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Fault tolerant direct torque control of pmsm fed by cascaded two-level inverter

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***Abstract*— In this paper, fault tolerant direct torque control of permanent magnet synchronous motor fed by cascaded two level inverters, having open-circuit fault is described. When an open-circuit fault occurs on switches of the inverter, the PMSM will stop if the control strategy will not be changed. By means of reconfiguring strategy proposed, the motor regains its nominal operation after few milliseconds. The effectiveness of the proposed strategy is verified by simulation results.**

***Keywords*— Permanent magnet synchronous motor (PMSM), Cascade two-level inverter, Fault tolerant DTC, open circuit fault.**

I. Introduction

Permanent magnet synchronous motors (PMSM) fed by inverters have been widely used in industry, aircrafts and electrical traction, due to their excellent performance of energy-saving and control. Whereas, operating safety of motor drive systems in safety-critical applications is being concerned by researchers, due to fragile power electronics switches. Therefore, many fault-tolerant methods are presented to keep running of these systems after fault occurring on power switches or motor windings [1], [2], [3]. The cascaded two-level inverter as a new topology is used in motor drives to improve the post-fault operating safety [4], [5].

This paper discuss the fault-tolerant direct toque control strategy of a permanent magnet synchronous motor fed by cascaded two-level inverter, when an open-circuit occurring on power switches on one inverter. The two inverters supplying the PMSM are connected to two electrically isolated sources. In this case the sum of the three phases currents is necessarily null.

II. Cascaded two level inverter fed PMSM drives

A. Cascaded two-level inverter topology

Permanent magnet synchronous motor fed by a cascaded two-level inverter is shown in Fig.1. Three-phase windings of the motor are split into separate ones without neutral point connected.

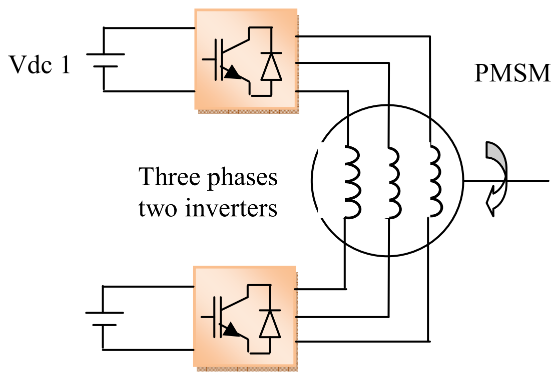

Fig.1 PMSM drive fed by the cascade two-level inverter

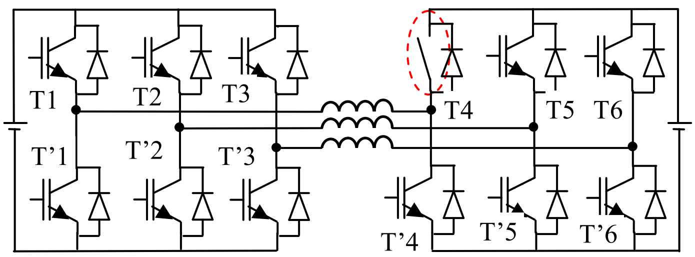

Fig.2 Reconfiguration after an open circuit fault

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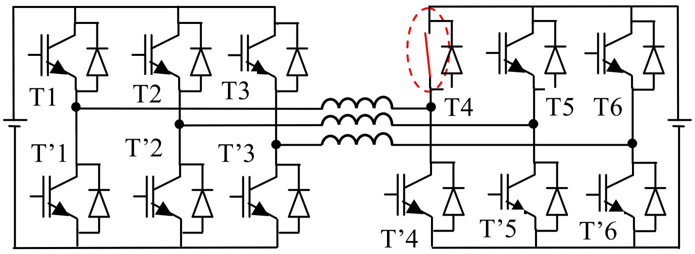

Fig.3 Reconfiguration after a short circuit fault

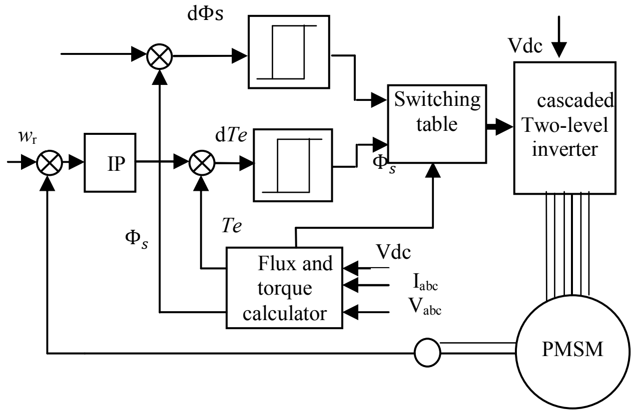

Fig.4 Block diagram DTC fault tolerant control of PMSM fed by cascaded two-level inverter

III. MODELING OF PMSM IN CASE OF OPEN CIRCUIT FAULT

In the open-open circuit fault on inverter supplying the permanent magnet synchronous motor (PMSM), the sum of three-phase currents can not restricted to zero, that is ia+ib+ic≠0. The voltage function for an ideal surface permanent magnet synchronous motor can be expressed as:

$$\begin{cases} U_a = R_a I_a + L_{aa}\frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \\ U_b = R_b I_b + M_{ba}\frac{di_a}{dt} + L_{bb}\frac{di_b}{dt} + M_{bc}\frac{di_c}{dt} + e_b \\ U_c = R_c Ic_a + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + L_{cc}\frac{di_c}{dt} + e_c \end{cases} \quad (1)$$

Where R_a, R_b and R_c are phase resistances, and $R_a = R_b = R_c = R$. L_{aa}, L_{bb} and L_{cc} are phase self inductances, and $L_{aa}=L_{bb}=L_{cc}=L_s$. $M_{ab}=M_{ba}$, $M_{bc}=M_{cb}$ and $M_{ca}=M_{ac}$ are the mutual inductances between ab, bc and ca, respectively. Due to symmetry of the three-phase winding and magnetic circuit, there is $M_{ab}=M_{ba} = M_{bc}=M_{cb} = M_{ca}=M_{ac}=M$. e_a, $e_b$and e_c are electromotive forces, respectively, and for a permanent magnet synchronous motor, they can be described as:

$$\begin{cases} e_a = -N_p \omega_m K_e sin\theta \\ e_a = -N_p \omega_m K_e \sin\left(\theta - \frac{2\pi}{3}\right) \\ e_a = -N_p \omega_m K_e \sin\left(\theta - \frac{4\pi}{3}\right) \end{cases} \quad (2)$$

Where N_p is number of motor pole-pairs, ω_m is rotor mechanical speed, K_e is PM flux linkage of the motor rotor, and θ is rotor position angle.

IV. PMSM DTC DRIVE SYSTEM

The block diagram of PMSM DTC drive system is shown in Fig. 4. The system basically comprises two hysteresis controllers, flux linkage and torque calculator, voltage vector switching table, two inverters, the relevant control circuit for the fault diagnosis and fault isolation, PMSM and load.

The electromagnetic torque of PMSM and the stator flux linkage of an inverter fed PMSM can be expressed as follows:

$$\begin{cases} \Phi_{s\alpha} = \int (u_{s\alpha} - R_s I_{s\alpha})dt \\ \Phi_{s\beta} = \int (u_{s\beta} - R_s I_{s\beta})dt \end{cases} \quad (3)$$

$$\|\Phi_s\| = \sqrt{({\Phi_{s\alpha}}^2 + {\Phi_{s\beta}}^2)} \quad (4)$$

$$T_e = \frac{3}{2} N_p (\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}) \quad (5)$$

$$\theta = \arctan\left(\frac{\Phi_{s\beta}}{\Phi_{s\beta}}\right) \quad (6)$$

A. Switching table

The principle of designing switching table is to simultaneously reduce torque error ΔTe and flux linkage error ΔΦs. So switching table to be adopted in this paper the switching table for DTC of healthy PMSM, is shown as in Table 1[6], [7].

TABLE.I SWITCHING TABLE

Estimator error		Sectors					
ΔΦs	ΔTe	S1	S2	S3	S4	S5	S6
0	0	V5	V6	V1	V2	V3	V4
0	1	V3	V4	V5	V6	V1	V2
1	1	V6	V1	V2	V3	V4	V5
1	0	V2	V3	V4	V5	V6	V1

Sector S1- sector S6 in Table 1 are stator flux linkage positions as shown in Fig.5. Torque estimator error ΔTe and flux linkage estimator error ΔΦs are defined as following discrete functions,

$$\Delta Te = \begin{cases} 1 & if\ T_e^* > T_e \\ 0 & if\ T_e^* < T_e \end{cases} \quad 7)$$

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$$\Delta\Phi s = \begin{cases} 1 & if\ \Phi s^* > \Phi s \\ 0 & if\ \ \Phi s^* < \Phi s \end{cases} \qquad (8)$$

On the basis of the flux linkage estimator error ΔΦs and torque estimator error ΔTe, voltage vector V1- V6 offered by inverter can be gotten via looking up Table 1. Fig.5 shows the symmetrical layout of six voltage vectors V1-V6 and six sectors S1-S6.

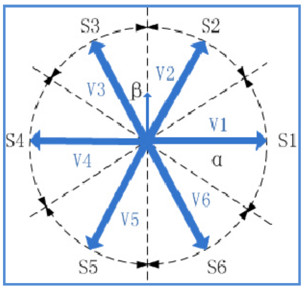

Fig.5 Layout of voltage vectors and sectors

V. SIMULATION RESULTS

To verify the proposed fault-tolerant control strategy, simulation model of 1.4 kW permanent magnet synchronous motor fed by cascaded two-level inverter are used.

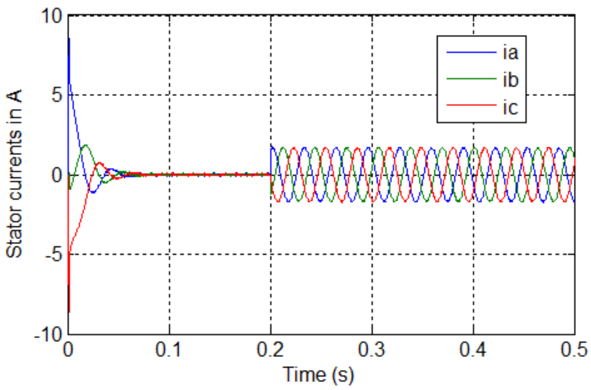

Fig.6 Stator currents in case of healthy mode

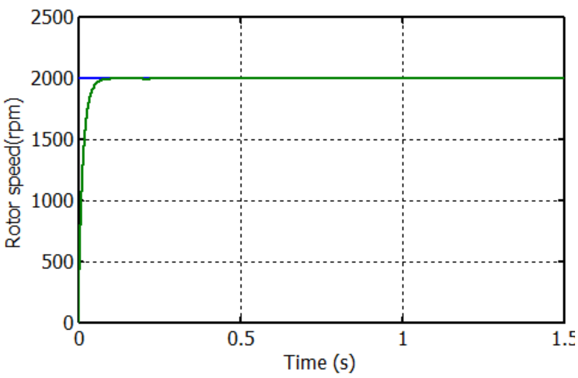

Fig.7 Rotor speed signal in case of healthy mode

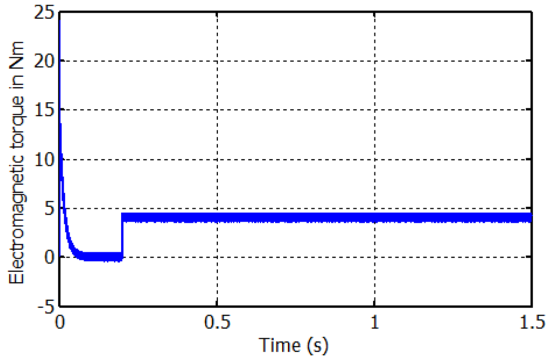

Fig.8 Electromagnetic torque in case of healthy mode

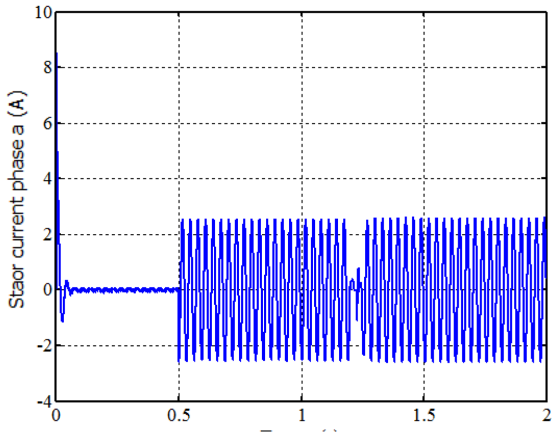

Fig.9 Stator current phase a in case of FTC mode

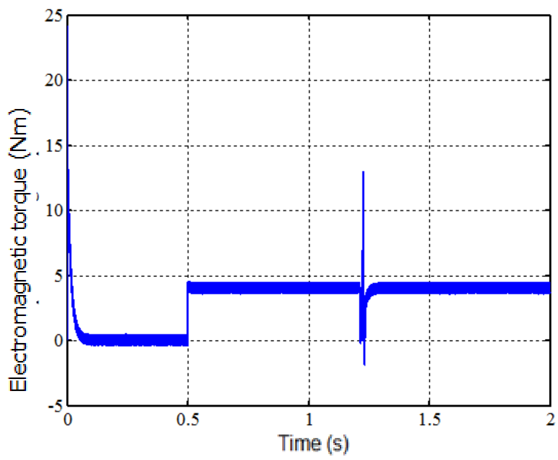

Fig.10 Electromagnetic torque in case of FTC mode

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It is noted that there are disturbances in the amplitudes of the currents at the time of failure (t = 1.2 s) and a suppression of the positive alternation of the current of the defective phase. The currents return to their normal values after a few milliseconds, as soon as the switchover takes place (response time of the fault tolerant control - time required to perform the diagnosis).

At the level of the electromagnetic torque, a certain number of ripple are observed at the time of the fault, then, on account of the tolerant control of the latter, the electromagnetic torque returns to its nominal state and retains its stability

TABLE.II Permanent magnet synchronous parameters

Parameters	Specifications	
R_{s}= 0.5Ω	Rated power	1.4kW
L_d = 4.2mH	Rated voltage	400V
L_q = 3.6 mH	Rated current	4.2A
Kt = 0.91	V_{dc}	540V
K_e = 0.2275V.s/rad	Number of pole pairs	4
J=0.00072 Kg.m²	Rated speed	3000 rpm
F = 10^{-6} Nm./rad	Rated torque	4.1 Nm

VI. Conclusion

The fault-tolerant control strategy of permanent magnet synchronous motor drive system is discussed in this paper. Cascaded two-level inverter is used in open-switch fault in a leg of one inverter fed, the permanent magnet synchronous motor drive system.

Several simulation results have validated the proposed methodology

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