

Sudan University of Sciences and Technology
College of Engineering
School of Electrical and Nuclear Engineering

*A Comparative Study between IP and PI Controllers
for Speed Control of Direct Current Motor*

دراسة مقارنة بين المتحكمات التناسبي-التكاملي و التكاملي-التناسبي
للتحكم فى سرعة محرك التيار المستمر

**A Project Submitted in Partial Fulfillment for the Requirements of
the Degree of B.Sc. (Honour) In Electrical Engineering**

Prepared By:

- 1. Moddathir Bushra Abd Algader Ali**
- 2. Mogdad Elheber Mustafa Abbas**
- 3. Mohammed Omer Mohammed Elfaki**
- 4. Musaab Salah Elkheder Edrees**

Supervised By:

Dr. Aamir Hashim Obeid Ahmed

October 2015

الآية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

قال تعالى: ﴿اللَّهُ لَا إِلَهَ إِلَّا هُوَ الْحَيُّ الْقَيُّومُ لَا تَأْخُذُهُ سِنَّةٌ

وَلَا نَوْمٌ لَهُ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ مَنْ ذَا الَّذِي

يَشْفَعُ عِنْدَهُ إِلَّا بِإِذْنِهِ يَعْلَمُ مَا بَيْنَ أَيْدِيهِمْ وَمَا خَلْفَهُمْ وَلَا

يُحِيطُونَ بِشَيْءٍ مِّنْ عِلْمِهِ إِلَّا بِمَا شَاءَ وَسِعَ كُرْسِيُّهُ

السَّمَاوَاتِ وَالْأَرْضَ وَلَا يَئُودُهُ حِفْظُهُمَا وَهُوَ الْعَلِيُّ الْعَظِيمُ

﴿٢٥٥﴾

سورة البقرة

DEDICATION

We dedicate this project to our families, teachers, and friends.

A CKNOWLEDGEMENT

First of all, we would like to express our thanks to God for his great help in completing this project. After that there are numerous of people we need to thank for their advice, help, assistance and encouragement throughout the completion of this project.

We would like to express our sincerest thanks to our supervisor, Dr. Aamir Hashim Obeid Ahmed for his support, guidance, and advice in completing this project.

Last but not least, we would like to thank our families for their patience and endless financial, and more importantly, moral support throughout our life.

ABSTRACT

At the present time, Direct Current (DC) motors have been widely used in many industrial applications. The main reason for their popularity is the ability to control their torque and flux easily and independently. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century. The most commonly used controller for the speed control of DC motors is conventional Proportional-Integral (PI) controller. In spite of the major features of the conventional PI controller, it has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and sluggish response due to sudden disturbance. To overcome these disadvantages, replacement of PI controller by Integral plus Proportional (IP) controller is proposed in this project. Performance of two controllers has been verified through simulation results using MATLAB/SIMULINK software. According to the simulation results, IP controller creates better performance in terms of overshoot, settling time, and steady state error compared to conventional PI controller. This shows the superiority of IP controller over conventional PI controller.

مستخلص

فى الوقت الحالى، فإن محركات التيار المباشر تستخدم فى العديد من التطبيقات الصناعية. السبب الرئيسى لشعبيتها هى المقدرة على التحكم فى العزم والفيض بسهولة وبشكل مستقل. ولذلك فإن التحكم فى سرعة محرك التيار المستمر مسألة مهمة حيث تمت دراستها منذ العقود الأولى فى القرن الماضى. يتم التحكم فى سرعة محرك التيار المستمر بصورة واسعة باستخدام الحاكمة التناسبية-التكاملية. على الرغم من السمات الرئيسية التى تمتاز بها الحاكمة التناسبية-التكاملية التقليدية، إلا أنها لديها بعض العيوب مثل بداية عالية للسرعة لتجاوز الهدف، وحساسيتها للتغير فى ثوابت الحاكمة، و الإستجابة البطيئة للتغيرات المفاجئة. للتغلب على هذه المشاكل، استبدلت الحاكمة التناسبية-التكاملية التقليدية بالحاكمة التكاملية-التناسبية فى هذه المشروع. تم التحقق من أداء الحاكمتين من خلال نتائج المحاكاة باستخدام برنامج MATLAB/SIMULINK. وفقاً لنتائج المحاكاة، نجد أن الحاكمة التكاملية-التناسبية أعطت أداء أفضل مما يتعلق بتجاوز الهدف، زمن الترسىخ، و الخطأ عند حالة الإستقرارية مقارنة مع الحاكمة التناسبية-التكاملية التقليدية. وهذا يدل على تفوق الحاكمة التكاملية-التناسبية على الحاكمة التناسبية-التكاملية التقليدية.

TABLE OF CONTENTS

الاية	i
DEDICATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
مستخلص	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	ix
LIST OF TABLES	x
LIST OF ABBREVIATIONS	xi
CHAPTER ONE	
INTRODUCTION	
1.1 General Concepts	1
1.2 Problem Statement	2
1.3 Objectives	2
1.4 Methodology	2
1.5 Project Layout	3
CHAPTER TWO	
BACKGROUND AND LITERATURE REVIEW	
2.1 Introduction	4
2.2 Types of DC Motors	4
2.2.1 A separately excited DC motor	5
2.2.2 Permanent magnets DC motor	5
2.2.3 Series DC motors	6
2.2.4 Shunts DC motors	7
2.2.5 Compound DC motors	7

2.3 Main Components of DC Motors	8
2.3.1 Stator	9
2.3.2 Rotor	10
2.4 Operation Principle of DC Motors	11
2.5 Speed Control of DC Motor	11
2.3.1 Armature resistance control method	12
2.3.2 Flux control method	13
2.3.3 Armature voltage control method	13
CHAPTER THREE	
MATHEMATICAL MODEL OF THE SEPARATELY EXCITED DC MOTOR	
3.1 Introduction	15
3.2 Model of the separated excitation DC Motor	16
3.2.1 System equations	16
3.2.2 State space equations	17
3.3 PI Controller Background	18
3.4 IP Controller Background	20
3.5 PI and IP Controllers Tuning	20
CHAPTER FOUR	
SIMULATION RESULTS AND DISCUSSION	
4.1 Introduction	22
4.2 MATLAB/ SIMULINK Model for DC Motor	22
4.2.1 S-Function block	22
4.2.2 S-Function m-file	24
4.2.3 Complete SIMULINK model of DC motor	26
4.3 Simulation Results	27

4.3.1 Constant speed command	27
4.3.2 Variable speed command	28
CHAPTER FIVE	
CONCLUSION AND RECOMMENDATIONS	
6.1 Conclusion	30
6.2 Recommendations	30
References	32

LIST OF FIGURES

Figure	Title	Page
2.1	A separately excited DC motor model	5
2.2	The permanent magnets DC motor model	6
2.3	The series DC motor model	6
2.4	The shunt DC motor model	7
2.5	The compound DC motor model	8
2.6	The main components of a typical DC motor	8
2.7	Lamination of field pole	9
2.8	Cutaway view of commutator	11
3.1	Block diagram of the conventional PI controller	18
3.2	A simplified block diagram of the speed control of the separately excited DC motor using the PI controller	20
3.3	A simplified block diagram of the speed control of the separately excited DC motor using the IP controller	20
4.1	Simulink library browser	23
4.2	Drag-drop the S-Function block to new page	23
4.3	Change S-Function name to dc_motor	24
4.4	S-Function m-file	24
4.5	Complete SIMULINK model of the DC motor	26
4.6	MATLAB/SIMULINK overall model of speed control of the separately excited DC motor using two controllers	27
4.7	Simulation result at constant speed	28
4.8	Simulation result at variable speed	29

LIST OF TABLES

Table	Title	Page
3.1	Parameters of the separately excited DC motor	18
3.2	PI controller characteristic parameters	19
4.1	Three types of flags	25
4.2	Types of Sys	26

LIST OF ABBREVIATIONS

DC	Direct Current
AC	Alternating Current
IP	Integral- Proportional
PI	Proportional-Integral

CHAPTER ONE

INTRODUCTION

1.1 General Concepts

The history of electrical motors goes back as far as 1820, when Hans Christain Orested discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive DC motor. Faraday went onto discover electromagnetic induction in 1831. Nicola Tesla first developed the poly-phase induction motor in 1886 and by 1890 the simple three-phase motor had been developed. Currently, the main types of electric motors are still the same, DC, Alternating Current (AC) asynchronous and synchronous, all based on Orested, Faraday and Tesla's theories developed and discovered more than a hundred years ago. An electric drive performs the conversion of electrical energy to mechanical energy or vice-versa. Electric drives may run at constant speed or at variable speed. Both DC and AC motors have been extensively used in control systems but each has its own characteristics [1].

DC motor drives, because of their simplicity, ease of application, high reliabilities, flexibilities and favorable cost have long been a backbone of industrial applications where speed control of motor are required. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century [1, 2]. The most commonly used controller for the speed control of the DC motors is conventional PI controller. Conventional PI controllers have several important features. The reason is that the conventional PI controller is easy to implement either by hardware or by software. No deep mathematical theory is necessary to understand how the conventional PI controller works, so everybody is able to imagine what is happening inside the controller during the control process. Furthermore, it has the ability to eliminate steady state

offset through integral action and it can anticipate the changes through derivative action. In addition to this, traditional PI controllers have very simple control structure and inexpensive cost. However, the PI controller has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and sluggish response due to sudden change in load torque disturbance. So, the relatively IP controller is proposed to overcome the disadvantages of the PI controller [3].

1.2 Problem Statement

Direct current motors are generally controlled by conventional PI controller. In spite of the major features of the classical PI controller, it has some disadvantages. This makes the use of traditional PI controller a poor choice for industrial variable speed drive applications where higher dynamic control performance with little overshoot and high efficiency is required.

1.3 Objectives

The main objectives of this project are listed as follows:

- (1) To formulate the complete mathematical model and state space representation of the separately excited DC motor.
- (2) To study and understand PI and IP controllers to control the speed of the separately excited DC motor.
- (3) To evaluate the performance of the speed control of the separately excited DC motor using two controllers.
- (4) To compare the performance of the PI and IP controllers via simulation results using MATLAB/SIMULINK software.

1.4 Methodology

The project methodology is undertaken according to these stages:

- (1) The development of linear mathematical model for the separately excited DC motor.

- (2) Construct the model of the separately excited DC motor using MATLAB/SIMULINK software.
- (3) Design of PI and IP controllers.
- (4) Perform simulation using MATLAB/SIMULINK software for PI and IP controllers.
- (5) Evaluate performance of speed control of the separately excited DC motor based on simulation results.

1.5 Project Layout

The project is presented in five chapters. The scope of each chapter is explained as stated below:

Chapter one gives an introduction to the project, including: general concepts, problem statement, objectives, and methodology.

Chapter two presents background theory and a literature review of DC motors. Various electrical DC motors types are discussed. Different DC motor control methods are then presented, including flux control method by changing Φ , armature voltage control, and armature resistance control.

Chapter three the mathematical model of the separately excited DC motor is introduced. Furthermore, types of mathematical models are discussed. Finally, the PI and IP controllers for the speed control of the separately excited DC motor are presented.

Chapter four presents the simulation results of PI and IP controllers using MATLAB/SIMULINK software. Furthermore, the comparison between the two controllers is done.

Chapter five draws general conclusions from the project and provides suggestions for further research work in this area.

CHAPTER TWO

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Electrical drives involving various types of DC motors turn the wheel of industry. The main advantages of DC motors are easy speed or position control and wide adjustable range. Therefore, DC motors are often used in a variety of industrial applications such as electrical equipment, computer peripherals, robotic manipulators, actuators, steel rolling mills, electrical vehicles, paper machine. Its applications spread from low horse power to the multi-mega watt due to its wide power, torque, speed ranges, high efficiency, fast response, and simple and continuous control characteristics. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century. Some of these methods were based on classical and also intelligent approaches. At present, PI controller, due to its simplicity, stability, and robustness, is a type of controller that is most widely applied. However, it is difficult to design when the accurate model of plant is complicated or the environment of the load on the plant is variable [1, 2]. This chapter will examine the different types of DC motors that can be made and explain the advantages and disadvantages of each. It will include a discussion of several methods of DC motor speed control.

2.2 Types of DC Motors

DC motors can be classified according to the electrical connections of the armature winding and the field windings. The different ways in which these windings are connected lead to motors operating with different characteristics. The field winding can be either self-excited or separately-excited, that is, the terminals of the winding can be connected across the input voltage terminals

or fed from a separate voltage source. Further, in self-excited motors, the field winding can be connected either in series or in parallel with the armature winding. These different types of connections give rise to very different types of DC motors. In this section each of these DC motor types are discussed and their relative advantages and disadvantages examined [1, 2].

2.2.1 A separately excited DC motor

The schematic circuit diagram of the separately excited DC motor is illustrated in following Figure 2.1. When the armature of a DC machine rotates in the stator field, a voltage is induced in the armature winding. In a DC motor, it is called counter emf or back emf. In either case, the level of this voltage can be calculated using Faraday's Law, which states that a voltage is induced. The field and armature circuits are totally separate. The field current is supplied from a secondary source [1, 2].

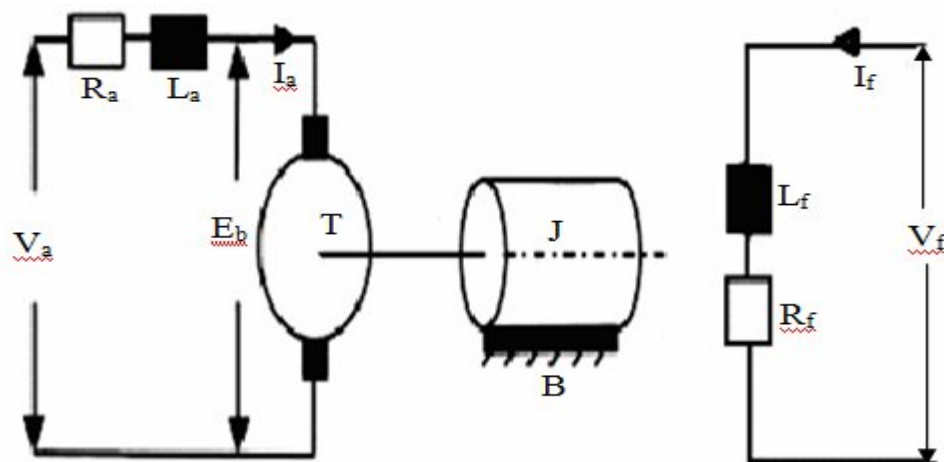


Figure 2.1: A separately excited DC motor model

2.2.2 Permanent magnets DC motor

The magnetic field of Permanent Magnets (PM) DC motors is generated by permanent magnets so no power is used to create the magnetic field structure. The stator magnetic flux remains essentially constant at all levels of armature current and, therefore, the speed vs. torque curve of the PM motor is linear

over an extended range. The schematic circuit diagram of a permanent magnets DC motor is illustrated in following Figure 2.2 [1, 2].

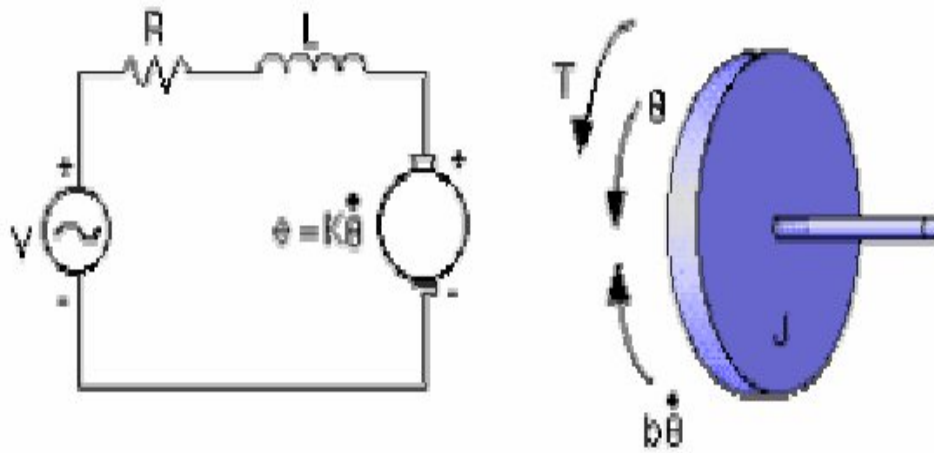


Figure 2.2: The permanent magnets DC motor model

2.2.3 Series DC motor

The schematic circuit diagram of a series DC motor is illustrated in following Figure 2.3. The series DC motor has, as the name suggests, the field winding in series with the armature winding. The field current I_f is therefore the same as the armature current I_a . torque. Series DC motor armatures are usually lap wound. Lap windings are good for high current, low voltage applications because they have additional parallel paths for current flow. Common uses of the series DC motor include crane hoists, where large heavy loads will be raised and lowered and bridge and trolley drives on large overhead cranes [1].

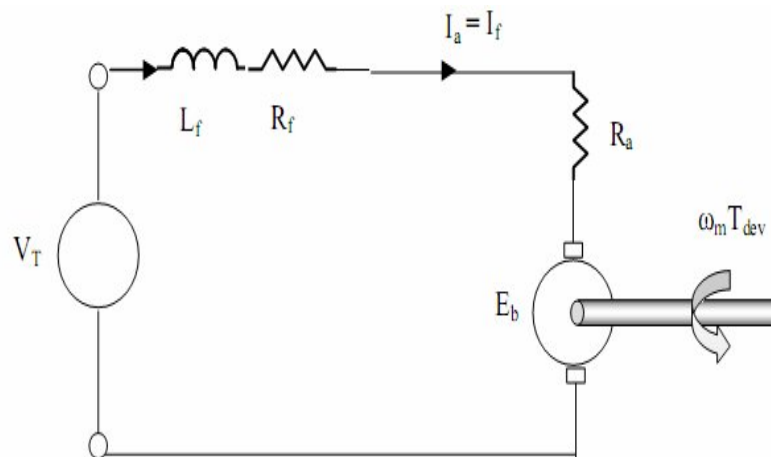


Figure 2.3: The series DC motor model

2.2.4 Shunt DC motor

The shunt DC motor is probably the most common DC motor used in industry today. Some of the common uses of the shunt DC motor are machine shop lathes, and industry process lines where speed and tension control are critical. The schematic of the shunt DC motor is shown in Figure 2.4. As the name suggests, the field winding is connected in parallel with the motor armature. The coils in the shunt field are composed of many turns of small wire, resulting in low shunt field current and moderate armature current. This motor provides starting torque that varies with the load applied and good speed regulation by controlling the shunt field voltage [1, 2].

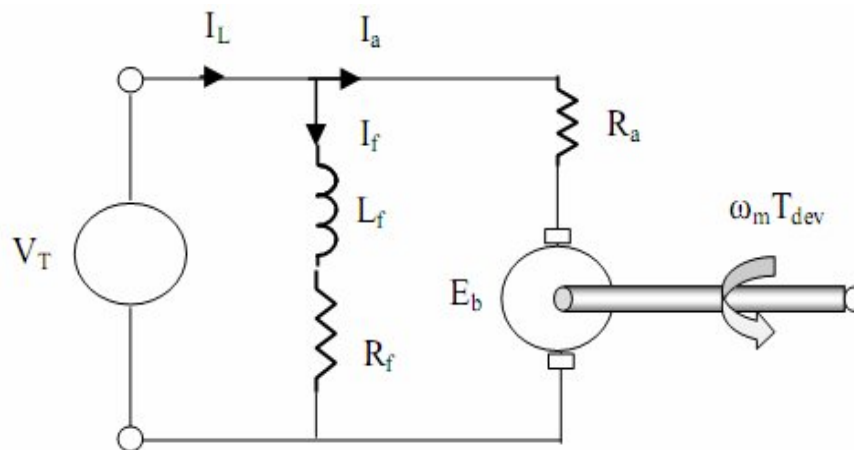


Figure 2.4: The shunt DC motor model

2.2.5 Compound DC motor

When comparing the advantages of the series and shunt DC motors, the series DC motor has greater torque capabilities while the shunt DC motor has more constant and controllable speed over various loads. These two desirable characteristics can be found in the same motor by placing both a series field and shunt field winding on the same pole. Thus, we have the compound DC motor. The schematic circuit diagram of a compound DC motor is illustrated in following Figure 2.5. Common uses of the compound DC motor include elevators, air compressors, conveyors, presses and shears [1, 2].

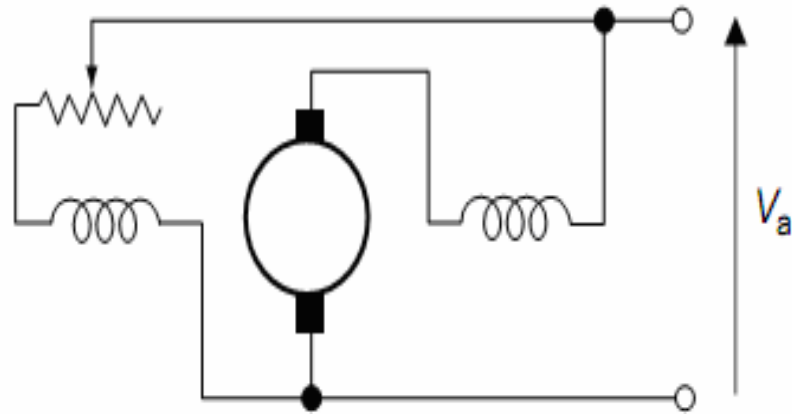


Figure 2.5: The compound DC motor model

2.3 Main Components of DC Motors

The major components of all DC motors are the same. The difference between DC motors occurs in the way the components are electrically connected. Figure 2.6 shows the components of a typical DC motor, the stator and the rotor.

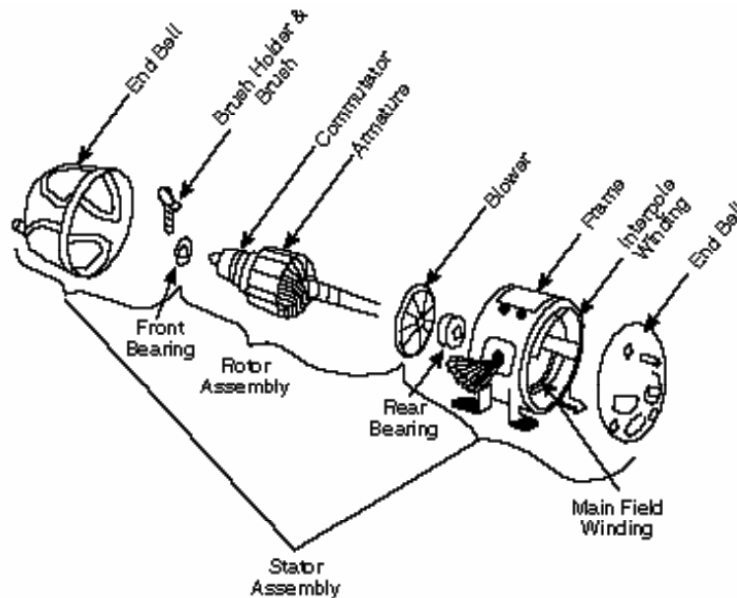


Figure 2.6: The main components of a typical DC motor

The stator is the stationary frame assembly of the DC motor. The stator assembly is made up of the frame, inter-pole windings, main field windings, brush-holder and brushes, and the end bells. The rotor is the rotating portion

of a DC motor. The rotor assembly is made up of the armature, commutator, and the blower. The rotor and the stator are mechanically connected through use of the front and rear bearings that allow the rotor to rotate while providing mechanical support [1, 2].

2.3.1 Stator

As discussed, the stator is the stationary portion of a DC motor. The stator consists of the following [1]:

(1) Frame: The frame of a DC motor provides the mechanical support for the stator components. The frame also provides for a method of mounting and moving the DC motor.

(2) Field Winding: The field winding is wound around a field pole that usually is made from laminated steel. The use of laminated steel reduces eddy current and hysteresis losses. Figure 2.7 shows a typical laminated field pole piece that would be bolted to the motor frame. The laminated field pole then is wrapped with coil wire to complete the main field winding assembly. When DC current is passed through these main field coils, a stationary magnetic field is produced. Several types of DC motors have an auxiliary winding that is mounted on the motor frame between the main field poles. This winding is called an inter-pole. The purpose of an inter-pole is to assist commutation and prevent sparking at the brushes.

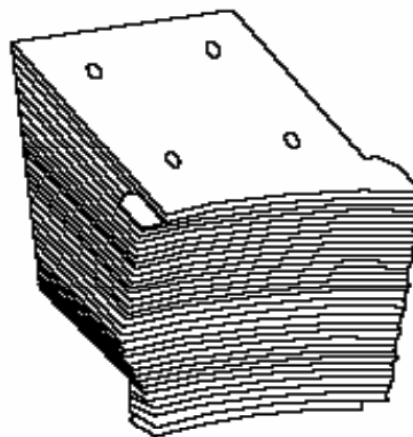


Figure 2.7: Lamination of field pole

(3) Brush rigging and brushes: Current flows into the armature winding through contacts called brushes. These brushes ride on the commutator bars. The brushes are made from a carbon compound and are mounted in a brush holder, as shown in Figure 2.6. The entire assembly is referred to as a brush rigging. The brush holder keeps the brush properly aligned with the commutator and maintains a constant pressure on the brush through use of a spring. The armature circuit consists of a current path from the power supply through the brushes, through a commutator bar, through a set of coils, through another commutator bar, through a second set of brushes, and back out to the power supply.

(4) End bells: The end bells are on either end of the motor. The end bells complete the frame of the motor and also house the bearing support for the motor.

2.3.2 Rotor

The rotor is the rotating portion of a DC motor. The rotor consists of the following components [1]:

(1) Armature: The armature consists of a group of coils that are imbedded in a laminated iron core. When a DC current is applied to the armature, a magnetic field will be produced.

(2) Commutator: The commutator is shown in Figure 2.6, is the mechanical means by which the direction of current is switched to the armature coils. The armature coils are connected to a commutator by copper bars that are called risers. A commutator is a copper cylinder that is divided into many sections or segments that are called bars. The segments are insulated from each other with mica.

(3) Blower: The blower is a fan that is mounted on the rotor shaft. The blower rotates with the rotor and forces air to pass through the DC motor. The blower is used to cool a DC motor. The Figure 2.8 shows a cutaway view of commutator which consists from segments (bars), rear string band, risers.

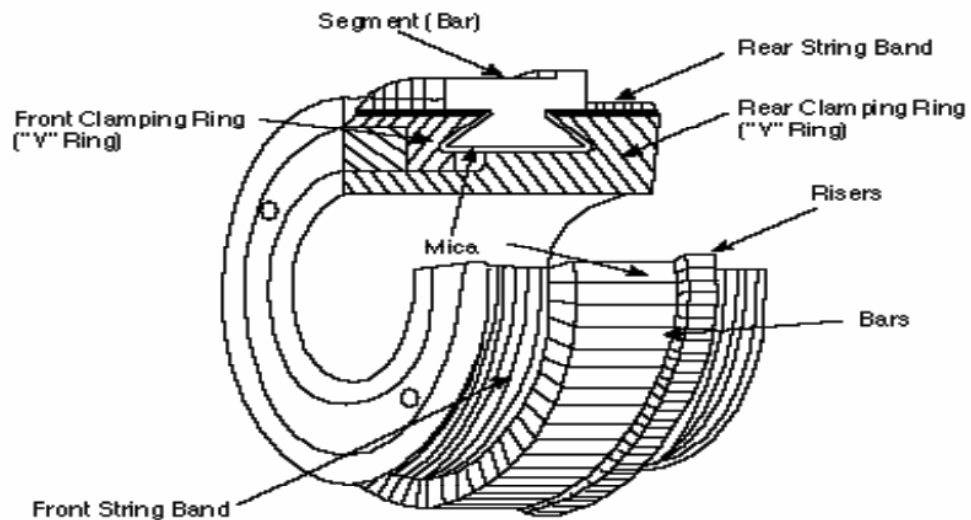


Figure 2.8: Cutaway view of commutator

2.4 Operation Principle of DC Motors

A DC Motor works on the principle that “whenever a current carrying conductor is placed in a magnetic field, it experiences a force. The magnitude is given by [1]:

$$F = B.I.L \quad (2.1)$$

Where:

F = Force in Newton’s.

B = Flux density in Web/ m^2 .

I = Current in amperes flowing through the conductor.

L = Length of the conductor in meters.

2.5 Speed Control of DC Motors

Speed control of a motor refers to the intentional change of the motor speed to a value needed for performing the required work. Many applications require the speed of a motor to be varied over a wide range. One of the most attractive features of DC motors in comparison with AC motors is the ease

with which their speed can be varied. Based on the operating parameters, the speed of DC motors governed by the equation:

$$\omega = \frac{V_a - R_a i_a}{\phi K_b} \quad (2.2)$$

On the right hand side of the Equation (2.2) there are three operating parameter, namely, the voltage applied to the armature circuit (V_a), the voltage drop in the armature circuit ($I_a R_a$) and the useful flux per pole (Φ). From this equation, it is evident that the speed can be varied by using any of the following methods [1, 2].

- (i) By varying the resistance (R_a) in the armature circuit. This is known as armature control method.
- (ii) By varying the flux per pole (Φ). This is known as flux control method.
- (iii) By varying the applied voltage (V_a). This is known as voltage control method.

2.5.1 Armature resistance control method

Armature resistance control provides a means of obtaining reduced speed by insertion external series resistance in the armature circuit. It can be used with series, shunt, and compound DC motors. For the last two types of DC motor, the series resistor must be connected between the shunt field and the armature, not between the line and the motor. It is a common method of speed control for series motors. Depending upon the value of the series resistance, the speed may vary significantly with the load, since the speed depends on the voltage drop in this resistance and hence on the armature current demanded by the load. A significant disadvantage of this method of speed control is that the power loss in the external resistor is large, especially when the speed is greatly reduced [1, 2].

2.5.2 Flux control method

Another approach to control the speed of a DC motor involves the control of the field current, which in turn controls the flux in the motor. The field current in a shunt DC motor can be controlled by inserting an external resistor in series with the field winding. Because the field current is a very small fraction of the total current intake of a shunt DC motor, the power dissipated by the external resistor is relatively small. Therefore, the flux control method is economically better than the armature resistance control method. To control the flux in a series DC motor, a field diverter resistor can be connected in parallel with the series field winding. If all the coils in a series field winding are connected in series, we can also change the flux in a series motor by connecting the coils in parallel. The addition of a resistance in series with the shunt field winding or in parallel with the series field winding causes the field current and thereby the flux in the motor to decrease. Since the speed of a motor is inversely proportional to its flux, a decrease in its flux results in an increase in its speed. Thus, the flux control method makes a motor operate at a speed higher than its rated speed. As the torque developed by a shunt DC motor is proportional to the product of the armature current and the flux per pole, a decrease in the flux must be accompanied by a corresponding increase in the armature current for the motor to deliver the same torque. This method of speed control is, therefore, not satisfactory for compound DC motors, because any decrease in the flux produced by the shunt field winding is offset by an increase in the flux produced by the series field winding owing to an increase in the armature current [1, 2].

2.5.3 Armature voltage control method

This method is usually applicable to the separately excited DC motors. In the armature voltage control method, the voltage applied to the armature circuit is varied without changing the voltage applied to the field circuit of the motor. Therefore, the motor must be separately excited to use armature voltage

control. The advantage of this method is that it has a wide range of speed control from zero up to the rated speed. However, it is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance [1, 2].

CHAPTER THREE

MATHEMATICAL MODEL OF THE SEPARATELY EXCITED DC MOTOR

3.1 Introduction

The general system description, loosely speaking, refers to a mathematical expression that appropriately relates the physical system quantities to the system components. This mathematical relation constitutes the mathematical model of the system. A system in operation involves the following three elements: the system's input (or excitation), the system itself, and the system's output (or response). The mathematical model of a system is a mathematical relation which relates the input, the system, and the output. This relation must be such as to guarantee that one can determine the system's output for any given input. From the above definition it follows that the mathematical model is not just any relation, but a very special relation, which offers the capability of system analysis, i.e., the capability to determine the system's response under any excitation. Furthermore, the foregoing definition reveals the basic motivation for determining mathematical models. This motivation is to have available appropriate tools that will facilitate the system analysis. It is well known that in order to analyze a system, it must have available its mathematical model. It should be also noted that the mathematical model is useful for other purposes, as for example to study the system's stability and other properties, to improve the system's performance by applying control techniques [2]. There are several types of mathematical models have been proposed for the description of system. The most popular ones are the following:

- (1) The differential equations.
- (2) The transfer function.
- (3) The state equations.

In this project the state space equations are used. The state space equation is description in time domain which may be applied to very wide category of systems, such as linear and nonlinear system. The term state of a system refers to the past, present, and future of the system. Usually, a system is described by a finite number of state variables [2].

3.2 Model of the Separately Excited DC Motor

Direct current motors are widely used for industrial and domestic applications. The control of the speed of a DC motor with high accuracy is required. There are two main ways of controlling a DC motor: The first one named armature control consists of maintaining the stator magnetic flux constant, and varying the armature current. Its main advantage is a good torque at high speeds and its disadvantage is high energy losses. The second way is called field control, and has a constant voltage to set up the armature current, while a variable voltage applied to the stator induces a variable magnetic flux. Its advantages are energy efficiency, inexpensive controllers and its disadvantages are a torque that decreases at high speeds. In this project, the separately excited DC motor model is chosen according to his good electrical and mechanical performances more than other DC motor models. The electric circuit of the separately excited DC motor is shown in Figure 2.1. The main objective is to control the speed of the separately excited DC motor by armature voltage control [1, 2].

3.2.1 System equations

From Figure 2.1, the dynamics of a separately excited DC motor may be expressed as [2]:

$$V_a = R_a i_a + L_a \frac{d i_a}{d t} + E_b \tag{3.1}$$

$$V_a = R_a i_a + L_a \frac{d i_a}{d t} + K_b \omega$$

$$T = K_T i_a = J \frac{d\omega}{dt} + B \omega \quad (3.2)$$

Where V_a is the input terminal voltage (armature voltage) in volt, E_b is the motor back emf in volt, R_a is the armature resistance in ohm, L_a is the armature inductance in H, K_b is the back emf constant in Vs/rad, ω is represents angular speed in rad/s, i_a is the armature current in A, J is the moment of inertia of the motor in kgm^2/s^2 , T is the motor torque in Nm, B is the viscous friction coefficient in Nms/rad, and K_T is the torque factor constant in Nm/A.

3.2.2 State space equations

Equation (3.3) and Equation (3.4) are rearranged to obtain:

$$\frac{di_a}{dt} = -\frac{R_a}{L_a} i_a - \frac{K_b}{L_a} \omega + \frac{V_a}{L_a} \quad (3.3)$$

$$\frac{d\omega}{dt} = \frac{K_T}{J} i_a - \frac{B}{J} \omega \quad (3.4)$$

In the state space model of a separately excited DC motor, the Equation (3.3) and Equation (3.4) can be expressed by choosing the angular speed (ω) and armature current (i_a) as state variables and the armature voltage (V_a) as an input. The output is chosen to be the angular speed [2].

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} i_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ \frac{K_T}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} V_a \quad (3.5)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix}$$

The physical and functional parameters of the separately excited DC motor used for simulation testing are given in Table 3.1.

Table 3.1: Parameters of the separately excited DC motor

Parameter	Description	Value
R_a	Armature Resistance	1Ω
L_a	Armature Inductance	$0.05H$
J	Moment of Inertia	$0.01\text{kgm}^2/\text{s}^2$
B	Viscous Friction Coefficient	0.00003Nms
K_T	Toque Constant	0.023Nm/A
K_b	Back EMF Constant	0.023Vs/rad

3.3 PI Controller Background

The conventional PI controller remains the most popular design approach used in industrial applications due to its simplicity and reliability for the control of first and second order plants, and even high order plants with well defined conditions. A well tuned PI controller is capable in achieving an excellent performance. However, the PI controller has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and sluggish response due to sudden change in load torque disturbance. Figure 3.1 shows the block diagram configuration of the conventional PI controller [3].

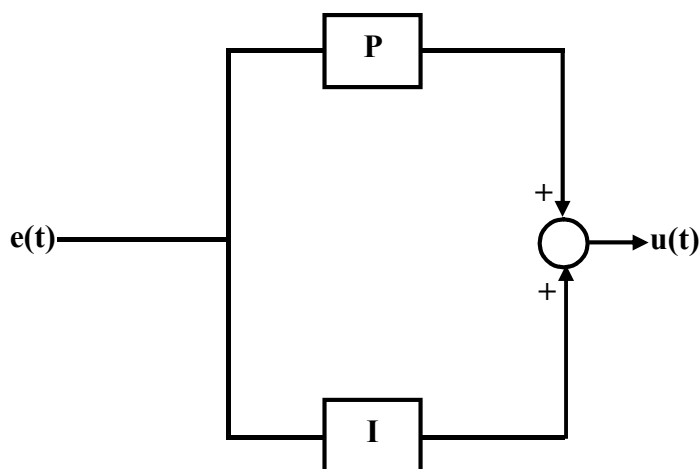


Figure 3.1: Block diagram of the conventional PI controller

Where it can be seen that in a PI controller the error $e(t)$ is used to generate the proportional and integral action with the resulted signals weighted and summed to form the control signal $u(t)$ applied to the plant model. The differential equation of a conventional PI controller is given by [3]:

$$u(t) = K_P e(t) + K_I \int e(t) dt \quad (3.6)$$

Where K_P is the proportional gain and K_I is the integral gain. The transfer function of a classical PI controller is expressed as follows:

$$G_{PI}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} \quad (3.7)$$

The effects of each gain controllers K_P and K_I on a closed-loop system are summarized as shown in Table 3.2.

Table 3.2: PI controller characteristic parameters

Close Loop Response	Rise Time (T_r) sec	Overshoot (Mp) %	Settling Time (T_s) sec	Steady State Error (e_{ss})
K_P	Decrease	Increase	Small Change	Decrease
K_I	Decrease	Increase	Increase	Eliminate

Note that these correlations may not be exactly accurate, because K_P and K_I are dependent of each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only used as a reference when we are determining the values of K_P and K_I . To improve the dynamic performance for transient state and avoid overshoot, the speed control is confided to an integral plus proportional controller [3]. The IP controller is considered the major contribution in this study. A simplified block diagram of the speed control of the separately excited DC motor using the PI controller is shown in Figure 3.2 [4].

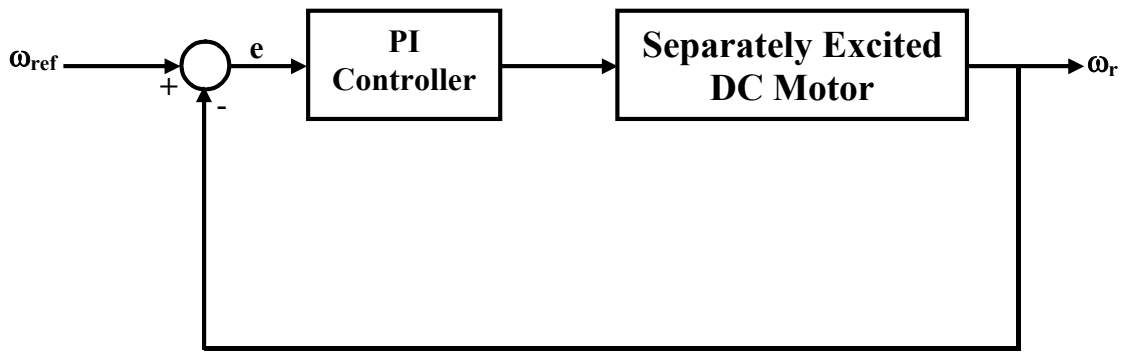


Figure 3.2: A simplified block diagram of the speed control of the separately excited DC motor using the PI controller

Where ω_{ref} is the reference rotor angular speed, ω_r is the rotor angular speed and $e = \omega_{ref} - \omega_r$ is the tracking speed error.

3.4 IP Controller Background

Takahashi, Harashima and Kondo suggested a new method of control called IP controller as a trial to solve the main problems of PI controller. Figure 3.3 shows IP controller along with the separately excited DC motor, where the proportional term is moved to the feedback path and it acts like a feedback compensation [4].

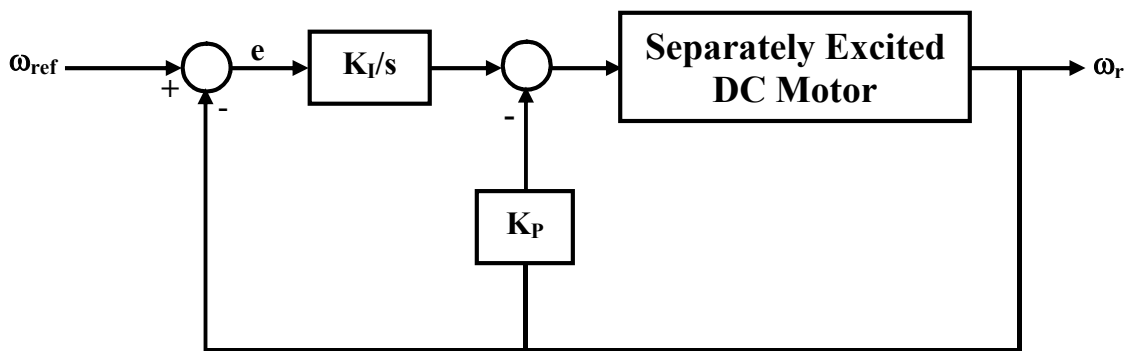


Figure 3.3: A simplified block diagram of the speed control of the separately excited DC motor using the IP controller

3.5 PI and IP Controllers Tuning

Tuning the PI and IP controller is adjust of its parameter gains K_P and K_I to the optimum values for the desired control response.

There are according various method for loop tuning, the traditional manual method for loop tuning is used in this project [3].

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

A comparative study of PI and IP control scheme for the separately excited DC motor has been done here. Two simulation tests for the separately excited DC motor were carried out using both IP controller and conventional PI controller. Simulation tests are based on the facts that whether the IP controller is better than the conventional PI controller or not.

4.2 MATLAB/ SIMULINK Model for DC Motor

MATLAB is a simple and flexible programming environment for a wide range of problems such as signal processing, optimization, linear programming and control systems. The basic MATLAB software package can be extended by using add-on toolboxes such as: fuzzy logic toolbox and control toolbox. With the complexity of medium-size to large-size nonlinear models, it may be more efficient to use a set of differential equations written in an m-file. These m-files will be accessed by SIMULINK through the S-Function block. Thus, this method mixes the advantages of an m-file with the graphical links to other SIMULINK blocks. The state space equations (3.5) and (3.6) can be written into MATLAB/SIMULINK by using S-Function block as follows [5]:

4.2.1 S-Function block

In the Simulink Library Browser, go to the User-Define Functions subdirectory as shown in Figure 4.1. Then open new page and drag-drop the S-Function block to new page as shown in Figure 4.2. Double-click on the S-Function block and change the S-Function name to dc_motor as shown in Figure 4.3 [5].

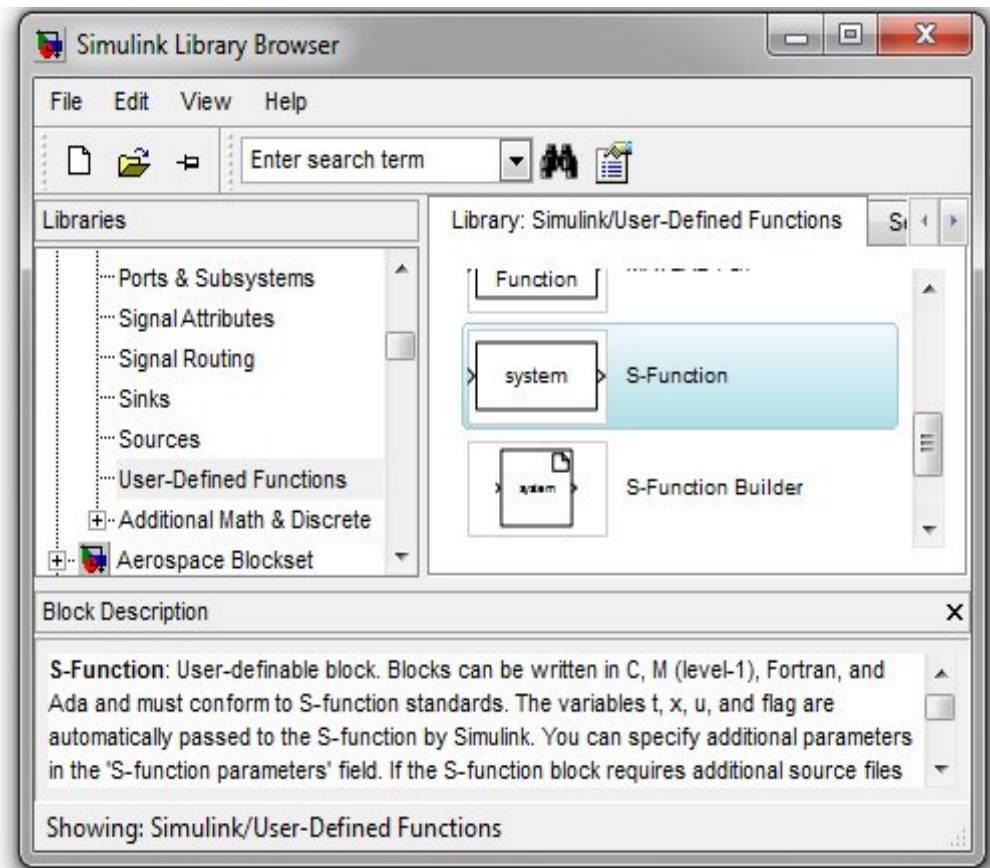


Figure 4.1: Simulink library browser

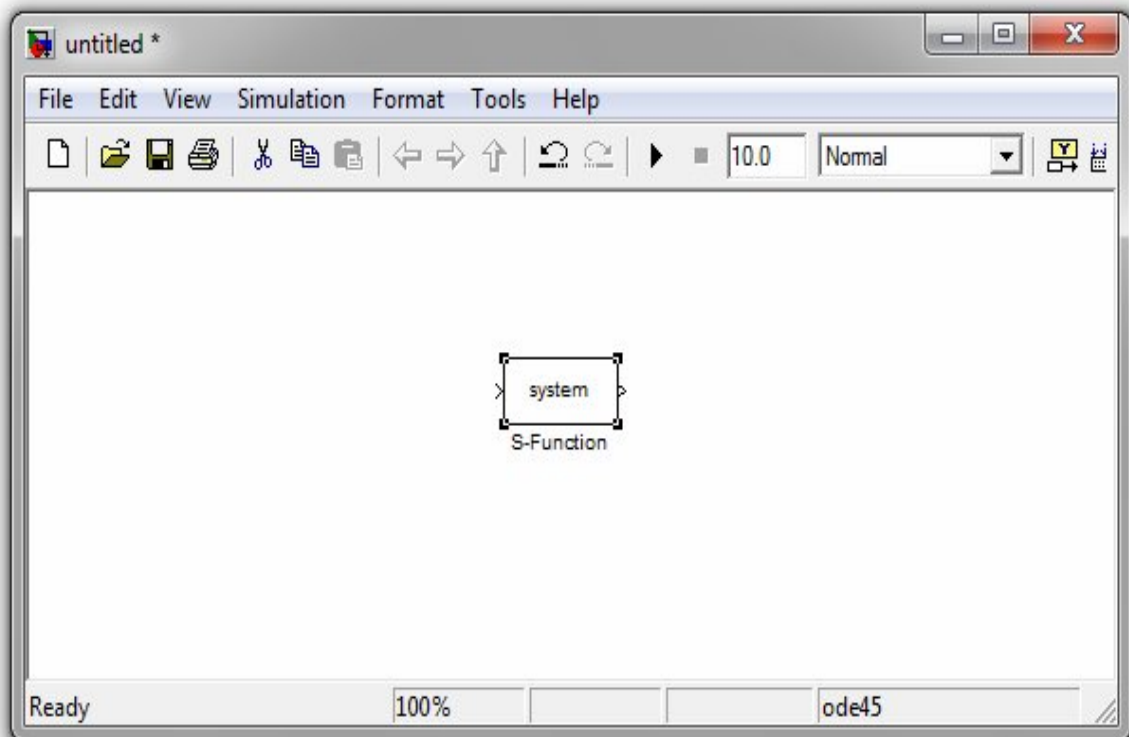


Figure 4.2: Drag-drop the S-Function block to new page

The first line specifies the S-Function name (here dc-motor), input and output arguments. The input and output arguments are classification as follows [5]:

(a) Input arguments

(i) t is the time variable.

(ii) x is the column-vector of state variables.

(iii) u is the column-vector of input variables (whose value will come from other SIMULINK blocks).

(iv) Flag is indicator of which group of information and/or a calculation is being requested by SIMULINK. There are many types of flags, here we described there flags as shown in Table 4.1.

Table 4.1: Three types of flags

Flag	Job/Data Request
0	<p>Initialization:</p> <p>a) Setup of input/output vector sizes and other setup modes</p> <p>b) Specification/calculation of initial Conditions for the state variables.</p>
1	<p>Derivative Equation Updating:</p> <p>a) Calculations involving input vectors</p> <p>b) Calculation of the derivatives</p>
3	<p>Output Calculations:</p> <p>Evaluating output variables as a function of the elements of the state vector (and in some case, also the elements of the input vector)</p>

(b) Output arguments

(i) sys is the main vector of results requested by SIMULINK. Depending on the flag sent by SIMULINK, this vector will hold different information as shown in Table 4.2.

(ii) x_0 is column vector of initial conditions.

Table 4.2: Types of Sys

<p>If flag = 0</p>	<p>$\text{sys} = [a, b, c, d, e, f, g]$ where: a is number of continuous time states b is number of discrete time states c is number of outputs d is number of inputs e = 0 (required to be 0, not currently used) f = 0 (no) or 1 (yes) for direct algebraic feed through of input to output. (This is relevant only if during flag=3, the output variables depend algebraically on the input variables) g is number of sample times. (for continuous process, we set this equal to 1)</p>
<p>If flag = 1</p>	<p>sys = a column vector of the derivatives of the state variables</p>
<p>If flag = 3</p>	<p>sys = a column vector of the output variables</p>

4.2.3 Complete SIMULINK model of DC motor

The complete MATLAB/SIMULINK model of the separately excited DC motor is shown in Figure 4.5.

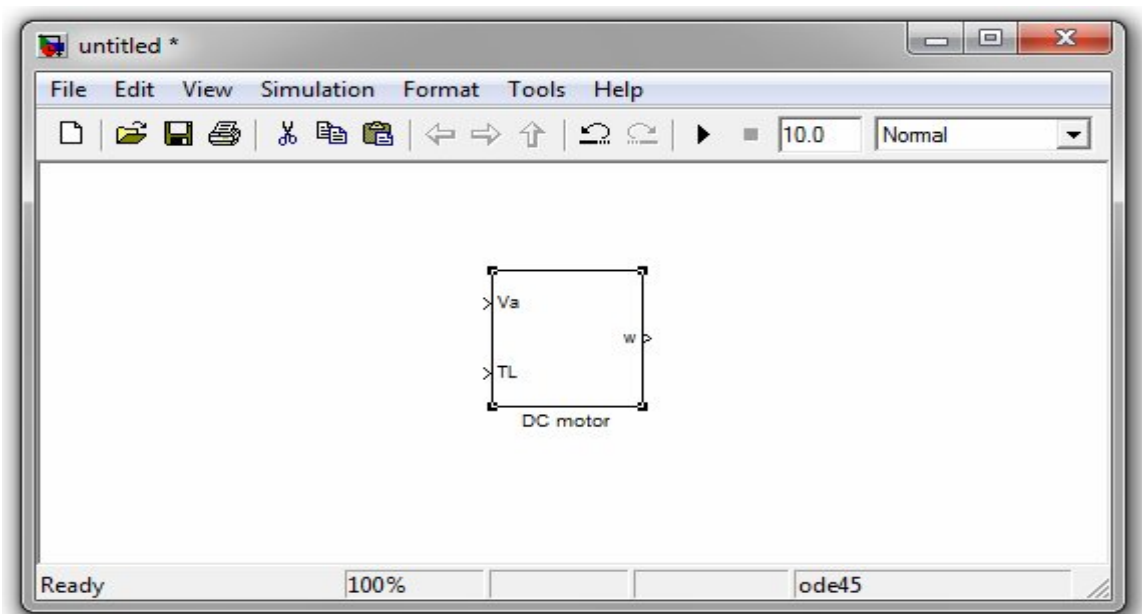


Figure 4.5: Complete SIMULINK model of the DC motor

4.3 Simulation Results

The MATLAB/SIMULINK overall model of system under study with conventional PI controller and IP controller is shown in Figure 4.6.

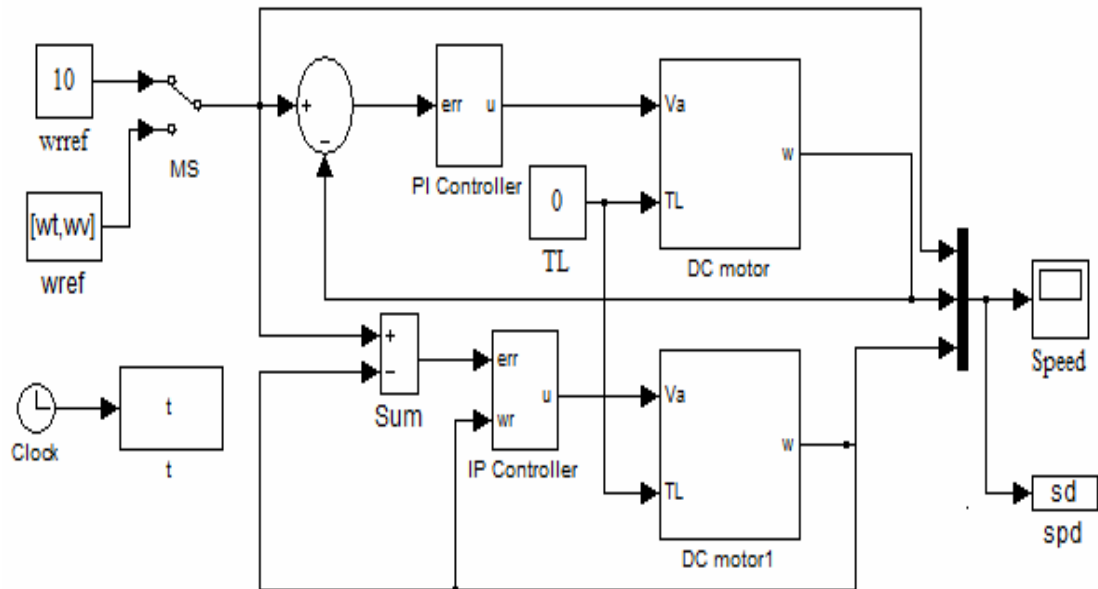


Figure 4.6: MATLAB/SIMULINK overall model of speed control of the separately excited DC motor using two controllers

4.3.1 Constant speed command

To test the performance of the speed control of the separately excited DC motor at a constant speed, the separately excited DC motor is started up from stand still to trace the speed command of 10rad/sec. Figure 4.7 gives the speed responses of the separately excited DC motor drive with IP controller and ordinary PI controller. In terms of the speed control trajectories shown in Figure 4.7, two controllers have a similar performance in term of fast tracking of the desired speed. Also, steady state error with both controllers is almost zero. However, in Figure 4.7 it can be easily observed that the speed response of the separately excited DC motor with IP controller shows no sign of overshoot as observed with classical PI controller thus reducing the settling time. However, the rise time for traditional PI controller is shorter than for IP controller.

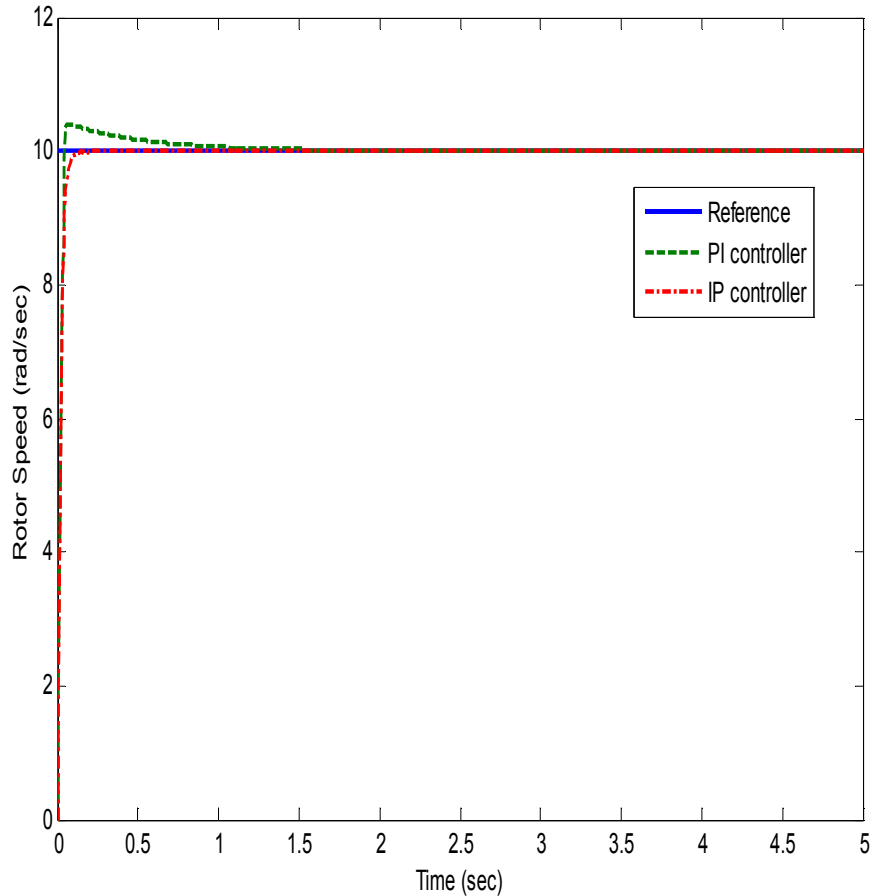


Figure 4.7: Simulation result at constant speed

4.3.3 Variable speed command

In this case, the separately excited DC motor is tested under variable speed command. The simulation is performed for 5 seconds. The speed command is 10rad/sec for the first three seconds then followed by 30rad/sec for the last two seconds. Figure 4.8 shows the speed response for a stepped speed reference for IP and standard PI controllers. It can be seen that there is a very good accordance between real speed and reference speed. However, from Figure 4.8 it is clear that IP controller provided optimum performance in terms of overshoot and settling time. Only rise time remained to be good for conventional PI controller.

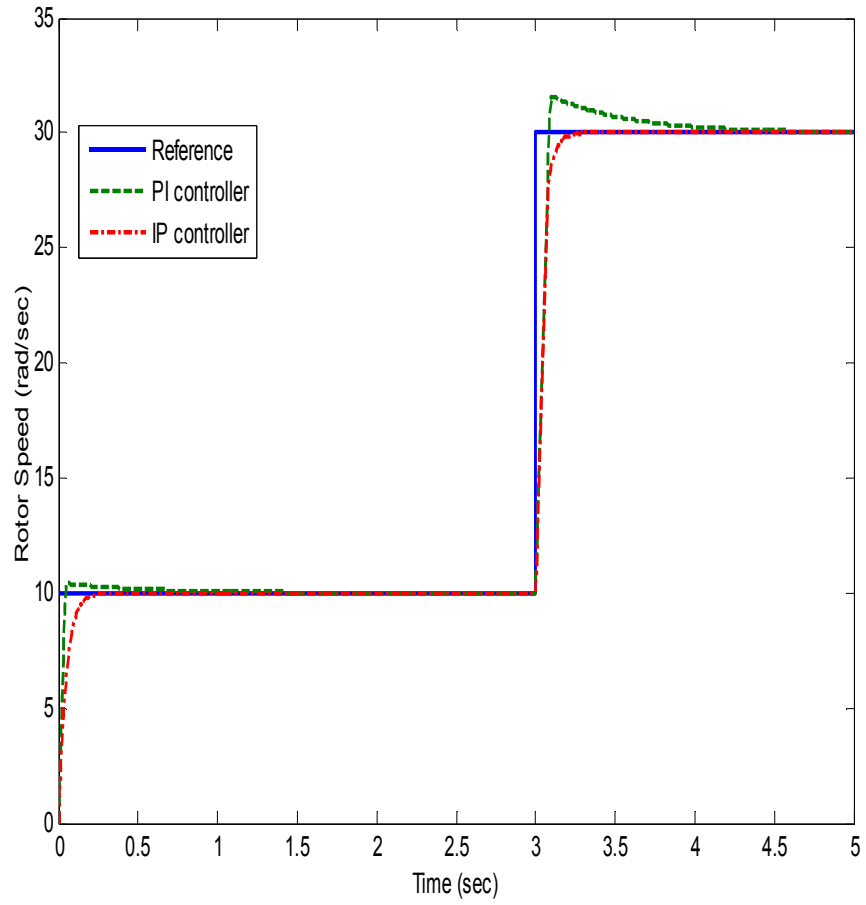


Figure 4.8: Simulation result at variable speed

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

High performance electric motor drives are considered an essential requirement for modern industrial applications. In the past, DC motors have been used extensively in the industry mainly because of the simple control strategies required to achieve good performance in speed control applications. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century. DC motors are generally controlled by conventional PI controller. In spite of the major features of the classical PI controller, it has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and the sluggish response due to sudden change in load torque disturbance. Thus, the relatively IP controller is proposed to solve the some disadvantages of the conventional PI controller and achieve accurate control performance of speed control of a DC motor. A series of simulation results have been conducted in order to evaluate the performances of the two controllers using MATLAB/SIMULINK software package. From the comparative simulation results, one can conclude that the two controllers demonstrate nearly the same performances. However, it is observed that IP controller provide important advantages over the traditional PI controller like limiting the overshoot in speed, thus the starting current overshoot can be reduced. In addition, the settling time for IP controller is shorter than for conventional PI controller.

5.2 Recommendations

The results of this project open some interesting and challenging problems of great importance. In what follows, we point out some of the possible future research directions:

1. It would be useful to further compare between IP controller and fuzzy logic control.
2. It would be useful to further compare between IP controller and neural network schemes for speed control of DC motor.
3. It would be useful to further compare between IP controller and sliding mode control.

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