Sudan University of Science &Technology
College of Engineering
School of Electrical &Nuclear Engineering

A Comparative Study between PID &FOPID Controllers for Speed Control of DC Motor

دراسة مقارنة بين الحاكمة التناسبية التكاملية التفاصلية والحاكمة التناسبية التكاملية التفاصلية كسرية الرتبة للتحكم في سرعة محرك التيار المستمر

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

Prepared By:

1. **Ahmed Mohammed Sharafeldeen Aboali**
2. **Alshafei Abdelhameed Mohammed Gasmallah**
3. **Mohammedelmostafa Sulaiman Mohammed Sulaiman**
4. **Mahmoud Abdelrahim Mohammed Ahmed**

Supervised By:

Dr. Aamir Hashim Obeid Ahmed

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الآية

بسم الله الرحمن الرحيم

قال تعالى:

{وَقُلِ اعْمَلُواْ فَسَيَرَى اللّهُ عَمَلَكُمْ وَرَسُولُهُ وَالْمُؤْمِنُونَ وَسَتُرَدُّونَ إِلَى عَالِمِ الْغَيْبِ وَالشَّهَادَةِ فَيُنَبِّئُكُم بِمَا كُنتُمْ تَعْمَلُونَ}

صدق الله العظيم

سورة التوبة الآية (105)

DEDICATIONS

This project is dedicated to our beloved parents, brothers, sisters and friends. We adore them for their effortless support every single moment till we reach this day. Without their love, patient and support, this project would not have been become possible and real.

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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.

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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. The most commonly used controller for the speed control of DC motor is conventional Proportional-Integral-Derivative (PID) controller. However, the conventional PID controller has some disadvantages. To overcome these disadvantages, various types of modified conventional PID controllers such as Fractional Order PID (FOPID) controllers were developed.

This project presents a comparison of time response specifications between FOPID and conventional PID controllers for a speed control of DC motor. Performance of two controllers has been verified through simulation results using MATLAB/SIMULINK software. Simulation results show that the FOPID controller performs better performance and more robustness than a conventional PID controller.

مستخلص

فى الوقت الحالى, فإن محركات التيار المستمر تستخدم فى العديد من التطبيقات الصناعية. والسبب الرئيسى لشعبيتها هو القدرة على التحكم فى عزم الدوران و الفيض لها بسهولة و بشكل مستقل. المتحكم الأكثر إستخداماً للتحكم فى سرعة محرك التيار المستمر هو المتحكم التناسبيي–التكاملي–التفاضلي التقليدي. و مع ذلك، فإن المتحكم التناسبي–التكاملي–التفاضلي التقليدي له بعض المساوئ. للتغلب على هذه المساوئ، تم تطوير أنواع مختلفة من المتحكم التناسبي–التكاملي–التفاضلي التقليدي مثل المتحكم التناسبي–التكاملي–التفاضلي كسري الرتبة. هذه المشروع يقدم مقارنة لمواصفات الإستجابة الزمنية بين المتحكم التناسبي–التكاملي–التفاضلي كسري الرتبة و المتحكم التناسبي–التكاملي–التفاضلي التقليدي للتحكم فى سرعة محرك التيار المستمر. تم التحقق من أداء المتحكمين من خلال نتائج المحاكاة بإستخدام برنامج MATLAB/SIMULINK. نتائج المحاكاة توضح أن المتحكم التناسبي–التكاملي–التفاضلي كسري الرتبة أظهر أداء أفضل و أكثر متانة من المتحكم التناسبي–التكاملي–التفاضلي التقليدي.

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LIST OF ABBREVIATIONS

DC	Direct Current
SEDC	Separately Excited Direct Current
PID	Proportional Integral Derivative
FOPID	Fractional Order Proportional Integral Derivative
P	Proportional
I	Integral
D	Derivative
PI	Proportional Integral
PD	Proportional Derivative
MATLAB	MATrix LABoratory
MIMO	Multi Input Multi Output
FC	Fractional Calculus
FOC	Fractional Order Control
CRONE	Command Robuste Ordre Non Enteir
AVR	Automatic Voltage Regulator
FOMCON	Fractional-Order Modeling and Control
TL	Torque Load
FLC	Fuzzy Logic Controller
AI	Artificial Intelligence
DSP	Digital Signal Processor

LIST OF SYMBOLS

K_P	Proportional gain
K_I	Integral gain
K_D	Derivative gain
ϕ	Flux, waber
t	Time, second
emf	Electro magnetic force
F	Force, N
B	Density of magnetic field
i	Current, A
L	Length of conductor, H
Eb	Electro magnetic force back, Volt
I_a	Armature current, A
I_l	Line current, A
V	Supply voltage, Volt
R_a	Armature resistance, Ω
Rf	Field resistance, Ω
L_f	Field inductance, H
L_a	Armature inductance, H
If	Field current, A
B	Viscous friction coefficient, Nms
J	Moment of inertia, kgm^2/s^2
K_T	The torque factor constant, Nm/A
θ	Theta, degree
K_b	The back EMF constant, s/rad
Ea	Armature voltage, Volt

δ	Fractional order
λ	Fractional order integral
μ	Fractional order derivative

CHAPTER ONE

INTRODUCTION

1.1 General Overview

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, 2].

There are many difference DC motor types in the market and all with it good and bad attributes. 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 robotic manipulator, production plants, home appliances, and transportation of people or goods where a wide range of motions are required to follow a predetermined speed or position trajectory under variable load. 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. Several methods are presented for controlling of their speed. The most commonly used controller for the speed control of the DC motors is conventional PID controller. Conventional PID controllers have several important features. The reason is that the conventional PID controller is easy to implement either by hardware or by software. No deep mathematical theory is necessary to understand how the conventional PID 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 trough integral action and it can anticipate the changes through derivative action. In addition to this, traditional PID controllers have very simple control structure and inexpensive cost. However, the PID 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 and machine parameter variations. Furthermore, the PID controller gains have to be carefully selected in order to obtain a desired response. This makes the use of traditional PID controller a poor choice for speed DC drive applications where higher dynamic control performance with little overshoot and high efficiency is required. So in this project, the relatively FOPID controller is proposed to overcome the disadvantages of the PID controller and achieve accurate control performance of speed control of a DC motor [1-5].

1.2 Problem Statement

Direct current motors are generally controlled by conventional PID controller. In spite of the major features of the classical PID controller, it has some disadvantages. This makes the use of traditional PID 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 of the Separately Excited DC (SEDC) motor.

(2) To study and understand PID and FOPID controllers to control the speed of the SEDC 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 two 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 PID and FOPID controllers.

(4) Perform simulation using MATLAB/SIMULINK software for two controllers.

(5) Evaluate performance of speed control of the separately excited DC motor based on simulation results.

1.5 Project Layout

This project consists of five chapters. The scope of each chapter is explained as stated below:

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

Chapter two presents background theory and a literature review of DC motors such as DC motor construction, principle of operation, DC motor classification, speed control of DC motors methods and model of the separately excited DC motor.

Chapter three briefly discuss PID controller. Furthermore, Fractional Calculus is discussed. Finally, the FOPID controller for the speed control of the separately excited DC motor is presented.

Chapter four presents the simulation results of FOPID and PID 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

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Electrical derives 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, PID 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 DC Motor Construction

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 2.1 shows the cross sectional view of DC motor [1, 2].

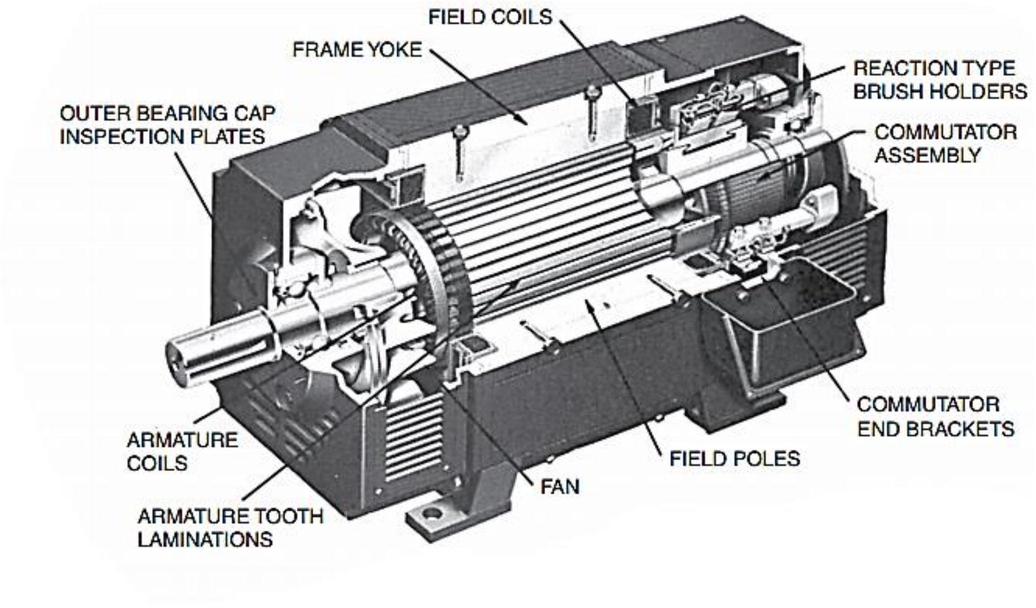

Figure 2.1: Cross sectional view of DC motor

The two main parts of DC motor as follows:

2.2.1 Stator

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 stator consists of the following [1, 2]:

(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 2.2 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.

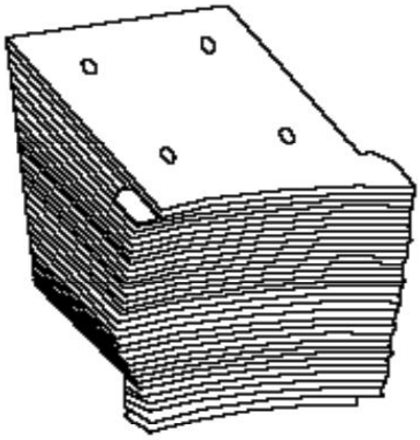

Figure 2.2: Lamination of field pole

(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.

2.2.2 Rotor

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 consists of the following components [1, 2]:

(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 2.3 shows a cutaway view of commutator which consists from segments (bars), rear string band, risers.

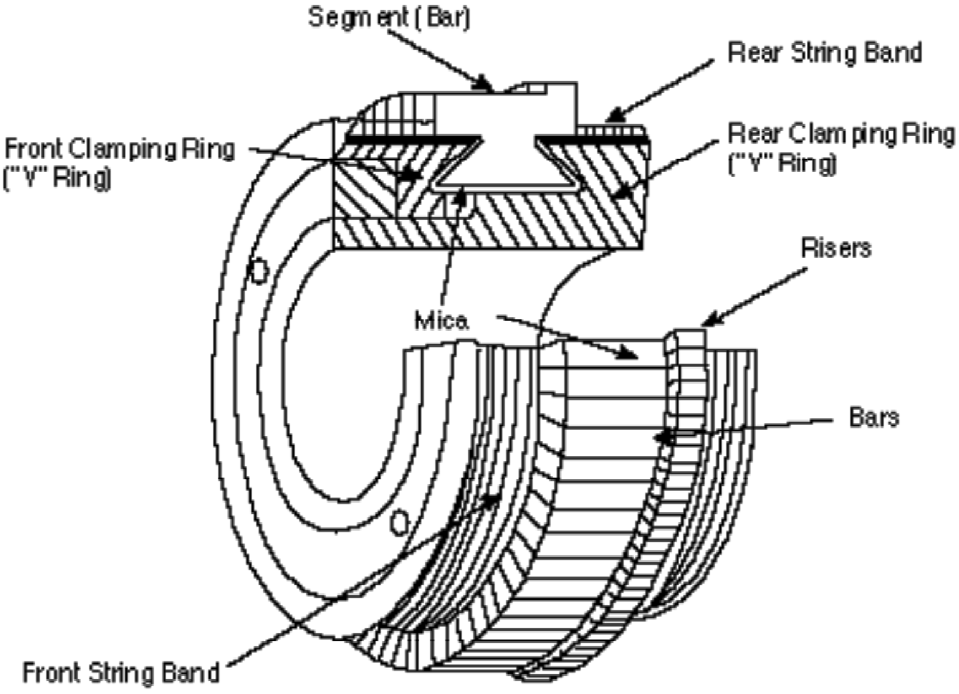

Figure 2.3: Cutaway view of commutator

The essential features and parts of DC motors and generators are the same. The DC motor has field coils, armature coils, and a commutator with brushes.

2.3 Principle of Operation

Consider a coil in a magnetic field of flux density B .When the two ends of the coil are connected across a DC voltage source, current (I) flows through it. A force is exerted on the coil as a result of the interaction of magnetic field and electric current. The force on the two sides of the coil is such that the coil starts to move in the direction of force. Figure 2.4 shows how the torque production in DC motor.

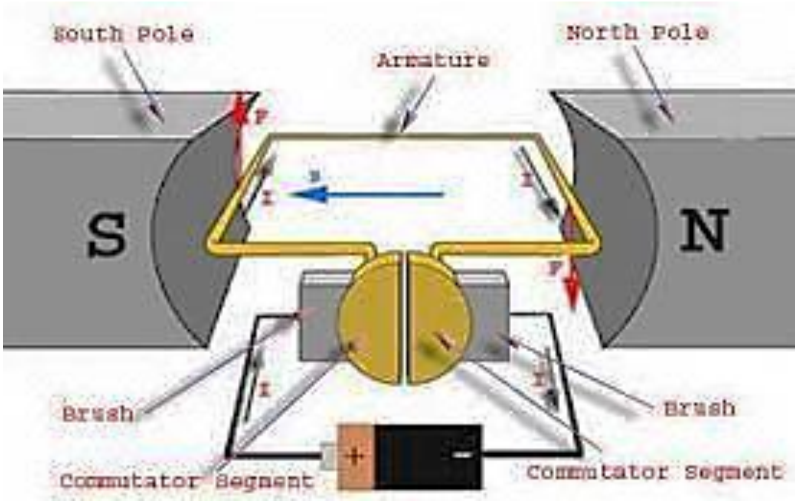

Figure 2.4: Torque production in a DC motor

In an actual DC motor, several such coils are wound on the rotor, all of which experience force resulting in rotation. The greater the current in the wire, or the greater the magnetic field, the faster the wire moves because of the greater force created. At the same time this torque is being produced, the conductors are moving in a magnetic field. At different positions, the flux linked with it changes, which causes emf to be induced [1, 2].

$$e = d\phi/dt \qquad (2.1)$$

As shown in Figure 2.7, this voltage is in opposition to the voltage that causes current flow through the conductor and is referred to as a counter-voltage or back emf.

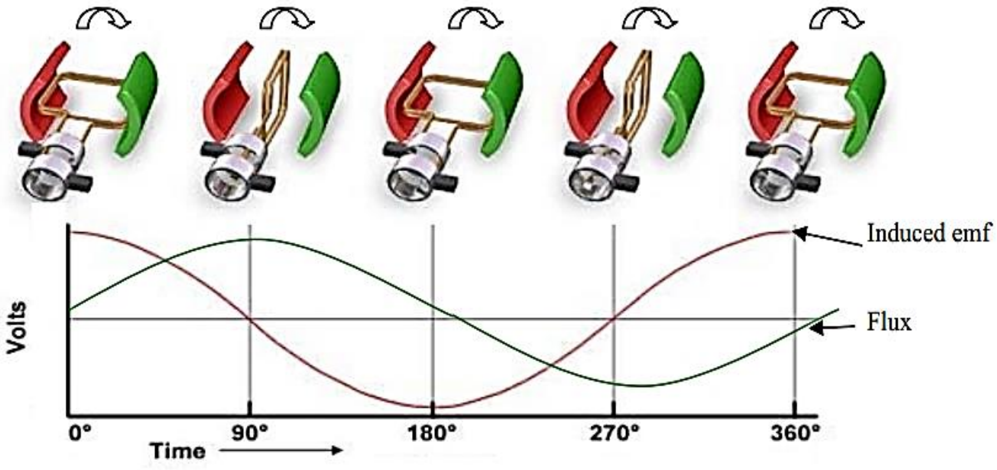

Figure 2.5: Induced voltage in the armature winding of DC motor

The value of current flowing through the armature is dependent upon the difference between the applied voltage and this counter-voltage. The current due to this counter-voltage tends to oppose the very cause for its production according to Lenz's law. It results in the rotor slowing down. Eventually, the rotor slows just enough so that the force created by the magnetic field equals the load force applied on the shaft. Then the system moves at constant velocity. The magnitude is given by [1, 2]:

$$F = BIL \tag{2.2}$$

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.

2.4 DC Motor Classification

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].

2.4.1 A separately Excited DC motor

The schematic circuit diagram of the separately excited DC motor is illustrated in following Figure 2.6. 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].

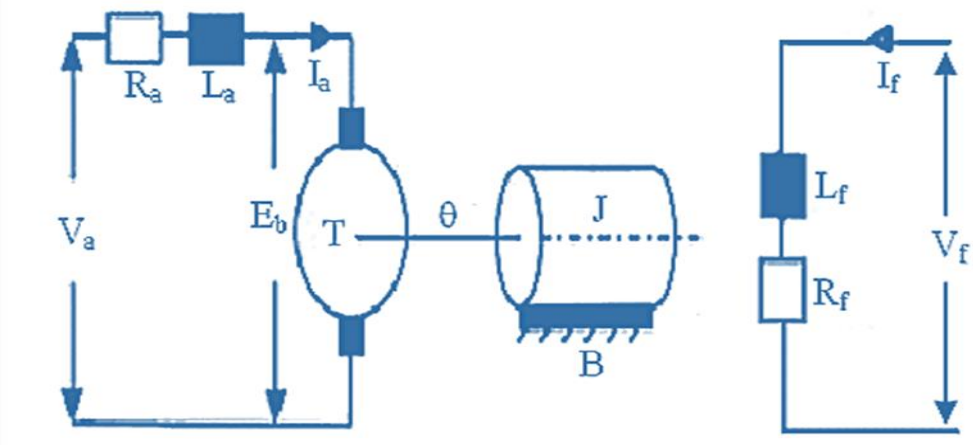

Figure 2.6: A separately excited DC motor model

2.4.2 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 2.7 [1, 2].

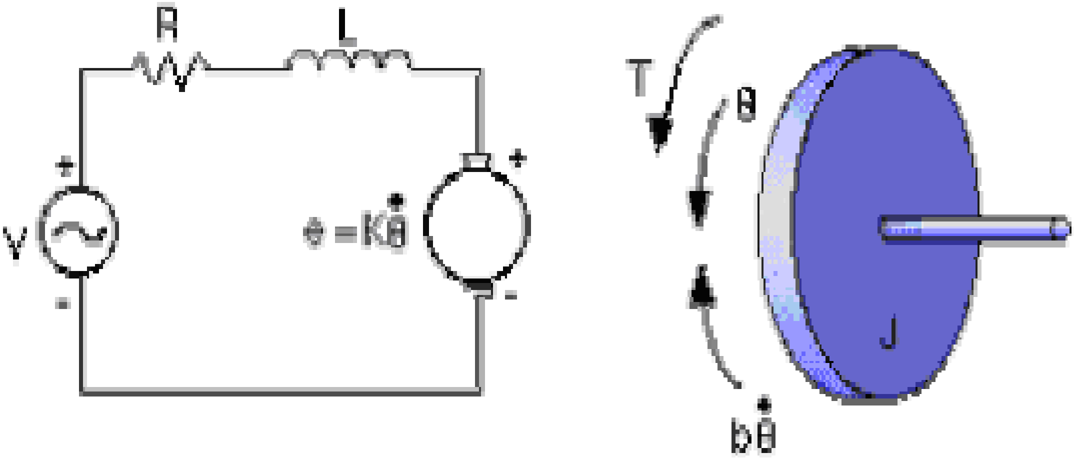

Figure 2.7: The permanent magnets DC motor model

2.4.3 Series DC Motor

The schematic circuit diagram of a series DC motor is illustrated in following Figure 2.8. 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].

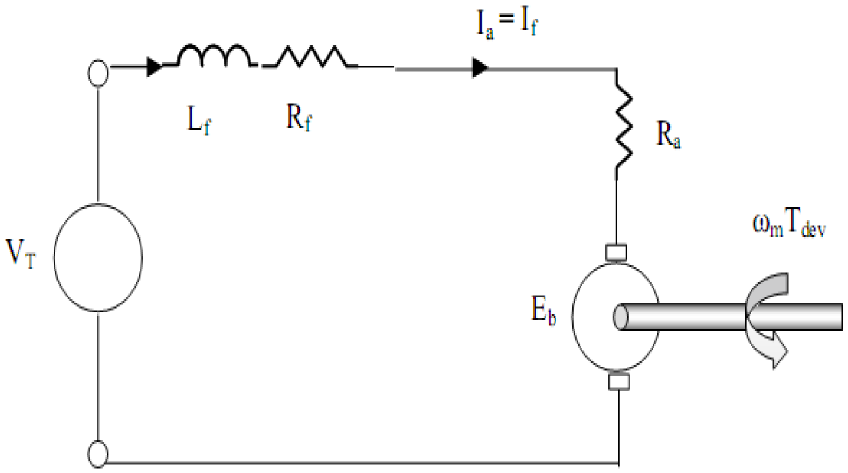

Figure 2.8: The series DC motor model

2.4.4 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 2.9. 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].

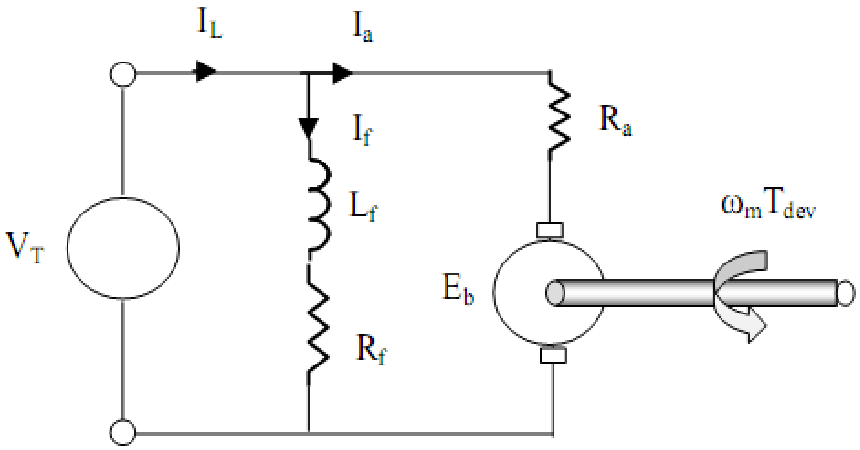

Figure 2.9: The Shunt DC Motor Model

2.4.5 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 2.10. Common uses of the compound DC motor include elevators, air compressors, conveyors, presses and shears [1, 2].

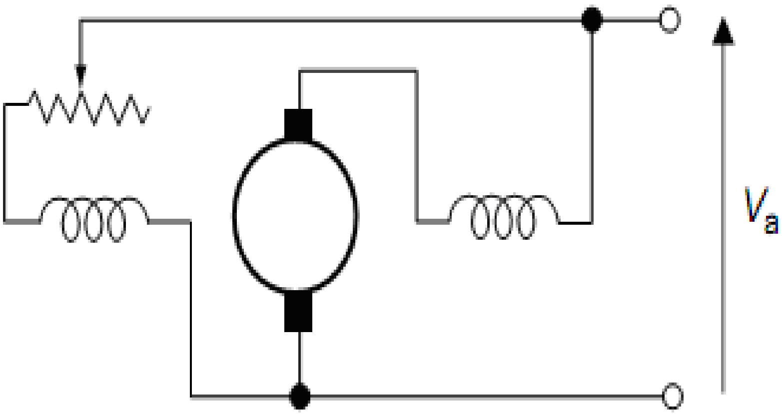

Figure 2.10: The Compound DC Motor Model

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 [1, 2]:

$$\omega = \frac{V_a - R_a i_a}{\phi K_b} \tag{2.3}$$

On the right hand side of the Equation (2.3) 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].

2.6 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 2.6. The main objective is to control the speed of the separately excited DC motor by armature voltage control [1, 2].

2.6.1 System Equations

From Figure 2.1, the dynamics of a separately excited DC motor may be expressed as [1, 2]:

$$\begin{aligned} V_a &= R_a i_a + L_a \frac{di_a}{dt} + E_b \\ V_a &= R_a i_a + L_a \frac{di_a}{dt} + K_b \omega \end{aligned} \tag{2.4}$$

$$\mathrm{T} = K_T i_a = \mathrm{J}\frac{\mathrm{d}\omega}{\mathrm{dt}} + B\omega \tag{2.5}$$

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.

2.6.2 Transfer function

Applying Laplace transform to Equation (2.4) and Equation (2.5), we have:

$$V_a(s) - K_b \omega(s) = \left(R_a + sL_a\right) I_a(s) \tag{2.6}$$

$$\begin{aligned} \mathrm{I}_a(\mathrm{s}) &= \left(\mathrm{Js} + B\right)\omega(s) \\ \mathrm{I}_a(\mathrm{s}) &= \frac{\left(\mathrm{Js} + B\right)\omega(s)}{K_T} \end{aligned} \tag{2.7}$$

Substitute Equation (2.7) into Equation (2.6), we get the transfer function of SEDC as:

$$V_a(s) - K_b\omega(s) = (R_a + sL_a)\left(\frac{(\mathrm{J}s + B)\omega(s)}{K_T}\right)$$

$$K_T V_a(s) - K_T K_b \omega(s) = \left[(R_a + sL_a)(\mathrm{J}s + B)\right]\omega(s)$$

$$K_T V_a(s) = \left[(R_a + sL_a)(\mathrm{J}s + B)\right]\omega(s) + K_T K_b \omega(s) \tag{2.8}$$

$$K_T V_a(s) = \left[(R_a + sL_a)(\mathrm{J}s + B) + K_T K_b\right]\omega(s)$$

$$\frac{\omega(s)}{V_a(s)} = \frac{K_T}{(R_a + sL_a)(\mathrm{J}s + B) + K_T K_b}$$

The block diagram of SEDC motor model is shown in Figure

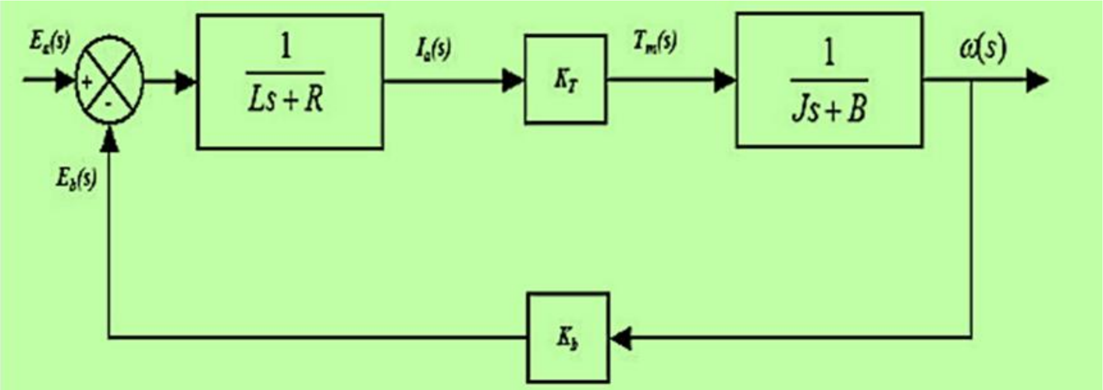

Figure 2.11: Block diagram SEDC motor model

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

Table 2.1: Parameters of the separately excited DC motor

Parameter	Description	Value
R_a	Armature Resistance	2.518Ω
L_a	Armature Inductance	0.028H
J	Moment of Inertia	0.003kgm^2/s^2
B	Viscous Friction Coefficient	0.0005Nms
K_T	Toque Constant	0.0924Nm/A
K_b	Back EMF Constant	0.0924Vs/rad

CHAPTER THREE

CONTROL SYSTEM DESIGN OF DC MOTOR

3.1 Introduction

In the past decades, modern control theories have made great advances. Control techniques including optimal control, fuzzy control, neural network control, predictive control, and so on, have been developed significantly. Nevertheless, the conventional PID controller has still been widely utilized in many industrial applications such as process control, motor drives, flight control. This is mainly because classical PID controllers have simple structure to be easily understood by engineers, and easiness to design and implement. However, it has been known that ordinary PID controllers generally do not work well for non-linear systems, and particularly complex and vague systems that have no precise mathematical models [3]. A simplified block diagram of the speed control of the SEDC motor using PID or FOPID controller is shown in Figure 3.2. Where ω_{ref} is the reference rotor angular speed, ω_r is the actual speed and $e=\omega_{ref}-\omega_r$ is the tracking speed error.

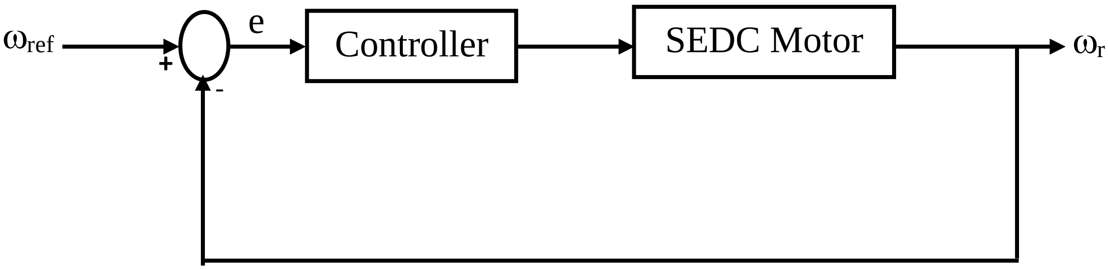

Figure 3.1: A simplified block diagram of the speed control of the SEDC motor using a controller

3.2 PID Controller

A proportional–integral–derivative controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A

PID is the most commonly used feedback controller. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. In the absence of knowledge of the underlying process, PID controllers are the best controllers. However, for best performance, the PID parameters used in the calculation must be tuned according to the nature of the system, while the design is generic; the parameters depend on the specific system. Figure 3.2 shows structural of the PID controller [3].

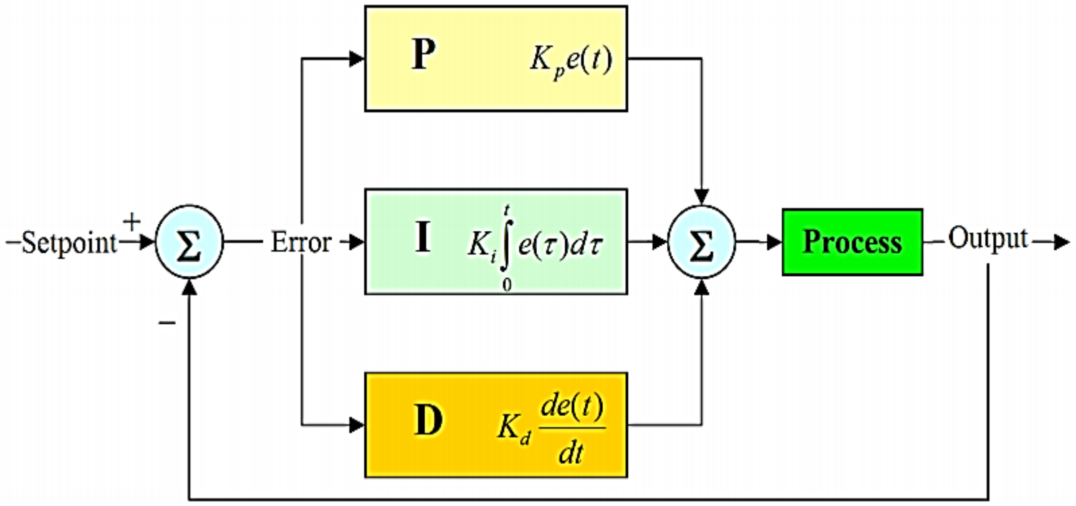

Figure 3.2: Structural of PID controller

The PID controller calculation (algorithm) involves three separate parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements [3].

The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability. Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, or P controller in the absence of the respective control actions. The differential equation of a conventional proportional-integral-derivative controller is given by [3]:

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \tag{3.1}$$

Where e(t) is the error signal and u(t) is controller's output. The parameters K_P, K_I, and K_D are the proportional, integral and derivative gains of the conventional PID controller, respectively. K_P, K_I, and K_D parameters usually take positive values. The transfer function of a classical PID controller is expressed as follows [6-8]:

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{3.2}$$

The desired closed loop dynamics is obtained by adjusting the three parameters K_P, K_I and K_D.

3.2.1 Proportional term

The proportional term (sometimes called gain) makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant (K_P), called the proportional gain. The proportional term is given by:

$$P_{out} = K_p e(t) \tag{3.3}$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive (or sensitive) controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. In the absence of disturbances, pure proportional control will not settle at its target value, but will retain a steady state error (known as droop) that is a function of the proportional gain and the process gain.

Specifically, if the process gain – the long-term drift in the absence of control, such as cooling of a furnace towards room temperature – is denoted by G and assumed to be approximately constant in the error, then the droop is when this constant gain equals the Proportional term of the output, P_{out}, which is linear in the error, $G = K_p e$, so $e = G / K_p$. This is when the proportional term, which is pushing the parameter towards the set point, is exactly offset by the process gain, which is pulling the parameter away from the set point. If the process gain is down, as in cooling, then the steady state will be below the set point, hence the term "droop". Only the drift component (long-term average, zero-frequency component) of process gain matters for the droop – regular or random fluctuations above or below the drift cancel out. The process gain may change over time or in the presence of external changes, for example if room temperature changes, cooling may be faster or slower.

Droop is proportional to process gain and inversely proportional to proportional gain, and is an inevitable defect of purely proportional control. Droop can be mitigated by adding a bias term (setting the set point above the true desired value), or corrected by adding an integration term (in a PI or PID controller), which effectively computes a bias adaptively. Despite the droop, both tuning theory and industrial practice indicate that it is the proportional term that should contribute the bulk of the output change [3].

3.2.2 Integral term

The contribution from the integral term (sometimes called reset) is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain (K_I). The integral term is given by:

$$I_{out} = K_i \int_0^t e(\tau)\, d\tau \tag{3.4}$$

The integral term (when added to the proportional term) accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the set point value (cross over the set point and then create a deviation in the other direction). For further notes regarding integral gain tuning and controller stability, see the section on loop tuning [3].

3.2.3 Derivative term

The rate of change of the process error is calculated by determining the slope of the error over time (i.e., its first derivative with respect to time) and multiplying this rate of change by the derivative gain (K_D). The magnitude of the contribution of the derivative term (sometimes called rate) to the overall control action is termed the derivative gain. The derivative term is given by:

$$D_{out} = K_D \frac{d}{dt} e(t) \tag{3.5}$$

The derivative noticeable close term slows the rate of change of the controller output and this effect is most to the controller set point. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability However, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large. Hence an approximation to a differentiator with a limited bandwidth is more commonly used. Such a circuit is known as a Phase-Lead compensator.

3.3 Fractional Calculus

The history of the Fractional Calculus (FC) covers over three hundred years, similar to that of classical differential calculus. In last two decades, the FC has become much popular among the researchers of different streams. Fractional calculus was not much popular earlier because of its highly complex mathematical expressions. But with the development of computational technologies it has become possible to deal with fractional calculus. Fractional calculus is an extension of integer order calculus in which ordinary differential equations have been replaced by fractional order differential equations. In fractional order differential equations, derivatives and integrals are not necessarily of integer order and they span a wider range of differential equations. Fractional calculus deals with fractional integration and differentiation. Therefore, a generalized differential and integral operator has been introduced as a single fundamental operator represented by ${}_aD_t^{\delta}$ where a and t denote the two integration limits related to the operation of the fractional differentiation, and δ is the order of fractional differentiation or integration. Positive δ indicates differentiation and negative δ indicates integration. The continuous integro-differential operator (D) is defined as follows [4]:

$$ {}_aD_t^{\delta} = \begin{cases} \dfrac{d^{\delta}}{dt^{\delta}}; & \delta>0 \\ 1; & \delta=0 \\ \int_a^t (d\tau)^{-\delta}; & \delta<0 \end{cases} \tag{3.6} $$

There are several definitions of fractional order integration and differentiation. Some of the definitions extend directly from integer order calculus. The most often used are Riemann Liouville (RL) definition and Grunwald-Letnikov (GL) definition. Recently the concept of FC is widely introduced in many areas in science and engineering.

3.4 FOPID Controller

Fractional Order Control (FOC) means controlled systems and/or controllers described by fractional order differential equations. Recently, there are increasing interests to enhance the performance of ordinary PID controller by using the concept of fractional calculus, where the orders of derivatives and integrals are non-integer. The idea of fractional order controller was first proposed by A. Oustaloup through Commande Robuste d’Ordre Non Entier (CRONE) controller in 1991. Later on, Igor Podlubny had initiated the most common form of fractional order PID in the form of $PI^{\lambda}D^{\mu}$ in 1999 involving an integrator of order λ and differentiator of order μ, where the values of λ and μ lie between 0 and 1. Clearly, depending on the values of the orders λ and μ, the numerous choices for the controller's type can be made. He also demonstrated that the response of this type of controller is better as compared to the classical PID controller. One of the most important advantages of the FOPID controller is the better control of dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the FOPID controllers are less sensitive to changes of parameters of a controlled system. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a fractional order control system.

However, up till now there is no systematic way to set the value for λ and μ. The fractional integro-differential equation of the FOPID controller is given by [5]:

$$u(t) = K_P e(t) + K_I D_t^{-\lambda} e(t) + K_D D_t^{\mu} e(t) \tag{3.7}$$

The transfer function of the FOPID controller is obtained through Laplace transform as follows:

$$G_{FOPID}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \tag{3.8}$$

Or:

$$G_{FOPID}(s) = \frac{U(s)}{E(s)} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \tag{3.9}$$

Where E(s) is an error and U(s) is controller's output. It is obvious that the fractional order PID controller not only needs design three parameters K_P, K_I, and K_D, but also design two orders λ and μ of integral and derivative controllers. Figure 3.3 shows the block diagram configuration of the FOPID controller [5].

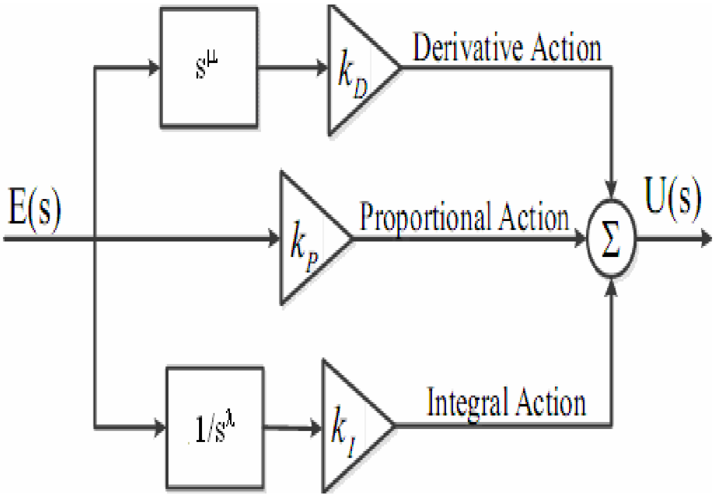

Figure 3.3: Block diagram of the FOPID controller

In Equation (3.8), s^λ and s^μ have fractional orders which are not directly compatible with MATLAB software and it becomes difficult to realize hardware of the FOPID controller. Therefore, there are several integer order approximation methods available for fractional order elements. In MATLAB fractional order PID controller is implemented using FOMCON toolbox where Oustaloup's approximation is realized [6]. Figure 3.4 depicts the FOPID controller and explains how the order of the integrator and the order of the differentiator can vary versus the horizontal and vertical axis. As shown in Figure 3.4, the fractional order PID controller generalizes the ordinary integer order PID controller and expands it from point to plane. This expansion could provide much more flexibility in ordinary PID controller design. Point (0, 0) corresponds to P controller, point (0, 1) corresponds to ordinary PD controller, point (1, 0) corresponds to ordinary PI controller and point (1, 1) corresponds to ordinary PID controller, where as the shaded portion between four corners represent the FOPID controllers. Evidently, all these classical types of PID controllers are special cases of the FOPID controller, when the values of λ and μ are integer values of 0 or 1 [5].

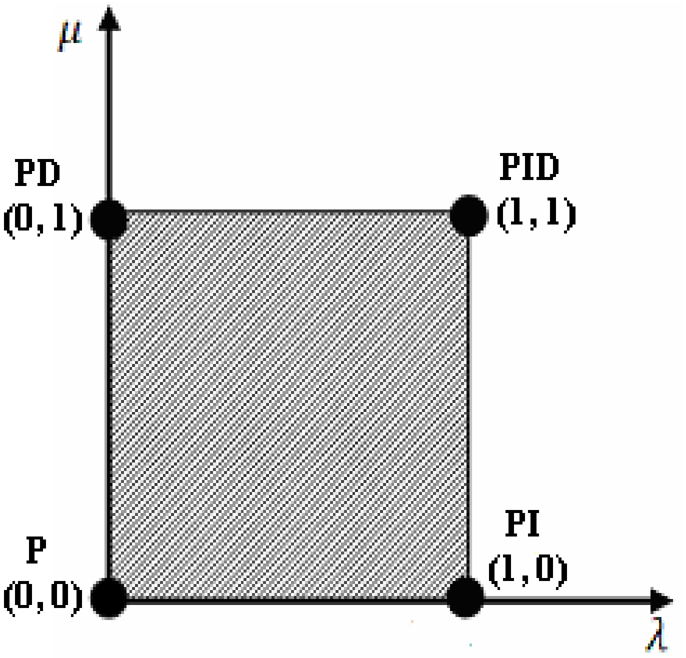

Figure 3.4: Pictorial representation of the FOPID controller

3.4 Controller Tuning Methods

Tuning controller is adjusted of its parameter gains to the optimum values for the desired control response. There are several methods for tuning controller; the traditional manual method for loop tuning is used in this project [3].

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results and Discussion

This section shows the simulation results of speed control of the separately excited direct current motor using FOPID controller and traditional PID controller. Simulation results are performed by MATLAB/SIMULINK software to compare the performances of both controllers under several operating scenarios. Simulation tests are based on the facts that whether the FOPID controller is better performance and more robust than the traditional PID controller or not. Figure 4.1 shows the MATLAB/SIMULINK overall model of speed control of the separately excited DC motor using fractional order PID controller and classical PID controller.

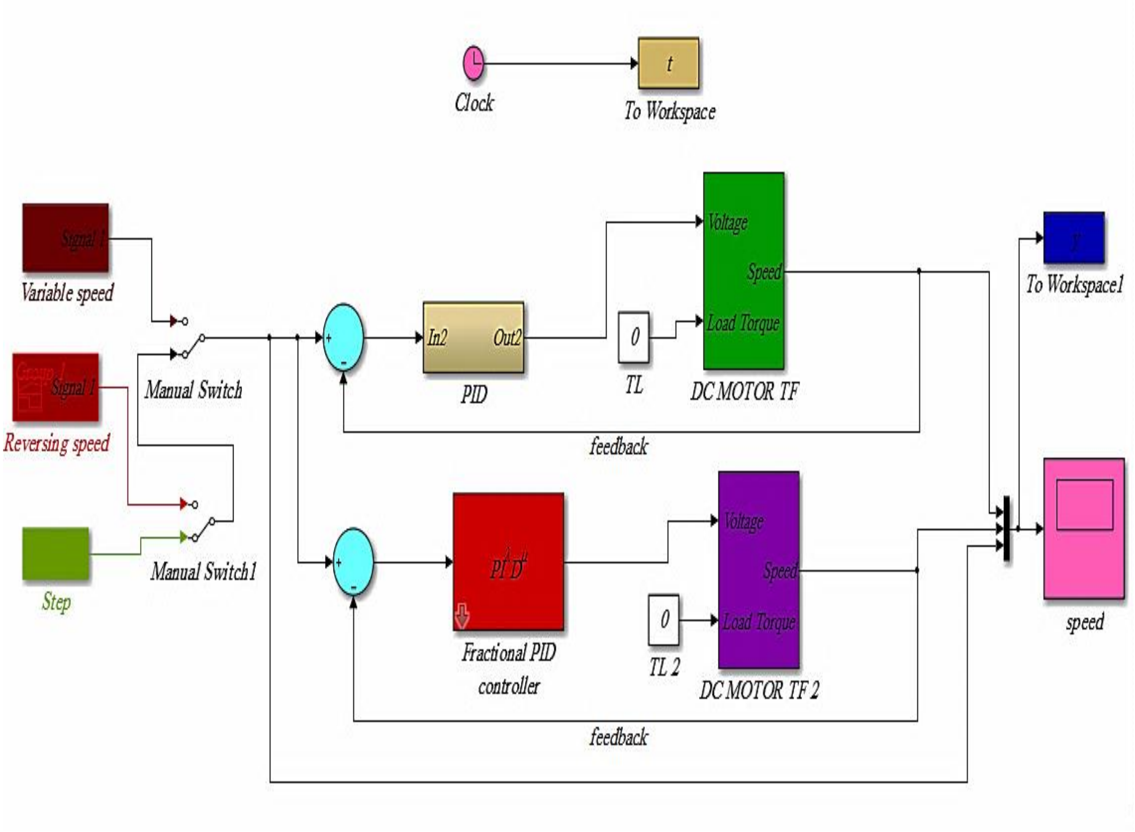

Figure 4.1: MATLAB/SIMULINK overall model of speed control of SEDC motor using FOPID and PID controllers

4.2 Constant Speed

To test the performance of the speed control of SEDC motor drive at a constant speed without any load torque. The SEDC motor drive is started up from stand still to trace the speed command of 10rad/sec. Figure 4.2 gives the speed responses of the separately excited DC motor drive with FOPID controller and ordinary PID controller.

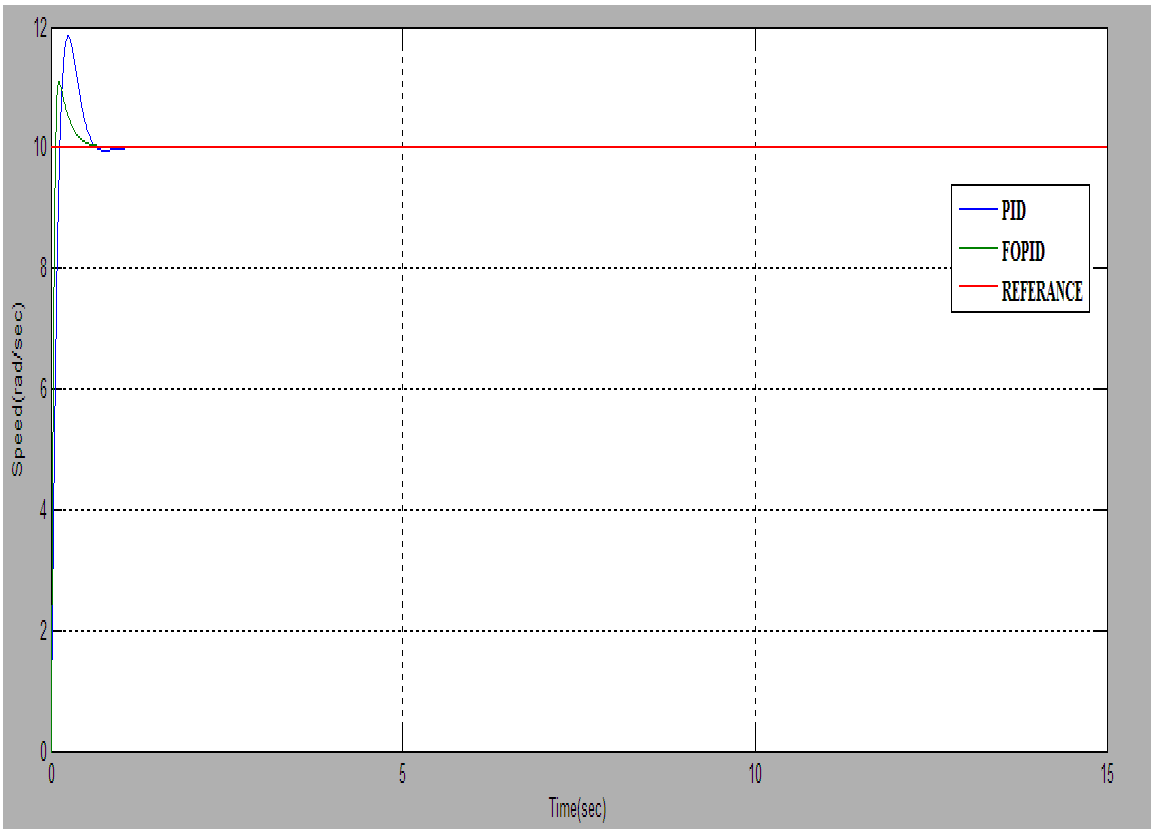

Figure 4.2: Step Response of SEDC using Ordinary PID and FOPID Controllers

In terms of the speed control trajectories shown in Figure 4.2, 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 4.2 it can be easily observed that the speed response of the separately excited direct current motor drive with FOPID controller shows less value of overshoot as observed in comparison to the classical PID controller thus reducing the settling time. Furthermore, the rise time for FOPID controller is smallest value than for traditional PID controller.

4.3 Variable Speed

For the checking of robustness, the separately excited direct current motor drive was tested by applying step changes in command speed at regular interval without load torque. The separately excited direct current motor drive is initially started from standstill to trace the speed of 5rad/sec, 15rad/sec and 10rad/sec respectively at a regular interval of 5sec. Figure 4.3 shows the speed response for a stepped speed reference for FOPID and standard PID controllers.

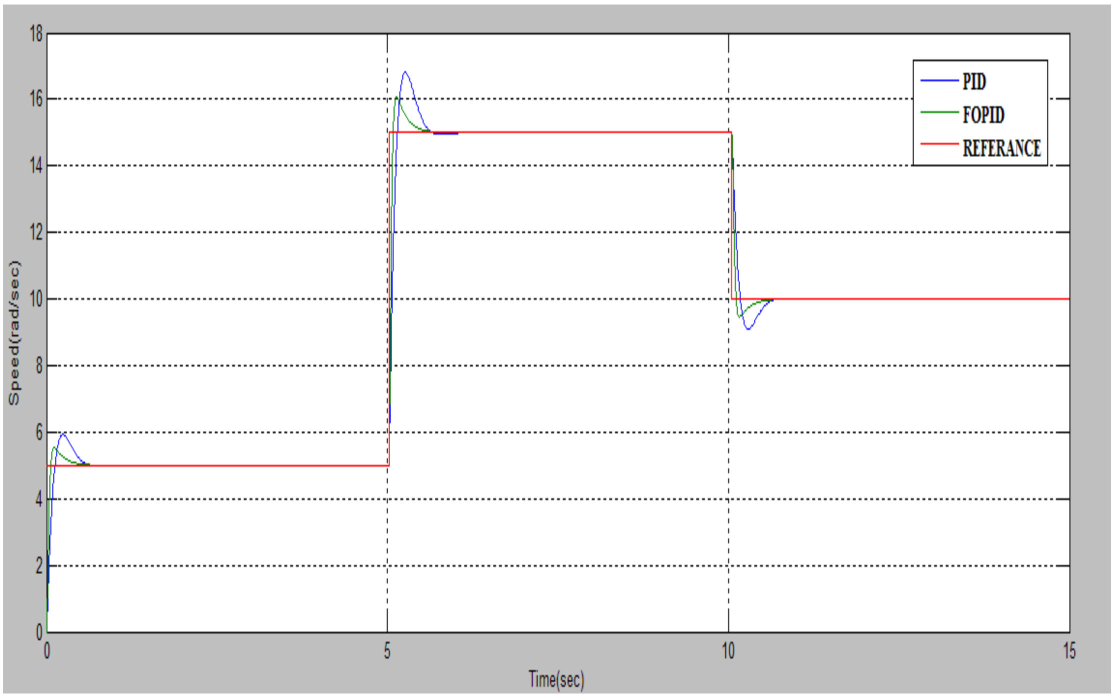

Figure 4.3: Simulation result at variable speed

It can be evident from the response graph shown in Figure 4.3 that FOPID controller gives better performance in comparison to ordinary PID controller. Furthermore, when carefully study Figure 4.3 according to time domain specifications such as settling time, rise time and overshoot, the best performance belongs to FOPID controller.

4.4 Inversion of the Speed

Figure 4.4 presents the simulation result obtained for speed inverting from 15rad/s to -15rad/s under no torque load. When the speed is inverted, the response of the SEDC motor shows overshoot and undershoot in case of ordinary PID controller whereas in FOPID controller speed settles smoothly without any remarkable overshoot and undershoot. In addition, the settling time and rise time for FOPID controller is shorter than for conventional PID controller.

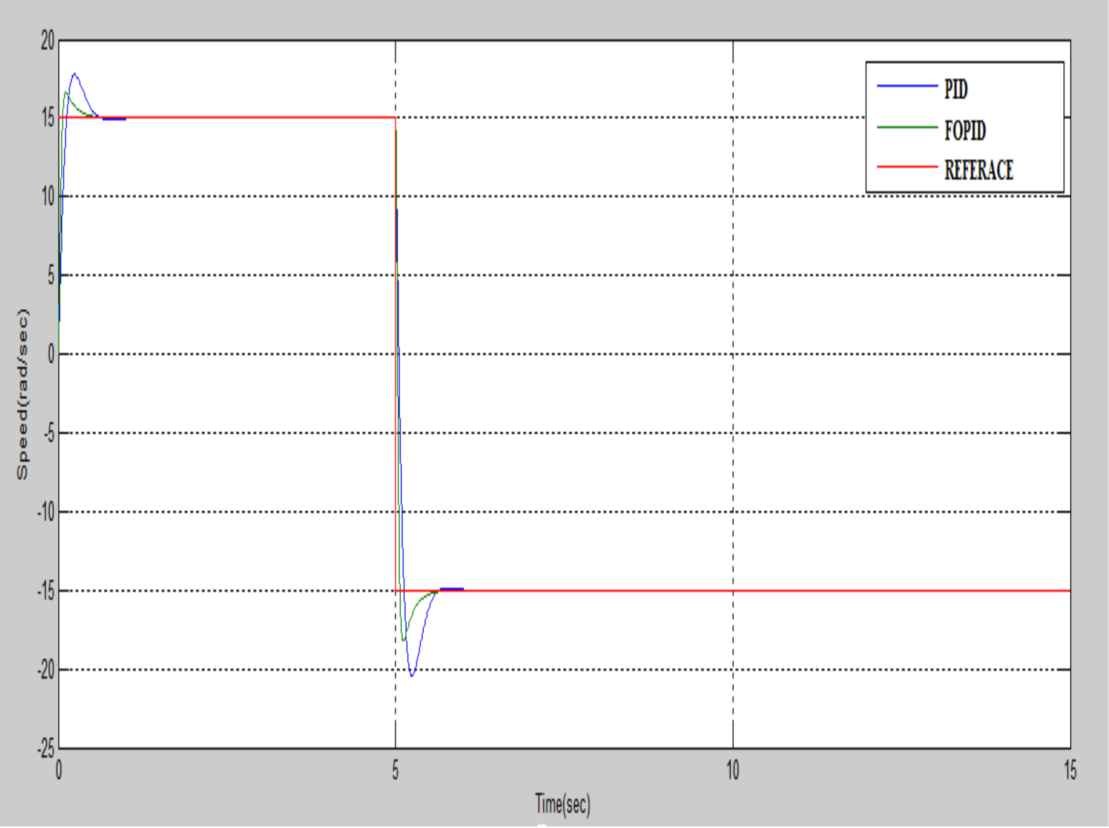

Figure 4.4: Speed Responses of FOPID and Ordinary PID Controllers with Reversing Speed

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 PID controller.

In spite of the major features of the classical PID 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 FOPID controller is proposed to solve the some disadvantages of the conventional PID 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 FOPID controller provide important advantages over the traditional PID controller like limiting the overshoot in speed, thus the starting current overshoot can be reduced. In addition, the settling time and rise time for FOPID controller is shorter than for conventional PID 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 FOPID controller and fuzzy logic control.
2. It would be useful to further compare between FOPID controller and neural network schemes for speed control of DC motor.
3. It would be useful to further compare between FOPID controller and sliding mode control.

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