Switching over technique to fault tolerant function of DC-bus battery in dual inverter motor drive

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Abstract. The dual inverter motor drive feeding an open-end winding PM motor is focused on for mileage improvement and autopilot technologies of hybrid and electric vehicles. Autopilot operation requires the fault tolerant functions which achieve to keep controlling the motor, even if some failure occurs in the system. In this paper, the fault tolerant function of the DC-bus battery in the dual inverter motor drive system is discussed. The system has a battery and a capacitor across the DC-bus of each inverter. The capacitor is utilized to keep operating the motor, instead of the failed battery in the fault tolerant function. In this time, however, it is necessarily to control the capacitor voltage of the failed side inverter at constantly with the space vector modulation (SVM). In particular, it is required to regulate the capacitor voltage of the failed inverter at a half of the battery voltage of the normal condition inverter. Therefore, the capacitor voltage must be discharged immediately after some failure is occurred in the battery of one of the inverters. In this paper, the switching over techniques from the normal condition to the fault tolerant function is proposed, and the proposed technique is examined through several computer simulations.

1. Introduction

Recently, the mileage improvement and autopilot technologies of hybrid and electric vehicles are focused on. However, the current system operates the motor by boosting the battery voltage and operating the 2-level inverter as shown in Fig. 1. It is difficult to improve the efficiency of the system and to achieve a fault tolerant function because the bidirectional chopper and the 2-level inverter are connected in series, and the system cannot drive the motor even if either the copper or the inverter is failed. Therefore, the dual inverter motor drive feeding an open-end winding PM motor with two inverters has been studied as shown in Fig. 2. The dual inverter system can generate the voltage across the motor windings by adding the output voltages of two inverters. Therefore, it does not require any voltage-boosting chopper, which is expected to improve the efficiency of the system. The dual inverter
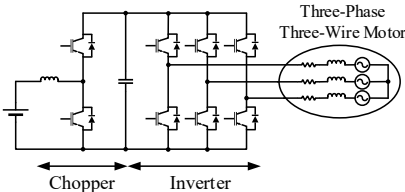

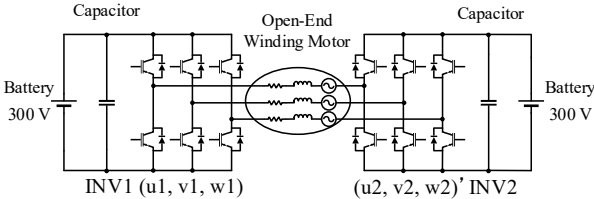**Figure 1.** Conventional single inverter motor drive.

Figure 2. Studied dual inverter motor drive.

system also can generate the multilevel voltage waveforms and also can achieve some fault tolerant functions, e.g., the DC-bus battery and the switching device. However, the fault tolerant function of the DC-bus battery in the dual inverter system has not been studied, although the fault tolerant functions of the switching devices have been studied[1]-[3]. Therefore, in this paper, the fault tolerant function of the DC-bus battery in the dual inverter motor drive is discussed. In the fault tolerant function, the inverter whose DC-bus battery is failed is operated with the capacitor, instead of the failed battery. The dual inverter motor drive with the capacitor has been already introduced[4]-[5]. On the other hand, it is novelty of this paper that the space vector modulation (SVM) is employed to control the capacitor voltage in the dual inverter motor drive. In particular, it is required to regulate the capacitor voltage of the failed inverter at a half of the battery voltage of the normal condition inverter. Therefore, the capacitor voltage must be discharged immediately after some failure is occurred in the battery of one of the inverters. In this paper, the switching over techniques from the normal condition to the fault tolerant function is proposed, and the proposed technique is examined through several computer simulations.

2. Dual inverter motor drive

In the dual inverter motor drive system studied in this paper, the left-hand side inverter is called the INV1 and the right-hand side is called the INV2, and both inverters have a battery and a capacitor across each DC-bus. The combination of the switching states of the INV1 and the INV2 is described as (u1,v1,w1) (u2,v2,w2)', and the switching devices in each leg are complementarily operated. In this paper, it is assumed that the battery of the INV2 is failed, and the failed battery is separated as shown in Fig. 3. In this case, however, it is required that the capacitor voltage is regulated at constant value to operate the INV2 with the capacitor in stead of the failed battery, which must be achieved at the same time of generating the multilevel voltage waveforms to the motor.

The dual inverter motor drive can generate the voltage vector by adding the output voltages of the two inverters. The output voltage vectors with the studied dual inverter system which are enlarged from 0 to 60 degree are shown in Fig. 4. The dual inverter system has a redundancy in the switching states, which achieves to generate particular voltage vectors with the several redundant states. The redundancy also achieves to control the capacitor voltage across the DC-bus of the failure side inverter, because the directions of the current flowing into the capacitor are different from each switching state. However, either capacitor charging or discharging mode can be used in particular redundant states in case of the DC-bus voltage ratio 1:1 as shown in Fig. 4 (a). On the other hand, both capacitor charging and
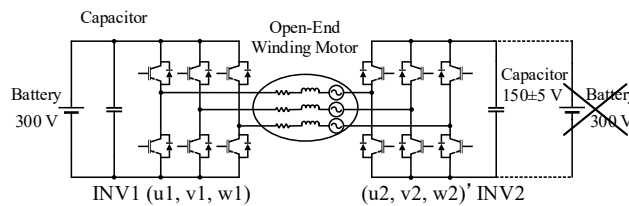

Figure 3. Fault tolerant function of DC-bus battery in dual inverter motor drive.
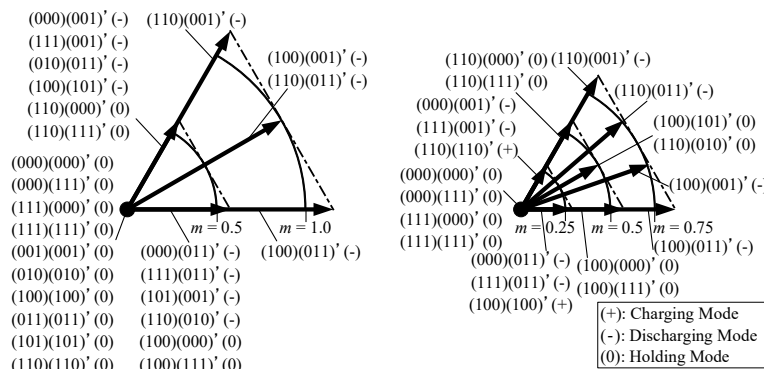

Figure 4. Redundancy of switching states and capacitor charging/discharging modes.

discharging modes can be used redundantly in case of the DC-bus voltage ratio 1:0.5 as shown in Fig. 4 (b). Therefore, the DC-bus voltage ratio 1:0.5 is employed in this paper, that is, the capacitor voltage of the failure side inverter is regulated at a half of the battery voltage of the other inverter. Fig. 4 also shows the definition of a modulation index m, where the maximum amplitude of the voltage vector generated with the dual inverter motor drive in the normal condition is defined as $m = 1.0$.

3. Capacitor voltage control technique with SVM

The fault tolerant function of the DC-bus battery in the studied dual inverter motor drive requires to control the capacitor voltage at constantly across the DC-bus of the failure side inverter, generating the multilevel voltage waveforms across the motor windings at the same time. The simultaneous control of the capacitor voltage and the multilevel voltage waveform generation is achieved with the redundancy of the switching state in the dual inverter system. As shown in Fig. 5, the simultaneous control can be achieved by selecting the switching state which charges/discharges the capacitor of the failure side inverter appropriately among several redundant states when particular voltages are generated. That is why, the SVM which can configure the switching sequence flexibly is employed in this paper.

However, the relationship between the capacitor charging/discharging modes and switching states is affected by the instantaneous motor power factor. The relationship between the phase of the motor line current vector and the line current polarities enlarged from 300 to 60 degree is indicated as Fig. 6 (a). Although the voltage vector V is generated as shown in Fig. 6 (a), the current polarity may be A or F because the motor has a inductive road, where the motor line current is delayed behind the output voltage vector, and the phase difference between the current vector and the voltage vector is up to 90 degree. And also, the current polarity may be B in case that the maximum torque-per-ampere (MTPA) control
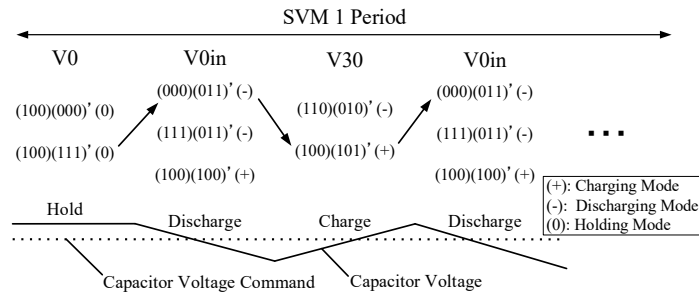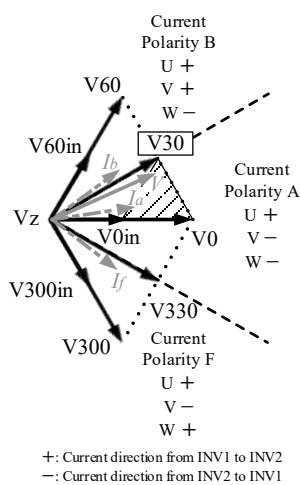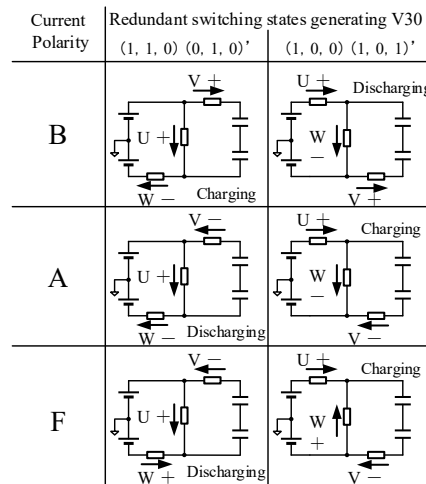

Figure 5. Capacitor voltage control technique with SVM.

(a). Relationship between phase of current vector and current polarities.

(b). Relationship between current polarity current polarity and capacitor charging/discharging modes.

Figure 6. Impact of instantaneous motor power factor.

is adopted and the *d*-axis current flows, because the phase of the current vector may be advanced rather than the output voltage vector. On the other hand, the relationship between the capacitor charging/discharging modes and the current polarity of the redundant switching states which generate the voltage vector V30 is indicated as Fig. 6 (b). The switching state (1,1,0) (0,1,0)' is the capacitor charging mode in case of the current polarity B, however, it is the capacitor discharging mode in case of the current polarity A or F. Therefore, it is required to select the appropriate switching state among the redundant states, considering the instantaneous motor power factor to control the capacitor voltage of the fault tolerant function in the studied dual inverter motor drive.

4. Switching over technique to fault tolerant function of DC-bus battery

The studied dual inverter motor drive in the normal condition is operated with the DC-bus voltage ratio 1:1 to enhance the operating area by adding the voltages of the two inverters. On the other hand, the studied system in the failure condition of the DC-bus battery is operated with the DC-bus voltage ratio 1:0.5 to utilize the redundancy of the switching state for the capacitor voltage control. In case that the failure of the DC-bus battery is occurred, therefore, it is required to smoothly discharge the capacitor voltage of the failure side inverter up to a half of the battery voltage, generating the multilevel voltage waveforms across the motor windings with the SVM.

In this paper, two switching over techniques to the fault tolerant function of the DC-bus battery are proposed as shown in Fig. 7. In case of $0 < m \leqq 0.25$, the zero voltage vector Vz whose amplitude is equal to 0, and the voltage vectors Va and Vb whose amplitude depend on the capacitor voltage are used for the SVM. In case of $0.25 < m \leqq 0.5$, on the other hand, the voltage vectors Va, Vb, Va', and Vb' whose amplitude depend on the capacitor voltage, and the voltage vectors Vc whose amplitude and phase depend on the capacitor voltage are used for the SVM. In this way, the capacitor voltage of failed inverter is discharged up to a half of the battery voltage of the other inverter, generating the multilevel voltage waveforms to the motor at the same time with the SVM, and it is achieved to switch over to the fault tolerant function smoothly. However, it is required to select the switching state which discharges the capacitor voltage among the redundant states, considering the instantaneous motor power factor.

5. Computer simulation

Several computer simulations were conducted to examine the proposed switching over techniques to the fault tolerant function. The control block diagram and simulation conditions are shown in Fig. 8 and Table 1, respectively. In the simulation, the open-end winding PM motor is controlled with the speed
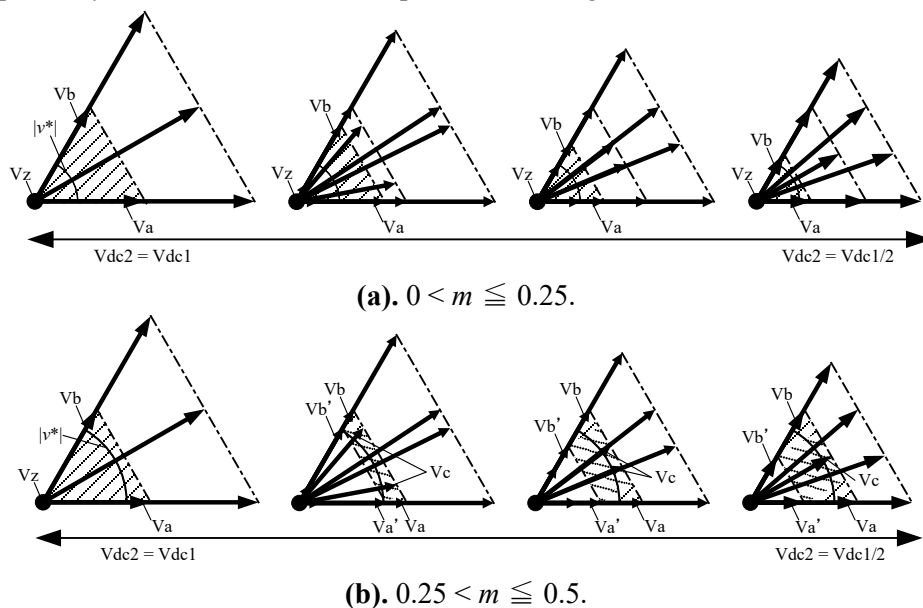

(a). $0 < m \leqq 0.25$.

(b). $0.25 < m \leqq 0.5$.

Figure 7. Proposed switching over technique to fault tolerant function with SVM.

control and the vector control with the studied dual inverter system. The instantaneous motor power factor is calculated from the difference between the phases of the output voltage vector and the motor current vector on the *dq* reference frame. The SVM is performed with the output voltage command, the motor power factor, the capacitor voltage of the INV2, and the fault signal of the DC-bus battery of the INV2. At first, the two inverters are operated with the battery across each DC-bus. After the fault signal of the battery of the INV2 is detected, the battery of the INV2 is separated with the relay and the INV2 is operated with the capacitor. The capacitor voltage is discharged with the proposed switching over techniques up to a half of the battery voltage of the INV1, and the dual inverter system is switched over to the fault tolerant function smoothly with the SVM. Then, the capacitor voltage of the INV2 is regulated at a half of the battery voltage of the INV1, generating the multilevel voltage waveforms across the motor windings with the SVM.

The computer simulation results on the condition of $m = 0.2$ and $m = 0.4$ are shown in Fig. 9. The motor rotation speed, the fault signal of the battery of the INV2, the capacitor voltage, and the U-phase voltage waveforms are indicated in the figure. In the normal condition, the dual inverter motor drive can generate the 5-level voltage waveforms across the motor windings. In the fault tolerant function at $m = 0.2$, the 5-level voltage waveform is generated with a half amplitude because the DC-bus voltage of the INV2 is regulated at a half of the battery voltage of the INV1. In the fault tolerant function at $m = 0.4$, on the other hand, the 9-level voltage waveform is generated. Furthermore, the dual inverter system is switched over to the fault tolerant function smoothly with the proposed techniques, generating the
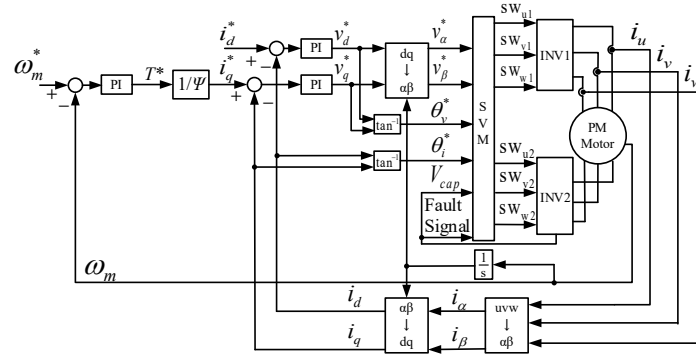

Figure 8. Control block diagram.

Table 1. Simulation conditions.

Switching frequency		10 kHz
Voltage of battery		300 V
Voltage command of capacitor (INV2)		150 ± 5 V
Capacitance of capacitor (INV2)		330 μF
Motor speed command		1150, 2300 r/min
Dead time		0 μs
Motor parameters	Number of poles	8
	Number of flux linkage	0.174 Wb
	Moment of inertia	0.00173 kgm^2
	Damping coefficient	0.005 N/rad/s
	Phase resistance	1.1 Ω
	Phase inductance	5 mH
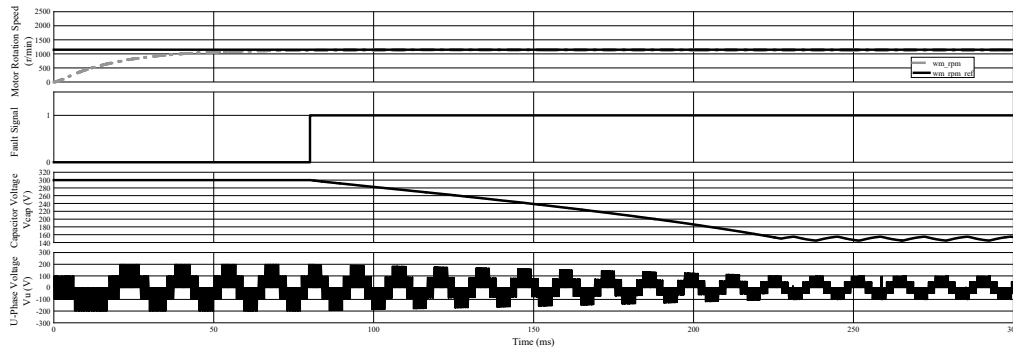
(a). *m* = 0.2 (1150 r/min).
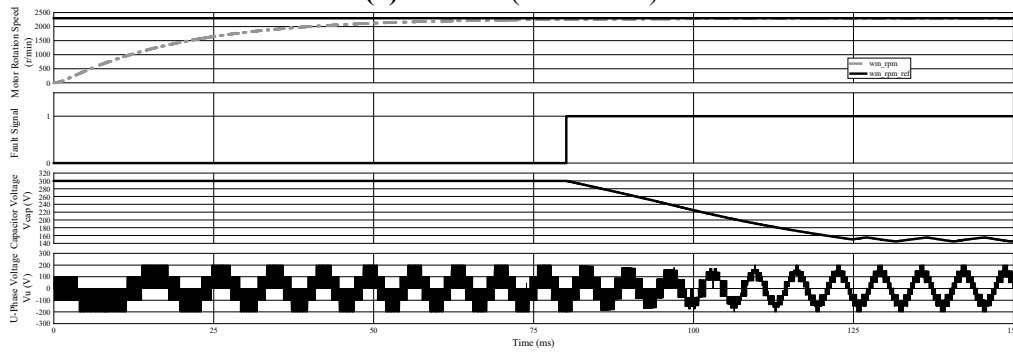
(b). *m* = 0.4 (2300 r/min).
Figure 9. Computer simulation results.

multilevel voltage waveforms to the motor, that is, the fault tolerant function of the DC-bus battery is achieved with the proposed techniques.

6. Conclusion

The fault tolerant function of the DC-bus battery in the dual inverter motor drive, which has a battery and a capacitor across the DC-bus of each inverter, is focused on in this paper. And the smooth switching over techniques to the fault tolerant function of the DC-bus battery are proposed. The proposed techniques were examined *m* < 0.5 through several computer simulations and the validity is verified. The consideration of the switching over technique to the fault tolerant function on the condition of m > 0.5 is our future work.

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