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Faculty of Science and Technology
Electrical Department

Thesis

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By : **Sohaib Suliaman Ahmad Abumustafa**

Subject

DETECTION OF ELECTRICAL AND MECHANICAL FAULTS IN STEPPER MOTORS

Presented and defended publicly, on 06/09/2022, before the jury members composed of:

Dr. GATTAL AZZEDINE	MCB	President
Dr. MAAMARI MAHMOUD	MCA	Supervisor
Dr. LOUDJANI ABD HAK	MAA	Examiner

Promotion: 2021/2022

DEDICATION

First and foremost, I want to thank Allah for giving me the strength and courage to do this humble job well.

I dedicate this work

To my dear parents, for all their sacrifices, their love, their tenderness, their support, and their prayers during my studies. You have always supported me and taught me a sense of responsibility, reason, duty, and above all, self-confidence.

May Allah keeps you healthy, dear MOM and DAD, my dear brothers, AYOUP and MOHAMMAD for their constant support, encouragement, and moral help. To all my sisters, my lovers, and all my friends especially ALAA, MAUTH, BAKER, ARAFAT, EID, ATEF, BAHA, IBRAHIE.

I dedicate peace and greetings to my lovely beautiful and occupied homeland Palestine, and I ask Allah to liberate this land.

I also dedicate this work to my second homeland, Algeria, and its great people who embraced us and gave a lot to our case.

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First and foremost, I am extremely grateful to my thesis advisor, Dr. MAAMARI MAHMOUD, for his invaluable advice, continuous support, and patience throughout my master's studies. His immense knowledge and rich experience have always encouraged me in my academic research. My sincere gratitude goes to the members of the juries Dr. LOUDJANI ABD HAK and Dr. GATTAL AZZEDINE who agreed to evaluate our dissertation. Finally, I would like to express my gratitude to my parents, family, special loved ones, and friends. Without their tremendous understanding and encouragement over the past few years, it would have been impossible for me to complete my studies.

Abstract

Due to the characteristics of stepper motors, which are the possibility of precisely controlling the number and speed of motor revolutions and the stopping angle. Steppers are most widely used in technological fields such as robotics, precision machinery, and medical industrial fields.

It is important to do a prior detection of the various faults that may occur in this type of motor, and this is in order to develop methods that allow diagnosing these faults and the possibility of monitoring them and predicting their failure to avoid the difficulties and challenges that may face us in the process of diagnosis and maintenance. In this work, we focus on finding simple and easy methods to diagnose some common electrical and mechanical faults that motors may be exposed to, especially hybrid stepper motors.

ملـــــخـــــص

نظرًا لخصائص محركات السائر ، والتي تتمثل في إمكانية التحكم بدقة في عدد وسرعة دورات المحرك وزاوية التوقف. يتم استخدام السائر على نطاق واسع في المجالات التكنولوجية مثل الروبوتات والآلات الدقيقة والمجالات الصناعية الطبية.

من المهم القيام بالكشف المسبق عن العيوب المختلفة التي قد تحدث في هذا النوع من المحركات وذلك من أجل تطوير طرق تسمح بتشخيص هذه الأعطال وإمكانية مراقبتها والتنبؤ بفشلها لتلافي الصعوبات والتحديات. التي قد تواجهنا في عملية التشخيص والصيانة. في هذا العمل ، نركز على إيجاد طرق بسيطة وسهلة لتشخيص بعض الأعطال الكهربائية والميكانيكية الشائعة التي قد تتعرض لها المحركات ، وخاصة محركات السائر الهجينة.

Résumé

En raison des caractéristiques des moteurs pas à pas, qui sont la possibilité de contrôler avec précision le nombre et la vitesse des tours du moteur et l'angle d'arrêt. Les steppers sont les plus largement utilisés dans les domaines technologiques tels que la robotique, les machines de précision et les domaines industriels médicaux.

Il est important de faire une détection préalable des différents défauts qui peuvent survenir dans ce type de moteur, et ceci dans le but de développer des méthodes qui permettent de diagnostiquer ces défauts et la possibilité de les surveiller et de prévoir leur panne pour éviter les difficultés et défis que nous pouvons rencontrer dans le processus de diagnostic et de maintenance. Dans ce travail, nous nous concentrons sur la recherche de méthodes simples et faciles pour diagnostiquer certains défauts électriques et mécaniques courants auxquels les moteurs peuvent être exposés, en particulier les moteurs pas à pas hybrides.

Notations and Symbols

PM	Permanent Magnet
VR	Variable Reluctance
HB	Hybrid
F_r	Resonant frequency
V_{p1}	Voltage of primary phase 1
V_{p2}	Voltage of primary phase 3
V_{s1}	Voltage off secondary phase 2
V_{s2}	Voltage off secondary phase 4
Q1, Q2, Q3, Q4	Phases of the motor
Tc	Thermocouple
N	Normal phase
S.C	Short-Circuit phase

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Summary

General Introduction

A stepper motor is one of the most accurate electric motors ever made because it can precisely control the position of the rotor, making it suitable for engineering applications that require precise position control. Stepper motors are used in 3D printers, lathes, CNC machines, and embedded systems. This motor is a brushless DC motor, which means there are no brushes on this motor, so it can supply applications with high torque and high pull-through force to control any situation and is easy to control with any type of microelectronic controller.

Therefore, stepper motors are widely used in various fields. One of them is medical and industrial robots, which require high working accuracy. Therefore, since the motors are used in large numbers, it is important to predict the various malfunctions that may occur in this motor in order to develop methods to monitor the operation and detect and predict faults to allow easy and low-cost maintenance, thus reducing material or human losses, especially when the motor is located in a difficult-to-access position to diagnose and detect faults.

In this thesis, we will study the hybrid stepper motor and apply some common electrical and mechanical faults and try to find several methods to diagnose and predict these faults with ease and with minimum effort and cost.

The thesis is divided into three chapters:

Chapter One: We will learn about stepper motors, their types, advantages and disadvantages, their construction, their main uses, and the methods to operate and control them.

Chapter Two: In this chapter, we will apply some common electrical faults in a hybrid motor and find the simplest methods to diagnose them.

Chapter Three: In this chapter, we will apply some common mechanical faults and try to find simple diagnostic methods for them.

Finally, we end this thesis with a general conclusion and proposition in which we highlight the interest of this thesis and give perspectives and recommendations for the future development of this thesis.

CHAPTER I : THE STEPPER MOTORS

I.1 Introduction

The development of the stepper motor can be traced back to the 19th century. The modern stepper motor was first invented in 1957 by Thomas and Fleischauer and was a variable reluctance type **[1]**. Stepper motors make it possible to directly convert a digital electrical signal into an angular positioning of incremental character. Each pulse sent by the control system to the power module results in the rotation of one step of the motor. The angular resolution of a stepper motor ranges from 4 to 400 steps. Stepper motors are now used in many industries around the world because they are suitable for both speed and position control. These motors are commonly used to operate machine tools and other equipment where precise positioning is required. Speed control of electrical motors has always been the field of interest of many researchers and scientists. The need to control the speed and/or the position of motors has countless applications in our daily life.

I.2 Definition

A Stepper motor is a brushless DC motor in which each rotation (revolution) is divided into a certain number of steps depending on the motor structure. Typically, a full 360° shaft rotation is divided into 200 steps, which means that a single step is performed every 1.8°. There are also motors where a single step is performed every 2°,2.5°,5°, 15°, or 30° **[2]**.

Figure I.1: photo of a stepper motor

I.3 Applications of stepper motor

There are several types of stepper motors are available in today's market over a wide range of sizes, step count, constructions, wiring, gearing, and other electrical characteristics. As these motors are capable to operate in discrete nature, they are well suitable to interface with digital control devices like computers. Due to the precise control of speed, rotation, direction, and angular position, these are of particular interest in industrial process control systems, CNC machines, robotics, manufacturing automation systems, and instrumentation.

I.4 Construction

The stepper motor consists of the stator and the rotor. The rotor is the movable part that has no windings, brushes, or commutator. Usually, the rotors are either variable reluctance or permanent magnet kind. The stator is often constructed with multi-pole and multi-phase windings, usually, three- or four-phase windings wound for a specific number of poles determined by the desired angular displacement per input pulse.

Unlike other motors, it uses programmed discrete control pulses applied to the stator windings via an electronic drive. The rotation occurs due to the magnetic interaction between the poles of the sequentially excited stator winding and the poles of the rotor **[3]**.

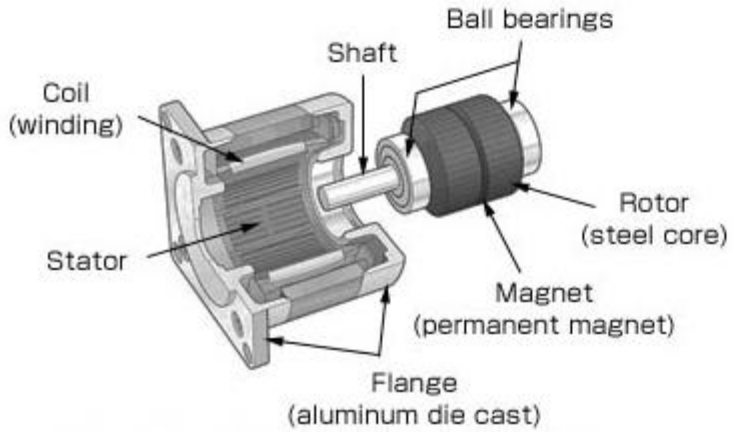

Figure I.2: Construction of a Stepper Motor

I.5 Type of stepper motors

There are three basic categories of stepper motors.

1. Permanent Magnet Stepper Motor.
2. Variable Reluctance Stepper Motor.
3. Hybrid Stepper Motor.

I.5.1 Permanent Magnet Stepper Motor (PM)

Permanent magnet motors use a permanent magnet (PM) in the rotor and operate on the attraction or repulsion between the rotor PM and the stator electromagnets.

This is the most common type of stepper motor compared to the other types of stepper motors available on the market. This motor contains permanent magnets for the construction of the motor. This type of motor is also known as tin-can/can-stack motor. The main advantage of this stepper motor is its lower manufacturing cost, this type of motor has 48-24 steps per revolution **[3]**.

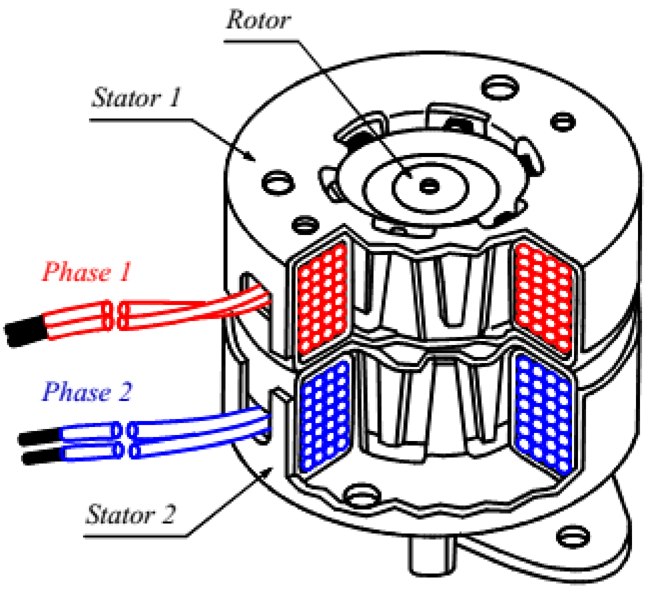

Figure I.3: PM or tin-can stepper motor

I.5.2 Variable Reluctance Stepper Motor (VR)

Variable reluctance motors (VR) have a plain iron rotor and operate based on the principle that a minimum reluctance occurs with a minimum gap, so that the rotor tips are attracted to the magnetic poles of the stator. As the name suggests, the angular position of the rotor depends mainly on the reluctance of the magnetic circuit that can be formed between the teeth of the stator and the rotor **[3]**.

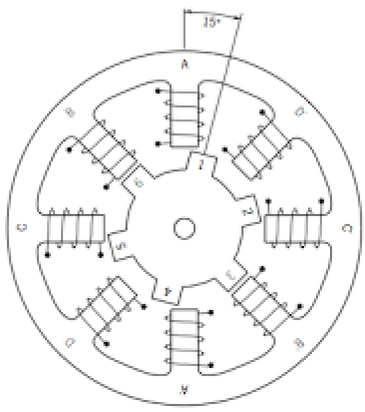

Figure I.4: VR stepper motor

I.5.3 Hybrid Stepper Motor (HB)

Hybrid stepper motors are named because they use a combination of permanent magnet (PM) and variable reluctance (VR) technology to achieve maximum performance in a small package. The most popular type of motor is the hybrid stepper motor because it offers good performance in terms of speed, step resolution, and holding torque compared to a permanent magnet rotor. However, this type of stepper motor is expensive compared to permanent magnet stepper motors. This motor combines the characteristics of the permanent magnet and variable reluctance stepper motors. These motors are used where a smaller step angle is required, such as 1.5°, 1.8°, and 2.5° **[4]**.

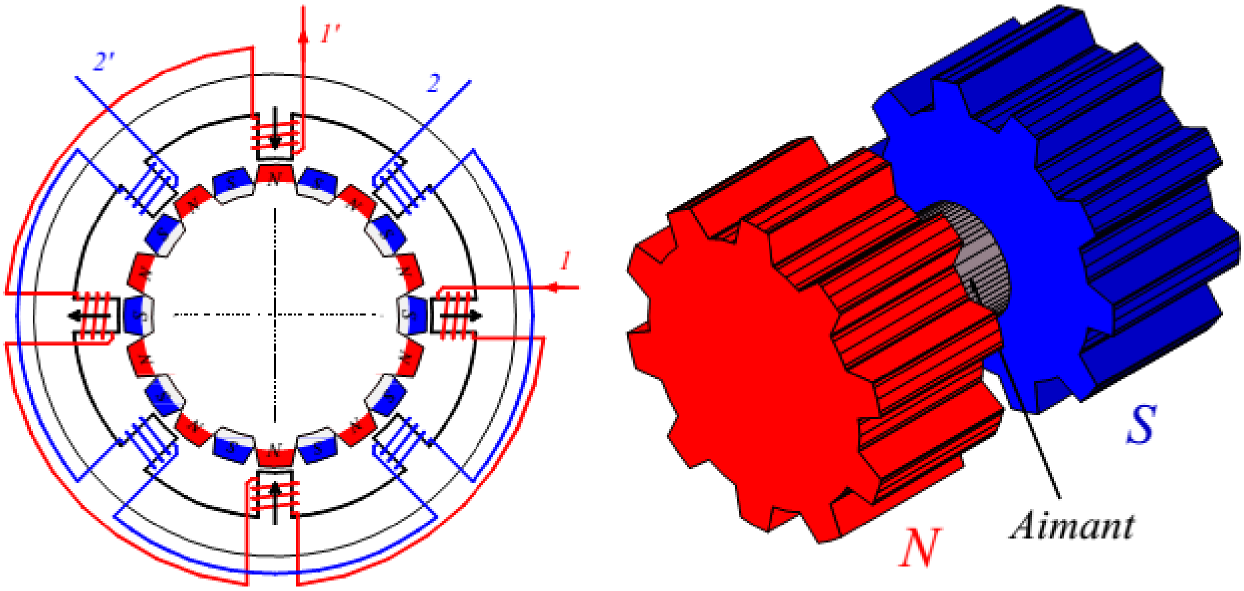

Figure I.5: HB stepper motor

I.6 Unipolar and Bipolar Stepper Motors

The above-discussed motors can be classified into two types based on the coil winding arrangements of the stator, which are Bipolar and Unipolar stepper motors.

I.6.1 The bipolar motor

Bipolar stepper motors consist of two windings and have four wires. Unlike unipolar motors, bipolar motors do not have center taps. The advantage of not having center taps is that the current flows through an entire winding at a time, not just half of the winding. Therefore, bipolar motors produce higher torque than unipolar motors of the same size. The disadvantage of bipolar motors compared to unipolar motors is that a more complex control circuit is required for bipolar motors. The current flow in the winding of a bipolar motor is bidirectional. This requires a change in polarity at each end of the windings. As shown in Figure 1.6, the current in winding 1 flows from left to right when 1a is positive and 1b is negative. The current flows in the opposite direction when the polarity is reversed at both ends. To change the polarity at the ends of a winding, a control circuit called an H-bridge is used. Each bipolar motor has two windings; therefore, two H-bridge control circuits are needed for each motor **[5]**.

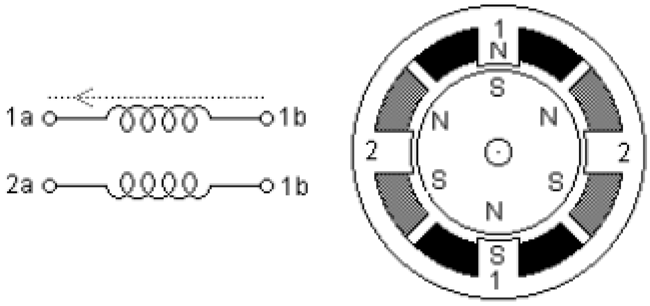

Figure I.6: Bipolar stepper motor construction

I.6.2 The unipolar motor

Unipolar stepper motors consist of two windings, each with a center tap. The center taps either run out of the motor as two separate wires (as shown in Figure 1.7) or internally connected together and run out of the motor as one wire.

Therefore, unipolar motors have 5 or 6 wires. Regardless of the number of wires, unipolar motors are driven in the same way. The center tap wire(s) are connected to a power supply and the ends of the coils are alternately grounded. Unipolar stepper motors, like all permanent magnet and hybrid motors, operate differently than variable reluctance motors. Rather than minimizing the length of the flux path between the stator poles and the rotor teeth, where the direction of current flow through the stator windings is irrelevant, these motors operate by pulling the north or south poles of the permanent magnet rotor toward the stator poles. Thus, in these motors, the direction of the current through the stator windings determines which rotor poles are attracted to which stator poles. The direction of current in unipolar motors depends on which half of a winding is energized. Physically, the halves of the windings are wound parallel to each other. Therefore, a winding act as either the north or south pole, depending on which half is energized **[5]**.

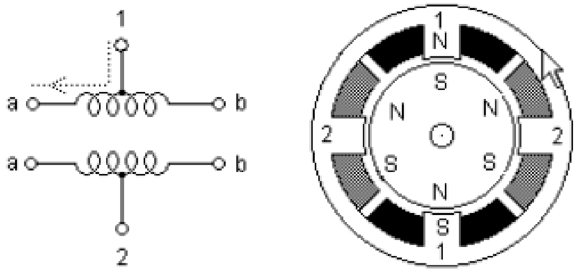

Figure I.7: Unipolar stepper motor construction

I.7 Comparison of types of stepper motors

The choice of stepper motor type depends on the application, and the choice of stepper motor depends on the requirements of torque, step angle, control technology, and other advantages and requirements. We have summarized the differences between stepper motor types in terms of advantages and disadvantages, and in terms of some features that characterize the types of stepper motors.

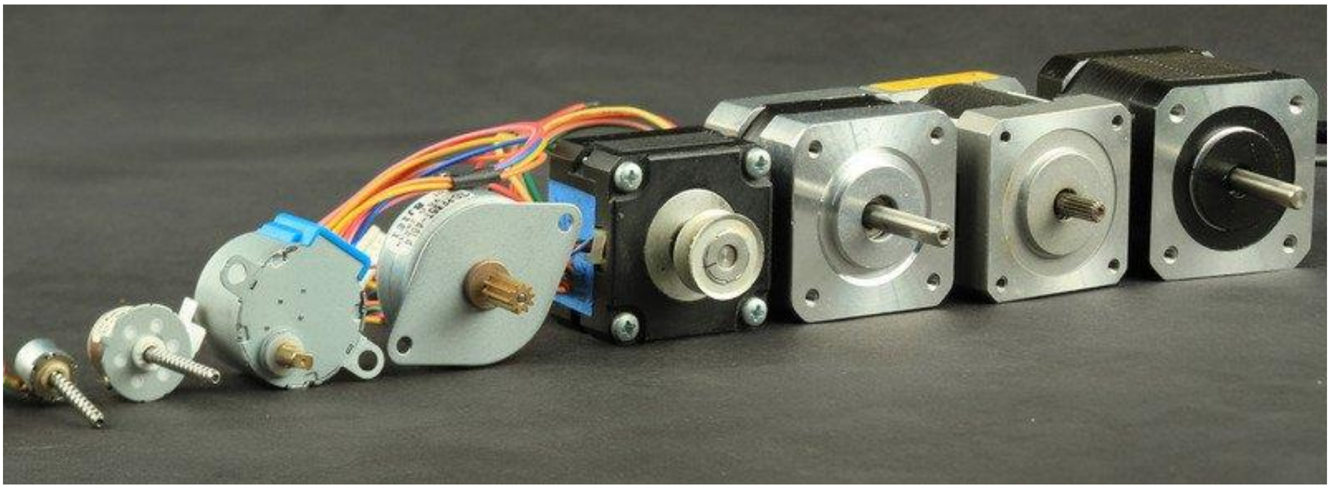

Figure I.8: Photo of different types of stepper motor

I.7.1 Comparison based on motors advantages and disadvantages

Motor type	**Advantages**	**Disadvantages**
Variable-reluctance (VR)	-Robust No magnet. -Smooth movement due to no cogging torque. -High stepping rate and speed slewing capability.	-Vibrations. -Complex circuit for control. - No smaller step angles. -No detent torque.
Permanent Magnet (PM)	-Detent torque. -Higher holding torque. -Better damping.	-Bigger step angle. -Fixed rated torque. -Limited power output and size.
Hybrid (HB)	-Detent torque. -No cumulative position error. -Smaller step angle. -Operate in open loop.	-Resonance. -Vibration.

Table I.1: Advantages and disadvantages of stepper motor types

I.7.2 Comparison based on different characteristics of stepper motor

Stepper motor type	Variable-reluctance (VR)	Permanent Magnet (PM)	Hybrid (HB)
Resolution (steps per revolution)	Good	Medium	High
Torque	Weak	High	High
Rotation direction	Depends: - the phase supply order.	Depends: - the phase supply order -the direction of the current in the coils.	Depends: - the phase supply order -the direction of the current in the coils.
Working frequency	High	Weak	High
Puissance	a few watts	A few tens of Watts	A few KWatts

Table I.2: Characteristics of stepper motor types [6]

I.8 Stepping Modes of a Stepper Motor

A typical stepping operation causes the motor to cycle step through a sequence of equilibrium positions in response to current pulses given to it. It is possible to vary the stepping operations in different ways simply by changing the sequence through which the stator windings are energized. The following are the most common modes of operation or drive of stepper motors.

1. Wave step
2. Full step
3. Half step
4. Micro-stepping

I.8.1 Wave step drive

This is the simplest way to drive a stepper motor, and it is not often used, but it is still worth knowing in order to understand how to drive a stepper motor. In this method, each phase or stator is activated in turn, side by side, using a special circuit. This magnetizes and demagnetizes the stator, causing the rotor to move step by step **[7]**. The table below shows the order through which coils are energized in a 4-phase stepper motor.

Step	**Coil(A)**	**Coil(B)**	**Coil(C)**	**Coil(D)**
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

Table I.3: Stepping sequence of wave drive

I.8.2 Full step drive

In this method, instead of activating stators one at a time, two stators are activated with a short time interval between them. In this mode, any two stators are active. This means that the first stator turns ON and the second stator becomes ON after a short interval while the first stator is still ON. This method results in high torque and allows the motor to drive a high load **[7]**. The table below shows the full step drive for 4-phase stepper motor.

Step	**Coil(A)**	**Coil(B)**	**Coil(C)**	**Coil(D)**
1	ON	ON	OFF	OFF
2	OFF	ON	ON	OFF
3	OFF	OFF	ON	ON
4	ON	OFF	OFF	ON

Table I.4: Stepping sequence of Full-wave drive

I.8.3 Half-step drive

This method is quite similar to the full-step drive. Here two stators placed next to each other will be activated first and then the third stator will be activated next; these two stators get deactivated. This cycle of activating two stators first and then one stator repeats to drive the stepper motor. This method results in increased resolution of the motor and at the same time reduces the torque **[7]**. The table containing the phase pulsing sequence for a 4-phase motor in half stepping is given below.

Step	Coil(A)	Coil(B)	Coil(C)	Coil(D)
1	ON	OFF	OFF	OFF
2	ON	ON	OFF	OFF
3	OFF	ON	OFF	OFF
4	OFF	ON	ON	OFF
5	OFF	OFF	ON	OFF
6	OFF	OFF	ON	ON
7	OFF	OFF	OFF	ON
8	ON	OFF	OFF	ON

Table I.5: Stepping sequence of Half-wave drive

I.8.4 Micro-step drive

This is the most commonly used driving method because it is very accurate. The driver circuit supplies the stator coils with a variable step current in the form of a sinusoidal waveform. These tiny step currents smoothly enhance the accuracy of each step greatly. This method is widely used because it provides high accuracy and largely reduces operating noise **[7]**.

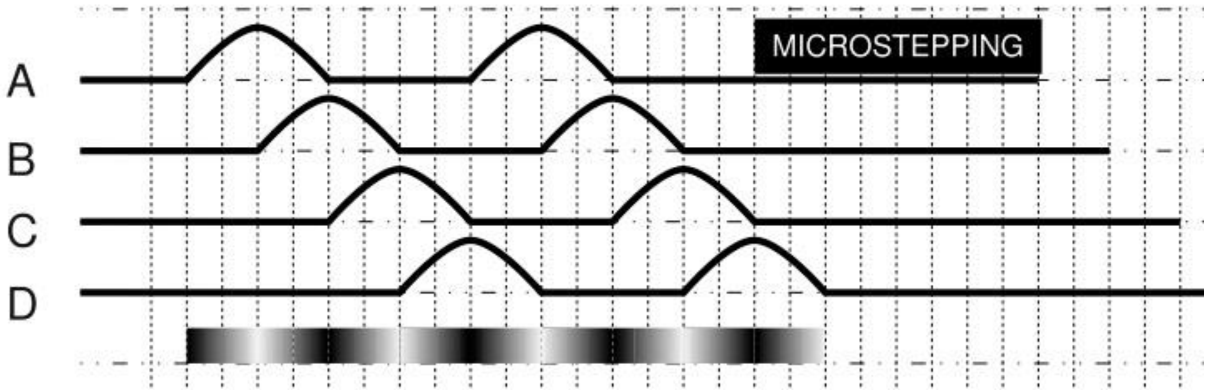

Figure I.9: Timing diagram of micro-stepping drive

All these stepping modes can be obtained by each type of stepper motor discussed above. However, the direction of current in each winding during these steps can be varied depending on the type of motor and whether it is unipolar or bipolar.

I.9 Stepper Motor controlling Circuit and its Operation

Stepper motors work differently than DC brush motors, which rotate when a voltage is applied to their terminals. Stepper motors, on the other hand, have several toothed electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external control circuit, such as a microcontroller.

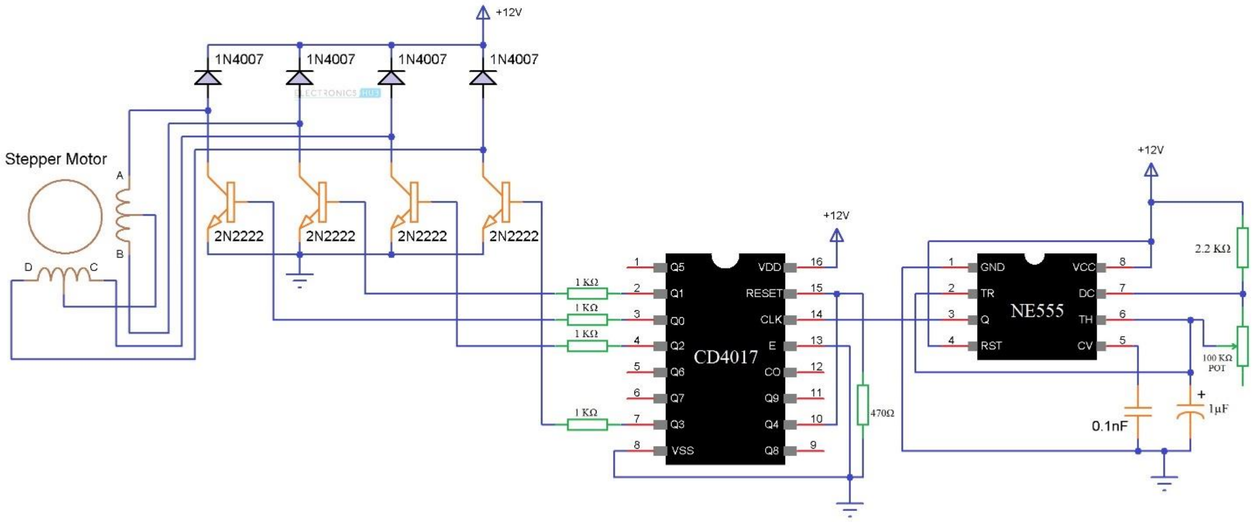

Figure I.10: Stepper motor controlling circuit

To make the motor shaft rotate, power is first supplied to an electromagnet, causing the teeth of the gear to be magnetically attracted to the teeth of the electromagnet. At the point where the teeth of the gear are aligned with the first electromagnet, they are slightly offset from the next electromagnet. So, when the next electromagnet is turned ON and the first is turned OFF, the gear turns slightly to align with the next one and from there the process is repeated. Each of these slight rotations is called a step, where an integer number of steps gives a full rotation.

In this way, the motor can be rotated with precision. Stepper motors do not rotate continuously but in steps. There are 4 coils attached to the stator at a 90o angle to each other. The connections of the stepper motor are determined by the way the coils are connected. In a stepper motor, the coils are not connected to each other. The motor has a 90o rotation step, where the coils are energized in a cyclic sequence that determines the direction of rotation of the shaft.

The operation of this motor is shown by operating the switch. The coils are activated in sequence at 1-second intervals. The shaft rotates 90o each time the next coil is activated. The torque at low speed varies directly with the current **[4]**.

I.10 Conclusion

In this chapter, we have given an overview of the history of stepper motors and their definition, as well as the applications in which they are used. We also talked about the structure of the motor and familiarized ourselves with the three types of motors (PM, VR, HB), and made a comparison between them in terms of advantages and disadvantages, as well as the main features that characterize each type. We also talked about the mechanism and stepping mood, the work of the motor, and the different ways to control and operate it.

CHAPTER II : DIAGNOSIS OF STEPPER MOTORS BY ELECTRICAL MEASUREMENTS

II.1 Introduction

The Stepper motor plays an important role in many industrial devices. It is an electromechanical device that performs precise and deliberate movements, for example, in 3D printers, robots, hard disk drives, and some devices that require precise movements. The frequent use of motors and the influence of external factors such as temperature, humidity, or dust cause the motor to fail. In this chapter, we will introduce some methods that can save our time and effort to diagnose common electrical failures of stepper motors and know their causes.

II.2 ORCAD software

OrCAD Systems Corporation was a software company that made OrCAD, a proprietary software tool suite used primarily for electronic design automation (EDA). The software is primarily used by electronic design engineers and electronics technicians to create electronic schematics and perform mixed-signal simulations and electronic printing for printed circuit board manufacturing. OrCAD was acquired by Cadence Design Systems in 1999 and was integrated into Cadence Allegro in 2005**[8]**.

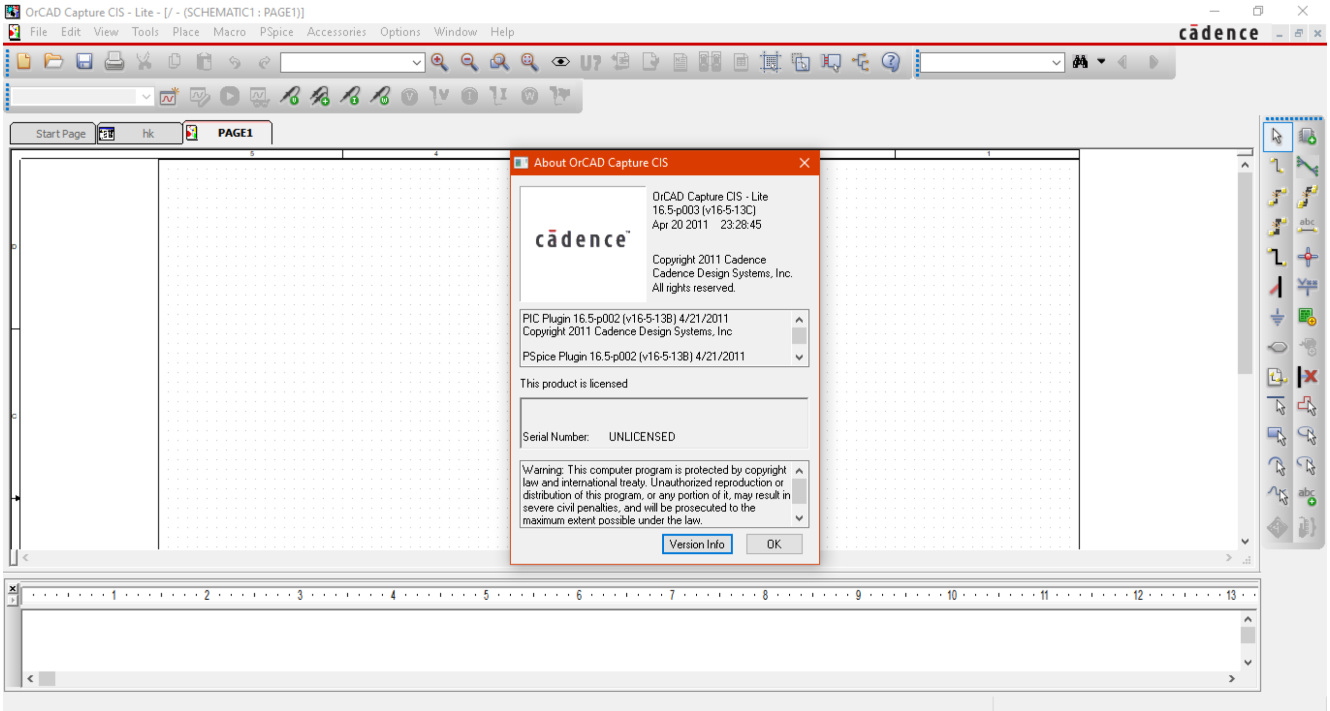

Figure II.1: ORCAD software interface

II.3 Diagnosis of the stepper motor by electrical methods.

To know if the stepper motor is in good condition or not, we just need to check if the phase windings are working properly. We will use two methods to check if the motor phases are identical. If one of these phases is damaged, this defect can be diagnosed using one of these methods.

II.3.1 Method 01: Series RLC resonant circuit

Resonance occurs in a series circuit when the supply frequency causes the voltages across L and C to be equal and opposite in phase.

The resonance frequency F_r of a series RLC circuit is defined by:

$$\boldsymbol{F_r = \frac{1}{2\pi\sqrt{LC}}} \qquad (E1)$$

$$\boldsymbol{L = \frac{1}{4\pi^2 F_r^2 C}} \qquad (E2)$$

- **Practical diagram of series RLC resonance**

R=1kΩ

C=47nF

Ve=5sin(wt)

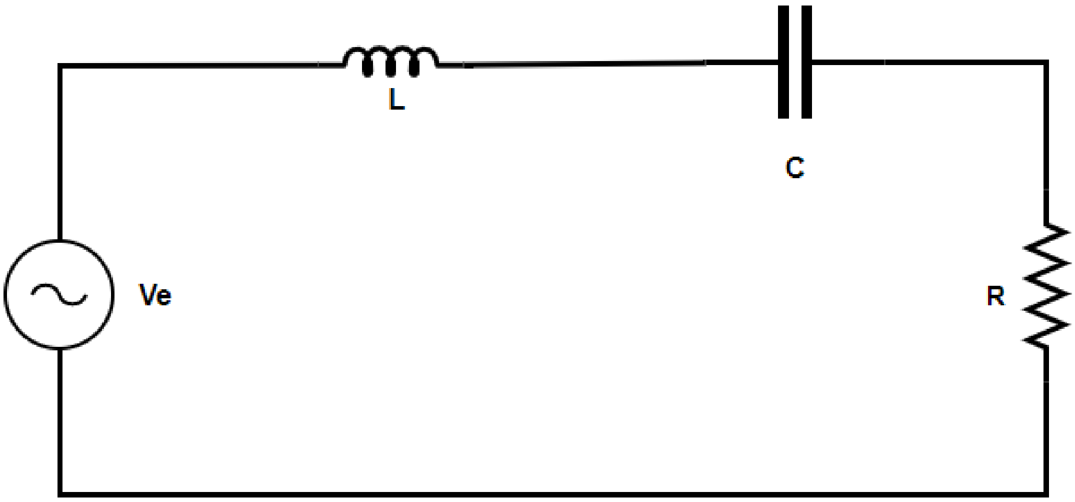

Figure II.2: Practical diagram of series RLC resonance

In the laboratory, we configured the previous resonant circuit and used the motor coils as inductors, and then studied its behavior in two cases:

II.3.1.1 Normal phases

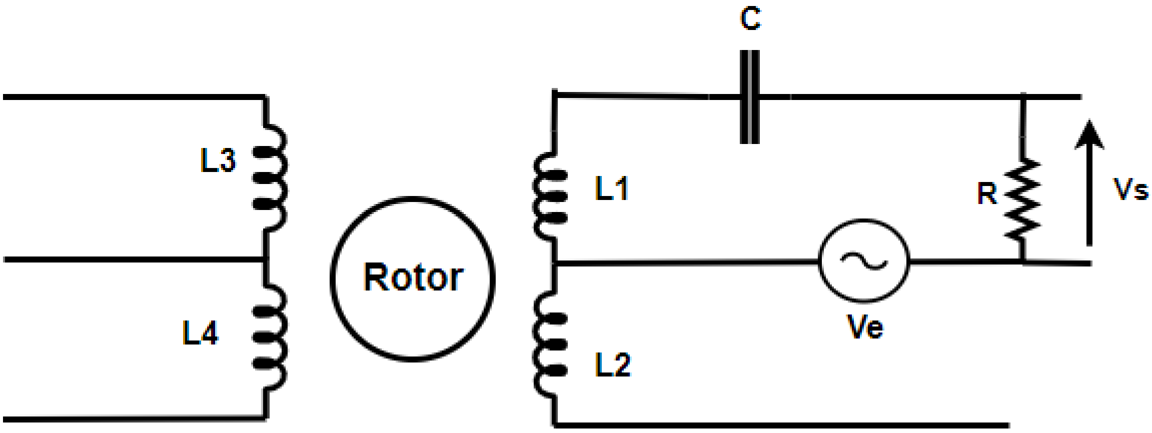

Figure II.3: RLC resonant circuit using normal phases as an inductor

We connected the previous resonant circuit to the oscilloscope and obtained the resonant frequency F_r = 6.78khz by switching the frequency in the signal generator.

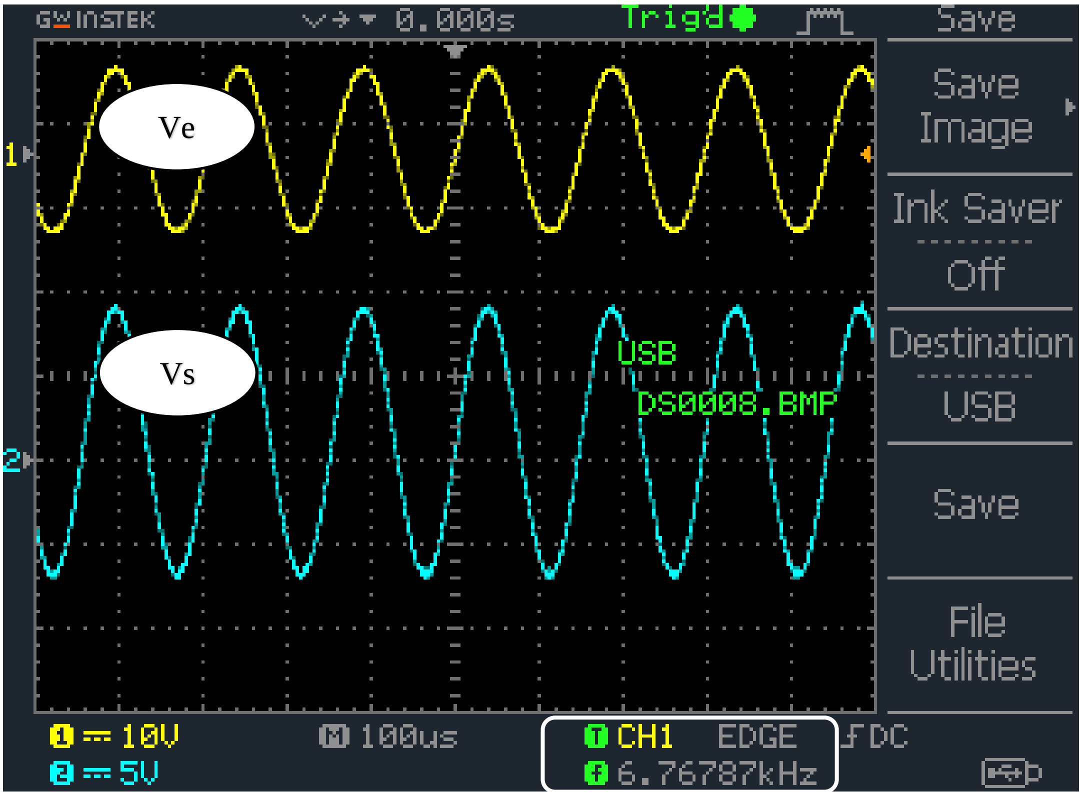

Figure II.4: Oscilloscope output of RLC resonant circuit (normal phases)

❖ Simulation diagram

Using the equations (E.1, E.2) we have found that L=11.7mH. In this step, we will apply the reverse operation to find the frequency value by using the ORCAD software.

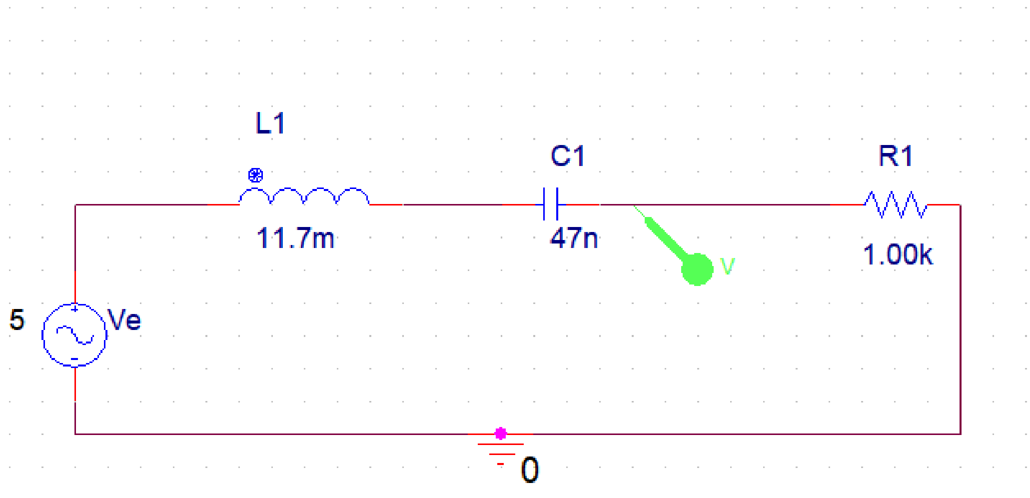

Figure II.5: RLC resonant circuit in ORCAD normal phase

❖ Results

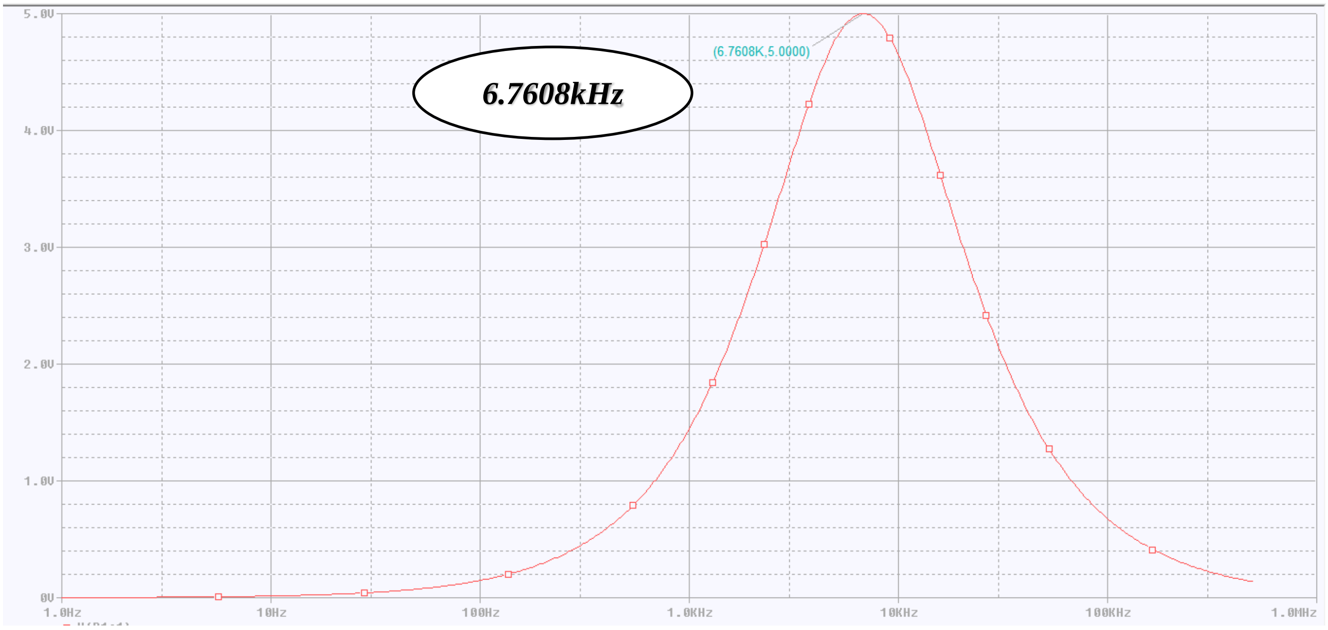

Figure II.6: RLC simulation result for the 4 normal phases

II.3.1.2 Short-circuit phase

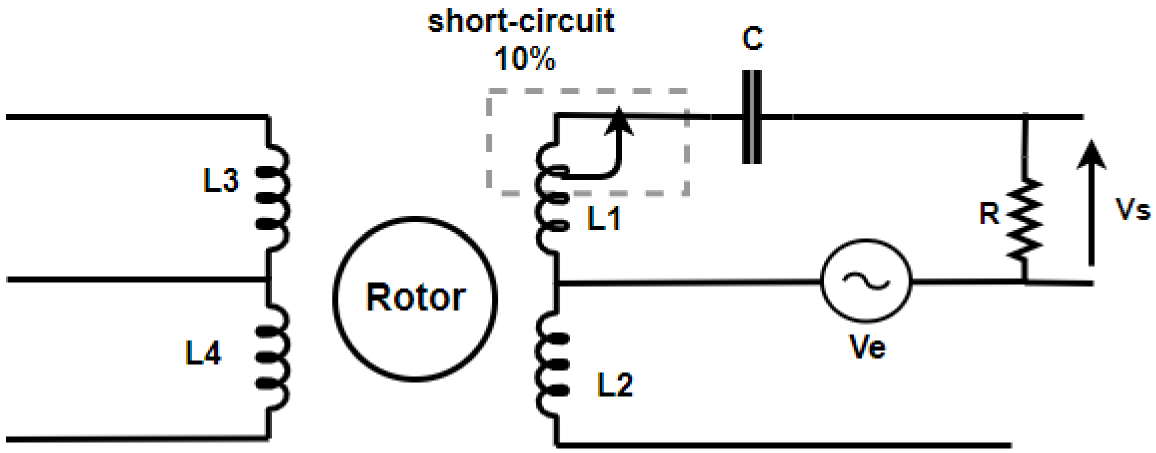

Figure II.7: RLC resonant circuit using short-circuit phases as an inductor

We connected the previous resonant circuit to the oscilloscope and obtained the resonant frequency F_r =7.07khz by switching the frequency in the signal generator.

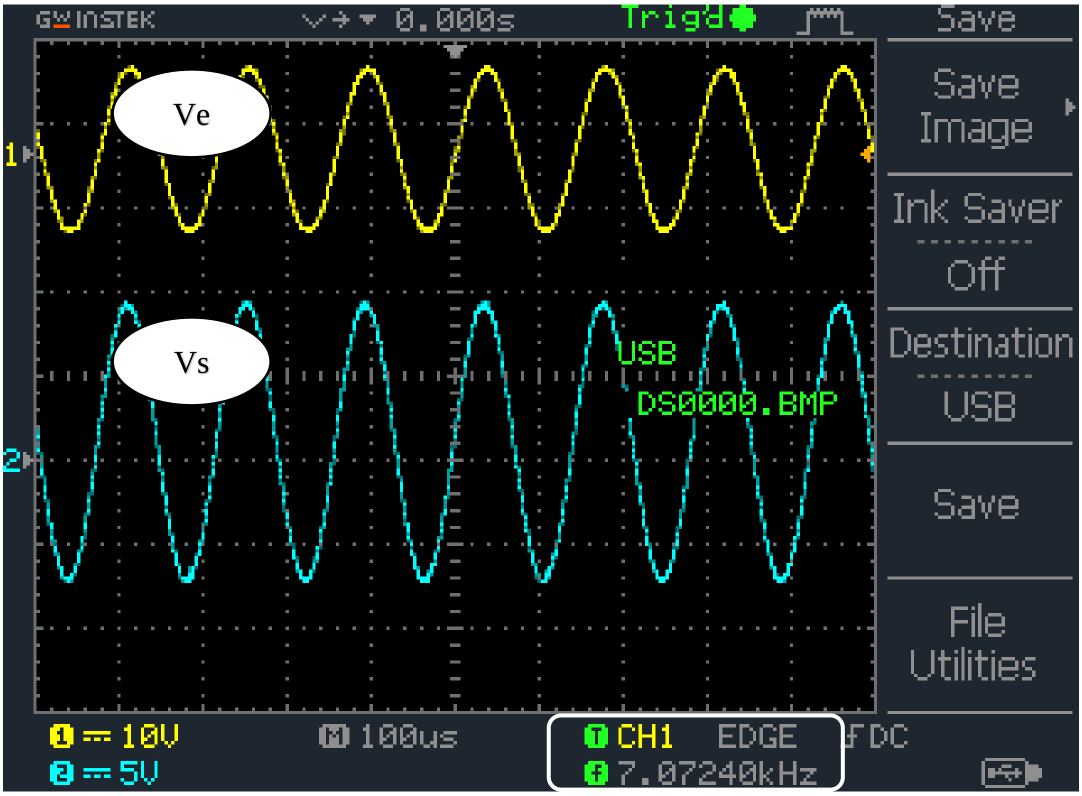

Figure II.8: Oscilloscope output of RLC resonant circuit (short-circuit phase)

The other phases L2, L3, and L4 are good (no short- circuit), and the resonance values are practically the same F_r =6.78khz and L2=L3=L4=11.7mH, from which we conclude that the motor has a damaged phase.

❖ Simulation diagram

By using the equations (E.1, E.2), we found out that L1=10.7mH so in this step, we will apply the reverse operation to find the frequency value by using ORCAD software.

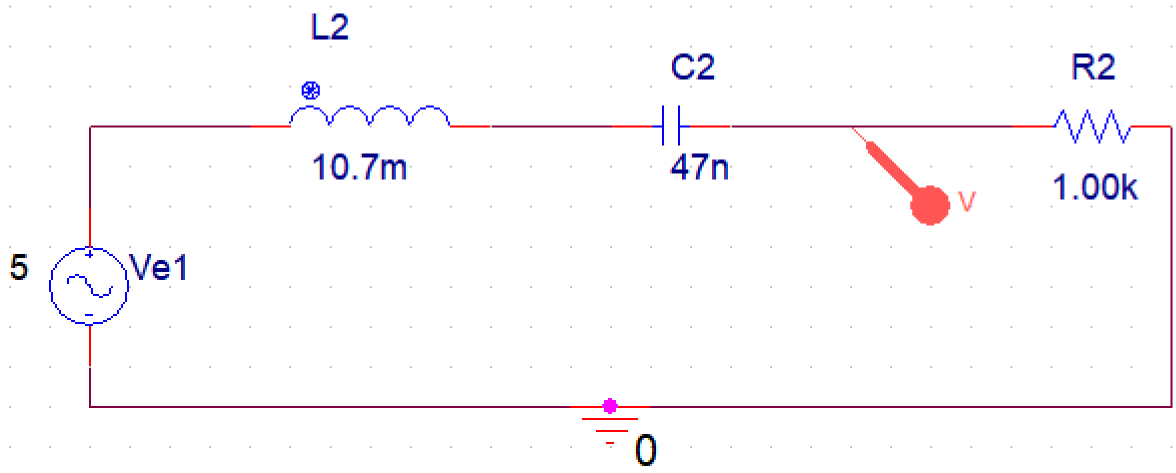

Figure II.9: RLC resonant circuit in ORCAD short-circuit phase

❖ Results

In the same way, we put the coils L2, L3, and L4, and we found the resonance frequency value F_r =7.07khz.

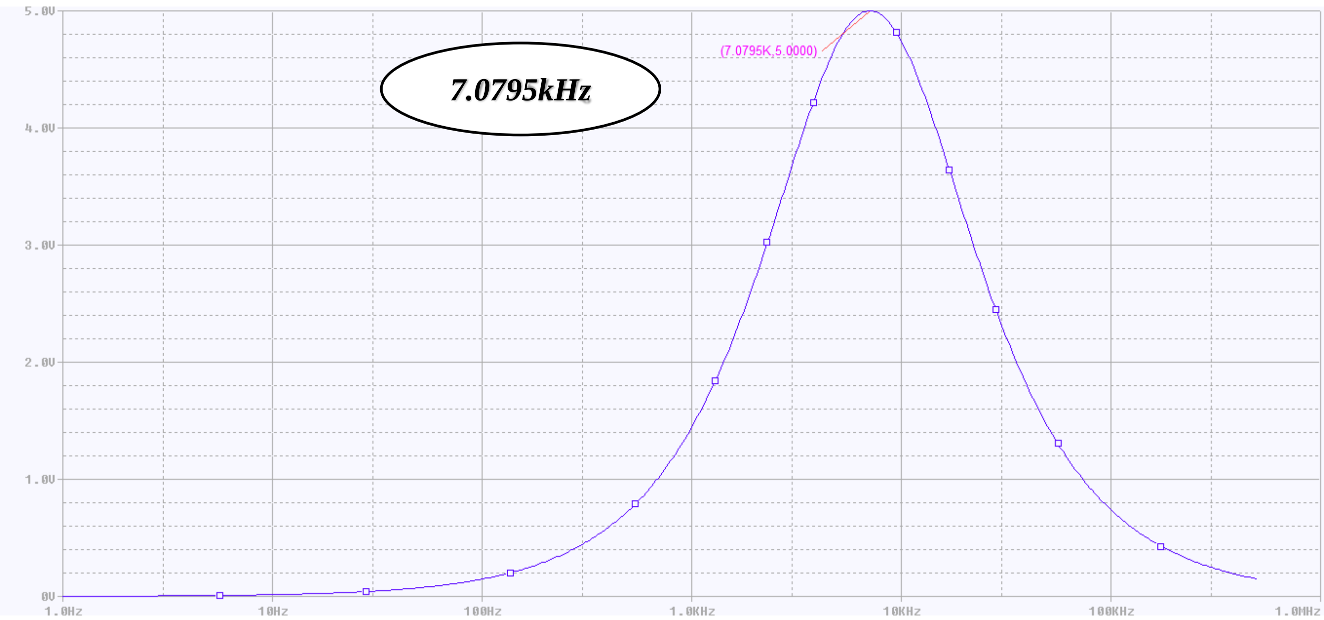

Figure II.10: RLC simulation result for the short-circuit phase

Based on the previous results, we note that there is a difference in the resonant frequencies in the previous two cases because, in the case of a short circuit, the resonant frequency is greater than in the correct case. Through this difference, we can assert that there is a fault in the motor coil and therefore a failure of the motor.

II.3.2 Method 02: Transformer

In this method, we assume that the motor works in the same way as the transformer because it contains four phases, two primary phases (Q1, Q3) and two secondary phases (Q2, Q4).

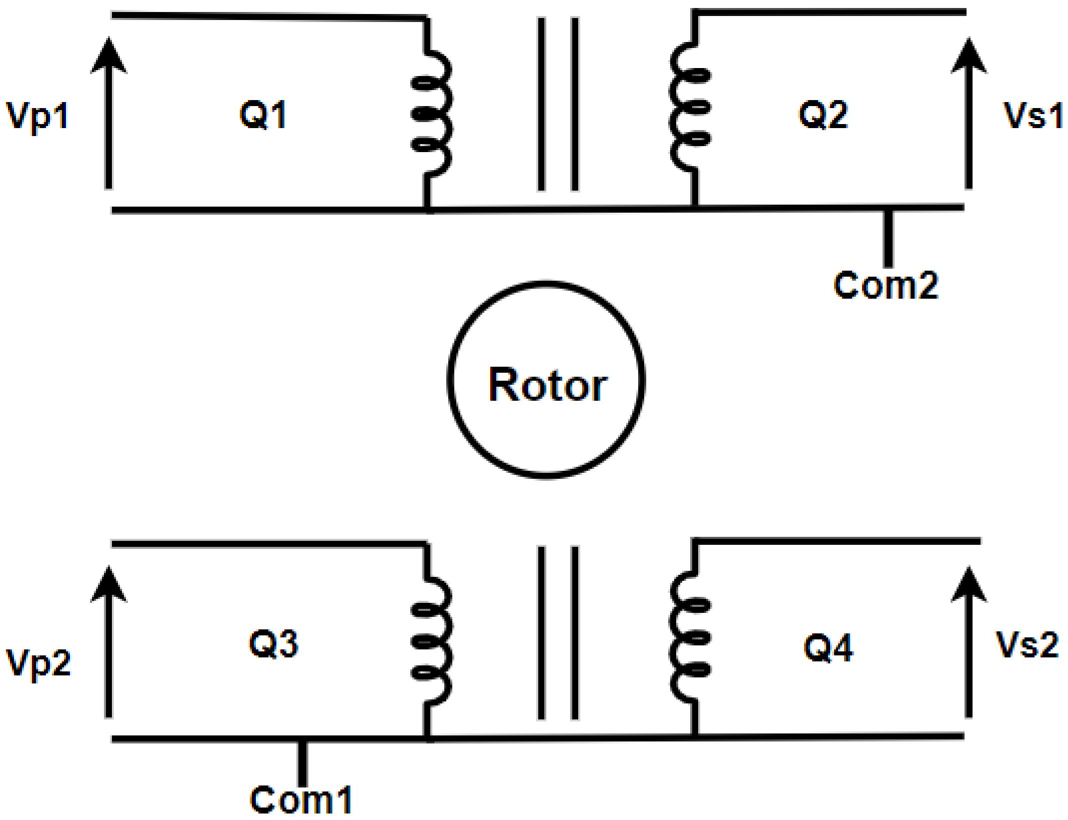

Figure II.11: Motor phases diagram

II.3.2.1 Normal phases

❖ **Practical diagram**

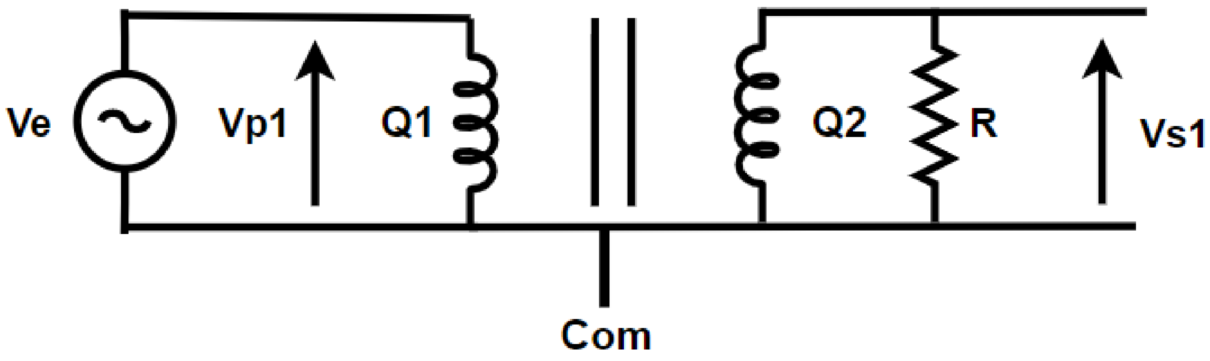

Figure II.12: Practical diagram of transformer (normal phase)

Every two phases (1,2 and 3,4) wound in the same coil with the same pole and in the same direction act like a transformer where the magnetic coupling, in this case, is approximately 1. Therefore, the phases are identical, so that the primary voltage is equal to the secondary voltage.

❖ **Results**

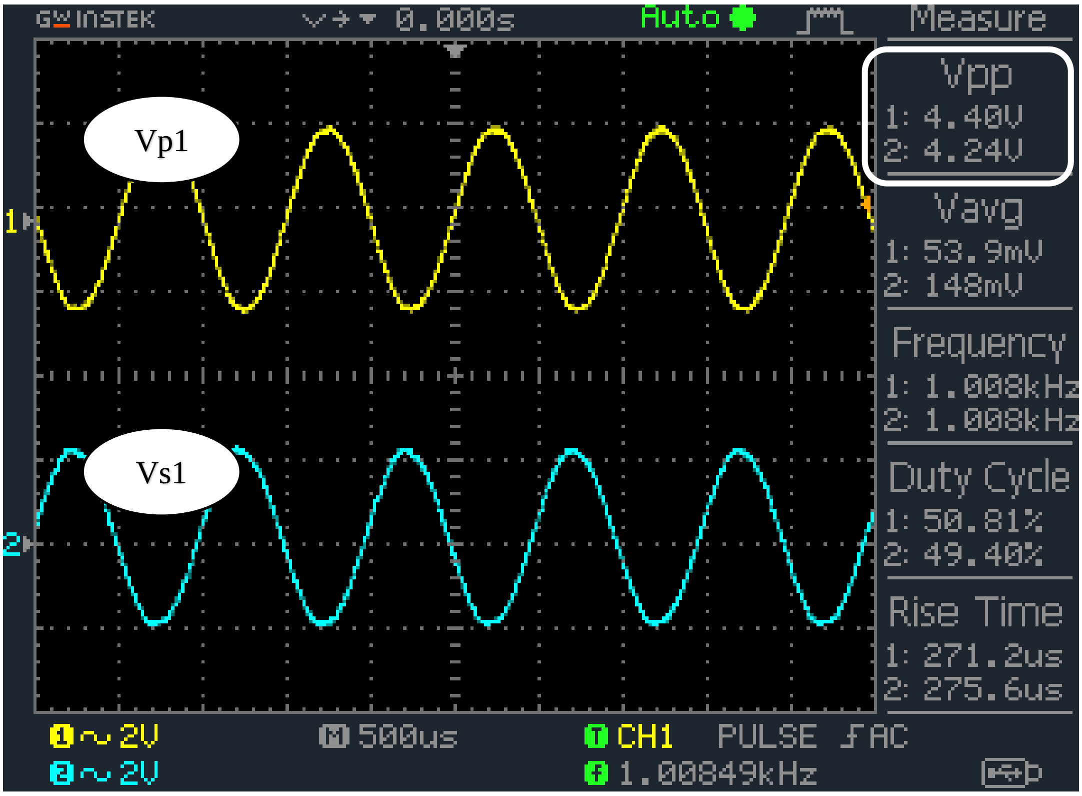

Figure II.13: Oscilloscope output (normal phases)

From the previous figure, we can see that the two signals (primary and secondary) have the same form and amplitude. From this we can conclude that Q1 and Q2 have the same number of turns, and also for the Q3 and Q4, so the 4 phases are identical no short-circuit therefore deduce that the phases are good, so the motor works well.

II.3.2.2 Short-circuit phase

❖ **Practical diagram**

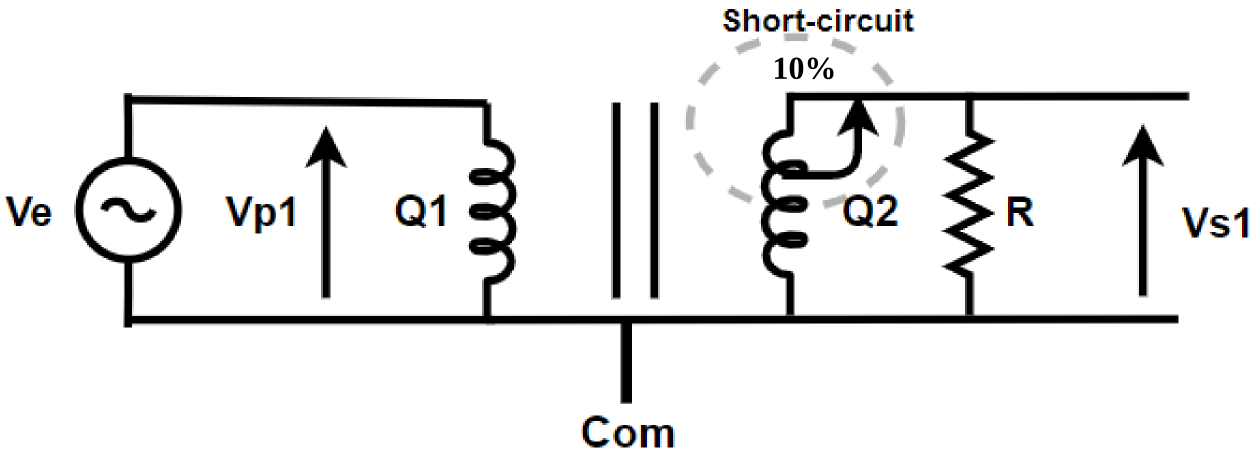

Figure II.14: Practical diagram of transformer (short-circuit phase)

In this case, we will make the number of turns of the primary coil Vp1 more than the secondary coil Vs1.

❖ **Results**

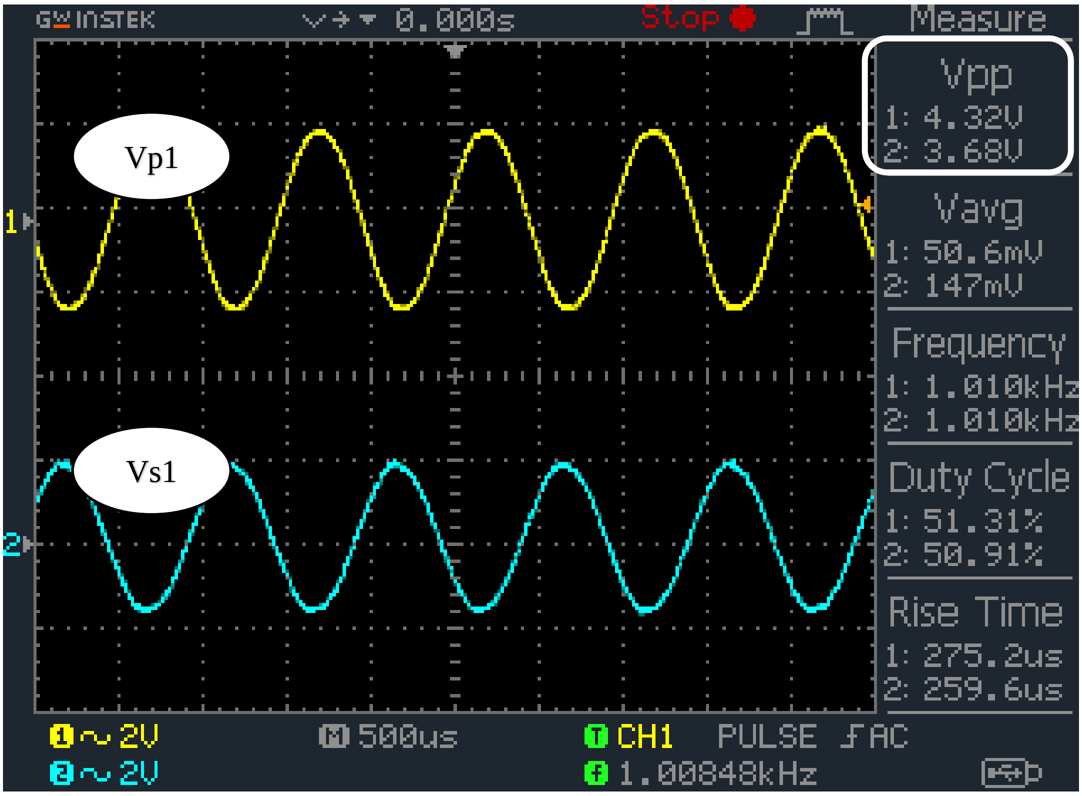

Figure II.15: Oscilloscope output (short-circuit phases)

We note that the voltage of the secondary coil is less than the voltage of the primary coil. From this, we can conclude that Q1 and Q2 do not have the same number of turns. From this, we conclude that the secondary coil has fewer turns than the first relay and therefore there is a short circuit in the secondary coil, which means that the motor has a defect.

II.3.3 Method 03: Temperature sensors

A temperature sensor is a device that detects and measures heat and cold and converts it into an electrical signal. Among the various temperature sensors that exist, the thermocouple is the most commonly used sensor.

- **Measurement Principle of Thermocouple**

Thermocouple theory is based on the circuit in Figure 2.16. A current flow when two dissimilar metals are connected at the ends, where T1 and T2 have two different temperatures. In actual application: A would be the measuring junction and connection B would go to a voltage measuring instrument. The output is a very small voltage called electromotive force.

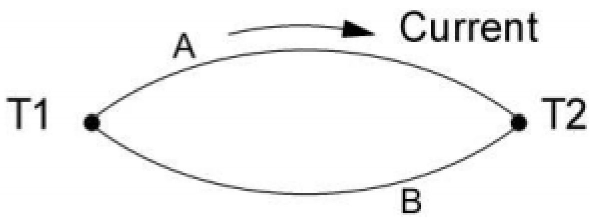

Figure II.16: Principle of Thermocouple

II.3.3.1 Measurement method

We placed a Tc temperature sensor inside the motor. It was glued to one of the coils containing the short-circuit phase.

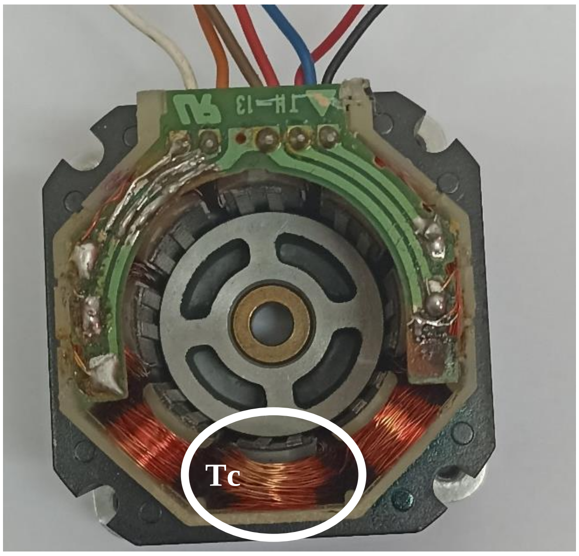

Figure II.17:Photo of a modified stepper containing a Tc

Then we fed the short circuit phase with 5 V to measure the temperature of the phase, we used the thermometer to read the output of the thermocouple, we chose one measurement every three minutes for a total of one-hour measurement and we repeat this process by exchanging the short- circuit phase with the normal phase (winding in the same coil) and we got the results as shown in the table below.

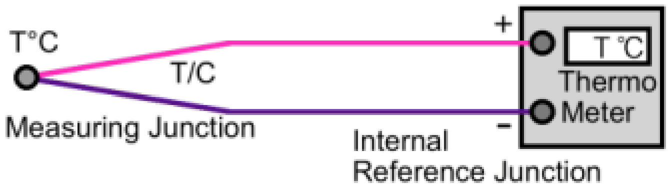

Figure II.18: Tc measuring circuit

II.3.3.2 Table of measurement

Time[min]	T1[c] phase N	T2[c] phase S.C
0	22.7	22.6
3	25.6	30.4
6	27.4	32.6
9	29	34.5
12	30.3	36.3
15	31.4	37.6
18	32.3	38.7
21	33.1	39.7
24	33.8	40.5
27	34.4	41.1
30	34.9	41.8
33	35.4	42.1
36	35.7	42.7
39	36	42.9
42	36.3	43.3
45	36.7	43.6
48	37	44
51	37.2	44.2

54	37.4	44.5
57	37.6	44.6
60	37.8	44.8

Table II.1: The captured temperatures through one hour

From the above results, we obtained this curve showing the difference between the temperatures of the two phases. We note that the S.C phase gives a higher temperature than the N phase, and it goes hot rapidly.

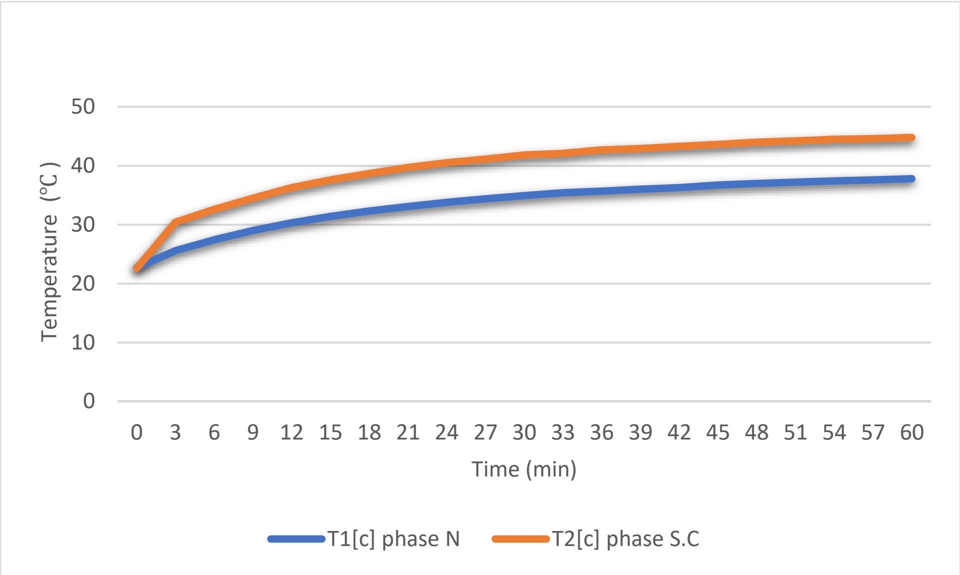

Figure II.19: The temperature curves of the two phases

In other work, they have used two NTC sensors instead of one TC sensor to measure the temperature of the stepper, they glued one of the NTCs on the normal phase and the other on the S.C. phase and they got that curve below.

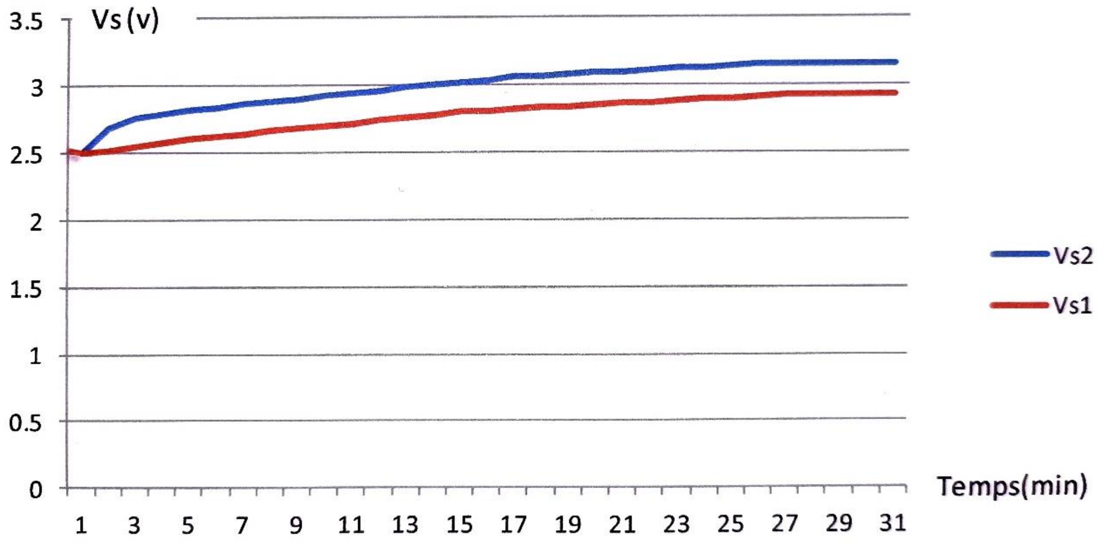

Figure II.20: Voltage curves of the two phases [11]

From previous experiments, we infer from the high temperature of one of the phases the presence of a short-circuit in one of them and thus a defect in the motor.

II.4 Conclusion

Electrical faults in a stepper motor can be detected in several ways. For example, we use the method of series resonance in each phase. They are tested separately. If the inductance of the phases is the same, we can conclude that the motor has no phase faults. However, if one phase has a partial short-circuit, it will have a lower inductance compared to the others.

In addition to resonance, the phases of the stepper motor are magnetically coupled, so it can be assumed that the motor contains two identical transformers with a transformation ratio of 1. If the two voltages (primary and secondary) are identical, we can conclude that the motor has no fault, but if the secondary voltage differs from the primary (the presence of a partial short-circuit), we can conclude that the motor has a malfunction.

Also, we can know if there is an electrical fault or not by using thermal sensors (NTC and thermocouples) attached to the coils. In this way, we can determine in which phase there is a partial short-circuit if we find that the temperature is higher than the others and therefore there is a defect in the motor.

CHAPTER III : DIAGNOSIS OF STEPPER MOTORS BY ACOUSTICS

III.1 Introduction

The hybrid motor is one of the most powerful stepper motors currently available. Hybrid stepper motors have the advantage of being rugged and simple in design, reliable, low maintenance, high torque at low speeds, and do not require position or speed feedback.

The stepper motor is prone to various internal problems (electrical and mechanical) that are sometimes difficult to detect and can cause complete damage. In this chapter, we explain some methods that will allow you to diagnose and detect these problems with the least effort, and time, using the acoustic signals coming from the motor. which will help protect the motor from damage or problems that may be exposed.

III.2 Stepper motor driver circuit

A stepper motor driver is a circuit used to drive or run a stepper motor. It provides the necessary current and voltage for a stepper motor and controls the speed so that it operates smoothly.

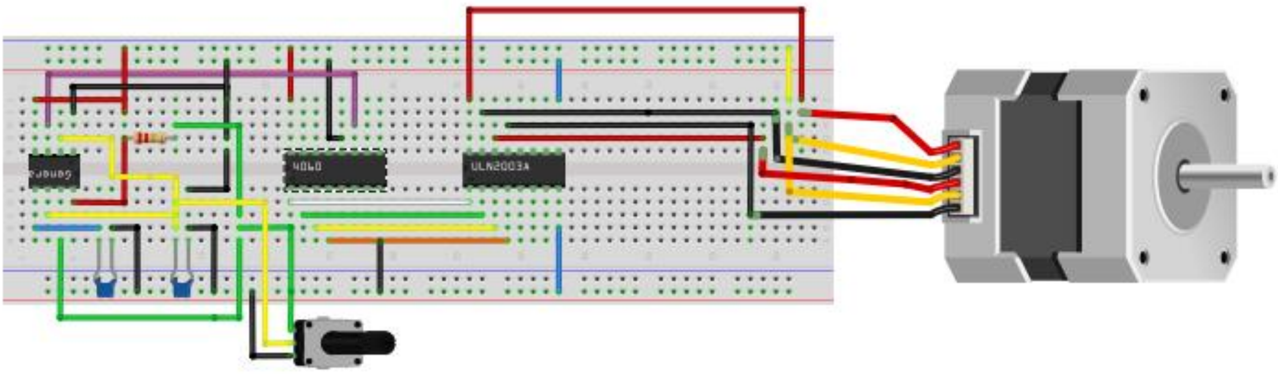

Figure III.1: Stepper motor driver simulation

In the lab, we installed the previous circuit and used it to run the motor. We also made the audio circuit for the diagnostic process, as you can see in the picture below.

❖ Schematic diagram

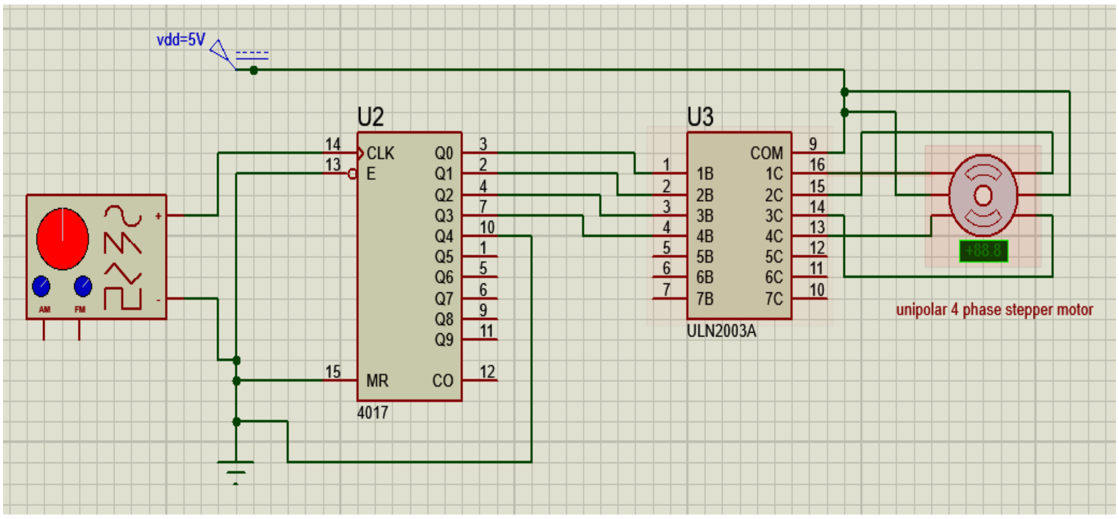

Figure III.2: Schematic diagram of stepper driver

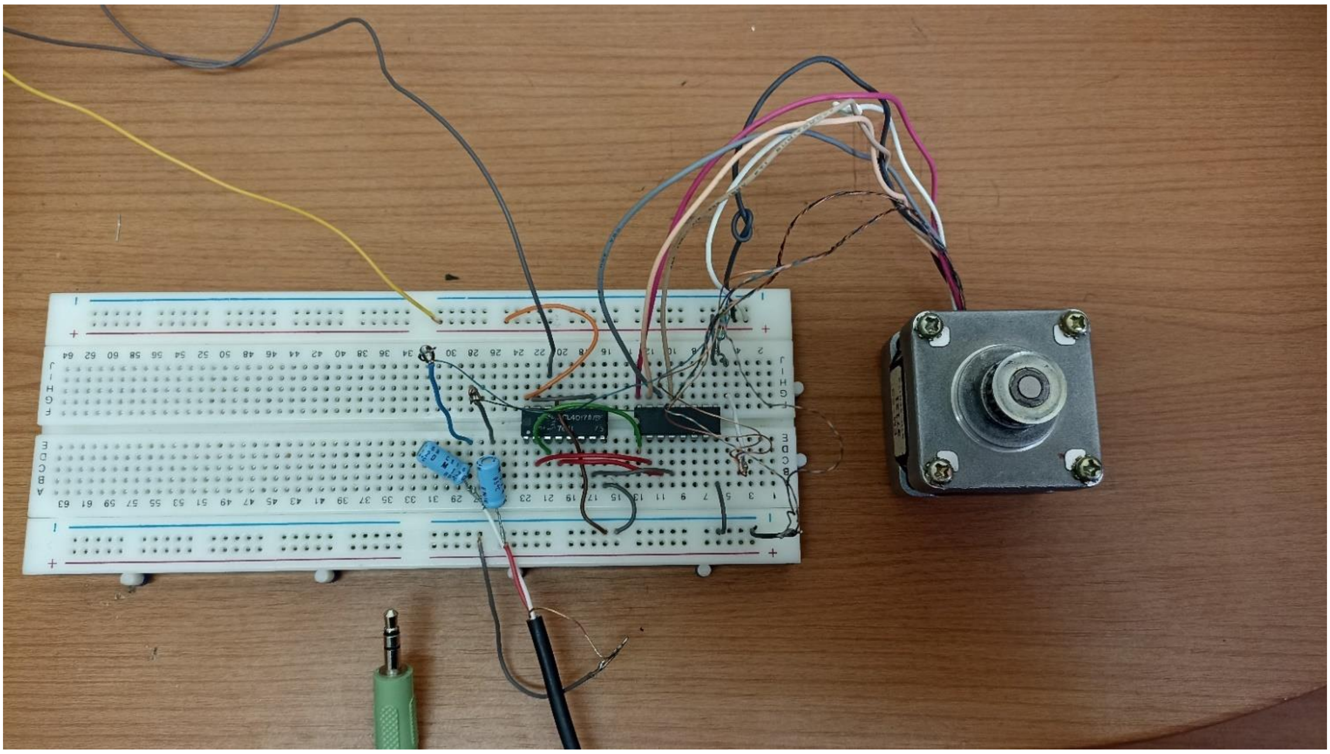

Figure III.3: Photo of stepper motor driver

- **Components of driver**

Uln2003

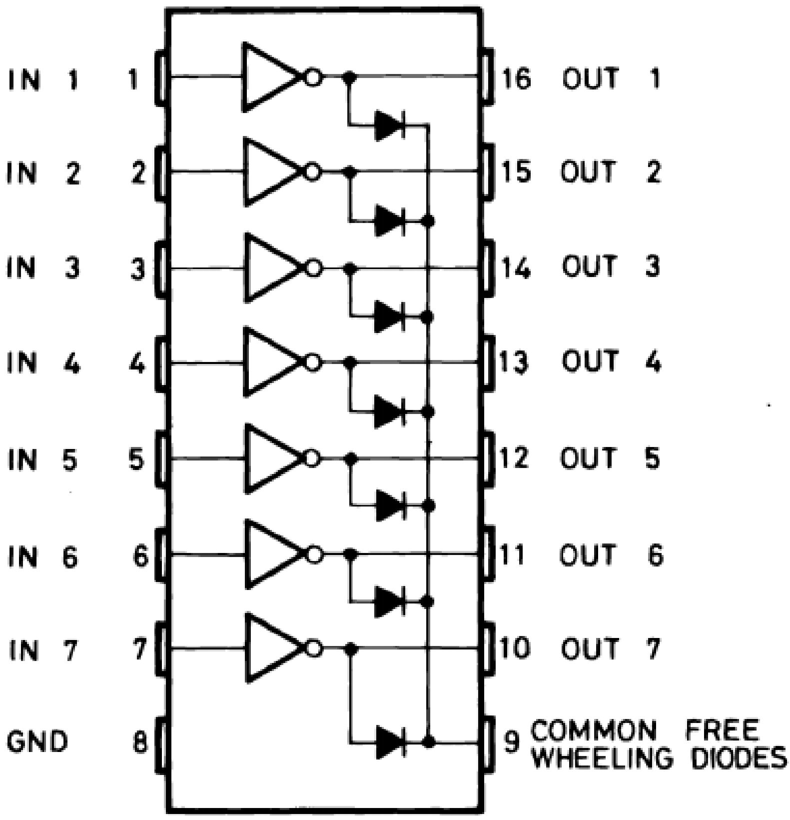

Figure III.4: Pin connections (top view)

Cd 4017

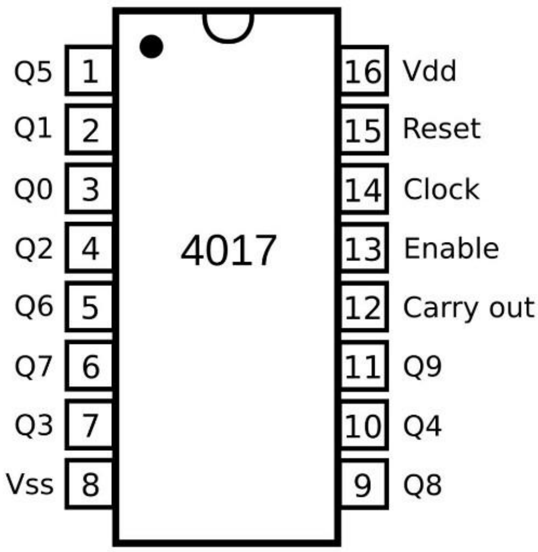

Figure III.5: Connection diagram

Signals generator [NE555]

Audio jack

Capacitors

Resistors

Wires

Breadboard

III.3 Microphones

III.3.1 General definition

A microphone is a device that captures audio signals by converting sound waves into electrical signals. This signal can be amplified as an analog signal or converted into a digital signal that can be processed by a computer or other digital audio device. Although all microphones (or "mics") perform the same basic function, they can capture audio in different ways.

Figure III.6: Principal of mic

III.3.2 Types of petite microphones

III.3.2.1 MEMS microphones

MEMS (Micro-Electro-Mechanical System) Microphones consist of components placed on a printed circuit board (PCB) and protected with a mechanical cover. A small hole is fabricated in the case to allow sound into the microphone. It is referred to as either "top-ported" when the hole is in the top cover, or "bottom-ported" when the hole is in the (PCB). The MEMS component is often developed with a mechanical diaphragm and a mounting structure built on a semiconductor chip **[9]**.

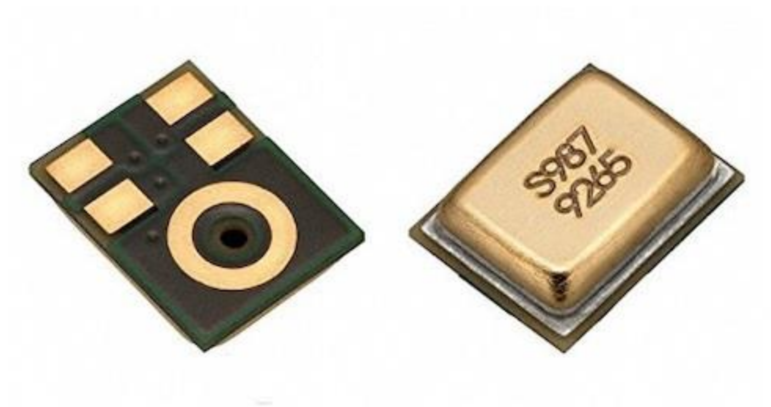

Figure III.7: MEMS mics

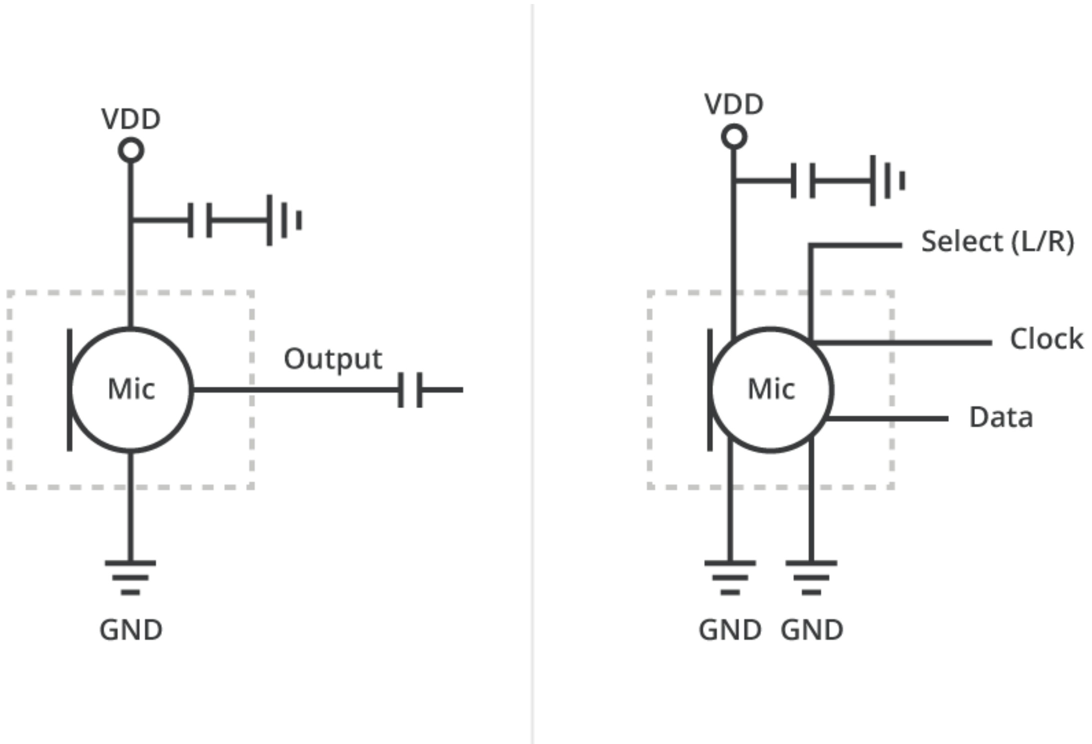

Figure III.8: Left: analog MEMS application schematic Right: digital MEMS application schematic

III.3.2.2 Electret Condenser Microphone (ECM)

An electret microphone is a type of condenser microphone that has a permanent charge. All microphones require a pair of charged plates (positive and negative plates) to function and record sound. General condenser microphones do not come pre-charged but require an external voltage to charge the microphone diaphragm in order for the microphone to function. Electret microphones, on the other hand, have a permanent built-in charge **[9]**.

Figure III.9: Electret Condenser Microphone Mounting Types

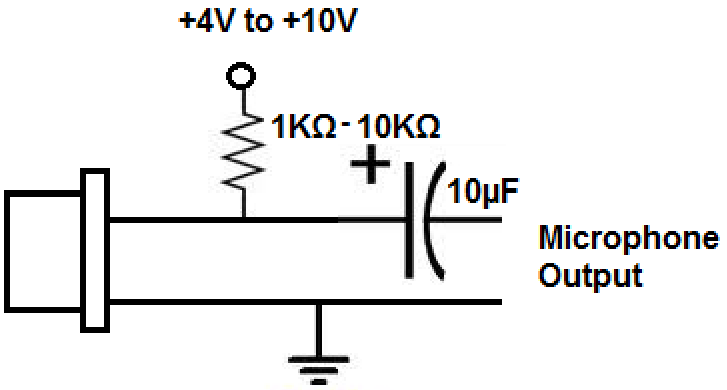

Figure III.10: ECM application schematic

In my project I used a MEMS microphone because it is small, Thermal stable, it is much less expensive than ECM, and it fits easily inside the stepper motor for the diagnosis operation.

III.4 Audacity program

Audacity is a free and open-source digital audio editor and recording application software, available for Windows, macOS, Linux, and other Unix-like operating systems **[10]**.

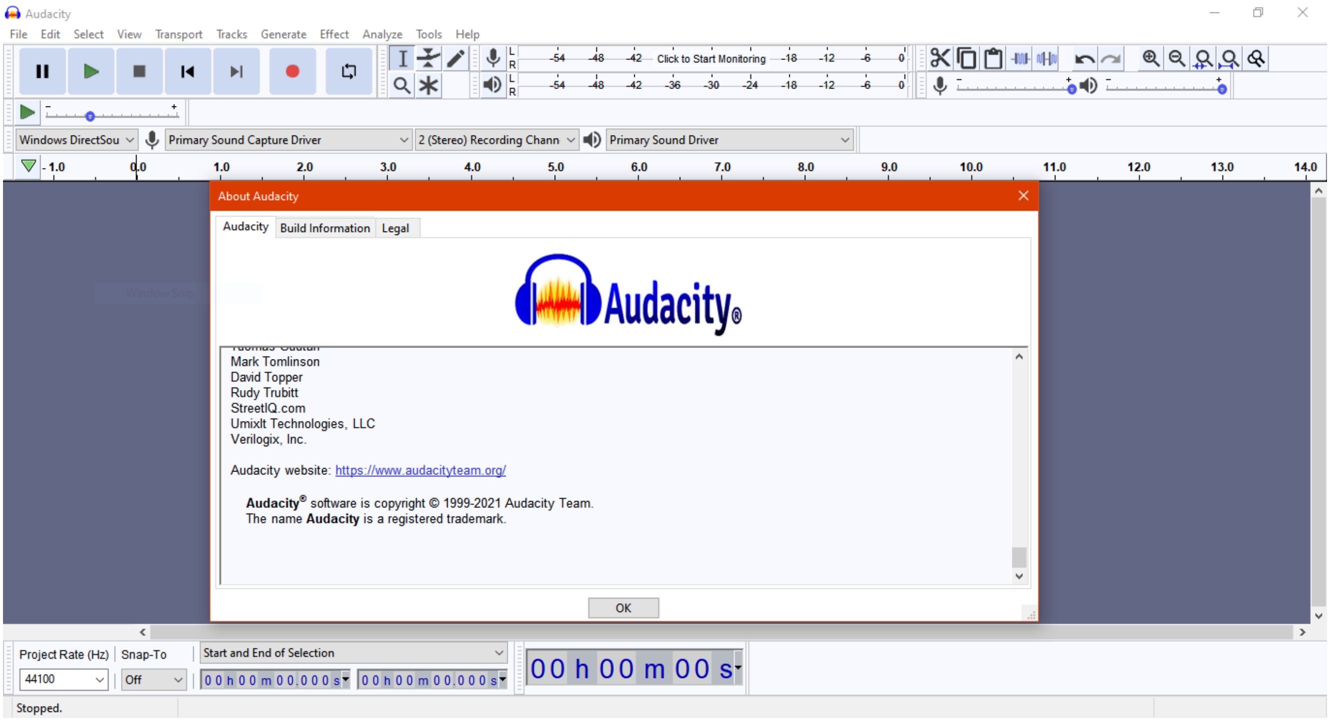

Figure III.11: Interface of Audacity software

III.5 The mechanical faults of the stepper motor

The motor is sometimes exposed to many problems as a result of external influences and factors, whether on the electrical or mechanical side, which affects the mechanism of the motor's work. In this chapter, we present some of the mechanical problems that motors often encounter and how to diagnose them.

III.5.1 Ball bearing problems

An accurate diagnosis of bearing damage is imperative to avoid repeated failures and additional costs. Rolling bearings are precision machine elements used in a wide variety of applications. They are usually very reliable even under the harshest conditions.

In the laboratory, we modified the stepper motor by adding two MEMS microphones inside the stepper motor, one next to the upper bearings and the other next to the lower bearings as you can see in the picture below.

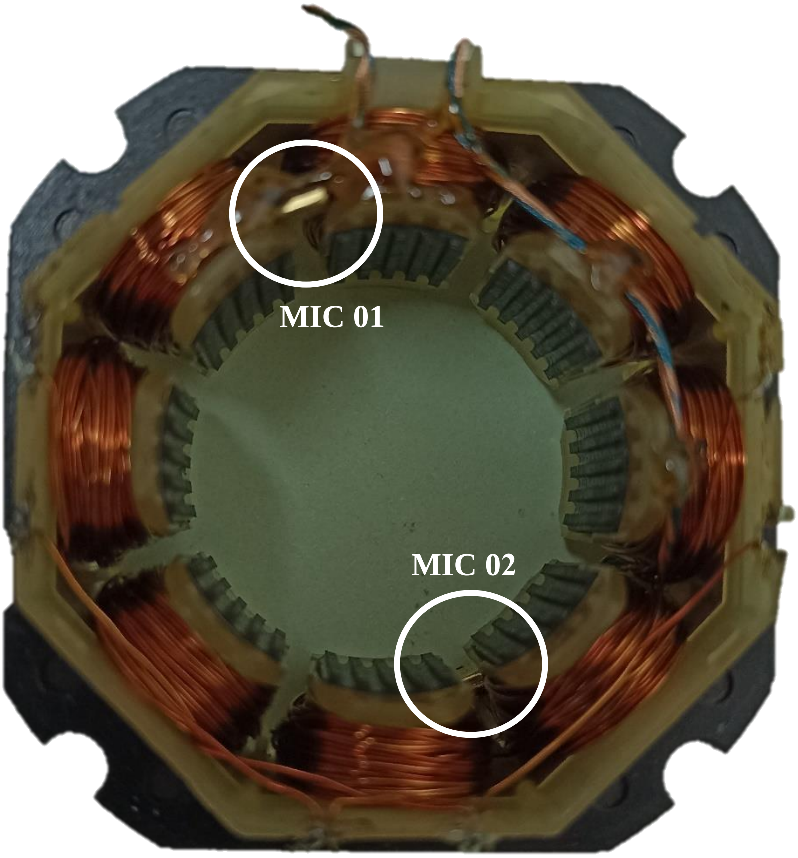

Figure III.12: Photo showing the two MEMS mics inside the motor

We also examined the condition of the stepper motor and diagnosed mechanical malfunctions based on the noise and vibration produced by the bearings in three cases at different speeds and frequencies to determine if there was a defect in the stepper motor.

Three types of bearings are used in the diagnosis operation of the stepper motor:

1) Normal bearing
2) Full rusty bearing
3) Rusty spot in the bearing

Figure III.13: Photo of different bearings (rusty spot, normal, full rusty)

III.5.1.1 Normal bearing

In this case, we put to the test a motor in a good condition with two normal ball bearings.

Figure III.14: Photo of normal bearing inside the motor

Then we record the coming sound by using Audacity at different speeds (20Hz up to 600Hz) and we have got the following signals.

- **20Hz up to 600Hz**

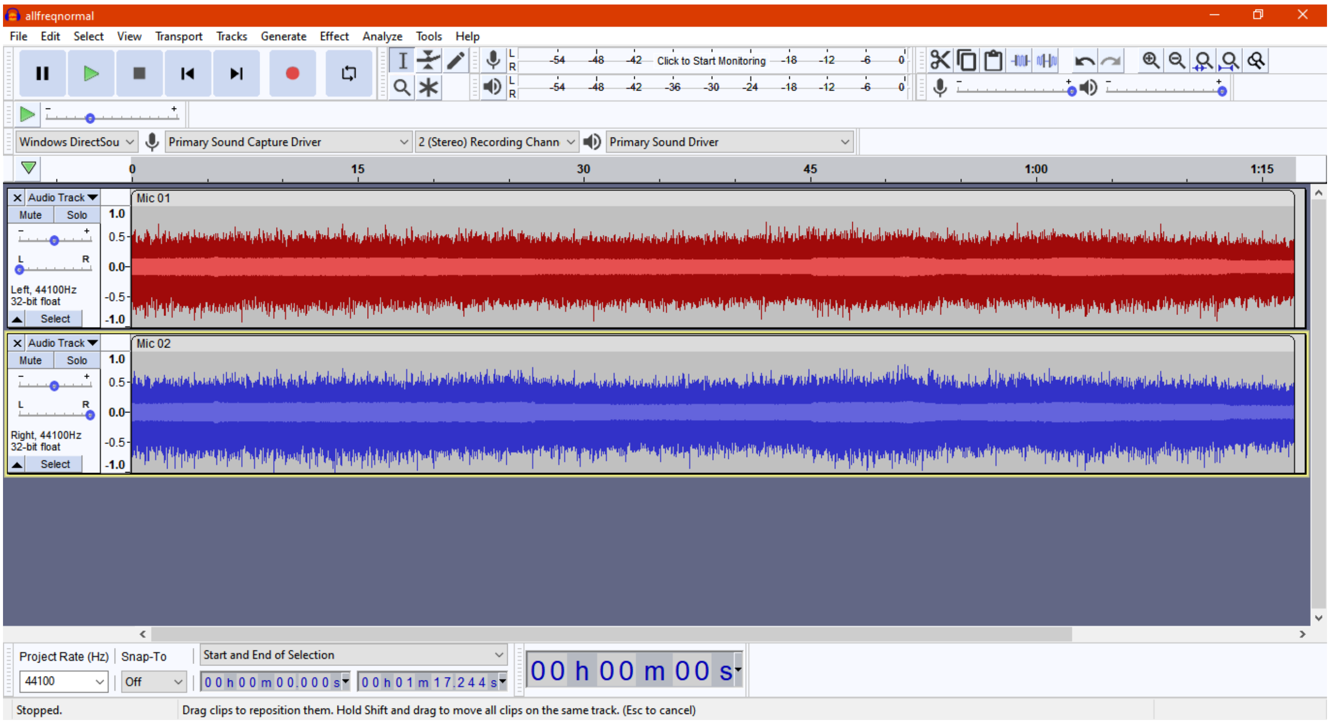

Figure III.15: Sound signal of the normal bearings at different frequency

As we can see from the figure above, the audio signal does not have any loud noise at all speeds, which indicates that the bearings are working well and smoothly.

III.5.1.2 Full rusty bearing

In this case, we replace the upper normal bearing (which is beside mic 01) with a rusty one in the stepper motor (it often works vertically, so it rusts completely) and leave the second normal one, as you can see in the picture below. Then we record the sound coming out of the bearings in the motor with the two microphones at different speeds and frequencies.

Figure III.16: Photo of a full rusty bearing inside the motor

We took noise recordings by the two mics during normal motor rotation (full rusty bearing and normal bearing) at different frequencies [100, 200,300,400,500,600] Hz.

Note: the red signal is the recording of the mic 01(near the rusty bearing) and the blue one is the recording of the mic 02(near the normal bearing).

- **100Hz**

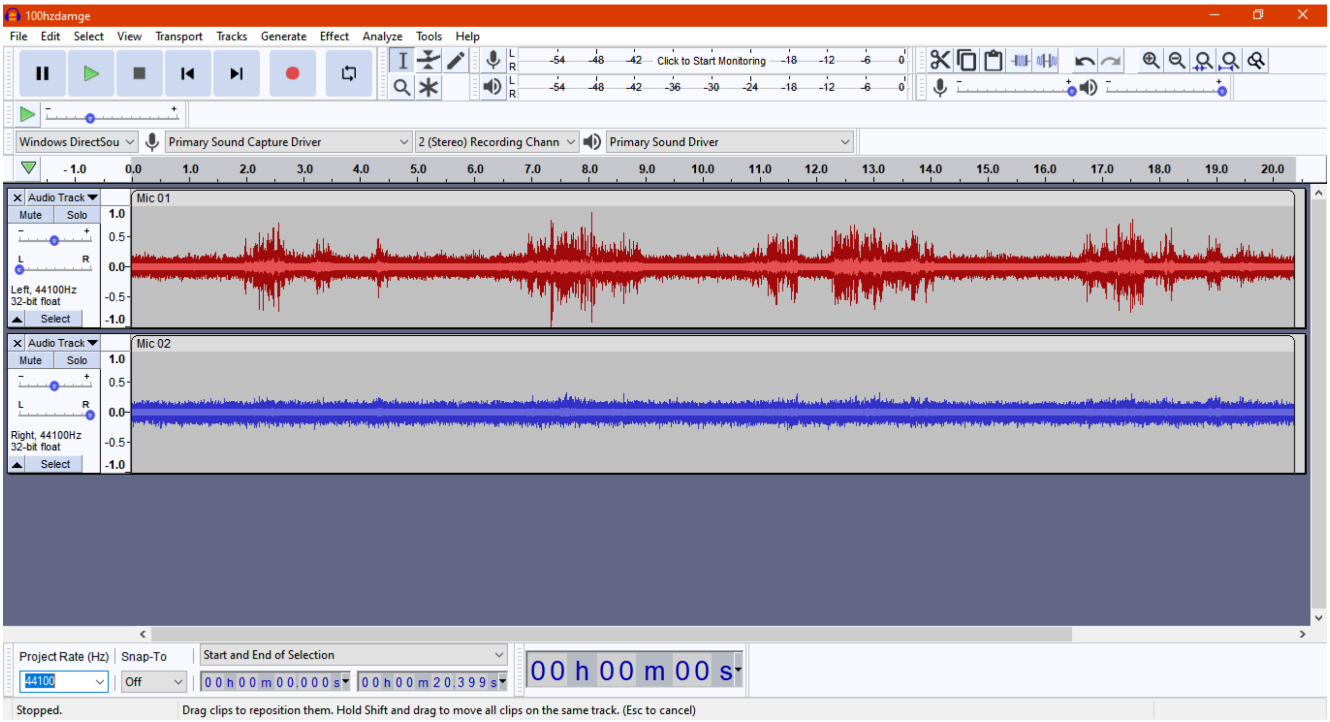

Figure III.17: Sound signals of the full rusty bearing at 100Hz

❖ **200Hz**

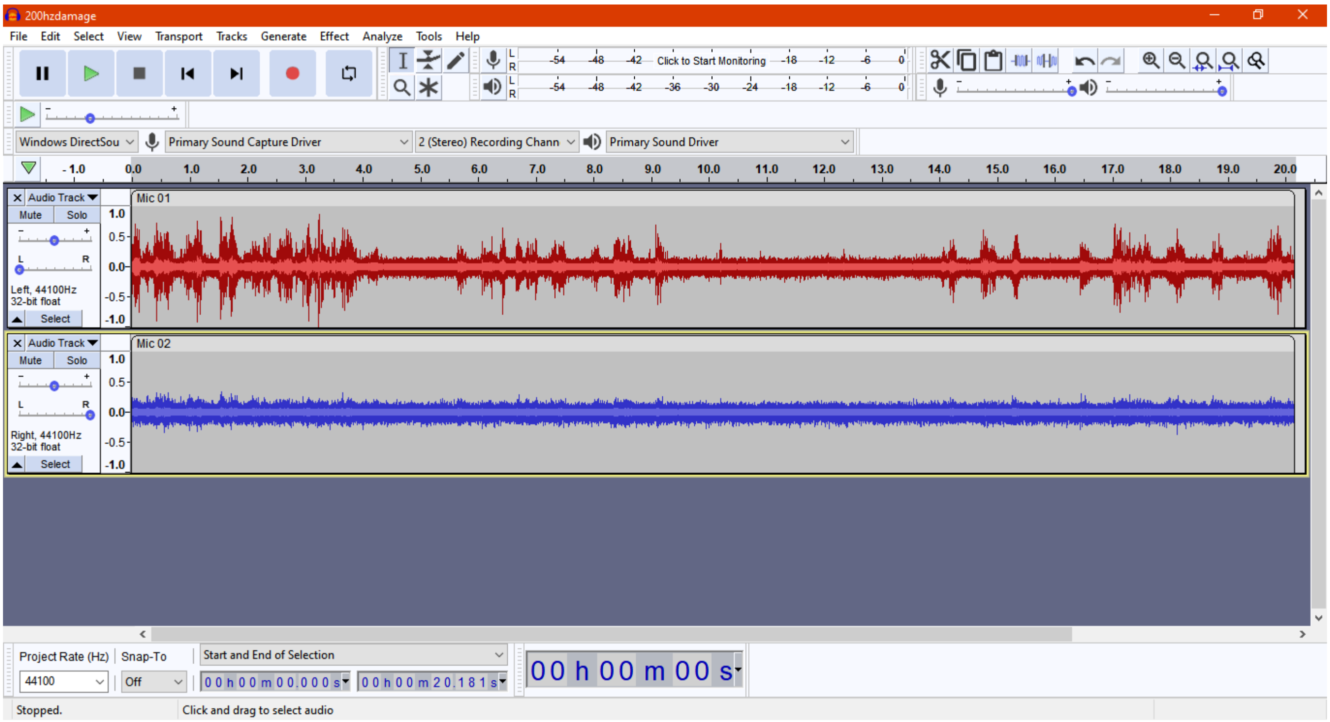

Figure III.18: Sound signals of the full rusty bearing at 200Hz

❖ **300Hz**

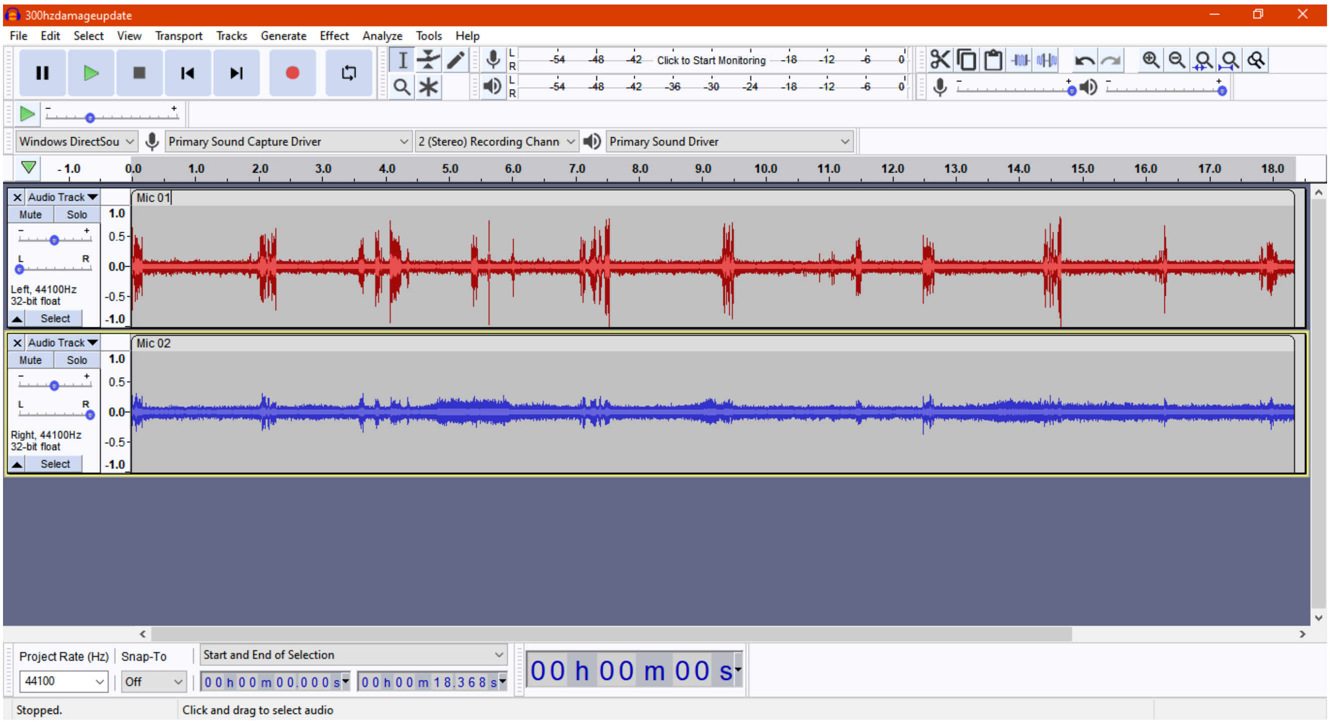

Figure III.19: Sound signals of the full rusty bearing at 300Hz

❖ **400Hz**

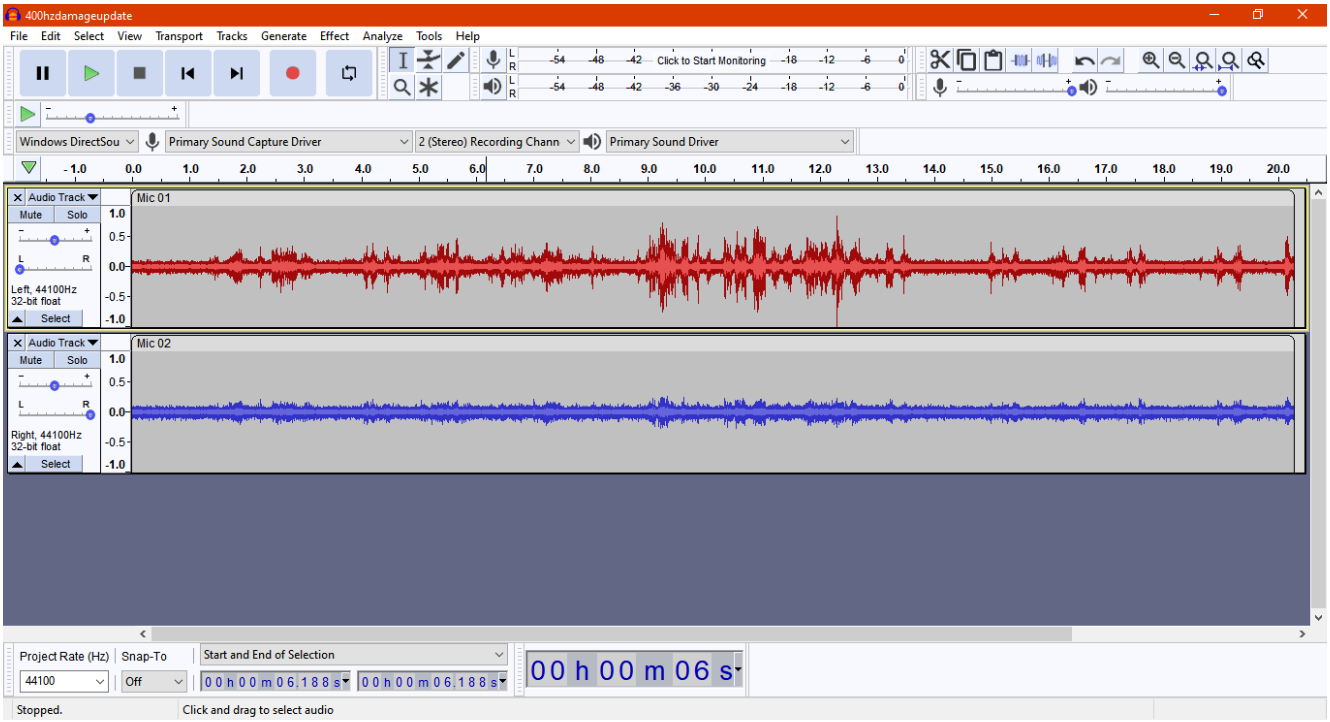

Figure III.20: Sound signals of the full rusty bearing at 400Hz

❖ **500Hz**

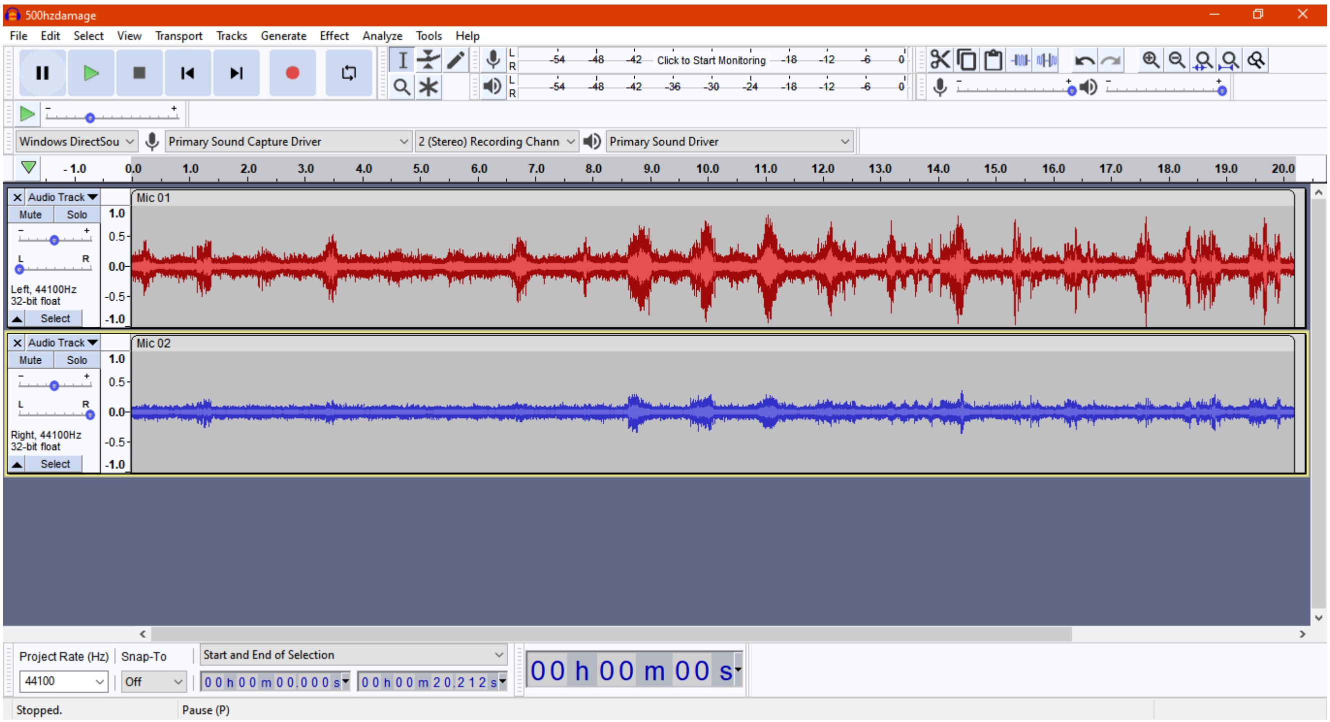

Figure III.21: Sound signals of the full rusty bearing at 500Hz

❖ **600Hz**

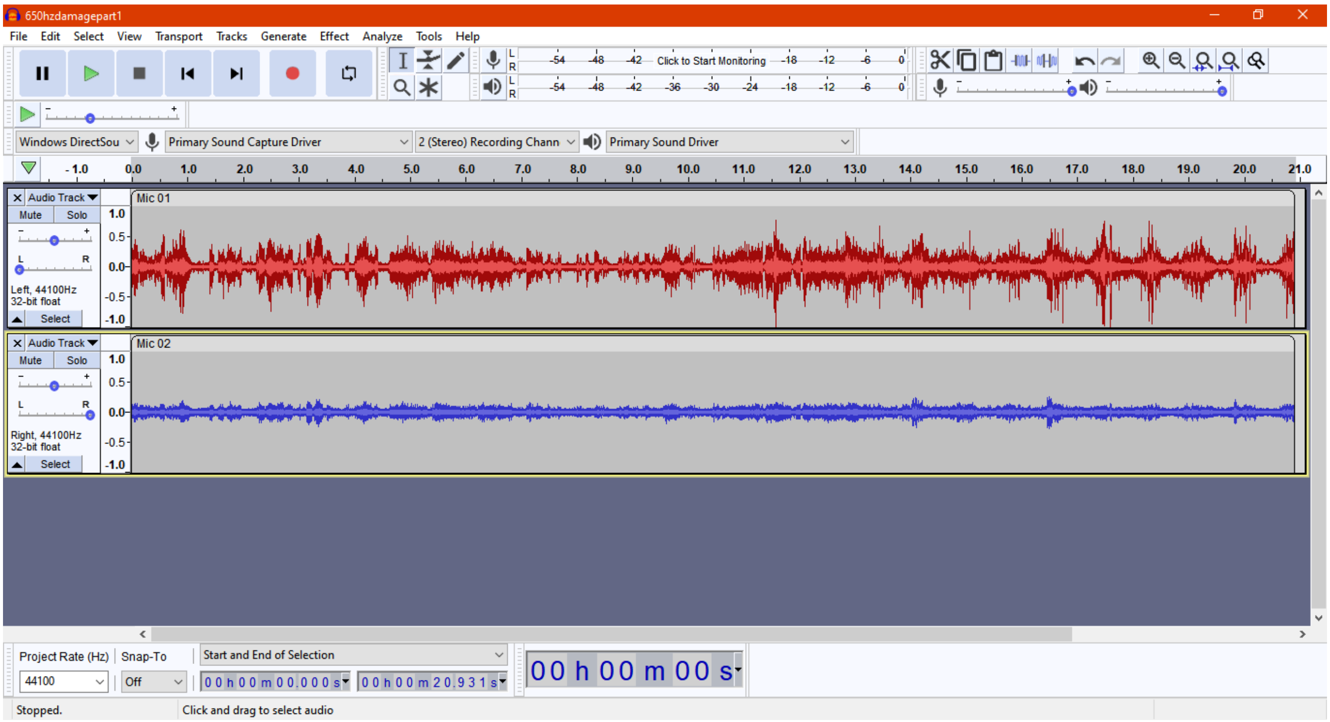

Figure III.22: Sound signals of the full rusty bearing at 600Hz

Note: In the previous figures you can see that the noise of the motor with a damaged bearing is more evident at high frequencies (high speeds).

III.5.1.3 Rusty spot in the bearing

In this case, we replace the normal bearing with a rusty spot bearing (which is beside the mic 01) and leave the second normal bearing (which is beside the mic 02) in the stepper motor (it often works horizontally so that it does not rust completely).

Figure III.23: Photo of a rusty spot bearing inside the motor

Then we record the coming sound by using Audacity at different speeds (20Hz up to 600Hz) and we have got the following signals.

- **20 Hz up to 600Hz**

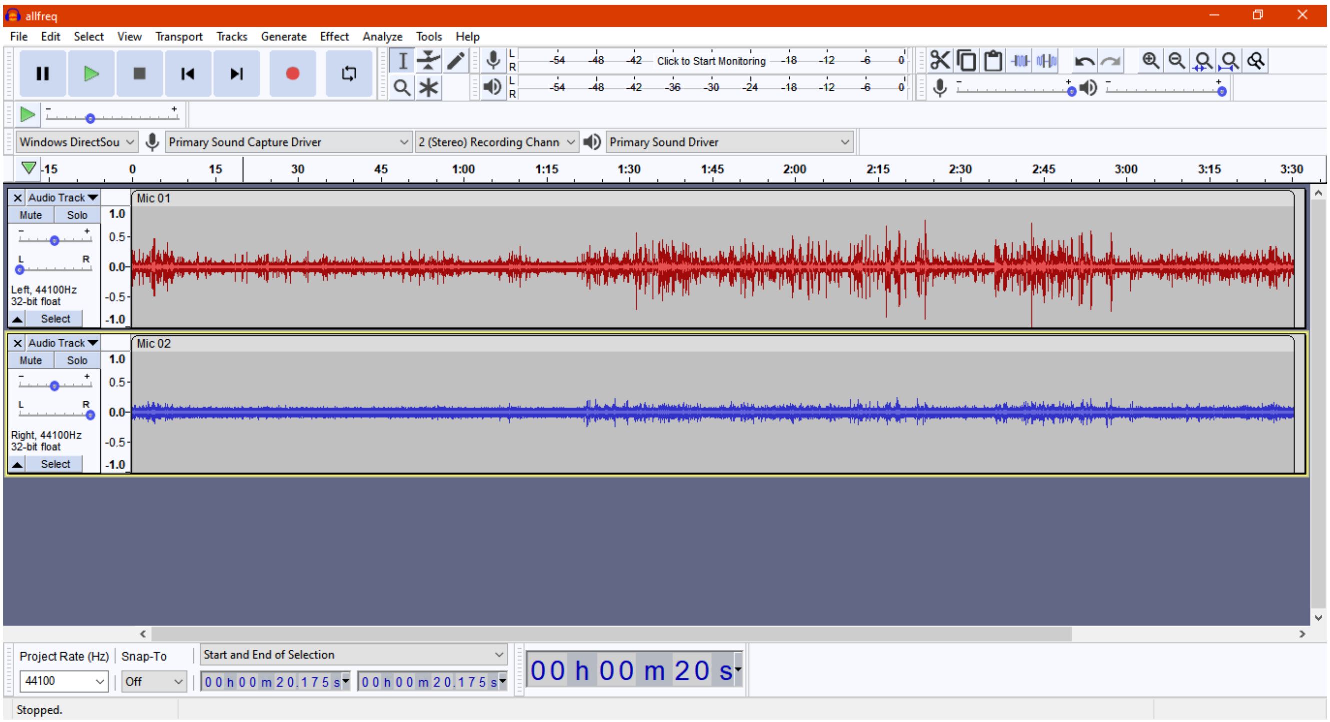

Figure III.24: Sound signal of the rusty spot bearing at different frequency

As we can see from the figure above, the audio signals have a loud and random noise at all speeds, which indicates that the bearings are not working well and smoothly.

III.5.2 Comparison between the three types of bearings

If we compare the three types of bearings in terms of the noise signal generated by the motor, we find that in the case of a normal bearing, the noise signal coming from the friction of the bearing is normal and has a low tone, so in this case, the bearing moves smoothly at all speeds (all frequencies), but in the case of a completely rusted bearing, we notice the friction of the bearing with a high and distinct sound and this sound increases as the speed increases, we see that the sound signal increases and becomes more distinct. Finally, in the case of the partially rusted bearing, we notice that the noise signal is not accurate and proportional due to the friction, and there is an analogy with the fully rusted bearing, so we cannot distinguish whether the bearing is partially or fully rusted.

III.6 Diagnosis port proposition

At this stage, we collect the diagnosis of electrical and mechanical faults in a port called the diagnostic port. This port consists of sensors (Tc and MEMS) that are installed in the motor. This port makes it easier for us to handle the motor in the diagnostic process, especially for heavy industries and expensive motors used in precision-controlled devices such as medical robots and CNC machines. We can connect this port to a microcontroller or an automated system so that we can monitor the changes in the motor and have the ability to predict any malfunctions that may occur and also the ability to easily diagnose them.

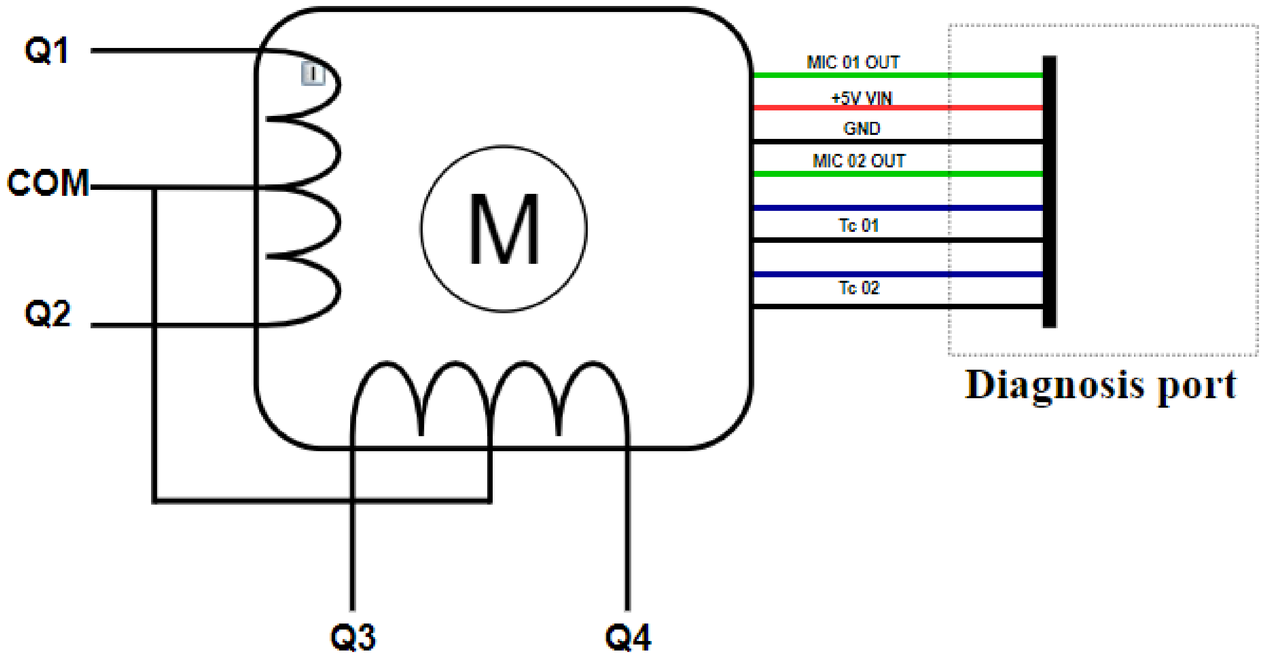

Figure III.25: Schematic diagram of stepper containing diagnosis port

Finally, we propose to the manufacturers of stepper motors the idea of a diagnostic port that will support the diagnostic process with ease, lower cost, and less effort.

III.7 Conclusion

With the microphones, we can diagnose the condition of the motor if it is working well or not. We can distinguish if the bearing is working well or if it has rust and friction based on the sound. With this method, we can also detect some mechanical faults, such as the decentralization of the rotor.

GENERAL CONCULSION

In this work, we have started by identifying stepper motors and their types and their importance in our practical and industrial life. Then we applied some common electrical and mechanical faults to find the best methods to diagnose them. At the electrical level, one of the most common faults that any motor, especially stepper motors, is exposed to is the presence of a short circuit. Therefore, we created a short circuit in one of the phases of the stepper motor and developed three methods to diagnose and detect this fault.

The first method is the series resonant circuit. In this method, we assume that the phases are the inductors of the resonant circuit. Then we monitor the resonant frequency and compare it with other phases. If there is a difference in the resonant frequency of one of these phases, we conclude that there is a short circuit.

The second method is through the so-called transformers. In this case, we assume that the coils of the motor are the primary and secondary coils of a transformer. If we get the same voltage in all phases, there is no short circuit. Otherwise, we conclude that there is a short circuit and therefore a defect in the motor.

The third method is using thermal sensors. We have added a thermocouple inside the coils and read the temperatures generated by the phases. If the temperature of one of the phases is higher than the other, we conclude that there is a short circuit, and with this method, we can diagnose and the motor works, unlike the previous two methods.

At the mechanical level, assuming that the driver of the motor is operating in a correct condition we studied the faults that bearings may be exposed to, such as rust and oil and grease wear in the bearing. For this diagnosis, we used two MEMS microphones. We placed the first microphone next to the upper bearing and the other microphone next to the lower bearing, then we recorded the noise produced by the correct bearings and used it as a reference, then we replaced one of these bearings with a completely rusted bearing, and we obtained a sound signal when we compared it with the original noise (in the case of a normal bearing). We notice a difference that increases as the motor speed increases. We also studied the noise that occurs when the bearing is partially rusted, and we found that there is a slight difference with a completely rusted bearing. With this method, we can determine the condition of the bearing through the acoustics, whether it is working well or not, and whether there is friction and difficulty in turning the motor or not. Also, this method can be used to know the state of the rotor, if it is centered or not.

Based on previous studies and experiences, as well as the importance of stepper motors in various industries and the importance of avoiding malfunctions and not interfering with important work processes, it was necessary to find methods to easily diagnose faults related to this motor without stopping it and disassembling it from the machines connected to it or moving it from its location to a repair shop to diagnose it. That's really what we got in our work, diagnostics with the least amount of effort and cost.

Finally, we are proposing stepper motor manufacturers, especially the important and expensive motors. Modify the motors and add a diagnostic port.

Moreover, this port can be connected to a microcontroller or an automation system that allows us to monitor the state of the motor, predict some faults before they occur, and warn us when the state of the motor changes, based on previous information that we use as a reference for comparison, so we gain the time and the effort.

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