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Fault-Tolerant Backup Control for a Leg-Based Two-Level Voltage Inverter Fed an Induction Motor

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Abstract – This paper investigates indirect vector control in the presence of an IGBT open-circuit fault and evaluates the feasibility of two-phase operation (two-phase control at maximum torque). Additionally, it explores a fault-tolerant control strategy employing a redundant leg.

I. INTRODUCTION

In recent years, three-phase induction machines have become increasingly popular in applications requiring variable speed. The integration of static converters with induction motors has gradually replaced DC motors in many industrial applications for speed control. The appeal of induction motors lies in their robustness, low cost, and high performance, which can be further enhanced by the development of advanced electronic components for sophisticated control strategies. However, control algorithms can become ineffective for both the system and the environment when a failure occurs. To ensure safety and minimize economic losses, it is crucial to continuously monitor and maintain the proper functioning of the motor. Increasing reliability, availability, and dependability has become a primary concern for manufacturers. In complex systems, such as those in aeronautics or nuclear power plants, detecting, locating, and reconfiguring faults is necessary, but it is not enough to guarantee operational safety. It is essential to modify the control strategy to ensure service continuity and maintain the minimum required performance levels [1].

However, both electrical and mechanical equipment are subjected to various internal and external stresses throughout their lifespan, which can lead to failures. Additionally, industrial requirements for reliability, maintainability, availability, and safety are critical factors. As a result, the industrial sector has a strong interest in techniques for assessing the condition of these drives [2].

Several monitoring methods rely on a system model to assess performance. The general principle of these approaches is to compare real-time data collected from the system with a behavioral model to check for consistency. The accuracy of the model directly impacts the performance of the monitoring system. Fault location may sometimes require the use of a model that represents the faulty system. Different levels of fault knowledge can be utilized, but it is important to note that obtaining an accurate model of faulty behavior is often challenging and expensive [3].

Depending on the monitoring requirements and system configuration, it is not always necessary to apply this level of effort to every component of the system. In some cases, using highly detailed models does not enhance the performance of the monitoring system; instead, it can increase design costs and significantly complicate data processing.

Significant progress has been made in diagnosing faults in variable-speed electric drives, particularly in the presence of faults in the asynchronous motor, such as broken or damaged bars, short-circuit ring sections, turn-to-turn winding short circuits, and various types of eccentricities. Additionally, faults in static converters (power supplies) have been extensively studied, including IGBT open-circuit faults, IGBT short-circuit faults, phase insulation failures, and DC bus short-circuit faults [4].

According to the existing literature, the most common and critical faults in inverters are primarily related to the semiconductor switches, specifically IGBTs in our case. Internal faults in the IGBT semiconductors account for approximately 31% of inverter failures. This percentage may be even higher when faults caused by control operations are considered [5].

In the field of static converter (inverter) diagnostics, several studies have focused on the detection and localization of IGBT open-circuit faults. Most of these methods are based on current analysis within the drive system. For instance, one approach proposes using the Park vector method to detect and localize IGBT open-circuit faults. This technique relies on the average value of the Park vector currents in the α-β plane and the determination of the phase angle. However, this method is highly load-dependent. To address this limitation, another approach introduces the normalized DC method, which is based on the direct components and the first harmonic coefficients of the AC currents. In this technique, the DC component is divided by the absolute value of the first harmonic and compared to a threshold (typically set at 0.45). While effective, this method has drawbacks when implemented in a closed-loop control system. To improve reliability and reduce false alarms, the same authors proposed a modified version of the normalized DC current method, refining the process for better performance [6].

The aim of this paper is to develop a simple model using the Park transform, which will also serve as the foundation for a model associated with vector control through rotor flux orientation. In the first part of this chapter, we will analyze the robustness of the PI controllers introduced in the CV-OFR (vector control by orientation of rotor flux) method, focusing on their performance under defined constraints, with results validated through simulation. The latter part of the article will explore indirect vector control in the presence of an IGBT open-circuit fault. Additionally, we will examine the operational possibilities of two-phase control under maximum torque conditions and study the control strategy using a redundant leg.

II. INDIRECT VECTOR CONTROL OF AN INDUCTION MOTOR WITH HEALTHY INVERTER

The objective of vector control is to operate the induction motor similarly to an independently excited *DC* machine, where natural decoupling exists between the flux-controlling current (excitation current) and the torque-producing current (armature current). This decoupling allows for a fast and precise torque response [7].

In flux orientation, the (*d*, *q*) axis system is aligned such that the d-axis is in phase with the flux.

$$\begin{cases} \varphi_{rd} = \varphi_r \\ \varphi_{rq} = 0 \end{cases} \quad (1)$$

The machine's equations in the reference frame aligned with the rotating field are as follows:

- **For the stator**

$$\begin{cases} V_{sq} = R_s I_{sq} + \sigma L_s \frac{dI_{sq}}{dt} + \omega_s \frac{M}{L_r}\varphi_r - \omega_s \sigma L_s I_{sd} \\ V_{sd} = R_s I_{sd} + \sigma L_s \frac{dI_{sd}}{dt} + \frac{M}{L_r}\frac{d\varphi_r}{dt} - \omega_s \sigma L_s I_{sq} \end{cases} \quad (2)$$

- **For the rotor**

$$T_r \frac{d\varphi_{rd}}{dt} + \varphi_r = M I_{sd} \quad (3)$$

$$\omega_{sl} = \omega_s - \omega_r = \frac{M}{T_r}\frac{I_{sq}}{\varphi_r} \quad (4)$$

The electromagnetic torque can be expressed as:

$$T_{em} = p\frac{M}{L_r}\varphi_r I_{sq} \quad (5)$$

Figure 1 below illustrates the vector control of a three-phase, two-level inverter through its block diagram:

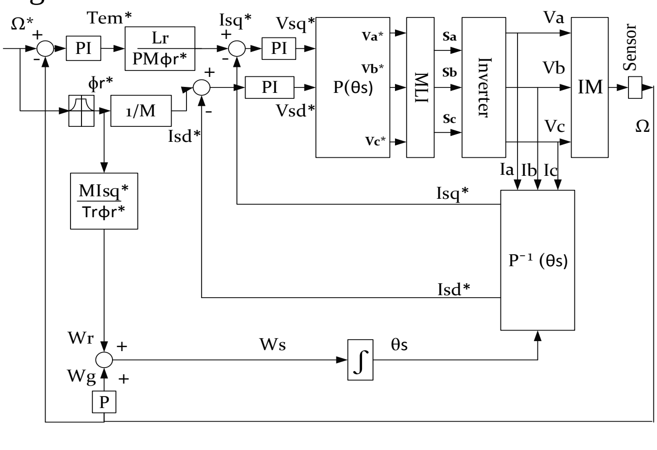

Fig. 1 Vector control diagram

Figure 2 presents the simulation results of indirect vector control with a fault-free inverter for the asynchronous motor. The control system is tested with a reference speed of 1000 rpm, and a load torque of 20 N·m is applied after 1 second.

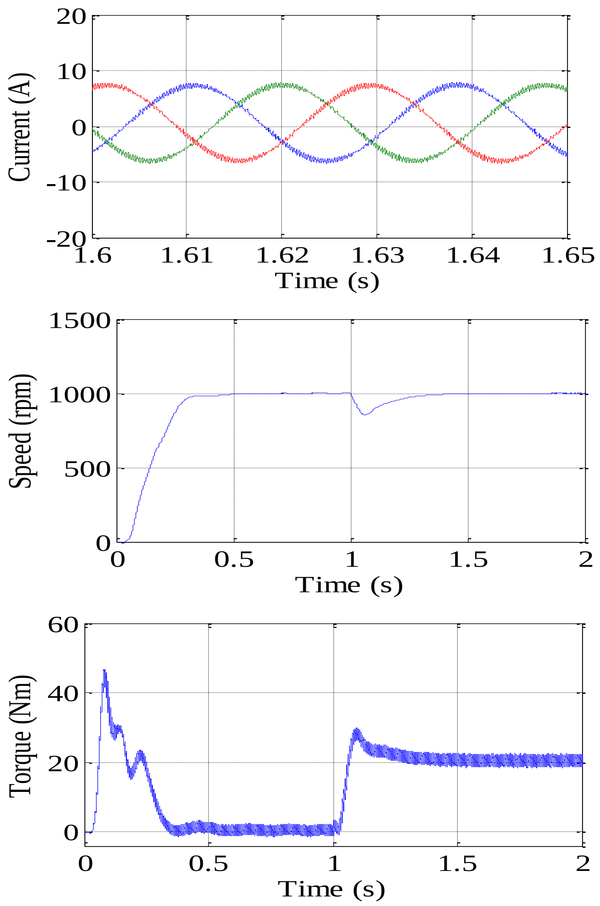

Fig. 2 Current, speed and torque

Figure 2 illustrates the behavior of the induction motor with a speed reference during startup under load. The speed curve closely follows the reference, reaching the desired speed swiftly and without overshoot. Although small oscillations in instantaneous torque occur during startup, they are brief in duration. Overall, the speed control loop performs well, demonstrating an acceptable rise time and effective disturbance rejection.

III. Indirect Vector Control of an Induction Motor in Degraded Operation

Two control strategies were employed in this fault mode of operation:

- Two-phase control strategy;
- Control with emergency leg connected to the affected phase.

A. *Two-Phase Control Strategy*

This control method involves regulating the two healthy phases after disconnecting the faulty phase. Fault isolation is achieved by an isolation switch at the moment the current in the faulty phase is interrupted. The currents in the two healthy phases must have equal amplitude, but they must be 180° out of phase with each other. The references for these currents are given by [8]:

$$\begin{cases} i_{as}^{*} = 0 \\ i_{bs}^{*} = -I^{*}\, sin(\varphi) \\ i_{cs}^{*} = I^{*}\, sin(\varphi) \end{cases} \quad (6)$$

The torque in the two-phase configuration is given by the following equation:

$$T_{em2ph} = \frac{2}{3}\, T_{em3ph} = \frac{2}{3}\frac{P\, M}{L_r}\varphi_r I_{sq} \quad (7)$$

The ratio of the torque in the healthy state to that in the open-circuit fault state is given by:

$$\frac{C_{em2ph}}{C_{em3ph}} \approx 0.666 \quad (8)$$

The symbol * in the above equations denotes a reference value.

With a fixed amplitude of phase currents, the torque in degraded mode is consequently lower than the torque in healthy mode.

Figure 3 presents the simulation results of the induction motor in two-phase mode. The vector control is tested with a reference speed of 1000 rpm, and a load torque of 20 N·m is applied after 1 s.

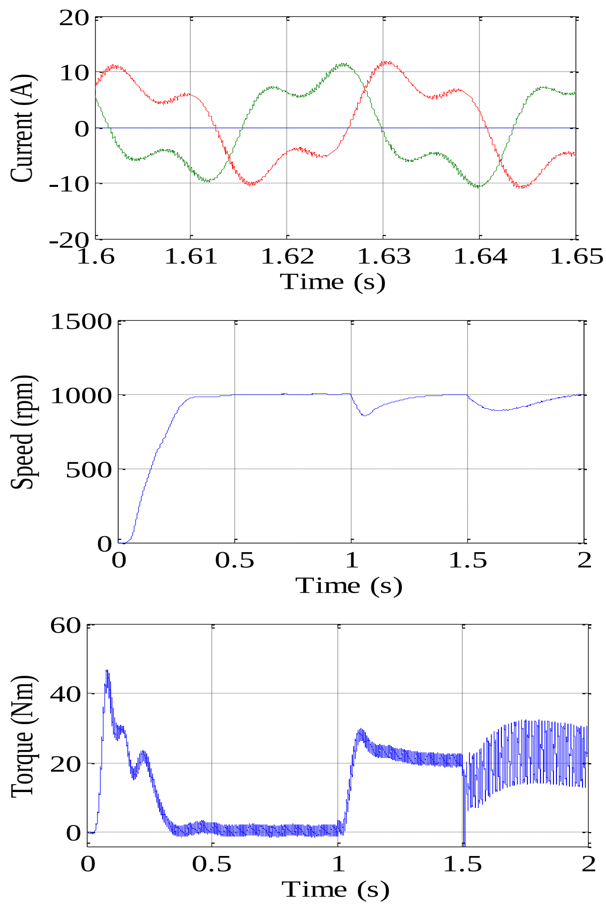

Fig. 3 Current, speed and torque

Figure 3 illustrates the increase in current amplitudes for operation in two-phase mode. This mode generates significant ripple in the electromagnetic torque and results in notable stator Joule losses, which are detrimental to the induction motor. The performance of the inverter-motor system in this topology, with the neutral isolated, is reduced, indicating that continuity of operation cannot be reliably maintained with this control strategy.

To enable two-phase degraded mode operation of an asynchronous motor, it is essential to adapt the power architecture and develop a control strategy that maintains maximum torque while minimizing oscillations caused by the missing phase. This requires the implementation of new control strategies within a fault-tolerant topology to ensure continuous operation with acceptable performance in degraded mode. To achieve this, a four-arm inverter will be used as the fault-tolerant topology.

B. *Control of an induction motor fed by a three-phase, four-arm inverter (with the emergency leg connected to the faulty phase)*

In the healthy state, the emergency arm remains passive, with all isolation switches closed and the connection switches open. The equations for the reference currents $i_{as}^*, i_{bs}^*, \; i_{cs}^*$ and $i_{ds}^*$are as follows [9]:

$$\begin{cases} i_{as}^* = i_{qs}^* \, cos(\varphi) + i_{ds}^* \, sin(\varphi) \\ i_{bs}^* = i_{qs}^* \, cos\left(\varphi - {}^{2\pi}/_{3}\right) + i_{ds}^* \, sin\left(\varphi - {}^{2\pi}/_{3}\right) \\ i_{cs}^* = i_{qs}^* \, cos\left(\varphi - {}^{4\pi}/_{3}\right) + i_{ds}^* \, sin\left(\varphi - {}^{4\pi}/_{3}\right) \\ i_{ds}^* = 0 \end{cases} \quad (9)$$

In the event of an open-circuit fault in a power IGBT, control of the fourth arm is managed through the control signals of the faulty leg.

In the case of an IGBT open-circuit fault, the reference current equations for $i_{as}^*, i_{bs}^*, \; i_{cs}^*$ and $i_{ds}^*$are given as follows:

$$\begin{cases} i_{as}^* = 0 \\ i_{bs}^* = i_{qs}^* \, cos\left(\varphi - {}^{2\pi}/_{3}\right) + i_{ds}^* \, sin\left(\varphi - {}^{2\pi}/_{3}\right) \\ i_{cs}^* = i_{qs}^* \, cos\left(\varphi - {}^{4\pi}/_{3}\right) + i_{ds}^* \, sin\left(\varphi - {}^{4\pi}/_{3}\right) \\ i_{ds}^* = i_{qs}^* \, cos(\varphi) + i_{ds}^* \, sin(\varphi) \end{cases} \quad (10)$$

Figure 4, illustrates the response of this strategy when a fault occurs in the arm of phase A, with the IGBT S_{a1} activated at t=1.5 s.

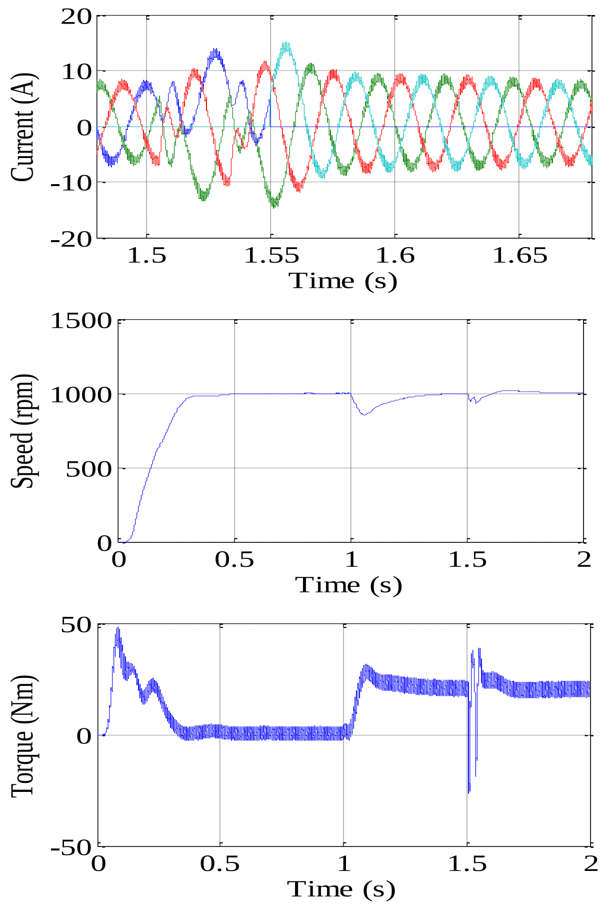

Fig. 4 Current, speed and torque

Figure 4 presents the response of this control strategy in the event of an open-circuit fault in the arm of phase A, introduced at t=1.5s. The results demonstrate that the performance of the inverter-asynchronous motor system is maintained after the fault, matching the pre-fault state. This is due to the fact that, after fault detection and a simple, quick reconfiguration, the control signals for the redundant arm are synchronized with those of the faulty arm. The fault detection and control reconfiguration processes are very rapid, allowing the system to resume normal operation with the same performance levels. The control of the redundant arm is straightforward, as it replicates the control signal of the faulty arm. However, a key drawback of this approach is the increased number of connection switches required.

IV. CONCLUSION

This paper presents a control reconfiguration technique for both types of three-phase inverter topologies. In the three-leg inverter topology, a two-phase control technique offers a promising solution in the event of an IGBT open-circuit fault. However, the main drawback of this approach is the oversizing of the drive system. In the four-leg inverter topology, the configuration can be adapted based on the connection of the backup leg, offering advantages in terms of efficiency, ease of implementation, and robustness.

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