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Study and Control of a Stepper Motor using an Arduino Card

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We also thank all the teachers and teachers, our parents, our brothers and sisters and our dear friends for their help and sacrifices.

Dedicate

We dedicate this humble work.

To those who helped us to do this modest work by their advice and encouragement:

• Our parents

• Our supervisor Dr BEKAKRAYoucef

• Our teachers

• Our dear friends

• To all the promotion 2017 /2018

We thank them and dedicate them to this work

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Abbreviations used:

DC	Direct Current
AC	Alternative Current
CNC	Machine used in Numerical Control
VRM	Variable Reluctance Motor
PMSM	Permanent Magnet Stepper Motor
HSM	Hybrid Stepper Motor
PI	Régulateur Proportionnel Intégrateur
P	Opérateur de Laplace
A	phase A Wnding
B	phase B Winding
Q	Switches
S1	The Switches Position (1= close, 0=open)
N	North
S	South

Mechanical grandeurs:

θ_r	Rotor Position
θ_s	Stator Position
θ_{fs}	Full Step Angel
θ_{hs}	Half Step Angle
θ	Step Angle in Degrees
$d\theta/dt$	Position Derivate

W	Rotor Speed
θ_M	The Maximum Angle.
T_D	Detent Torque
Ω	Mechanical Rotor Speed.
a	Constant.
b	Constant.
α	Angel Variable
B	Angle Variable

Electrical grandeurs:

V_a	Phase A Tension
V_b	Phase B Tension
I_a	Phase A Current
I_b	Phase B Current
di/dt	Current Derivate

Motor Parameters:

Nr	Number of Rotor Teeth
R	Phase Resistant
L	Inductance of The Phase Winding
K_m	Constant Torque
K_d	Detent Torque
T_L	Load Torque.
J	Rotor Inertia.
B	Viscous Friction.
T	Period (Time).
rmp	Medium Speed.
N_s	Number of Stator Teeth
N_r	Number of Rotor Teeth
m	Number of Phases
T_H	Holding Torque

Repère:

X	Axis
Y	Axis

γ	Position.
r	Radiation Output Between X and Y

General Introduction

General introduction:

The stepper motor was invented by Marius Lavet in 1936. It is a DC electrical motor that transfers an electrical pulse into angular movement. It composed of several elements and receives impulses which a jerky movement as the oscillating mass. Stepper motors are used widely in applications in industrial control, computers, printers, robotic, specifically for CNC machines and so on …..

A servo motor is a rotary actuator that allows for precise control angular position. It requires a servo drive to complete the system. The drive uses the feedback sensor to precisely control the rotary position of the motor. By running the system closed-loop, servo motors provide a high performance. Servo motors are widely used in robotic domain.

Our project is a detail study and control of the stepper motor, it is divided to three essential parts: study on the stepper motor, modeling of the hybrid stepper motor and a practical control on the stepper motor using a PID controller implemented by MATLAB-SIMULINK software. It contains a simulation and profound investigations about the behavior of the hybrid stepper motor.

Objective of the project:

After all this basic information that leads us to one simple questions, why we choose the stepper than servo motor? The main problem in our work is how to get a precise control with best performance but with a low cost?

This work is divided in three parts:

The first chapter is a profound study about the stepper motor, we start about a definition, construction, types of the steppers, how it works, comparison among its types, excitations modes and how to select a motor. At the end of this chapter, the applications, the advantages and the disadvantages of the stepper motors are presented.

The second chapter contains everything that needs to be known to model the hybrid stepper motor, we present the model of the motor.

The third chapter presents the control of the motor by a PID controller under Matlab/Simulink with an Arduino card.

CHAPTER I: *Generality on the Stepper Motor.*

I.1 Introduction:

Stepper motor is a special type of electric motor; they are DC motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". By energizing each phase in sequence, the motor will rotate one step at a time. The size of the increment is measured in degrees and can vary depending on the application. Due to precise control, stepper motors are commonly used in medical, satellites, robotic and control applications. There are several features common to all stepper motors that make them ideally suited for these types of applications. Stepper motor requires sequencers and driver to operate. Sequencer generates sequence for switching which determines the direction of rotation and mode of operation. Driver is required to change the flux direction in the phase windings. The block diagram of stepper motor system has been presented in Figure 1.1 [1] [2]

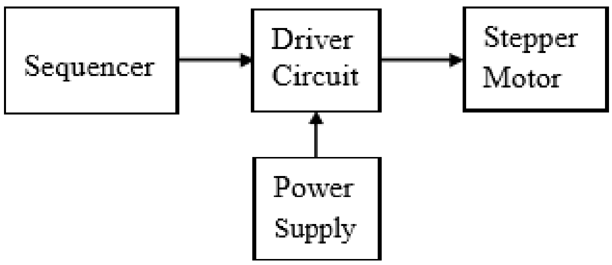


Figure I.1 Block diagram of stepper motor system.

In this chapter, we present a basic knowledge and generality about the stepper motor, its principals and its types.

I.2 Construction:

There are three types of stepper motor: permanent magnet, variable reluctance type and hybrid motor. The excitation voltage in the coils of the stepper motors is DC, and the number of phases indicates the number of windings. The excitation windings are in the stator in every case. In case of a permanent magnet type step motor the rotor is a permanent magnet with a number of poles. On the other hand the rotor of a variable reluctance type motor is of a cylindrical structure with a number of projected teeth. [3]

I.3 How Does It Work?

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. The stator has eight poles, and the rotor has six poles. The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives.**[4]**

I.4 Types of Stepper Motors:

It can be classified into several types according to machine structure and principle of operation as explained by Kenjo (1984). Basically there are three types: [5]

1- Variable Reluctance Motor (VRM)

2- Permanent Magnet Stepper Motor (PMSM)

3- Hybrid Stepper Motor (HSM)

I.4.1 Variable Reluctance Motor:

The Variable reluctance type step motors do not have any holding torque at the same time do not require reversing of current through the coils. It consists of a soft iron multi-toothed rotor and a wound stator. When the stator windings are energized with DC current, the poles become magnetized. Rotation occurs when the rotor teeth are attracted to the energized stator poles. Both the stator and rotor materials must have high permeability and be capable of allowing high magnetic flux to pass through even if a low magneto motive force is applied. When the rotor teeth are directly lined up with the stator poles, the rotor is in a position of minimum reluctance to the magnetic flux. A rotor step takes place when one stator phase is energized and the next phase in sequence is energized, thus creating a new position of minimum reluctance for the rotor as explained by Kenjo (1984). Cross-section of variable reluctance motor has been presented in Figure 1.2 [6][7]

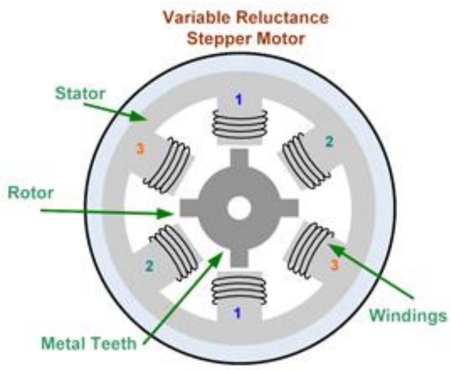


Figure I.2 Cross-section of variable reluctance motor.

I.4.2 Permanent Magnet Stepper Motor:

A stepper motor using a permanent magnet in the rotor is called a PMSM. The rotor no longer has teeth as with the VRM. Instead the rotor is magnetized with alternating north and south poles situated in a straight line parallel to the rotor shaft. The principle of step motor can be understood from the basic schematic arrangement of a small permanent magnet step motor is shown in Fig 3. This type of motor is called a two-phase two pole permanent magnet step motor; the number of windings being two (phase 1 and phase 2) each split into two identical halves; the rotor is a permanent magnet with two poles. So winding A is split into two halves A1 and A2. They are excited by constant DC voltage V and the direction of current through A1 and A2 can be set by switching of four switches Q1, Q2, Q3 and Q4 as has been shown in Fig.2(a). For example, if Q1 and Q2 are closed, the current flows from A1 to A2, while closing of the switches Q3 and Q4 sets the direction of current from A2 to A1. Similar is the case for the halves B1 and B2 where four switches Q5-Q8 are used to control the direction of current as shown in Fig 4(b). The directions of the currents and the corresponding polarities of the induced magnets are shown in Fig 3. [2] [8]

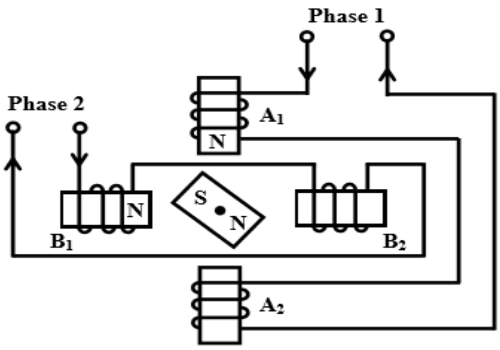


Figure 1.3 Schematic diagram of a two-phase two-pole permanent magnet stepper motor. [26]

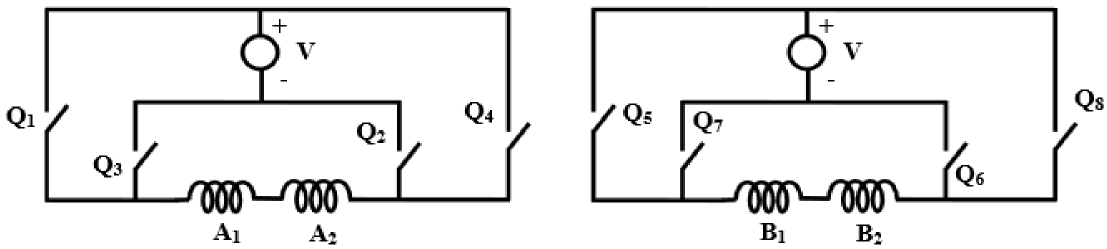


Figure I.4 Switching sequence for Fig1. 3. [26]

Now consider Fig 5. Let Winding A be energized and the induced magnetic poles are as the Fig 5 (a) present (we will denote the switching condition as S1=1). The other winding B is not energized. As a result the moving permanent magnet will align itself along the axis of the stator poles as shown in Fig 5 (a). In the next step, both the windings A and B are excited simultaneously, and the polarities of the stator poles are as shown in Fig 5 (b). We shall denote S2=1, for this switching arrangement for winding B. The rotor magnet will now rotate by an angle of 45^o and align itself with the resultant magnetic field produced. In the next step, if we now make S1=0 (thereby de-energizing winding A), the rotor will rotate further clockwise by 45^o and align itself along winding B, as shown in Fig 5 (c). In this way if we keep on changing the switching sequence, the rotor will keep on rotating by 45^o in each step in the clockwise direction. The switching sequences for the switches Q1 to Q8 for first four steps are tabulated in Table 1. [9]

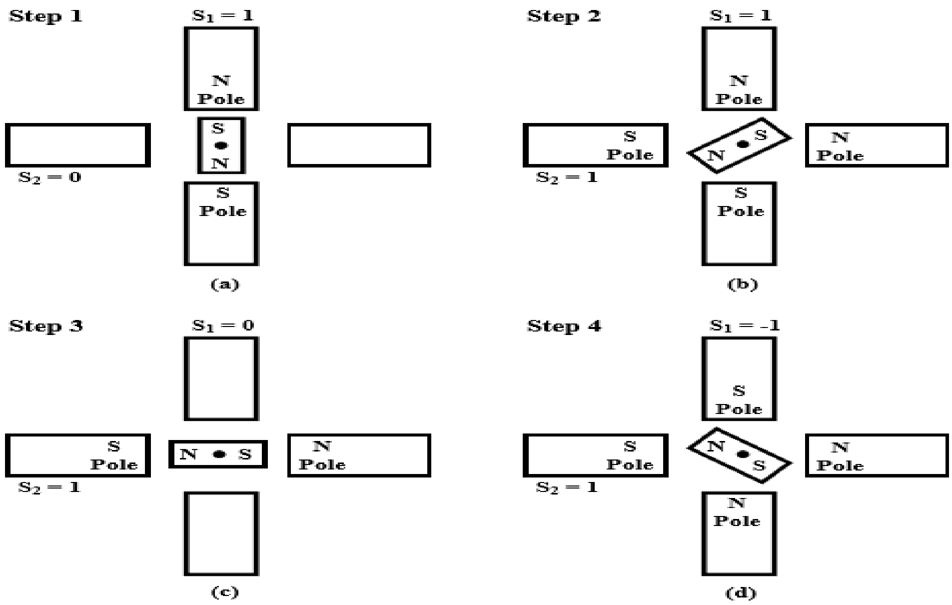


Figure I.5 stepping sequence (half-stepping) for a two-phase two-pole PM step motor for clockwise rotation. [26]

Table I.1: Switching sequence corresponding to the movement as shown in Fig 5.

	Step 1	Step2	Step3	Step4
Q1-Q2	ON (S1=1)	ON (S1=1)		
Q3-Q4				ON (S1=-1)
Q5-Q6				
Q7-Q8		ON (S2=1)	ON (S2=1)	ON (S2=1)

It is apparent from Table 1 and Fig 5 that for this type of switching the step angle is 45^o and it takes 8 steps to complete a complete revolution. So we have 8 steps / revolution. It can also be seen from Table 1 that a pair of switch (say Q7-Q8) remains closed during consecutive three steps of rotation and there is an overlap at every alternate step where both the two windings are energised. This arrangement for controlling the step motor movement is known as half stepping. The direction of rotation can be reversed by changing the order of the switching sequence. It is also possible to have an excitation arrangement where each phase is excited one at a time and there is no overlapping where both the phases are energised simultaneously, though it is not possible for the configuration has been shown in Fig.1, since that will require the rotor to rotate by 90o in each step and in the process, may inadventedly get locked in the previous position. But full stepping is achievable for other cases, as for example for the two-phase six-pole permanent magnet stepper motor as shown in Fig 6 in this case, the stator pitch θ_s =90^0 and the rotor pitch θ_r =60^0, the full step angle is given by $\theta_{fs} = \theta_s - \theta_r$ =30^0 and the half step angle $\theta_{hs} = (\theta_s - \theta_r)/2$ =15^0 .The desired direction of rotation can be achieved by choosing the sequence of switching. [9]

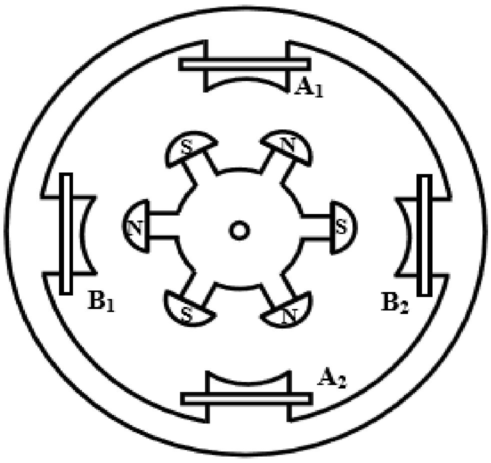


Figure I.6: Two-phase six-pole permanent magnet stop motor. [26]

The advantage of a permanent magnet step motor is that it has a holding torque. This means that due to the presence of permanent magnet the rotor will lock itself along the stator pole even when the excitation coils are de-energized. But the major disadvantage is that the direction of current for each winding needs to be reversed. This requires more number of transistor switches that may make the driving circuit unwieldy. This disadvantage can be overcome with a variable reluctance type step motor. Another way of reducing the number of switches is to use unipolar winding. In unipolar winding, there are two windings per pole, out of which only one is excited at a time. The windings in a pole are wound in opposite direction, thus either N-pole or S-pole, depending on which one is excited [10].

I.4.3 Hybrid Stepper Motor:

Hybrid motors share the operating principles of both permanent magnet and variable reluctance stepping motors. The rotor for a hybrid stepping motor is multi toothed, like the variable reluctance motor, and contains an axially magnetized concentric magnet around its shaft (see Figure 5). The teeth on the rotor provide a path which helps guide the magnetic flux to preferred locations in the air gap. The magnetic concentric magnet increases the detent, holding and dynamic torque characteristics of the motor when compared with both the variable reluctance and permanent magnet types. The important feature of the HSM is its rotor structure. A cylindrical or disk-shaped magnet lies in the rotor core. Stator and rotor end-caps are toothed. The coil in pole 1 and pole 3 is connected in series consisting of phase A and poles 2 and 4 are for phase B. If stator phase A is excited pole 1 acquires north polarity while pole 2 acquires south polarity. Pole 1 attracts the rotor's South Pole while pole 3 aligns with the rotor's North Pole. [11]

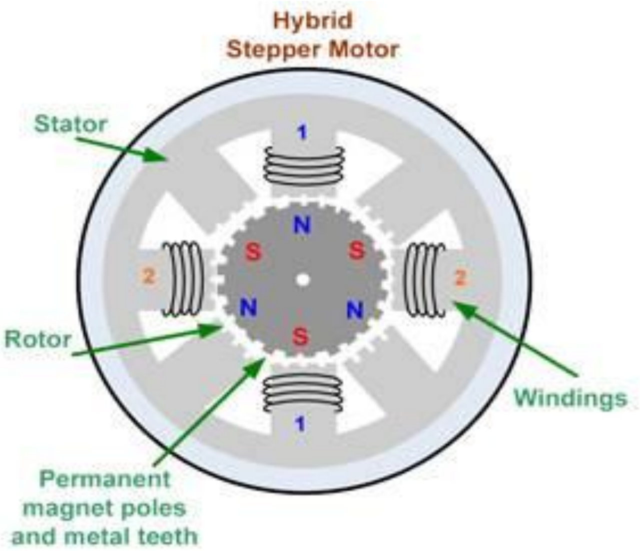


Figure I.4: Cross-section of HSM.

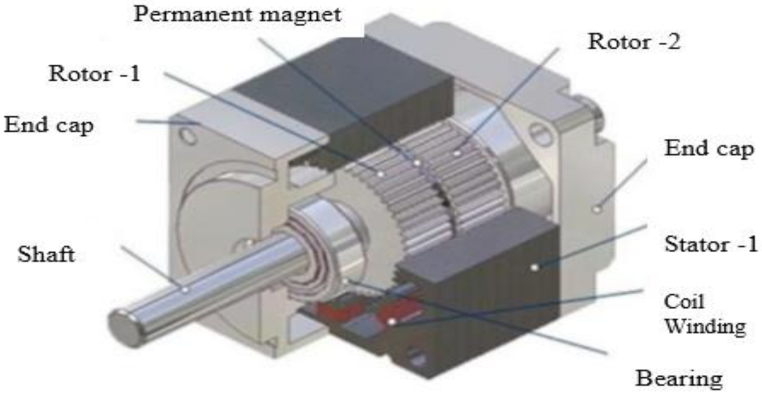


Figure I.5 Cut view of HSM.

When the excitation is shifted from phase A to phase B, in which case the stator pole 2 becomes north pole and stator pole 4 becomes south pole, it would cause the rotor to turn 90^0 in the clockwise direction. Again phase A is excited with pole 1 as south pole and pole 3 as north pole causing the rotor to move 90^0 in the clockwise direction. If excitation is removed from phase A and phase B is excited, then pole 2 produces south pole and pole 4 produces north pole resulting in rotor movement of 90^0 in the clockwise direction. A complete cycle of excitation for the HSM consists of four states and produces four steps of rotor movement. The excitation state is the same before and after these four steps and hence the alignment of stator/rotor teeth occurs under the same stator poles as explained by Kenjo (1984). The step length for a HSM and angle through which the rotor moves for each step pulse is known as step angle and is calculated by: [12][13]

$$\text{Step length} = 90^o/Nr \tag{1.1}$$

Step angle is calculated using the formula

$$\theta = \frac{360}{m*Nr} \text{ or } \theta = \frac{360*(Ns-Nr)}{m*Nr} \tag{1.2}$$

Where

θ - Step angle in degrees

N_s- Number of stator teeth

N_r- Number of rotor teeth

m- Number of phases

Mechanical angle represents the step angle of the step. In the full step mode of a 1.8° motor, the mechanical angle is 1.8°. In the 10 micro step mode of a 1.8° motor, the mechanical angle is 0.18º. An electrical angle is defined as 360° divided by the number of mechanical phases and the number of micro step. In the full step mode of a 1.8° motor, the electrical angle is 90°. In the 10 micro step excitation of a 1.8° motor, the electrical angle is 9°. HSM material properties for each part and standard step angle of HSM are tabulated in Table 1.1 and Table 1.2 respectively. [14]

Table I.2 Material properties of HSM

S. No	Motor Part	Material
1.	Shaft	Non-Magnetic materal
2.	Magnet	Neodymuim Iron Boron(NdFe)/Samarium Cobalt($SMCO_5$)
3.	Rotor core	Steel sheet
4.	Stator core	Steel sheet
5.	Coil	Copper

After all this comparison it's obviously that the Hybrid stepper Motor is the motor of choice where you looking for precision position.

I.4.3.1 Unipolar HSM:

Unipolar drivers, always energize the phases in the same way. One lead, the "common" lead, will always be negative. The other lead will always be positive. Unipolar drivers can be implemented with simple transistor circuitry. The disadvantage is that there is less available torque because only half of the coils can be energized at a time.

I.4.3.2 Bipolar HSM:

Bipolar drivers use H-bridge circuit try to actually reverse the current flow through the phases. By energizing the phases with alternating the polarity, all the coils can be put to work turning the motor.

A two phase bipolar motor has 2 groups of coils. A 4 phase unipolar motor has 4. A 2-phase bipolar motor will have 4 wires - 2 for each phase. Some motors come with flexible wiring that allows you to run the motor as either bipolar or unipolar [5].

I.5 Control of Stepper Motors:

In many cases step motors are used for accurate positioning of tools and devices. Precision control over the rotation of the motor is required for these cases. Control of step motors can be achieved in two ways: open loop and closed loop. The open loop control is simpler and more widely used, such a scheme is shown schematically in Fig 6. The command to the pulse generator sets the number of steps for rotation and direction of rotation. The pulse generator correspondingly generates a train of pulse. The Translator is a simple logical device and distributes the position pulse train to the different phases. The amplifier block amplifies this signal and drives current in the corresponding winding. The direction of rotation can also be reversed by sending a direction pulse train to the translator. After reversing a directional pulse the stepper motor reverses the direction of rotation.

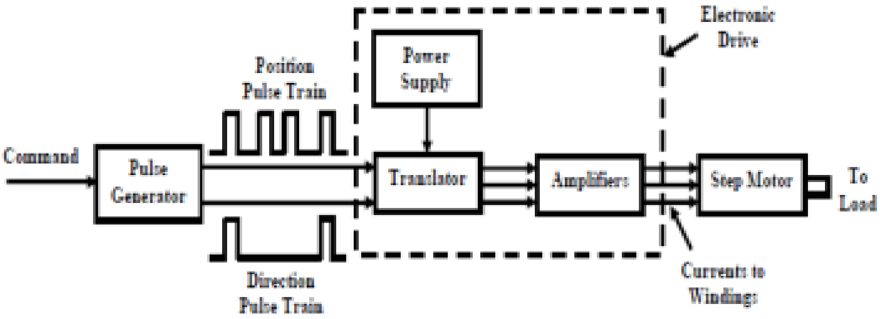


Figure I.6: Open loop control of a stepper motor.

The major disadvantage of the open loop scheme is that in case of a missed pulse, there is no way to detect it and correct the switching sequence. A missed pulse may be due to malfunctioning of the driver circuit or the pulse generator. This may give rise to erratic behavior of the rotor. In this sequel the closed loop arrangement has the advantage over open loop control, since it does not allow any pulse to be missed and a pulse is send to the driving circuit after making sure that the motor has rotated in the proper direction by the earlier pulse sent. In order to implement this, we need a feedback mechanism that will detect the rotation in every step and send the information back to the controller. Such an arrangement in Fig 7 presents. The incremental encoder here is a digital transducer used for measuring the angular displacement [15], [16].

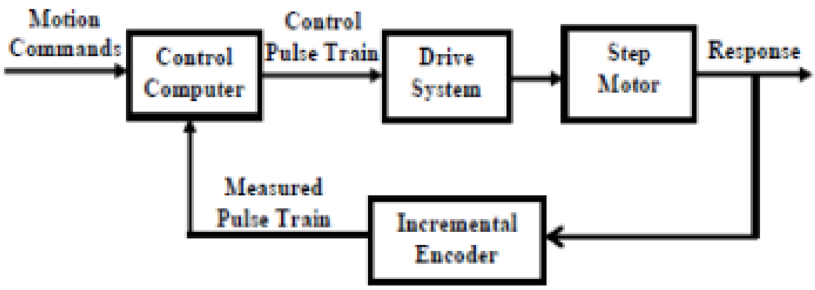


Figure I.7: Feedback control of a stepper motor.

I.6 Comparison of Stepper Motor Types:

The choice of the type of the stepper motor depends on the application. Selection of stepper motor depends on torque requirements, step angle and control technique. [5]

The complexity of the controller circuits are explained detail by Athani (2005). Comparisons based on motor advantages and disadvantages, motor characteristics and different phases are tabulated in Tables (1.3 - 1.5). [17]

Table I.3 Comparison based on motor advantages and disadvantages

Motor type	Advantages	Disadvantages
Variable Reluctance Motor	1. Robust No magnet 2. Smooth movement due to no cogging torque. 3. High stepping rate and speed slewing capability.	1. Vibrations 2. Complex circuit for control 3. No smaller step angle 4. No detent torque.
Permanent Magnet Stepper Motor	1. Detent torque 2. Higher holding torque 3. Better damping	1. Bigger step angle 2. Fixed rated torque. 3. Limited power output and size
Hybrid Stepper Motor	1. Detent torque 2. No cumulative position error 3. Smaller step angle 4. Operate in open loop	1. Resonance 2. Vibration

Table I.4 Comparison based on motor characteristics

Specifications	**Motor types**		
	VRM	PMSM	HSM
Step angle	0.66 º 30º	3.75 º 45º	0.45º 5º
Phases	3,4,5	2,4	2,5
Drive type	Unipolar	Unipolar/Bipolar	Bipolar
Rotor inertia	Low	High	Medium

Table I.5 Comparison based on different phase properties. [18]

Type of Phases	Properties
2 phase	1. Simple driver circuit with low heat dissipation. 2. Less step error compared to other phases. 3. Higher accuracy due to more number of stator Poles.
3 phase	1. Torque ripple is more. 2. Poor peak torque ratio. 3. Power transistors are less.
4 phase	1. Low torque ripple. 2. Good peak torque ratio.
5 phase	1. Lower torque ripple. 2. More expensive controller.

The increased number of phases requires complicated control circuits, which provide better dynamics and considerable increase in the number of steps.

I.7 Selection of Motor:

Stepper motor can be selected based on the following specifications:

I.7.1 Electrical specifications include number of phases, step angle, winding voltage, winding resistance , inductance, holding torque, pull-out torque, maximum slew rate, positional accuracy, temperature rise and power supply & drive circuits.

I.7.2 Mechanical specifications includes shaft length & shape, motor length, shape of flange face, lead wire length and connector type [18].

I.8 Characteristics of stepper motor:

The construction features between the various types of SM are different, but their behaviors are similar. Some additional characteristic details about HSM are given below:

I.8.1 Static Characteristics: [17]

I.8.1.1 Torque Angle Curve:

The torque increases, almost sinusoidal with angle from equilibrium position as the figure 8 shows. S is the step angle (deg) and M is the maximum angle.

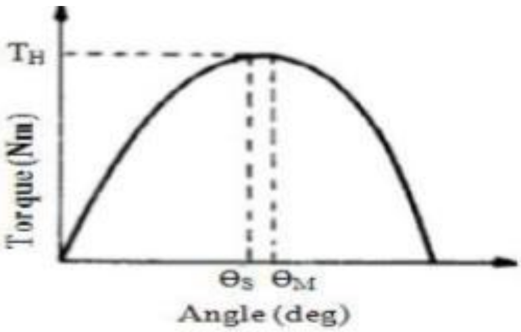


Figure I.8: Torque- angle curve of stepper motor.

I.8.1.2 Holding Torque (TH):

It is the maximum load torque which the energized stepper motor can withstand without slip from position.

I.8.1.3 Detent Torque (TD):

It is the maximum load torque which an un energized stepper motor can withstand without slipping and is also known as cogging torque. It is due to residual magnetism and about 5-10% of holding torque. Detent torque is typically fourth harmonic torque as figure 9 shows:

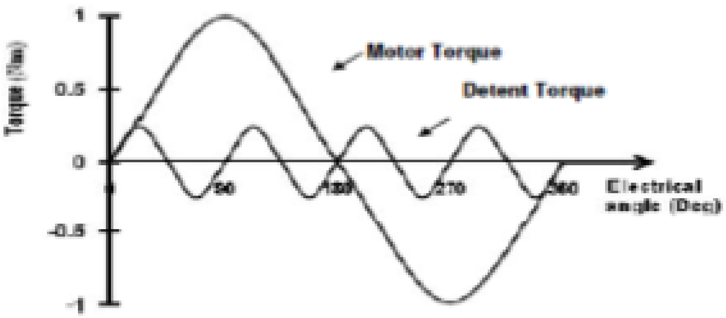


Figure I.9: Torque and detent torque profiles of stepper motor.

I.8.2 Dynamic Characteristics:

Torque versus speed relationship of a stepper motor has been shown in Figure 10. The two curves are the pull-in torque and the pull-out torque curve and intermediately pull-out region is called the slewing curve **.**

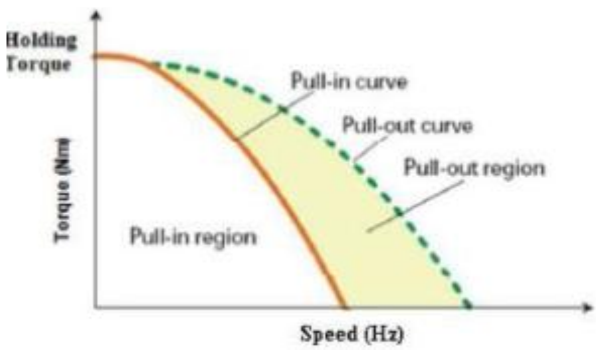


Figure I.10: Torque Vs Speed curves of stepper motor. [27]

The pull-out torque versus speed curve represents the maximum friction-torque load that a stepping motor can drive before losing synchronism at a specified stepping rate with the magnetic field and motor stall. The pull-in torque versus speed curve represents the maximum frictional load at which the stepper motor can start without failure of motion when a pulse train of the corresponding frequency is applied. The pull-in torque depends on the inertia of the load connected to the motor. The pull-in region is defined as the maximum control frequency at which the unloaded motor can start and stop without losing steps. The pull-out region is defined as the maximum frequency at which the unloaded motor can run without losing steps and is alternatively called the maximum pull-out rate. [17]

I.9 Different Modes of Excitation:

Different types of excitation schemes of the stepper motor are explained by Kenjo (1984), they are:

Full step

Half step

Micro step

I.9.1 Full-Step:

The stepper motor uses a four-step switching sequence, which is called a full-step switching sequence which is already described above. [18]

I.9.2 Half-Step:

Another switching sequence for the stepper motor is called an eight-step or half-step sequence. The switching diagram for the half-step sequence is presenting in Fig 1.11. The main feature of this switching sequence is that you can double the resolution of the stepper motor by causing the rotor to move half the distance it does when the full-step switching sequence is used. This means that a 200-step motor, which has a resolution of 1.8°, will have a resolution of 400 steps and 0.9°. The half-step switching sequence requires a special stepper motor controller, but it can be used with a standard hybrid motor. The way the controller gets the motor to reach the half-step is to energize both phases at the same time with equal current.

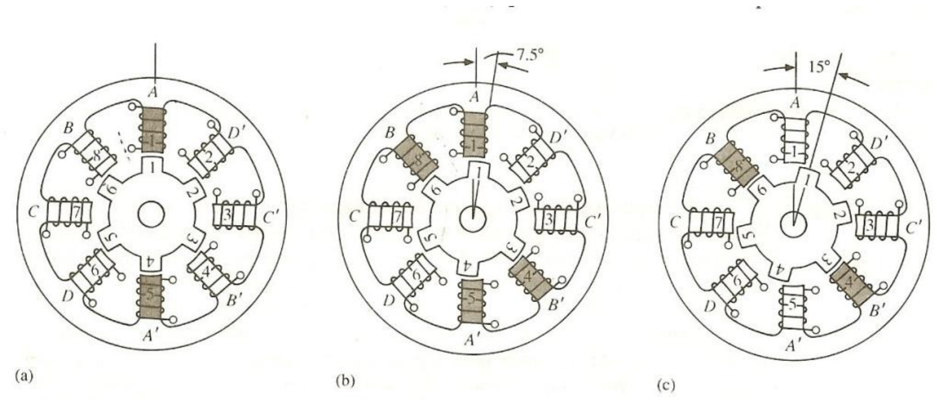


Figure I.11: The switching sequence for the eight-step input (half-step mode).

In this sequence the first step has SW1 is on, and SW2, SW3 and SW4 are off. The sequence for the first step is the same as the full-step sequence. The second step has SW1 and SW2 are on and all of the remaining switches are off. This configuration of switches causes the rotor to move an additional half-step because it is acted upon by two equal magnetic forces and the rotor turns to the equilibrium position which is half a step angle. The third step has SW2 is on, and SW1, SW4 and SW3 are off, which is the same as step 2 of the full- step sequence. The sequence continues for eight steps and then repeats. The main difference between this sequence and the full-step sequence is that the energizing sequence for half step is A AB B BC C CD D DA. [18]

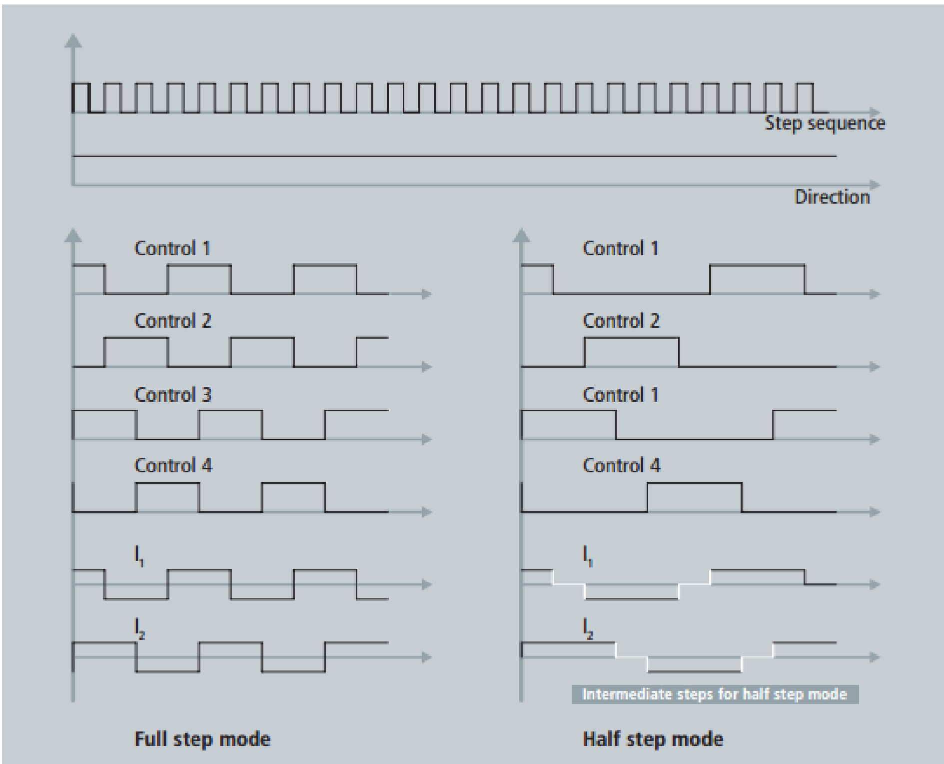
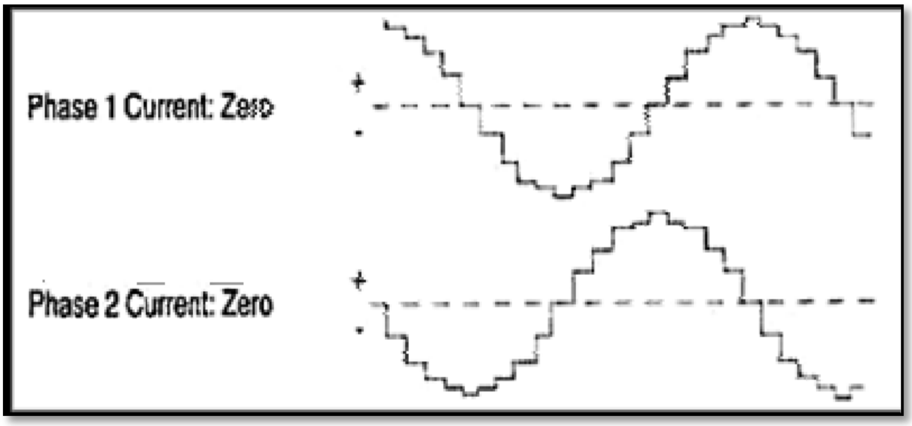


Figure1.12: Differences in the control modes for stepper motors (left: full step, right: half step). [29]

I.9.3 Micro Step Mode:

The full-step and half-step motors tend to be slightly jerky in their operation as the motor moves from step to step. The amount of resolution is also limited by the number of physical poles that the rotor can have. The amount of resolution (number of steps) can be increased by manipulating the current that the controller sends to the motor during each step. The current can be adjusted so that it looks similar to a sine wave. Figure 13 shows the waveform for the current to each phase. From this diagram you can see that the current sent to each of the four sets of windings is timed so that there is always a phase difference with each other. The fact that the current to each individual phase increases and decreases like a sine wave and that is always out of time with the other phase will allow the rotor to reach hundreds of intermediate steps. In fact it is possible for the controller to reach as many as 500 micro steps for a full-step sequence, which will provide 100,000 steps for each revolution. [19]



FIgureI.13: Phase-current diagram for a stepper motor controller in micro step mode

I.10 Type of Driver:

The basic function of a motor driver is to provide the rated current to the motor windings in the shortest possible time. Driver voltage plays a large part in a step motor's performance. Higher voltage forces current into the motor windings faster, helping to maintain high speed torque. The main function of the driver circuit is to change the current and flux direction in the phase windings. Driving a controllable amount of current through the windings and thereby enabling maintains of short current rise and fall time is good for high speed performance. The direction change is done by changing the current direction, and this may be done in two different ways using a unipolar or a bipolar drive as explained by Acarnely (2002). [19]

I.10.1 Unipolar Driver:

Winding has three leads each at the end and one in the middle. Half of the winding only is used in motor operation at any instant of time. To change the direction of rotation, end leads are chosen and the current flows in the same direction. copper volume of winding and therefore incurs twice the loss of a bipolar drive at the same output power. Unipolar winding driver circuit is simple as shown in Figure 1.14, [20].

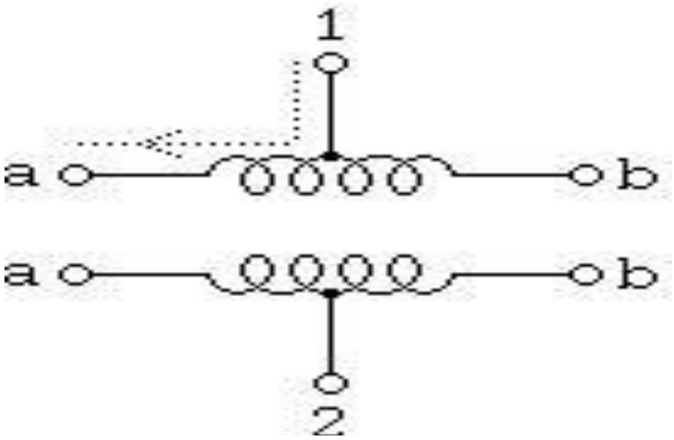


Figure 1.14: Unipolar winding.[30]

I.10.2 Bipolar Drive

In bipolar winding current flows in both directions as shown in Figure I.15. Unipolar winding can be configured into bipolar if the centre lead is ignored. Bipolar drives are most widely used drives for industrial applications. Although they are typically more expensive to design, they offer high performance and high efficiency.[20]

The bipolar drive method requires one winding per phase. The motor winding is fully energized by turning on one set (top and bottom) of the switching transistors. Comparison between different drivers is tabulated in Table 1.6.

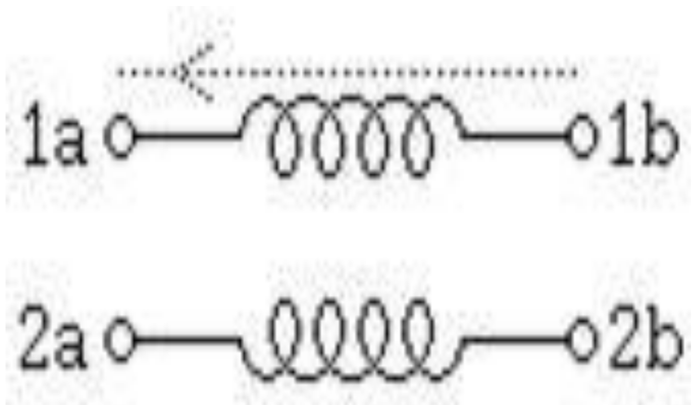


Figure 1.15: Bipolar winding. [30]

I.11 Comparison Between Drivers:

Table I.6 Comparison between drivers

Unipolar driver	Bipolar driver
Winding with a center tap, or two separate windings per phase	One winding per phase
Two switches per phase	Four switches per phase, in the form of an H-bridge
Utilizes only half the available copper volume of winding	Motor winding is fully energized
Incurs twice the loss of a bipolar drive at the same output power	Loss is minimum compared to unipolar drive

I.12 Stepper Motor Applications:

Stepper motors are used in a wide variety of applications in industry, including computer peripherals, business machines, motion control, and robotics, which are included in process control and machine tool applications. A complete list of applications is shown below:

I.12.1 Industrial Machines: stepper motors are used in automotive gauges and machine tooling automated production equipments.

I.12.2 Security: new surveillance products for the security industry.

I.12.3 Medical: stepper motor are used inside scanners, samplers, and also found inside digital dental photography, fluid pumps, respirators and blood analysis machinery.

I.12.4 Consumer Electronics: stepper motor in cameras for automatic digital camera focus and zoom functions.

I.12.5 Robotics: stepper motors are used in making robots for angular motion. Stepper motors are also used in business machines applications, computer peripherals applications, ect. [21]

I.13 Advantages of Stepper Motors Compared with other Motors:

In contrast to other motors stepper motors have a high holding torque even at low speed, and even on standstill. Another advantage is the simple control of stepper motors:

alternate energizing of the individual coils causes the motor to move step by step. The fixed number of steps per revolution always enables the current position to be determined if the steps are counted and the motor is operated within its performance limits. No encoder is required for simple positioning tasks within the performance limits. Stepper motors are therefore ideally suited as cost-effective solutions for simple positioning tasks. [22]

I.14 Disadvantages of Stepper Motor:

- Resonances can occur if not properly controlled.
- Not easy to operate at extremely high speeds [23].

I.15 Conclusion

This chapter gives a profound idea about the types of the stepper motor, its principal, its construction and theses advantages and disadvantages. In the next chapter, we will present the mathematical model and the simulation results of the hybrid stepper motor.

CHAPTER II:

Modeling and Simulation of the Hybrid Stepper Motor

II.1 Introduction:

To test the dynamic response of the hybrid stepper motor (HSM), a mathematical model must be used. In addition, this model consists of electrical and mechanical equations. A mathematical model is a description of a system using mathematical concepts and language. Mathematical models are used not only in the research and engineering disciplines, but also in the curriculum of social sciences. A model may help to explain a system in a better way to investigate the effects of different components and to make predictions about behavior. In this chapter, the model of the hybrid stepper motor is presented, the simulation results will be exposing and investigations with comparison among different kind of excitations will be made. [3] [5]

II.2 Explain Some Important Meaning:

Before all of that, it is important to define some technical means such as:

II.2.1 Simulation

A simulation is a representation of something, not real. At times you might perform a simulation as practice for real life, such as a flight simulation that's used to train pilots. The word can also be used, often dismissively, to describe something that is a fake, like a simulation of excitement or the simulation of a perfect diamond. The simulation of the hybrid stepper motor in this chapter is achieved by MATLAB-SIMULIN. [6]

II.2.2 MATLAB-SIMULINK:

The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix Software developed by the LINPACK and EISPACK projects. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

1- Math and computation
2- Modeling, simulation and prototyping.
3- Data analysis, exploration, and visualization
4- Scientific and engineering graphics
5- Application development, including graphical user interface building

MATLAB features a family of add-on application specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.[7]

Simulink, developed by the MathWorks which is a commercial tool for modeling, Simulink is an environment for simulation and model-based design for dynamic and embedded systems simulating and analyzing dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for simulation and design. This training will give you the basic knowledge of Simulink and how you can use it together with MATLAB.[8]

II.2.3 Mathematical Model:

Dynamic models typically are represented with difference equations or differential equations. Mathematical models are usually composed of variables, which are abstractions of quantities of interest in the described systems, and operators that act on these variables can be algebraic operators, functions, differential operators etc. If all the operators in a model exhibit linearity, the resulting mathematical model is defined as linear. It is also defined as an abstract and simplified of a system which specifies:

- Importance components
- Assumptions/approximations about how the system works

Not an exact re-creation of the original system!

II.2.4 Modeling:

Modeling is about building representations of things in the ‘real world’ and allowing ideas to be investigated, it is central to all activities in the process for building or creating an artifact of some form or other. In effect, a model is a way of expressing a particular view of an identifiable system of some kind. Models are:

- A means of understanding the problems involved in building something;

- An aid to communication between those involved in the project, especially between the requirements analyst (a development role) and the user, as part of some deliverable, And component of the methods used in development activities such as the analysis of the requirements for an artifact and the design of the artifact.

A model is an **abstraction**, which allows people to concentrate on the essentials of a (complex) problem by keeping out non-essential details. [9]

II.2.5 Pulse:

Pulse generators are items of electronic test equipment that are used to generate pulses normally rectangular pulses. These pulse generators are used for a wide variety of applications, but most commonly as bench test equipment when developing logic circuits of various forms. The pulse generators can be used to generate pulses that can stimulate logic circuit. In order to be able to provide the right kinds of pulses a considerable degree of adjustment is required for the pulses in terms of length, delay, repetition rate and the like. Many of the functions of a pulse generator are similar to those of a function generator or arbitrary waveform generator. As a result, many function or arbitrary waveform generators include function generator capabilities, making them multi-purpose test instruments. [1]

II.3 Why And How To Study A System:

1- Mesure/estimate performance
2- Improve operation
3- Prepare for failures

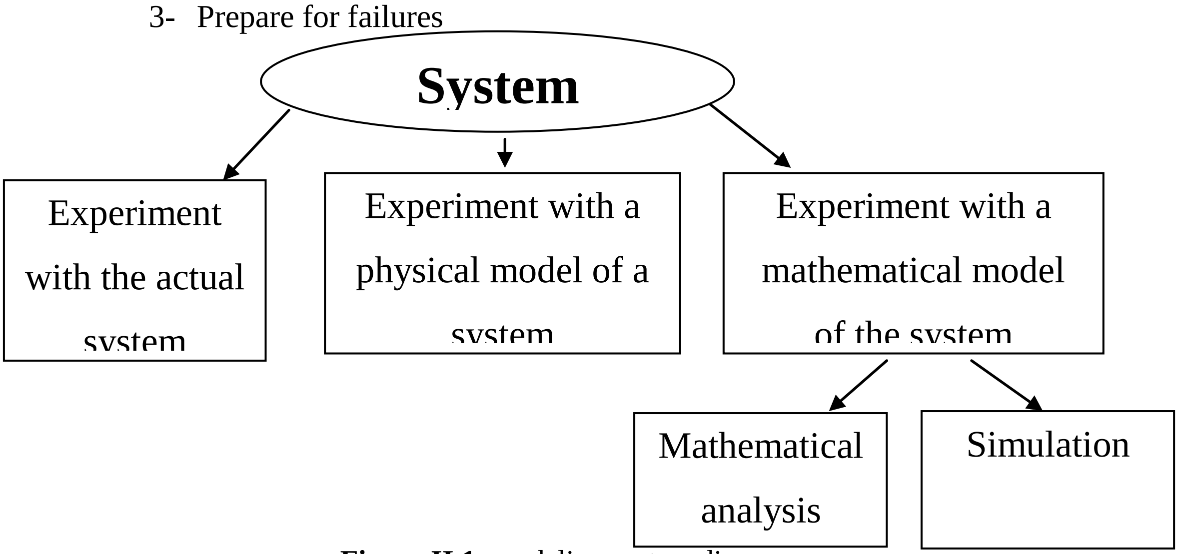
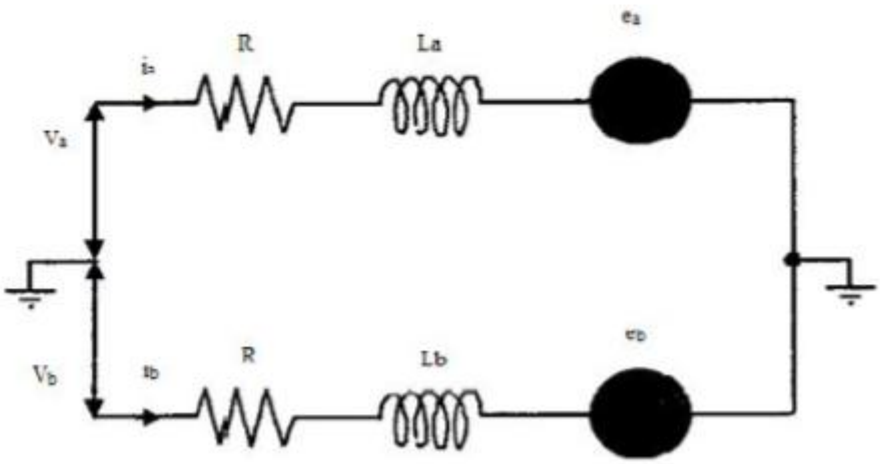


Figure II.1: modeling system diagram.

II.4 Dynamic Model of Hybrid Stepper Motors:

The hybrid stepper motor in SIMULINK consisted of two sections: electrical part and mechanical part. The electrical section is represented by equivalent circuit, configuration of which depends on the motor type. The various stepper motor is available for research. In hybrid stepper motor have permanent magnet in rotor which is toothed magnetic structure and stator have also same structure, so permanent-magnet torque can be generated in rotor and reluctance torque in stator. The rotor of hybrid motor is composed with two semi rotors, which have opposite magnetic polarity and 180-degree phase displacement in teeth position. Heretically, the motor can considered as a multi pole synchronous motor. Mathematical model of hybrid stepper motor is to study the dynamic behavior of motor. Model consists of electrical dynamic of stator together with the shaft mechanical dynamics. Electric response is much faster than the mechanical response, which allowed considering mathematical model only. Consider the mathematical model which is electrical and mechanical equations. [2][10][11][12]



FigII.2 the equivalent circuit of a two phase stepping motor.

II.4.1 Mathematical model of HSM:

The electrical equations are given by: [13]

$$dia/dt \equiv \left(\frac{Va - Ria + KmW \sin(Nr\theta)}{L} \right) \quad \text{(II.1)}$$

$$dib/dt \equiv \left(\frac{vb - Rib + KmW \cos(Nr\theta)}{L} \right) \quad \text{(II.2)}$$

The mechanical equations are given by:

$$d\omega/dt \equiv \left[\frac{\text{- KmIa} * \sin(\text{Nr}\theta) + Km\text{I}b * \cos(\text{N}r\theta) - \text{B}\omega - \text{T}L - Kd * \sin(4\text{N}r\theta)}{J}\right] \quad \text{(II.3)}$$

$$d\theta/dt \equiv \omega \quad \text{(II.4)}$$

The electromechanically equation can be represented as:

$$Te \equiv Km(Ib.\cos(\theta) - Ia.\sin(\theta)) \quad \text{(II.5)}$$

After passing from the dynamical equation to the transfer function we got:

$$PIa \equiv \left(\frac{Va - RIa + KmW\sin(\text{N}r\theta)}{L}\right) \quad \text{(II.6)}$$

$$PIb \equiv \left(\frac{Vb - RIb + KmW\sin(\text{N}r\theta)}{L}\right) \quad \text{(II.7)}$$

$$Pw \equiv \left[\frac{\text{- KmIa} * \sin(\text{Nr}\theta) + Km\text{I}b * \cos(\text{N}r\theta) - \text{B}\omega - \text{T}L - Kd * \sin(4\text{N}r\theta)}{J}\right] \quad \text{(II.8)}$$

$$P\theta \equiv \omega \quad \text{(II.9)}$$

The relationship between electrical and mechanical of rotor of the motor is given by:

$$\theta e = \text{N}r * \theta m \quad \text{(II.10)}$$

Where, Ia and Ib are the currents in phases A and B respectively (Amp), Va and Vb are the voltages on phases A and B respectively (Volt), ω is the rotor speed (rad/sec), θ is rotor position (rad), R is the resistance of the phase winding (Ω), L is the self-inductance of the phase winding (H). Km is the motor torque constant (Nm/A), B is the viscous friction (Nms2/rad), J is the rotor inertia (Kg.m2). TL is the load torque (Nm). The detent torque is due to permanent magnet interacting with the magnetic material of stator pole. It is negligible, as its magnitude is less than holding torque. With respect to load Variation of J and B were negligible.

II.4.2 Assumptions:

The mathematical model is derived based on the following assumptions as explained by Kenjo (1984)

1. Mutual inductance is neglected as being dominated by the self Inductance.

2. Variation of self inductance with the mechanical angle is assumed to be sinusoidal around the mean value.

3. Fluxes due to permanent magnet are sinusoidal with the same periodicity of the reluctance flux.

4. Detent torque is assumed to be negligible compared to magnitude of holding torque.

II.4.3 Stepper Motor Design In MATLAB-SIMULINK:

Fig.2 shows how to drive the stepper motor by delivering current in phases according to the mode of excitation and as per requirement of position and resolution. Mainly three type of excitation mode is defined through which motor was operated. Full step wave drive having any of the one phases is on at a time or in other words current passing only through one phase at a time. Full step two phase on have excitation achieved in the half step source which deliver at a time two phase on and current passing through both the winding. Half step excitation mode involves alternating single and dual phase operation and provides twice the resolution than full step mode, which increased smoothness at low speed.

The stepper motor model in MATLAB-SIMULINK is designed as:

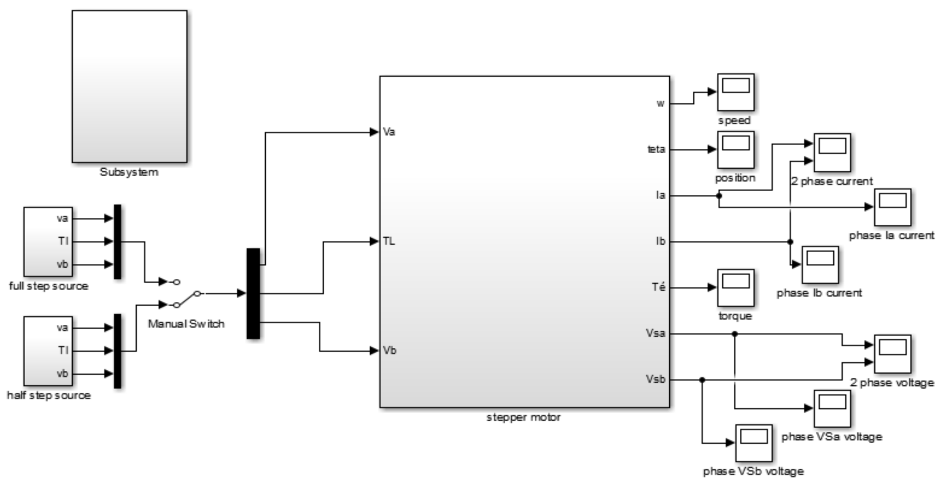


Figure II.3: stepper motor design.

Where it contains tow essential part:

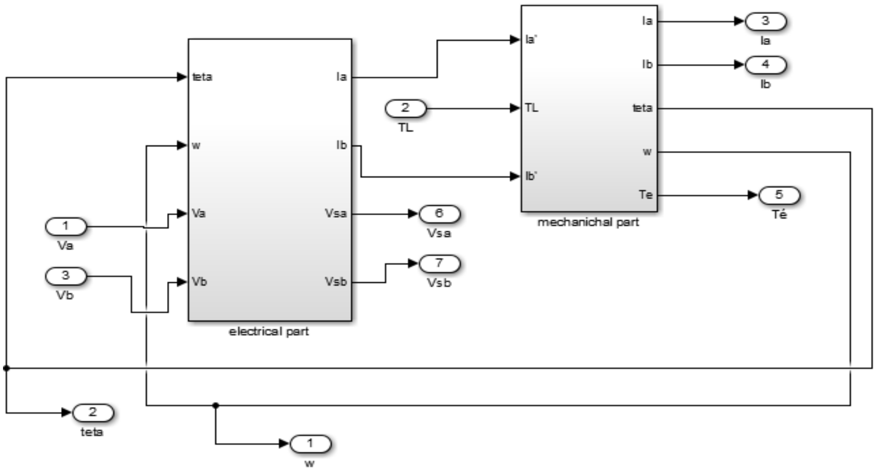


Figure II.4: subsystem contains.

The electrical part designed as:

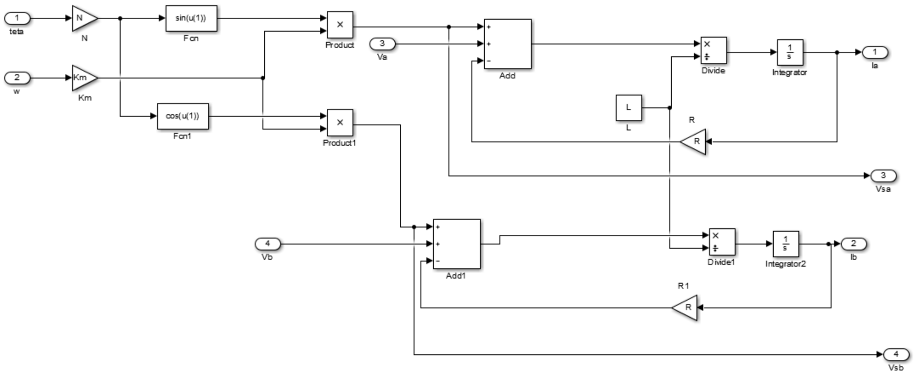


Figure II.5: electrical part.

And the mechanical part designed as:

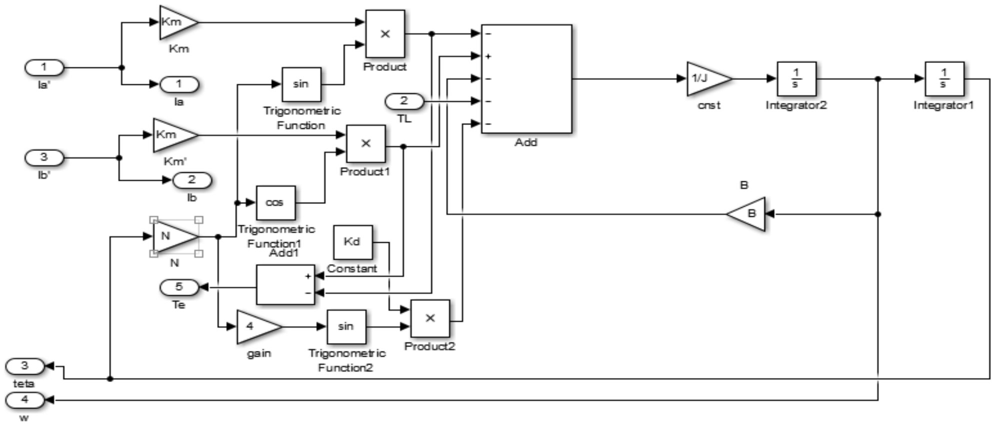


Figure II.6: mechanical part design.

Where the hybrid stepper motor parameter is given in the table below:

Motor Parameters	Value
Winding Inductance L	0.04mH
Winding Resistance R	36 Ω
Number of rotor teeth, N_r	100
Torque constant K_m	0.18166Nm/A
The coefficient of viscous friction B	0.0014N.m.s/rad
The detent torque K_d	1e-9[Nm]
Inertia constant J	1.1e-6kgm^2

Table II.1: hybrid stepper motor (HSM) parameter.

II.5 Excitation Mode:

There are actually three types of mode excitation, this chapter is a studding for two types which given as under:

II.5.1 Full Stepping Mode:

In this mode the duty cycle of the pulse is 25%, according to the pulse require torque is generated and the current is passing through the winding as per the pattern of mode, after the calculating the frequency define time period for the pulse rate on with motor can operate. Time period for full step mode is calculated by:

$$T = 0.3/rmp \quad (II.11)$$

Calculated T is only for 1 pulse, here two phase motor is use so it has for windings so the total time is 4T. [14]

II.5.2 Half Stepping Mode:

In half stepping mode duty cycle of pulse is 37.5% and the resolution of motor is double than the full stepping mode and even the Time period for switching the current in the phase is half than the full stepping mode. At a same time 2 phase excite with current passing through it so motor rotate in the resultant direction of the both forces witch act by the both phase. [15]

II.5.3 Voltage Source:

The source of voltage applied on the tow phase is given as:

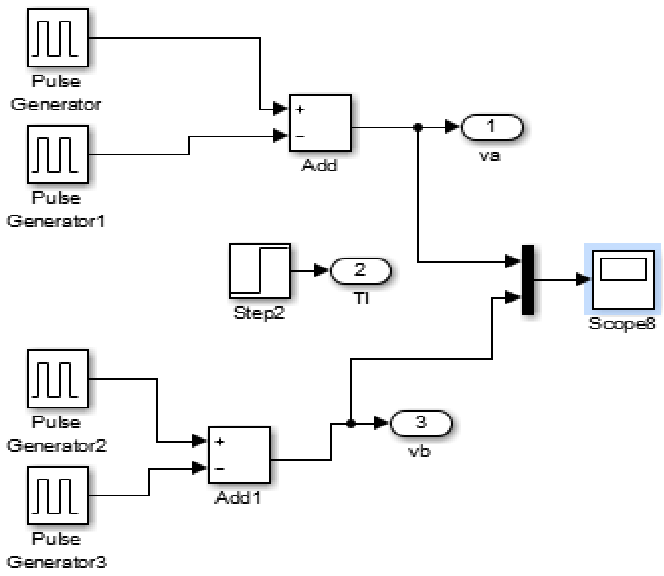


Figure II.7: impulse generator.

The pulse generator delivered as:

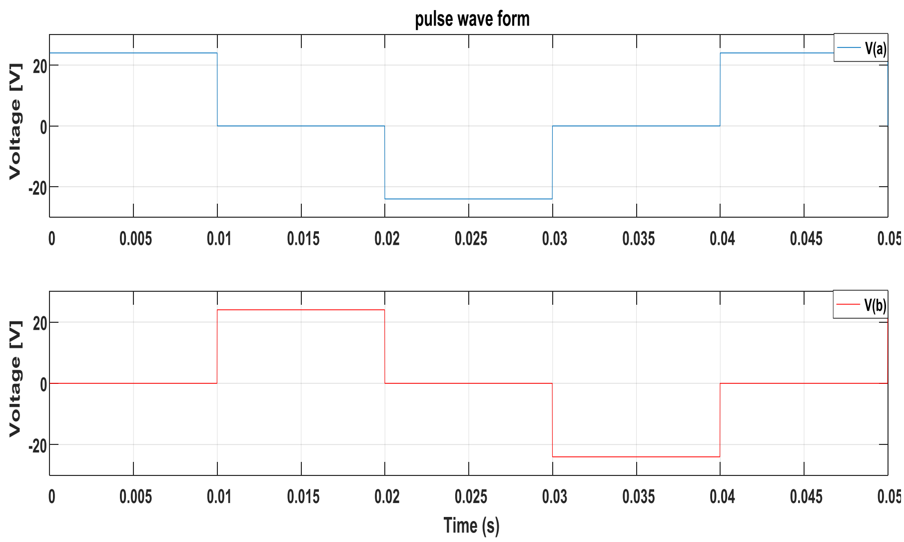


Figure II.8: full step sequence of voltage.

Fig.8 shows the voltage delivered to the hybrid stepper motor according to full step excitation mode and as per requirement of position and resolution. There are actually three types of excitation mode is defined through which motor was operated. Full step wave drive having any of the one phase is on at a time or in other words current passing only through one phase at a time.Fig14 shows the drive voltage waveforms. Full step two phase on have excitation shown in Fig.8 which shows that at a time two phase on and current passing through both the winding.

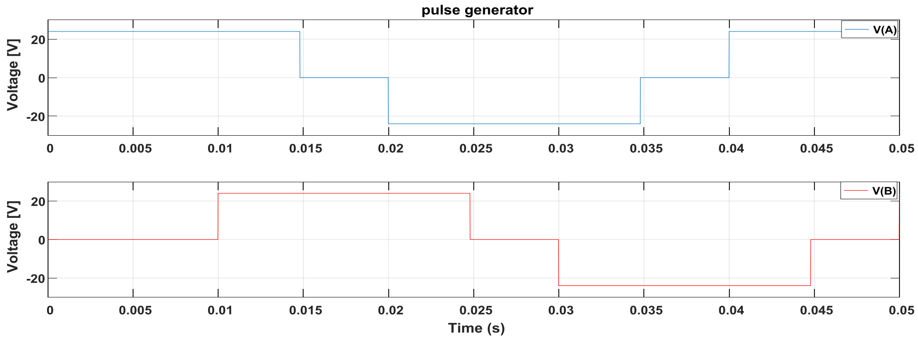


Figure II.9: Half step sequence of voltage.

Half step excitation mode involves alternating single and dual phase operation and provides twice the resolution than full step mode as it is shown on Fig.9, which increased smoothness at low speed. The voltage given to the stepper motor is the same voltage delivered from the driver which is depends on torque requirement for desire speed. [15]

II.6 Simulation Results:

The simulation results have been shown for 2s.Two sinusoidal inputs phase shifted according to the mode of excitation is given as input to the stepper. The pulses are given to the hybrid stepper motor. Overall simulation diagram of full and half stepping operation of hybrid stepper motor are shown in Fig 9 and Fig 10. Each phase is connected to a 24V DC voltage source. Fig 9 and Fig 10 shows the voltage waveforms of the two phases respectively.Simulation of hybrid stepper motor transient performance characteristics under no-load. Speed, position, torque and current waveforms are given in Figures bellow.

II.6.1 Full Stepping Mode:

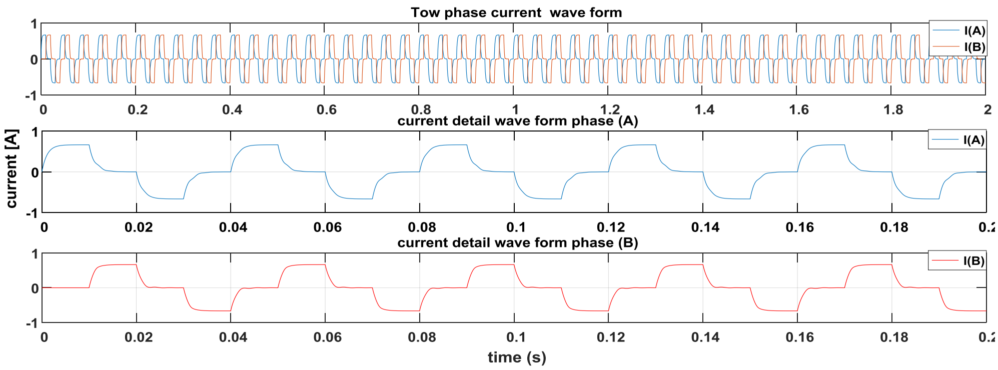


Figure II.10: two phases current wave form using full step mode.

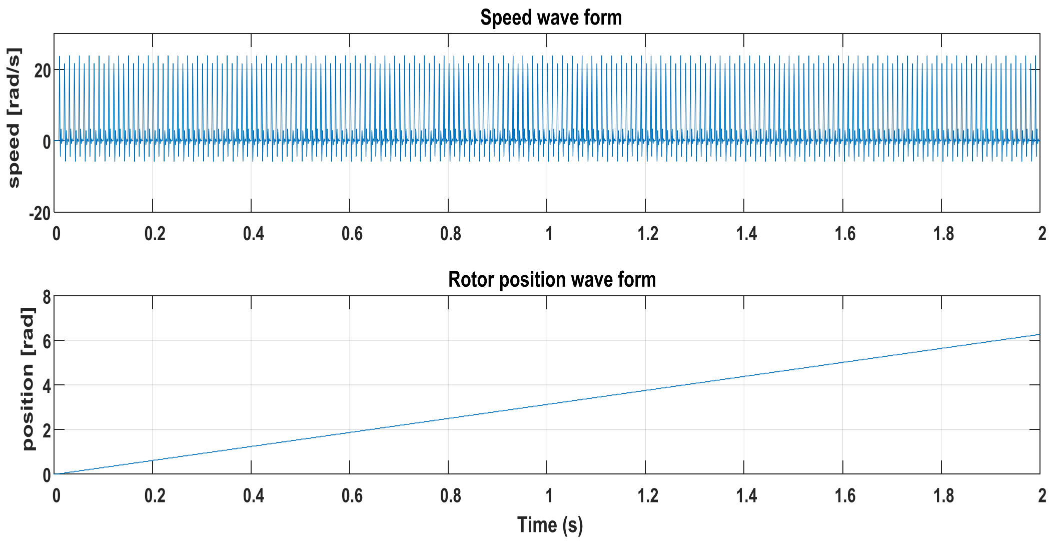


Figure II.11: speed and position wave form.

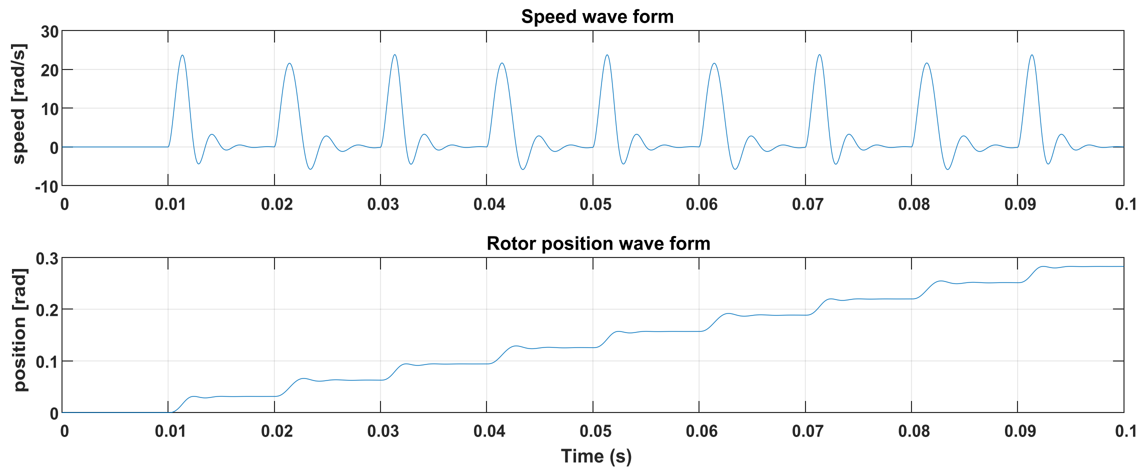


Figure II.12: detail speed and position wave form.

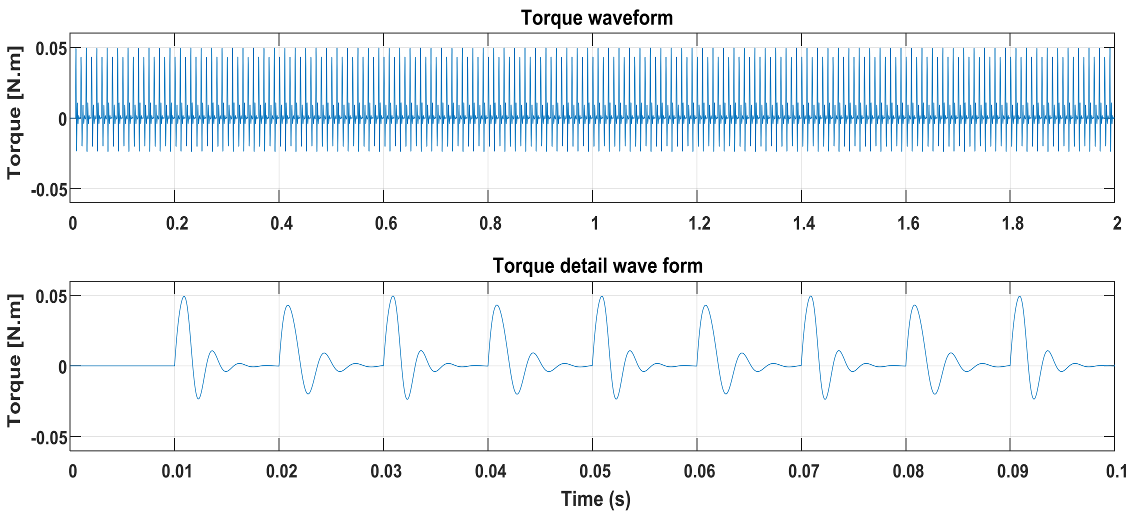


Figure II.13: Torque wave form.

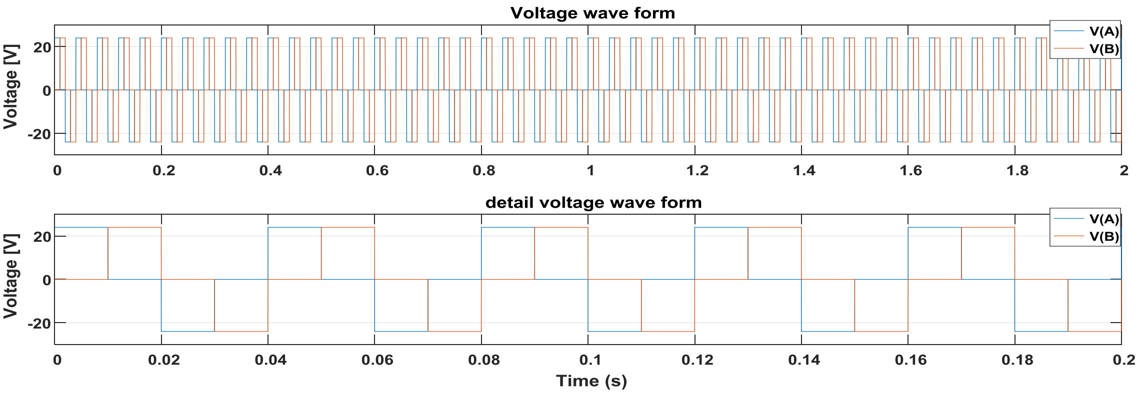


Figure II.14: detail tow phase voltage V(A),V(b).

II.6.2 Discussions:

Fig.10 shows the performance of the motor with full stepping mode, it allow us take a look about the tow phase current wave form which increase to 0.8 [A] then decrease up to -0.8[A] (mean=0A), each phase shifted by 90^0 with a sine wave form and it takes a 0.04 [s] to finish one wave. Fig.11 shows the speed and position wave form of the stepper motor which increase to 24 [rad/s], it present overtake and the position to 6.2 [rad] in linear form, every step repeat after 0.01[s]. The speed of the motor is oscillatory because the change of step is very fate, there are also a little lateness it takes to move which takes 0.01 s. Fig.13 shows the performance of the motor torque is same as the speed wave form in fig.11 but with different value, it delivers a 0.05[N.m].Fig.14 shows the voltage wave form given the motor with a maximum value equal to 24[V] it present a quadrate wave form, each phase shifted by 90^0. The period time equal to 0.04[s] with frequency equal to 50 [HZ].This motor gives good performance with this kind of mode step.

II.6.3 Half Stepping Mode:

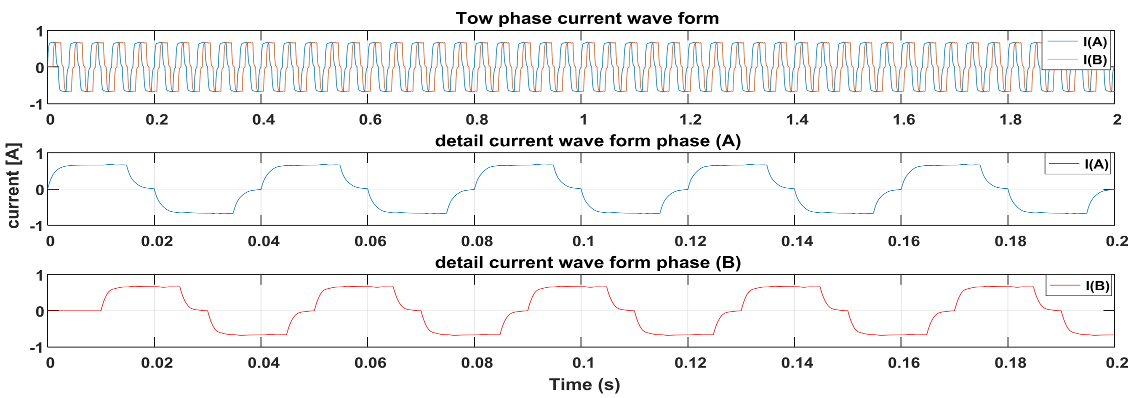


Figure II.15: Tow phase current wave form with half mode step.

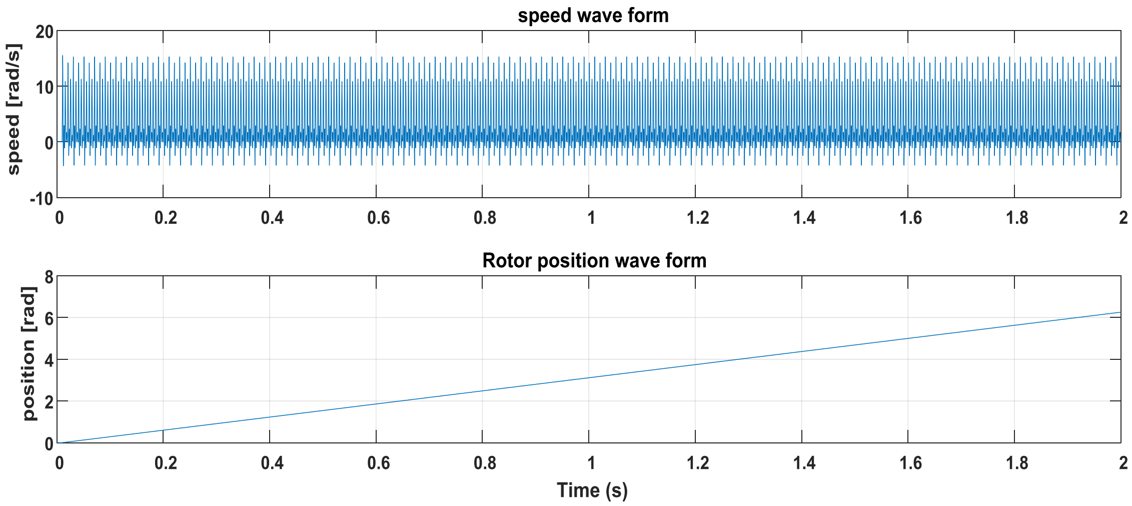


Figure II.16: Speed and rotor position wave form.

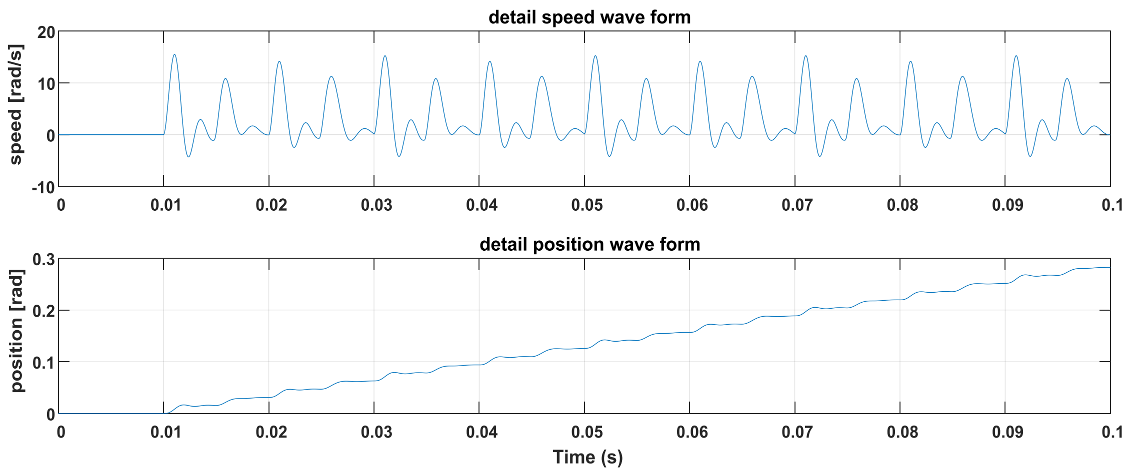


Figure II.17: detail speed and rotor position wave form with half step mode.

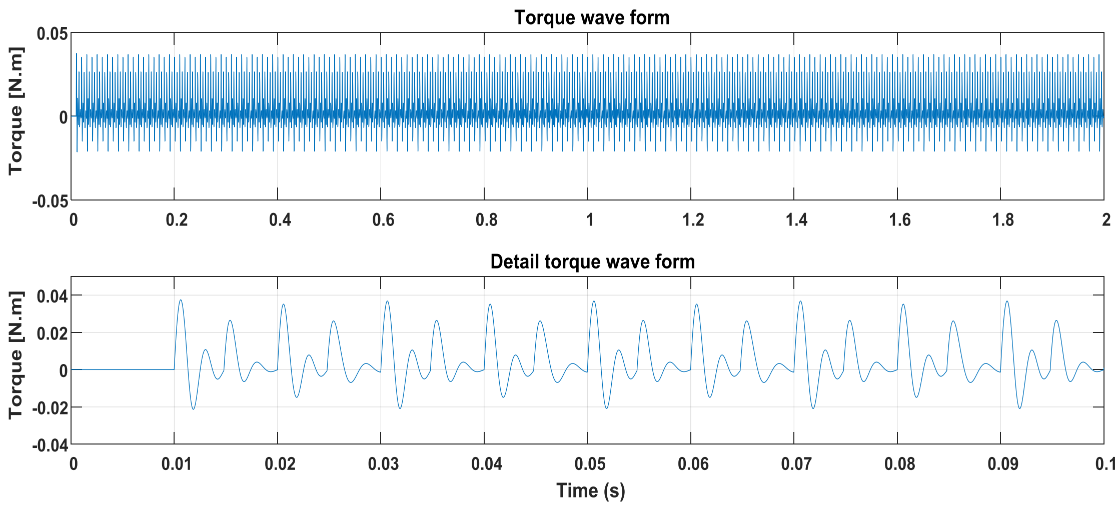


Figure II.18: Torque wave form using half step mode.

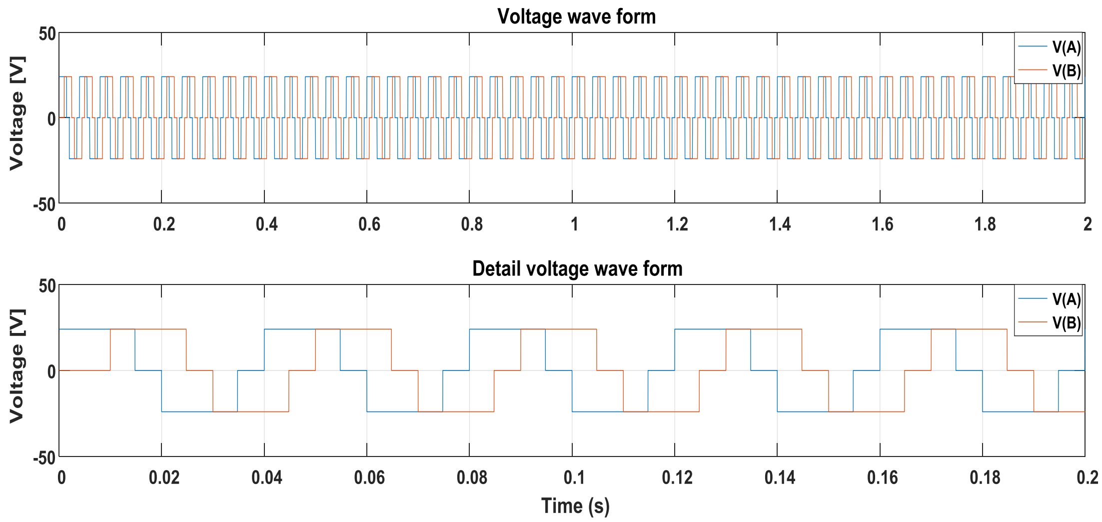


Figure II.19: two phase voltage wave form using half step mode.

II.6.4 Discussions:

Fig.15 shows the same wave form of current with full stepping mode and with the same value but the two phases is not shifted by 90^0 in that case it is actually shifted by 66.6^0 and the wave became a little latte. Fig.16 shows the same speed and position wave form but Slowest with half step mode in which it turned with 15 [rad/s], however it moves twice then using the full step mode in the same period, it represent also overtake equal to 15 [rad/s], the position remain to 6.2 [rad] in linear form, every step repeat after 0.005[s]. The speed of the motor is oscillatory because the change of step is fast. Fig.18 that the motor torque shortage to 0.04[N.m], the motor need to product the torque twice in the same period because of the change of the step.Fig.19 shows the voltage wave form given the motor using the half step mode with a maximum value equal to 24[V] it present a quadrate wave form either, but each phase is not shifted by 90^0 it is shifted actually by 66.6^0 The period time equal to 0.04[s] with frequency equal to 50 [HZ].

II.7 Comparison:

II.7.1 Current:

Extending to the simulation results the wave forms doesn't really matched with all different kind of excitation modes, however from the simulation results that have been investigated it can be seen that:

II.7.1.1 Using Full Step Mode:

It can be seen that the two phases current wave forms complete each other, in other word when the phase current in phase A is about to stop the phase B wave is applied in face that it looked simulated and shows one wave combined. The maximum current value is 0.8 [A]

II.7.1.2 Using Half Step Mode:

when the current passing through the phase A is steal applied the current in phase B is already applied too, in other word the current in phase B applied even when the current passing through the face A is steal applied with the same period and the same frequency, the two phases complete each other but the phase B start even when the current passing through the phase A not actually stopped. There is no different in the current value.

II.7.2 Speed And Position:

the simulation results shows the different of the wave forms extending to the excitation mode, according to the speed and position wave forms it can be seen that:

II.7.2.1 Using Full Step Mode:

II.7.2.1.1 Speed:

the rotor does not start moving immediately it takes actually 0.01s before it accelerate then it present a linear wave form with an overshoot equal to 24[rad/s] then it start getting steady to 0 rad/s, the wave form represented for 0.01s also in meaning that every step takes a 0.01s.

II.7.2.1.2 Position:

the same Remarque that is can be seen with the position the rotor doesn't steppes immediately it takes also 0.01s to start moving it represent a linear wave form and steady, every step takes also 0.01s, for 2s the rotor moves for 6.2 [rad]

II.7.2.2 Using Half Step Mode:

II.7.2.2.1 Speed:

The wave form matched with only one thing which is it takes a 0.01s to move, after it moves and for the same period in case full stepping mode, it moves twice then using the full stepping mode in other meaning it accelerate with the same period twice, and that because of the half stepping mode generate two pulse in the same period, it means in the half of the first acceleration it accelerate again. There is also a change in the speed level in which it decreased to 15 [rad/s].

II.7.2.2.2 Position:

Even with position wave form it share only one thing with the two different excitation modes which is it takes 0.01s to start moving then it moves twice in half step mode then the full step mode for the same period t=0.01s. It can be notice that in the half of the period it moves again. For 2s the rotor moves for 6.2 [rad] either.

II.7.3 Torque:

Even with couple wave form it shared the same lateness for 0.01s**,** however let's see the different between the two wave forms according to the mode of excitations, from the simulations results it can be seen:

II.7.3.1 Using Full Step Mode:

The torque wave form have the same speed wave form but with different value equal to 0.05 N.m, it takes 0.01s for each step it present a linear wave form start with a overshoot equal to 0.05 N.m then it steady to zero.

II.7.3.2 Using Full Step Mode:

it can be notice that the torque wave form using that kind of stepping mode is matched with the speed wave form with different value in which it decrease to 0.04N.m and the motor provide the torque twice then using the full stepping mode in the same period and it shows a linear wave form and steady again. Each step takes 0.005s which mean for 0.01s it provide torque twice. It can be notice that the motor provided a good speed at low torque.

II.7.4 Voltage:

The two phase voltage wave forms is taken from the voltage delivered to the two winding which is equal to 24V, it depends of the excitation mode applied crossing the two winding, the different between the two waves can be seen as:

II.7.4.1 Using Full Step Mode:

The two phases is shifted by 90^0 presenting a rectangle wave form for a period t=0.4s.

II.7.4.2 Using Half Step Mode:

The two phases is shifted by 66.6^0 presenting a rectangle wave form for a period T=0.4s.wail the phase A is steal applied another pulse will be generated on the phase B at 66.6^0.

II.8 Conclusion:

In this chapter, the stepper motor model is presented. The motor can be operated in two different stepping modes namely full-step and half-step. The modeling of the two phases hybrid stepper motor was implemented in MATLAB-SIMULINK. From the simulation results it can be seen that the voltage waveforms of the two phases are 90^0 and 66.6^0 displaced according to the excitation mode. Current waveforms of two phases are similar to sine and cosine waveforms.

Chapter III:

Control of the Stepper Motor

III.1 Introduction:

this chapter contains basics knowledge that explains how to control the stepper and every component that it is necessary to be known, a PID controller is used to control the position of the hybrid stepper motor and to enhance the performance of the open loop control for a given reference input using three modes; full step, half step, and micro step. The experimental results of these three modes are presented using Matlab/Simulink software version 13.a. In addition, a discussion and investigation has been made among the three modes.

III.2 Some Basic Definitions:

III.2.1 What is a System?

A system is a collection of components that interact with one another and with their environment. Such us Human beings, mechanical devices, an electrical switch, plants, animals, the atmosphere, the stock market, the political system, helicopters, missiles, avionics, and so on. [1]

III.2.2 Control System:

A control system is an interconnection of components forming a system configuration that will provide a desired system response. Control is used to modify the behavior of a system so it behaves in a specific desirable way over time. The basic for analysis of a system is the foundation provided by linear system, which assumes a cause effect relationship for the components of a system. A component or process to be controlled can be represented by a block as Figure1 shows. All these are being accomplished today by control methods and what automatic control systems are designed to do, without human intervention. Control is used whenever quantities such as speed, altitude, temperature, or voltage must be made to behave in some desirable way over time. There are two main types of control loops: Open loops, which operate with human input, and closed loops, which are fully autonomous. Some loops can be switched between closed and open modes. When open, a switchable loop is manually controlled and when closed it is fully automated. [2] [3] [4]

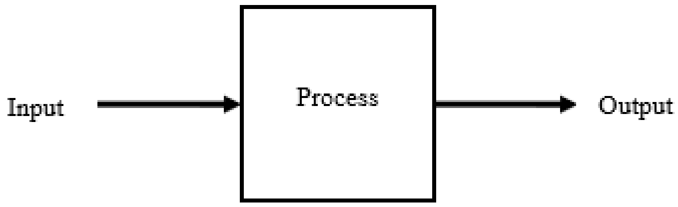


Figure III.1: Process under control.

III.2.2.1 Open-Loop Control:

An open-loop control system utilizes a controller or control actuator to obtain the desired response as Figure 2 shows. The open-loop control system utilizes an actuating device to control the process directly without using device. An example of an open-loop control system is an electric toaster or supposes that you want to control the speed of a motor, once the speed is set there is nothing else that needs to be done. But suppose you have three fans. Even if you give their knobs the same amount of turn, the speeds are likely to be slightly different. This may happen due to inaccuracy in the settings, inconsistency in ball bearings performance, imperfect setting of the fan blades causing different amount of drag on the blades, or maybe due to non-standard performance of the electronic components. So, essentially an open loop system is one where there is no way to correct the error between the desired output and the actual output. [1][2]

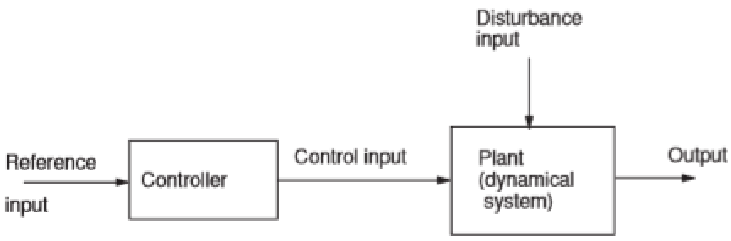


Figure III.2: Open-loop control system (no feedback).

III.2.2.1.1 The Advantages And The Disadvantages of The Open Loop Control:

The advantages of this type of "open-loop motor control" is that it is potentially cheap and simple to implement making it ideal for use in well-defined systems were the relationship between input and output is direct and not influenced by any outside disturbances. Unfortunately this type of open-loop system is inadequate as variations or disturbances in the system affect the speed of the motor. Then another form of control is required. [5]

III.2.2.2 Closed-loop Systems

Closed-loop Systems use feedback where a portion of the output signal is fed back to the input to reduce errors and improve stability Systems in which the output quantity has no effect upon the input to the control process are called open-loop control systems, and that open-loop systems are just that, open ended non-feedback systems. But the goal of any electrical or electronic control system is to measure, monitor, and control a process and one way in which we can accurately control the process is by monitoring its output and "feeding" some of it back to compare the actual output with the desired output so as to reduce the error and if disturbed, bring the output of the system back to the original or desired response. Then closed-loop control systems use feedback to determine the actual input to the system and can have more than one feedback loop. [5]

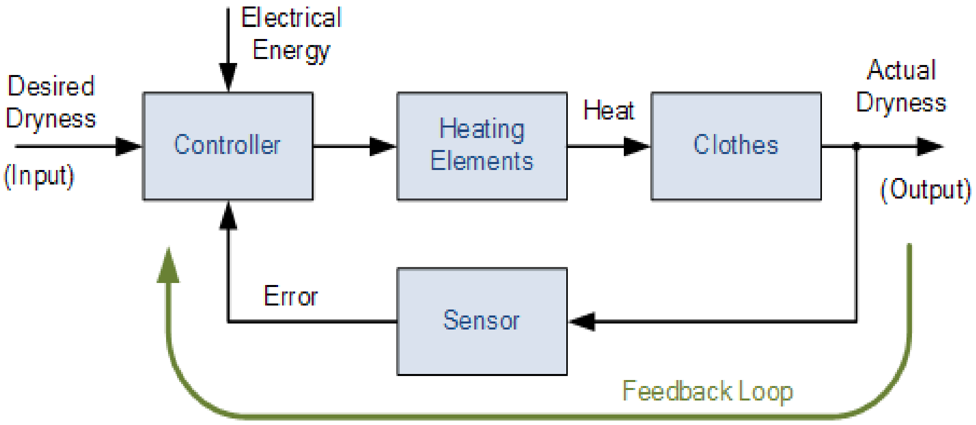


Figure III.3: Closed-loop Control representative schema.

III.2.2.2.1 Advantages And Disadvantages of The Closed-Loop:

Closed-loop control systems have many advantages over open-loop systems. One advantage is the fact that the use of feedback makes the system response relatively insensitive to external disturbances and internal variations in system parameters such as temperature. It is thus possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given process or plant. In addition to the ability to reduce a system's sensitivity to external disturbances, for example opening of the dryer door, giving the system a more robust control as any changes in the feedback signal will result in compensation by the controller. However, system stability can be a major problem especially in badly designed closed-loop systems as they may try to over-correct any errors which could cause the system to loss control and oscillate. [5]

III.2.2.2.2 Closed-loop System Transfer Function

The Transfer Function of any electrical or electronic control system is the mathematical relationship between the systems input and its output, and hence describes the behavior of the system. Note also that the ratio of the output of a particular device to its input represents its gain. Then we can correctly say that the output is always the transfer function of the system times the input. Consider the closed-loop system below. [5]

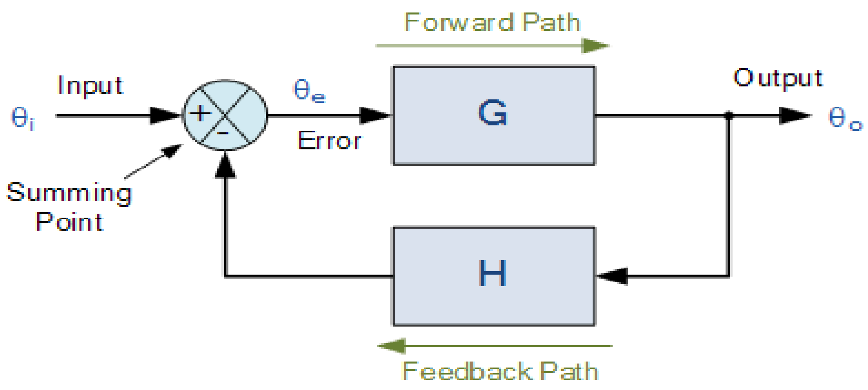


Figure III.4: Typical Closed-loop System Representation.

Where: block G represents the open-loop gains of the controller or system, and block H represents the gain of the sensor.

The output from the system is equal to: $Output = G \times Error$ (III.1)

The output from the summing point is equal to: $Error = Input - H \times Output$ (III.2)

If H = 1 (unity feedback) then:

The output from the summing point will be: $Error(\theta e) = Output - Input$ (III.3)

We can see that when H = 1 (unity feedback) and G is very large, the transfer function approaches unity as:

$$\frac{Output}{Input} \rightarrow 1 \qquad \text{(III.4)}$$

III.2.3 Feedback:

The term feedback is used to refer to a situation in which two (or more) dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled. The use of feedback to control a system has a fascinating history. The first applications of feedback control appeared in the development of float regulator mechanisms in Greece [6]. By dynamical system, we refer to a system whose behavior changes over time, often in response to external stimulation or forcing. Simple causal reasoning about a feedback system is difficult because the first system influences the second and the second system influences the first, leading to a circular argument. This makes reasoning based on cause and effect tricky and it is necessary to analyze the system as a whole. A consequence of this is that the behavior of feedback systems is often counter-intuitive and it is therefore necessary to resort to formal methods to understand them. [7]

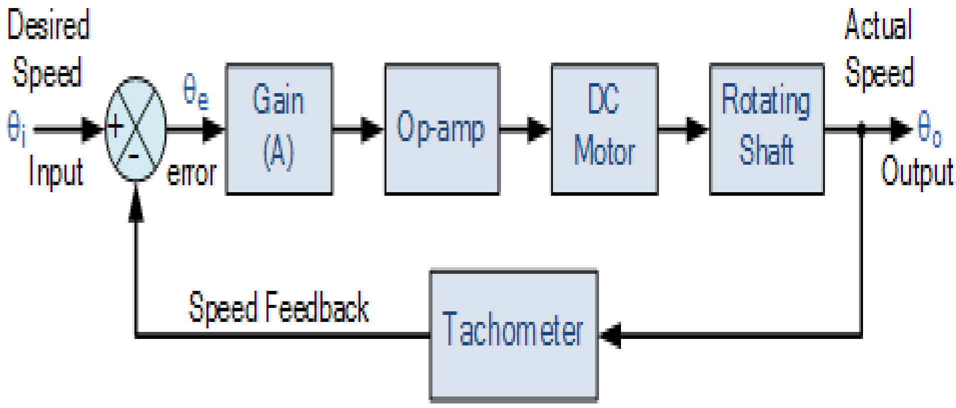


Figure III.5: Block Diagram for the Feedback Controller.

III.3 Manipulation:

In order to control the stepper motor it's necessary to use some components such us:

III.3.1 Arduino:

Arduino was born at the Ivrea Interaction Design Institute as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. As soon as it reached a wider community, it is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board. To do so you use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing. Over the years Arduino has been the brain of thousands of projects, from everyday objects to complex scientific instruments. [8]

III.3.2 The Easy Driver:

The Easy Driver is designed by Brian Schmalz, and is designed around the A3967 IC. This IC enables you to drive bipolar stepper motors that are 4, 6, or 8-wire configurations. The board can either work with 3.3V or 5V systems, making it extremely versatile. Two mounting holes on-board give the user the option to mechanically stabilize the Easy Driver. The L293 and L293D are quadruple high-current half-H drivers. The Easy Driver gives you the capability to drive bipolar stepper motors between 150mA to 700mA per phase. The L293 is designed to provide bidirectional drive currents of up to 1 A at voltages from 4.5 V to 36 V. The L293D is designed to provide bidirectional drive currents of up to 600-mA at voltages from 4.5 V to 36 V. Both devices are designed to drive inductive loads such as relays, solenoids, dc and bipolar stepping motors, as well as other high-current/high-voltage loads in positive-supply applications. [9][10][11]

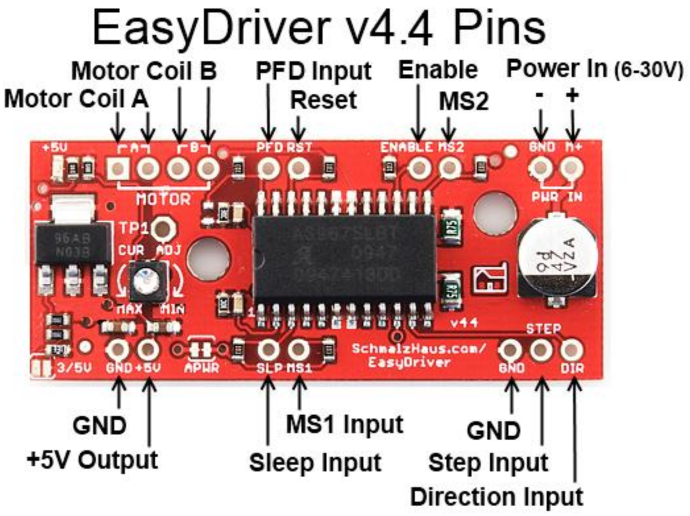


Figure III.6: The L293 pins interface**.**

III.3.3 PID Controller:

The PID controller is the most common form of feedback. In process control today, more than 95% of the control loops are of PID type, most loops are actually PI control. PID controllers are today found in all areas where control is used. It is an important ingredient of a distributed control system. The controllers are also embedded in many special-purpose control systems. PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing. Many sophisticated control strategies, such as model predictive control, are also organized hierarchically. PID control is used at the lowest level; the multivariable controller gives the set points to the controllers at the lower level. PID controllers have survived many changes in technology, from mechanics and pneumatics to microprocessors via electronic tubes, transistors, integrated circuits. The microprocessor has had a dramatic influence on the PID controller. Practically all PID controllers made today are based on microprocessors. This has given opportunities to provide additional features like automatic tuning, gain scheduling, and continuous adaptation. The control signal is thus a sum of three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error), and the D-term(which is proportional to the derivative of the error). The algorithm of the PID is represented by: [13] [12]

$$u(t) = \mathrm{K}\left(e(t) + \frac{1}{\mathrm{T}i}\int_0^t e(\tau)d\tau + \mathrm{T}d\,\frac{de(t)}{dt} \right) \qquad \text{(III.5)}$$

Where y is the measured process variable, r the reference variable, u is the control signal and e is the control error (e = ysp− y). The controller parameters are proportional gain K, integral time Ti, and derivative time Td.

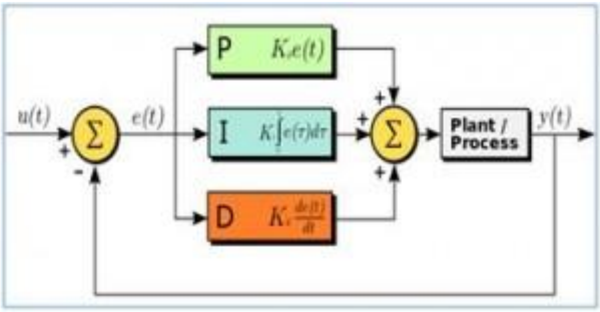


Figure III.7: Block diagram of a basic PID control algorithm.

III.3.4 Encoder:

In order to control the rotation of a motor a rotary encoder can be used to measure the rotation of the motor, or the position of a dial or knob. Encoders are a type of sensor that measures the movement of a mechanical parts. An encoder has two major components: a disk, and a detector. The disk is covered with a unique pattern that the detector will be able to read when it moves across them. For example, optical encoders use light sensors to read the contrasting sections on the surface, while a mechanical encoder uses brushes to read gaps in a metal surface on a circuit board. As the detector moves across the pattern, the encoder generates a signal then sends this detected pattern out to be processed by the encoder interface. A linear encoder could measure the position of a piston in a robot, or it could be used in a digital caliper to precisely measure the width of the object it's gripping. Both devices work on the same principle, but a rotary encoder can be thought of as a linear encoder that has been "rolled up" into a circle. Encoders are often used in control systems, as a type of feedback to ensure that a mechanical part is moving exactly as much as planned. For example, when you use a DC motor, it will usually spin as fast as it can based on how much power you provide it with. [14]

The most common method to send out the rotational information from the encoder to the encoder interface is Quadrature Encoding.[14]

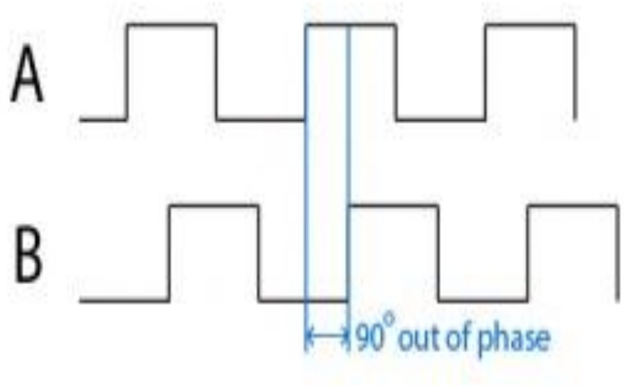


Figure III.8: Quadrature Encoding

The encoder that is used in this work can be shown below:

Figure III.9: Encoder Interfaces.

III.3.5 Encoder Disk

Figure III.10: Encoder disk.

III.3.6 Jumper Wires Premium 6" M/M - 20 AWG (10 Pack):

Jumper wires are awesome. Just a little bit of stranded core wire with a nice solid pin connector on either end. They have the flexibility of stranded wire but will fit directly into breadboards and female pin headers. The only downside to the standard jumper wires we carry is that they’re a tad too thin to use for most power applications. These 20AWG jumper wires work just like our smaller gauge premium jumpers except that they can handle a little more juice. [9]

Figure III.11: Jumper wires.

III.3.7 Stepper Motor with Cable:

This is a simple, but very powerful stepper motor with a 4-wire cable attached. it is a Bipolar Motor.

Figure III.12: Stepper Motor with 0.9°.

III.3.8 MATLAB- SIMULINK:

The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix Software developed by the LINPACK and EISPACK projects.

III.4 Practical Control of The Stepper:

This part represents the position control of the stepper using MATLAB-SIMULINK and Arduino card. To achieve that, two parts need to be done:

III.4.1 The Interconnection of The Hardware Part:

To connect that circuit we need an easy driver, arduino card, encoder, stepper motor, jumpers, encoder disk, test board, PC for controlling the stepper.

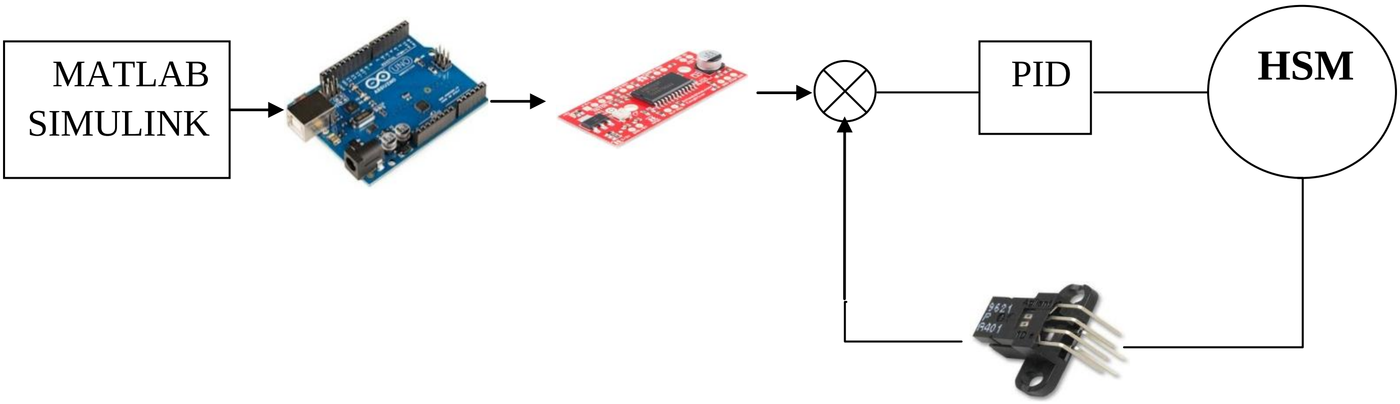
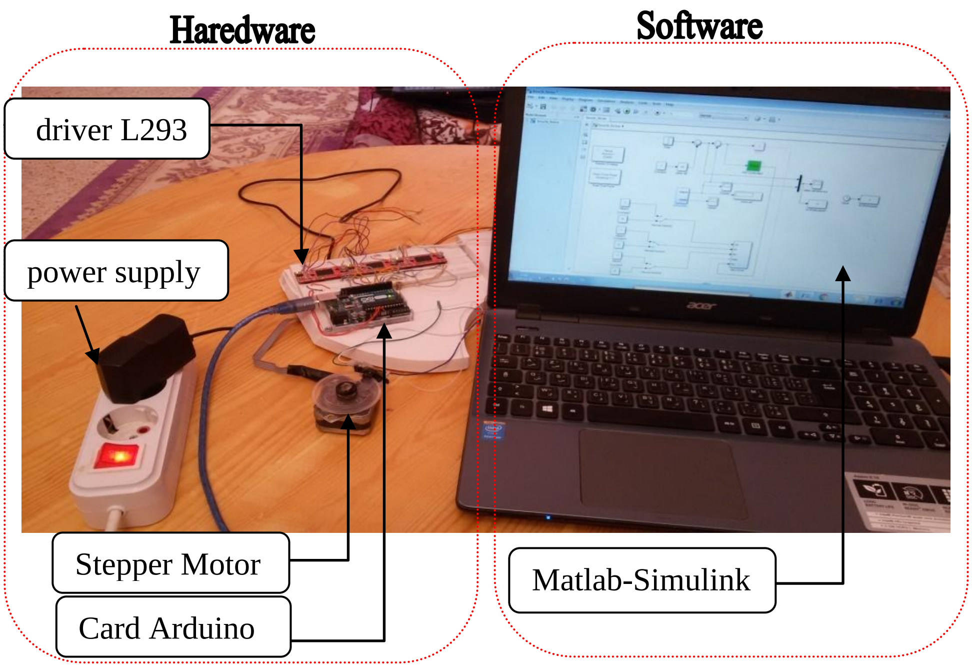


Figure III.13: Controlling the stepper motor using a PID controller diagram.



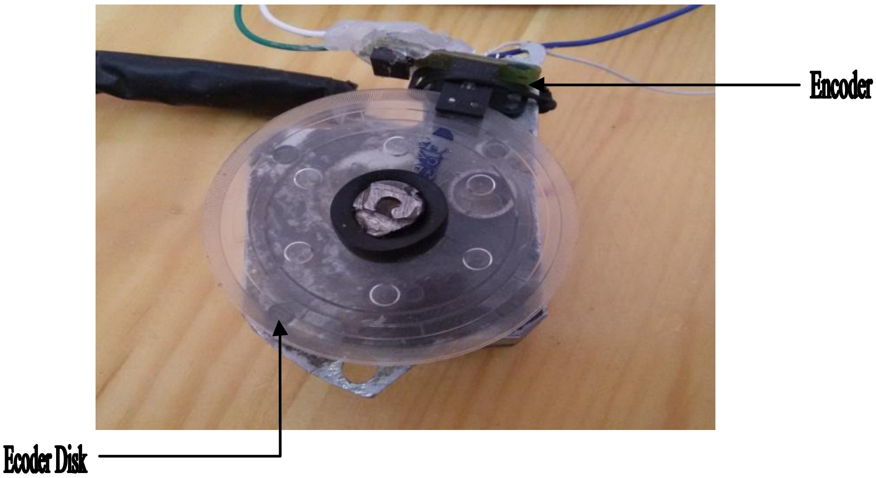


Figure III.14: Photos of our experiment

III.4.2 The Interconnection of The Software Part:

This part means the SIMULINK schematic to control the stepper which can be represent as bellow:

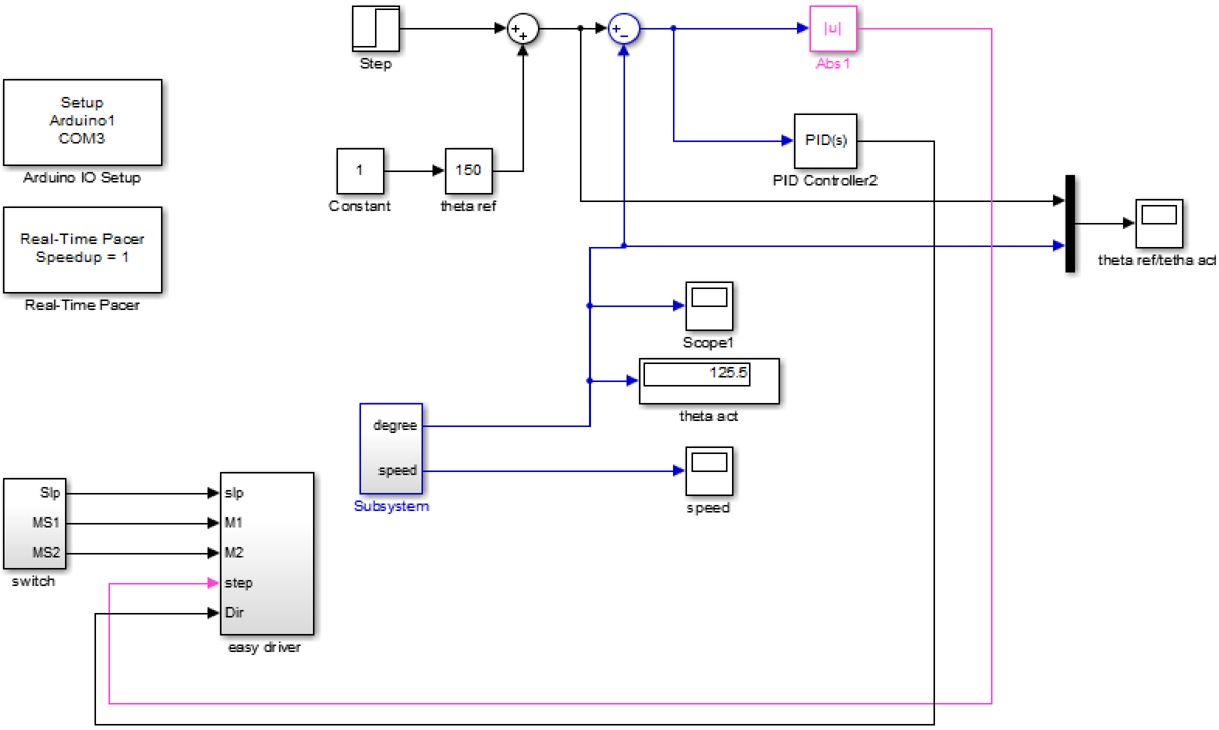


Figure III.15: stepper motor control in SIMULINK.

III.4.3 How to Control the Stepper?

To control the stepper motor we star with given the position reference in SIMULINK, after the simulation the program will transfer to the arduino card which transfers also the orders to the easy driver to give the pulses to the stepper. After all the stepper start turning. The encoder will read every time the actual position and the PID controller reduce the error between the reference position and the actual position. This diagram explains every step to control the stepper:

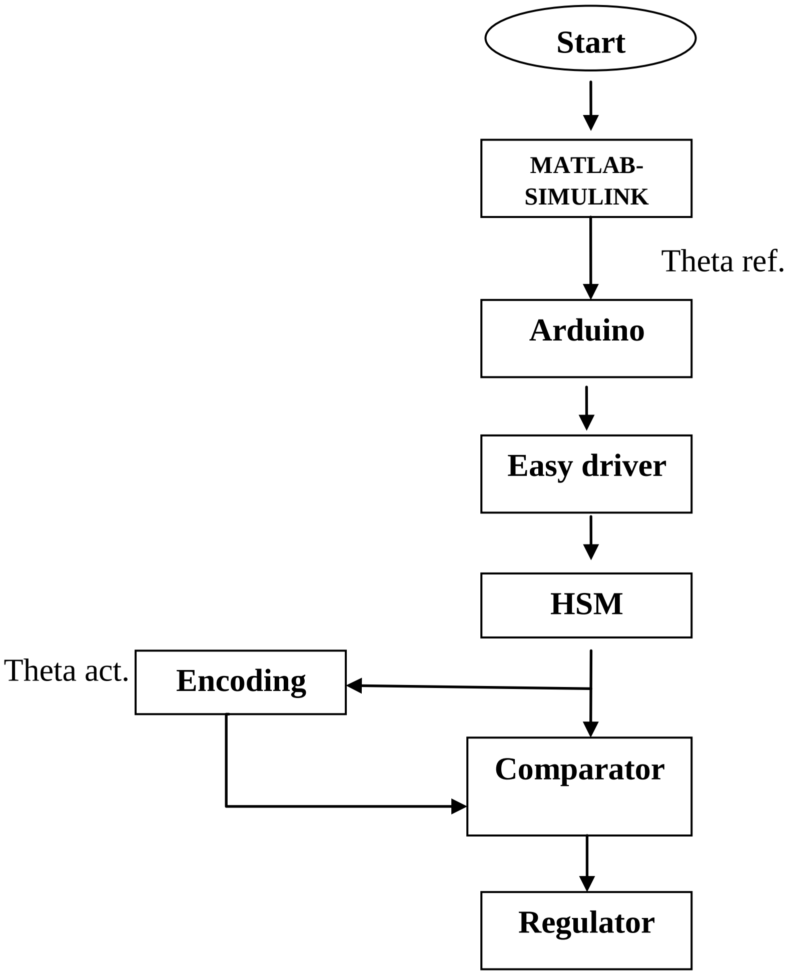


Figure III.16: Stepper motor control diagram.

III.4.4 The PID Controller Parameters:

To achieve the control of the stepper we use these parameters so the system agrees well:

K_p: 75.3

K_i: 0.95

K_d: 0.5

These parameters were founded experimentally.

III.4.5 The Practical Results:

In this work we control only the position, so the results bellow presents the position results only with the three different modes of excitations. We try to make the stepper moves to 120° then moves again to 20°, the encoder will read the actual position and the PID will try to reduce the error between the reference position and the actual position as it is shown below:

III.4.4.1 Using Full Step Mode:

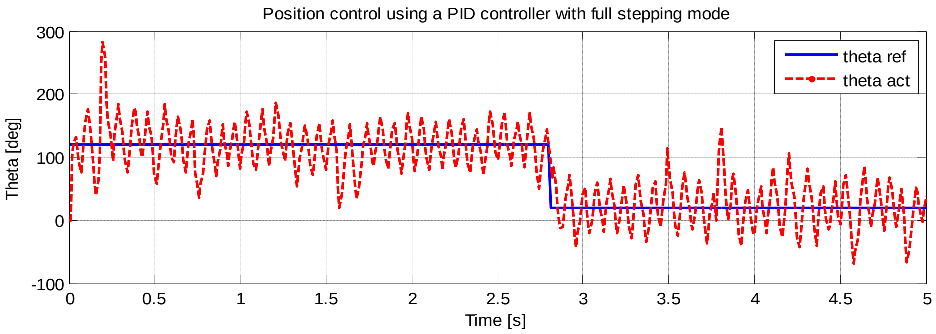


Figure III.17: Stepper position with full stepping mode using a PID regulator.

III.4.4.2 Discussion:

120° was given as a reference to the stepper from the practical results it can be seen that the stepper is respond well in which it try to moves to the reference position and allot more and with a great response time but the PID tried every time made it stable at this position, we can see also there is some overshoot but the PID always make it stable. At the half of the time we try to make it moves again to 20° and the stepper respond well either with a little overshoot but the PID controller make it stable every time it try to runs off. So it can be agreed about the PID controller is agree well with this kind of work.

III.4.4.3 Using Half Step Mode:

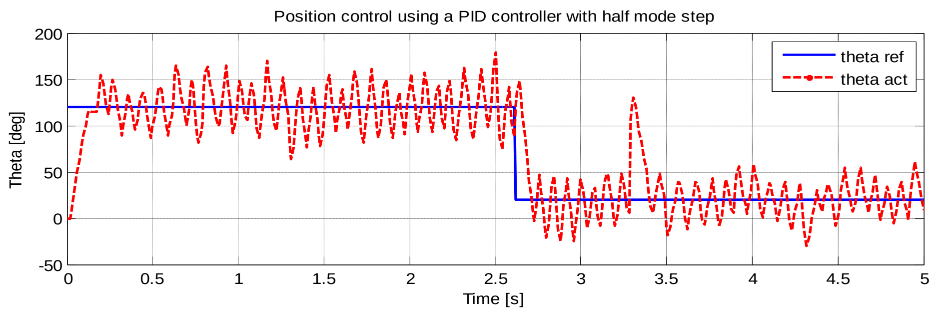


Figure III.18: Stepper position with half step mode using a PID regulator.

III.4.4.4 Discussion:

The same condition was given to the stepper but with different mode of excitation, this time we excite the stepper with the half step mode. It can be seen that the stepper respond well with this kind of excitation and the PID try to make it moves with the same reference but we can notice that there is a little lateness to respond. When we change the reference to 20° it responds well either but it present overshoot then it star became stable. The PID controller and the Stepper agree well either with this kind of excitation and with better precision.

III.4.4.5 Using Micro Stepping Mode:

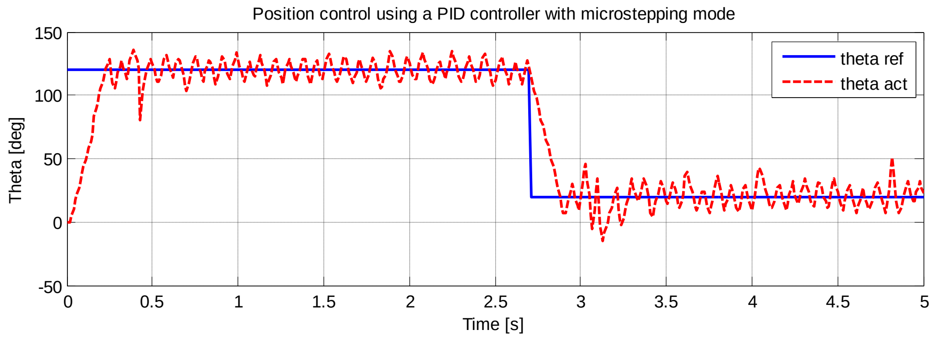


Figure III.19: Stepper position with micro stepping mode using a PID regulator.

III.4.4.6 Discussion:

We keep the same condition in this part either the only thing that is change is the mode of excitation in which this time we use the micro stepping mode. From the practical results it can be seen that time response getting more lateness then the two other modes, the stepper tried in every time to go over but the PID agree well even with this mode of excitation, it make the stepper some kind of stable in the same reference position and in the same two cases. The system is precise compared with the two other modes.

III.4.4.7 Comparison:

The three modes were agreeing well with our stepper but every mode gives an advantages and disadvantages, to compare among this three modes we put on your hands this resume as it given bellow:

Using Full Step Mode: the time response was very short and the stepper made it moves back to the reference position but the stepper tried every time to move away, so the precision in that kind of excitation is lower but it moves fast and respond well.

Using Half Step Mode: the time response got a little lateness, but with a better precision then the full step mode. The PID made it moves in the same reference position and the stepper moves less fast than the full step.

Micro Stepping Mode: with this type of mode the time response got more lateness but with more precision from the other modes, but it get more lateness than the last two modes on excitation.

III.4.6 Application:

This part presents an application of a robot arm.

III.4.6.1 Introduction:

The stepper motor could improve that it can be replacement with expensive servo motor, it could improve its performance in many cases. This is an application of the stepper motor in robotics domain, another test to show that the stepper can be effective in that kind of cases. The application represents a Robot Arm that contains two arms and a rotary base.

Figure III.20: Robot Arm.

III.4.6.2 Calculating angles necessary to reach a position on a 2D plane for two robot arms in a row:

Constructing a simple robot with two arms connected in a row. It is simple to find what point the arms will reach given the angles.

Lengths of the arms a,b are constant. Angles α,β are variables.

$$x = a\cos(\alpha) + b\cos(\alpha + \beta) \qquad \text{(III.6)}$$

$$y = a\sin(\alpha) + b\sin(\alpha + \beta) \qquad \text{(III.7)}$$

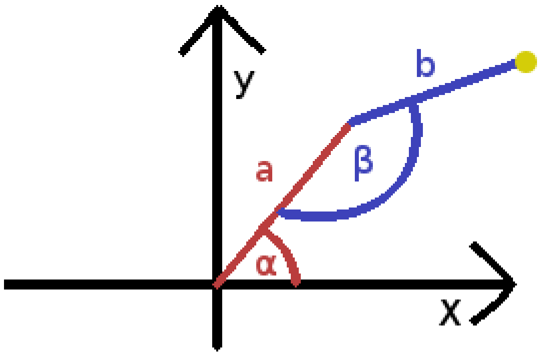


Figure III.21: The two arms position in the axes X.Y.

Your equations for X and Y are not quite correct, it can be given as:

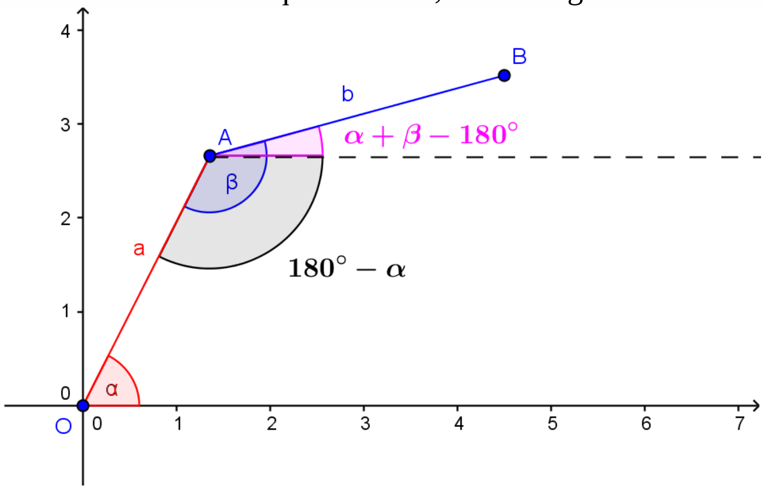


Figure III.22: equations diagram in the two axes X.Y.

It can be seen that the direction angle for vector B⟶ is not α+βbut rather α+β−180°. This changes the sign of the second term in the formulas is giving by:

$$x = acos(\alpha) - bcos(\alpha + \beta) \qquad \text{(III. 8)}$$

$$y = asin(\alpha) - bsin(\alpha + \beta) \qquad \text{(III. 9)}$$

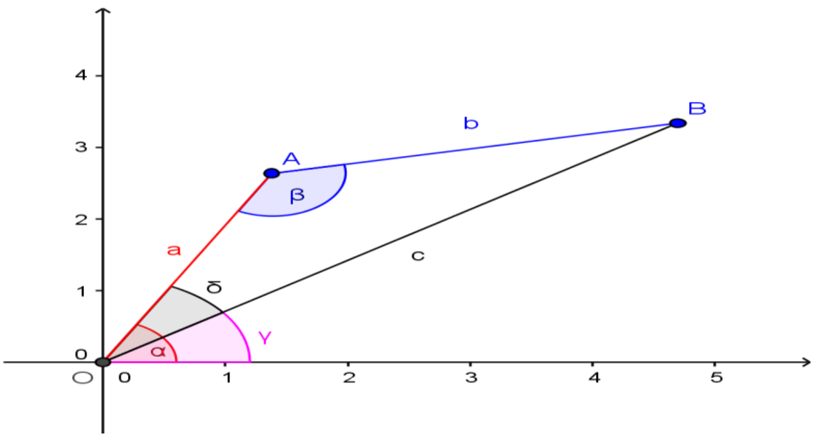


Figure III. 23: The two arms position.

In this diagram, C is the distance from the origin to the desired position. We than have a triangle with sides a,b,c, though the notation does not match the standard one. By the law of cosines we have:

$$C^2 = a^2 + b^2 - 2abcos\beta \qquad \text{(III. 10)}$$

So:

$$\beta = cos^{-1}\left(\frac{a^2+b^2-c^2}{2ab}\right) \qquad \text{(III. 11)}$$

We see that α=γ+δ, so we want to find γ and δ.

We can find γ with:

$$\gamma = atan2(X, Y) \qquad \text{(III. 12)}$$

Where atan2 is the arctangent function with two arguments. If you don't like atan2, you can use:

$$\gamma = \tan^{-1}\frac{X}{Y} \qquad \text{(III. 13)}$$

though that does not quite work correctly for x≤0.

We can find δ from another use of the law of cosines.

$$\delta = cos^{-1}\left(\frac{a^2+c^2-b^2}{2ac}\right) \qquad \text{(III. 14)}$$

You can tell there is no solution if you get a "domain error" when finding the arccosines: i.e. you attempt to find the arccosine of a value outside the interval [−1,1].This will happen when c is outside the interval [|a−b|,a+b].

You can tell there is one solution if β=0° or β=180°.

These calculations only give you one of the solutions. When a=b and the object is at the origin. In particular, both atan2 and atan fail at x=y=0. You would need to take that into account in a real solution.

You do not state the range of possible values for α or β, though by given the diagram you probably want 0°≤β<360°. The range for α could be [0°,360°)or (−180°,180°].In your final solution you will probably need to adjust your answers to stay in the desired ranges. The arms a and b are two sides of a triangle.

The third side of the triangle is the segment from the origin to the far end of arm b (the yellow dot in figure 21).Let the length of the third side be r. Then:

$$r^2 = X^2 + Y^2 \qquad \text{(III. 15)}$$

Where (X,Y) is the point at the far end of arm b.

Working backwards given x and y, you can use Equation (1) to find r. You then know all three sides of the triangle. Given all three sides of a triangle allows you to determinate the angles. One way to find an angle of the triangle is to use the Law of Cosines, for example,

$$r^2 = a^2 + b^2 - 2abcos\beta \qquad (III.16)$$

Since we know a, b, and r, we can solve for β.
In your figure, the angle α is the sum of two angles θ, the angle between side r and the X axis, and γ, the angle between sides a and r. Another possible configuration of the arms makes α=θ−γ. The angle θ is found by solving

$$Y = Xtan\theta \qquad (III.17)$$

The angle γ can be found either by applying the Law of Cosines again, or, since you know all three sides and an angle now you can use the Law of Sins. [15]

III.5 Conclusion

The stepper motor can be using in open loop and closed loop and in three modes named full step, half step and micro step. The control of the stepper motor needs a basic knowledge about every component that you need to achieve the control. The control of the stepper in this chapter was implemented in MATLAB-SIMULINK using a PID controller with the three modes of excitations under no load. From the practical results it can be seen that the three modes of excitations are agree well with the stepper and the PID controller was effect well, the simulation results were discussed and investigated. In the end of this chapter, an application of a robot arm is made.

General Conclusion

General conclusion:

This work presents simulation and practical control of a hybrid stepper motor. We started by a general idea about this motor and every important basic information about it, its characteristic, the way of the control, comparison and application of that kind of motors.

The hybrid stepper motor model has been implemented and simulated in MATLAB-SIMULINK software using the dynamic equation model. The simulation results has been presented and discussed.

The control of the hybrid stepper motor has been implemented with three different modes of excitation using a PID controller using an Arduino UNO card. The experimental results have been presented, it show good control where the output position tracks its command with small oscillation.

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A4988 Driver Stepper Motor

A4988 is a complete microstepping motor driver with built-in translator for easy operation. This product is available in full, half, 1/4, 1/8 and 1/16 step modes operate bipolar stepper motors, output drive capacity of up to 35 V and ± 2 A. A4988 includes a fixed off-time current regulator, the regulator in slow or mixed decay modes. A4988 converter is the key to the easy implementation. As long as the "step" input inputting one pulse drives the motor one microstep. There are no phase sequence tables, high frequency control lines, or complex interfaces to program. A4988 interface is very suitable for complex microprocessor is unavailable or is overburdened.

In the micro-step operation, A4988 chopping control inside automatically selects the current decay mode (Slow or Mixed). In mixed decay mode, the device is initially set to a fixed downtime in some fast decay, then the rest of the slow decay downtime. Mixed decay current control scheme results in reduced audible motor noise, increased step accuracy, and reduced power consumption. Internal synchronous rectification control circuitry is provided to improve the pulse-width modulation (PWM) operation power consumption. Internal circuit protection includes: thermal shutdown with hysteresis, undervoltage lockout (UVLO), and crossover-current protection. Special power sequencing.

A4988 surface mount QFN package (ES), a size of 5 mm × 5 mm, nominal overall package height of 0.90 mm, with an exposed pad for enhanced thermal dissipation. This package is Pb (suffix-T), with 100% matte tin leadframe plating.

Features and Benefits

· Low RDS (On) Output
· Automatic current decay mode detection / selection
· Mix with slow current decay modes
· Synchronous rectification for low power dissipation
· Internal UVLO
· Cross-current protection
· 3.3 and 5 V compatible logic supply
· Thermal shutdown circuitry
· Ground fault protection
· Load short-circuit protection
· Optional step five modes: full, 1/2, 1/4, 1/8 and 1/16

color : red

ملخص:

العمل المقدم في هذه المذكرة يمثل معارف معمقة حول المحرك الخطوي , كيفية تصنيعه الافتراضي, محاكاته و كيفية التحكم به. هذا المشروع هو عمل تطبيقي يشرح كيفية التحكم في المحرك الخطوي باستعمال لوحة الأردوينو. التحكم في الموضع محقق باستعمال المصحح الطردي- التكامل-المشتق.

الكلمات المفتاحية:

المحرك الخطوي،المصحح (الطردي، التكامل، المشتق)، بطاقة أردوينو، التحكم في الموضع.

Abstract:

The work presented in this thesis is a deep basic knowledge about a stepper motor, how to modeling, simulates and control of the stepper motor. This project is a practical work that shows how to control a stepper motor using an Arduino card. The position control is achieved using a PID controller.

Keywords:

Stepper Motor, PID Controller, Arduino card, Position Control.

Résumé:

Le travail présenté dans ce mémoire est une notion de base sur le moteur pas à pas, comment modelé le, sa simulation et sa commande. Ce projet est un travail pratique qui explique comment contrôler ce moteur à partir une carte Arduino. Le control de la position est assuré par un régulateur PID.

Mots clés:

Moteur Pas à Pas, régulateur PID, Carte Arduino, Control de position.