Improving reliability in electric drive systems during IGBT short-circuit fault

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Abstract
To improve the reliability of electric drive systems during the insulated-gate bipolar transistor short-circuit fault, a control method is proposed for Y-connected 3-phase induction motors. This method allows the operation of 3-phase induction motor drives under the insulated-gate bipolar transistor short-circuit fault without the requirement of a specific inverter topology and control strategy. At first, a modified inverter topology that can rectify the problem produced by an insulated-gate bipolar transistor short-circuit fault is presented. Then, based on the introduced inverter topology, a developed model for Y-connected 3-phase induction motors is presented. According to this model, an indirect vector control system for the faulted drive system based on the calculation of forward and backward magneto-motive force of the motor is proposed. The performance of the control system is validated using experimental tests for a 1HP Y-connected 3-phase induction motor drive system. This research also compares the performance of the proposed indirect vector control technique with conventional indirect vector control techniques during the insulated-gate bipolar transistor short-circuit fault.

1 | INTRODUCTION

An electrical motor is one of the main sectors in many industries. Electrical motors produce the mechanical force by changing the electrical energy into mechanical energy. Generally, Y-connected 3-Phase Induction Motors (3-PIMs) are used in low/medium power industrial applications due to their rugged construction, low cost and maintenance, simple structure, and so on [1–3]. 3-PIMs are designed to work at a constant velocity. Recent technologies need various velocities in different applications. An adjustable speed drive is a device that adjusts the output velocity, or output electromagnetic torque. In 3-PIM drive systems, electrical and mechanical sensors such as current and speed sensors provide information about the real operating condition of the electrical motor. Then, a control system using this information generates suitable voltage or current signals. Finally, these voltages or currents are modified through a power electronics system and applied to the electrical motor [4].

With increasing demands for industrial systems with higher performances, 3-PIM drive systems have been developed. The development of 3-PIM drive systems needs more safety and reliability. To improve the safety and reliability of 3-PIM drive systems, reconfiguration methods should be added to guarantee the operation of drive systems. On the other hand, in some industrial applications such as aerospace, medical equipment, and electric vehicles, uninterrupted operation of 3-PIM drive systems is required. Consequently, to increase the dependability and safety of 3-PIM drive systems, Fault-Tolerant Control (FTC) systems have attracted important attention in many industries [5–10]. Generally, FTC systems contain two important tasks: (1) fault detection and isolation mechanism and (2) a control method for Post-Fault Operation (PFO).

The 3-leg Voltage Source Inverter (VSI) has widely been used in many industrial applications due to its low cost, simple structure, low size, and high performance [11]. Nevertheless, the robustness and reliability of the 3-leg VSI suffer commonly from the fault on power switches. As stated in [12], 31% of faults in the inverter are related to power switches, 21% of faults in the inverter are related to capacitors, 18% of faults in the inverter are related to capacitors, and 18% of faults in the inverter are related to capacitors. 8% of faults in the inverter are related to power switches. As stated in [12], 31% of faults in the inverter are related to power switches, 21% of faults in the inverter are related to capacitors, 18% of faults in the inverter are related to capacitors, and 8% of faults in the inverter are related to drivers.
related to control unit and protection systems, and other faults are related to resistors and inductors. Faults in power switches can be generally classified into two types: (1) short-circuit fault [13–15] and 2) open-circuit fault [16–18]. One common form of faults in power switches of inverters is the short-circuit fault of the Insulated-Gate Bipolar Transistor (IGBT). During this fault, the motor phases are uninterruptedly connected to negative/positive side of the inverter DC bus. Obviously, the significant amount of DC current in the motor windings can cause an additional failure in the motor or/and secondary failures in the rest of the VSI legs. This fault can degrade performances of the drive system notably and can lead to catastrophic failures [19]. Consequently, when a short-circuit fault in the inverter switches happens, it should be isolated from the motor.

Investigation on PFO of 3-PIM drives during IGBT faults can be classified into two main trends: (1) inverter topologies and (2) control systems. Different inverter topologies, according to some hardware redundancy, have been recommended for PFO of 3-PIM drives under IGBT short-circuit faults. Generally, these topologies can be classified into three categories: (1) adding extra bidirectional switches to bypass the faulted IGBT using the Neutral Point (NP) of the 3-PIM [7], (2) adding a redundant power switch in the conventional topology that can be switched on/off in the case of IGBT faults [20], and (3) connecting the NP of the 3-PIM to the Middle-Point of the DC Bus (MPDCB) [21]. Most of the presented strategies for PFO of 3-PIM drives during the IGBT short-circuit fault in the literature have focused on the inverter topologies, and post-fault control of 3-PIM drives during the IGBT short-circuit fault is rarely discussed.

Some control techniques for open-phase fault in 3-PIM drives have been suggested in the literature which can be used for post-fault control of 3-PIM drives during IGBT short-circuit faults. For example, in [22, 23], scalar control techniques and in [24], a Vector Control (VC) technique for delta-connected 3-PIM drives during open-phase fault were proposed. Scalar control methods are cheap, simple, and well-implementable control techniques. However, these methods cannot provide an accurate speed–torque control. In [21, 25], VC strategies for Y-connected 3-PIM drives during open-phase fault using current controllers have been proposed. Due to the lack of control on motor currents in current controller systems, these techniques are not suitable under light-load conditions. In [8], an approach for FTC of Y-connected 3-PIM drives against open-phase fault based on injecting zero-sequence voltage in a feedforward manner was proposed. In recent years, several works for Indirect VC (IVC) and Direct VC (DVC) of Y-connected 3-PIM drives during open-phase fault using asymmetrical transformation matrices have been reported [1, 26–29]. Unfortunately, these control methods require a complex implementation since different transformation matrices are used. In addition, the control techniques presented in [1, 26, 28, 29] are not accurate control strategies due to the ignorance of leakage inductance in the VC equations. In [30], a method for FTC of Y-connected 3-PIM drives under open-phase fault based on the conventional transformation matrix was proposed. The VC method used in [30] has very complex control structure due to the use of two VC algorithms.

The main objective of this paper is to propose a novel control method based on IVC strategy for PFO of Y-connected 3-PIM drives during the IGBT short-circuit fault. At first, a fault tolerant VSI is presented. Then, according to the presented inverter topology, the 3-PIM model during this fault is presented. Using this model, a novel IVC system for the faulted drive system is developed. The main advantage of the proposed post-fault control strategy is not only good performances during the IGBT short-circuit fault but also simple hardware implementation and low computational complexity of the algorithm. A further achievement of the introduced IVC strategy is that the proposed control algorithm with some changes can be utilized for pre-fault operation of Y-connected 3-PIM drives (IVC of healthy Y-connected 3-PIM drives). Unlike [21, 25], the proposed IVC scheme is suitable for high power applications due to the use of a voltage control system. The IVC system proposed in this research, with minor changes in the structure of the conventional IVC method, can be developed for Y-connected 3-PIM drives after the IGBT short-circuit fault. In other words, unlike the conventional active FTC schemes such as [9, 31, 32], the control strategy proposed in this research does not need different control methods during healthy and faulty conditions. Additionally, the control system proposed in this paper is more accurate than the previous published papers [1, 26, 28, 29] due to the consideration of the leakage inductance in the VC equations. Furthermore, different from [27], the IVC method presented in this research has simple control structure and low computational difficulties due to the use of the conventional transformation matrix for stator voltage and current variables. The main contributions of this paper can be highlighted as follows:

- An FTC system for Y-connected 3-PIM drives during the IGBT short-circuit fault is presented
- A simple control method for Y-connected 3-PIM drives after the IGBT short-circuit fault based on the conventional transformation matrix is proposed
- A modified IVC strategy can be shared for Y-connected 3-PIM drives during normal and IGBT short-circuit fault conditions

In this research, the experimental results under different reference speeds, including low- and high-speed, confirm the good performance of the proposed IVC system in decreasing the speed and dq current ripples for the Y-connected 3-PIM drive after the IGBT short-circuit fault. The experimental results also confirm the capability of the presented IVC method to balance the 3-PIM line currents.

This paper is organized as follows. In Section 2, the fault-tolerant VSI is reviewed. In Section 3, a developed model for the Y-connected 3-PIM during the IGBT short-circuit fault based on the modified VSI is presented. In addition, in this section, the main idea of the proposed control strategy is presented. Furthermore, in Section 3 the IVC scheme introduced to handle the
IGBT short-circuit fault in the 3-PIM drive system is shown. In Section 4, experimental results are illustrated in order to demonstrate the good performance of the proposed IVC system during different operating conditions. Finally, Section 5 presents conclusion.

2 DIFFERENT SCENARIOS FOR THE SHORT-CIRCUIT FAULT IN THE IGBT AND THE USED INVERTER TOPOLOGY IN THIS PAPER

As mentioned before, the short-circuit fault in the IGBT can cause a catastrophic fault in drive systems. In some cases, this fault in 3-PIM drive systems may lead to complete shutdown of the drive system.

As a solution, whenever this fault occurs, the faulted inverter leg can be isolated from the motor. The faulted inverter leg can be isolated from the motor using three fast-acting fuses as displayed in Figure 1 [Figure 1(a) shows the isolation mechanism for a delta-connected 3-PIM drive during the faulty condition and Figure 1(b) shows the isolation mechanism for a Y-connected 3-PIM drive during the faulty condition].

As shown in Figure 1, when a short-circuit fault happens, for example in $T_5$, the Fuse opens due to the high current. According to Figure 1(a), when the faulted IGBT ($T_5$) is isolated from the delta-connected 3-PIM, the stator currents cannot be controlled individually. In this case, the 3-PIM operates as a single-phase motor. Based on Figure 1(b), when the faulted IGBT ($T_5$) is isolated from the Y-connected 3-PIM, the stator currents cannot also be controlled individually, unless the NP of the 3-PIM connects to the MPDCB. The NP of the 3-PIM can be connected to the MPDCB using a triac as displayed in Figure 2 [33].

This inverter topology incorporates three fast-acting fuses and a triac provides a good fault isolation capability and very low cost due to the use of small number of electronics components. The presented inverter topology of Figure 2 can be utilized for both pre-fault and post-fault operations of the drive system. During pre-fault operation, the triac is blocked and the system is operated as the standard 3-leg VSI. In this condition, the resulting inverter configuration can be illustrated as Figure 3. Based on Figure 3, eight combinations of status of switches and consequently, eight voltage vectors can be produced [5].

Based on Figure 2, whenever the IGBT short-circuit fault happens, its corresponding fuse opens due to the high current. In the meantime, the triac is triggered and the NP of the 3-PIM connects to the MPDCB. In this condition, the resulting inverter configuration can be illustrated as Figure 4. According to Figure 4, after inverter reconfiguration, four combinations of status of switches and consequently, four voltage vectors can be produced [5].
3 | MODIFIED IVC STRATEGY

3.1 | Model

Based on Figure 4, dq’ and stator magnetizing axes can be shown as Figure 5 [26].

In Figure 5, the superscript s indicates a stationary reference frame. Based on Figure 5, $ab \rightarrow dq'$ transformation matrix for the stator components can be expressed by [26]:

$$K_{f_{amb}} = \sqrt{2} \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

(1)

According to Equation (1), the dynamic model of the 2-PIM can be described by the following equations [26]:

$$v_{ds} = r_{sc}i_{ds} + L_{ds}p_{c}s_{ds} + L_{d}s_{dr}$$

(2)

$$v_{qs} = r_{sc}s_{qs} + L_{qs}p_{c}s_{qs} + L_{q}s_{qr}$$

(3)

$$v_{dr} = 0 = r_{sc}i_{dr} + L_{r}p_{c}s_{dr} + \Omega_{r}L_{r}i_{ds} + \Omega_{r}L_{r}i_{qs}$$

(4)

$$v_{qr} = 0 = r_{sc}i_{qr} + L_{r}p_{c}s_{qr} - \Omega_{r}L_{r}i_{ds} - \Omega_{r}L_{r}i_{qs}$$

(5)

$$\lambda_{ds} = L_{ds}i_{ds} + L_{d}s_{ds}$$

(6)

$$\lambda_{qs} = L_{qs}s_{qs} + L_{q}s_{qr}$$

(7)

$$\lambda_{dr} = L_{dr}i_{dr} + L_{d}s_{dr}$$

(8)

$$\lambda_{qr} = L_{qr}i_{qr} + L_{q}s_{qr}$$

(9)

$$\tau = \frac{\text{pole}}{2} (L_{q}s_{qr}i_{qr} - L_{d}s_{dr}i_{dr})$$

(10)

In Equations (2)–(10), $L_{ds} = L_{d} + L_{q}, L_{qs} = L_{d} + \frac{1}{\sqrt{3}}L_{q}, L_{d} = \frac{3}{2}L_{arm}, L_{q} = \sqrt{\frac{3}{2}}L_{arm}, p = \frac{d}{dx}$ [26].

3.2 | Main Idea

The Magneto-Motive Force (MMF) of the 2-PIM based on Figure 6 can be expressed by Equation (11):

$$\begin{bmatrix} MMF_{ds} \\ MMF_{qs} \end{bmatrix} = \begin{bmatrix} N_{d} & 0 \\ 0 & N_{q} \end{bmatrix} \begin{bmatrix} \hat{e}_{ds} \\ \hat{e}_{qs} \end{bmatrix}$$

(11)

where

$$\begin{bmatrix} \hat{e}_{ds} \\ \hat{e}_{qs} \end{bmatrix} = \begin{bmatrix} \cos \alpha - \sin \alpha \\ \sin \alpha \cos \alpha \end{bmatrix} \begin{bmatrix} e_{ds} \\ e_{qs} \end{bmatrix}$$

(12)

In Equation (12), the superscript e indicates a rotational reference frame. Based on Equations (11) and (12), the MMF of the 2-PIM in a stationary reference frame can be written as Equation (13):

$$\begin{bmatrix} MMF_{ds}^e \\ MMF_{qs}^e \end{bmatrix} = \begin{bmatrix} N_{d} \cos \alpha - N_{d} \sin \alpha \\ N_{q} \sin \alpha \end{bmatrix} \begin{bmatrix} \hat{e}_{ds} \\ \hat{e}_{qs} \end{bmatrix}$$

$$= \begin{bmatrix} \left(\frac{N_{d} + N_{q}}{2}\right) \cos \alpha - \left(\frac{N_{d} + N_{q}}{2}\right) \sin \alpha \\ \frac{N_{d} + N_{q}}{2} \sin \alpha \end{bmatrix} \begin{bmatrix} e_{ds} \\ e_{qs} \end{bmatrix}$$

(13)
Based on Equation (13), the MMF of the 2-PIM in a rotational reference frame can be written as Equation (14):

\[
\begin{bmatrix}
\cos \alpha & \sin \alpha \\
\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
MMF_{df}^f \\
MMF_{qf}^f
\end{bmatrix}
\]

\[
= \left( \frac{N_d + N_q}{2} \right) \begin{bmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\ell_{df}^f \\
\ell_{qf}^f
\end{bmatrix}
\]

\[
+ \left( \frac{N_d - N_q}{2} \right) \begin{bmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\cos \alpha & -\sin \alpha \\
-\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\ell_{df}^b \\
\ell_{qf}^b
\end{bmatrix}
\]

which gives,

\[
\begin{bmatrix}
MMF_{df}^f \\
MMF_{qf}^f
\end{bmatrix}
= \left( \frac{N_d + N_q}{2} \right) \begin{bmatrix}
\ell_{df}^f \\
\ell_{qf}^f
\end{bmatrix}
+ \left( \frac{N_d - N_q}{2} \right) \begin{bmatrix}
\ell_{df}^b \\
\ell_{qf}^b
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
\ell_{df}^f \\
\ell_{qf}^f
\end{bmatrix}
= \begin{bmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\ell_{df} \\
\ell_{qf}
\end{bmatrix}
\]

As can be seen from Equation (15), the resultant MMF of the 2-PIM can be considered as two symmetrical single-phase motors with \(\frac{N_d + N_q}{2}\) and \(\frac{N_d - N_q}{2}\) turn numbers as depicted in Figure 7.

As a result, the asymmetrical model of the 2-PIM in a stationary reference frame can be written as two sets of equations with a symmetrical structure in a rotational reference frame.

### 3.3 Proposed IVC Strategy

IVC strategies are widely utilized to control electric motors like 3-PIMs, due to its high dynamic performance. From Equation (15), it is seen that the structure of the forward MMF is similar to the structure of the MMF of a healthy 3-PIM. In other words, the backward MMF causes oscillations in the speed and torque of the 2-PIM. The control system used in this research is based on forcing the backward MMF to a value equal to zero. In order to control a 2-PIM, the backward MMF can be set to zero by controlling the stator line currents, as shown in Figure 8.

The proposed control technique in Figure 8 can also be used during normal condition without affecting the controller performance. In this case, the block diagram of the proposed control system for pre-fault control of the 3-PIM drive (IVC of the healthy 3-PIM) can be shown as Figure 9. As shown in Figures 8 and 9, by changing only the transformation matrices, Figure 8 can be used for normal and IGBT short-circuit fault conditions.

During normal condition, the magnitude of the backward current components \((\ell_{df}^b, \ell_{qf}^b)\) of Figure 9 is very small. Consequently, the outputs of the backward current PI controllers \((v_{df}^b, v_{qf}^b)\) of Figure 9 are negligible and do not affect the control system performance. However, during the faulty condition, the magnitude of the backward current components of Figure 8 will have a significant value. This value is processed through a PI current controller in the \(d\)-axis and a PI current controller in the \(q\)-axis.

To compare the proposed IVC method of Figure 8 with the conventional IVC method, the block diagram of the conventional IVC has been shown in Figure 10 [34].
EXPERIMENTAL EVALUATION

The experimental validation of the introduced IVC strategy is implemented in a TMS320F28335 board. In the experiments, the IGBT short-circuit fault occurs in $T_5$ using a relay. The experimental setup consists of a 1HP Y-connected 3-PIM with accessibility of the NP and 380 V nominal voltage, 5.1 N.m nominal torque, a 3-leg VSI with a switching frequency of 10 kHz and the dead time of 1 $\mu$s, a DC generator, a resistive unit, and a control board. In tests, in order to reduce the effect of the NP current on the DC bus voltage during the fault, high size capacitors and damping resistors in parallel with the capacitors were used. A triac is connected between the NP of 3-PIM and the MPDCB. During normal condition, no current will flow to the motor neutral wire; consequently, the triac is “off”. The triac is triggered “on” when the fault is detected [25].

Based on the inverter topology used in this research, during the IGBT short-circuit fault, the faulted inverter leg is disconnected from the motor. In other words, the fault detection mechanism which is
used in the case of open-phase fault can be utilized for the IGBT short-circuit fault. Different techniques such as residual signal, current signature analysis, zero sequence voltage monitoring etc. were presented for detection of the IGBT short-circuit fault and open-phase fault [15, 35–41]. Since the contribution of this research focuses on the control strategy, a fast fault detection as presented in [37] is considered.

The motor parameters are listed in Table 1. Moreover, Figure 11 displays the experimental setup.

Different control strategies during normal and IGBT short-circuit fault conditions have been performed. Experimental tests include five scenarios. For scenarios A–E, the reference rotor speed, reference stator $d$-axis current, and load are as Figures 12–16, respectively.

**TABLE 1** The motor parameters

| $r_s$ | $r_r$ | $L_r$ | $L_{ms}$ | $L_{ls}$ | pole | $J$ |
|-------|-------|-------|----------|----------|------|-----|
| 10.44 Ω | 14.64 Ω | 0.607 | 0.398 | 0.009 | 2    | 0.016 kg.m² |

**FIGURE 10** Block diagram of the conventional IVC technique [34]

**FIGURE 11** The experimental setup

**FIGURE 12** The reference rotor speed, reference stator $d$-axis current, and load for scenario A

**FIGURE 13** The reference rotor speed, reference stator $d$-axis current, and load for scenario B

**FIGURE 14** The reference rotor speed, reference stator $d$-axis current, and load for scenario C

**FIGURE 15** The reference rotor speed, reference stator $d$-axis current, and load for scenario D
4.1 Comparison of the conventional IVC system and the proposed IVC system during normal and IGBT short-circuit fault conditions for a step change in the motor speed (scenario A)

Figure 17 displays the experimental results of different control systems during different conditions for a step change in the motor speed. This figure shows the comparison of the conventional IVC system based on Figure 10 after the IGBT short-circuit fault when the NP is connected to the MPDCB, the proposed IVC system based on Figure 8 after the IGBT short-circuit fault, and the proposed IVC system based on Figure 9 during normal condition. Subfigure 1 illustrates the motor speed, subfigure 2 illustrates the stator $d$-axis current, subfigure 3 illustrates the stator $q$-axis current, and subfigure 4 illustrates the zoom of motor line currents.

Figure 17(a)–(c) illustrates that using the conventional and proposed controllers, the motor speed and stator $d$-axis current signals can follow their desired values during different speeds and conditions. Nevertheless, after the IGBT short-circuit fault, the proposed IVC has better performances compared to the conventional IVC during both transient and steady-state conditions [see Figure 17(a) and (b)]. As shown, the time to recover the speed from 110 to 70 rad/s under the proposed system during the fault is faster than that obtained under the conventional system during the fault; but slower than that obtained under the proposed system during normal condition.
Additionally, the speed, stator $d$-axis current, and stator $q$-axis current ripples under the proposed IVC system during the fault is lower than those obtained under the conventional IVC system during the fault; but higher than those obtained under the proposed IVC system during the normal condition. Furthermore, from Figure 17(a) and (b) it is observed that, the motor line currents under the proposed IVC system, compared to the conventional IVC system, are more sinusoidal. From Figure 17(c) it is seen that using the proposed controller, the speed and stator $d$-axis current signals can follow their desired values suitably during normal condition. In this case, the stator $q$-axis current has reasonable ripples and the motor line currents are perfectly sinusoidal.

4.2 Comparison of the conventional IVC system and the proposed IVC system during normal and IGBT short-circuit fault conditions for a ramp change in the motor speed (scenario B)

Figure 18 displays the experimental results of different control systems during different conditions for a ramp change in the motor speed. This figure shows the comparison of the conventional IVC system based on Figure 10 after the IGBT short-circuit fault, the proposed IVC system based on Figure 8 after the IGBT short-circuit fault, the proposed IVC system based on Figure 9 during normal condition, and the conventional IVC system based on Figure 10 during normal condition. Subfigure 1 illustrates the motor speed, subfigure 2 illustrates the stator $d$-axis current, and subfigure 3 illustrates the stator $q$-axis current. It can be seen that using the proposed controller, the speed and stator $d$-axis current signals can follow their desired values suitably during both normal and IGBT short-circuit fault conditions [see Figure 18(b) and (c)]. The comparison between Figure 18(a) and (b) shows that after the IGBT short-circuit fault, the performances of the proposed strategy are better than the performances of the conventional strategy. The results of Figure 18(a) and (b) indicate that using the proposed scheme, the speed, stator $d$-axis current, and stator $q$-axis current ripples which are caused by this fault can significantly reduce. In addition, the comparison between Figure 18(c) and (d) shows that the performances of the proposed strategy during normal condition are similar to the performances of the conventional strategy during normal condition.

In the IVC strategy, the stator $d$-axis current and stator $q$-axis current are proportional to the rotor flux and torque, respectively. Therefore, using the proposed controller, the flux and torque ripples during the fault can significantly reduce.

4.3 Comparison of the conventional IVC system and the proposed IVC system during normal and IGBT short-circuit fault conditions at low speed operation (scenario C)

Figure 19 displays the comparison of the proposed IVC system based on Figure 8 after the IGBT short-circuit fault, the
Comparison of the conventional IVC system based on Figure 9 during normal condition, and the conventional IVC system based on Figure 10 during normal condition. Subfigure 1 illustrates the motor speed, subfigure 2 illustrates the stator \( d \)-axis current, and subfigure 3 illustrates the stator \( q \)-axis current.

As shown, using the proposed IVC strategy and under normal and IGBT short-circuit fault conditions, the speed and stator \( d \)-axis current can follow their reference values appropriately [see Figure 19(a) and (b)]. Additionally, in all three tests, the stator \( q \)-axis current has reasonable ripples and its average value is zero due to the no-load condition. Additionally, the comparison between Figure 19(b) and (c) shows that the performances of the proposed IVC system during normal condition are similar to the performances of the conventional IVC system during normal condition.

Comparison of the conventional IVC system and the proposed IVC system during normal and IGBT short-circuit fault conditions under the mechanical load (scenario D)

Figure 20 displays the experimental results of different control systems during different conditions under the mechanical load equal to 2 N.m. It is worth noting that the maximum allowable load for a Y-connected 3-PIM under two-phase mode operation is almost 38% of the nominal load [28]. This figure shows the comparison of the conventional IVC system based on Figure 10 after the IGBT short-circuit fault when the NP is connected to the MPDCB, the proposed IVC system based on Figure 8 after the IGBT short-circuit fault, the proposed IVC system based on Figure 9 during normal condition, and the conventional IVC system based on Figure 10 during normal condition. Subfigure 1 illustrates the motor speed, subfigure 2 illustrates the stator \( d \)-axis current, subfigure 3 illustrates the stator \( q \)-axis current, and subfigure 4 illustrates the zoom of motor line currents.

The results shown in Figure 20(b) and (c) confirm the effectiveness of the proposed IVC system during normal and fault condition even in the presence of a load disturbance. Figure 20(b)–(d) shows that the stator \( q \)-axis current has reasonable ripples and its average value during no-load conditions is zero and during the load is proportional to the applied mechanical load. As can be seen, during the fault, the proposed controller provides better transient and steady-state performances compared to the conventional controller [see Figure 20(a) and (b)]. Additionally, the comparison between Figure 20(c) and (d) illustrates that the performances of the introduced controller during normal condition are similar to the performances of the conventional controller during normal condition. As shown in Figure 20(a) and (b), the motor line currents using the proposed IVC system are more sinusoidal compared to the conventional IVC system. Moreover, the motor line currents using the conventional and proposed IVC systems during normal condition are perfectly sinusoidal and balanced [see Figure 20(c) and (d)].

FTC operation of the proposed system (scenario E)

Figure 21 displays the experimental results of the proposed IVC strategy during normal and IGBT short-circuit fault conditions. Figure 21 shows the motor speed, stator \( d \)-axis current, stator \( q \)-axis current, and motor line currents. In this figure, the drive system operates in normal mode. Then, at \( t = 20.8 \) s, the short-circuit fault happens.

As shown, a fast fault detection is accomplished at \( t = 20.93 \) s, since it takes only 0.13 s. It can be observed that using the proposed IVC strategy, the speed and stator \( d \)-axis current signals can track their reference values appropriately during both normal and IGBT short-circuit fault conditions. In addition, the stator \( q \)-axis current has reasonable ripples during different modes and its average value is zero due to the no-load condition. Furthermore, the motor line currents are perfectly sinusoidal in both healthy and faulty modes.

CONCLUSION

Continuous operation of electric drive systems during power semiconductor faults, such as IGBT short-circuit faults, has attracted great attention in recent years because of safety and economy reasons. On the other hand, Y-connected 3-PIMs are widely used in low/medium power industrial applications for their low cost, high efficiency, low maintenance, and outstanding performances. In this research, a method for PFO of Y-connected 3-PIM drives under the short-circuited IGBT fault is proposed. The proposed system is implemented in an experimental setup and its performances are assessed. The experimental results show that the proposed IVC technique has good performances during both normal and IGBT short-circuit fault
Experimental results of different IVC systems during different conditions under the mechanical load: (a) the conventional IVC system based on Figure 10 after the IGBT short-circuit fault when the NP is connected to the MPDCB, (b) the proposed IVC system based on Figure 8 after the IGBT short-circuit fault, (c) the proposed IVC system based on Figure 9 during normal condition, (d) the conventional IVC system based on Figure 10 during normal condition.

Experimental results of the proposed IVC strategy during normal and IGBT short-circuit fault conditions. Based on the results, it is seen that the proposed system has good dynamic and steady-state performances compared to conventional IVC strategies during the IGBT short-circuit fault condition.

Nomenclature

\[ \mathcal{K}_{\text{fault}} \]  
\( dq \) transformation matrix for the components of the stator during the faulty condition

\( p \)  
Differential operator

\( \tau_e \)  
Electromagnetic torque

\( \lambda_s^{dr}, \lambda_s^{dqr}, \lambda_s^{qs}, \lambda_s^{qsr}, v_s^{dr}, v_s^{qsr} \)  
Rotor \( dq \) fluxes, currents, and voltages in a stationary reference frame

\( \Omega_r, \Omega_c \)  
Rotor speed and slip speed

\( \alpha \)  
Rotor flux angle

\( \epsilon_e^{dr}, \epsilon_e^{qsr} \)  
Stator \( dq \) currents in a rotational reference frame

\( \lambda_s^{dr}, \lambda_s^{dqr}, \lambda_s^{qs}, \lambda_s^{qsr}, v_s^{dr}, v_s^{qsr} \)  
Stator \( dq \) fluxes, currents, and voltages in a stationary reference frame

\( L_s^{dr}, L_s^{qsr}, L_r \)  
Stator and rotor \( dq \) self-inductances

\( r_s, r_r \)  
Stator and rotor resistances

\( L_s^{leak}, L_s^{mag} \)  
Stator leakage and magnetizing inductances

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