



DTC FOR MATRIX CONVERTERS WITH REDUCED COMMON MODE VOLTAGE

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Abstract: This paper presents a novel Direct Torque Control (DTC) method for matrix converter fed Permanent Magnet Synchronous Machines (PMSM) applying the six rotating space vectors. This approach reduces the Common Mode Voltage and thus the leakage zero current, which can cause damages to the machine bearings and therefore lifetime reduction of the machine. It is shown how the utilized rotating vectors are determined by simple look-up tables. The technical feasibility of the proposed control scheme is verified by Matlab/Simulink simulation results as well as by measurements at the laboratory experimental setup.

Key Words: PMSM, DTC, common mode voltage

1. INTRODUCTION

In 1986 and 1988 for the first time the Direct Self Control and the Direct Torque Control were presented for voltage source inverter-fed induction motors [1, 2]. Then in 1997 the implementation of Direct Torque Control for voltage source converters was investigated for PMSM drives. The differences between the DTC for the induction machine and PMSM were explored in [3]. And in 2001 for the first time the DTC was published for an induction motor driven by a matrix converter [4]. Building there upon in the following years the Direct Torque Control algorithm was applied to the combination matrix converter and PMSM, for example in [5-7]. This aggregation of matrix converter, PMSM and DTC combines the advantages of its single parts. The main advantages of matrix converters are the inherent bidirectional power flow capability, the possibility to adjust the input power factor and the absence of electrolytic capacitors. A good matrix converter technology overview is given in [8]. Compared to induction machines PMSMs offer a better dynamic behavior and a higher power density [7]. The fundamental benefits of the DTC method are fast torque response, simple flux- and torque hysteresis comparators and no need for coordinate transformation from the alpha-beta system into the d-q-plane.

This paper introduces a novel DTC scheme for matrix converters, that uses the six rotating vectors for reducing the common mode voltage. First a brief survey of the matrix converter and common mode voltage is given. Then the DTC principle is explained and the newly

developed switching table including rotating vectors is presented. Finally measurement results confirm the practicability of the proposed method.

2. MATRIX CONVERTER AND COMMON MODE VOLTAGE

The matrix converter is able to produce 27 output voltage vectors, i.e. 27 stator voltage vectors, which are divided into 18 active, six rotating and three zero vectors. Most DTC algorithms use the 18 active and the three zero vectors only [5-7]. Few researchers only also include the rotating ones into their Space Vector Modulation control schemes [9, 10]. One important disadvantage of using only active and zero vectors is the common mode voltage they produce. The common mode voltage in turn generates a leakage zero current that causes damages to the machine bearings and windings and shortens the machines lifetime [9]. Fig. 1 demonstrates how the leakage zero current flows in the drive system.

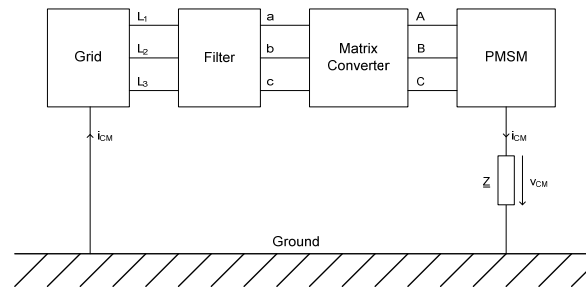


Fig. 1. Common mode voltage v_{cm} and leakage zero current i_{cm}

Equation (1) computes the common mode voltage (v_{cm} is the common mode voltage and v_{AG} , v_{BG} and v_{CG} are the matrix converter output voltages related to the ground).

$$v_{cm} = \frac{1}{3} (v_{AG} + v_{BG} + v_{CG}) \quad (1)$$

In Table 1 it is shown how the common mode voltage depends on the switched output voltage vector.

Table 1. Common mode voltage of matrix converter switching states

No.	ABC	v_{cm}	No.	ABC	v_{cm}
1	aaa	v_a	15	cac	$(v_a+2v_c)/3$
2	bbb	v_b	16	bba	$(v_a+2v_b)/3$
3	ccc	v_c	17	ccb	$(v_b+2v_c)/3$
4	abb	$(v_a+2v_b)/3$	18	aac	$(v_c+2v_a)/3$
5	bcc	$(v_b+2v_c)/3$	19	aab	$(v_b+2v_a)/3$
6	caa	$(v_c+2v_a)/3$	20	bbc	$(v_c+2v_b)/3$
7	baa	$(v_b+2v_a)/3$	21	cca	$(v_a+2v_c)/3$
8	cbb	$(v_c+2v_b)/3$	22	abc	0
9	acc	$(v_a+2v_c)/3$	23	cab	0
10	bab	$(v_a+2v_b)/3$	24	bca	0
11	cbc	$(v_b+2v_c)/3$	25	acb	0
12	aca	$(v_c+2v_a)/3$	26	bac	0
13	aba	$(v_b+2v_a)/3$	27	cba	0
14	cbcb	$(v_c+2v_b)/3$			

No.: switching state number, ABC: matrix converter output, v_{cm} : common mode voltage

Table 1 illustrates that the rotating vectors (No. 22-27) create no common mode voltages. Thus it makes sense to use them for the DTC, too. In contrast to the rotating vectors the zero vectors and the active vectors generate a common mode voltage with an alternating absolute value, so they should be avoided if possible.

3. DTC PRINCIPLE

In this paper a permanent magnet synchronous machine with surface mounted magnets is considered, so the magnetic resistances for the direct-axis and the quadrature-axis are equal and thus also L_d is equal to L_q . With this assumption the torque for a PMSM can be calculated with (2).

$$T = \frac{3}{2} \frac{p}{L_d} |\underline{\psi}_s| |\underline{\psi}_r| \sin \vartheta \quad (2)$$

When the stator flux absolute value in (2) is controlled to a constant value, the torque depends on the load angle. If the stator voltages and stator currents are known, the current position of the stator flux vector in the complex alpha-beta plane is determined by the following equations (3-5):

$$\psi_{sa} = \int (v_{sa} - R_s i_{sa}) dt + \psi_{sa}(t_0) \quad (3)$$

$$\psi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt + \psi_{s\beta}(t_0) \quad (4)$$

$$\varphi_{\psi_s} = \arctan\left(\frac{\psi_{s\beta}}{\psi_{sa}}\right) \quad (5)$$

In general the resistance of the stator winding is small, therefore the voltage drop across this resistor can be neglected. It follows that the change of the stator flux vector is directly influenced by the applied stator voltage vector \underline{V}_s and its switching-on time t (6).

$$\underline{\psi}_s = \underline{V}_s \cdot t + \underline{\psi}_s(t_0) \quad (6)$$

Or written in alpha-beta-coordinates (7, 8):

$$\psi_{sa} = u_{sa} \cdot t + \psi_{sa}(t_0) \quad (7)$$

$$\psi_{s\beta} = u_{s\beta} \cdot t + \psi_{s\beta}(t_0) \quad (8)$$

Before the DTC for the matrix converter is described, the basic principle of DTC will briefly be explained for the standard voltage source inverter. It is known that the voltage source inverter generates eight space vectors, which are divided into six active vectors (\underline{V}_1 - \underline{V}_6) and two zero vectors (\underline{V}_7 - \underline{V}_8). Fig. 2 shows the basic DTC scheme of a two-level voltage source inverter. The associated look-up table is Table 2. The utilization of zero vectors (\underline{V}_7 - \underline{V}_8) is not intended in this paper since their effect on the torque is smaller than that of the active voltage vectors.

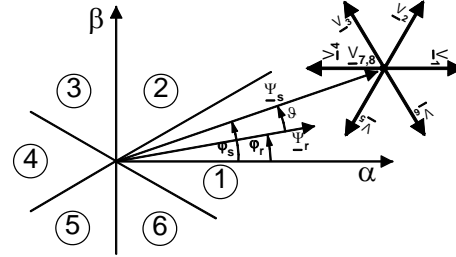


Fig. 2. Basic DTC principle.

Table 2. Base voltage vector look-up table

F	T	stator flux sector					
		1	2	3	4	5	6
0	0	1	5	6	3	4	2
0	1	3	4	4	6	1	2
1	0	6	1	2	3	4	5
1	1	2	3	4	5	6	1

F: flux, T: torque, 0: decrease F or T, 1: increase F or T

Every active voltage vector has a radial component and a tangential component in reference to the stator flux vector. Taking the result of the equations (6-8) into account it follows that the voltage vectors tangential component varies the load angle and hence the torque and that the radial component of the voltage vector modifies the amplitude of the stator flux vector. So the torque and the flux can be adjusted at the same time by applying the appropriate switching state according to Table 2.

Once the DTC fundamentals are hereby explained, we can now proceed to the matrix converter DTC. For a better understanding a matrix converter DTC block diagram is given in Fig 3.

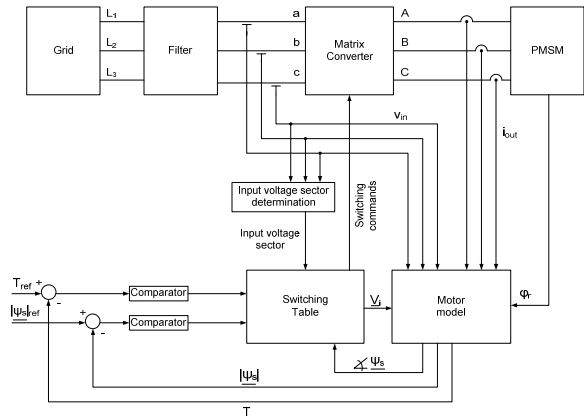


Fig. 3. Block diagram of a matrix converter DTC

Compared to a classical DTC structure of the two-level voltage source inverter here it is necessary to detect the mains voltage space vector sector, because the two-level voltage source inverter works with a constant dc-link voltage and the matrix converter operates with the alterable mains voltages. As stated above the matrix converter altogether offers 27 different switching states. Transferring them to the DTC basic scheme leads to Fig. 4. It can be seen that the six base voltage vectors of the two-level voltage source inverter from Fig. 2 are replaced by 21 voltage vectors now. Depending on the sector of the mains voltage space vector and the selected base vector with the needed orientation derived from Table 2 the look-up Table 3 determines the corresponding voltage vector for the matrix converter. Table 3 is valid for the maximum voltage space vectors. The first mains voltage vector sector is from 0° to 60° , the second mains voltage sector sweeps an area from 60° to 120° and so on. Similar tables can be deduced for the middle and minimum voltage space vectors, too.

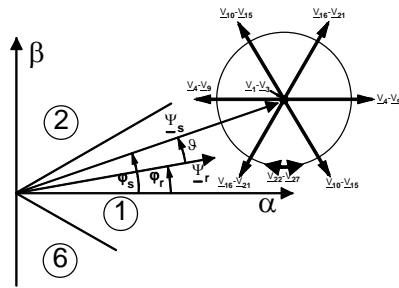


Fig. 4. Voltage vectors and matrix converter DTC scheme

Table 3. Matrix converter DTC switching table for the maximum voltage vectors

Base voltage vector	Sector of mains voltage vector					
	1	2	3	4	5	6
1	9	5	7	6	8	4
2	18	20	16	21	17	19
3	15	11	13	12	14	10
4	6	8	4	9	5	7
5	21	17	19	18	20	16
6	12	14	10	15	11	13

4. NOVEL DTC METHOD

The matrix converter DTC algorithm illustrated in section 3 uses the 18 active vectors only without consideration of the six rotating ones which produce no common mode voltage. Hence now we will introduce a kind of DTC method that employs also the rotating vectors. It is demonstrated step by step how the novel DTC switching tables are derived and a concrete example is illustrated.

First the complex alpha-beta plane for the stator flux, the mains voltage and the stator voltage vector is grouped into 12 sectors as shown in Fig. 5. The relationship between the sector of the mains voltage vector and the sector of the six possible output voltage vectors is the second essential information for the novel DTC-technique, see Table 4. Depending on the instantaneous sector of the mains voltage vector each

rotating output voltage vector lies in a certain sector, too. Vectors 22, 23, 24 rotate anti-clockwise with a phase displacement of 120° , the movement of the vectors 25, 26, 27 is clockwise also with a phase difference of 120° . For instance the main voltage vector in Fig. 5 lies in sector 10. Thus the six possible rotating output voltage vectors are arranged as depicted on the right side.

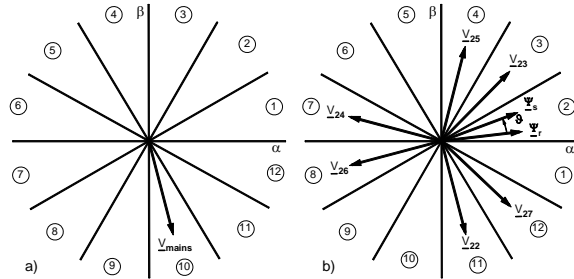


Fig. 5. a) mains voltage sectors, b) sectors of PMSM fluxes and output voltage vectors

Table 4. Relationship between the sector of the mains voltage vector and the sector of the six possible rotating output voltage vectors

Sector of mains voltage vector	Sector of output voltage vector no.					
	22	23	24	25	26	27
1	2	6	10	1	5	9
2	3	7	11	12	4	8
3	4	8	12	11	3	7
4	5	9	1	10	2	6
5	6	10	2	9	1	5
6	7	11	3	8	12	4
7	8	12	4	7	11	3
8	9	1	5	6	10	2
9	10	2	6	5	9	1
10	11	3	7	4	8	12
11	12	4	8	3	7	11
12	1	5	9	2	6	10

Furthermore for the new DTC method it is necessary to know in which sector the output voltage vector must be located to fulfill the requirements of the flux and torque decrease or increase instruction according to the current stator flux vector sector. This interrelation is illustrated in Table 5.

Table 5. Interrelation between stator flux sector, modification of torque and flux and the consequential necessary output voltage vector sector

F	T	stator flux sector											
		1	2	3	4	5	6	7	8	9	10	11	12
0	0	8, 9	9, 10	10, 11	11, 12	12, 1	1, 2	2, 3	3, 4	4, 5	5, 6	6, 7	7, 8
0	1	5, 6	6, 7	7, 8	8, 9	9, 10	10, 11	11, 12	12, 1	1, 2	2, 3	3, 4	4, 5
1	0	11, 12	12, 1	1, 2	2, 3	3, 4	4, 5	5, 6	6, 7	7, 8	8, 9	9, 10	10, 11
1	1	2, 3	3, 4	4, 5	5, 6	6, 7	7, 8	8, 9	9, 10	10, 11	11, 12	12, 1	1, 2

F: flux, T: torque, 0: decrease F or T, 1: increase F or T

Now all information needed is available to derive altogether 12 DTC tables for the novel DTC approach including the six rotating vectors. To give an example the switching tables for stator flux sector 2 and 3 are shown below, see Tables 6 and 7.

Table 6. Novel DTC table for stator flux sector 2

		Sector of mains voltage vector (stator flux sector 2)											
F	T	1	2	3	4	5	6	7	8	9	10	11	12
0	0	24, 27	21	17	23, 25	23, 25	19	18	22, 26	22, 26	20	16	24, 27
0	1	23	23	27	27	22	22	25	25	24	24	26	26
1	0	25	25	24	24	26	26	23	23	27	27	22	22
1	1	18	22, 26	22, 26	20	16	24, 27	24, 27	21	17	23, 25	23, 25	19

F: flux, T: torque, 0: decrease F or T, 1: increase F or T

Table 7. Novel DTC table for stator flux sector 3

		Sector of mains voltage vector (stator flux sector 3)											
F	T	1	2	3	4	5	6	7	8	9	10	11	12
0	0	24	24	25	25	23	23	26	26	22	22	27	27
0	1	6	23, 27	23, 27	8	4	22, 25	22, 25	9	5	24, 26	24, 26	7
1	0	22, 25	9	5	24, 26	24, 26	7	6	23, 27	23, 27	8	4	22, 25
1	1	26	26	22	22	27	27	24	24	25	25	23	23

F: flux, T: torque, 0: decrease F or T, 1: increase F or T

In Fig. 5 the stator flux vector is positioned in sector 2 and the mains voltage vector lies in sector 10. Following Table 6 and its column No. 10 the considered voltage vectors are 20, 24, 27, 23 and 25 subject to the demanded flux/torque combination. From Table 4 and Tables 6 and 7 it can be seen that it is not possible to switch one of the rotating vectors in every instant of time to comply with the desired flux/torque combination. These table gaps are filled up by the longest active voltage vectors from the group 4-21. When there are two feasible rotating vectors the one is applied that causes less switching losses.

3. SIMULATION AND EXPERIMENTAL RIG MEASUREMENT RESULTS

In order to confirm the benefit of the proposed DTC scheme, detailed Matlab/Simulink simulations were designed. They comprise the complete power electronics part, the PMSM and the new DTC control method. Fig. 6 illustrates the common mode voltage of the classical DTC method using the active vectors 4-21 only. Fig. 7 shows the result for the DTC including of the rotating vectors 22-27. The simulation records were made with an effective mains phase-neutral voltage of 230V. It can be seen that the new DTC algorithm clearly improves the common mode voltage characteristics. The calculated root mean square (RMS) common mode voltage value for the classical method is 101V and for the novel DTC technique it is 53V. That means an enhancement of almost 50%.

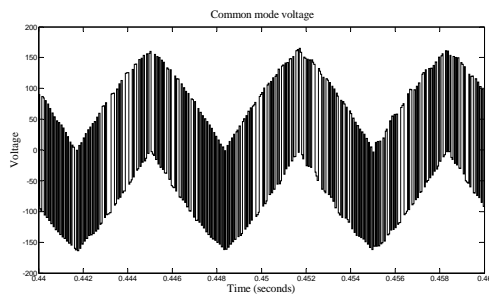


Fig. 6. Matlab/Simulink simulation: Common mode voltage of the classical DTC method

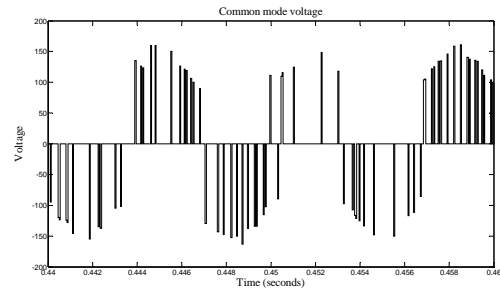


Fig. 7. Matlab/Simulink simulation: Common mode voltage of the new DTC method

A practical verification of the method at the laboratory experimental rig is documented by Figs. 8 and 9. The applied effective mains phase-neutral voltage was 100V. Here the improvement with the rotating vector-DTC is also obvious. The RMS common mode voltage value in Fig. 8 is 44V and in figure 9 22,5V. Thus also here an improvement of nearly 50% can be observed.

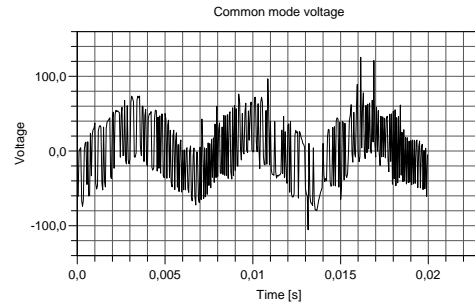


Fig. 8. Experimental rig measurement: Common mode voltage of the classical DTC method

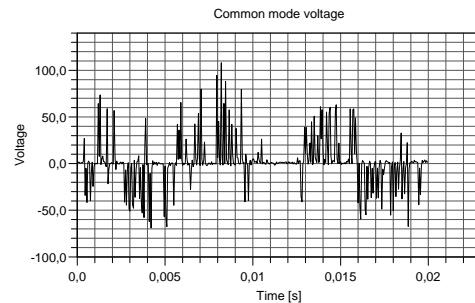


Fig. 9. Experimental rig measurement: Common mode voltage of the new DTC method

2. CONCLUSION

In this paper a novel DTC scheme for matrix converter fed PMSMs has been proposed. The method utilizes the rotating vectors in order to decrease the common mode voltage. It is shown how the new DTC switching tables were developed, and simulation and test stand measurement results are presented to verify the approach. The common mode voltage is not completely reduced, but a reduction of 50% is a significant value in

order to document that the new approach improves the common mode characteristics and it is an basis for further research studies.

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