, and the corresponding voltage vector is P. When the open-circuit fault occurs at T_{u1}, the current cannot flow through T_{u1}, but through D_u and T_{u2}. At this time, the output voltage of u-phase is 0, and the corresponding voltage vector is O, which is shown in Fig 5-(a). On the other hand, the system will not be able to produce a voltage vector of type P--, and its distribution diagram is shown in Fig 6-(a), where the red vector refers to the basic voltage vector lost due to the system failure, and the blank part refers to the voltage vector region that cannot be synthesized after the system failure.

B. Open-circuit fault at T_{u2}

As shown in Fig 5-(b) and Fig 5-(c), if $i_u > 0$, when the pulse control signal of the leg of u-phase is [1100], under normal circumstances, the current flows through T_{u1} and T_{u2}, and the output voltage vector of u-phase is P. When open circuit fault occurs in T_{u2}, the current cannot flow through T_{u2}, but through D_{u3} and D_{u4}. At this time, the output voltage vector of u-phase is N. When the pulse control signal of the leg of u-phase is [0110], the current flows through D_u and T_{u2} under normal circumstances. The output voltage vector of u-phase is O in this moment. At a word, in the case of open circuit fault of T_{u2}, the current cannot flow through T_{u2}, but through D_{u3} and D_{u4}, at this point, the output voltage vector of u-phase is N. Therefore, when open-circuit fault occurs at T_{u2}, the system cannot normally generate the voltage vectors of types of P-- and O--, as shown in Fig 6-(b).

C. Open-circuit fault at T_{u3}

The open-circuit fault at T_{u3} is similar to the fault at T_{u2}. As shown in Fig 5-(d) and Fig 5-(e), when $i_u < 0$, if the pulse signal is [0110], the voltage vector output by the leg of u-phase will change from O in normal time to P; if the pulse signal is [0011], the output voltage vector of the u-phase will change from N to P. The system will not be able to generate the voltage vectors of type O-- and type N--, as shown in Fig 6-(c).

D. Open-circuit fault at T_{u4}

The open-circuit fault at T_{u4} is similar to the fault at T_{u1}. As shown in Fig 5-(f), When $i_u < 0$, if the pulse signal is [0011], the voltage vector output by the u-phase will change from N in normal time to O, so that the system will not be able to generate the voltage vectors of type N--voltage, as shown in Fig 6-(d).

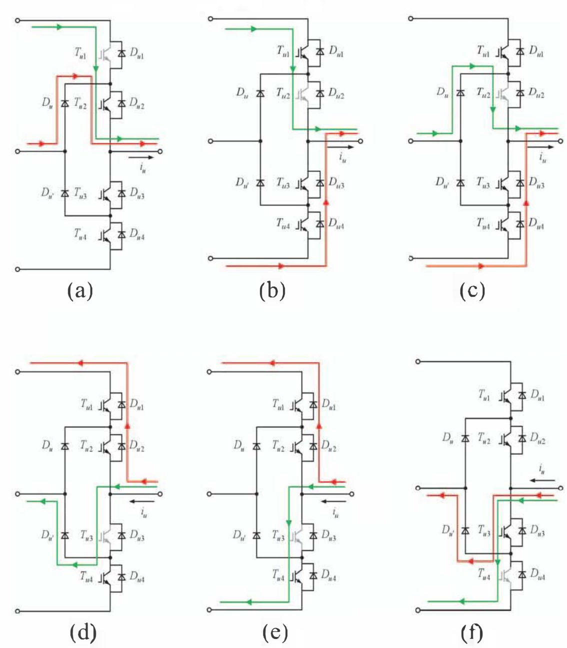


Fig 5. Current path before(green line) and after(red line) open-circuit fault. (a) T_{u1} failure and [1100], i_u>0. (b) T_{u2} failure and [1100], i_u>0. (c) T_{u2} failure and [0110], i_u>0. (d) T_{u3} failure and [0011], i_u<0. (e) T_{u3} failure and [0110], i_u<0. (f) T_{u4} failure and [0011], i_u<0.

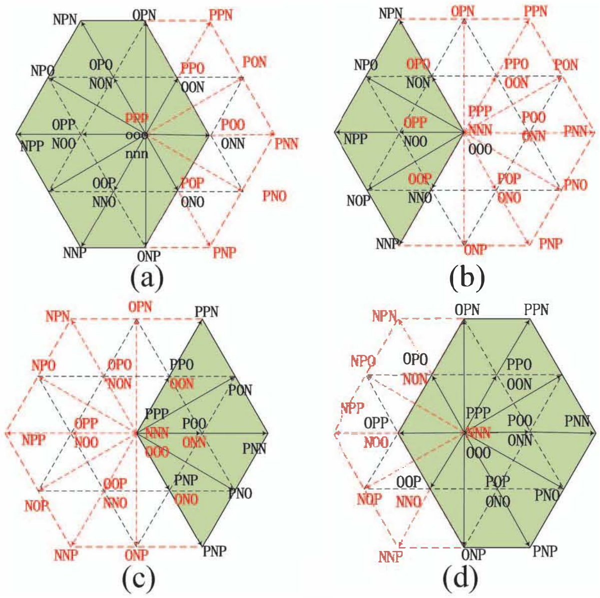


Fig 6. Voltage vector distribution after switch fault. (a) T_{u1} failure. (b) T_{u2} failure. (c) T_{u3} failure. (d) T_{u4} failure.

3.2 Fault-tolerant method for low speed condition

When the train is running at low speed, if an open-circuit fault occurs in T_{u1} or T_{u4}, the amplitude of the reference voltage vector that the system needs to synthesize is less than $U_{dc}/2$. At this time, only zero voltage vectors and small voltage vectors are used to synthesize the reference voltage vector (U_{ref}) for the system. So reference voltage vector U_{ref} could be synthesized by redundant small and zero voltage vectors after open-circuit faults occur, which only needs to replace the small vectors lost due to failures such as PPO, POO and PNO with small vectors OON, ONN and ONO respectively. However, in order to balance the output of the inverter, the small vectors NON, NOO and NNO should be replaced by OPO, OPP and OOP respectively.

On the other hand, if the open-circuit fault occurs at T_{u2} or T_{u3}, it can be seen from Fig 6-(b) and Fig 6-(c) that the system cannot use the redundant vectors to synthesize a rotating reference voltage. Consequently, the fault-tolerant strategy for T_{u1} and T_{u4} is inapplicable for such faults.

When such open-circuit fault occurs, the fault leg needs to be isolated immediately, and the fault u-phase is connected to the zero potential point of the DC circuit, so that the inverter could drive the motor by three-phase sinusoidal wave that combined by the residual v-phase and w-phase, which is an effective and feasible fault-tolerant method for the faults at T_{u2} or T_{u3}.

3.3 Fault-tolerant method for high speed condition

When the train is running at high speed, the amplitude of the reference voltage vector $\boldsymbol{u}_{ref}$ will be greater than $U_{dc}/3$, and the modulation depth will be greater than 0.5. If the open-circuit fault occurs at T_{u1} or T_{u4}. It can be seen from Fig 6-(a) and Fig 6-(d) that some large voltage vectors cannot be synthesized by the system, resulting in abnormal output of the system.

According to Formula (2) in the second chapter, the amplitude of the reference voltage vector $\boldsymbol{u}_{ref}$ can be reduced by reducing the flux size so that the reference voltage vector $\boldsymbol{u}_{ref}$ can rotate in the small hexagon. In this way, redundant basic voltage vectors can be used to synthesize the required reference voltage after failure, which is similar to the low speed case.

However, if the open-circuit fault occurs at T_{u2} or T_{u3}, the fault leg is also needed to be isolated immediately and be connected to the zero potential point of the DC circuit. Then, similar to the fault of the external switch, the reference voltage vector $\boldsymbol{u}_{ref}$ is limited to a small hexagon in the space voltage vector distribution by using the strategy of weak magnetism. At this point, in order to balance the three-phase current output, the small fundamental voltage vectors used to synthesize the reference voltage vector $\boldsymbol{u}_{ref}$ would be replaced by the redundant O--type small vectors.

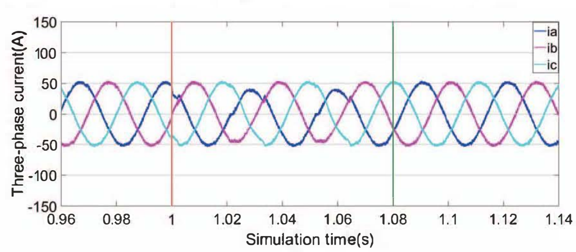
4 SIMULATION RESULTS

The proposed fault-tolerant strategies for three-level NPC inverter used for traction is simulated by using MATLAB/Simulink software package. The experimental object is the simulation model of CRH2 high-speed train control system adopting Field-Oriented Control (FOC). To evaluate the performance of the proposed fault-tolerant methods, in this section, the fault-tolerance control is carried out respectively when the train is in the state of low speed (50km/h) and high speed (200km/h), taking the open-circuit fault at T_{u1} and T_{u2} of u-phase leg as an example. The open-circuit fault at T_{u3} is similar to that at T_{u2}, and the open-circuit fault at T_{u4} is similar to that at T_{u1}, with the same speed curve and opposite current direction.

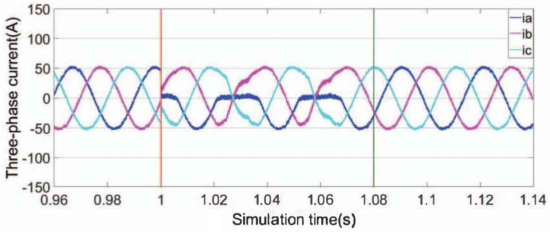
4.1 Effect of fault tolerance for low speed condition

Assuming that the train run at a speed of 50km/h, fault-tolerant control can be carried out by replacing some of the voltage vectors without changing the topological structure in case of open-circuit fault at T_{u1} or T_{u4}.

However, in the case of open-circuit fault in T_{u2} or T_{u3}, the fault phase leg should be isolated and connected the output terminal to the mid-point of the DC bus. The three-phase current waveform before and after adopting the fault-tolerant methods for open-circuit fault at T_{u1} and T_{u2} is shown in the Fig 7, and the train speed curve is shown in the Fig 8, where the fault is injected at 1s (the red line) and fault-tolerant control is carried out at 1.08s (the green line).

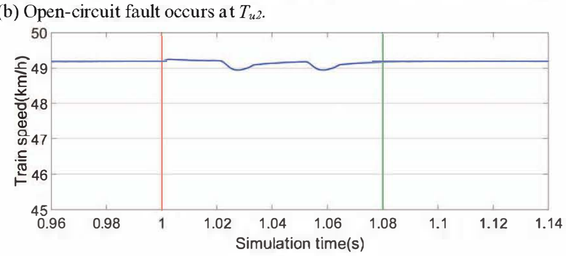


(a)

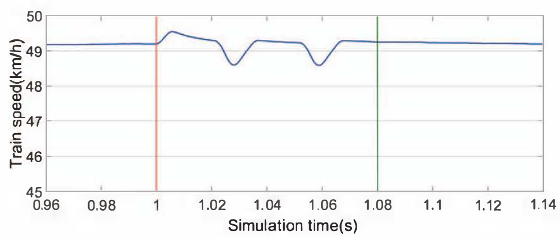


(b)

Fig 7. Three-phase current waveform. (a) Open-circuit fault occurs at T_{u1}. (b) Open-circuit fault occurs at T_{u2}.



(a)

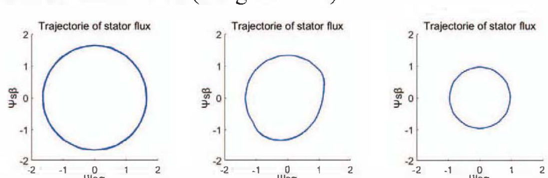


(b)

Fig 8. Train speed curve. (a) Open-circuit fault occurs at T_{u1}. (b) Open-circuit fault occurs at T_{u2}.

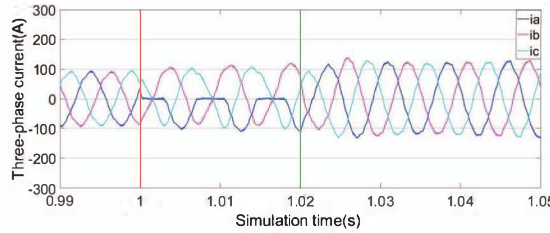
4.2 Effect of fault tolerance for high speed condition

When the running speed of the train is 200km/h, the modulation ratio of the inverter will be greater than $\sqrt{3}/4$, so that the system cannot use redundant basic voltage vectors to synthesize a circular reference voltage vector $\boldsymbol{u}_{ref}$. From the Fig 9, when an open-circuit fault occurs at T_{u1}, the stator flux trace of the motor would be distorted instead of being a regular circle, which is the leading reason for the distortion of the three-phase current after failure. However, the stator flux trace of the system after adopting the fault-tolerant method is a regular circle with a reduced radius by reducing the flux linkage, which ensures a symmetrical three-phase current output and a steady speed. The fault-tolerant effect including the three-phase current and train speed for open-circuit fault of T_{u1} and T_{u2} is shown in Fig 10 and Fig 11 respectively, where the fault is injected at 1s (the red line) and fault-tolerant control is carried out at 1.02s (the green line).

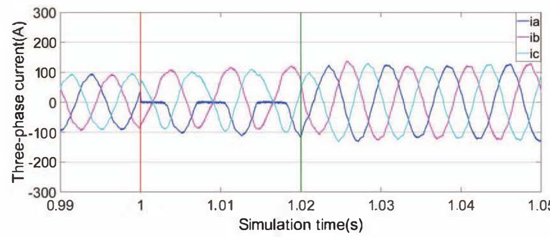


(a) (b) (c)

Fig 9. Stator flux trace diagram. (a) before failure in T_{u1}. (b) after failure in T_{u1}. (c) After adopting fault-tolerant control.

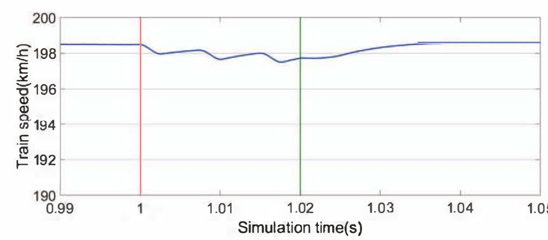


(a)

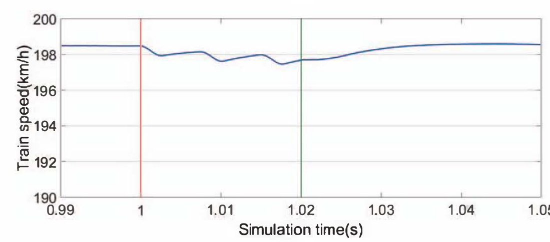


(b)

Fig 10. Three-phase current waveform. (a) Open-circuit fault occurs in T_{u1}. (b) Open-circuit fault occurs in T_{u2}.



(a)



(b)

Fig 11. Train speed curve. (a) Open-circuit fault occurs in T_{u1}. (b) Open-circuit fault occurs in T_{u2}.

From the simulation results, it can be seen that after an open-circuit fault occurs in one phase leg, obvious distortion will occur to the three-phase current, and the train speed will also fluctuate to different degrees, which is obviously not conducive to the healthy operation of the train. When the train is running at low speed, the fault-tolerant methods proposed in this paper can be restored to a healthy running state in a short time, and the three-phase current is almost exactly the same as before the fault. When the train is running at high speed, the fault-tolerant strategy can also make the system run stably with larger three-phase current, but compared with the condition on low speed, it take longer transition time to reach the new steady state for the system. The performance including the THD of i_a and the speed for the system is shown in Table 2 and Table 3 respectively.

Table2. Performance For The Fault At T_{u1}

T_{u1} fault	Low-speed condition		High-speed condition	
	THD	speed (km/h)	THD	speed (km/h)
health	4.62%	49.2	7.40%	198.5
failure	10.19%	48.9-49.1	40.70%	198-198.4
tolerance	4.69%	49.2	8.02%	198.5

Table3. Performance For The Fault At T_{u2}

T_{u2} fault	Low-speed condition		High-speed condition	
	THD	speed (km/h)	THD	speed (km/h)
health	4.62%	49.2	7.40%	198.5
failure	41.74%	48.6-49.0	41.28%	197.5-198
tolerance	4.69%	49.2	8.02%	198.5

5 CONCLUSION

For a system used for traction, stable operation is of great significance. Based on SVPWM principle, this paper proposes different fault-tolerance methods for different operating conditions. Through simulation and analysis, it can be seen that when the train is running at low speed, the system can almost achieve pre-failure performance. However if the train is running at high speed, the three-phase current will increase in a certain extent. Fault-tolerant control is a measure to ensure that the system can complete its basic functions within the specified time at the cost of system performance loss, therefore, the maintenance and replacement of equipment should be carried out as soon as possible when the fault occurs.

REFERENCES

[1] Wikstron P W, Terens L A, Kobi H. Reliability, availability, and maintainability of high-power variable-speed rive systems[J]. IEEE Trans. Ind. Applica.2000, 36(1):231-241.

[2] Jih-Sheng Lai and Fang Zheng Peng. Multilevel converters-a new breed of power converters. IEEE Transactions on Industry Applications, vol. 32, no.3, 509-517, May-June 1996.

[3] Chen H, Jiang B, Chen W, et al. Edge Computing-Aided Framework of Fault Detection for Traction Control Systems in High-Speed Trains[J]. IEEE Transactions on Vehicular Technology, 2020, 69(2):1309-1318.

[4] X. Hao, Z. Jian, Q. Jie, W. Tianzhen and H. Jingang, "RPCA-SVM fault diagnosis strategy of cascaded H-bridge multilevel inverters," 2014 First International Conference on Green Energy ICGE 2014, Sfax, 2014.

[5] E. Babaei, S. Laali and Z. Bayat, "A Single-Phase Cascaded Multilevel Inverter Based on a New Basic Unit With Reduced Number of Power Switches," in IEEE Transactions on Industrial Electronics, vol. 62, no. 2, Feb. 2015.

[6] Li B, Shi S, Wang B, et al. Fault Diagnosis and Tolerant Control of Single IGBT Open-Circuit Failure in Modular Multilevel Converters[J]. IEEE Transactions on Power Electronics, 2016, 31(4):3165-3176.

[7] Guohua Li,Chunwu Liu,Yufeng Wang. Voltage Space Vector Equivalent Substitution Fault-Tolerance Control for Cascaded H-Bridge Multilevel Inverter with Current-Tracking[J]. Electronics,2020,9(1).

[8] P. W. Hammond, "Enhancing the reliability of modular medium-voltage drives," in IEEE Transactions on Industrial Electronics, vol. 49, no. 5, pp. 948-954, Oct. 2002.

[9] D. Zhou, Y. Li, J. Zhao, F. Wu and H. Luo, "An Embedded Closed-Loop Fault-Tolerant Control Scheme for Nonredundant VSI-Fed Induction Motor Drives," in IEEE Transactions on Power Electronics, vol. 32, no. 5, May 2017.

[10] M. Zhang, Z. Li, Y. Guo and X. Zhang, "Fault tolerance and overmodulation algorithm for three level neutral point clamped inverters," 2017 36th Chinese Control Conference (CCC), Dalian, 2017.

[11] X. Guo, Y. Yang, B. Wang and F. Blaabjerg, "Leakage Current Reduction of Three-Phase Z-Source Three-Level Four-Leg Inverter for Transformerless PV System," in IEEE Transactions on Power Electronics, vol. 34, no.7, 6299-6308, July 2019.

[12] M. Aleenejad, H. Mahmoudi, P. Moamaei and R. Ahmadi, "A New Fault-Tolerant Strategy Based on a Modified Selective Harmonic Technique for Three-Phase Multilevel Converters With a Single Faulty Cell," in IEEE Transactions on Power Electronics, vol. 31, no. 4, pp. 3141-3150, April 2016.

[13] A. Kiselev, G. R. Catuogno, A. Kuznietsov and R. Leidhold, "Finite Control Set MPC for Open-Phase Fault Tolerant Control of Synchronous Reluctance Motor," 2020 IEEE International Conference on Industrial Technology (ICIT), Buenos Aires, Argentina, 2020.

[14] R. Krishna, E. S. Deepak, S. K. Kottayil and M. Leijon, "Space vector modulation method to balance the neutral voltage for a three level inverter," 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India, New Delhi, India, 2010.

[15] D. B. Matos, J. O. Estima and A. J. Marques Cardoso, "Performance of a synchronous reluctance motor drive with a fault-tolerant three-level neutral point clamped inverter," 2016 XXII International Conference on Electrical Machines (ICEM), Lausanne, 2016.

[16] Shijie Yan, Qun Zhang and Heng Du, "A simplified SVPWM control strategy for PV inverter," 2012 24th Chinese Control and Decision Conference (CCDC), Taiyuan, 2012.

[17] W. Zhang, Y. Chen, Y. Xing and J. Wang, "A Three-level SVPWM Control Algorithm," 2018 IEEE 3rd International Conference on Integrated Circuits and Microsystems (ICICM), Shanghai, 2018.