Open-circuit fault-tolerant operation of permanent magnet synchronous generator drives for wind turbine systems using a computationally efficient model predictive current control

Imed Jlassi © | Antonio J. Marques Cardoso ©

CISE – Electromechatronic Systems Research Centre, University of Beira Interior, Covilhã, Portugal.

Correspondence
Imed Jlassi, CISE—Electromechatronic Systems Research Centre, University of Beira Interior, Calçada Fonte do Lameiro, 6201–001, Covilhã, Portugal.
Email: jlassi-imed@hotmail.fr

Funding information
European Regional Development Fund, Grant/Award Numbers: POCI-01-0145-FEDER-029494; FCT - Portuguese Foundation for Science and Technology, Grant/Award Numbers: PTDC/EEI-EEE/29494/2017, UIDB/04131/2020, and UIDP/04131/2020

1 | INTRODUCTION

Modern wind turbine systems based on direct-drive permanent magnet synchronous generators (PMSGs) with back-to-back (BTB) power converters have become a standard for wind turbine manufacturers, where the development of finite control set model predictive control techniques for both generator and grid-connection control has gained substantial interest in recent years.

Although wind turbines have been exploited for more than 4 decades, their reliability and availability levels remain lower than expected [1]. The power converter of a wind turbine is usually associated with a failure rate higher than that of other applications [2]. Power switches are one of the main causes of critical failures [2, 3]. In general, these can be divided into open-circuit (O-C) and short-circuit faults. Standard power converters include hardware protection against short-circuit failures, whereas there is no protection in the case of O-C failures.

Numerous reliable fault-diagnosis techniques requiring no additional hardware have been proposed in the literature [4–13] for power switch O-C faults in BTB converters. The methods can be classified as current-based or voltage-based. Recently, diagnosis through adaptive thresholds was proposed in [10, 11] and later improved in [12, 13] with added sensor diagnostic capabilities. These approaches proved that compared with conventional fixed thresholds, an adaptive threshold enables very high immunity to false diagnostics under strong current transients and fast speed variations. Therefore, fault diagnostics are not the topic of this paper.

Several topologies have been proposed to endow the grid-side converter (GSC) with fault-tolerant capabilities. Redundant topologies have been proposed for creating a different paths for current flow by using TRIACs to connect an extra leg to converter legs [14] or to the motor neutral point [15], allowing for replacement of the affected leg and maintaining drive system operation at the rated power. Nevertheless, redundant solutions increase system costs.

On the other hand, non-redundant topologies use supplementary and cheaper devices, making them cost-effective solutions that are acceptable to the industry. Such non-

Abstract
Model predictive fault-tolerant current control (MPFTCC) of permanent magnet synchronous generator (PMSG) drives can make a valuable contribution to improving the reliability and availability levels of wind turbines, because back-to-back (BTB) converters are prone to failure. However, MPFTCC suffers from excessive computational burden, because the BTB converter is treated as one system where all feasible voltage vectors (VVs) are used for prediction and evaluation. Accordingly, a computationally efficient MPFTCC algorithm for a PMSG drive is developed and proposed with the ability to handle insulated-gate bipolar transistor open-circuit faults. The candidate VVs of both machine- and grid-side converters are separately predicted and evaluated, which significantly reduces calculation effort. The proposed reconfigurable converter is a five-leg power converter with a common leg that connects the generator first phase to the grid three-side inverter. Moreover, a three-switch rectifier is adopted to achieve fault tolerance of the PMSG-side rectifier. Performance of the considered MPFTCC strategies is evaluated by experimental means.
redundant topologies force converter oversizing or derating due to the reduced voltage and current capabilities of the converter. Several topologies have been investigated: connecting the DC bus midpoint to the three-phase converter [16, 17] or transformer/generator neutral point [18] through three additional TRIACs. Thus, the DC-link voltage must be doubled to achieve the rated power, or the three-phase current amplitude must be increased by a factor of 3 compared with standard BTB converter capability. However, voltage fluctuations and current stresses are imposed on capacitors due to the DC bus split, requiring an extra voltage sensor to limit fluctuations and the proper design of DC-link capacitors. In [19], a reconfigurable BTB topology was proposed to maintain operation under multiple faults. Apart from the split of the DC bus capacitors, six TRIACs are required to achieve fault tolerance, which leads to increased system cost and complexity.

With the aim to avoid the connecting of DC bus capacitors, five-leg power converter (FLC) topologies with a common leg have been adopted by connecting the three-phase machine through three TRIACs to the phases of a similar three-phase grid [20–25]. Similar converter topologies were addressed in [26–33] by connecting symmetrical legs in multimotor drives. Apart from the aforementioned advantage, these topologies can be easily implemented and require fewer devices (only three TRIACs). However, the voltage capability of the converter is reduced, and all legs must be designed for twice the rated current. An alternative FLC with a shared leg between the machine phase and the grid transformer neutral point was proposed in [34]. This configuration increases converter voltage capability, but the shared leg current is four times higher than the rated current. Moreover, a transformer is required, and neutral point access must be considered in making the desired connections. In [35], multimotor neutral points were connected for postfault operation where phase currents were increased by a factor of 3. Again, other components should be involved to achieve converter fault tolerance but may not be available.

After hardware modification, a postfault control strategy is required for optimising drive performance. Hysteresis current control with fault-tolerance capabilities was proposed in [18, 23, 24, 30, 34] and revealed excellent dynamic performance, parameter independence and low calculation time. On the other hand, simple implementation, low parameter dependence and fast response are achieved by the direct control technique [17, 20 and 34]. However, both control schemes generate substantial current and torque ripples. Pulse-width modulation was widely used in [14–16, 21, 23–29, 34, 35]. Despite the high tuning effort required by proportional integral (PI) controllers, they present high steady-state performance because of the superior modulation strategy. Recently, the development of model predictive fault-tolerant control (MPFTC) has gained considerable interest. It presents several advantages such as fast control dynamics, a straightforward concept and the ability to include multiple constraints into the cost function, thus making it a promising alternative for power converters. For a BTB converter operating normally, both converters are separately controlled, in which case eight predictions and one cost function are needed for each power converter. However, for a shared-leg-based FLC, the constraint imposed by the shared-leg structure must be considered. For FLCs, MPFTC schemes have been developed in [22, 31–33]. However, in [31] the FLC was treated as one system to be controlled by a standard MPFTC, where 32 voltage vectors (VV) are employed for prediction and evaluation in a single cost function, making control computationally demanding. To reduce the number of VVs, an adjacent VV scheme was proposed, but control performance is strongly affected by when VVs are reduced. In [32, 33], the simultaneous consideration of both the converters and the FLC as a single system by the MPFTC gives rise to another approach to minimise the number of VVs. Both converters were separately evaluated through two cost-function designs. A third cost function was designed for FLC evaluation. Another approach with fewer predictions and evaluations of only 16 VVs was addressed in [22] by considering both converters and the FLC as a single system. For each shared leg state (0 or 1), the computation of three cost functions were required. As a result, six cost functions must be designed for FLC evaluation. Although the aforementioned approaches reduce the number of candidate VVs, these design procedures are not intuitive and are complicated, therefore increasing algorithm complexity. The application of artificial intelligence algorithms is a significant trend in fault-tolerant control [36–38]; however, these algorithms are computationally demanding.

As opposed to the GSC reconfiguration, the semi-controlled machine-side converter (MSC) using a three-switch rectifier (TSR) proposed in [17, 34, 39, 40] does not require extra devices or system oversizing, making it very attractive for MSC fault tolerance. Nevertheless, generator torque ripple due to the TSR's physical limitations, as well as its minimisation, has not been considered. In [18], different control schemes have been proposed for torque ripple reduction. Another converter topology and control approach are proposed in [41] for rectifier fault tolerance with d-axis current injection and a modified PI anti-windup strategy. However, the topology does not consider BTB operation, and the reconfigured currents remain at zero for a short period, resulting in poor control performance. Although direct and vector control techniques have been employed, the use of MPFTC for the TSR has not yet been investigated.

Accordingly, this study's contributions are as follows:

– A new cost-effective FLC topology is proposed for GSC fault tolerance that relies on one shared leg of the MSC connected to the GSC's three phases through three TRIACs. Only the shared leg must be designed, with a rated current two times as high as the remaining converter legs, avoiding the classical shared-leg-based FLC in [20–33] with twice the current rating in all of the converter legs.

– As opposed to the predictive schemes in [22, 31–33] that consider FLC as a single converter and require either the evaluation of 32 VVs or the design of at least three cost functions for VV minimisation, a simple model predictive fault-tolerant current control (MPFTCC) with reduced computational effort is developed in this study, where both the MSC and the GSC are separately controlled,
thus requiring only 16 VVs and two cost function designs for predictions and evaluations. The postfault operation is ensured by comparing both cost functions and giving priority to control of each converter in each sampling period.

- A TSR topology without additional devices or system oversizing is adopted for MSC fault tolerance. As opposed to the direct and vector control techniques in [17, 18, 34, 39–41] that require control modifications for selecting the optimum VV of the TSR topology, a simpler MPFTCC is proposed and analysed herein, where the optimum VV is obtained from cost function minimisation without extra control modifications.

The effectiveness of the proposed fault-tolerant converter topologies and control strategies are verified by means of experimental results.

2 | FAULT-TOLERANT CONVERTER

The considered BTB converter topologies are based on two standard six-switch converters with three additional TRIACs that connect each GSC phase to the first phase of the MSC and remain open under healthy operation, as shown in Figure 1a. The TRIACs are required in order to reconfigure the GSC topology and to allow current flow between the grid and generator phases. For GSC postfault operation, as shown in Figure 1b, the GSC operates by two healthy phases, being the faulty phase connected to the MSC common leg by triggering the corresponding TRIAC, which changes the standard BTB converter from a six-leg converter to an FLC topology. Only one shared leg is needed to support twice the current rating, avoiding the standard connection of similar legs in [20–33], resorting to six common legs. On the other side, to achieve the MSC fault tolerance, a different path for current flow is possible through the anti-parallel diodes of the TSR without extra devices or system oversizing, as can be seen in Figure 1c.

3 | FINITE CONTROL SET-MODEL PREDICTIVE CONTROL OF BACK-TO-BACK AND FIVE-LEG POWER CONVERTERS

3.1 | Finite control set-model predictive control of machine-side converter

Assuming that the dq synchronous reference frame is controlled in such a way that the rotor flux space vector is always aligned with the d-axis, the current dynamic model of a surface-mounted PMSG \( I_{sd} = I_{sq} = I_{sl} \) is given by

\[
\begin{align*}
\frac{di_{sd}}{dt} &= R_s i_{sd} + \omega_L i_{sq} + \frac{1}{L_s} v_{sd} \\
\frac{di_{sq}}{dt} &= R_s i_{sq} - \omega_L i_{sd} - \omega_L \psi_{PM} + \frac{1}{L_s} v_{sq}
\end{align*}
\]

where \( v_{sdq} \) and \( i_{sdq} \) are the stator voltages and currents in the dq synchronous reference frame, respectively, \( R_s \) and \( L_s \) are the stator resistance and inductance, respectively, \( \psi_{PM} \) is the permanent magnet flux linkage and \( \omega_s \) is the synchronous electrical frequency.

![Figure 1](image-url)  
**Figure 1** Proposed converter topologies: (a) Normal operation (b) After fault in leg ‘C’ (I3 or I6) of the grid-side converter (c) After fault in the machine-side converter (R1, R2 or R3)
Therefore, the generator electromagnetic torque is given by

\[ T_e = \frac{3}{2} p \psi_{PM} i_{sq} \]  

(2)

where \( p \) is the pole pairs number.

Using the standard Euler approximation, the discrete version of (1) at the \((k+1)\)th sampling period is expressed as

\[
\begin{align*}
\frac{i_{sd}^{k+1}}{i_{sd}^{k}} &= 1 - \frac{T_R}{L_s} + T_s \omega_i i_{sq}^{k} + \frac{T_s}{L_s} v_{sd}^{k} \\
\frac{i_{sq}^{k+1}}{i_{sq}^{k}} &= 1 - \frac{T_R}{L_s} - T_s \omega_i i_{td}^{k} - T_s \omega_i \psi_{PM} + \frac{T_s}{L_s} v_{eq}^{k}
\end{align*}
\]

(3)

where \( i_{sd}^{k} \) and \( i_{sq}^{k} \) are the stator currents at the instant \( k \), \( T_s \) is the sampling interval and \( v_{sd}^{k} \) and \( v_{eq}^{k} \) are the stator voltages constructed from the optimal VV applied to the MSC at the instant \( k \).

In real-time implementation, the calculation time of the control algorithm forces one-step time delay that must be compensated [42]. Therefore, \( i_{sd}^{k+1} \) rather than \( i_{sd}^{k} \) and \( i_{sq}^{k+1} \) rather than \( i_{sq}^{k} \), are used in the cost function. They can be predicted at the \((k+2)\)th control period in a way similar to (3):

\[
\begin{align*}
\frac{i_{sd}^{k+2}}{i_{sd}^{k}} &= 1 - \frac{T_R}{L_s} + T_s \omega_i i_{sq}^{k+1} + \frac{T_s}{L_s} v_{sd}^{k+1} \\
\frac{i_{sq}^{k+2}}{i_{sq}^{k}} &= 1 - \frac{T_R}{L_s} - T_s \omega_i i_{td}^{k+1} - T_s \omega_i \psi_{PM} + \frac{T_s}{L_s} v_{eq}^{k+1}
\end{align*}
\]

(4)

where \( v_{sd}^{k+1} \) are constructed from the eight VVs that the MSC can synthesise.

In a PMSG drive, the torque reference \( T_e^* \) can be obtained from the speed controller. Accounting for the direct relation between the torque and current references \( (i_{sq}^* = 2T_e^*/3p\psi_{PM}) \) and imposing \( i_{sd}^* = 0 \) for a maximum torque per ampere ratio, the cost function is defined as

\[
g_{1/S_\ldots} = \left( i_{sd}^* - i_{sd}^{k+1} \right)^2 + \left( i_{sq}^* - i_{sq}^{k+1} \right)^2 + i_{im}
\]

(5)

where

\[
i_{im} = \begin{cases} \infty, \text{ if } \frac{i_{sd}^{k+1}}{i_{sd}} > \frac{|i_{sd}|}{|i_{sd}^{k+1}|}, \\
|\frac{i_{sd}^{k+1}}{i_{sd}}| > |i_{sq}^{k+1}|, \\
0, \text{ otherwise.}
\end{cases}
\]

The symbol \( * \) denotes the reference value, the current \( i_{im} \) represents the over current protection term and \( i_{max} \) refers to the current limit value.

If the generator current exceeds the limit value, the corresponding VV is ignored. Thus, the optimal VV for the MSC can be determined by minimising (5):

\[
g_{1/S_i} = \min_{l \in \{0, \ldots, 7\}} \left( g_{1/S_0}, \ldots, g_{1/S_7} \right) \]

(6)

where \( g_{1/S_i} \) is the minimum current error corresponding to the optimal VV of the MSC.

### 3.2 Finite control set-model predictive control of the grid-side converter

In the GSC, grid active and reactive powers can be indirectly controlled by evaluating the grid currents in the cost function. Considering that the \( dq \)-axes rotate at the grid voltage frequency and that the grid voltage space vector is always aligned with the \( q \)-axis, the grid current dynamic model can be represented as follows:

\[
\begin{align*}
\frac{di_{gd}^{kl}}{dt} &= -\frac{R_f}{L_f} i_{gd}^{kl} + \omega_i i_{gd}^{kl} + \frac{1}{L_f} v_{gd} \\
\frac{di_{gq}^{kl}}{dt} &= -\frac{R_f}{L_f} i_{gq}^{kl} - \omega_i i_{gq}^{kl} + \frac{1}{L_f} v_{gq}
\end{align*}
\]

(7)

where \( v_{gd} \) and \( i_{gd} \) are the grid voltages and currents in the \( dq \) synchronous reference frame, respectively, \( v_{cdq} \) are the GSC voltages, \( R_f \) and \( L_f \) are the filter resistance and inductance, respectively, and \( \omega_i \) is the grid electrical frequency.

The active power \( p_g \) is indirectly controlled through the current \( i_{gp} \) while the reactive power \( q_g \) is indirectly controlled through the current \( i_{gd} \). They are given by

\[
p_g = \frac{3}{2} v_{gq}^* i_{gq}, \quad q_g = \frac{3}{2} v_{gd} i_{gd}
\]

(8)

The predicted current at the \((k+1)\)th instant is given by

\[
\begin{align*}
\frac{i_{gd}^{k+1}}{i_{gd}^k} &= 1 - \frac{T_R}{L_f} + T_s \omega_i i_{gs}^{k+1} + \frac{T_s}{L_f} v_{gd}^k \\
\frac{i_{gq}^{k+1}}{i_{gq}^k} &= 1 - \frac{T_R}{L_f} - T_s \omega_i i_{qs}^{k+1} - \frac{T_s}{L_f} v_{gq}^k
\end{align*}
\]

(9)

where \( v_{gd}^k \) and \( i_{gd}^k \) are the grid voltages and currents at the instant \( k \), respectively, and \( v_{cdq}^k \) are constructed from the optimal VV applied to the GSC at the instant \( k \). The currents at the \((k+2)\)th instant can be expressed as

\[
\begin{align*}
\frac{i_{gd}^{k+2}}{i_{gd}^{k+1}} &= 1 - \frac{T_R}{L_f} + T_s \omega_i i_{gs}^{k+2} + \frac{T_s}{L_f} v_{gd}^{k+1} \\
\frac{i_{gq}^{k+2}}{i_{gq}^{k+1}} &= 1 - \frac{T_R}{L_f} - T_s \omega_i i_{qs}^{k+2} - \frac{T_s}{L_f} v_{gq}^{k+1}
\end{align*}
\]

(10)

where the \( v_{cdq}^{k+1} \) are computed from the eight candidate VVs of the GSC. For a small sampling period with respect to grid
fundamental frequency, it can be assumed that \( \varepsilon_{gq}^{k+1} = \varepsilon_{gq}^k \). Therefore, the cost function is defined as

\[
g_2/S_\text{Sl} = \left( i_{gq}^* - i_{gq}^{k+2} \right)^2 + \left( i_{gq}^* - i_{gq}^{k+2} \right)^2 + i_{gm} \quad \text{(11)}
\]

where

\[
 i_{gm} = \begin{cases} 
 \infty, & \text{if } \left| i_{gq}^{k+2} \right| > \left| i_{gm} \right| \\
 0, & \text{otherwise.}
\end{cases}
\]

Current \( i_{gm} \) stands for the PMSG over current protection and \( i_{gm} \) refers to the current limit value. It is important to emphasise that \( i_{gq}^* \) is set to zero to impose a unity grid power factor (\( q_g = 0 \)), while \( i_{gq}^* \) is generated by the DC-link voltage controller. Finally, the optimal VV for the GSC is selected by minimising (11):

\[
g_2/S_\text{Sl} = \min_{l} g_2(S_\text{Sl}^{l}): \quad l \in \{0, ..., 7\} \quad \text{(12)}
\]

where \( g_2/S_\text{Sl} \) is the minimum current error corresponding to the optimal VV of the GSC.

### 3.3 Finite control set-model predictive control of the five-leg power converter

Accounting for the physical limitations of the FLC topology, both optimum VVs to be applied to the MSC and GSC must have identical states of the shared leg to achieve independent control. To fulfil this condition, a control priority should be assigned to one of the converters every sampling interval. This can be accomplished by comparing both of the minimum current errors \( g_1/S_\text{Sl} \) and \( g_2/S_\text{Sl} \) resulting from cost function minimisations (6) and (12), respectively. At this stage, the converter with priority should have a minimum error higher than the other. Then, the states of the shared and faulty legs must also be compared, with the aim to redistribute the optimum VVs. Accordingly, the converter with priority is controlled with its optimum VV, while the other is subjected to its optimum VV or a zero VV depending on the states of the shared and faulty legs. For instance, considering that leg ‘C’ is affected (see Figure 1b), if \( g_1/S_\text{Sl} \) is higher than \( g_2/S_\text{Sl} \), meaning that the minimum current error from the MSC increases, while the one from the GSC is kept small, priority is assigned to the control of the MSC. In this case, if the switching signal of the shared leg is different from that determined for the affected leg (\( S_a \neq S_C \)), the MSC is controlled through its optimum VV, whereas the GSC is subjected to a zero VV by forcing its switching signals to be equal to \( S_a \) (either \{000\} or \{111\}). Conversely, if \( g_1/S_\text{Sl} \) is less than \( g_2/S_\text{Sl} \), the control priority should be given to the GSC. Thus, if \( S_a \neq S_C \), the optimum VV of the GSC and a zero VV of the MSC are selected. It is important to emphasise that if \( S_a = S_C \), each power converter is controlled through its optimum VV as in the healthy mode independently of the \( g_1/S_\text{Sl} \) and \( g_2/S_\text{Sl} \) values. Consequently, a reduced current harmonic distortion is achieved by assigning priority to control each of the power converters. The previous consideration is summarised in Table 1 for the different scenarios of postfault control strategies.

### 3.4 Five-leg power converter voltage and current capabilities

In FLC, the linear modulation range is defined as

\[
V_s + V_c \leq \frac{V_{dc}}{\sqrt{3}}
\]

where \( V_{dc} \) is the DC-link voltage. \( V_c \) and \( V_s \) are the GSC and MSC phase-to-neutral voltage amplitude, respectively. Considering that the \( V_c \) value is fixed by the constant grid voltage and that the \( V_s \) value is proportional to the PMSG speed; only the \( V_{dc} \) value can be increased and/or the PMSG speed can be reduced with the aim to keep the drive operation within the region defined in (13). Assuming that \( V_s = V_{dc} \), the voltage capability of the converter is decreased by 29%, which requires the \( V_{dc} \) to be doubled as well as drive component oversizing. On the other hand, the required \( V_{dc} \) can be decreased by limiting the generator speed. Thus, the maximum admissible speed is limited by \( V_{s,max} \) given by

\[
V_{s,max} = \frac{1}{\sqrt{3}}V_{dc,max} - V_c
\]

where \( V_{dc,max} \) stands for the maximum value of \( V_{dc} \).

The current value in the shared leg (\( I_{sh} \)) is the sum of the grid phase current (\( I_{Grid} \)) and the machine phase current.

| Fault | Priority condition | State | MSC | GSC |
|-------|--------------------|-------|-----|-----|
| Phase A | \( g_1/S_\text{Sl} > g_2/S_\text{Sl} \) | \( S_a = S_A \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_A \) | \( S_{abc} \) | \( S_{A} \) |
|        | \( g_1/S_\text{Sl} < g_2/S_\text{Sl} \) | \( S_a = S_A \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_A \) | \( S_{A} \) | \( S_{ABC} \) |
| Phase B | \( g_1/S_\text{Sl} > g_2/S_\text{Sl} \) | \( S_a = S_B \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_B \) | \( S_{abc} \) | \( S_{A} \) |
|        | \( g_1/S_\text{Sl} < g_2/S_\text{Sl} \) | \( S_a = S_B \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_B \) | \( S_{A} \) | \( S_{ABC} \) |
| Phase C | \( g_1/S_\text{Sl} > g_2/S_\text{Sl} \) | \( S_a = S_C \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_C \) | \( S_{abc} \) | \( S_{A} \) |
|        | \( g_1/S_\text{Sl} < g_2/S_\text{Sl} \) | \( S_a = S_C \) | \( S_{abc} \) | \( S_{ABC} \) |
|        |                    | \( S_a \neq S_C \) | \( S_{A} \) | \( S_{ABC} \) |

Abbreviations: GSC, grid-side converter; MSC, machine-side converter.
\( I_{ph} = I_{\text{PMG}} + I_{\text{Grid}} \) \hspace{1cm} (15)

Considering the direct relation between the torque and current, and assuming that the grid current is proportional to the machine mechanical power, the current-per-unit in the shared leg \( I_{sh}^{pm} \) can be expressed as follows:

\[ I_{sh}^{pm} = T_L^{pm}(1 + a_L^{pm}) \] \hspace{1cm} (16)

where \( a_L^{pm} \) and \( T_L^{pm} \) are the speed and torque per unit, respectively.

To avoid shared leg oversizing by considering system derating, the shared leg current should be limited. Considering the speed limitation restricted by (14), the torque also should be limited according to (16).

It is important to emphasize that to achieve continuous operation under the rated power, the current in the common leg must be twice the value of the current of the standard converter. In comparison with the FLC with the common leg connected to the transformer neutral point and machine phases [34], where the shared leg must assume a current value four times as high, the proposed FLC has improved current capability.

4 | FINITE CONTROL SET-MODEL PREDICTIVE CONTROL OF THE THREE-SWITCH RECTIFIER

When an O-C fault occurs in the MSC, the fault can be isolated by forcing the command signals to zero for the three bottom or upper insulated-gate bipolar transistors (IGBTs), depending on whether a bottom or upper switch is damaged, respectively, changing the converter topology from a standard rectifier to a TSR. Consequently, the sinusoidal currents cannot be formed in some regions of the complex plane (see Figure 2) due to the limited number of candidate VVs [39]. Let us use TSR with bottom power switches (Figure 1c) as an example and assume that voltage and current are in phase opposition. When one of the IGBTs R4, R5 or R6 is turned on, the current flows through it, while the diode of R1, R2 or R3 from the same leg is reverse-biased. On the other hand, when IGBT R4, R5 or R6 is turned off, the diode R1, R2 or R3 from the same leg is forward-biased, and the current must flow through it. Therefore, two different phase current conditions must be considered depending on phase current polarity (see Table 2). First, when two of the three-phase currents are negative, the TSR has two degrees of freedom associated with the states of the IGBTs corresponding to the two negative phase currents, resulting in four possible switching states. As a result, four of the eight VVs are available. Similar cases can be found in sectors II, IV and VI, where there are four feasible VVs.

\[ \text{feasible voltage vectors} \]

Second, if only one phase current is negative, which is the case in sectors I, III and V, only one degree of freedom is associated with the state of the switch in the leg corresponding to the negative phase current, and therefore, only two VVs are feasible.

As opposed to vector and direct control techniques that require redistribution of the suitable VVs according to Table 2, in MPFTCC there is no need for additional changes because all eight VVs that the converter can synthesise are used for prediction and evaluation in the cost function (5). Accordingly, eight errors between the currents and their references are produced in every sampling interval. For instance, considering the TSR in Figure 1c, during sector I of Table 2, both current errors that correspond to the participating VVs \( V_5 \) and \( V_7 \) are less than the six errors of the remaining candidate VVs. Then, in cost function minimisation (6), only the VV from both candidates that produces the minimum current error will be applied to the TSR during the next sampling period. The previous consideration is also valid for the other remaining sectors, therefore applying the same analysis.

When \( i_{ad}^* = 0 \), the displacement between the current and the stator flux space vectors is load-dependent, being reduced when the load torque increases. Therefore, such a control technique applied to a TSR leads to high current distortion and torque oscillation as load torque increases. Therefore, to achieve minimum current distortion, the angle between the current and stator flux space vectors should equal 90° [18]. This can be accomplished by imposing a non-zero current reference, \( i_{ad}^* \), defined as

\[ i_{ad}^* = -\frac{1}{2} \left( \frac{\psi_{PM}}{L_s} - \sqrt{\left( \frac{\psi_{PM}}{L_s} \right)^2 - 4\pi^2} \right) \] \hspace{1cm} (17)
\[ i_{s} = i_{sd} + j i_{sq} \]  

(18)

Therefore, shifting the current space vector reference \( i_{s} \) is given by

As a consequence of a non-zero \( i_{sd} \), the generator current will increase. To avoid exceeding the PMSG rated current, the \( i_{sq} \) value should be limited by

\[ |i_{sq}| \leq \frac{L_{s}}{\psi_{PM}} \left( \frac{I_{PM}}{L_{s}} \right)^{2} - I_{sq}^{4} \]  

(19)

where \( I_{sq} = \frac{2T_{n}}{3\psi_{PM}} \).

\( T_{n} \) stands for the torque rated value. It should be noted that the procedure for obtaining (17) and (19) is explained in [18].

5 | EXPERIMENTAL RESULTS

The experimental test rig comprises a 2.2 kW PMSG (Table 3) coupled to a load machine, two Powerex POW-R-PAK VSIs in a BTB topology, a dSPACE DS1103 controller, a TRIAC and a filter of 20 mH. The block diagram of the experimental test bench is shown in Figure 3. Due to the limitation of the experimental setup, all experimental tests were performed for a grid phase-to-phase RMS voltage of 50 V and a DC-link voltage of 290 V, allowing the machine to reach the maximum admissible reference speed of 1100 rpm for normal drive operation.

The proposed and standard MPFTCC are implemented in the controller using Matlab/Simulink software. Considering that the execution time must be lower than \( T_{r} \) and that control variable ripples highly depend on \( T_{n} \), the \( T_{r} \) of the proposed and standard algorithms are set to 50 and 100 μs, respectively. Table 4 shows that the considered algorithm takes only 41.5 μs to complete the code thanks to the reduced number of VVs, proving to be quite a good choice for the fault-tolerant PMSG drives. The standard algorithm is computationally demanding (93.1 μs) because selecting the optimum VV requires prediction of 32 VVs that the FLC can synthesise.

To better evaluate postfault control performance, total harmonic distortion (THD) and total waveform oscillation (TWO) are employed to quantify the current distortion and ripple of a given quantity, respectively. They are given by

\[ THD_{eq} = \sqrt{\frac{THD_{A}^{2} + THD_{B}^{2} + THD_{C}^{2}}{3}} \times 100\% \]  

(20)

\[ TWO = \sqrt{\frac{X_{dRMS}^{2} - X_{DC}^{2}}{|X_{DC}|}} \times 100\% \]  

(21)

where \( THD_{eq} \) is the equivalent THD considering the three phases. \( X_{dRMS} \) and \( X_{DC} \) are the RMS and average values, respectively.

Figure 4 and Table 5 present the experimental results of the reconfiguration process for the MPFTCC strategy under a GSC reconfiguration. A reference mechanical speed of 720 rpm and 50% of load torque are considered. At the instant \( t = 0.301 \) s, an O-C fault occurs in IGBT I3. As a result, the current in the affected phase only assumes negative values, generating more distorted current waveforms and pulsating active and reactive power waveforms. Despite this, the fault does not influence MSC performance, but it strongly affects the performance of the GSC, forcing system shutdown if remedial strategies are not quickly triggered. After an imposed time delay equal to one grid current period, remedial procedures are applied by forcing the IGBT gate signals of leg ‘C’ (I3 and I6) to zero and by turning on the TRIAC TRc, connecting the affected phase to the shared leg, as illustrated in Figure 1b. Simultaneously, the optimal switching vectors to be applied to the MSC and GSC are reformulated with the aim to control both converters with priorities according to Table 1. Because the DC-link voltage is enough to produce the desired voltages in FLC topology and satisfy (13), speed is maintained equal to the original value. On the other side, the original torque value is

**Table 3** Parameters of the experimental permanent magnet synchronous generator

| Power, 2.2 kW | Speed, 1750 rpm | Frequency, 145.8 Hz |
|--------------|----------------|------------------|
| Voltage, 316 V | Current, 5.3 A | Torque, 12 Nm |

**Figure 3** General view of the experimental setup

**Table 4** Execution time of the model predictive fault-tolerant current control algorithms

| Converter topology | Standard MPFTCC | Proposed MPFTCC |
|---------------------|-----------------|-----------------|
|                     | Number of VVs  | Execution time (μs) | Number of VVs | Execution time (μs) |
| FLC                 | 32              | 93.1            | 16             | 41.5             |

Note: 93.1 μs = 6.9 μs + 81.4 μs + 4.8 μs; 41.5 μs = 6.9 μs + 28.9 μs + 5.7 μs. \(^{1}\) data acquisition and PI controllers. \(^{2}\) prediction and cost function. \(^{3}\) other processes.

Abbreviations: FLC, five-leg power converter; MPFTCC, model predictive fault-tolerant current control; VVs, voltage vectors.
able to maintain operations in the range of (16) without overcurrent in the shared leg. As a consequence of the hardware and software reconfigurations, the grid currents maintain a sinusoidal waveform very similar to that of normal operation with approximately the same amplitude. The slight increase in grid current THD and the active and reactive powers of the TWO values are due to the control priority assigned to each power converter. Nevertheless, the three phase currents and DC-link voltage control remain possible under postfault operation, allowing a unity power factor. The PMSG speed follows its reference value after a transient due to the reconfiguration process. Thus, the machine develops a smooth torque and generates a three-phase current system very similar to the healthy case.

The fault-tolerant MSC and its corresponding postfault control modifications are considered in Figure 5 and Table 6. A speed reference of 600 rpm and torque value of 75% are imposed. First, an IGBT O-C fault happens in IGBT R1 at \( t = 0.332 \) s. Because the MSC operates as a rectifier, there is an alternative path through its anti-parallel diode for current flow in the positive direction after a short period during which the current is zero. Despite an O-C fault in the MSC being less severe than an O-C fault in the GSC, current

### Figure 4
Experimental results of the reconfiguration process under an O-C fault of the grid-side converter in insulated-gate bipolar transistor I3

### Table 5
Performance evaluation of the grid-side converter

|                         | Normal operating control | Fault-tolerant control |
|-------------------------|--------------------------|------------------------|
| Grid RMS current        | \( i_a \) 2.45 A          | \( i_a \) 2.49 A       |
|                         | \( i_b \) 2.46 A          | \( i_b \) 2.47 A       |
|                         | \( i_c \) 2.46 A          | \( i_c \) 2.52 A       |
| Current THD\(_{eq}\)   | 4.54 %                   | 5.81 %                 |
| Active power TWO        | 5.89 %                   | 7.22 %                 |
| Reactive power TWO      | 105 %                    | 124 %                  |
| Power factor            | 0.995                    | 0.986                  |

Abbreviations: RMS, root mean square; THD, total harmonic distortion; TWO, total waveform oscillation.

### Figure 5
Experimental results of the reconfiguration process under an O-C fault in insulated-gate bipolar transistor R1 of the machine-side converter
distortion allows a pulsating torque waveform and a rising speed oscillation that impose large mechanical stresses on the generator shaft and all moving parts, leading to system shutdown if remedial postfault control strategies are not applied to the MSC. Then, at $t = 0.422$ s, the fault is isolated by turning off the gate signals of R1, R2 and R3, resulting in converter operation as a TSR (see Figure 1c). This leads to a significant increase in current THD and torque TWO values compared with their original values in the healthy mode. Finally, at $t = 0.5$ s, software compensation is considered by imposing a non-zero direct current reference (17). Consequently, current distortion is minimised as illustrated in the zoomed current. It can be confirmed that a significant reduction in current THD is achieved. As a result, marked reductions in torque oscillation and its TWO value occur. The slight increase in RMS currents is due to the new current reference value. On the other hand, the speed continues to follow its reference after transients due to fault occurrence and isolation. Therefore, considering that extra devices are avoided by employing the TSR, a satisfactory performance is achieved by the proposed MPFTCC, allowing PMSG drive operation under high load torque values as well as under the rated operating conditions.

6 | CONCLUSION

A computationally efficient predictive scheme is proposed for a BTB converter of PMSG drives with O-C fault-tolerant capabilities. Both the MSC and the GSC are separately controlled and their voltage hexagons independently predicted, and thus, calculation time is significantly reduced. For the GSC reconfiguration, a shared-leg-based FLC is investigated that connects the first MSC phase to the three GSC phases by employing three additional TRIAcs. For an independent control, both the MSC and GSC cost functions are compared to assign control to each power converter and redistribute the switching vectors. Thus, the original VVs are applied to the power converter with priority, and the other power converter is subjected to original or zero VVs. For MSC fault tolerance, a simple TSR is adopted without requiring extra hardware. To minimise torque oscillation, a non-zero direct current reference is imposed, whereas no control modification is required to reformulate the switching vectors. Experimental results show that based on the proposed fault-tolerant algorithms, low execution time is achieved, and continuous drive operation is ensured under either the MSC or the GSC O-C, which confirms that the converter and control architectures considered have the required features to be accepted by wind turbine manufactures.

ACKNOWLEDGEMENTS

This work was supported by the European Regional Development Fund (ERDF) through the Operational Programme for Competitiveness and Internationalisation (COMPETE 2020), under Project POCI-01-0145-FEDER-029494, by National Funds through the FCT - Portuguese Foundation for Science and Technology, under Projects PTDC/EEI-EEL/29494/2017, UIDB/04131/2020, and UIDP/04131/2020.

ORCID

Imed Jlassi https://orcid.org/0000-0003-0294-1624
Antonio J. Marques Cardoso https://orcid.org/0000-0001-8737-6999

REFERENCES

1. Qiao, W., Lu, D.: A survey on wind turbine condition monitoring and fault diagnosis-part I: components and subsystems. IEEE Trans. Ind. Electron. 62(10), 6536–6545 (2015)
2. Spinato, F., et al.: Reliability of wind turbine subassemblies. IET Renew. Power Gener. 3(4), 387–401 (2009)
3. Choi, U.M., Blaabjerg, F., Lee, K.B.: Study and handling methods of power IGBT module failures in power electronic converter systems. IEEE Trans. Power Electron. 30(5), 2517–2533 (2015)
4. Estima, J.O., Gyftakis, K.N.: Voltage-source inverter-fed drives. In: Cardoso, A.J.M. (ed.) Diagnosis and fault tolerance of electric machines, power Electronics and drives. The Institution of Engineering and Technology IET, pp. 7–75 London 978-1-78561-531-3 (2018)
5. Zhao, H., Cheng, L.: Open-circuit faults diagnosis in back-to-back converters of DF wind turbine. IET Renew. Power Gener. 11(4), 417–424 (2017)
6. Freire, N.M.A., Estima, J.O., Cardoso, A.J.M.: A voltage-based approach without extra hardware for open-circuit fault diagnosis in closed-loop PWM AC regenerative drives. IEEE Trans. Ind. Electron. 61(9), 4960–4970 (2014)
7. Campos-Delgado, D.U., et al.: Diagnosis of open-switch faults in variable speed drives by stator current analysis and pattern recognition. IET Electr. Power Appl. 7(6), 509–522 (2013)
8. Freire, N.M.A., Estima, J.O., Cardoso, A.J.M.: Open-circuit fault diagnosis in PMSG drives for wind turbine applications. IEEE Trans. Ind. Electron. 60(9), 3957–3967 (2013)
9. Lee, J., Lee, K., Blaabjerg, F.: Open-switch fault detection method of a back-to-back converter using NPC topology for wind turbine systems. IEEE Trans. Ind. Appl. 51(1), 325–335

| TABLE 6 Performance evaluation of the machine-side converter |
|---------------------------------------------------------------|
| Normal operating control | Fault isolation | Fault-tolerant control |
|---------------------------|-----------------|------------------------|
| PMSG RMS current          |                 |                        |
| $i_a$                     | 3.31 A          | 3.91 A                 | 4.03 A |
| $i_b$                     | 3.31 A          | 3.89 A                 | 4.07 A |
| $i_c$                     | 3.32 A          | 3.95 A                 | 4.08 A |
| Currents THD$_{eq}$       | 3.27 %          | 27.11 %                | 6.58 % |
| Torque TWO                | 2.41 %          | 16.82 %                | 6.27 % |

Abbreviations: PMSG, permanent magnet synchronous generator; RMS, root mean square; THD, total harmonic distortion; TWO, total waveform oscillation.
10. Jlassi, I., et al.: Multiple open-circuit faults diagnosis in back-to-back converters of PMSG drives for wind turbine systems. IEEE Trans. Power Electron. 30(5), 2689–2702 (2015)
11. Rodriguez-Blanco, M.A., et al.: Fault detection for IGBT using adaptive thresholds during the turn-on transient. IEEE Trans. Ind. Electron. 62(3), 1975–1983 (2015)
12. Jlassi, I., et al.: A robust observer-based method for IGBTs and current sensors fault diagnosis in voltage-source inverters of PMSM drives. IEEE Trans. Ind. Appl. 53(3), 2894–2908 (2017)
13. Jlassi, I., Cardoso, A.J.M.: A single method for multiple IGBTs, current- and speed-sensor faults diagnosis in regenerative PMSM drives. IEEE J. Emerg. Sel. Top. Power Electron. 8(3), 2583–2599 (2020)
14. Karimi, S., et al.: FPGA-based real time power converter failure diagnosis for wind energy conversion systems. IEEE Trans. Ind. Electron. 60(12), 4299–4308 (2008)
15. Zhu, Z.Q., et al.: Direct torque control of three-phase PM brushless AC motor with one phase open-circuit fault. IEEE International Conference on Industrial Electronics Machines and Drives Conference, 1180–1187. Miami, FL, USA (2009)
16. Sae-Kok, W., Grant, D.M., Williams, B.W.: System reconfiguration under open-switch faults in a doubly fed induction machine. IET Renew. Power Gener. 4(5), 458–470 (2010)
17. Freire, N.M.A., Cardoso, A.J.M.: A fault-tolerant direct controlled PMSG drive for wind energy conversion systems. IEEE Trans. Ind. Electron. 61(2), 821–834 (2014)
18. Freire, N.M.A., Cardoso, A.J.M.: A fault-tolerant PMSG drive for wind turbine applications with minimal increase of the hardware requirements. IEEE Trans. Ind. Appl. 50(3), 2039–2049 (2014)
19. Zhou, D., Zhao, J., Liu, Y.: Independent control scheme for non redundant two-leg fault-tolerant back-to-back converter-fed induction motor drives. IEEE Trans. Ind. Electron. 63(11), 6790–6800 (2016)
20. Jlassi, I., Marques Cardoso, A.J.: Fault-tolerant back-to-back converter for direct-drive PMSG wind turbines using direct torque and power control techniques. IEEE Trans. Power Electron. 34(5), 11215–1122 (2019)
21. Jlassi, I., Bento, F., Cardoso, A.J.: Fault-tolerant PMSG direct-drive wind turbines, using vector control techniques with reduced DC-link ratings. In: IEEECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, 1214–1219 (2018)
22. Zhou, D., Zhao, J., Li, Y.: Model-predictive control scheme of five-leg ac–dc–ac converter-fed induction motor drive. IEEE Trans. Ind. Electron. 63(7), 4517–4526 (2016)
23. Jacobina, C.B., et al.: Fault-tolerant reversible ac motor drive system. IEEE Trans. Ind. Appl. 39(4), 1077–1084 (2003)
24. Jacobina, C.B., et al.: Reduced switch count dc-link ac–ac five-leg converter. IEEE Trans. Power. Electron. 21(5), 1301–1310 (2006)
25. Shalhaz, M., et al.: FPGA-based reconfigurable control for fault-tolerant back-to-back converter without redundancy. IEEE Trans. Ind. Electron. 60(8), 3360–3371 (2013)
26. Bousacrol, A., et al.: Control implementation of a five-leg ac–ac converter to supply a three-phase induction machine. IEEE Trans Power Electron. vol. 20(1), 107–115 (Jan. 2005)
27. Jones, M., et al.: Five-leg inverter PWM technique for reduced switch count two-motor constant power applications. IET Electric. Power Appl. 2(5), 275–287 (2008)
28. Dušic, D., et al.: A general PWM method for a (2n + 1) leg inverter supplying n three-phase machines. IEEE Trans. Ind. Electron. 56(10), 4107–4118 (2009)
29. Hamouda, M., Blanchette, H.F., Al-Haddad, K.: A hybrid modulation scheme for dual-output five-leg indirect matrix converter. IEEE Trans. Ind. Electron. 63(12), 7299–7309 (2016)
30. Wang, W., Zhang, J., Cheng, M.: A dual-level hysteresis current control for one five-leg VSI to control two PMSMs. IEEE Trans. Power Electron. 32(1), 804–814 (2017)
31. Lim, C.S., et al.: Model predictive control of a two-motor drive with five-leg inverter supply. IEEE Trans. Ind. Electron. 60(1), 54–65 (2013)
32. Lim, C.S., et al.: A comparative study of synchronous current control schemes based on FCS-MPC and PI-PWM for a two-motor three-phase drive. IEEE Trans. Ind. Electron. 61(8), 3867–3878 (2014)
33. Lim, C.S., et al.: A fault-tolerant two-motor drive with FCS-MP-based flux and torque control. IEEE Trans. Ind. Electron. 61(12), 6603–6614 (2014)
34. Freire, N.M.A., Cardoso, A.J.M.: Fault-tolerant PMSG drive with reduced dc-link ratings for wind turbine applications. IEEE J. Emerg. Sel. Top. Power Electron. 2(1), 26–34 (2014)
35. Pulvirenti, M., et al.: fault-tolerant AC Multidrive system. IEEE J. Emerg. Sel. Top. Power Electron. 2(2), 224–235 (Jun. 2014)
36. Lin, F., et al.: Recurrent fuzzy neural cerebellar model articulation network fault-tolerant control of six-phase permanent magnet synchronous motor position servo drive. IEEE Trans. Fuzzy Syst. 24(1), 153–167 (2016)
37. Lin, F., et al.: Fault-tolerant control of a six-phase motor drive system using a Takagi–Sugeno–Kang type fuzzy neural network with asymmetric membership function. IEEE Trans. Power Electron. 28(7), 3557–3572 (2013)
38. Lin, F., Hung, Y., Tsai, M.: Fault-tolerant control for six-phase PMSM drive system via intelligent complementary sliding-mode control using TSKFNN-AMF. IEEE Trans. Ind. Electron. 60(12), 5747–5762 (2013)
39. Krahnenhul, D., Zawyssig, C., Kolar, J.W.: Half-controlled boost rectifier for low-power high-speed permanent-magnet generators. IEEE Trans. Ind. Electron. 58(11), 5066–5075 (2011)
40. Oliveira, D.S., et al.: A three-phase high-frequency semicontrolled rectifier for PM WECS. IEEE Trans. Power Electron. 25(3), 677–685 (2010)
41. Hackl, C.M., Pecha, U., Schechner, K.: Modelling and control of permanent-magnet synchronous generators under open-switch converter faults. IEEE Trans. Power Electron. 34(3), 2966–2979 (2019)
42. Cortes, P., et al.: Delay compensation in model predictive current control of a three-phase inverter. IEEE Trans. Ind. Electron. 59(2), 1323–1325 (2012)

How to cite this article: Jlassi I, Marques Cardoso A J. Open-circuit fault-tolerant operation of permanent magnet synchronous generator drives for wind turbine systems using a computationally efficient model predictive current control. IET Electr. Power Appl. 2021;15:837–846. https://doi.org/10.1049/elp2.12062