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DETECTION AND CLASSIFICATION OF PHASE FAILURE FAULTS FOR A THREE-PHASE INDUCTION MOTOR USING ALGORITHM BASED ON RULES DERIVED FROM SIMULATION OF THESE FAULTS

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ABSTRACT

A three-phase induction motor (IM) is one of the most widely used motors in various industrial and commercial applications due to its reliability, robustness, simplicity, low maintenance...etc. Despite its many features, it is exposed to many faults that affect its performance and may cause damage and burning of its coils. Among these faults is opening of phase during its operation which leads to an increase in the temperature of its windings. In this research, a highly efficient algorithm is designed to detect and classify 19 different types of open phase faults. This algorithm is based on rules or conditions derived from simulating the different types of open phase faults in three motor modes (steady-state, transient, and standstill modes). The proposed algorithm uses the per-unit values of the phase voltages, line currents and speed as well of the motor and thus can be applied to different motors. The proposed algorithm has been designed and tested using the simulink window in MATLAB software. All test results proved that the proposed algorithm works very efficiently and is characterized by its speed and high accuracy in detecting these faults. Therefore, it can be used and integrated within the main protection system of a 3-phase IM to detect and classify the various open phase faults.

KEYWORDS: Induction Motor, Motor Protection, Fault Diagnosis, Phase Loss Fault, and MATLAB/Simulink.

اكتشاف وتصنيف أعطال فقدان الطور للمحرك الحثي ثلاثي الأطوار باستخدام خوارزمية معتمدة على قواعد مستنتجة من محاكاة هذه الأعطال

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الملخص

يعد المحرك الحثي ثلاثي الأطوار أحد المحركات الأكثر استخدامًا على نطاق واسع في مختلف التطبيقات الصناعية والتجارية نظرًا لموثوقيته ومتانته وبساطته وقلة صيانته..إلخ. وعلى الرغم من ميزاته الكثيرة إلا أنه يتعرض للعديد من الأعطال التي تؤثر على أدائه وقد تتسبب في تلف واحتراق ملفاته. من بين هذه الأعطال فقدان أحد أطواره أثناء تشغيله والذى يؤدي إلى ارتفاع درجة حرارة ملفاته. في هذا البحث، تم تصميم خوارزمية عالية الكفاءة لإكتشاف وتصنيف تسعة عشر نوعا مختلفا من أعطال الطور المفتوح. تعتمد هذه الخوارزمية على قواعد أو شروط مستنتجة من محاكاة الأنواع المختلفة لأعطال الطور المفتوح في ثلاثة أوضاع للمحرك (وضع الحالة المستقرة، والعابرة، والتوقف). تستخدم الخوارزمية المقترحة قيم الوحدة لكلا من جهود الطور وتيارات الخطوط والسرعة للمحرك، وبالتالي يمكن تطبيقها على محركات مختلفة. تم تصميم واختبار الخوارزمية المقترحة باستخدام نافذة المحاكاة ببرنامج ماتلاب. أثبتت جميع نواتج الاختبارات بأن الخوارزمية المقترحة تعمل بكفاءة عالية وتتميز بسرعتها ودقتها العالية في اكتشاف تلك الأعطال، ولذلك يمكن استخدامها ودمجها ضمن نظام الحماية الرئيسي للمحرك الحثى ثلاثي الأطوار لإكتشاف وتصنيف أعطال الطور المفتوح المختلفة.

الكلمات المفتاحية : المحرك الحثى، وقاية المحرك، تشخيص الأعطال، عطل فقدان الطور، محكاة الماتلاب.

1. INTRODUCTION

Electrical machines are considered as one of the main components of the engineering system and are widely used in industries [1–3]. Among all the electrical machines, the induction motor (IM) is extensively employed in industries due to several features like its reliability, robustness, simplicity, low maintenance [4-6]. Despite its many advantages, it is subject to many internal and external faults. These faults affect the 3-phase motor’s performance, increase its temperature, and may lead to burning its coils. Among these faults is the loss of phase during motor operation, which causes more current to flow through the other two healthy phases, thus heating its coils and possibly burning them [7]. A phase loss fault is also called phase failure, open phase, or single phasing [8]. There are several reasons for the phase loss fault of a 3-ph IM, like fuses blowing, wires getting damaged or broken, switches not working properly, contacts becoming worn or rusted, physical damage, and melted wires [9 - 12].

Based on leading standard organizations, approximately 30% of motor failures are caused by insulation breakdown, while around 60% result from overheating [12, 13]. Additionally, thermal overloading and single-phasing faults account for about 44% of all cases of faults [12]. If a three-phase motor tries to start but is missing one of the phases, it won't be able to rotate because it doesn't have enough torque to start but makes a humming sound [12]. In the event that one phase is lost during the motor's operation, it can sustain rotation by drawing additional current from the remaining two phases in order to resist the load [9, 12, 14]. In this case, if motor is running with two phases, it won't immediately cause harm or problems. However, if this fault is not recognized using the motor protection devic, it can lead to motor running under stress to drive the load and getting too hot. This excessive heat can result in the motor windings getting burned [11, 15].

If an induction motor experiences a phase loss, it encounters a significant imbalance in voltage, leading to increased current draw and imbalanced losses. As a result, the stator windings become overloaded with heat, which damages the insulation [12, 16]. Several researchers conducted a study on the impact of voltage unbalance on motor drives and asserted that even slight voltage imbalances, as low as 3%, could result in a significant 25% increase in motor temperature [17, 18]. When a motor operates at full load, the unbalanced percentage in the motor currents is about 6 to 10 times higher than the unbalanced percentage in the motor supply voltages [10, 19]. One of the most important reasons that causes the motor voltage unbalance is the opening of one of the phases of the motor supply [9]. Additionally, when a phase loss fault occurs, negative sequence currents are generated in the motor, which generates unwanted magnetic fields, ultimately decreasing torque [17]. This also causes motor overheating and dangerous side effects [20].

The motor protection field is currently witnessing a shift towards utilizing digital relays powered by microprocessors. In terms of accuracy, speed of response, and reliability, these relays provide several benefits compared to electromagnetic relays [21]. Most commonly utilized motor protection devices, such as circuit breakers or relays of thermal overload, are not specifically designed to detect open-phase faults [14]. Under open phase faults of a lightly loaded three-phase induction motor, its currents increase by the square root of three ($\sqrt{3}$). Consequently, the drawn current is approximately 20% greater than the full load current indicated on the motor's nameplate. Despite the overload device setting at 125% of the rated value, there remains a potential for damage due to circulating currents [11, 14]. So, multiple protective mechanisms have been created to safeguard motors against open-phase failure. One such device is the three-phase monitor relay, which not only shuts down the equipment being protected but can also provide an alert to the monitoring system in the event of a problem. Additionally, alternative protection devices have been extensively discussed in [16], which protect motors from this fault.

Several engineers have created various algorithms to detect open-phase faults of 3-ph induction motors. These algorithms allow the right actions to be taken at the right time, thus preventing more serious situations from occurring. Several research studies have been conducted in the area of the motor protection from the open-phase faults [22-31]. Fault detection algorithms can be classified into two categories based on the speed of fault detection in relation to the time it takes to identify the fault after it has occurred: slow and fast methods [8]. The method of direct-quadrature (DQ) current oscillations is used to detect the open phase [32]. A unique feature is utilized to identify faults. During normal motor operation, the direct and quadrature currents exhibit a relatively consistent pattern. When there is an open phase, these currents oscillate, making detecting the fault straightforward. Although this approach allows for quick detection of faults, it is vulnerable to the impact of measurement noise.

The technique of zero current was used to quickly detect open phase faults [33]. For each phase current, they utilized a filter of second order to identify instances of zero current. This filter tracks the change rate of currents, allowing faults to be detected as the current is expected to decrease quickly until it reaches zero. However, this technique poses challenges in fine-tuning and computational requirements, which negates its main advantages. Furthermore, there needs to be more information regarding their efficiency over transient periods. The method employed in [34-36] is referred to as average phase currents. This approach shares similarities with the detection techniques of zero-current, but it focuses on the average current analysis over the fundamental period. In [35], a minor enhancement is introduced to this method based on fuzzy logic to enhance the speed and reliability of the detection of faults. However, circumstances where the speed abruptly changes were not covered by the results.

The Discrete Fourier Transformation (DFT) technique was used in open phase detection, which is a well-known method for detecting signal distortion [37]. By analyzing the signals using DFT, they were able to identify instances of this failure caused by an open phase, which can lead to notable distortions in voltages and currents. The technique of middle current detection, renowned for its rapid identification of open-phase faults, is elaborated upon in [38, 39]. This technique exhibits effective performance even in the presence of signal noise. Another method discussed to identify phase loss faults [40, 41]. Here, the current shape is examined and compared to the expected shape, and thus the fault is detected when there is a noticeable difference between them. However, this method has certain limitations. Its implementation and calibration can be arduous, and it loses effectiveness when dealing with distorted currents as it has low overall reliability.

Many researchers have created various software algorithms to detect the open-phase faults for three-phase induction motors. However, most of these algorithms need a comprehensive classification system for this fault. Consequently, this research aims to address this gap by designing a highly efficient algorithm capable of detecting and classifying 19 types of open- phase faults. The algorithm is constructed based on rules or conditions derived from simulation results for various open-phase faults occurring in three motor modes: steadystate, transient, and standstill modes. The proposed system can detect and classify open-phase faults by identifying the faulty phase (A, B, or C) and determining whether it originated from the motor's power supply or occurred after the relay location in steady-state and transient modes. Additionally, it can detect and classify open-phase faults (A, B, and C) originating from the motor's power supply when it is in standstill mode. Detecting phase loss faults in standstill mode is crucial to prevent starting a motor with two phases missing a third because it causes over currents to pass through the other two healthy phases. One significant advantage of the proposed protection algorithm is its applicability to various motors with varying power. This is possible because the algorithm is based on the per-unit values of the motor's currents, phase voltages, and speed as inputs. The proposed method has been tested and validated using MATLAB/Simulink, encompassing normal operating conditions and various scenarios of open-phase fault, including motor disconnection events and motor restarts. Results of the simulation show that the proposed algorithm is highly efficient and accurately detects and classifies open-phase faults of a 3-ph, 50 Hz induction motor within a short timeframe of less than two cycles from the onset of the fault occurrence time. Hence, the suggested algorithm can be viewed as a simple and dependable choice for the primary protection system of a 3-phase IM to detect and classify the various open phase faults in steady-state, transient, and standstill conditions.

2. METHODOLOGY OF RESERCH

The process of developing the suggested algorithm for detecting and diagnosing various open-phase faults for a 3-phase IM involves four primary stages, outlined as follows:

- **Stage 1:** The motor system creation.
- **Stage 2:** The open phase faults simulation.
- **Stage 3:** The proposed algorithm design.
- **Stage 3:** Evaluation of the proposed algorithm.

Figure 1 shows the working stages diagram of designing and evaluating the proposed algorithm for detecting and diagnosing the various open-phase faults for a 3-ph IM.

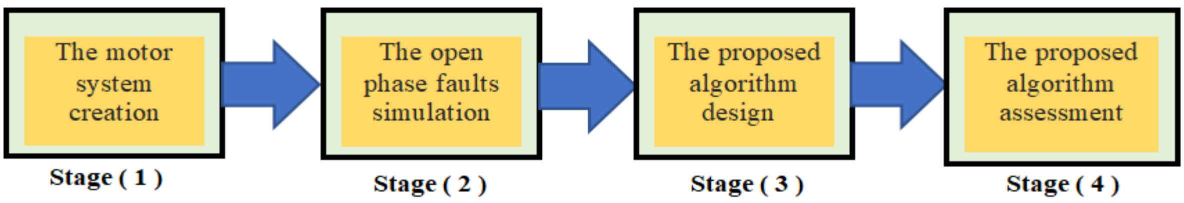


Fig. 1. Block diagram showing the stages of working to desgin and evaluate the suggested algorithm.

2.1 Creation of the Motor System

In this article, the motor system under study has been conducted using MATLA B Simulink software on a motor model simulating a 3-ph induction motor. This motor is squirrel-cage type, 50 Hz, 5.4 HP, 400 V, 1430 rpm, with star-connected windings. The data for this motor used in Matlab/Simulink, such as the resistance values of both the stator and the rotor referred to the stator, as well as the inductance of both the stator and the rotor referred to the stator, and the magnetizing inductance, are listed in **Table 1** [42, 43]. The studied system diagram in the Simulink window of MATLAB software is shown in **Fig. 2**. This diagram includes different blocks within the simulink window in MATLAB, which are described in **Table 2**.

Table 1: The data of motor used in the Simulink window of MATLAB software.

Parameter of motor	Value	Unit
Rated power	5.4	HP
The RMS value of the motor line voltage	400	Volts
Speed of motor	1430	RPM
The motor source frequency	50	Hz
Motor pole pairs	2	---
Resistance of stator (Rs)	1.405	Ω
Inductance of the stator (Ls)	0.005839	mH
Resistance of the rotor referred to stator (Rr')	1.395	Ω
Inductance of the rotor referred to stator (Lr')	0.005839	mH
Inductance of mutual (Lm)	0.1722	mH
The Inertia	0.0131	$Kg.m^2$

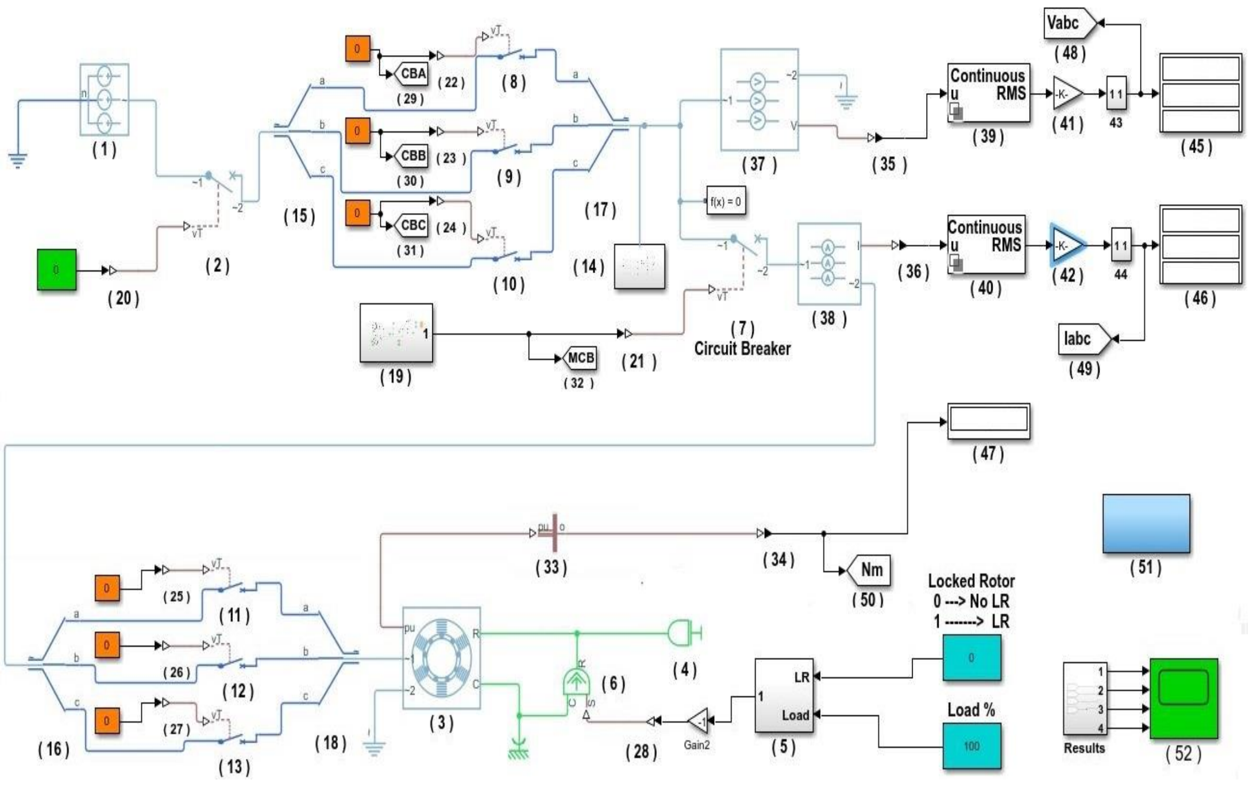


Fig. 2. The studied system diagram in the Simulink window of MATLAB software.

Table 2. Description of blocks in MATLAB Simulink window to simulate the studied system of motor.

Block No.	Block Name in MATLAB/Simulink	The block description displayed in the Simulink window of MATLAB
1	Voltage Source (Three-Phase)	This particular block simulates the power supply to a three-phase induction motor.
2	Circuit Breaker (Three-Phase)	This block simulates a three-phase circuit breaker that includes an input to be controlled by an external signal. This block has been used to connect and disconnect the supply source No. 1 to the motor system.
3	Induction Machine Squirrel Cage	This block simulates a three-phase induction motor with a squirrel-cage rotor, and it represents the fundamental parameters using either per-unit or the International System of Units (SI).
4	Inertia	The block represents an ideal mechanical rotational inertia.
5	Subsystem	The purpose of designing this block is twofold: firstly, to inhibit the motor rotation in the event of phase loss failure during startup, and secondly, to enable its operation at various loads as a percentage of the full load.
6	Ideal torque source	The block, which produces torque at its terminals proportionate to the input physical signal, is a perfect example of a torque source.
7	Circuit Breaker (Three-Phase)	This block simulates a three-phase circuit breaker that can start and stop the motor at any time by using an external signal.
8	Circuit Breaker	This block represents a single-phase circuit breaker to simulate a phase loss fault for phase "A" from the source by controlling an external signal.
9	Circuit Breaker	This block represents a single-phase circuit breaker to simulate a phase loss fault for phase "B" from the source by controlling an external signal.
10	Circuit Breaker	This block represents a single-phase circuit breaker to simulate a phase loss fault for phase "C" from the source by controlling an external signal.
11	Circuit Breaker	This block represents a breaker for simulation of the open-phase fault for phase "A" after location of the relay. This fault could be due to various reasons, such as the opening of phase "A" in the motor winding or the cable between the location of the motor and relay, or an issue in the motor junction box caused by a wiring error.
12	Circuit Breaker	This block represents a breaker for simulation of the open-phase fault for phase "B" after location of the relay by controlling an external signal.
13	Circuit Breaker	This block represents a breaker for simulation of the open-phase fault for phase "C" after location of the relay by controlling an external signal.
14	Subsystem	This block addresses a problem during the simulation process when a open-phase failure occurs from the motor power supply when the motor is at rest. In simulation, when one phase is lost from the motor source while the motor is in standstill mode, there is a voltage at the breaker end of the open phase, which is different from what happens in reality. This is because the phase loss by the breaker represents a high resistance and thus leads to a voltage at the end of the breaker in such cases. To solve this problem, Block No. 14 is specifically designed to eliminate this problem.

15-18	Phase Splitter	These blocks enlarge a composite three-phase connection into its individual phases. The resulting output ports are electrical conserving ports.
19	Subsystem	The purpose of this block is to simulate the motor control circuit, generating signals of start and restart and a signal to stop the motor in the event of an open-phase fault.
20-28	Simulink-PS Converter	The input Simulink signal is transformed into a physical signal by this block. Consequently, this block links Simulink sources or other Simulink blocks to a Simscape physical network's inputs.
29-32	Goto	These blocks pass a signal from block to another without connecting them. They are used to connect the modes of breakers 8-10 & block 19 to block 14.
33	Induction Machine Measurement	This block outputs a measurement per unit associated with a connected IM according to the choice. In our model, it is used to display the motor speed.
34-36	PS-Simulink Converter	The physical signal is transformed into a Simulink output signal by this block. It links Simscape physical network's outputs to Simulink scopes.
37	Phase Voltage Sensor (3-Phase)	This block represents an ideal three-phase voltage sensor. It is used to measure the motor phase voltages across the terminals of motor.
38	Current Sensor (Three-Phase)	This block simulates the sensor of a three-phase current. It is used to measure the motor line currents.
39	RMS Measurement	This block calculates the root-mean-square values of the input signal. Here, it calculates the RMS values of the motor phase voltages.
40	RMS Measurement	This block calculates the root-mean-square values of the input signal. Its application involves measuring the RMS values of the motor line currents.
41	Gain	The input is multiplied by a constant value (gain) in this block. It is used to convert the motor phase voltages (RMS) to their per-unit values by dividing them by the rated value of the motor phase voltage.
42	Gain	This block converts the motor currents (RMS) to their per-unit values by dividing them by the motor rated current.
43-44	Subsystem	These blocks are designed so that any value of the per-unit voltages or the per-unit currents that is very close to zero is set exactly to zero.
45-47	Display	This blocks show the value of the input data. They are used to display the per-unit values for the motor's phase voltages, currents, and speed.
48-50	Goto	These blocks pass a signal from one block to another without connecting them. They are used to connect the per-unit values of the motor's phase voltages, currents, and speed to block No. 51 of the proposed algorithm, which is explained later.
51	Subsystem	This block contains a subset of blocks within the model or system. It has been designed to simulate the proposed algorithm for detecting and classifying open-phase faults, which will be explained later in this section.
52	Scope	This block displays the simulation results. It is used to display the proposed algorithm outputs and the status of the reset pushbutton (0 or 1) with the per-unit values for the motor phase voltages and line currents.

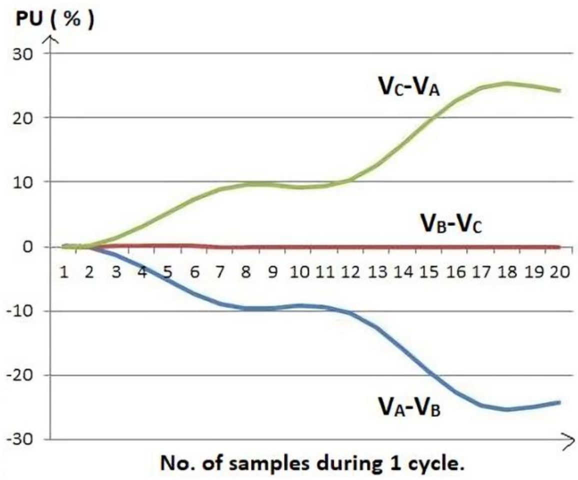
2.2 *Simulation of the Open Phase Faults*

The open-phase faults of an IM, whether in phases A, B, or C, will be simulated during the three action modes of the motor. The three action modes considered are steady-state, transient, and standstill modes. In each case of an open-phase fault during these three modes, the values in per-unit of the motor phase voltages and line currents have been collected using a sampling frequency of 1 kHz (20 samples per cycle). The values in per-unit of the motor phase voltages are (V_A, V_B, and V_C), which are based on the rated phase voltage of motor. The values in per-unit of the motor line currents are (I_A, I_B, and I_C), which are based on the rated current of motor. Then, the differences or changes between the per-unit values of the motor phase voltages (V_A-V_B, V_B-V_C, V_C-V_A) and line currents (I_A-I_B, I_B-I_C, and I_C-I_A) are calculated. The values resulting from calculating these differences are drawn and monitored during one cycle (20 samples per cycle) after the occurrence of a phase-opening fault. Drawing and monitoring these values is for two reasons: the first is to clarify their changes due to the occurrence of this fault, and the second is to deduce the rules that differentiate between each fault case. These rules inferred from the changes resulting from the differences mentioned previously will be relied upon during the final design of the proposed algorithm, which will be explained later in Subsection 2.3.

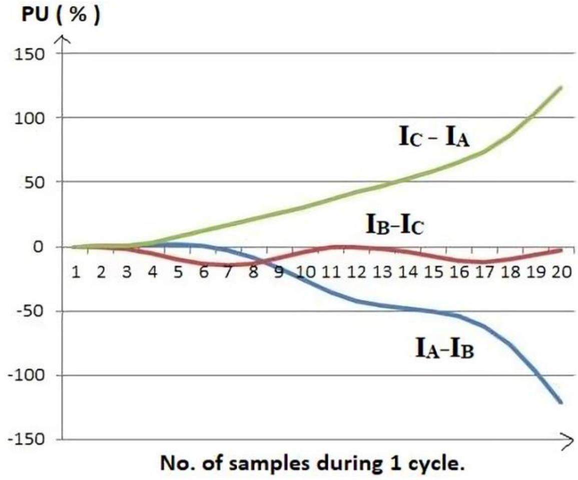
2.2.1 *Simulation of the open phase faults in the motor steady-state mode*

Here, the open-phase faults of phases A, B, and C have been simulated from the source or beyond the relay location, when the motor operates in steady-state mode. Initially, the open-phase fault from the motor source for phase "A" will be simulated when the motor is operating in steady-state mode under full load. **Figure 3** shows the values resulting from the differences between the per-unit values of the phase voltages (V_A-V_B, V_B-V_C, and V_C-V_A) and the line currents (I_A-I_B, I_B-I_C, and I_C-I_A) during one cycle (20 samples) after this fault occurs. Several things are clear from this figure as follows:

- The value of (V_C-V_A) increases above zero and becomes higher than 20% (pu) during the first cycle after the occurrence of this fault, while it is less than -20% (pu) for the value of (V_A-V_B).
- The value of (I_C-I_A) increases above zero and becomes higher than 100% (pu) during the first cycle after the occurrence of this fault, while it is less than -100% (pu) for the value of (I_A-I_B).



(a) The per-unit changes of the phase voltages.



(b) The per-unit changes of the line

Fig. 3. The per-unit changes of the motor phase voltages and line currents during one cycle (20 samples) after opening phase "A" of the motor supply, when the motor is operating in steady state mode.

In the same way, many different cases of this type of fault have been simulated under different operating conditions of the motor, such as various loads and different source voltages within the range of normal operating conditions of the motor. Thus, by observing all the simulation results, the first suitable rule for detecting this type of fault has been deduced. This rule is listed in **Table 3** (No. 1), which must fulfill all of the following conditions:

- The value of (V_C -V_A) is ≥ 4 % and the value of (V_A - V_B) is ≤ - 4%.
- The value of (I_C - I_A) is > 30 % and the value of (I_A - I_B) is < - 30%.

The numerical values mentioned in this rule have been chosen to detect this type of fault and also to avoid fulfilling this rule in the event of an acceptable imbalance in phase voltages and line currents of the motor during its normal operating conditions.

In the same way, when the motor is operating in steady state mode, the rules have been deduced for the fault detection of the open phase from the source for the other phases, B and C, as well as the rules for the open phase faults occurring after the relay location. All of these rules derived for different phase loss cases, whether from the source or behind the relay when the motor is running in a steady state, are mentioned in **Table 3**.

The values resulting from the voltage changes (4%, -4%) mentioned in all the rules have been chosen in this way in order to avoid fulfilling these conditions when the voltages are unbalanced during the motor normal operation. Also, the values resulting from the current changes (30%, -30%) mentioned in all rules have been chosen like this for two reasons. The first reason is to avoid fulfilling these conditions when the currents are unbalanced during the normal operation of the motor. The second reason is to ensure that the conditions resulting from

Table 3: Rules for detecting the open-phase faults in the steady-state mode of motor.

Fault type	The rule for detecting the open-phase fault in the motor steady-state mode.						When the rule is achieved.
	$V_A - V_B$ (PU)	$V_B - V_C$ (PU)	$V_C - V_A$ (PU)	$I_A - I_B$ (PU)	$I_B - I_C$ (PU)	$I_C - I_A$ (PU)	Output
Loss of phase "A" from the power source	≤ - 4 %	----	≥ 4 %	< - 30 %	----	> 30 %	1
Loss of phase "A" beyond the relay location	> - 4 %	----	< 4 %	< - 30 %	----	> 30 %	2
Loss of phase "B" from the power supply	≥ 4 %	≤ - 4 %	----	> 30 %	< - 30 %	----	3
Loss of phase "B" beyond the relay location	< 4 %	> - 4 %	----	> 30 %	< - 30 %	----	4
Loss of phase "C" from the power supply	----	≥ 4 %	≤ - 4 %	----	> 30 %	< - 30 %	5
Loss of phase "C" beyond the relay location	----	< 4 %	> - 4 %	----	> 30 %	< - 30 %	6

the voltage changes (4%, -4%) are met before fulfilling the conditions resulting from the current changes (30%, -30) in the event of phase loss faults from the source. Thus, we avoid fulfilling the rules for detecting phase-loss faults after the location of the relay at the beginning of the occurrence of phase-open faults from the source due to small changes in voltages during this period. As given in **Table 3**, when the conditions of any rule are met, it is expressed with a different value than others as an output for the purpose of classifying these faults in steady-state mode of the motor. In order to avoid fulfilling these rules during short circuit faults, it is preferable to add another condition to all of these rules, which is that the per unit value of the minimum current for the motor currents be less than 25%.

2.2.2 *Simulation of the open phase faults in the motor transient mode*

In this subsection, the open-phase faults of phases A, B, and C have been simulated from the source or beyond the location of relay when the motor operates at the start moment or during the transient mode of motor. From the simulated results of these faults, it is clear that the same rules given in **Table 3** are used in the transient mode, but with a simple difference. The values resulting from current changes have been set (80%, -80%) instead of (30%, -30) in all rules. Another condition has been added to all rules: the minimum value of all currents is less than 80%. The reason for this is to avoid fulfilling these rules because of the unbalanced currents during the starting period of motor without causing faults. A delay time of 5 ms is also applied to the rules of phase-loss faults after the relay location to avoid being verified at the beginning of any open-phase fault occurring from the motor power supply. Thus, all the rules for detecting various types of open-phase faults in the transient mode of motor are listed in **Table 4**.

Table 4: Rules for detecting open phase faults during the transient mode of motor.

Fault type	The rule for detecting any phase loss fault in transient mode.							When the rule is achieved.	
	$V_A - V_B$ (PU)	$V_B - V_C$ (PU)	$V_C - V_A$ (PU)	$I_A - I_B$ (PU)	$I_B - I_C$ (PU)	$I_C - I_A$ (PU)	I_{min} (PU)	Time delay	Output
Loss of phase "A" from the power supply	≤ - 4 %	----	≥ 4 %	< - 80 %	----	> 80 %	< 80 %	---	7
Loss of phase "A" beyond the relay location	> - 4 %	----	< 4 %	< - 80%	----	> 80 %	< 80 %	5 ms (1/4 cycle)	8
Loss of phase "B" from the power supply	≥ 4 %	≤ - 4 %	----	> 80 %	< - 80 %	----	< 80 %	---	9
Loss of phase "B" beyond the relay location	< 4 %	> - 4 %	----	> 80 %	< -80 %	----	< 80 %	5 ms (1/4 cycle)	10
Loss of phase "C" from the power supply	----	≥ 4 %	≤ - 4 %	----	> 80 %	< -80 %	< 80 %		11
Loss of phase "C" beyond the relay location	----	< 4 %	> - 4 %	----	> 80 %	< -80 %	< 80 %	5 ms (1/4 cycle)	12

2.2.3 Simulation of the open phase faults when motor is in standstill mode

When the motor is in standstill mode, it is important to detect phase loss faults to prevent starting a motor with two phases missing a third because it causes over currents to pass through the other two healthy phases. Thus, the rules in the motor stanstill mode have been derived for cases of loss of one or more phases, as given in **Table 5**. Here all the rules are derived using the per- unit values for the phase voltages of the motor because the currents are zero during this mode. It is noted from this table that when the motor is in stanstill mode and the per-unit value of voltage of any phase of its supply source is higher than 80%, there is no loss of this phase of the source. When the per-unit values of all the phase voltages of the motor power supply are less than 30% of the rated motor phase voltage, in this case the power supply is cut off or all phases are lost. In this last rule, a delay time of 5 ms is applied to avoid achieving this rule at the first sample values of voltages that are less than 30% at the start of operation of the motor's power source.

Table 5: Rules for detecting the Phase loss faults when the motor is in the standstill mode.

Fault type	The rules for detecting the phase loss faults when motor is in the standstill mode.			When the rule is achieved.	
	V_A (PU)	V_B (PU)	V_C (PU)	Time delay	Output
Phase "A" is lost from the motor power source	< 30 %	≥ 80 %	≥ 80 %	-----	13
Phase "B" is lost from the motor power source	≥ 80 %	< 30 %	≥ 80 %	-----	14
Phase "C" is lost from the motor power source	≥ 80 %	≥ 80 %	< 30 %	-----	15
Phases "A & B" are lost from the motor power source	< 30 %	< 30 %	≥ 80 %	-----	16
Phases "B & C" are lost from the motor power source	≥ 80 %	< 30 %	< 30 %	-----	17
Phases "C & A" are lost from the motor power source	< 30 %	≥ 80 %	< 30 %	-----	18
Power supply outage or three phases are missing from the source.	< 30 %	< 30 %	< 30 %	5 ms (1/4 cycle)	19

2.3 Design of the Proposed Algorithm

After deriving the rules from the simulation cases for the open-phase faults during steady-state, transient, and standstill modes for the motor, the design of the proposed algorithm based on these rules is described in this subsection. For ease of describing the proposed algorithm, it is described using a flow chart shown in **Fig. 4**. which consists of 8 steps as follows:

- **Step 1:** In this step (the beginning of the scheme), algorithm outputs is set to zero (OP = 0).
- **Step 2:** In this step, the user enters the data for the motor and measuring devices, as follows:
  - Rated values for the motor voltage, line current and speed {V_R (V), I_R (A), N_R (rpm)}. These values are used to calculate the per-unit values in step 5.
  - Ratio of the voltage transformers (VTs), current transformers (CTs) and speed sensor of the motor. These values help in converting the measured values into their actual values.
- **Step 3**: In this step, the readings are read from the measuring devices as follows:

- The instantaneous phase voltages of motor (Va , Vb , Vc) in volts.
- The instantaneous line currents of motor (I_a , I_b , I_c) in amperes.
- The motor speed (N) in rpm.
- The Push button case of Reset (0 / 1).

- **Step 4:** In this step, the continuous RMS values for the phase voltages and line currents of the motor that were read in the previous step are prepared.
- **Step 5:** In this step, the actual values of the RMS phase voltages, RMS currents, and speed of motor are calculated and then converted to their per-unit values as follows:
  - The RMS phase voltages based on the rated phase voltage of motor (V_A, V_B, V_C).
  - The RMS line currents based on the motor rated current (I_A, I_B, I_C).
  - The motor speed based on the rated motor speed (N_m).
- **Step 6**: In this step, the motor mode (MC) is categorized into three modes. The first mode occurs when the motor is stationary, and in this case, MC is assigned a value of zero. The second mode occurs when the motor is operating in a transient mode, and MC is set to 1. The third mode occurs when the motor is running in a steady state, with a speed exceeding 90% of its rated speed and line currents below 125% pu, considering an overload tolerance. In this last mode, MC is assigned a value of 2, which remains constant until motor is stopped.
- **Step 7**: In this step, the rules derived from the simulation process in subsection 2.2 are applied. When the value of MC is equal to 2, the rules listed in Table 3 for detecting open phase faults are applied when the motor is operating in the steady state mode. When the value of MC is equal to 1, the rules listed in Table 4 for detecting open phase faults are applied when the motor is operating in the transient mode. When the value of MC is equal to 0, the rules listed in Table 5 for detecting open phase are applied when the motor is stopping.
- **Step 8:** In this step, the operating circuit of the three-phase induction motor is disconnected in the event of a trip (T = 1) due to any open-phase fault.
- **Step 9:** In this step, the results of the algorithm are displayed, showing the per-unit phase voltages, per-unit currents, and the status of the reset push-button (0 or 1). These results illustrate the algorithm performance during both normal operation and instances of open-phase faults. Subsequently, the algorithm returns to step No. 3 to reacquire the measured values from the measuring devices, repeating the preceding steps in an ongoing cycle.

2.4 Results and Discussion

Once the proposed algorithm for detecting the open phase faults for 3-ph induction motor has been designed, it needs to undergo testing across various scenarios. The purpose of testing is to verify the effectiveness of the suggested algorithm in identifying the phase failure for the motor under different operating conditions. To achieve this, the proposed algorithm has been tested under two conditions: normal motor operation and upon the occurrence of any of the open-phase faults listed in **Tables 3, 4 and 5**. These tests have been conducted at various loads and voltages and at different open-phase fault times. Throughout the simulations, the output of the suggested algorithm (referred to as OP) has been displayed over time, along with the values in per-unit for both the line currents and phase voltages of the motor, and the status of the reset pushbutton. It is assumed that the signal generated of Reset button in the simulation lasts for half a cycle (10 ms).

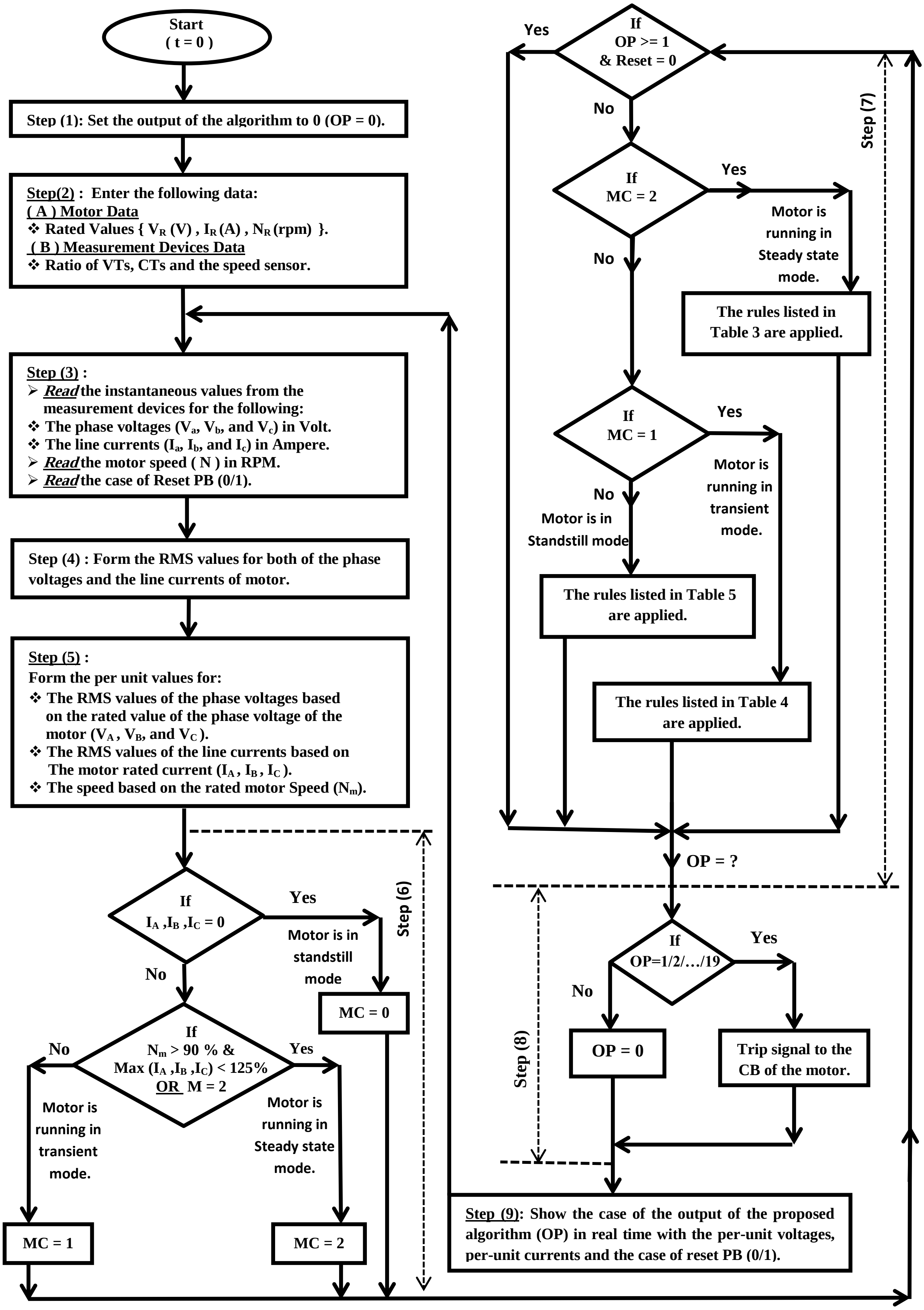


Fig. 4: Flow chart of the proposed algorithm for detection and classification of the open phase faults (OP) for 3-phase induction motor.

2.4.1 Normal conditions

To evaluate the effectiveness of the algorithm in normal conditions, the motor has been operated under various loads without experiencing any phase loss. The simulation results showed that the proposed algorithm works very efficiently under normal motor operating conditions and that its output is equal to zero. **Fig. 5** shows one of these cases. This case represents normal motor operation at 20.30 ms under full load and rated voltage without any phase loss fault. It is show from this figure that the suggested algorithm works well and its value is equal to zero when the motor operates normally in its the transient and steady modes without any phase loss faults.

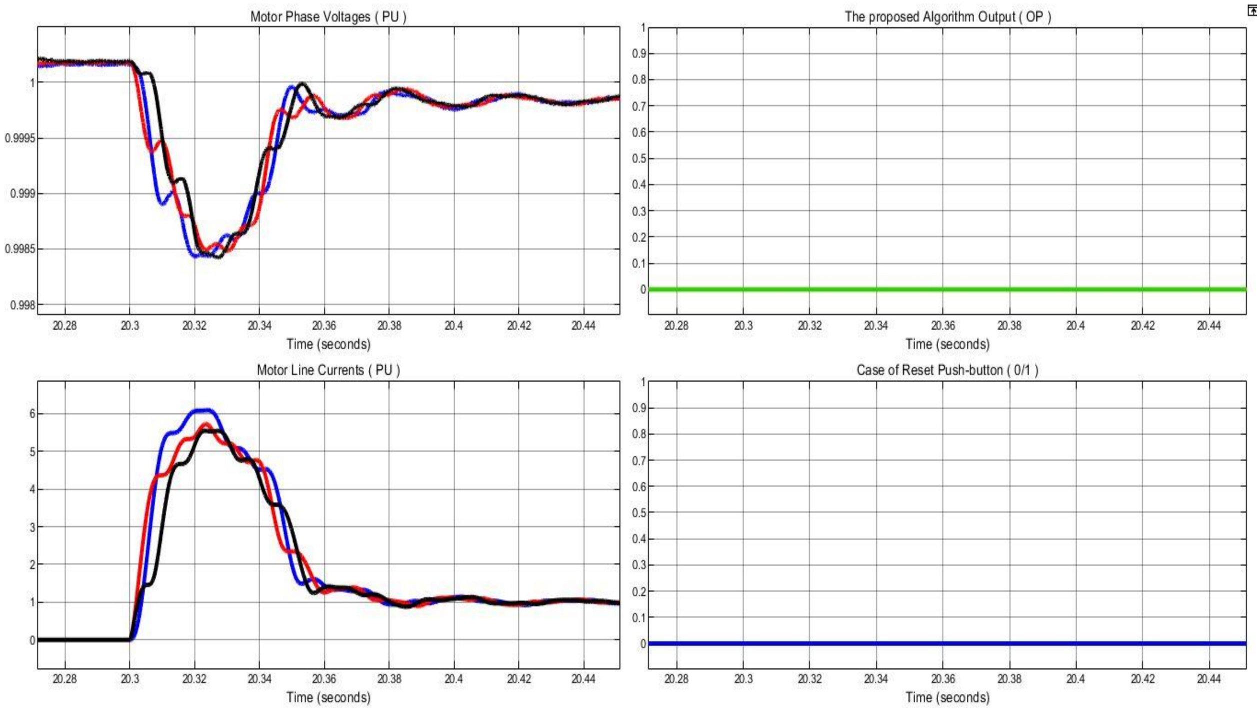


Fig. 5. Algorithm ouput (OP) in case of the normal operation of 3-ph induction motor at 20.30 ms under full load and rated voltage without any phase loss fault.

2.4.2 Results of Phase loss faults in the steady-state mode of motor

Here, the proposed algorithm has been tested for 48 cases of open-phase faults, whether from the motor power supply or behind the locaion of relay, when the motor operates in steady-state mode. All results for these cases prove that the algorithm behaves very efficiently in detection and diagnosis these faults. Among these cases is an open phase fault for phase "A" from the source at 30.34 seconds when the motor is running in the steady state mode under full load at its rated voltage. **Figure 6** shows the algorithm output for that case (Case 7 in **Table 6**). It is clears from this figure that the proposed algorithm detects and classifies this fault correctly (OP=1, as listed in **Table 3**) at a time of 30.352 seconds, and then the motor is stopped. Thus, the algorithm operation time is 12 ms. To illustrate the algorithm performance during and after pressing the Reset pushbutton after repairing that fault, we assumed in the simulation that the fault is quickly repaired at 30.42 seconds and Reset pushbutton is pressed at 30.44 sec. We notice from this figure that the algorithm output returns to zero after repairing the fault when the reset pushbutton is pressed. **Table 6** lists the test results for 24 various cases of the open-phase faults from the source in the motor steady state at different loads, voltages, and time periods.

Figure 7 shows another case (Case 19 in **Table 7**) of the open-phase fault in the motor mode of the steady state for phase "C" after the location of relay. This fault occurs at 20.32 seconds in the steady-state mode of motor under 60% of the rated load and 90% of its rated voltage. It is show from this figure that the suggested algorithm detects and classifies this fault correctly (OP=6, as listed in **Table 4**) at 20.336 sec. Thus, the time of algorithm operation is 16 ms. In the same way, the algorithm output returns to zero when the reset pushbutton is pressed at 20.42 seconds after this fault is repaired at 20.40 sec. **Table 7** lists the test results for 24 cases of the open-phase faults after the location of relay in the motor steady-state at different loads, voltages, and time periods.

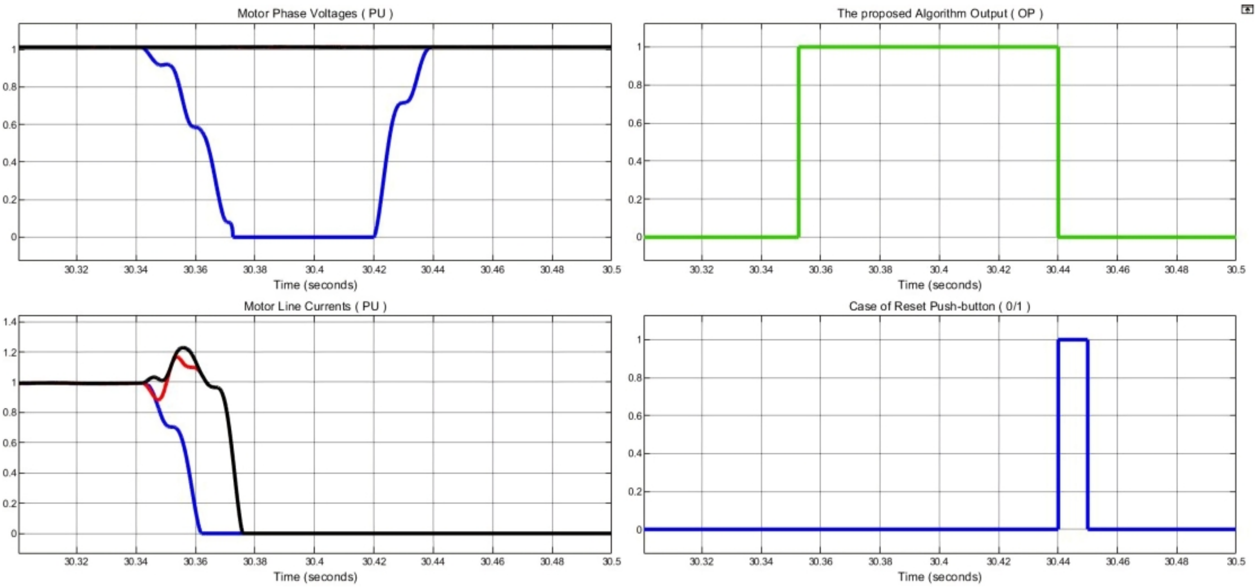


Fig. 6. Algorithm ouput (OP) in case of open phase fault for phase "A" from the source at 30.34 seconds in the steady-state mode, when the motor operates under full load with its rated voltage.

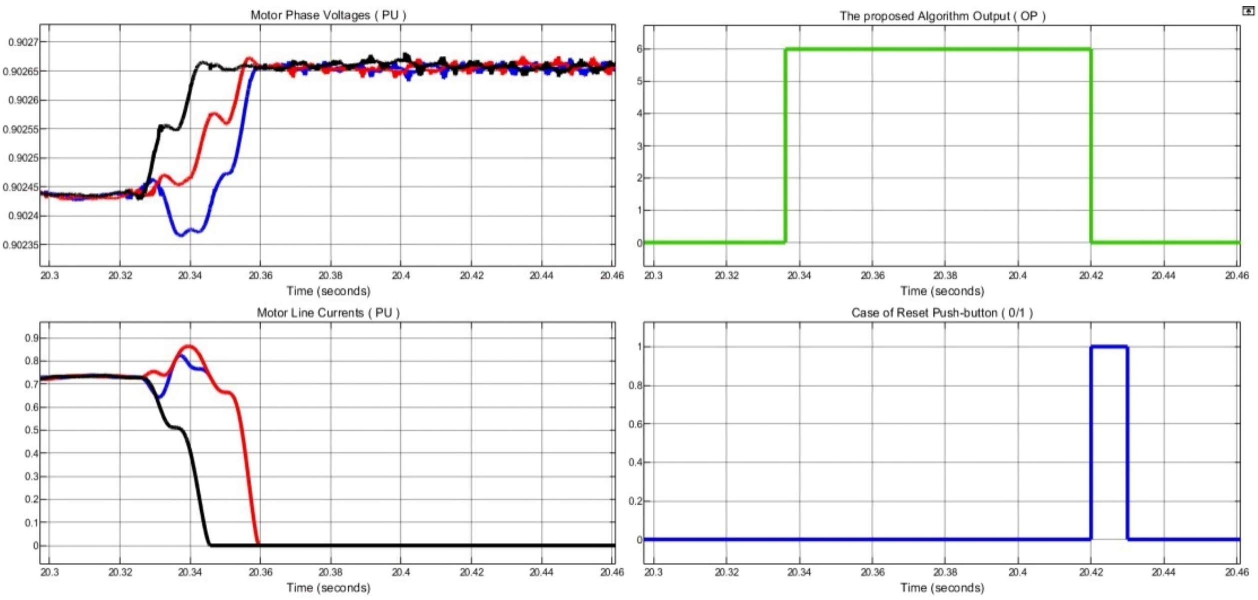


Fig. 7. Algorithm ouput (OP) in case of fault of open phase "C" occurring after relay location at 20.32 seconds in the steady-state mode of motor under 60% of the rated load and a voltage of 90% of its rated values.

Table 6: Proposed algorithm result (OP) during the occurrence of a phase loss fault (A, B, or C) from the motor source during its operation in the steady state mode at different conditions (t_{st} at 0.1 sec.).

No.	The open phase (Fault)	The motor loading (%)	Source voltage ± 0.5 % (PU %)	Fault inception Time (Sec.)	The algorithm output (OP)	The time of fault detection (Sec.)	Time of algorithm operation (ms)	The time of fault repair (Sec.)	Time of Reset (Sec.)	Algorithm output (OP)after Reset
1	A	10	100	10.300	1	10.319	19	10.380	10.400	0
2	A	30	105	20.305	1	20.329	24	20.385	20.405	0
3	A	60	90	30.310	1	30.323	13	30.390	30.410	0
4	A	70	100	40.315	1	40.331	16	40.395	40.415	0
5	A	80	105	10.250	1	10.260	10	10.330	10.350	0
6	A	90	90	20.335	1	20.350	15	20.415	20.435	0
7	A	100	100	30.340	1	30.352	12	30.420	30.440	0
8	A	105	105	40.355	1	40.370	15	40.435	40.455	0
9	B	10	100	10.300	3	10.316	16	10.380	10.400	0
10	B	30	105	20.305	3	20.326	21	20.385	20.405	0
11	B	60	90	30.310	3	30.329	19	30.390	30.410	0
12	B	70	100	40.315	3	40.328	13	40.395	40.415	0
13	B	80	105	10.250	3	10.267	17	10.330	10.350	0
14	B	90	90	20.335	3	20.347	12	20.415	20.435	0
15	B	100	100	30.340	3	30.357	17	30.420	30.440	0
16	B	105	105	40.355	3	40.366	11	40.435	40.455	0
17	C	10	100	10.300	5	10.323	23	10.380	10.400	0
18	C	30	105	20.305	5	20.323	18	20.385	20.405	0
19	C	60	90	30.310	5	30.326	16	30.390	30.410	0
20	C	70	100	40.315	5	40.325	10	40.395	40.415	0
21	C	80	105	10.350	5	10.364	14	10.430	10.450	0
22	C	90	90	20.335	5	20.343	8	20.415	20.435	0
23	C	100	100	30.340	5	30.353	13	30.420	30.440	0
24	C	105	105	40.355	5	40.363	8	40.435	40.455	0

Table 7: Proposed algorithm result (OP) during the occurrence of a phase opening fault (A, B, or C) after location of relay during the steady-state mode of motor at different conditions (t_{st} at 0.1 sec.).

No.	The open phase (Fault)	The motor loading (%)	Source voltage ± 0.5 % (PU %)	Fault inception Time (Sec.)	The algorithm output (OP)	The time of fault detection (Sec.)	Time of algorithm operation (ms)	The time of fault repair (Sec.)	Time of Reset (Sec.)	Algorithm output (OP)after Reset
1	A	10	108	30.310	2	30.330	20	30.390	30.410	0
2	A	30	100	40.325	2	40.348	23	40.405	40.425	0
3	A	60	90	20.320	2	20.332	12	20.400	20.420	0
4	A	70	107	10.325	2	10.345	20	10.405	10.425	0
5	A	80	100	20.350	2	20.361	11	20.430	20.450	0
6	A	90	92	10.330	2	10.340	10	10.410	10.430	0
7	A	100	106	20.340	2	20.350	10	20.420	20.440	0
8	A	105	100	30.355	2	30.370	15	30.435	30.455	0
9	B	10	108	30.310	4	30.327	17	30.390	30.410	0
10	B	30	100	40.325	4	40.345	20	40.405	40.425	0
11	B	60	90	20.320	4	20.339	19	20.400	20.420	0
12	B	70	107	10.325	4	10.341	16	10.405	10.425	0
13	B	80	100	20.350	4	20.367	17	20.430	20.450	0
14	B	90	92	10.330	4	10.347	17	10.410	10.430	0
15	B	100	106	20.340	4	20.356	16	20.420	20.440	0
16	B	105	100	30.355	4	30.366	11	30.435	30.455	0
17	C	10	108	30.310	6	30.332	22	30.390	30.410	0
18	C	30	100	40.325	6	40.341	16	40.405	40.425	0
19	C	60	90	20.320	6	20.336	16	20.400	20.420	0
20	C	70	107	10.325	6	10.335	10	10.405	10.425	0
21	C	80	100	20.350	6	20.364	14	20.430	20.450	0
22	C	90	92	10.330	6	10.343	13	10.410	10.430	0
23	C	100	106	20.340	6	20.353	13	20.420	20.440	0
24	C	105	100	30.355	6	30.363	8	30.435	30.455	0

2.4.3 Results of Phase loss faults in the transient mode of motor

Here, the suggested algorithm has been tested for 48 cases of open-phase faults, whether from the motor power supply or behind the location of relay, when the motor operates in the transient mode. All results for these cases prove that the suggested algorithm is characterized by its efficiency and high accuracy in detection and diagnosis these faults. Among these cases is an open phase fault in the motor transient mode for phase "B" from the motor source at 2.11 seconds when the motor operates with its rated voltage at 2.105 seconds . **Figure 8** shows the output of the proposed algorithm for that case (Case 10 in **Table 8**). It is clears from this figure that the proposed algorithm detects and classifies this fault correctly (OP=9, as listed in **Table 4**) at a time of 2.137 seconds, and then the motor is stopped. Thus, the time of algorithm operation to detect and classify this fault is 27 ms. To illustrate the suggested algorithm performance during and after pressing the Reset pushbutton after repairing that fault, we assumed in the simulation that the fault is quickly repaired at 2.19 seconds and the Reset pushbutton is pressed at 2.21 seconds. It is noted from this figure that when the reset button is pressed after repairing that fault, the output of the suggested algorithm returns to its normal state before the fault occurred, equal to zero. **Table 8** lists the test results for 24 different cases of the open-phase faults from the side of source when the motor starts in the transient periods with different voltages, and at different times.

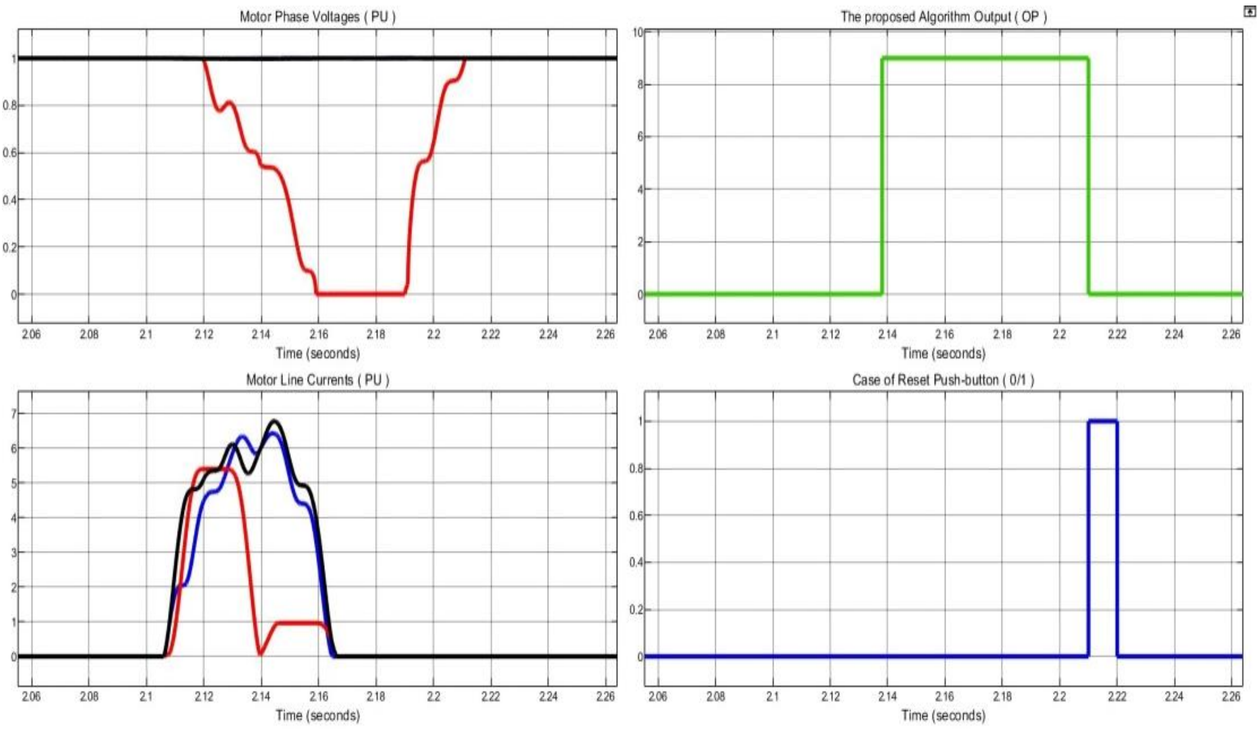


Fig. 8: Algorithm ouput (OP) in case of open phase fault in the transient mode for phase "B" from the source at 2.11 seconds when the motor operates at 2.105 seconds with its rated voltage.

Figure 9 shows another case (Case 7 in **Table 9**) of the open-phase fault for phase "A" but after the location of relay, when motor starts in the transient mode. This fault occurs at 7.31 seconds at the moment of the motor starting in transient mode at 7.31 seconds with 95% of its rated voltage. It is show from this figure that the algorithm detects and classifies this fault correctly (OP=8, as listed in **Table 4**) at 7.319 sec. Thus, the algorithm operation time is 9 ms.

In the same way, the algorithm output returns to zero when the reset pushbutton is pressed at 7.41 seconds after this fault is repaired at 7.39 sec. **Table 9** lists the test results for 24 cases of the open-phase faults after the location of relay in the motor transient mode with different voltages, and at different times.

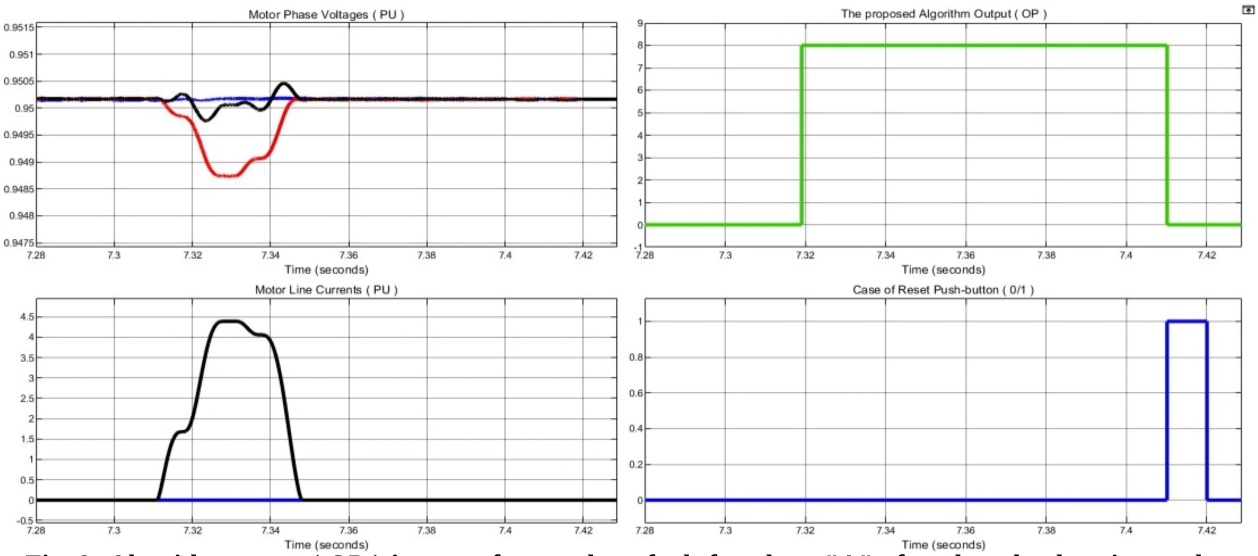


Fig. 9: Algorithm ouput (OP) in case of open phase fault for phase "A" after the relay location at the moment of the motor starting in the transient mode at 7.31 seconds with 95% of its rated voltage.

Table 8: Proposed algorithm result (OP) during the occurrence of a phase opening fault (A, B, or C) from the motor power supply during its operation in its transient mode at various conditions.

No.	The open phase (Fault)	Motor starting time (Sec.)	Source voltage ± 0.5 % (PU %)	Fault inception time (Sec.)	The algorithm output (OP)	The time of fault detection (Sec.)	Time of algorithm operation (ms)	Time of fault repair (Sec.)	Time of Reset (Sec.)	Algorithm output (OP)after Reset
1	A	1.100	95	1.100	7	1.103	3	1.180	1.200	0
2	A	2.105	100	2.110	7	2.130	20	2.190	2.210	0
3	A	3.110	107	3.110	7	3.113	3	3.190	3.210	0
4	A	4.115	95	4.125	7	4.150	25	4.205	4.225	0
5	A	5.200	100	5.200	7	5.203	3	5.280	5.300	0
6	A	6.305	107	6.315	7	6.340	25	6.395	6.415	0
7	A	7.310	95	7.310	7	7.313	3	7.390	7.410	0
8	A	8.315	100	8.330	7	8.350	20	8.410	8.430	0
9	B	1.100	95	1.100	9	1.127	27	1.180	1.200	0
10	B	2.105	100	2.110	9	2.137	27	2.190	2.210	0
11	B	3.110	107	3.110	9	3.138	28	3.190	3.210	0
12	B	4.115	95	4.125	9	4.147	22	4.205	4.225	0
13	B	5.200	100	5.200	9	5.227	27	5.280	5.300	0
14	B	6.305	107	6.315	9	6.337	22	6.395	6.415	0
15	B	7.310	95	7.310	9	7.337	27	7.390	7.410	0
16	B	8.315	100	8.330	9	8.355	25	8.410	8.430	0
17	C	1.100	95	1.100	11	1.123	23	1.180	1.200	0
18	C	2.105	100	2.110	11	2.134	24	2.190	2.210	0
19	C	3.110	107	3.110	11	3.133	23	3.190	3.210	0
20	C	4.115	95	4.125	11	4.144	19	4.205	4.225	0
21	C	5.200	100	5.200	11	5.223	23	5.280	5.300	0
22	C	6.305	107	6.315	11	6.334	19	6.395	6.415	0
23	C	7.310	95	7.310	11	7.333	23	7.390	7.410	0
24	C	8.315	100	8.330	11	8.352	22	8.410	8.430	0

Table 9: Proposed algorithm result (OP) during the occurrence of a phase opening fault (A, B, or C) after the location of relay during operation of motor in its transient mode at various times and voltages values.

No.	The open phase (Fault)	Motor starting Time (Sec.)	Source voltage ± 1% (PU %)	Fault inception time (Sec.)	The algorithm output (OP)	The time of fault detection (Sec.)	Time of algorithm operation (ms)	The time of fault repair (Sec.)	Time of Reset (Sec.)	Algorithm output (OP)after Reset
1	A	1.100	95	1.100	8	1.107	7	1.180	1.200	0
2	A	2.105	100	2.110	8	2.136	26	2.190	2.210	0
3	A	3.110	107	3.110	8	3.117	7	3.190	3.210	0
4	A	4.115	95	4.125	8	4.156	31	4.205	4.225	0
5	A	5.200	100	5.200	8	5.207	7	5.280	5.300	0
6	A	6.305	107	6.315	8	6.346	31	6.395	6.415	0
7	A	7.310	95	7.310	8	7.319	9	7.390	7.410	0
8	A	8.315	100	8.330	8	8.356	26	8.410	8.430	0
9	B	1.100	95	1.100	10	1.133	33	1.180	1.200	0
10	B	2.105	100	2.110	10	2.143	33	2.190	2.210	0
11	B	3.110	107	3.110	10	3.143	33	3.190	3.210	0
12	B	4.115	95	4.125	10	4.153	28	4.205	4.225	0
13	B	5.200	100	5.200	10	5.233	33	5.280	5.300	0
14	B	6.305	107	6.315	10	6.343	28	6.395	6.415	0
15	B	7.310	95	7.310	10	7.343	33	7.390	7.410	0
16	B	8.315	100	8.330	10	8.361	31	8.410	8.430	0
17	C	1.100	95	1.100	12	1.129	29	1.180	1.200	0
18	C	2.105	100	2.110	12	2.140	30	2.190	2.210	0
19	C	3.110	107	3.110	12	3.139	29	3.190	3.210	0
20	C	4.115	95	4.125	12	4.150	25	4.205	4.225	0
21	C	5.200	100	5.200	12	5.229	29	5.280	5.300	0
22	C	6.305	107	6.315	12	6.340	25	6.395	6.415	0
23	C	7.310	95	7.310	12	7.339	29	7.390	7.410	0
24	C	8.315	100	8.330	12	8.358	28	8.410	8.430	0

2.4.4 Results of Phase loss faults when motor is in standstill mode

Here, when the motor is in the stanstill mode, the proposed algorithm has been tested for 24 cases of faults of loss of one or more phases from the motor power source. All results for these cases prove that the proposed algorithm behaves very efficiently in detection and diagnosis these faults. Among these cases is an open phase fault for phase "B" from the the motor power source at 2.25 seconds when the motor is in the stanstill mode and the source voltage is equal to the rated value of the motor voltage. **Figure 1**0 shows the suggested algorithm output for this case (Case 5 in **Table 10**). It is clears from this figure that the proposed algorithm detects and classifies this fault correctly (OP=14, as listed in **Table 5**) at a time of 2.27 seconds, and then trip signal is sent to block the motor control circuit. Thus, the operation time of algorithm to detect and classify this fault is 20 ms. This fault is quickly repaired in the simulation at 2.33 seconds and the Reset pushbutton is pressed at 2.35 seconds. It is noted from this figure that when the reset button is pressed after repairing that fault, the algorithm output returns to its value of zero.

Figure 11 shows another case (case 13 in **Table 10**) of a two-open-phases fault (B & C) from the motor supply when the motor is in the stanstill mode. This fault occurs at a time of 1.20 seconds when the source voltage is 95% of the motor rated voltage. It is show from this figure that the proposed algorithm detects and classifies this fault correctly (OP=17, as listed in **Table 5**) at 1.219 sec. Thus, the algorithm operation time is 19 ms. Also, the algorithm output returns to zero when the reset pushbutton is pressed at 1.30 seconds after this fault is repaired at 1.28 sec. **Table 10** lists the test results for 20 cases of faults of loss of one or more phases from the source.

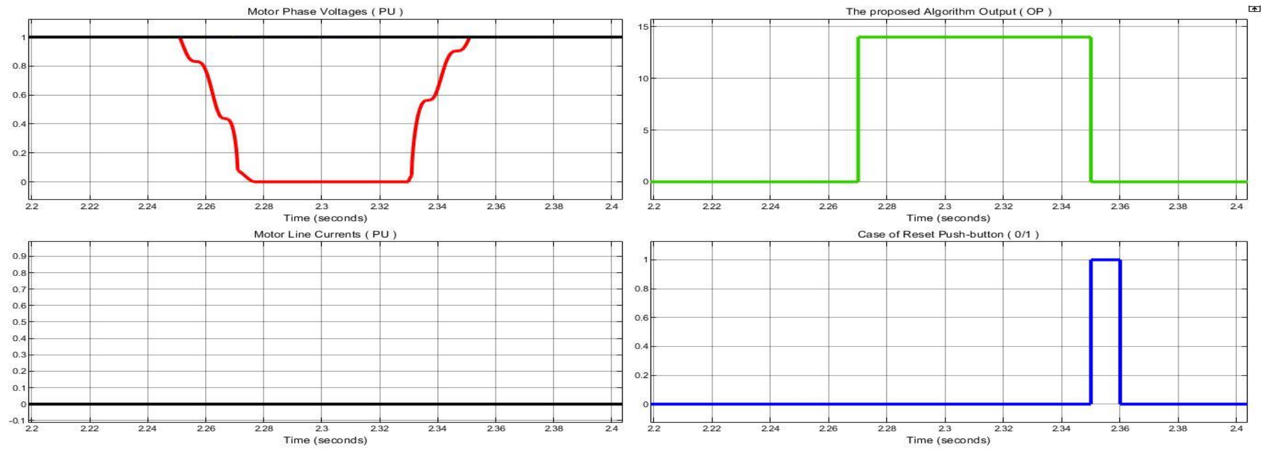


Fig. 10: Algorithm ouput (OP) in case of open-phase fault for phase "B" from the the motor power source at 2.25 seconds, when motor is in its standstill mode and the voltage is the rated voltage of the motor.

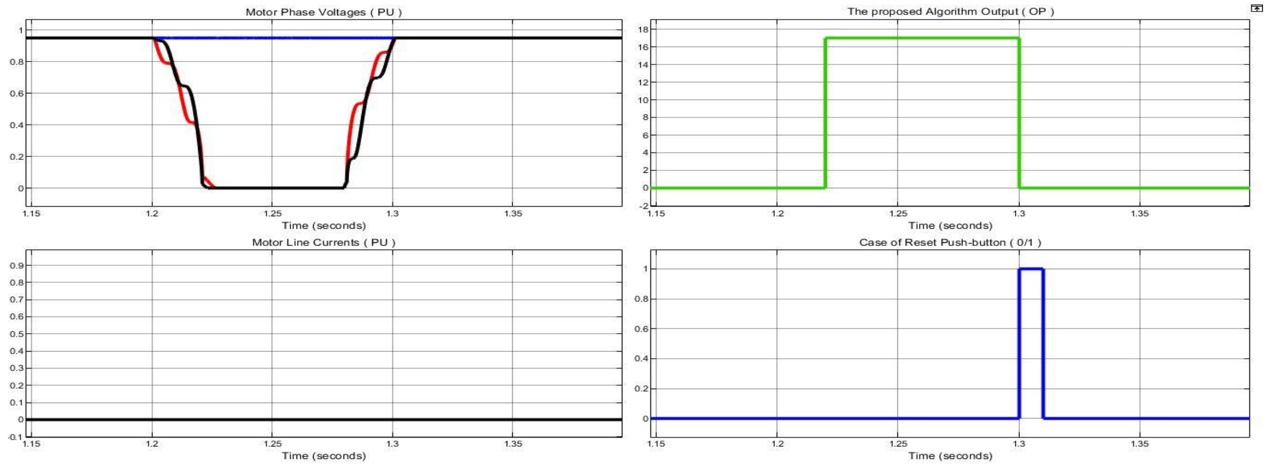


Fig. 11: Algorithm ouput (OP) in case of open phase fault for phases "B & C" from the motor power source at 1.20 seconds, when motor is in its standstill mode and the voltage is 95% of its rated voltage.

Table 10: Algorithm result (OP) during lossing of one or more phases from the motor source at various source voltages and different times, when motor is in its standstill mode.

No.	The open phase (Fault)	Source voltage ± 1% (PU %)	Fault inception Time (Sec.)	The algorithm output (OP)	The time of fault detection (Sec.)	Time of algorithm operation (ms)	The time of fault repair (Sec.)	Time of Reset (Sec.)	Algorithm output (OP)after Reset
1	A	95	1.20	13	1.216	16	1.28	1.30	0
2	A	100	2.25	13	2.266	16	2.33	2.35	0
3	A	105	3.30	13	3.317	17	3.38	3.40	0
4	B	95	1.20	14	1.219	19	1.28	1.30	0
5	B	100	2.25	14	2.270	20	2.33	2.35	0
6	B	105	3.30	14	3.320	20	3.38	3.40	0
7	C	95	1.20	15	1.219	19	1.28	1.30	0
8	C	100	2.25	15	2.269	19	2.33	2.35	0
9	C	105	3.30	15	3.319	19	3.38	3.40	0
10	A-B	95	1.20	16	1.219	19	1.28	1.30	0
11	A-B	100	2.25	16	2.270	20	2.33	2.35	0
12	A-B	105	3.30	16	3.320	20	3.38	3.40	0
13	B-C	95	1.20	17	1.219	19	1.28	1.30	0
14	B-C	100	2.25	17	2.270	20	2.33	2.35	0
15	B-C	105	3.30	17	3.320	20	3.38	3.40	0
16	C-A	95	1.20	18	1.219	19	1.28	1.30	0
17	C-A	100	2.25	18	2.269	19	2.33	2.35	0
18	C-A	105	3.30	18	3.319	19	3.38	3.40	0
19	A-B-C	95	1.20	19	1.225	25	1.28	1.30	0
20	A-B-C	100	2.25	19	2.276	26	2.33	2.35	0

SUMMARY AND CONCLUSIONS

This paper introduces a highly efficient algorithm to detect and classify 19 types of open-phase faults for a three-phase IM. This algorithm has been based on rules or conditions derived from simulating the different cases of open-phase faults in three motor modes (steady-state, transient, and standstill modes). Simulating these faults and testing the proposed algorithm are carried out using MATLAB/Simulink software. Many tests, more than 116 cases, have been conducted to evaluate the proposed algorithm under normal operating conditions and various scenarios of open-phase fault, including motor disconnection events and motor restarts. The algorithm has been tested for 48 cases of the open-phase faults when the motor is already running in steady-state mode, 48 cases when it is operating in its transient periods, and 20 cases when it is in standstill mode. All test results proved that the proposed algorithm works very efficiently and is characterized by its excellent accuracy and high speed in detecting open-phase faults. This algorithm can be applied to a variety of motors since it is based on the per-unit values for the phase voltages, currents and speed of motor. Thus, it can be used and integrated within the main system of protection of a 3-ph IM to detect and diagnose the open-phase faults.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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