Switching Strategies for Fault Tolerant Operation of Single DC-link Dual Converters

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Abstract

This paper proposes a method that allows the operation with direct torque control under incipient faults of the power switching devices in single DC-link dual-inverters. Once the fault onset of the switching device is detected the troubled devices are put under trigger suppression to regain operation. The proposed control algorithm makes use of additional states, termed opportunistic states to maintain control of the induction machine. Simulations and experimental results confirm the capabilities of the technique for up to six devices under trigger suppression.

Index Terms

AC motor drives, Fault tolerance, Drives, Inverters

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I. INTRODUCTION

The migration from traditional electromechanical and hydraulic drives in critical equipment to power electronic drives raises concern about the reliability of critical equipment controlled by power electronic components and drives. Examples of this migration can be observed in the aeronautic industry as in the proposed “fly by wire” (aircraft control) initiative and in the automotive industry with the electric steering wheel concept. Furthermore, there is a strong push in the aeronautics industry to produce complete solid-state technology based power converters and for military applications to implement the main parts of hybrid vehicles using a similar approach. The same trend discussed above can be observed in the main power drive where reliability is essential. Additionally, Power electronic converters, drives and related modern electric machines continue to play a more critical role in the performance and overall operation of ships, aircraft, and ground vehicles. The electric power and propulsion systems developed for the military are being rapidly modernized [1]. The new trend is to create designs that integrate motor drive systems (power electronics), into a monolithic structure for propulsion and generation, power transformers, new storage devices, power cells, etc. These new technologies present new challenges in methods of operation and automated health management in order to accomplish the goal of creating a more versatile, robust, efficient, and reliable system.

The problem of increasing the system reliability can be tackled following two strategies. The first approach is to improve the performance of standard topologies and early/post diagnostics of the power devices [2], [3]. The second approach is to develop new fault tolerant topologies for power drives. Standard power drives are based on a controller with the traditional six transistor structure that drives induction or synchronous Permanent Magnet (PM) machines. Fault tolerant operation of multilevel converters has been investigated in literature [4]–[9]. In this work, the use of a dual converter is proposed and analyzed as an alternative for a more reliable operation of drives under faulty conditions. This topology has been previously described in the literature, mainly for its multilevel operation [10]–[14]. As with any multilevel topology, the power and voltage ratings of the inverter are increased without increasing the voltage rating of the switching device, and the \( \frac{dv}{dt} \) of the converter is reduced [15]. Also, dual converters have the drawback of doubling the switching devices count when compared with conventional two-level converters, but present a higher potential for extended operation in critical operation [16], [17]. The analysis and advantages of different fault tolerant strategies in single DC-link dual converters are presented in this paper.

II. EARLY DIAGNOSTIC TECHNIQUE

There are several methods for the early identification of the degradation of power electronic devices. These diagnostic techniques allow and enhance the application of fault tolerant techniques [4], [18], [19]. Early pre-failure
characterization of switching devices is mainly based on the operating condition of a power drive. The operating frequency band of a standard power drive can be divided in three ranges. The low frequency range, usually below 200 Hz, provides the main electrical signal for the motor and achieves the control objective of the power drive. The second range, between 10 kHz and 200 kHz is due to the Pulse Width Modulation (PWM) signal, and is used to modulate the main or fundamental signal of the power drive. The third band corresponds to frequencies greater than 1-MHz and is the consequence of system’s resonance and high frequency harmonics in the PWM step waveforms. This high frequency band is of main interest for modeling and diagnosing transistor aging through changes in the “ringing characteristics” of the power devices [20]. In the ringing characterization method specific frequencies are identified and tracked for changes such as the devices degradation over time [21]. In the ringing characterization method the system’s response to high frequency components injected during the inverter switching can be used as a signature to track the aging in the power devices. These high frequency components interact with the parasitic elements present in all power devices, giving rise to the “ringing” response that changes with the deterioration of the device. When the early diagnostics fail, a strategy based on the de-saturation protection used in intelligent drives is employed. In this case the protection circuitry triggers a shutdown of the troublesome device, and this period allows the recovery of the device thanks to its self-healing properties [18], [22]–[24].

A supervisory fault detector system monitoring the switching devices is required, and depending on the fault detected a corresponding corrective action should be taken by the controller for the different type of faults, such as shorted or open switching device, missing or randomly suppressed gate signals, etc. This paper proposes what action to take when a fault requires trigger suppression of the relevant switching devices.

Once a satisfactory early diagnostic technique is in place the goal is to continue the operation of the converter, while the troubled switching device is under trigger suppression.

III. DUAL CONVERTER

A diagram of the converter being analyzed in this paper, for switch suppression operation, is shown in Fig. 1. The particular topology of this dual converter is comprised of two three-phase two-level inverters sharing the same DC link. In this topology the dual converter can be considered as a six phase converter, where the number of possible states are $4^6=4096$, of which $4^6-3^6=3367$ are forbidden states because they short-circuit the DC link, from the valid states $3^6-2^6=665$ have at least one “fly-wheeling” floating branch and only $2^6=64$ are well established and in general considered as usable states for normal operation, resulting in 19 different voltage space vectors shown in Fig. 2.

For simplicity the power drives are some times analyzed assuming switching with on and off states, and assuming the loads to be without regeneration capabilities or purely resistive. This generates what has been previously called usable states. However, when the load has regenerative capabilities or energy storage properties such as inductances or electrical machines, the energy storage provides additional control alternatives expressed in additional transient usable states. In the case of fault tolerant strategies, these additional states could provide an important tool for optimization during trigger suppression. In this paper these states are defined as “opportunistic states” since they can only be used when they become available, and the control algorithm can favor their occurrence since they are
determined by current circulating in the winding of the machine under control. When these “opportunistic states” are available, the application of “regenerative vectors” can be achieved.

Since the two sub-converters making up the dual-converter share a common DC-link, the modulation strategies used to synthesize the space vector in each sub-converter need to avoid the injection of zero sequence components, as they will result in corresponding zero sequence currents flowing through the load [25], [26].

In this dual converter topology the voltage levels in each phase of the induction machine are: \{+V_{DC}\}, obtained when the associated branch in sub-converter 1 is in high level and its paired branch in sub-converter 2 is in low level, and when there is enough energy stored in the machine inductances the following voltage levels can be applied: \{0\}, when the both branches feeding the phase winding are simultaneously in high or low level in both sub-converters, and \{-V_{DC}\}, when the associated branch in sub-converter 1 is in low level and its paired branch in sub-converter 2 is in high level. In this way the space vectors in the dual converter can be classified in the following sets.

- First a set of six “positive” small size voltage space vectors obtained with the combination of voltage levels \{0, +V_{DC}\}.
- A second set of six “negative” small size voltage space vectors obtained with the combination of voltage levels \{-V_{DC}, 0\}.
- A third set of six medium size voltage space vectors obtained with one phase set to \(-V_{DC}\), the other phase to 0, and the last phase to \(+V_{DC}\) between each winding terminals.
- A fourth set of six large size voltage space vectors obtained using voltage levels \(V_{DC}\) and \(+V_{DC}\) between the winding terminals.
- Finally a set of three zero magnitude voltage space vectors obtained when the voltage in the three winding terminals are the same \{(\(-V_{DC}, \(-V_{DC}, \(-V_{DC}\), (0, 0, 0), (\(+V_{DC}, \(+V_{DC}, \(+V_{DC}\))\)\).

The resulting space vector locations are shown in Fig. 3. The zero sequence voltage, responsible for the zero sequence current in the induction machine phases, is defined as [25]:

\[ v_{ZS} = \frac{1}{3} (v_{a1a2} + v_{b1b2} + v_{c1c2}) \]  

(1)

The control algorithm used in this paper for healthy as well as switch suppressed operation is the classical direct torque control (DTC) as proposed by Takahashi and Noguchi [27]. During normal operation DTC can take advantage of the additional space vectors produced by the dual converter, and produce less ripple in the system’s state variables [28]–[30]. However, in this paper the focus is on the operation of the machine during switch suppression. Thus, the classical DTC algorithm using the medium size space vectors is used for healthy switching operation.

IV. DTC ALGORITHM

The classical direct torque control (DTC) was originally proposed by I. Takahashi and T. Noguchi [27]. It is based on the computation of the instantaneous stator flux and electric torque in the machine. The calculated values are compared to the flux and torque references to produced error signals that together with the information of the
angular stator flux location are employed in the switching state selection for the inverter. In the classical DTC algorithm the hexagonal space vector area is divided in six zones, the requirements of flux and torque for each zone and the corresponding space vector for two level-converters are summarized in Table I. In this paper the space vectors are obtained using Clarke's transformation,

\[ f' = f_x + jf_y = \sqrt{2 \over 3}(f_a\alpha^0 + f_b\alpha^1 + f_c\alpha^2) \]  

(2)

where \( \alpha = e^{j2\pi/3} \). The stator flux linkage \( \Psi_s \) can be obtained by integrating the stator equation of the induction machine model [27].

\[ \vec{\Psi}_s = \int \left( \vec{v}_s - R_s\vec{i}_s \right) dt \]  

(3)

and the electric torque by multiplying the stator flux linkage and the stator current space vectors.

\[ \tau_e = \vec{\Psi}_s \times \vec{i}_s \]  

(4)

In the simplified algorithm, used in this paper for normal operation, one branch is at -V_{DC}, another at 0 V while the last one is at V_{DC}. Therefore, the voltage supplying the machine does not contain a zero sequence component. The states that satisfy this combination are termed medium size voltage space vectors, and from Fig. 2 they are \( \vec{v}_{m1} = \{14,36\} \), \( \vec{v}_{m2} = \{24,35\} \), \( \vec{v}_{m3} = \{21,65\} \), \( \vec{v}_{m4} = \{41,63\} \), \( \vec{v}_{m5} = \{42,53\} \), \( \vec{v}_{m6} = \{12,56\} \), and the null vector \( \vec{v}_0 = \{00,11,22,33,44,55,66,77\} \). Figure 4 shows the medium size space vectors and the resulting hexagonal region covered by this set of space vectors. From (1) it follows that an advantage of the medium size vectors for the dual converter is that they do not inject zero sequence voltage, hence there are no zero sequence

![Diagram of the dual converter with one DC supply feeding an open-end induction machine.](image)
Fig. 2: Voltage space vectors with their respective switching states in base 8.

Fig. 3: Sets of voltage space vectors in the dual converter.
Fig. 4: Medium size space vectors.

currents injected into the load. Any other selection of space vector will inject a zero sequence component and its influence on the load needs to be considered before using them.

TABLE I: Switch selection for classical DTC [27].

<table>
<thead>
<tr>
<th>$O_{\psi}$</th>
<th>$O_{\tau}$</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
<th>$Z_3$</th>
<th>$Z_4$</th>
<th>$Z_5$</th>
<th>$Z_6$</th>
</tr>
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<tbody>
<tr>
<td>↓</td>
<td>$\vec{v}_5$</td>
<td>$\vec{v}_6$</td>
<td>$\vec{v}_1$</td>
<td>$\vec{v}_2$</td>
<td>$\vec{v}_3$</td>
<td>$\vec{v}_4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td></td>
</tr>
<tr>
<td>↑</td>
<td>$\vec{v}_3$</td>
<td>$\vec{v}_4$</td>
<td>$\vec{v}_5$</td>
<td>$\vec{v}_6$</td>
<td>$\vec{v}_1$</td>
<td>$\vec{v}_2$</td>
<td></td>
</tr>
<tr>
<td>↓</td>
<td>$\vec{v}_6$</td>
<td>$\vec{v}_1$</td>
<td>$\vec{v}_2$</td>
<td>$\vec{v}_3$</td>
<td>$\vec{v}_4$</td>
<td>$\vec{v}_5$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td>$\vec{v}_0$</td>
<td></td>
</tr>
<tr>
<td>↑</td>
<td>$\vec{v}_2$</td>
<td>$\vec{v}_3$</td>
<td>$\vec{v}_4$</td>
<td>$\vec{v}_5$</td>
<td>$\vec{v}_6$</td>
<td>$\vec{v}_1$</td>
<td></td>
</tr>
</tbody>
</table>
TABLE II: Common mode voltage for the positive and negative small voltage space vectors.

<table>
<thead>
<tr>
<th>(v_a)</th>
<th>(v_b)</th>
<th>(v_c)</th>
<th>voltage space vector</th>
<th>(v_{2S})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{DC})</td>
<td>(V_{DC})</td>
<td>(V_{DC})</td>
<td>(\vec{v}_0)</td>
<td>(V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(-V_{DC})</td>
<td>(-V_{DC})</td>
<td>(-V_{DC})</td>
<td>(-\vec{v}_0)</td>
<td>(-V_{DC})</td>
</tr>
<tr>
<td>(V_{DC})</td>
<td>(-V_{DC})</td>
<td>0</td>
<td>(\vec{v}_1)</td>
<td>(V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>(-V_{DC})</td>
<td>0</td>
<td>(\vec{v}_1)</td>
<td>(-\frac{1}{2}V_{DC})</td>
</tr>
<tr>
<td>(V_{DC})</td>
<td>(V_{DC})</td>
<td>0</td>
<td>(\vec{v}_2)</td>
<td>(\frac{1}{2}V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>(-V_{DC})</td>
<td>(\vec{v}_2)</td>
<td>(-\frac{1}{2}V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>(V_{DC})</td>
<td>0</td>
<td>(\vec{v}_3)</td>
<td>(\frac{1}{2}V_{DC})</td>
</tr>
<tr>
<td>(-V_{DC})</td>
<td>0</td>
<td>(-V_{DC})</td>
<td>(\vec{v}_3)</td>
<td>(-\frac{1}{2}V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>(V_{DC})</td>
<td>(V_{DC})</td>
<td>(\vec{v}_4)</td>
<td>(\frac{1}{4}V_{DC})</td>
</tr>
<tr>
<td>(-V_{DC})</td>
<td>0</td>
<td>0</td>
<td>(\vec{v}_4)</td>
<td>(-\frac{1}{4}V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>(V_{DC})</td>
<td>(\vec{v}_5)</td>
<td>(\frac{1}{4}V_{DC})</td>
</tr>
<tr>
<td>(-V_{DC})</td>
<td>(-V_{DC})</td>
<td>0</td>
<td>(\vec{v}_5)</td>
<td>(-\frac{1}{4}V_{DC})</td>
</tr>
<tr>
<td>(V_{DC})</td>
<td>0</td>
<td>(V_{DC})</td>
<td>(\vec{v}_6)</td>
<td>(\frac{1}{4}V_{DC})</td>
</tr>
<tr>
<td>0</td>
<td>(-V_{DC})</td>
<td>0</td>
<td>(\vec{v}_6)</td>
<td>(-\frac{1}{4}V_{DC})</td>
</tr>
</tbody>
</table>

V. DTC OPERATION FOR SWITCH TRIGGER SUPPRESSION

The large amount of switching states in the dual converter allow the implementation of different machine control algorithms. For this work the DTC is chosen for implementation. Depending on the amount of switches under trigger suppression there is a certain number of voltage space vectors available to perform the DTC on the machine, or to enforce the conditions to use all the space vectors. Since the DTC uses a computation of the stator flux linkage, the use of (3) requires the voltage at the machine terminals. The use of the switching state of the dual inverter for estimation of the stator voltage assumes that each terminal of the machine is connected at \(+V_{DC}\) or 0. This restriction limits the failure to one switch per branch. A fully asymmetric operation of the inverter is considered in the case of six switches with trigger suppression, i.e. trigger suppression in three upper switches in one sub-converter and trigger suppression in three lower switches in the other sub-converter. The classical DTC algorithm remains unchanged for healthy or trigger-suppressed operation, but for the dual converter, the healthy case uses the medium size space vectors versus the use of the small size space vectors in the trigger suppression mode. This requires a 30 degrees rotation in the region selection of the stator flux \((Z_1, Z_2, ..., Z_6)\) shown in Fig. 4.
A. Trigger suppression in one and two devices

In this case, trigger suppression is applied to one or two devices. The effect of trigger suppression in one switch is that the current does not flow in the direction controlled by the suppressed device. However, if regenerative operation allows for a valid state to be established then all the original voltage space vectors are available for the control of the load. When the conditions do not allow the establishment of a known state, trigger suppression in one device affects 32 out of the 64 usable states shown in Fig. 3, but due to the redundancy of the dual converter only five voltage space vectors out of 19 are affected. An additional trigger suppression in the complementary sub-converter and complementary level of the former device affects 16 additional states, corresponding to five additional voltage space vectors. The effects of the trigger suppression for one and two power devices in phase ‘a’ are illustrated in Fig. 5. The devices under trigger suppression are: sub-converter 1, high side phase ‘a’ (\(a_1H\)) and sub-converter 2, low side phase ‘a’ (\(a_2L\)). Trigger suppression and no regeneration in one of the aforementioned devices prevent the establishment of the outer space vectors in Fig. 5 (\(\vec{v}_{l2}, \vec{v}_{m1}, \vec{v}_{l1}, \vec{v}_{m6}, \vec{v}_{l6}\)), and the additional trigger suppression in the second device prevent the establishment of the additional space vectors (\(\vec{v}_{m2}, \vec{v}_{s2}, \vec{v}_{s1}, \vec{v}_{s6}, \vec{v}_{m5}\)). Some states associated with voltage space vectors (\(\vec{v}_0, \vec{v}_{s3}, \vec{v}_{s4}, \vec{v}_{s5}\)) are affected, but the redundancy in the number of states in the dual converter allows the establishment of the associated voltage space vectors. If the second device with trigger suppression is (\(a_{2H}\)), the voltage space vectors affected are (\(\vec{v}_{l3}, \vec{v}_{m3}, \vec{v}_{l4}, \vec{v}_{m4}, \vec{v}_{l5}\)). A proper control of the load with DTC can be achieved through the injection of a zero sequence component in the load current. Then all the switching states are available for control thanks to regenerative operation in the suppressed devices. This zero sequence injection can be controlled with the proper selection of the switching state and its associated common mode voltage.

Due to the symmetry of the dual converter, the pattern of voltage space vectors affected by trigger suppression in one or two devices are rotated by the same amount as the associated phase. Some resulting patterns for two devices with trigger suppression are shown in Fig. 6.

For the case depicted in Fig. 5 the voltage space vectors available for DTC are those with phase ‘a’ at \(-V_{DC}\), shown in Table III:

For two devices associated with the same phase and the same sub-converter there is no possible combination of remaining switching devices that can impress the desired current value in that phase. Therefore, no opportunistic states are available for control and a different control strategy should be considered.

B. Trigger suppression in six switches (asymmetric operation)

For this kind of operation only 50% of the switching devices are available for controlling the current in the load. In this case the resulting power stage topology is similar to the asymmetric converter employed in the control of switched reluctance machines (SRM) [31]. In this work, the operation of the converter under this circumstances is termed asymmetric operation, and is considered when trigger suppression is done in complementary devices of the same phase as shown in Fig. 7. Different modes of operation for the induction machine fed by an asymmetrical converter have been presented in [32]. In this work the DTC algorithm is employed using the positive and negative
Fig. 5: Voltage space vectors for one and two trigger suppressed devices ‘$a_{1H}$’ and ‘$a_{2L}$’.

Fig. 6: Example of different space vectors affected in the case of trigger suppression in one and two power devices.
TABLE III: States available for trigger suppression in two switches of phase ‘a’ as presented in Fig. 5.

<table>
<thead>
<tr>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>voltage space vector</th>
<th>$v_{ES}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-$V_{DC}$</td>
<td>-$V_{DC}$</td>
<td>-$V_{DC}$</td>
<td>$\vec{v}_{s0}$</td>
<td>-$V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>-$V_{DC}$</td>
<td>0</td>
<td>$\vec{v}_{s5}$</td>
<td>$\frac{2}{3}V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>-$V_{DC}$</td>
<td>+$V_{DC}$</td>
<td>$\vec{v}_{t5}$</td>
<td>$\frac{1}{3}V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>0</td>
<td>-$V_{DC}$</td>
<td>$\vec{v}_{s3}$</td>
<td>$\frac{2}{3}V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>0</td>
<td>0</td>
<td>$\vec{v}_{s4}$</td>
<td>$\frac{1}{3}V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>0</td>
<td>+$V_{DC}$</td>
<td>$\vec{v}_{m4}$</td>
<td>0</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>+$V_{DC}$</td>
<td>-$V_{DC}$</td>
<td>$\vec{v}_{t3}$</td>
<td>$\frac{2}{3}V_{DC}$</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>+$V_{DC}$</td>
<td>0</td>
<td>$\vec{v}_{m3}$</td>
<td>0</td>
</tr>
<tr>
<td>-$V_{DC}$</td>
<td>+$V_{DC}$</td>
<td>+$V_{DC}$</td>
<td>$\vec{v}_{t4}$</td>
<td>$\frac{1}{3}V_{DC}$</td>
</tr>
</tbody>
</table>

or regenerative set of space vectors. Under this operating conditions all the switching states become available thanks to the opportunistic states described above.

For trigger suppression in the devices shown in Fig. 7 the only known state that can be impressed on the machine at any time is $\{1, 1, 1\}$, corresponding to the null vector. All the other states require a current flow in each particular branch to operate with regenerative states. Once the establishment of regenerative states is assured all the 64 states and 19 voltage space vectors become available for DTC. However, the regenerative states are obtained at the expense of zero sequence injection into the load. The strategy to control the zero sequence injection is similar to the one employed in the case of trigger suppression with one and two devices. The opportunistic states (space
TABLE IV: Induction machine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Resistance ($R_s$)</td>
<td>3.8 Ω</td>
</tr>
<tr>
<td>Stator Inductance ($L_s$)</td>
<td>282.7 mH</td>
</tr>
<tr>
<td>Rotor Resistance ($R_r$)</td>
<td>2.5 Ω</td>
</tr>
<tr>
<td>Rotor Inductance ($L_r$)</td>
<td>282.7 mH</td>
</tr>
<tr>
<td>Mutual Inductance ($L_m$)</td>
<td>270.5 mH</td>
</tr>
</tbody>
</table>

vectors synthesized with 0 and $−1$ states) are used until a predefined threshold is reached. Then a space vector is synthesized using states 0 and 1 which increases the energy in the machine leakage reactances and goes back to the use of opportunistic states.

VI. SIMULATION AND EXPERIMENTAL RESULTS

The proposed fault-tolerant strategies are first simulated in SIMULINK using the Piece-wise Linear Electrical Circuit Simulation (PLECS) package for the machine and power electronics modules. The circuit diagram in PLECS is shown in Fig. 8, while the control strategy is implemented in SIMULINK. The parameters of the machine used for the simulation and experimental tests are presented in Table IV, the sampling rate of the controller is fixed at 10 kHz.

For the experimental test, the proposed algorithm is implemented on a custom build floating-point DSP-(ADSP-21369) based test rig, shown in Fig. 9. The power stage in each sub converter uses six 50 A, 1200V insulated gate bipolar transistors (IGBTs) with a 2200 μF, 450 V capacitor in the DC-link. The interface between the DSP processing unit and the peripherals (power devices and sensors) is done with a SPARTAN-Xilinx field programmable gate array (FPGA). This interface is programmed to enable or disable each IGBT present in the power stage, using a 6-bit mask, one mask per sub-converter. Also, the switching frequency for the controller, and for sampling the sensors (10 kHz), is programmed in this FPGA. Once the number of suppressed IGBTs is known, the control algorithm selects the proper common mode injection strategy to ensure the use of all the available space vectors, thanks to the availability of opportunistic states. In all cases the DTC operates with TABLE I, but using the space vectors shown in Fig. 3, depending on the operation mode, medium size space vector for healthy operation and the small size space vectors for operation under trigger suppression.

In the first test the single DC-link dual converter is simulated for healthy operation with the set of medium voltage space vectors. The advantage of this selection for healthy operation is that there is not zero sequence injection at any time. Figure 10 shows the simulated stator currents, stator flux, electric torque and rotor speed for a healthy operation of the dual converter. It can be seen from Fig. 10a that no zero sequence component is present in the stator current. Also, since the classical DTC algorithm is employed, the torque shows the large ripple that is characteristic
Fig. 8: Circuit diagram.

of this kind of controllers. Figure 11 shows the experimental results obtained for healthy operation with DTC with the medium size set of space vectors, the experimental stator current waveforms confirm that for healthy operation with the selected set of space vectors there is not zero sequence injection.

Figure 12 shows the corresponding simulated state variables for trigger suppression in one or two switches associated to one phase winding ($a_1L$ and $a_2H$), in this case the current flowing through phase ‘$a$’ can take only positive values, and to insure known switching states in the dual converter the phase current has to be positive at all time ($i_{sa} > 0$). If the trigger suppression is in the complementary switches ($a_1H$ and $a_2L$) the current will be required to be negative at all times to ensure operation of the dual converter under fault operation with known states. For trigger suppression in devices ($a_1L$ and $a_2H$) the control strategy is to use the set of regenerative space vectors whenever the current flowing through the affected phase is above certain threshold that insures the use of opportunistic states, otherwise use the non regenerative set of small space vectors to increase the stored energy in the affected winding for use of opportunistic states in subsequent control cycles.

Although trigger suppression in six switches will affect all the space-vectors synthesized by the dual converter, there are still known states available to store energy in the machine inductances. This brings the possibility of achieving proper control of the dual converter if enough energy can be stored in the machine inductances so that through regeneration the opportunistic states become available. Thereby all the space vectors can be used and the switching state of the dual converter is known. Figure 14 shows the simulated state variables for the dual converter...
Fig. 9: Experimental test rig for the dual converter.

Fig. 10: Simulated stator currents, stator flux, rotor speed and torque for normal operation with DTC using medium size voltage space vectors.

operating under six switches with trigger suppression. The switches with trigger suppression are \((a, b, c)_{1L}\) and \((a, b, c)_{2H}\). The control strategy used in this case is similar to the one used previously and consists of applying
the opportunistic states as long as there is enough energy stored in the machine leakage inductances, and then switch to the complementary states to increase the stored energy when the energy is not sufficient to use the opportunistic states. For the case under test the opportunistic states can be used if the phase currents are above a predefined minimum value, i.e. each phase circuit is operating in a continuous switching mode. Figure 15 shows the experimental results, that confirm the results obtained previously in the simulation. Although there is a high zero sequence voltage and current component injected in the machine terminals, this zero sequence does not produce any braking torque because there is not zero sequence component in the stator flux. The disadvantage of this operating mode is that for the same electrical torque the machine is operating with higher rms currents and hence with increased power losses and reduced system efficiency. This results in higher thermal stress and reduced life span for the operating power components.

Figure 16 shows the instantaneous transition between healthy operation and switch trigger suppression in two
Fig. 13: Experimental stator currents, stator flux, rotor speed and torque for trigger suppression in $a_1L$ and $a_2H$.

Fig. 14: Simulated stator currents, stator flux, rotor speed and torque for trigger suppression in six switches, $\{a_1L, b_1L, c_1L\}$ and $\{a_2H, b_2H, c_2H\}$.

Fig. 15: Experimental stator currents, stator flux, rotor speed and torque for trigger suppression in six switches, $\{a_1L, b_1L, c_1L\}$ and $\{a_2H, b_2H, c_2H\}$. 
power devices. Since the stator flux and torque are maintained constant before and after the change in operating mode, the transition of the remaining state variables towards steady state is fast.

Table V shows the rms value of the stator currents and the THD for the dual-converter when operating under healthy condition, as well as with two switches under trigger suppression and also with six switches under trigger suppression. From these results it is clear that there is an increase in both rms current and the THD in most phases, which in turn results in an increase in the machine’s temperature for the same output torque.

TABLE V: RMS current and THD for healthy operation, two switches trigger suppression and six switches trigger suppression.

<table>
<thead>
<tr>
<th></th>
<th>RMS (A)</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
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</tr>
<tr>
<td>$i_a$</td>
<td>0.9731</td>
<td>0.0647</td>
</tr>
<tr>
<td>$i_b$</td>
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<td>0.0574</td>
</tr>
<tr>
<td>$i_c$</td>
<td>1.0160</td>
<td>0.0608</td>
</tr>
<tr>
<td>2sts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_a$</td>
<td>0.2913</td>
<td>—</td>
</tr>
<tr>
<td>$i_b$</td>
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<td>0.2143</td>
</tr>
<tr>
<td>$i_c$</td>
<td>1.8834</td>
<td>0.2325</td>
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</table>

VII. CONCLUSION

In this paper a fault-tolerant DTC algorithm for a single DC-link dual-converter feeding an induction machine has been proposed and verified for trigger suppression in up to six power devices. This extended operation compensates
and improves over the apparent reduction in reliability due to the increase in power devices. The proposed algorithm shows that operation of the machine is still possible, and although there is a penalty in the thermal stress of the system. It presents an alternative to maintain operation in critical systems. The experimental test at different operating conditions verify the proposed control strategy and the simulation results.

REFERENCES


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