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Effect of DC link capacitor short-circuit on an inverter fed induction motor performance

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ABSTRACT

Induction motors are widely used in industrial power plants because of their durability, reliability and high performance under different operating conditions of the electrical system. It is also important to note that most of these motors are controlled by variable frequency drives. By adjusting the drive parameters, the motor can be managed according to design. The reliability of motor control systems based on variable speed drives is therefore crucial for industrial applications. Unlike induction motors, the power supply components of these electrical machines are delicate and susceptible to faults. To enhance the performance of the control-motor system, it is essential for researchers to understand how faults affect the drive system as a whole. In this context, this paper addresses short-circuit faults in the intermediate circuit capacitor of an induction motor driven by an inverter. The simulation results of these capacitors faults are presented, and their impact on the behavior of the rectifier, the inverter, and the induction motor is analyzed and interpreted.

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1. INTRODUCTION

The squirrel cage induction motor (IM) is widely recognized as one of the most commonly used electromechanical energy converter in various fields, including industry and transport. Modern electrical drive systems are highly dependent on the control of induction motors. Pulse width modulation (PWM) is one of the most well-known control techniques [1].

Thanks to the development of power electronics, the control mechanisms for these motors have become simpler and more economical, achieving performance similar to that of DC motors. However, the extensive utilization of induction motors in process automation has raised concerns about their reliability under different fault conditions. Motors can be part of basic drive systems [2], [3] or more complex systems such as wind energy conversion systems [4]. They can be powered by conventional inverters or matrix inverters [5]. The research community is always keen in improving the reliability of inverter fed induction motors. Therefore, fault analysis remains a vital issue in the design of a fault tolerant systems.

In many industrial applications, induction motors run at variable speeds. Their power supply comes from a conversion chain consisting of a rectifier, a DC link, and an inverter; which requires a careful attention to study motor's behavior in the presence of faults in the conversion chain. As noted in [6]-[11], the two components most likely to become faulty in electrical drives are the electrolytic filtering capacitors in the DC link and the power semiconductors switches. Among these, the most typical power semiconductor faults are open-circuit and short-circuit faults, known respectively as high impedance and low impedance failures of an IGBT switch. The fault probability mentioned above has already been calculated by considering several factors, with a detailed study provided in the following papers [12]-[14]. The reliability evaluation of wind turbine system components shows that the highest failure rate occurs at the level of the converters, of which the DC link is a part [15].

Some researchers claim that semiconductor reliability has significantly improved. However, it remains a fact that in the past, the probability of control circuit faults was 53.1%, primarily due to the lower reliability, and sophistication of PWM chips compared to modern controller technology. Thus, the risk of IGBT's faults has been reduced. Although these faults occur within the inverter structure, they have direct negative consequences on the mechanical parts of the machine due to the various faults investigated. The different degraded operations of the motor due to these faults may cause high inertia and vibrations leading to accelerated aging of the motor's mechanical components and ultimately resulting in total deterioration. A research study found that over half of the failures in switching power supplies are linked to faults in the DC link capacitor.

The faults on DC link capacitors were notified by several researchers in their fault studies; however, they did not investigate this problem thoroughly. A review on improving the DC link capacitor reliability in power electronic static converters is presented in [16]. Fault modes, their causes, and capacitor lifetime models are explained and summarized to better understand failure mechanisms and improve DC link design. This paper emphasizes the significance of DC link monitoring. A DC link short-circuit fault occurs due to a capacitor short-circuit, often resulting from connector breakage [16]. The results indicate that the capacitor is susceptible to faults. An important point to consider is that the equivalent series resistance (ESR) of the capacitor gradually increases over time. This problem is not typically encountered in conventional circuits. However, it becomes relevant when the capacitor is used in a switching circuit, the equivalent series resistance (ESR) may interact with the switching frequency, potentially causing self-heating that can indirectly result in capacitor failure. In general, some research has been conducted on DC link short-circuit faults and their impact on induction motors [17]-[21]. A recent study provided a review of both internal and external faults in various components of a motor connected to an inverter.

However, none of these studies addressed the impact on the three-phase rectifier. This literature review shows that most of the research on fault analysis has focused on variable-speed induction motors is related to the fault analysis of IGBT switches. However, the susceptibility of the capacitor necessitates a detailed analysis of the behavior of the rectifier, inverter, and induction motor when this type of fault occurs. This paper presents an analysis of a capacitor short circuit fault in the DC link. A simulation of the drive system's behavior under this fault condition was developed to assist in the formulation of the mathematical analysis. The results obtained can assist researchers in designing and enhancing fault-tolerant systems, as well as in developing optimal protection system designs. Unlike our previous paper, this only dealt with different types of control in the static case.

2. DC LINK CAPACITOR SHORT-CIRCUIT FAILURE MODEL

The short circuit of the intermediate circuit capacitor creates two states: a transient state and a steady state. Figure 1 shows the diagram of the AC–DC–AC inverter feeding a three-phase induction motor. Figure 2 illustrates an equivalent electrical circuit of a conversion chain consisting of a rectifier, an inverter, and an induction motor for a variable-speed application. The three-phase voltages from the electrical network, Va, Vb, and Vc, are converted into a DC voltage, Vdc, through a controlled three-phase rectifier. The voltages in the conversion chain, which consist of the rectifier, are generated using the application of pulse width modulation (PWM), the inverter produces nearly sinusoidal output currents, which are reflected in the stator currents of the induction motor, as they also exhibit a sinusoidal form.

2.1. Analysis of the electrical network and faults on the rectifier side

This fault causes the DC link capacitor to short-circuit the rectifier's output voltage, which in turn short-circuits the electrical network phases. To clarify this phenomenon, Figure 3 is provided. It depicts a simplified circuit representing the issue [22]. Let us focus on the rectifier side and the electrical network. In Figure 3, the switch K is placed in parallel with the filter capacitor, while the DC voltage source supplies a voltage that charges the capacitor. Udc serves as a simplified model of the output from the three-phase rectifier implemented in the simulation setup of the electrical drive system. At time t = 0, prior to closing switch K, the voltage present across the capacitor is as (1).

$$U_{(t=0)} = U_{DC} \quad (1)$$

In other words, the filter capacitor voltage is equal to the rectifier's output DC voltage. Therefore, when the capacitor voltage is equal to U_{DC}, the current is zero.

$$i_c(t = 0) = 0 \quad (2)$$

In the variable speed system design, the presence of a single capacitor at the DC-link level implies that no additional device is available to limit or stop the sudden change in current. Consequently, at t=0, when the switch K is closed, the capacitor is short-circuited. Given that the resistance is nearly zero, the source current increases exponentially.

$$i_{c\,(t=0)} = {}^{U}/_{R} \quad (3)$$

Since R tends to zero, (3) becomes (4).

$$i_{c(t=0)} = \infty \quad (4)$$

After closing switch K, the circuit operates under the same conditions as an RC circuit, then as (5).

$$i = Ae^{({}^{t}/_{RC})} \quad (5)$$

Here, A represents a constant, RC = τ is the time constant, and t is the time.

After closing the switch K, the resistance R approaches zero. If R = 0, the circuit produces an extremely large current that theoretically tends toward infinity. As a result, if the appropriate fuses are not selected, this fault may lead to significant damage to the rectifier appropriately rated.

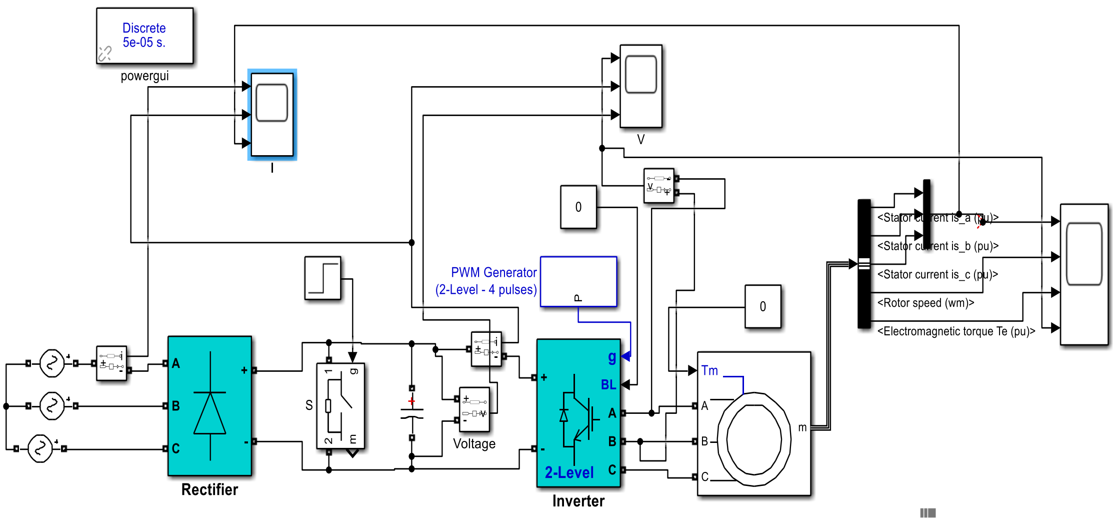

Figure 1. Simulation configuration

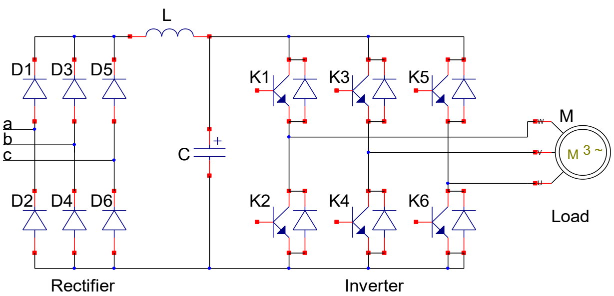

Figure 2. Equivalent electrical circuit of a MAS coupled with a static converter

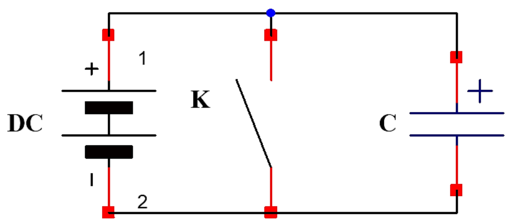

Figure 3. Simplified diagram of an equivalent circuit for a capacitor short-circuit fault

2.2. Fault analysis on the inverter and induction motor sides

We will now analyze the inverter and the induction motor sections. The electromotive force (EMF) is represented as a sinusoidal voltage source, and the motor windings are modeled using a series combination of resistance and inductance for each of the three phases. The IGBTs function as switches, either connecting or disconnecting the DC-link from the induction motor, as illustrated in Figure 2. For instance, in a state where IGBTs K1, K4, and K6 are conducting (closed) while K2, K3, and K5 are not conducting (open), Figure 4 presents a simplified circuit depicting the fault on the inverter and induction motor side [23], [24].

At this moment, the phase-A current equals the combined currents of phase-B and phase-C. This condition is shown in (6).

$$i_a = i_b + i_c \tag{6}$$

Since the current flows from phase-A, which is connected to the positive terminal of the DC-link. The voltage equation for the phase A is given in (7).

$$U_{a0} = U_z + E_{ba} \tag{7}$$

Where U_{ao} is phase-A voltage relative to ground, U_z is the line impedance voltage drop, and E_{ba} is the induction motor EMF return for phase-A. So, (7) becomes (8).

$$U_{a0} = R.i + L({}^{di}/_{dt}) + E_{ba} \tag{8}$$

After the short circuit at DC bus the voltage at the inverter output will become zero as indicated in [25]. As a result, (8) becomes (9).

$$-E_{ba} = R.i + L({}^{di}/_{dt}) \tag{9}$$

At the moment (t = 0), the current expression is given by (10).

$$i_{r(t=0^{-1})} = i_{l(t=0^{-1})} = \frac{(E_{ba} - U_{DC})}{R} \tag{10}$$

Since the circuit contains an inductance L, it opposes sudden changes in current, preventing it from varying instantaneously. However, the current will follow the specific solution given as (11) and (12).

$$i_{r(t=0^{-1})} = i_{l(t=0^{-1})} = \frac{E_{ba}}{R} \tag{11}$$

$$i = \frac{\left({}^{E_{ba}}/_{R}\right)}{(1-e^{\frac{t}{\tau}})} \tag{12}$$

The transient short-circuit current decreases indefinitely due to the presence of the winding resistor R. The time constant τ\tauτ determines the duration required to eliminate the transient effects of the stator current. In steady-state operation, the voltage applied to the motor drops to zero, leading to an immediate shutdown of the induction motor.

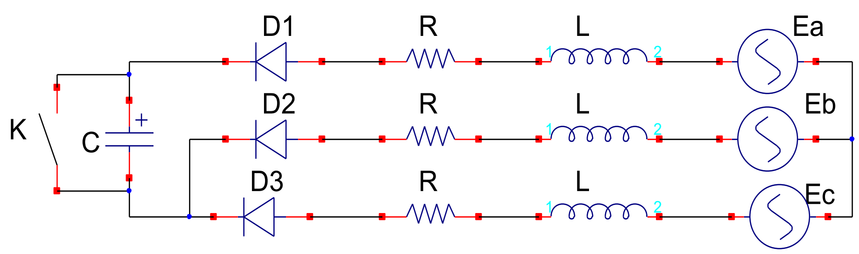

Figure 4. Fault equivalent circuit on the inverter and the induction motor side under DC-link capacitor

3. RESULTS AND DISCUSSION

The motor is powered by a two-level inverter and controlled by pulse width modulation (PWM). Simulation results will be presented in MATLAB Simulink for the healthy case and faulty case in the DC link capacitor. The motor parameters are shown in Table 1.

3.1. Simulation results: healthy case and discussions

The induction motor is connected to the inverter output via three phases, and the sampling frequency is 2 kHz. The average voltage of the three-phase rectifier output is given as in (13).

$$U_{DC} = \frac{3\sqrt{3}}{\pi} V_m \quad (13)$$

Where V_m maximum voltage. The motor was running at steady state before the fault occurred, as shown by the waveforms in Figure 5. The motor starts up and reaches its rated speed in a very short time (0.05 s).

Table 1. Parameters of the IM

S.L.	Description	Value (unit)
1	Power supply	400 V
2	Rated power	4 kW
3	Rated speed	1430 RPM
4	Stator resistance	0.03513 Ω
5	Rotor resistance	0.03488 Ω
6	Stator cyclic inductance	0.04586 Ω
7	Rotor cyclic inductance	0.04586 Ω
8	Mutual inductance	1.352 Ω
9	poles pairs number	2
10	Moment of inertia	0.0404 $kg.m^2$
11	Coefficient of viscous friction	rad^{-1} s

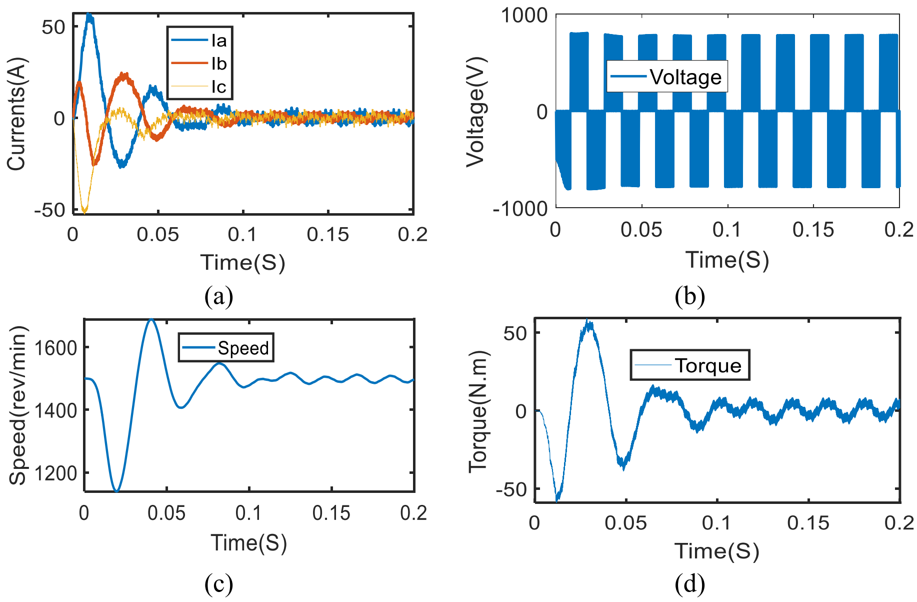

Figure 5. MAS performance under healthy conditions: (a) currents, (b) voltage, (c) speed, and (d) torque

3.2. Simulation results: faulty case and discussions

The faulty case in Figure 6, presented as a short circuit, can in practice be linked to overcurrents and thermal stresses of the DC bus capacitor. This faulty case can be a serious problem if the MAS is running at high speed and if its inertia is high. The greater the inertia, the longer the duration of back EMF generation. These counter-electromotive forces diminish and cancel with the inverter output voltages, creating transient currents of significant amplitude, overcurrent and thermal stress. Induction motor stator phase currents at t = 0.1: the transient currents are considerably high and then decrease to reach a zero value. The voltage curve at t = 0.1: the voltage value decreases considerably without reaching the zero value and then stabilizes for the short-circuit duration. The rotation speed curve: the motor was running at its rated speed before the fault occurred. When the fault occurs at t=0.1 s, the speed gradually decreases and then stabilises. The electromagnetic torque curve: When the fault occurs at t=0.1 s, the torque gradually decreases and then stabilises after the short-circuit duration. Finally, it is important to point out that in practice the way of detecting these types of faults, which are possible in real cases, are through the measure of the DC bus voltage level.

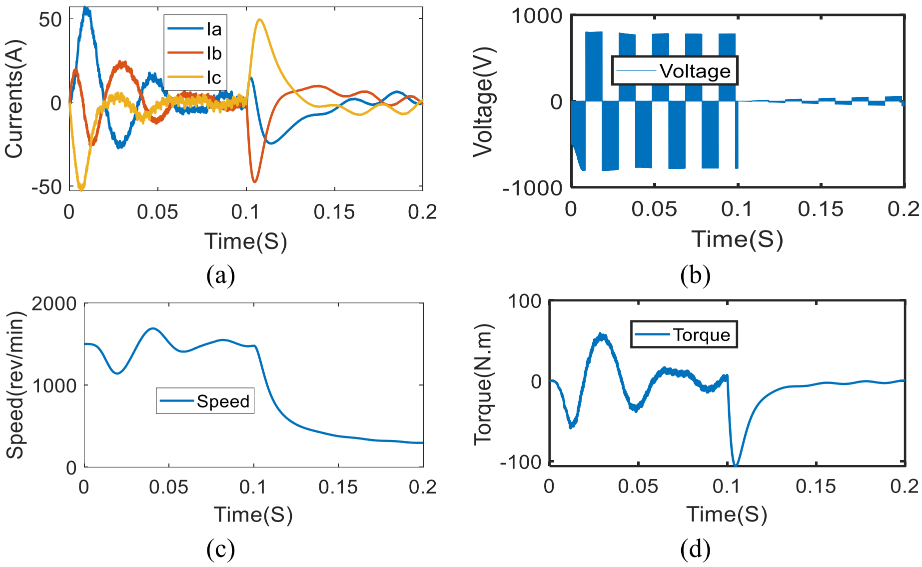

Figure 6. MAS performance under healthy conditions (DC link fault): (a) currents, (b) voltage, (c) speed, and (d) torque

4. CONCLUSION

This paper highlights the impact of a short-circuit at the intermediate capacitor circuit. It also highlights the sensitive components of a system whose failure can be fatal to the system. In addition, it shows the electrical and mechanical behaviour of a complete electric drive system consisting of an induction motor fed by a variable-speed system (a rectifier, a DC link and an inverter). The theory and mathematical analysis presented have been verified by simulations. This work has enabled us to gather information on the behaviour of the rectifier, inverter and induction motor during a short-circuit fault of the DC link capacitor. A detailed analysis certainly contributes to the diagnosis and design of robust fault-tolerant systems, as well as to the improvement of fault detection techniques. In fact, it can be said that the effect on the system at the moment the fault appears is accompanied by a gradual reduction in speed and torque, before stabilising. However, it should not be forgotten that this type of fault can sometimes lead to motor stopping.

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Cheikh Oudaa	✓	✓			✓	✓	✓	✓	✓					
Ethmane Isselem Arbih Mahmoud	✓	✓			✓				✓			✓		
Mohamed Amine Khelif		✓			✓	✓	✓		✓					
Ahmed Mohamed Yahya		✓				✓				✓		✓		
Bendiabdellah Azeddine		✓				✓				✓		✓		
Abdel Kader Mahmoud	✓				✓	✓			✓				✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are openly available in International Journal of Electrical and Computer Engineering, at http://doi.org/10.11591/ijece.v8i2.pp763-770, reference number [2].

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