Impact on the torque and on the copper losses under fault-tolerant Control of 5-phase PMSG

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Abstract

Here an analysis of the impact on the torque and on the copper losses under fault operation is done. The goal of each adopted torque control strategy is to generate current references to maximize the average torque and to minimize the copper losses. An itemized analysis is done.

Introduction

Five-phase Permanent magnet synchronous generator PMSG seems to be an interesting solution in the context of renewable energy source energy [1]-[2]. It offer many advantages. For exemple when it associated to AC-DC converter the converted power and the operating of the energy conversion chain are increased. In this paper an analysis of the impact on the torque and on the copper losses under fault-tolerant Control of 5-phase PMSG is done. The goal of each adopted torque control strategy is to generate current references to maximize the average torque and to minimize the copper losses. Torque control strategy of five-phase permanent magnet synchronous machine, under fault operation, have already been proposed in [3]-[10].

This work focuses on a detailed theoretical analysis of the impact on the torque and on the copper losses under fault operation but the current control performances of the five-phase PMSG (Fig. 1) achieved thanks to a robust and accurate AC current controller under one-phase is permanently open is presented. Figure 1 shows the control scheme of the 5-phase PMSG under the *e*-phase is permanently open. The choice of the faulty phase is the *e*-phase and it is given as example.

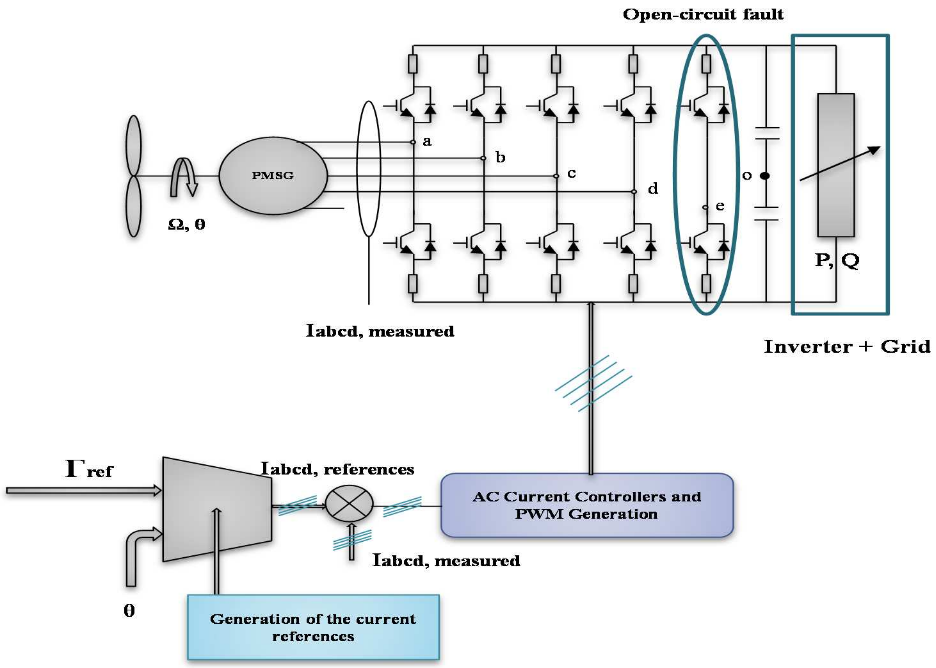


Fig. 1: Control scheme of the 5-phase PMSG under fault operation

Electrical model of the 5-phase PMSG under fault operation mode in the abcde frame

For the 5-phase PMSG, under fault operation, the used model is given by [4] for one open phase and two open phases.

One open phase

Under normal operation, in the abcde frame, the electrical equations of the generator can be written in the following matrix form:

$$[E] = [R][I] + [L]\frac{d}{dt}[I] + [V] \tag{1}$$

Where $[R] = \begin{bmatrix} r & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & 0 \\ 0 & 0 & r & 0 & 0 \\ 0 & 0 & 0 & r & 0 \\ 0 & 0 & 0 & 0 & r \end{bmatrix}$, $L = \begin{bmatrix} L_1 & L_2 & L_3 & L_3 & L_2 \\ L_2 & L_1 & L_2 & L_3 & L_3 \\ L_3 & L_2 & L_1 & L_2 & L_3 \\ L_3 & L_3 & L_2 & L_1 & L_2 \\ L_2 & L_3 & L_3 & L_2 & L_1 \end{bmatrix}$, $[V] = \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix}$, $[E] = \begin{bmatrix} E_a \\ E_b \\ E_c \\ E_d \\ E_e \end{bmatrix}$

and $[I] = [I_a \quad I_b \quad I_c \quad I_d \quad I_e]^t$

[R], [L] are respectively the resistance matrix and the inductance matrix. The inductance matrix is always real, circular and symmetrical whatever the winding [16]. [E], [V], [I] are respectively the EMF vector, the voltage vector and the current vector.

Let us assume that the e-phase is continually open, after a fault, $I_e = 0$. The new current vector becomes $[I] = [I_a \quad I_b \quad I_c \quad I_d]^t$

The voltage equation of the e-phase, in the abcde frame, is given by:

$$V_e = E_e - \left(L_2 \frac{dI_a}{dt} + L_3 \frac{dI_b}{dt} + L_3 \frac{dI_c}{dt} + L_2 \frac{dI_d}{dt}\right) \tag{2}$$

As the neutral point of the machine is not connected, $I_a + I_b + I_c + I_d = 0$, then:

$$V_a + V_b + V_c + V_d + V_e = 0 \tag{3}$$

The voltage across each healthy phase can be expressed as a function of the output voltages of the inverter as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \end{bmatrix} = \begin{bmatrix} V_{ao}-V_{No} \\ V_{bo}-V_{No} \\ V_{co}-V_{No} \\ V_{do}-V_{No} \end{bmatrix} \tag{4}$$

N is the neutral point of the machine.
Using (3) and (4) the voltage V_{No} are obtained:

$$V_{No} = \frac{1}{4}(V_{ao} + V_{bo} + V_{co} + V_{do} + V_e) \quad (5)$$

Using (4) and (5), the voltage equation across each healthy phase becomes:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \end{bmatrix} = \begin{bmatrix} V_{ao}\text{-}V_{No} \\ V_{bo}\text{-}V_{No} \\ V_{co}\text{-}V_{No} \\ V_{do}\text{-}V_{No} \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}\begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \\ V_{do} \end{bmatrix} - \frac{1}{4}V_e \quad (6)$$

Let us consider $\begin{bmatrix} V_a' \\ V_b' \\ V_c' \\ V_d' \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}\begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \\ V_{do} \end{bmatrix}$

By substituting (2) in (6), (6) becomes:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \end{bmatrix} = \begin{bmatrix} V_a' \\ V_b' \\ V_c' \\ V_d' \end{bmatrix} - \frac{1}{4}\left(E_e - \left(L_2\frac{dI_a}{dt} + L_3\frac{dI_b}{dt} + L_3\frac{dI_c}{dt} + L_2\frac{dI_d}{dt}\right)\right) \quad (7)$$

Where $\begin{bmatrix} V_a' \\ V_b' \\ V_c' \\ V_d' \end{bmatrix}$ is the new voltage vector

Based on (1) and (7) the new electrical equation, for the remaining healthy phases, under the e-phase open-circuit fault can be written as follows:

$$[E'] = [R'][I] + [L']\frac{d}{dt}[I] + [V'] \quad (8)$$

Where : $[R'] = \begin{bmatrix} r & 0 & 0 & 0 \\ 0 & r & 0 & 0 \\ 0 & 0 & r & 0 \\ 0 & 0 & 0 & r \end{bmatrix}$, $[L'] = \begin{bmatrix} L_1 + \frac{1}{4}L_2 & L_2 + \frac{1}{4}L_3 & L_3 + \frac{1}{4}L_3 & L_3 + \frac{1}{4}L_2 \\ L_2 + \frac{1}{4}L_2 & L_1 + \frac{1}{4}L_3 & L_2 + \frac{1}{4}L_3 & L_3 + \frac{1}{4}L_2 \\ L_3 + \frac{1}{4}L_2 & L_2 + \frac{1}{4}L_3 & L_1 + \frac{1}{4}L_3 & L_2 + \frac{1}{4}L_2 \\ L_3 + \frac{1}{4}L_2 & L_3 + \frac{1}{4}L_3 & L_2 + \frac{1}{4}L_3 & L_1 + \frac{1}{4}L_2 \end{bmatrix}$

[R'], [L'] are respectively the new resistance matrix and the new inductance matrix.
Hence the new fictitious equivalent EMF vector is given by:

$$[E'] = \begin{bmatrix} E_a' \\ E_b' \\ E_c' \\ E_d' \end{bmatrix} = \begin{bmatrix} E_a + \frac{1}{4}E_e \\ E_b + \frac{1}{4}E_e \\ E_c + \frac{1}{4}E_e \\ E_d + \frac{1}{4}E_e \end{bmatrix}$$

Now the expression of the total generator's electromagnetic torque can be deduced:

$$\Gamma = \frac{1}{\Omega}\left(E_a'I_a + E_b'I_b + E_c'I_c + E_d'I_d\right) \quad (9)$$

Where Ω is the mechanical angular speed.
Finally the same approach can be applied to any open phase. It can be noticed that following the open phase the inductance matrix [L'] changes

Two open phases

The faulty phases is selected arbitrary. Let us assuming that the d-phase ($I_d = 0$) and the e-phase ($I_e = 0$) are permanently open. The new current vector becomes $[I] = [I_a \quad I_b \quad I_c]^t$
The voltage equations of the d-phase and the e-phase, in the abcde frame, are given by:

$$V_d = E_d - \left(L_3\frac{dI_a}{dt} + L_3\frac{dI_b}{dt} + L_2\frac{dI_c}{dt}\right) \tag{10}$$

$$V_e = E_e - \left(L_2\frac{dI_a}{dt} + L_3\frac{dI_b}{dt} + L_3\frac{dI_c}{dt}\right) \tag{11}$$

As the neutral point of the machine is not connected, $I_a + I_b + I_c = 0$, then:

$$V_a + V_b + V_c + V_d + V_e = 0 \tag{12}$$

The voltage across each healthy phase can be expressed as a function of the output voltages of the inverter as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{ao}-V_{No} \\ V_{bo}-V_{No} \\ V_{co}-V_{No} \end{bmatrix} \tag{13}$$

Using (12) and (13) the voltage V_{No} are obtained:

$$V_{No} = \frac{1}{3}\left(V_{ao} + V_{bo} + V_{co} + V_e + V_d\right) \tag{14}$$

Using (13) and (14), the voltage equation across each healthy phase becomes:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{ao}-V_{No} \\ V_{bo}-V_{No} \\ V_{co}-V_{No} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix} - \frac{1}{3}V_d - \frac{1}{3}V_e \tag{15}$$

Let us consider $\begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix}$

By substituting (10) and (11) in (15), (15) becomes:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix} - \frac{1}{3}\left(E_d - \left(L_3\frac{dI_a}{dt} + L_3\frac{dI_b}{dt} + L_2\frac{dI_c}{dt}\right)\right) - \frac{1}{3}\left(E_e - \left(L_2\frac{dI_a}{dt} + L_3\frac{dI_b}{dt} + L_3\frac{dI_c}{dt}\right)\right) \tag{16}$$

Where $\begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix}$ is the new voltage vector

Based on (1) and (16) the new electrical equation, for the remaining healthy phases, under two-phase open-circuit fault can be written as follows:

$$\left[E'\right] = \left[R'\right][I] + \left[L'\right]\frac{d}{dt}[I] + \left[V'\right] \tag{17}$$

Where : $\left[R'\right] = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix}$, $\left[L'\right] = \begin{bmatrix} L_1 + \frac{1}{3}L_3 + \frac{1}{3}L_2 & L_2 + \frac{2}{3}L_3 & L_3 + \frac{1}{3}L_2 + \frac{1}{3}L_3 \\ L_2 + \frac{1}{3}L_3 + \frac{1}{3}L_2 & L_1 + \frac{2}{3}L_3 & L_2 + \frac{1}{3}L_2 + \frac{1}{3}L_3 \\ L_3 + \frac{1}{3}L_3 + \frac{1}{3}L_2 & L_2 + \frac{2}{3}L_3 & L_1 + \frac{1}{3}L_2 + \frac{1}{3}L_3 \end{bmatrix}$

$[R']$, $[L']$ are respectively the new resistance matrix and the new inductance matrix.
Hence the new fictitious equivalent EMF vector is given by:

$$\left[E'\right] = \begin{bmatrix} E_a' \\ E_b' \\ E_c' \end{bmatrix} = \begin{bmatrix} E_a + \frac{1}{3}E_d + \frac{1}{3}E_e \\ E_b + \frac{1}{3}E_d + \frac{1}{3}E_e \\ E_c + \frac{1}{3}E_d + \frac{1}{3}E_e \end{bmatrix}$$

Now the expression of the total generator's electromagnetic torque is now given by:

$$\Gamma = \frac{1}{\Omega}\left(E_a'I_a + E_b'I_b + E_c'I_c\right) \tag{18}$$

Finally, the same approach can be applied to any combination of two open phases. In the remainder the case of one-phase open-circuit fault is studied. The choice of the faulty phase is the e-phase and it is given as example. The proposed control strategy can be applied to any open phase.

Torque control strategy of the phase the 5-phase PMSG

Assuming the *e*-phase is open due to the failure of power devices, torque ripples appear.
In order to reduce the torque ripples and to minimize the copper losses, the chosen torque control strategy consists to impose optimal current references in the remaining four phases. The reactive power is equal to zero when the EMF and current vectors of the machine are collinear:

$$\frac{E_a^{'}}{I_{aref}} = \frac{E_b^{'}}{I_{bref}} = \cdots = \frac{E_d^{'}}{I_{dref}} \qquad (19)$$

Generation of the current references under fault operation mode in the abcde frame

In fault operation mode, the copper losses are minimal when the current and EMF vectors, corresponding to the healthy phases, are collinear. When one or i (i≤3) phases of the machine is open due to the failure of power devices, the current references of the healthy phases are expressed in the following form:

$$I_{zref} = \frac{E_z}{\sum_{z=a}^{e}(s_z E_z^2)} \Gamma_{dref}\Omega \qquad (20)$$

Where
z = a, b, c, d, e, $s_z = 1$ for the healthy phases and $s_z = 0$ for the open phases.
E_z : EMF
Γ_{dref} : the reference torque under fault operation
When the neutral of the machine is not connected of the midpoint to the DC bus or if the sum of the imposed currents must be zero, the expression of the current references of the healthy phases becomes:

$$I_{zref} = \frac{E_z'}{\sum_{z=a}^{e} E_z'^{2}} \Gamma_{dref}\Omega \qquad (21)$$

Where
$E_z' = s_z E_z - \frac{1}{n-i} \sum_{z=a}^{e} s_z E_z$ and i the number of open phases
The Fourier analysis of the EMF of the machine under consideration is summarized in Table 1. Table 1 summarizes the normalized magnitude of each harmonic of the considered machine.

Table 1 Fourier analysis of the EMF profile

EMF Harmonic	1	3	7	9
Magnitude/Fundamental %	100%	30%	0.2%	0.7%

The Fourier analysis of the EMF shows that the ninth harmonic and the seven harmonic are very low and can be neglected.

Robust current controller

The next figure shows a basic scheme where the chosen current controller has been used in DC/AC converters. It runs in sliding mode and offers an accurate current control. At high and low frequencies, it operates in different ways, i.e. at high frequency it operates for frequency switching control and at low frequency it operates for current control [11]-[12].

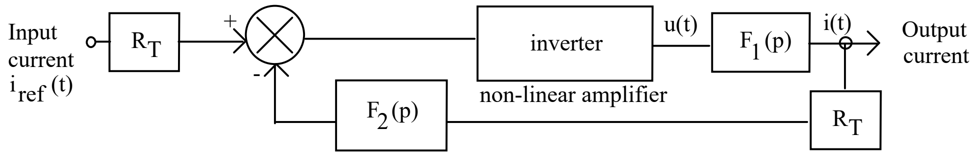
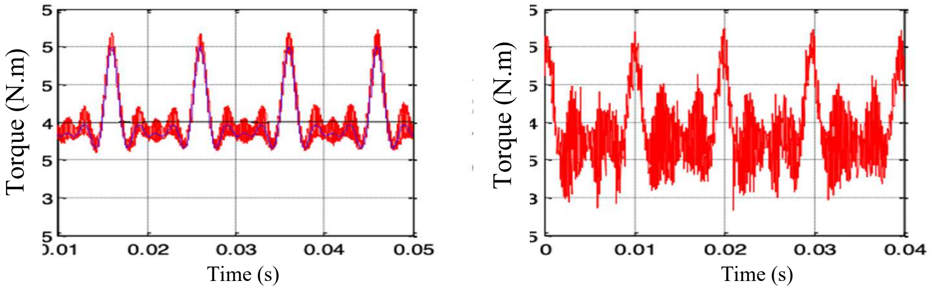


Figure 3: Scheme of the inverter current control loop

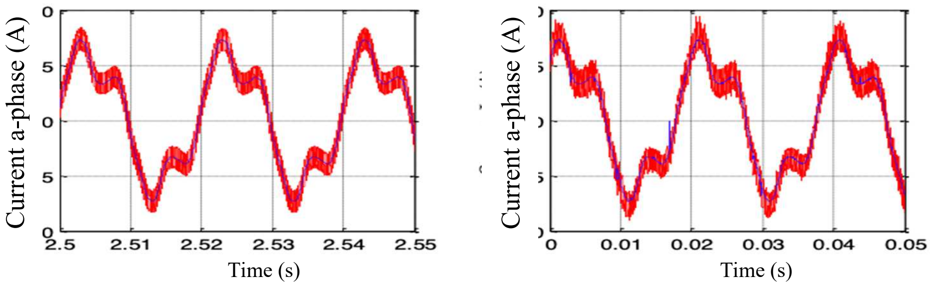
Simulations and Experimental results

Now, simulation and experiments are done to show the current control performances under open-circuit fault to validate the torque control strategy. Therefore the *e*-phase is permanently open. The choice of the faulty phase is the *e*-phase and it is given as example.



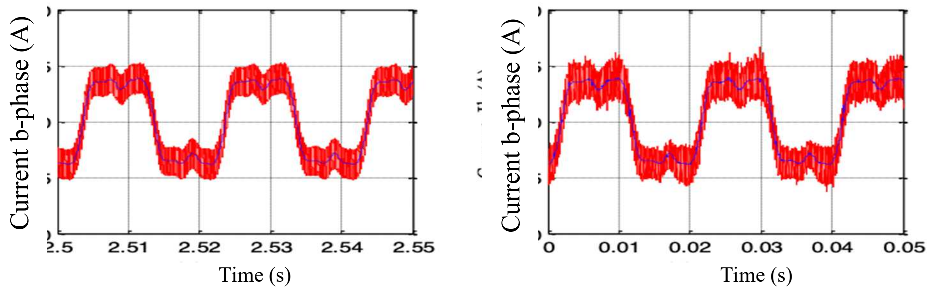
a) simulation result b) experimental result

Fig. 3: Generator electromagnetic torque, under open-circuit fault



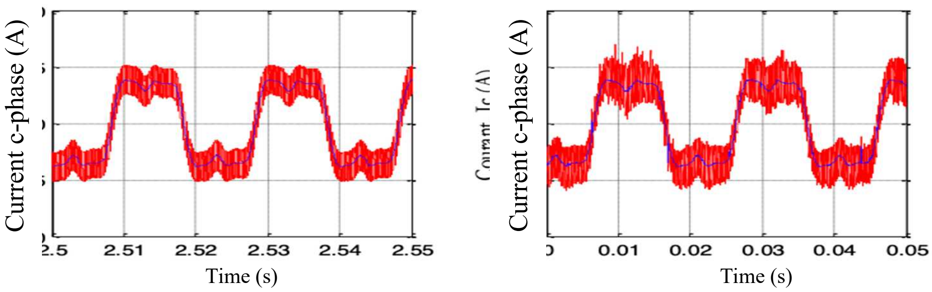
a) simulation result b) experimental result

Fig. 4: Currents in the a-phase, under open-circuit fault



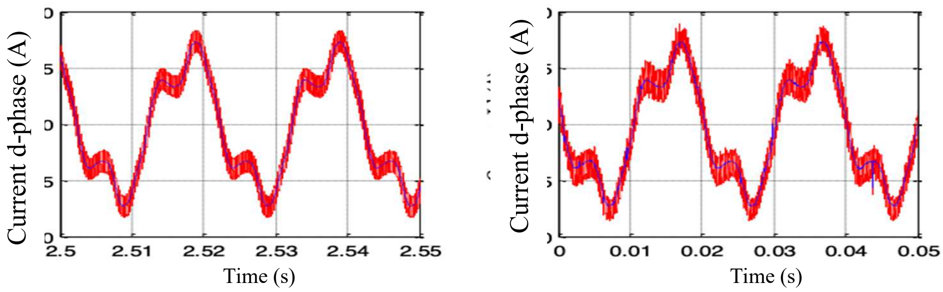
a) simulation result b) experimental result

Fig. 5: Currents in the b-phase, under open-circuit fault



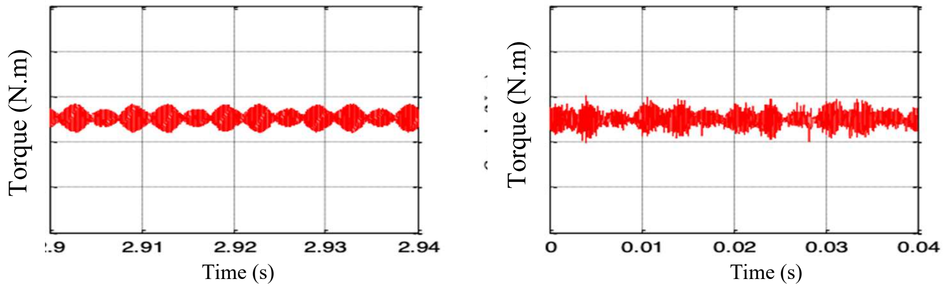
a) simulation result b) experimental result

Fig. 6: Currents in the c-phase, under open-circuit fault



a) simulation result b) experimental result

Fig. 7: Currents in the d-pha nder open-circuit fault



a) simulation result b) experimental result

Fig. 8: Generator electromagnetic torque, under open-circuit fault, new current references applied

Fig. 3 shows the generator electromagnetic torque under fault operation when the same currents under normal operation and their magnitudes are maintained. The generator torque is pulsating and the average value decreases. Under fault operation (the e-phase is open), the new current references are imposed in the four healthy phase. The generator torque is kept constant (Fig. 8) thanks to the good performance of the robust current controllers which accurately track its references (Fig. 4, Fig. 5, Fig. 6 and Fig. 8).

Impact on the torque and on the copper losses

In this part, a theoretical analysis of the impact on the torque and on the copper losses, under fault operation, is studied. This impact depend to the configurations of the adopted torque control strategy. Three cases are considered, one open phase (for exemple phase *e*), two open adjacent phases (phases *d and e*) and two open non-adjacent phases (phases *c and e*).

The expression of the generator electromagnetic torque, under fault operation, is given by :

$$\Gamma_d = \frac{1}{\Omega} \sum_{z=a}^{e} (s_z E_z I_z) \tag{4}$$

Where

z = a, b, c, d, e, $s_z = 1$ for the healthy phases and $s_z = 0$ for the open phases.

The expression of the copper losses is given by :

$$P_{jd} = r < \left(\sum_{z=a}^{e} (s_z I_z)^2\right) > \tag{5}$$

Where

z = a, b, c, d, e, $s_z = 1$ for the healthy phases and $s_z = 0$ for the open phases.

Using (2) and (5) or (3) and (5), the expression of the copper losses can be rewritten as a function of the torque reference in degraded mode [7]. Thus, at given copper losses, the torque reference in degraded mode can be calculated.

Table 2 shows, for each configurations studied, the impact on the copper losses when it is not limited and the torque reference in degraded mode is equal to 5 N.m. In normal operation mode, for this same value torque reference, the copper losses obtained in simulation are:

- neutral of the machine is not connected of the midpoint to the DC bus, $P_{jN} = 24{,}47\ W$
- neutral of the machine is connected of the midpoint to the DC bus and the homopolar EMF is exploited, $P_{jN} = 24{,}05\ W$

Table 2 Impact on the copper losses

Configurations	$\frac{P_{jd}}{P_{jN}}$ %
One open phase Neutral not connected to the midpoint of the DC bus	+36
Two open adjacent phases Neutral not connected to the midpoint of the DC bus	+1663 (**)
Two open non-adjacent phases Neutral not connected to the midpoint of the DC bus	+79
One open phase Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	+25
Two open adjacent phases Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	+70
Two open non-adjacent phases Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	+69

In the case of two open adjacent phases, at constant torque, the copper losses increase by +1663 (Table 2) which is every high and can have very serious consequences for the machine. This increase is due to the amplitude of the current references which is very high. The adopted control strategy is not good. By connecting the machine neutral to the midpoint of the DC bus and by imposing the sum of the current references is not egal to zero, the copper losses increase by + 70% (Table 2).

Table 3 Impact on the copper losses

Configurations	$\frac{\Gamma_{dref}}{\Gamma_{ref}}$ %
One open phase Neutral not connected to the midpoint of the DC bus	-14
Two open adjacent phases Neutral not connected to the midpoint of the DC bus	-76 (**)
Two open non-adjacent phases Neutral not connected to the midpoint of the DC bus	-25
One open phase Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	-10
Two open adjacent phases Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	-23
Two open non-adjacent phases Neutral connected to the midpoint of the DC bus Sum of the current references is not equal to zero	-23

Table 3 shows, for each considered configurations, the impact on the electromagnetic torque when the copper losses in degraded mode are kept equal to the copper losses in normal mode. In the case of one open phase, the torque reference decreases by -14% (Table 3) if the machine neutral is not connected. When it is connected to the midpoint of the DC bus and the sum of the imposed current references is not equal to zero, the torque reference decreases by -10% (Table 3). When two adjacent phases are opened with the machine neutral not connected, the torque reference decreases by -76% (Table 3). This is no good for the machine.

Conclusion

In this paper a theoretical analysis of the impact on the torque and on the copper losses, under fault operation, has been done. Firstly the current control performances under open-circuit fault to validate the torque control strategy is presented. Simulation and experimental results prove the effectiveness of the torque control strategy. Finally, the itemized analysis shows the impact on the copper losses and on the torque in fault operation.

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