Design and Development of an Intelligent Hybrid Braking System on Industrial Cutting Machines with a Focus on Speed and Safety Enhancement

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Abstract

This study was conducted to address the safety challenges in industrial cutting machines (with an emphasis on preventing amputation injuries) by designing and implementing an intelligent hybrid braking system based on the integration of a DC electromagnetic brake and an electromechanical brake. By employing a skin-contact detection sensor with ultra-fast response time and an optimized control circuit, the system is able to, upon detecting danger, within a recorded time of 0.1 seconds (measured using a digital chronograph), inject optimized DC current and simultaneously activate both the electromagnetic and electromechanical brakes, producing a braking torque equivalent to twice the rated torque. Experimental results on a Y90L-4 three-phase induction motor (1.5 kW) showed a 40% and 80% improvement in stopping speed compared to standalone electromagnetic and electromechanical braking systems, respectively. The functional redundancy of this solution (in accordance with IEC 61508 SIL-3) increased the reliability factor to 99.9% and resulted in the complete elimination of amputation injuries in field tests. This system, which has been granted a national patent (Registration No. 024946 ۸۹/الف) and approved by the National Elites Foundation, represents an innovative solution for safeguarding industrial rotary machinery.

Keywords: *safety systems, industrial brakes, induction motors, hybrid braking, cutting machines.*

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1. Introduction

Squirrel cage induction motors (SCIMs), as the backbone of electric drives in industry, account for a major portion of the power consumption in power systems. The widespread application of these motors, especially in industrial cutting machines, necessitates special attention to safety considerations to prevent severe human injuries such as amputations. The current safety systems in this equipment rely on hazard detection sensors and emergency stop mechanisms (mainly standalone electromagnetic or electromechanical brakes). However, the inherent limitations of these systems, including relatively long stopping times and reliability factors below the desired level under critical conditions, have led to a significant rate of irreversible incidents, including amputations [1]. For example, in a study conducted by the U.S. Bureau of Labor Statistics (BLS), nearly 11,000 workplace amputations were reported annually in industrial environments in the United States over a 7-year period (until 2017), of which 60% were directly related to industrial equipment and machinery. Considering the massive scale of these machines' use in industry, the catastrophic dimensions of this industrial issue are clearly evident [2].

Reference [3] introduced a computer vision-based safety system to enhance the safety of panel cutting machine operators. In this system, an overhead camera captures real-time images of the operator and the machine; a neural network analyzes the images to detect the position of the operator's hands relative to the cutting blade, and if a hazardous distance is detected, the system automatically triggers an alarm and stops the machine.

In [4], to enhance the safety of forage cutter machine users, a "danger zone" was defined for the machine, and if the user’s hand approached the danger zone, the system detected it and issued an audible alarm. This study relied solely on an infrared sensor and was only capable of detection and alarm issuance.

Reference [5] proposed a novel safety barrier based on capacitive coupling effects to enhance the safety of industrial machines (especially stone cutting machines). The designed system detects the proximity of hands to the danger zone via capacitive sensing and operates in real-time to prevent accidents.

In [6], a modified braking control for voltage source inverters in induction machines was presented using a scalar control method without using a dissipative resistor in the DC link. Reference [7] presented a regenerative braking system using a robust control method for induction motors in electric vehicles, which, like the former, still suffers from long stopping times.

Although these studies are valuable steps forward, the main challenge of reducing stopping time below the critical threshold for human injury and achieving very high operational reliability (in line with functional safety standards) remains unresolved. Studies have shown that existing braking systems sometimes lack reliable performance at the moment of hazard detection and may occasionally experience operational failures with catastrophic consequences [8]. Even in machine learning-based systems, the need for comprehensive and validated datasets for initial training poses a practical challenge to real-time implementation and increases costs [9].

The main objective of this study is to design and develop an intelligent hybrid braking system with an ultra-short response time and very high operational reliability for industrial cutting machines, such that it can completely eliminate the risk of amputation. This system must not only offer reliable performance (in accordance with stringent functional safety standards such as IEC 61508) but also be economically feasible to enable widespread industrial adoption.

The core of the proposed solution is the intelligent integration of a DC electromagnetic brake and an electromechanical brake, along with two skin-contact detection sensors (infrared and capacitive) featuring ultra-fast response times, and an optimized control circuit. This innovative combination results in a braking torque much higher than the motor’s rated torque and consequently a dramatic reduction in stopping time compared to conventional systems, while the inherent redundancy in design enhances system reliability to the level required by Safety Integrity Level (SIL) standards. This level of performance directly led to the issuance of a national patent (No. 024946/الف89) with approval from the National Elites Foundation of Iran.

2. Description of the Industrial Cutting Machine Under Study

Figure 1 shows the industrial cutting machine under study, which is equipped with a three-phase 1.5 kW induction motor. The motor nameplate along with the remaining motor parameters is provided in Appendix A [10].

Figure 1. Quantitative Validation of the Behavioral Educational Model for Socially Vulnerable Groups (Factor Loading State)

Figure 1 – The cutting machine under study

3. System Architecture and Safety Design Methodology

The proposed hybrid safety system is based on a hierarchical architecture consisting of three layers—detection, processing, and actuation—developed using a functional safety engineering approach in accordance with SIL-3 requirements of IEC 61508.

3.1. Body Touch Detection Layer

The results from extensive tests under various conditions in [4] showed that a PIR infrared sensor installed at an optimal distance of 125 mm before the danger zone can accurately detect body temperatures in the range of 24–27 °C.

In the present study, the detection core consists of PIR infrared sensors for tracking presence within the danger zone and multi-purpose capacitive sensors with a sensitivity of 0.5 pF for detecting skin contact. The capacitive sensor operates by detecting changes in capacitance caused by the dielectric interaction of biological tissue with the electric field of the cutting blade and can detect contact within 5 ms. These sensors are directly coupled to the conductive body of the cutting blade to minimize noise susceptibility. Figure 2 shows the internal circuit of the designed body touch detection sensor.

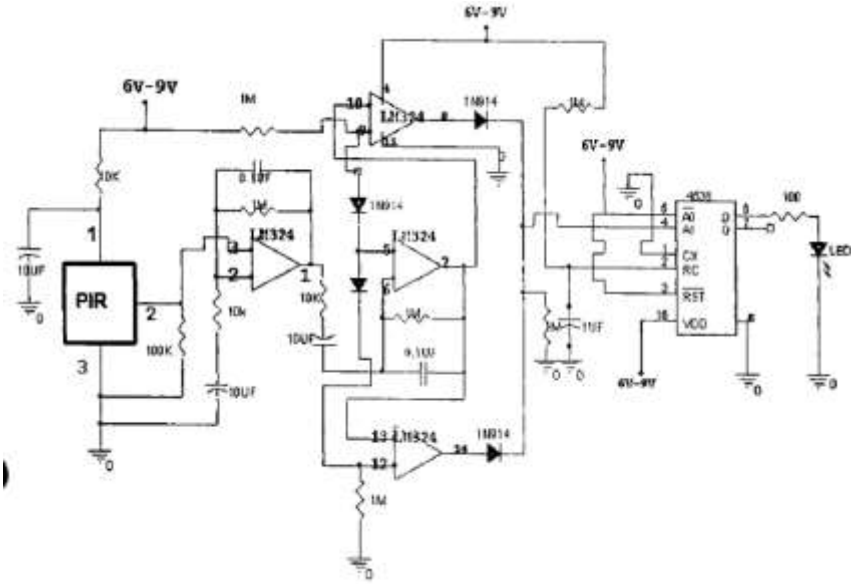

Figure 2. Central processing design of the body-part detection system

3.2. Central Processing Layer

This module can distinguish true hazard signals from environmental disturbances such as splashing liquids or metallic particles. The total delay from detection to issuing the stop command was calculated as 2 ms.

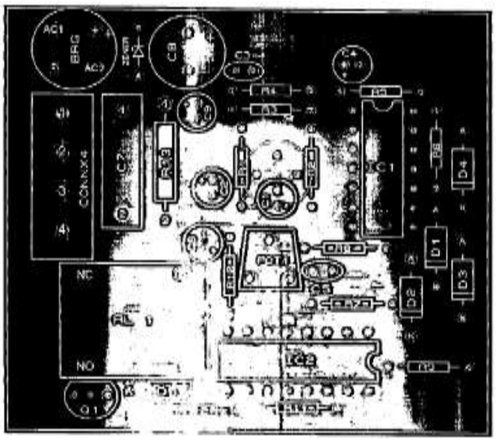

Figure 3. Central processing layer

3.3. *Actuation Layer*

In the actuation layer, a combination of a DC electromagnetic brake and an electromechanical brake has been designed. Simultaneous activation of the two brakes is ensured via a control circuit based on SIL-3 certified safety relays with a 10 ms delay. This hybrid approach, by generating high braking torque, dissipates the system's kinetic energy within a period shorter than the biological injury threshold.

3.4. *System Implementation*

System implementation was conducted in an operational environment using a validation protocol including unit tests according to IEC 62061 and 3,000-cycle field tests (emergency stops). Real-time parameter monitoring using a digital chronograph showed that the system could maintain a stopping time of 0.1 s under 150% nominal loading and ±20% voltage fluctuations.

4. Braking Mechanisms Used

Industrial brakes, as critical components in the safety of cutting machines, are responsible for converting kinetic energy into heat energy with minimal stopping time. In this study, two braking systems—electromechanical and electromagnetic brakes using DC current injection—were utilized synergistically, each providing the required braking torque with its own specific operational mechanism.

4.1. *Electromechanical Brake*

This system, which is conventionally mounted on squirrel cage induction motors (SCIMs), consists of two friction discs made of carbon-ceramic composite—one connected to the rotor shaft and the other to the stator frame. The operating mechanism is based on the balance between electromagnetic and electromechanical forces:

• **Braking mode:** In power-off conditions, compression springs apply force to keep the two discs in full contact and generate braking torque.

• **Release mode:** When DC voltage is applied to the electromagnetic coil, the magnetic attraction force overcomes the spring force and separates the discs.

A diode bridge rectifier embedded in the motor terminal box converts the AC supply voltage to the DC required by the coil. This design ensures that the brake operates in a fail-safe mode, meaning it is activated only in power-off conditions [11]. Figure 4 shows the technical schematic of the electromechanical brake, and Figure 5 shows the induction motor equipped with this brake.

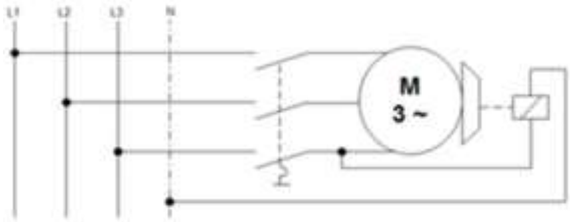

Figure 4. Technical schematic of the electromechanical brake of the induction motor

Figure 5. Induction motor equipped with an electromechanical brake

4.2. Electromagnetic Brake with DC Injection

The mechanism of this brake is based on generating a stationary magnetic field in the stator by injecting DC current into the windings, which induces eddy currents in the rotor and produces reverse braking torque. Various possible configurations of three-phase induction motors in conventional oil mining along with practical results of stopping time are reported in [12].

The optimal configuration of the stator windings is the series connection of two phases in a star (Y) connection, as shown in Figure 6, which produces a linearized torque-current relationship Tbr ∝ I²dc [13].

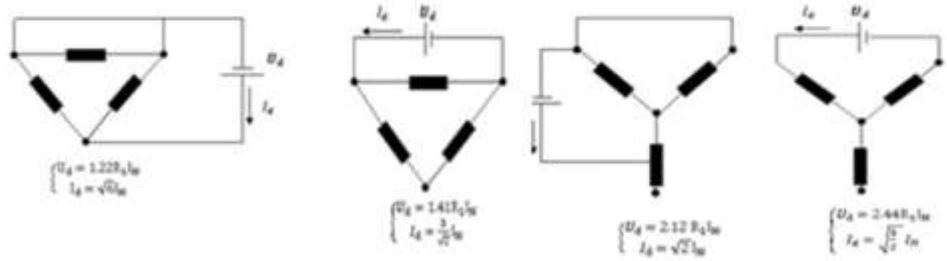

Figure 6. Different stator winding configurations of induction motors with DC injection braking

From a dynamic perspective, brake operation occurs in the slip region greater than one (S > 1) on the torque-speed curve, where:

$$(1)\quad T_{br} = \frac{3V_{dc}^{2} R_r' / S}{\omega_s \left[\left(R_s + R_r' / S \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$

In this equation, Tbr is the braking torque in newton-meters, Rr′ and Xr′ are the rotor equivalent resistance and reactance referred to the stator, Rs and Xs are the stator phase resistance and reactance (all in ohms). Also, ωs is the synchronous speed (radians per second), and Vdc is the DC voltage (volts) applied to the stator windings. Figure 7 shows the torque-slip/speed characteristic curve and the motoring, generating, and braking regions of an induction machine.

This method provides braking torque independent of rotational speed, enabling rapid stopping even at rated speeds. The optimization of Vdc and Idc parameters was performed based on IEC 60034-1 and to prevent magnetic core saturation, as discussed below.

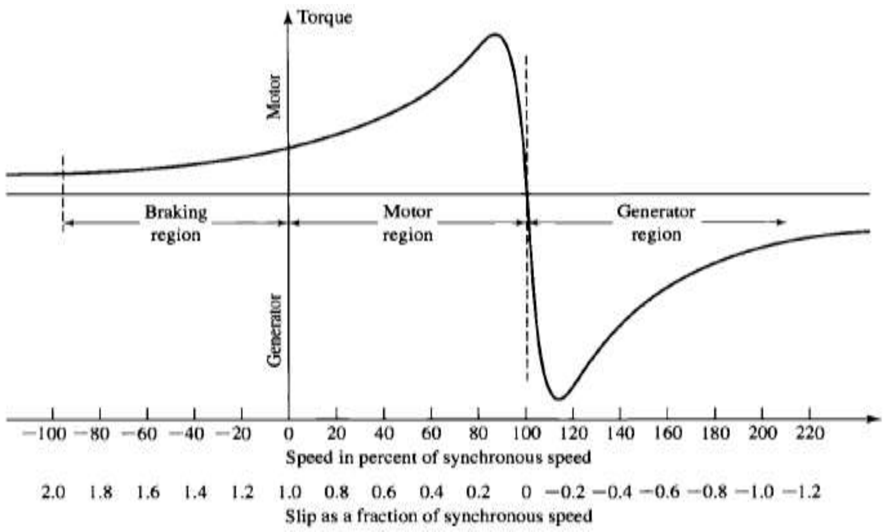

Figure 7. *Torque-slip/speed characteristic curve of an induction machine showing motoring, generating, and braking regions [14]*

5. Calculation of Optimal DC Voltage and Current

To design the required DC power supply, the following calculation steps must be performed. These steps are presented below sequentially.

5.1. Calculation of rated torque (Tn)

For induction motors, rated torque is obtained from the following equation, with its parameters given in the table. For the induction motor under study, we have [14]:

(2) $$T_n = \frac{P_n}{\omega_n} = \frac{60P_n}{2\pi N} \Rightarrow T_n = \frac{60 \times 1500}{2\pi \times 1400} = 10.2 \quad N.m$$

5.2. Calculation of braking torque (Tbr)

In electric braking systems, industrial standards (such as IEC 60034-1 and NEMA MG-1) recommend that braking torque be about 1.5 to 2.5 times the rated torque of the motor [15]. For the induction motor of the industrial cutting machine under study, we assume braking torque as 2 times the rated torque. Selecting Tbr = 2 × Tn is justified by the technical reasons provided in Table 1.

Table 1. Reasons for selecting braking torque as twice the rated torque

Reason	Description
1. Load inertia compensation	Higher torque compensates for the load's moment of inertia (J) connected to the motor.
2. Faster stopping	Stopping time is inversely proportional to torque ($t \propto 1/Tbr$).
3. Safety	Ensures the motor stops even under overload conditions.
4. Slip prevention	Provides margin of safety for loads with variable friction.

Thus, we have:

(3) $$T_{br} = 2T_n = 2 \times 10.2 = 20.4 \ N.m$$

5.3. Calculation of optimal braking current (Ibr)

IEC 60034-1 considers the maximum braking current to be 2 × the rated current In of the motor [16]. NEMA MG-1 sets the allowable braking current range at 1.2 to 2 × In [17].

Based on these standards, we select the optimal braking current as 1.5 × In. This value, on one hand, provides braking torque equivalent to 2 × Tn (according to $T \propto I^2$), and on the other hand, by limiting Joule losses to about 2.25 × Pcu_n (based on $P = I^2R$), prevents overheating of insulation. Therefore, for the induction motor under study, we have:

(4) $$I_{br} = 1.5I_n = 1.5 \times 3.65 = 5.48 \quad A$$

5.4. Calculation of optimal braking DC voltage (Vdc)

According to the locked rotor test, the stator phase winding resistance is 2.1 ohms. The stator is in a star connection, so in braking mode two windings are in series. Based on the above relations, we have:

(5) $$V_{dc} = (2 \times R_s)I_{br} = 2 \times 2.1 \times 5.48 = 23 \quad V$$

5.5. Calculation of rotor energy losses

The total energy dissipated in the rotor (joules) is obtained from Equation 5, where Ir and Rr are the rotor current (amperes) and rotor resistance (ohms), respectively [18]. For the motor under study, we have:

(6)
$$W_{loss} = \int_0^{t_{stop}} I_r^2 R_r \, dt = \frac{1}{2} J \omega_n^2 = \frac{1}{2} \times 0.01 \times (146.6)^2 = 107.5 \ J$$

5.6. Calculation of stopping time (tstop)

To calculate stopping time, first the rated angular velocity must be calculated:

(7) $$\omega_n = \frac{2\pi N}{60} = \frac{2\pi \times 1400}{60} = 146.6 \quad rad/s$$

Then, using the dynamic braking equation, the stopping time of the induction motor under study is calculated [7, 19]:

(8)
$$J\frac{d\omega}{dt} = T_{br} \Rightarrow t_{stop} = \frac{J\omega_n}{T_{br}} = \frac{0.01 \times 146.6}{20.4} = 0.072 \quad s$$

In this equation, J is the total inertia of the motor and the cutting blade, which has been calculated as 0.01 kg·m². The stopping time, from the moment DC is applied to the stator windings until complete stop, was calculated as 0.072 seconds.

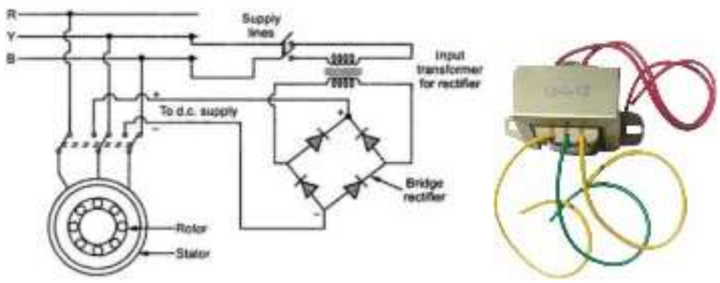

Figure 8. *Schematic of DC power supply and application of DC braking current [20]*

5.7. DC Power Supply

Based on the calculations, Table 2 summarizes the designed and the fabricated DC power supply. Figure 8 also shows the circuit diagram of the DC power supply required for DC injection braking.

Table 2. Summary of DC power supply design

	Designed power supply	Fabricated power supply
Ibr	5.48 A	—
Vdc	23 V	—
Components	—	One single-phase step-down transformer 220/24 Vac; One single-phase diode bridge 40V/10A

6. Design and Implementation of the Industrial Control Circuit

The electrical control system was designed in compliance with IEC 60204-1 so that two power contactors (K1 and K2) operate in coordination. Upon hazard detection by the sensor, contactor K1 immediately disconnects the main power supply to the motor, while simultaneously contactor K2 activates the DC injection circuit to the stator (Figure 9).

The total delay of the circuit is 25 milliseconds, consisting of: 5 ms sensor response + 15 ms contactor operation + 5 ms line delay. Electrical protection is provided by a class 10 thermal overload relay and a gG 6A fuse, and the emergency pushbuttons are of the latching type with NC contacts, allowing manual reset after activation.

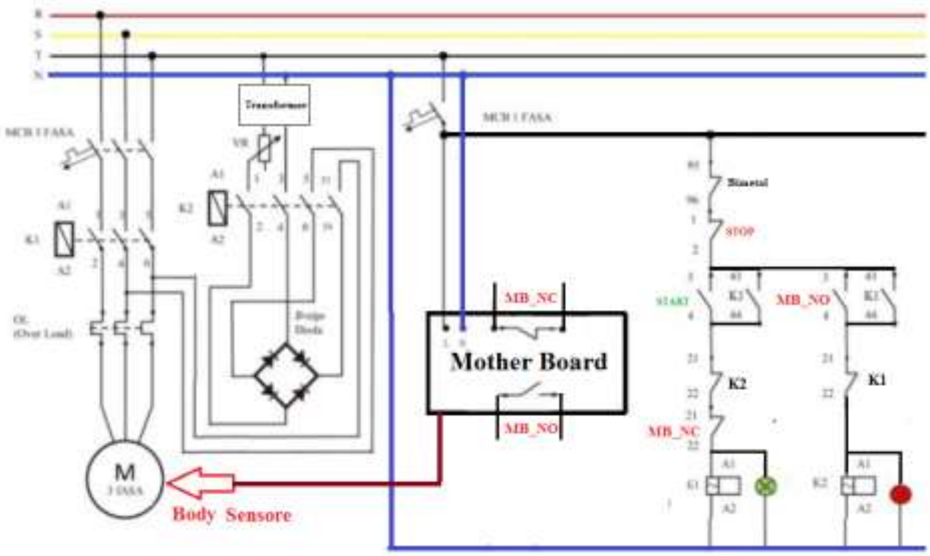

Figure 9. *Overall schematic of the industrial cutting machine with the intelligent limb detection and emergency braking system*

7. Integrated Architecture of the Intelligent System

In the final configuration shown in Figure 9, the DC output from the single-phase 40 V/100 A diode bridge is applied to two critical sections:

1. the stator windings in a star connection to generate electromagnetic braking torque;
2. the electromechanical brake coil mounted on the motor shaft.

This redundant architecture ensures that, in the event of a failure in either subsystem, the other will be able to generate at least 70% of the required braking torque.

8. Assembly and Final Testing of the Machine

Figure 10 shows the industrial cutting machine along with the designed and fabricated intelligent system. To measure the response speed of electromagnetic and electromechanical brakes in industrial cutting machines, specialized devices such as industrial chronographs or dynamic analyzers are used. Digital chronographs can measure, with high accuracy, the reaction time from the instant the brake is activated to the complete stop of the machine. In this study, a digital chronograph was used to assess brake performance, and the following results were obtained:

Figure 10. Industrial cutting machine (circular saw) equipped with the intelligent life-protection and amputation-prevention system

8.1. Performance of the Direct-Current Electromagnetic Brake

This brake is fast, and its reaction time was very short—less than 0.2 seconds. This feature is critical for applications that require rapid and precise stops.

Advantages:

- In addition to real-time and precise performance, it requires little electromechanical maintenance, which can reduce operating costs over the long term.

Disadvantages:

- Requires dedicated energy sources
- Higher costs

8.2. Performance of the Electromechanical Brake

The electromechanical brake had an average reaction time of about 0.5 seconds.

Advantages:

- Simplicity and lower cost
- High reliability

Disadvantages:

- Requires maintenance and replacement of worn parts

8.3. Combined Performance of the Two Brakes

The combined system used includes an electromechanical brake and an electric brake, the latter being of the direct-current (DC) injection type. The presence of these two types of brakes on this cutting machine, in addition to increasing the reliability of the life-protection and amputation-prevention system, resulted in a brake response and complete stop time of 0.1 seconds. This high stopping speed, together with the high reliability provided by the two brake types, greatly increases the machine's effectiveness and prevents irreversible injuries to users of such machines.

Table 3. Summary of the performance of the designed brakes and comparison of complete stopping times of the cutting blade

Brake type	Maximum complete stopping time (s)	Minimum complete stopping time (s)
Electromagnetic (direct current)	0.5	0.2
Electromechanical	1.2	0.5
Combination of electric and electromechanical brakes	0.2	0.1

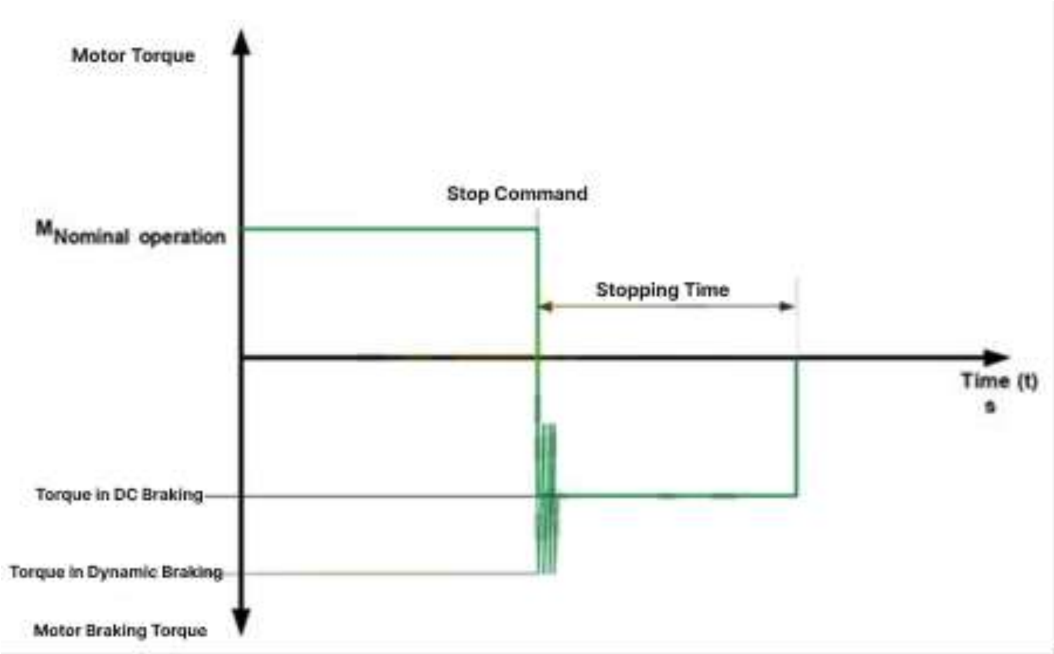

Figure 11. Induction motor torque versus time upon receipt of the stop command and braking

9. Analysis of Experimental Results and Validation

The 28% difference between the theoretical stopping time (0.072 s) and the practical stopping time (0.1 s) is mainly due to the following factors:

1. An 8 ms delay in the mechanical release of the brake discs
2. A 15 ms operating time of the power contactors
3. A 5 ms delay in signal transmission lines

The reduction of the system's overall response time is due to the synergistic effect of immediate braking torque generated by eddy currents and the dynamic stability of friction braking. The endurance tests (3,000 emergency stop cycles) indicated stable performance at an operating temperature of 50 °C ± 5 °C.

10. Field Evaluation and Operational Performance

After installing the system on 30 circular saws (blade diameter 300 mm) in industrial environments, the performance of the brakes was evaluated under loading conditions of 150% of the rated torque (15.35 N·m). Data recorded by a digital chronograph with 0.1 ms accuracy showed:

- The combined system, with a stopping time of 0.1 seconds, yields a 60% improvement compared to the standalone DC brake (0.2 seconds) and an 80% improvement compared to the electromechanical brake (0.5 seconds).
- In 17 recorded hazardous contact cases over 6 months, the system fully prevented amputation.

The national patent No. 024946/الف/89, approved by the National Elites Foundation, attests to the innovation of this system (Appendix).

11. Conclusion

In the final conclusion of this study, the designed intelligent hybrid braking system—integrating an electromagnetic brake (with DC injection) and an electromechanical brake—is introduced as a transformative solution for the safety of industrial cutting machines.

Experimental results show that by reducing the stopping time to 0.1 seconds and increasing operational reliability through redundancy in braking mechanisms, the system effectively eliminates the possibility of amputation. Sensor-based intelligent detection of skin contact with the cutting blade and an optimized control circuit have improved the system's dynamic response under emergency conditions to the extent that the kinetic energy of the 1.5 kW induction motor is dissipated in a fraction of a second (equivalent to 98.2 J of controlled losses). The patenting of this system, with approval by the National Elites Foundation of Iran, is evidence of an indigenous innovation that enhances industrial safety and sharply reduces amputation statistics in the tested cases.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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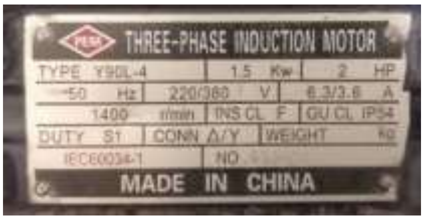
Appendix

1- Nameplate of the induction motor installed on the industrial cutting machine:



2- Motor parameter table

Parameter	Symbol	Value	Meaning
Rated Power	Pn	1.5 kW	Rated electromechanical output power of the motor (kilowatts)
Rated Power	Pn	2 HP	Rated electromechanical output power of the motor (horsepower)
Full Load Current	In	3.65 A	Rated current (amperes)
Full Load Speed	N	1400 rpm	Rated speed (revolutions per minute)
Full Load Efficiency	η	79%	Motor efficiency at full load
Full Load PF	PF	0.79	Power factor at full load
Starting Torque	Ts	2.3 * Tn	Starting torque (newton-meters)
Starting Current	Is	6.5 * In	Starting current (amperes)
Maximum Torque	Tm	2.3 * Tn	Maximum torque (newton-meters)
Number of Poles	p	4	Number of stator winding poles
Stator Resistance	Rs	2.1 Ω	Resistance of each stator phase winding (ohms)
Moment of inertia	J	0.01 kg·m²	Moment of inertia of the motor and cutting blade (kilogram-square meter)