NONLINEAR PID CONTROL OF A FACTORY BELT DRIVE SYSTEM

Solomon Asayehegn wassu

A Thesis Submitted to

Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Master of Science Degree in Electrical Power and Control Engineering (Specialization in Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this Master Thesis entitled "Nonlinear PID Control of a Belt Drive System with VFD In Kesem Sugar Factory" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Solomon Asayehegn	______________________	_____________
Name of the student	Signature	Date

RECOMMENDATION

I, the advisor of the thesis, hereby certify that I have read the revised version of the thesis entitled "Nonlinear PID Control of a Belt Drive System with VFD In Kesem Sugar Factory" prepared under my guidance by Solomon submitted in partial fulfillment of the requirements for the degree of Master of Science in Control Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Prof. Gang Gyoo Jin ____________________ __________

Advisor Signature Date

APPROVAL PAGE

I, the advisor of the thesis entitled "Nonlinear PID Control of a Belt Drive System In Kesem Sugar Factory" and developed by Solomon Asayehegn, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Prof. Gang Gyoo Jin		
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Solomon Asayehegn have read and evaluated the thesis entitled "Nonlinear PID Control of a Belt Drive System in Kesem Sugar Factory." and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Control Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
Dr Beteley Teka		Sept 26, 2024
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis are contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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School Dean	Signature	Date
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LIST OF ACRONYMS

BDCS	Belt Drive Conveyor Systems
BLDC	Brushless DC
DC	Direct Current
DCS	Distribution Control System
FOPID	Fractional-Order Proportional-Integral-Derivative
GAs	Genetic Algorithms
IAE	Integral Absolute Error
IAEU	Integral Absolute Error and Control Signal
IM	Induction Motor
ISE	Integral Square Error
ITAE	Integral Time Absolute Error
ITSE	Integral Time Square Error
NPID	Nonlinear Proportional-Integrate-Derivative
PID	Proportional-Integral-Derivative
PMDC	Permanent Magnet DC
PMSMs	Permanent Magnet Synchronous Motor
PWM	Pulse Wave Modulation

ABSTRACT

Belt drive systems offer a versatile solution for positioning motors relative to loads, reducing conveyor inertia and enabling quick responses in robotic applications. However, their flexible dynamics can compromise positioning accuracy. This trade-off between control simplicity and precision arises from the challenges of rejecting time-varying disturbances caused by belt flexibility and mitigating system resonance. To address these issues, this paper presents a comprehensive model of a belt drive conveyor system, incorporating a detailed DC motor model and a realistic friction model. This enhanced model is expected to improve the positioning accuracy of the belt-driven mechanism. High-capacity belt conveyors are essential for efficient bagasse transport in open-pit operations to meet boiler demands. This paper investigates such a conveyor system, including its structure and performance evaluation. The conveyor is driven by a DC motor, and a simulation model of the motor-drive assembly is developed to analyze transient behaviors like starting, speed adjustment, and braking. Belt drives have a long history in this industry but present significant challenges due to slippage, tension variations, and belt-pulley interactions, leading to nonlinear behavior, large vibrations, and complex contact dynamics. These issues are exacerbated in the Kassem sugar factory's belt drive system, which suffers from slow response and poor tracking accuracy due to the existing DCS control with simple ON/OFF mechanisms. Effective motion control for belt drives is crucial across various industries and is influenced by these factors.

Keywords: Belt-drive system, nonlinearities modeling, tracking control, NPID control

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Belt drives are extensively used in different fields of mortal exertion to transmit the mechanical energy from the rotating shaft to the objects of the control. There are numerous exemplifications of belt drives perpetration in our life similar as buses, audio and videotape bias, computer bias, etc. In assiduity similar drives can be used for objects control positioning (for case, precise positioning of electronic chips on circuit plates) or transportation (for illustration, conveyors)

Historically belt system has been used to transmit power at up to 98% efficiency between rotational machine elements. Typical application for such system is a conveyor, the first prototype of which has been used since 19th century. Moreover, already in 1913 Henry Ford introduced the first conveyor belt-based assembly line in Ford Motor Company's factory. Nowadays, belt drive systems are widely spread in automotive industry and in conveyor type application (Selezneva, 2007).

For high precision applications using of belt has become appropriate because of rapid development of motor and drive technology as well as the implementation of timing belts in belt-driven systems. Toothed or timing belts with correct tension exclude slippage and increase the precision of motion. As a result, the use of belts in drives has caused a number of advantages. Systems can provide high speed and acceleration, accurate and repeatable motion, high efficiency, long stroke lengths and low cost.

1.2 statement of problem

The primary challenge I encountered at Kessem Sugar Factory was the inadequate speed and position control of the belt drive system feeding bagasse to the boiler combustion chamber. The boiler, often referred to as the factory's heart, generates 75 m^3 of dry steam at 64 bar pressure per hour using bagasse, water, and heated air. The energy released from burning bagasse converts water into steam.

Bagasse, the fibrous residue from sugarcane milling, is the primary fuel for the boiler. It's transported from the final mill to the boiler furnace via the belt drive system. The generated steam powers the turbine, producing electricity. However, the current system only allows for start and stop operations, lacking the precision control needed to regulate speed and position.

As a result, bagasse is frequently lost during transport due to inaccurate position control. Additionally, the inconsistent speed of the belt, caused by the absence of a control mechanism, affects the boiler's performance. Further complicating the issue, the belt's friction and elasticity lead to nonlinear deformations. Overall, the existing control system is insufficient for optimal operation.

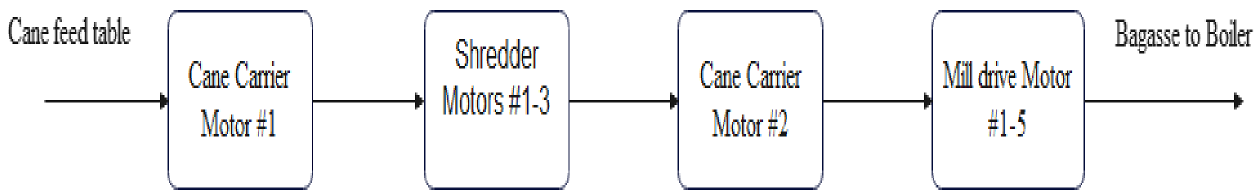


Figure 1.1 Belt drive system in Kassem sugar factory bagasse from mill house to boiler house

1.3 Objectives of the Study

1.3.1 General Objectives

The primary objective of this thesis is to obtain the model of the belt drive system in Kesem Sugar Industry and design a nonlinear PID controller for speed control.

1.3.2 Specific Objectives

- Obtain the model of the belt drive system in Kesem sugar.
- Design an NPID controller for accurate speed control of the belt drive system
- Optimize the controller parameters and get the system responses by reducing settling time, rise time, peak time, and overshoot.
- Analyze the performance of the overall NPID controlled system

1.4 Scope and Limitation of the thesis

This research focuses on modeling and simulating the performance of a Nonlinear PID controller applied to a belt drive system within the Kesem Sugar Factory, using MATLAB® 2021a as the simulation platform

1.5 The Motivation of the Study

The belt drive's noncontact technology offers significant benefits over traditional bagasse transportation methods. To optimize this advanced system, this research investigates the design and implementation of a Nonlinear PID controller for the belt drive system at Kesem Sugar Factory.

1.4 Scope of the study

The thesis will focus on modeling of DC motor drive system mechanism and assess the efficacy of various DC motor drive techniques, with particular emphasis on speed control using the NPID controller.

1.6 Significance of The Study

To save the power of the generation turbine and smooth the plant operation in Kesem sugar factory, wastage of bagasse minimized and continuous product improved.

1.7 Organization of the Thesis

This thesis is organized as follows.

Chapter one: introduces the background of the Belt drives system. It also includes the detailed objective, statement of problem, scope, limitation, motivation, and significance of the thesis.

Chapter two: discusses about the theoretical background and related works on the control of Belt drives system and its controller.

Chapter three: deals with the methodology followed and the mathematical model of the DC motor system. develop PID and NPID control strategies to adjust the proposed controller parameters.

Chapter four: the simulation results and detailed analysis of the results are presented in this chapter.

Finally: provides the conclusion and recommendation for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

A belt conveyor is a transportation system that uses a continuous loop of flexible material to move items between locations. Unlike other conveyor types relying on chains, spirals, or hydraulics, belt conveyors employ an endless belt running over rollers. Powered by an electric motor, this simple yet efficient mechanism can transport a wide range of materials, products, and even people.

2.2 Review of related work

Belt Drive Conveyor Systems (BDCS) are prevalent power transmission systems that convert electrical energy into mechanical motion. Widely utilized across industries such as agriculture, power generation, robotics, and textiles, BDCS offer advantages including simplicity, lightweight design, affordability, and flexible motor placement. However, precision control of BDCS is hindered by challenges like nonlinear friction, vibration, and belt flexibility, which can negatively impact system reliability. To overcome these limitations, researchers have developed control algorithms aimed at reducing vibration and enhancing system performance in uncertain conditions. The work of Katsioula et al. in 2018 exemplifies this research direction.

Existing belt conveyor control methods often result in rapid speed adjustments, leading to belt tearing and slippage. This paper proposes a speed control method that accounts for the conveyor's elastic properties. By incorporating elastic constraints into the control system, the method analyzes the speed regulation process and employs a PID controller to maintain the desired speed. Experimental results demonstrate reduced energy consumption, decreased wear on conveyor components, and extended conveyor lifespan (Yan et al., 2019).

In the works of Belyaev et al. (2017), a looped drive belt on identical pulleys was modeled as a Caserta rod, considering geometric nonlinearity, tension, and transverse shear. Assuming rigid, frictionless pulleys, the problem was simplified by analyzing a quarter of the belt, divided into free and contact sections. A dimensionless material coordinate transformed the system into a ninth-order differential equation, numerically solved using shooting and finite difference methods. The model calculated belt shape, forces, moments, and contact pressure, revealing a gradual increase in pressure toward the contact area end without concentrated force development.

Belyaev et al. (2018) investigated a looped belt encircling two identical pulleys under the influence of gravity. Employing a geometrically nonlinear model incorporating tension and transverse shear, the belt was modeled, while the pulleys were considered rigid bodies with frictionless contact. Exploiting the system's symmetry, the problem was reduced to analyzing a belt half, comprising two free spans and a contact segment. A dimensionless material coordinate transformed the system into a set of ordinary differential equations, solved numerically using the finite difference method. The model determined belt shape, forces, moments, and contact pressure, revealing increasing pressure near contact area endpoints without concentrated force formation. The study also analyzed gravity's impact on contact pressure.

Stogl et al. (2017) address the challenge of robustly grasping unknown objects from moving conveyor belts in industrial settings. Their approach combines an external depth sensor and an industrial robot to track, reconstruct, and grasp objects. The system includes algorithms for estimating object position, velocity, and shape, as well as conveyor path prediction and robot interception trajectory calculation. While designed for rotationally symmetric objects, the reconstruction algorithm can identify asymmetric features and detect hollowness, aiding grasp planning. A 3D object mesh is generated for precise grasping, and the robot's interception and grasping trajectory is calculated in real-time. Successful grasping was demonstrated for conveyor speeds exceeding 10 cm/s.

Recent studies on belt drive systems have identified limitations in predictive maintenance and fault detection. Manual condition assessments often require production halts, leading to costly downtime. Additionally, while vibration analysis can help predict faults, current methods are still evolving and may not be reliable under all operating conditions (Pollak et al., 2021).

In Velmurugan et al.(2014), a conveyor belt is a continuous loop of material that travels around two or more pulleys. One or both pulleys are powered to move the belt forward, carrying materials with it. The powered pulley is called the drive pulley, while the unpowered one is the idler.

A key constraint lies in the mechanical performance of belts during operation. Belt systems are susceptible to wear, slippage, and unpredictable dynamic loads caused by environmental fluctuations and varying workloads. These factors can lead to fatigue and premature failure, especially in high-demand applications where precision and reliability are paramount(Control Techniques, n.d.).

There are two primary industrial applications for conveyor belts: general material handling and bulk material handling. General material handling involves transporting items like boxes within factories, while bulk material handling focuses on moving large quantities of materials such as grain, coal, or ore, often in outdoor environments. These two industries typically have separate suppliers. Additionally, conveyor belts are used in various commercial settings, such as grocery stores. Conveyor belts are composed of one or more layers of material, commonly rubber. Many general material handling belts have a two-layer structure: a carcass for strength and shape, usually made of cotton or plastic, and a cover for durability, often made of rubber or plastic compounds. For specialized applications, covers can be constructed from materials like silicone for heat resistance or gum rubber for enhanced traction.

Despite advancements in design optimization techniques, achieving a balance between vibration suppression, energy efficiency, and durability in belt drive systems, particularly in multidisciplinary applications, remains a significant challenge(Yuan et al., 2018).

In Udgave & Khot (2014), conveyor systems are mechanical devices that transport materials between locations. Widely used in industries like chemicals, manufacturing, automotive, mining, pharmaceuticals, and electronics, they enhance efficiency and productivity. Conveyor types include gravity roller, belt, slat, bucket, flexible, belt-driven live roller, and chain conveyors. The optimal choice depends on factors such as material volume, speed, size, weight, distance, material properties, and production method. Material handling equipment ranges from manual to fully automated systems, with the level of automation determined by specific handling needs. Material handling encompasses the movement of materials within a manufacturing process, including loading, transporting, and unloading. A slat conveyor utilizes open chain links to drag material along the bottom of a fixed mild steel or stainless-steel trough. The conveyor's mechanical components, called slats, are attached between two chain strands and move along the trough. Available in various widths and lengths, slats create a small gap with the trough. Slat conveyors are designed for horizontal and inclined transportation of materials like sawdust, chips, and bagasse. Traditionally, they are the primary method for distributing bagasse to boilers.

(Shamseldin et al., 2018) introduces an enhanced nonlinear PID (NPID) controller designed to accurately track predefined speed profiles for brushless DC motor drive systems. The controller's performance is robust against parameter variations and external disturbances. To evaluate its effectiveness, we compare the NPID with traditional linear PID and fractional-order PID (FOPID) controllers in both speed regulation and tracking scenarios. Optimal parameters for each controller were determined using a Genetic Algorithm based on a specific cost function. Our results demonstrate that the proposed NPID controller outperforms both PID and FOPID controllers.

PID controllers have been a staple in industrial process control for decades due to their simplicity and effective performance, especially for slower systems. While capable of achieving low overshoot and short settling times, their performance can be further refined through the incorporation of fractional-order derivatives and integrals.

In the works of (Muhammad Shahid | Md Ghaysuddin, 2019) a mathematical model of a bagasse belt conveyor line driven by a DC motor was developed based on fundamental physical principles. To address the issue of production line speed and process desynchronization, a PID controller with an N-order filter was designed and implemented as a speed synchronizer. The controller's parameters were carefully selected to accommodate system uncertainties. The results demonstrate successful synchronization of conveyor line speed with empty and full bagasse inspection unit speeds. Conveyor systems are essential for efficient material handling, transporting various materials quickly and effectively between locations. Their widespread use in industries such as manufacturing and packaging is due to their versatility. Chain conveyors, a common type, are available in floor and overhead configurations and utilize enclosed tracks, I-beams, towlines, or power and free trolleys.

Belt conveyor systems are critical components in the manufacturing of a wide range of products, including automobiles, electronics, and computers. Their speed, reliability, and accuracy make them indispensable in modern industrial processes. Conveyor systems transport products between processing stations, where machines perform specific operations. However, improper product positioning can lead to product damage, accidents, and production inefficiencies. This study addresses these challenges by developing a mathematical model of the conveyor system, assessing its controllability, designing a PID controller, analyzing system stability, and validating the model through simulation (Chimezirim O. A, 2019).

DC motors are ubiquitous in modern control engineering. Many industrial applications rely on PID controllers to regulate motor speed or position. While conventional PID controllers excel in linear systems, most real-world systems exhibit nonlinearities that render them ineffective. The inability of standard PID controllers to adapt their gain parameters to counteract these nonlinearities is a significant limitation. Nonlinear PID controllers offer a solution by dynamically adjusting gain parameters to accommodate system variations, thereby improving overall performance(Chopra, 2012).

A nonlinear PID controller designed based on stability criteria is proposed. This approach significantly enhances the performance of traditional linear PID controllers by integrating a nonlinear gain element within the standard PID control structure.(Maddi et al., 2014).

The nonlinear process modelling and identification over its widespread operating region plays a dynamic role in controller performance and its design due to variation in operating condition from time to time. The multiple model technique evades these issues in nonlinear system modelling, which is formulated by splitting the entire operating region into different regions and then the local PID controller is tuned for each region(Manigandan, 2016).

Recent research has focused on enhancing traditional linear PID controllers through the incorporation of nonlinear elements. These Nonlinear PID (NPID) controllers vary widely based on how nonlinearities are applied. Previous studies have proposed NPID controllers using Gaussian error functions and genetic algorithms for parameter tuning, as well as controllers combining error, integral error, and time-based nonlinear gain functions to improve tracking and noise rejection. Others have introduced NPID controllers with nonlinear gains coupled to the integral term and tuning rules based on dimensional analysis and genetic algorithms. This paper presents a self-tuning controller incorporating an NPID function and a self-tuning mechanism to maintain optimal performance. The NPID component is implemented using a neural network emulating a previously proposed tuning rule. It consists of a linear PD term and a nonlinear I term with a nonlinear gain. Optimal parameters are determined using dimensional analysis and genetic algorithms. The self-tuning function identifies a process model, recommends controller parameters, and updates them based on operator input. The proposed method's effectiveness is evaluated across three different processes (Garbaabaa et al., 2020).

Proportional and derivative control actions respond directly to the error and its rate of change, respectively. Integral action addresses steady-state error by accumulating past errors. However, excessive integral action can lead to overshoot, integral windup, and reduced stability. To balance rapid response and steady-state accuracy, the integral action should be dynamically adjusted. This paper proposes a nonlinear PID controller that modifies only the integral term while retaining the linear proportional and derivative components. The integral action is scaled by a nonlinear function of the error to achieve the desired balance between transient and steady-state performance (Jin & Son, 2019).

2.3 Electrical Drives

Electric motors have undergone continuous development since their inception in the early 19th century, becoming integral to modern life. A vast array of motor types has emerged to serve countless applications in contemporary industry. This work focuses on servo drives, specifically designed for precise position control. An electrical servo system comprises a servomotor, power amplifier, sensors, and a control unit. Advanced closed-loop control systems enable servo drives to deliver exceptional dynamic performance and efficiency. These systems are poised to meet the demanding requirements of future applications(Zhu, n.d.).

The modern servo systems are characterized by the strong requirements for the next important properties.

- ✓ Positioning accuracy
- ✓ Speed accuracy
- ✓ Torque stability
- ✓ overload capability
- ✓ dynamic performance

Servo drives are essential components in a wide range of applications, including robotics, assembly lines, conveyors, elevators, and coordinate measuring machines. Despite the widespread use of electric motors, the demand for precise motion control continues to drive the growth of the servo drive market(Breaz et al., 2008).

A servo drive is composed of four primary components. Motor selection is a critical decision within servo system design. Numerous motor options exist, each with its own set of advantages and drawbacks. The chosen motor significantly influences the servo drive's characteristics, dictating the requirements for the power converter and controller. While many motor possibilities exist, only a select few possess the comprehensive capabilities necessary for the precise motion control demanded by machine tool applications.

- ✓ High speed-to-torque ratio
- ✓ Four-quadrant application
- ✓ Ability to produce a torque at a standstill.
- ✓ High power-to-weight ratio
- ✓ High system reliability

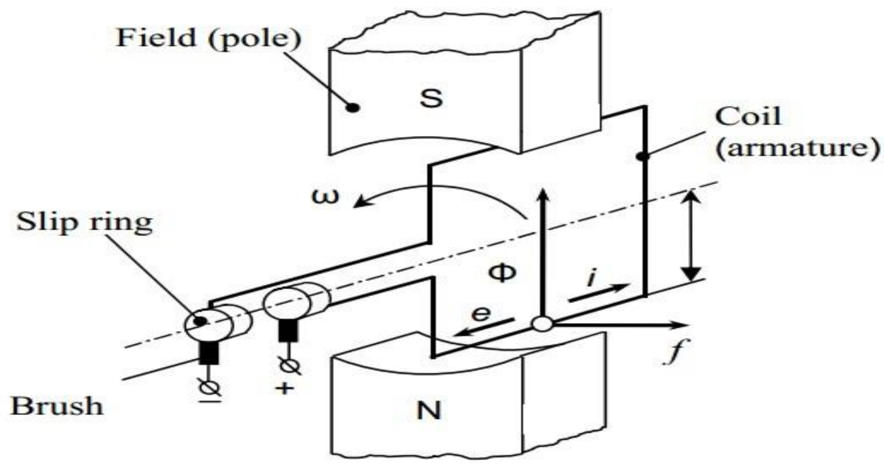
The following motor types can satisfy the criteria listed above and they are widely used in servo systems:

- ✓ Brushed DC motors
- ✓ Brushless DC motors
- ✓ Permanent magnet synchronous motors (PMSMs)
- ✓ Induction motors
- ✓ Stepper motors
- ✓ Linear motors

2.4 Motor types and motor selection criteria in belt drive system motion control

2.4.1 Brushed DC motor.

DC machine is the first practical device, which converts electrical power into the mechanical and vice versa in its generator mode. The simplest example of the DC motor is shown in Figure 2.1. In this case, the stationary magnetic flux Φ is produced by poles and when voltage is applied on the brushes, current flows through the armature and generates force *f* which forms torque and causes.



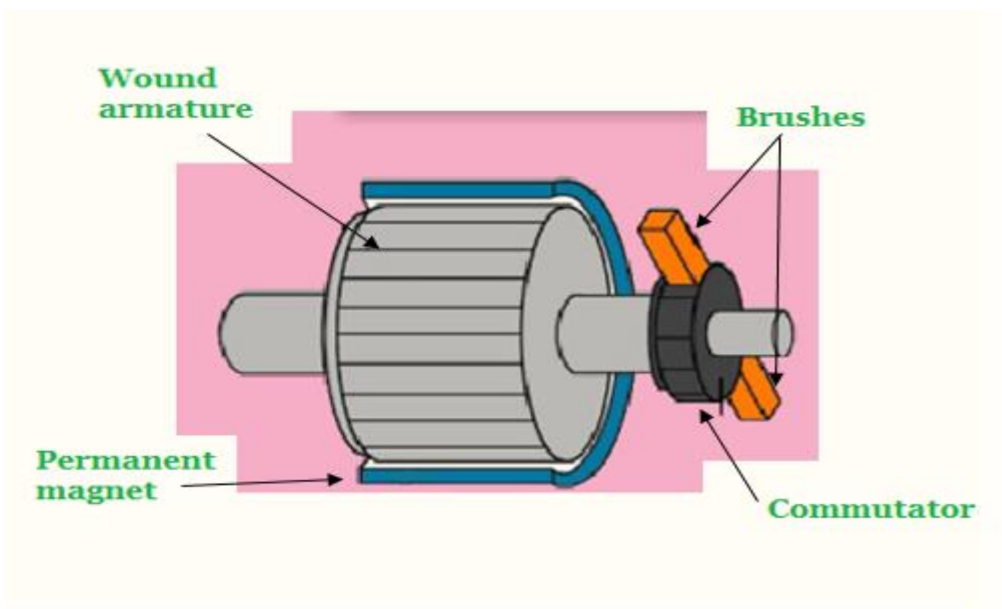


Figure 2.1 Figure 2.1 Brushed dc motor (Cros et al., 2001)

The reasons for widespread expansion of the DC motor in many types of industrial drive applications are good control characteristics (speed versus voltage and speed versus torque), good performance and high efficiency(Control Techniques, n.d.). Insite of rapid development of the lower-cost motors, advantages associated with inherent stability and relatively simple control of DC machine, are indisputable. In separately excited DC motors torque and thus also the speed can be controlled by armature current by adjusting the armature voltage. The field can be controlled by adjusting the excitation current of the separate magnetizing winding.

The flux and torque are therefore separately controllable. On this basic principle was built thyristor control for higher-power rating of drives used for printing and paper industry and chopper control for lower-power applications. Development in permanent magnet materials led to invention of permanent magnet DC motors (PMDC), in which the stator excitation windings were replaced by permanent magnets. Reasons for using PMDC are extremely linear speed-torque characteristics, small torque ripple at low speeds, absence of copper losses in excitation windings and small rotor diameter.

DC motors are not well-suited for applications demanding high reliability, extended service intervals, and low noise levels due to the inherent limitations of their commutator design. The mechanical and electrical constraints imposed by the commutator, coupled with the need for regular carbon brush maintenance, make them less ideal for these conditions(Cros et al., 2001).

Another limitation of DC motors is the risk of commutator flashover. As motor speed increases, voltage between commutator segments rises. Combined with high armature current, this can lead to a destructive electrical arc. Such incidents damage the commutator, brushes, and reduce motor lifespan. Consequently, DC motor operating conditions are constrained by several factors. Despite these drawbacks, many applications still rely on brushed DC motors. While they offer good control characteristics, the aforementioned limitations hinder their suitability for high-performance, reliable belt drive systems.

2.4.2 Induction motor

The induction motor (IM) was invented in the late 19th century. Its operating principles are well-understood, and advancements in power electronics have enabled efficient and stable variable-speed control through variable-voltage/current, variable frequency supplies. This has led to superior dynamic performance compared to traditional phase-controlled DC drives. A key characteristic of induction motors is slip, the difference in speed between the rotor and stator magnetic field. IMs are the most commonly used type of motor, with squirrel-cage induction motors being particularly popular due to their advantages over other designs.

- Rugged
- Lower maintenance

- More reliable
- Lower cost, weight, volume
- Higher efficiency
- Able to operate in dirty and explosive environments.

Induction motors exhibit non-linear relationships between speed, torque, and control voltage, making them unsuitable for precise control required in servo systems. Consequently, they are not ideal for belt-drive applications that demand accurate motion control. Figure 2.2 shows induction machine.

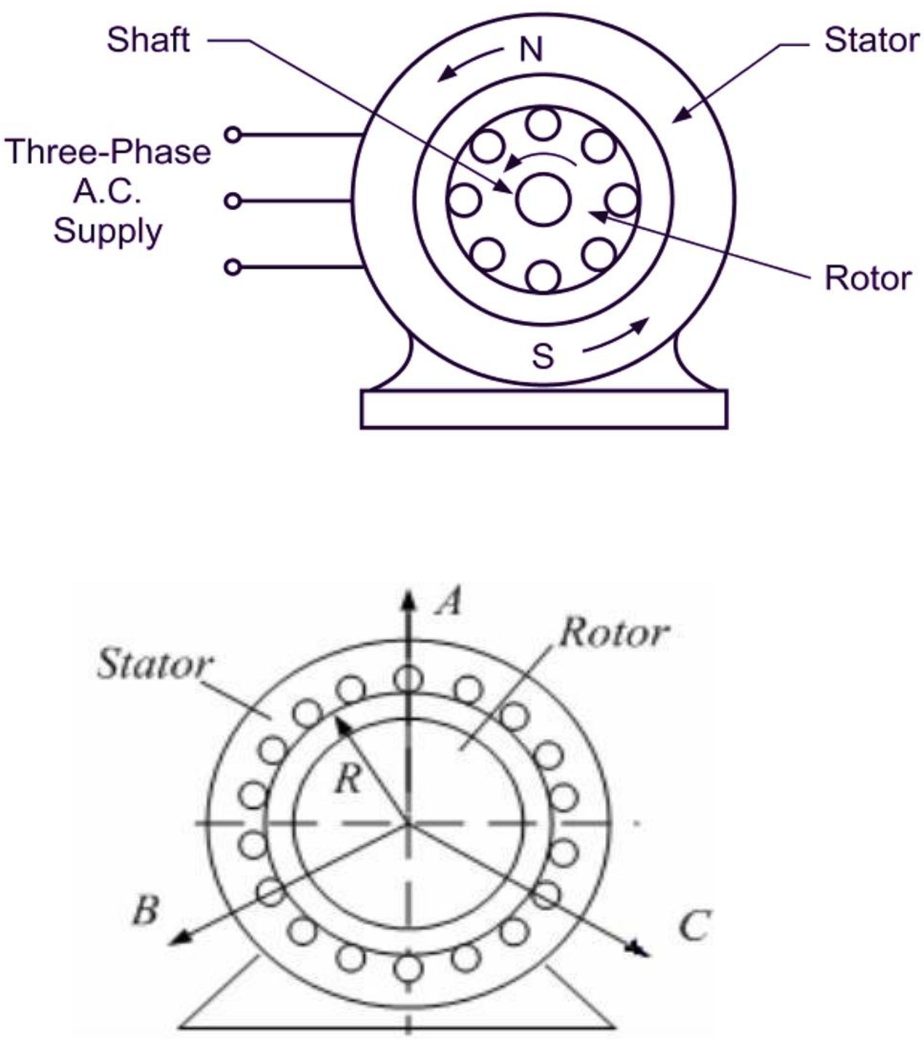


Figure 2.2 Induction machine(Control Techniques, n.d.)

2.4.3 Brushless DC motors

The demand for high-performance, reliable, and low-maintenance motors in computer peripherals and aerospace spurred the development of brushless DC motors (BLDC). Typically, a BLDC motor has a three-phase stator and a rotor with surface-mounted magnets, creating a rectangular air gap flux pattern. The motor is driven by rectangular or trapezoidal voltage pulses synchronized with the rotor position. To maximize torque, the stator and rotor flux should be nearly perpendicular. The commutation process requires only basic position sensing, typically achieved with simple Hall Effect sensors or low-resolution optical encoders. Figure 2.3 illustrates the BLDC motor geometry and associated current and back-EMF waveforms.

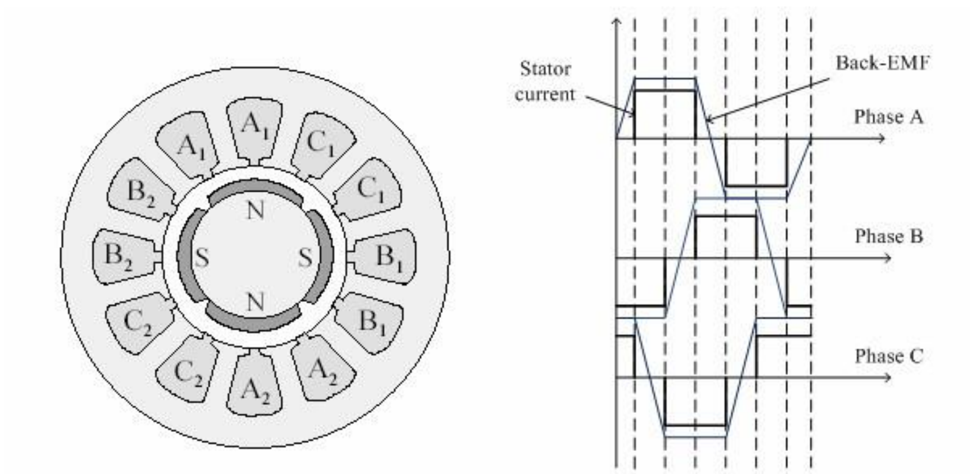


Figure 2.3 Brushless DC motor (Anon, 1975)

Brushless DC (BLDC) motors operate on a similar principle to brushed DC motors but eliminate the need for physical brushes. Unlike brushed motors that rely on physical contact between brushes and commutator segments to deliver power to the rotor, BLDC motors use electronic commutation. This process involves precisely timing the application of electrical current to the stator windings to create a rotating magnetic field that drives the rotor.

The widespread adoption of brushless DC motors in industry is driven by several factors. Advancements in power electronics, including reduced costs and sophisticated control algorithms for PWM inverters, have been instrumental. Additionally, the development of stronger magnetic materials, precise position controllers, and compact integrated systems have contributed to their popularity. Furthermore, the direct relationship between torque and current simplifies motor control.

Compared to brushed DC motors, brushless DC motors offer several advantages. Primarily, their construction enables direct heat dissipation into the environment without relying on air gaps or bearings for heat transfer.

Consequently, additional cooling systems are typically unnecessary. Secondly, brushless DC motors offer more precise overload protection as the temperature of the hottest component can be directly monitored. The absence of a mechanical commutator also provides several advantages:

There is no sparking; that is the motor can be used in hazardous environments.

- ✓ Maintenance costs are reduced; brushless DC motors do not require regular service of the brush gear.
- ✓ The speed-torque limits caused by commutator are eliminated.

While brushless DC motors offer several advantages, they are typically more expensive than their brushed counterparts due to the complex electronic commutation system required. This system replaces the mechanical commutator in brushed motors and consists of a power bridge, rotor position encoder, and control logic to ensure precise torque generation.

Brushless DC motors also exhibit certain drawbacks. They tend to produce speed and torque ripples due to the square wave current switching between phases, although these can be mitigated by increasing the rotor's moment of inertia. Additionally, they typically draw higher currents compared to brushed motors. A critical design challenge lies in the permanent magnet rotor, as the junction between the magnet and rotor can fail under high speeds and accelerations. Consequently, brushless DC motors are commonly used for applications up to 20kW. Beyond this power level, vector-controlled induction motors are generally preferred. Given their cost-effectiveness and suitability, brushless DC motors excel in low-power belt-driven systems.

2.4.4 Permanent magnet synchronous motor

Permanent Magnet Synchronous Motors (PMSMs) are highly efficient and reliable brushless motors. Their compact design delivers high torque due to the use of permanent magnets in the rotor, eliminating the need for rotor current. Unlike traditional AC synchronous motors, PMSMs require no DC supply, simplifying their construction. They generate a sinusoidal back electromotive force (EMF) and can produce torque even at zero speed. To achieve optimal performance, PMSMs necessitate a digitally controlled inverter.

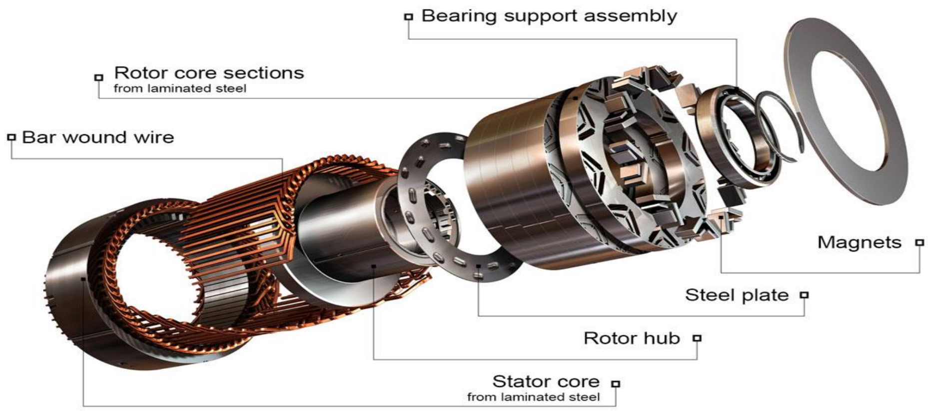


Figure 2.4 Structure of a permanent magnet synchronous motor(Pillay & Krishnan, 1989).

Permanent Magnet Synchronous Motors (PMSMs) emerged as a dominant force in servo drives during the latter half of the 20th century, finding widespread industrial application, particularly in wind turbines and propulsion systems. Early PMSMs suffered from magnet demagnetization under high starting currents and temperature limitations. However, advancements in permanent magnet materials during the 1970s addressed these issues. PMSM performance is significantly influenced by rotor design, with embedded and surface magnet configurations being common. Surface magnet motors generally exhibit lower direct axis inductance, enhancing overload capacity but limiting field weakening range. Conversely, they offer lower inertia. Due to their exceptional controllability and absence of mechanical commutators, PMSMs are well-suited for belt drive systems(Pillay & Krishnan, 1989).

The drawback of PMSM is their relatively higher costs compared to the other types of motors.

2.4.5 Stepper motors

Stepper motors are DC motors that move in precise, discrete steps rather than continuous rotation**.** Unlike traditional DC motors, they excel at maintaining specific positions. Their popularity stems from their ease of control by computers and microcontrollers, which can accurately direct the motor's rotation through the application of digital signals.(Grant, 2005).

Digital signals are converted into current pulses which are sequentially applied to the motor coils. This operation transforms the motor into an incremental actuator, converting digital input into analog output in the form of shaft rotation. The motor's rotational speed is determined by the pulse frequency, while the total rotation angle depends on both the pulse count and the incremental step angle. Stepper motors excel in open-loop position and speed control due to their precise operation. They are commonly used in applications like disc drives, machine tool slides, and printer heads, often driving components directly or via belts. Akey advantage for servo drive applications is their inherent accuracy of ±1 step in open-loop systems. This eliminates the need for position and speed sensors, significantly reducing overall system cost.

- ✓ Stepper motors can generate high output torques at low angular velocities.
- ✓ Connection circuitry of the stepper motor is digital simplifying the interface to the programmable controller or control computer.
- ✓ Mechanical construction of the stepper motor is simple and robust.

A critical factor to consider with stepper motors is resonance, a phenomenon that affects all motors to some degree. Stepper motors operate based on digital pulses generated by an oscillator, often controlled by analog voltage, digital logic, or a microprocessor. The motor's rotational speed is directly tied to the frequency of these pulses, with the total shaft angle determined solely by the pulse count(Le et al., 2017). Consequently, higher pulse frequencies result in faster step execution. It's important to note that single step times vary based on motor size, step angle, and load conditions, as ideal single step performance is often unattainable. Additionally, due to their incremental nature, stepper motors require knowledge of the initial rotor position to accurately determine absolute position after a step sequence. To ensure precise positioning, the step counter should be reset when the motor shaft is at its starting point.

Therefore, the stepper motor can be applied in very particular applications due to its specific characteristics.

2.4.6 Linear motors

Linear motors are essentially electric motors that have been "unrolled." Unlike traditional motors that produce rotational motion, linear motors generate straight-line movement. This is achieved by flattening the stator, the typically stationary part of a motor, and allowing the moving part (similar to a rotor) to glide over it. While linear motors can use various technologies, a common type employs superconducting magnets. These magnets, cooled to extremely low temperatures, significantly reduce power consumption and enhance motor efficiency.

Nowadays linear applications are more demanding than ever before. There are many brushless linear motors available for the motion control with large stroke length, high speed and accuracy, load capacity and stiffness at the moment. The linear motor concept is not new. Early machines had limitations in high-speed operation due to commutation bar and brushes. Brushless servo motor technology and implementation electronics to drive them allow avoiding the above limitations. Commutation is manufactured electronically by Hall-effect sensors and therefore commutation is not limiting factor(Control Techniques, n.d.). Thus, brushless linear motors have a sum of advantages:

- ✓ High-speed operation. The maximum of linear motor speed is bounded only bus voltage and speed of control electronics. Typical speed of linear motor is 3 meters per second with 1 micron resolution.
- ✓ High precision. The accuracy, resolution and repeatability of motor depend on controlled feedback device. Wide range of linear feedback devices allow to appropriate device limiting only control system bandwidth.
- ✓ Fast response. The response rate of a linear motor driven device can be over 100 that of a mechanical transmission.
- ✓ Zero backlash. No backlash due to absence of mechanical transmission components.
- ✓ Maintenance free operation. There is no wear due to absence of contacting parts in modern linear motors.

Side by side with all benefits, list of drawbacks such as high cost, sizing, heating exists.

2.5 Measurement devices in motion control

Precise control of speed, position, or acceleration necessitates accurate measurement systems. When these variables fluctuate rapidly, the measurement system's dynamic response becomes crucial. Conversely, for slowly changing variables, static performance is paramount. Before exploring sensor options, it's essential to consider key characteristics like resolution and accuracy.(Olsson, 1993).

The resolution of a feedback device indicates its precision in measuring shaft rotation. For incremental encoders, resolution is expressed as the number of pulses generated per shaft revolution. In contrast, analog feedback devices like resolvers determine resolution through their associated resolver-to-digital converters. The accuracy of sensor can be described as position deviation within one measuring step.

Encoder accuracy is influenced by factors such as the encoder shaft's alignment, elasticity, and coupling, as well as the quality of the graduation markings and electronic signal processing. For analog feedback devices like resolvers, accuracy is determined by winding configuration, air gap consistency, and the physical characteristics of the resolver shaft and its coupling.

2.5.1 Tachogenerator

Electromechanical generators transform rotational mechanical energy into electrical energy. When no load is applied, they produce a voltage directly proportional to their shaft speed. Engineered for precision, these generators can provide highly accurate voltage outputs within specific speed ranges. Due to this characteristic, they are commonly employed as tachometers or tachogenerators for measuring shaft speed in machinery (Safiullin & Yangirov, 2020). Often, the word "tach" (pronounced "tack") is used rather than the whole word.

The DC tachogenerator is electromagnetic transducer that converts mechanical rotation into DC output voltage commonly used as speed feedback device. The output voltage is directly proportional to the rotational speed. The basic fundamentals of tachogenerators are the same as DC motor, besides, significant features of its operation are following:

- ✓ Linearity of the output; that is output voltage proportional to the shaft speed with defined linearity.
- ✓ Smooth output: the output voltage should be free from ripple in range of frequency where drive is operating.
- ✓ Independence output voltage of temperature; the output voltage for given speed should be constant with changing temperature.

Tachogenerators exhibit non-ideal output characteristics. Ripple voltage can significantly impact performance, typically reaching a peak-to-peak value of 5-6% under normal conditions and potentially up to 23% with specialized equipment. Temperature variations also affect tachogenerator performance, with the degree of influence dependent on design and materials. Additionally, hysteresis losses in the armature core can compromise the linearity of the output voltage.(*SIEM-1 (English) Ministry of Education and Science of Ukraine Dnipro University of Technology Department of Electrical Engineering*, 2021), output current drain, and armature reaction and saturation effect particularly in very-high speed applications. In that way, application of tachogenerators can be quite reasonable in motion control systems if speed transducer is required.

2.5.2 Encoder

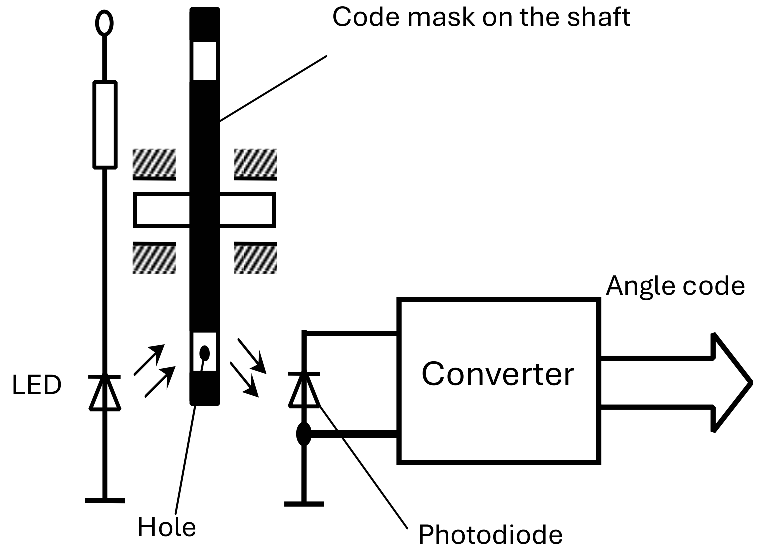


Figure 2.5 Photoelectric encoder(Zhao et al., 2019)

Encoders are devices that directly measure position and velocity. While velocity can be calculated from position data over time, encoders provide a dedicated output proportional to velocity. Widely used in robotics and machine tools, encoders are categorized as absolute or incremental. Both types consist of an optical receiver (typically a phototransistor or photodiode), a light source (like an LED or filament bulb), and a coded disc. The key difference between the two lies in the code disc's pattern and how the output signal is interpreted by the control system. Incremental encoders provide relative position information by generating signals that indicate changes in position. In contrast, absolute encoders directly output a code representing the exact position at any given moment (Zhao et al., 2019).

The significant advantage of the encoders is digital output in form of pulses train, and their frequency is not affected by temperature or weakening of long runs as in analog signal generator or resolver, therefore it is more reasonable using encoders in digital control systems.

2.5.3 Resolver

Resolvers are a type of synchro**.** Synchro's are a family of devices that sense angular position and can either produce a rotational torque or generate a signal based on their rotational position. Resolvers are specifically designed to convert angular position into coordinate data, making them suitable for control systems.(Pankhurst, 2010). Resolver**s** are electromechanical devices with two stator windings and typically one or two rotor windings positioned at a 90-degree angle. Their primary function is to convert polar coordinate input (angle) into Cartesian coordinate output (sine and cosine values). They can also be physically rotated. To integrate seamlessly with control electronics, resolvers often have a specific voltage transformation ratio between primary and secondary windings. There are various types of resolvers, including computing, brushless, and multipole models. Key characteristics of resolvers are their high precision, low electrical errors, and minimal sine wave deviation. The basic configuration of the resolver is shown in Figure 2.6.

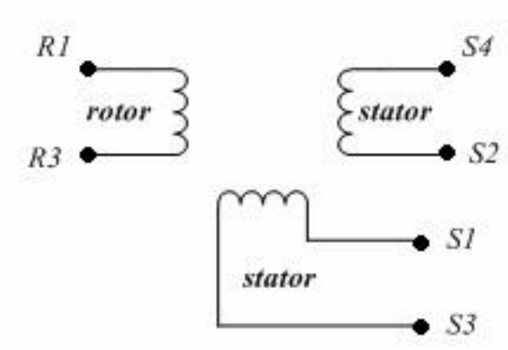


Figure 2.6 Basic configuration of resolver(Pankhurst, 2010).

Resolver performance can be impacted by several factors, including discrepancies in the primary-to-secondary transformation ratio, electrical phase shifts, and zero shift errors between secondary windings. Additionally, resolvers generate analog output, necessitating the use of a resolver-to-digital converter for integration into digital motion control systems. This adds cost and limits high-frequency operation. Resolvers, while precise, are sensitive devices with limited input signal range and relatively large size, making them unsuitable for compact applications like belt-drive systems.

CHAPTER THREE

METHODOLOGY AND SYSTEM MODELING

3.1 Chapter Overview

This chapter outlines the materials, methods, and mathematical modeling employed in this research. We delve into the specific techniques used to conduct our analysis and derive the mathematical representation of the DC motor.

3.2 Materials Used

In this research work, software such as MATLAB/2021a, Microsoft office 2016, draw.io, Math Type 6.0 equation, and Mendeley Desktop 1.19.8 are used. MATLAB is a computing software package that includes technical toolboxes and Simulink. The thesis documentation is edited using Microsoft office. draw.io is drawing software used to draw block diagrams and flowcharts. Math Type 6.0 version is used for writing mathematical formulas and equations in Microsoft offices word and PowerPoint presentation tools. Mendeley 1.19.8 is used for citation of references in the thesis document body as well as to list the references in the standard style.

3.3 Methods

The following methodologies are used to complete this research work successfully. The methodology starts with a thorough review of the literature to gain a better understanding of the system; this includes studying the belt drive system, comprehending the NPID design method, and reviewing any previous related works in this area. Second, data is collected by reviewing recorded data from varies studies related to this research work. Thirdly, the dynamic modeling that describes the system is derived. Fourth, NPID control technique that treats a non-linear system in over large operation regions is designed to improve tracking performance by minimizing overshoot, settling time, rise time, and peak time.

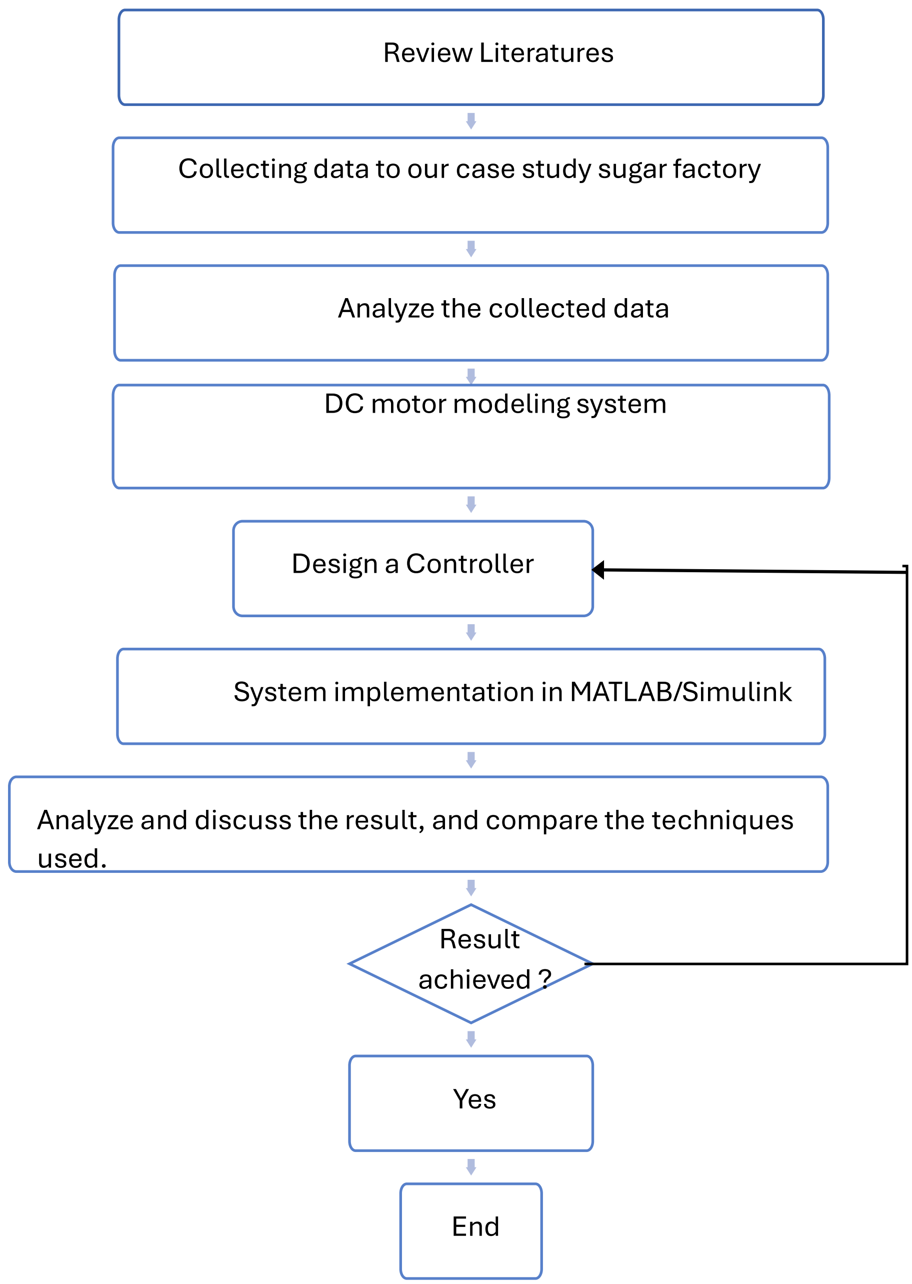


Figure 3.1block diagram of the research methodology

3.4 Control System Block Diagram

The provided block diagram figure 3.2 illustrates a control system designed to regulate the speed of a DC motor. The system primarily consists of:

- AC power supply**:** The source of electrical energy.
- 3-phase converter**:** Converts the AC power to DC power suitable for the DC motor.
- DC motor**:** The mechanical actuator to be controlled.
- Belt drive system**:** Transmits mechanical power from the motor to the load.

Control Loop Components

- Reference speed (ω_{ref})**:** The desired speed of the DC motor.
- Comparator**:** Compares the reference speed with the actual speed.
- NPID controller**:** A non-proportional, integral, and derivative controller that generates a control signal based on the error between the reference and actual speed.
- Current source inverter**:** Converts the DC control signal into a 3-phase AC current to drive the DC motor.

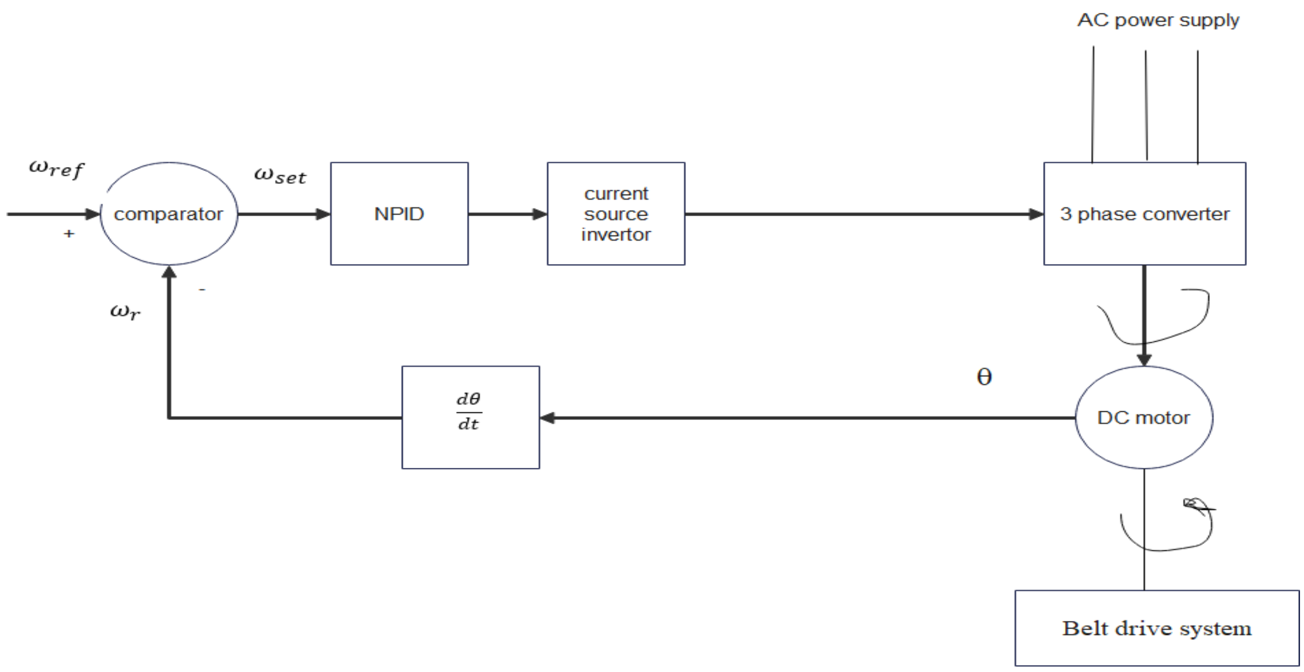


Figure 3.2 Control System Block Diagram

3.5 Mathematical Model of a DC Motor With the Load Coupled by Gears

When selecting a DC or AC motor for a belt drive system, the choice can significantly influence performance, efficiency, and maintenance. Here's a comparison based on their characteristics in belt drive applications:

- **Speed Control:** DC motors excel at precise speed control and high torque at low speeds, making them ideal for applications with frequent starts and stops.
- **Torque:** AC motors can also produce high torque, but DC motors often offer superior starting torque and consistent torque across their speed range. This is crucial for heavy loads and frequent starts.
- **Efficiency:** DC motors are generally more energy-efficient than AC motors, especially at lower speeds. This can be a significant advantage in belt drive systems where energy conservation is a priority.
- **Cost:** DC motors typically have a lower initial cost compared to AC motors.

Consider a DC machine with the load coupled by gears to the motor spindle. Figure 3.1 shows the equivalent model.

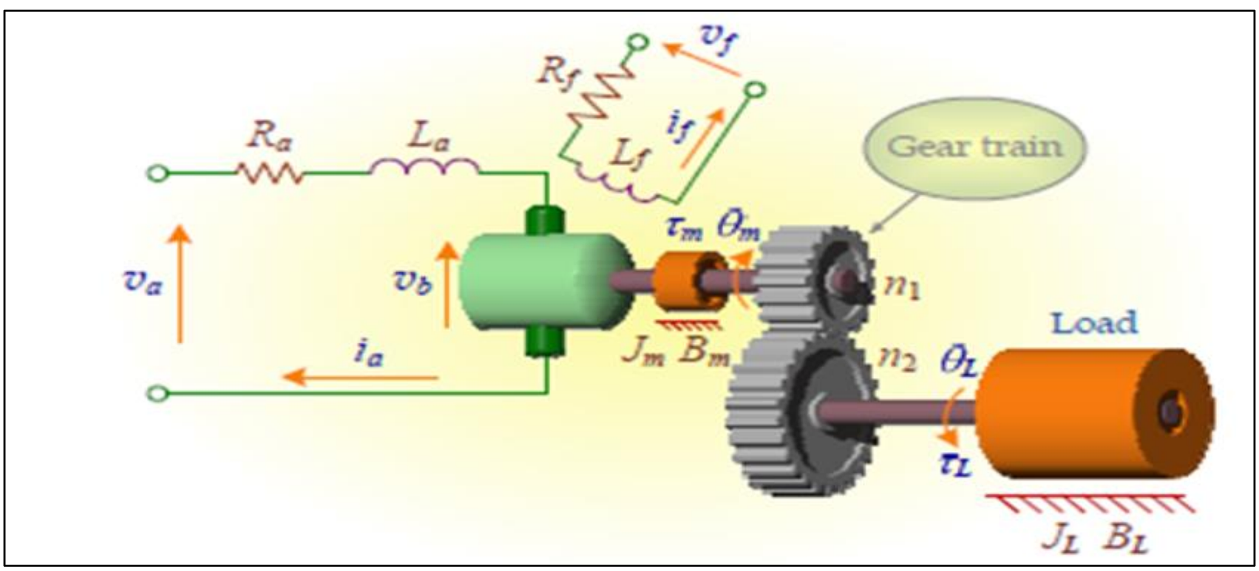


Figure 3.3 DC machine (Aborisade, 2014)

The system consists of electrical subsystem, mechanical subsystem, and gear and load subsystems

3.5.1 Electrical subsystem

Applying the Kirchhoff's voltage law in the armature circuit gives the following equation

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + v_b \tag{3.1a}$$

where v_a is Armature voltage, i_a is Armature current, R_a is Armature resistance, L_a is Armature inductance, and v_b is the back electromotive force that is described by

$$v_a = K\phi\omega_m = K_b\omega_m \tag{3.1b}$$

where ω_m is the angular velocity and K_b is the armature back emf constant (= $K\phi$).

The torque τ_m developed by the motor is given by

$$\tau_m = K_m i_a \tag{3.2}$$

where τ_m is the electromagnetic torque and K_m is torque constant.

3.5.2 Mechanical subsystem

Since the motor is connected to a load, the model of the mechanical part can be given by

$$\tau_m - \tau_L = J_m \frac{d\omega_m}{dt} + B_m\omega_m \tag{3.3}$$

where τ_L is the load torque (kgm^2sec^2), J_m is the load inertia (kgm^2) and B_m is the viscous friction coefficient (Nm/rad/s).

3.5.3 Gear train and load model

Often, the speed required by the load is too low as compared to the nominal speed of the motor. In this case, a gear train composing two or more interlocking gears is used between the motor and the load, thus reducing by a factor *r* the angular velocity of the load itself. As a general rule, when dealing with two gears, if the driving gear (motor side) is bigger than the driven gear (load side), the latter will turn more quickly, and vice versa. Figure 3.4 shows a typical two gear system.

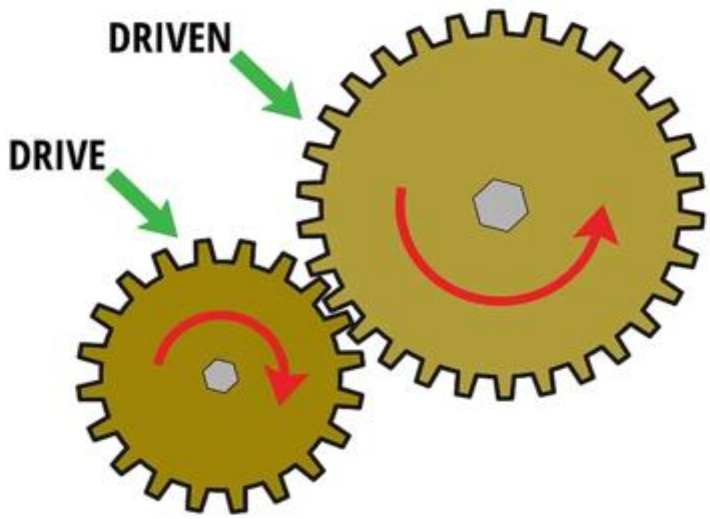


Figure 3.4 Two gear system (Chris Deziel, 2018)

This basic concept can be expressed with the gear ratio *r*. The formula is defined by

$$r = \frac{n_2}{n_1} \tag{3.4}$$

where n_1 is the number of teeth on the driving gear and n_2 is the number of teeth on the driven gear. Since gear ratio is inversely proportional to angular velocity, the relationship between angular velocities of the gear on the motor and load sides can be expressed by

$$\omega_L = \frac{\omega_m}{n} \tag{3.5}$$

where ω_L is the angular velocity of the load side. While angular velocity decreases with a higher gear ratio, torque increases proportionally. The relationship between torques of the gear on the motor and load sides can be expressed by

$$\tau_L = r\tau_m \tag{3.6}$$

where τ_L and τ_m is the torques of the load and motor sides, respectively.

From that fact that the power exerted by the motor is the same at the input and at the output of the gear, and Equations (3.5) and (3,6), it can be written

$$\omega_L \tau_L = \omega_m \tau_m \tag{3.7}$$

3.6 Transfer Function Model of a DC Motor with the Load Coupled by Gears

3.6.1 Electrical subsystem

Applying the Laplace transform to Equations (3.1) and (3.2), we can obtain the following equations.

$$\begin{aligned} V_a(s) &= R_a I_a(s) + L_a s I_a(s) + K_b \Omega_m(s) \\ &= (R_a + L_a s) I_a(s) + K_b \Omega_m(s) \end{aligned} \tag{3.7}$$

$$T_m(s) = K_m I_a(s) \tag{3.8}$$

3.6.2 Mechanical subsystem

Applying the Laplace transform to Equation (3.3), we can obtain the following equation.

$$\begin{aligned} T_m(s) - T_L(s) &= J_m s \Omega_m(s) + B_m \Omega_m(s) \\ &= (J_m s + B_m) \Omega_m(s) \end{aligned} \tag{3.9}$$

3.6.3 Gear train and load model

Applying the Laplace transform to Equations (3.5) and (3.6), we can obtain the following equation.

$$\Omega_L = \frac{1}{r} \Omega_m \tag{3.10}$$

$$T_L = r T_m \tag{3.11}$$

$$\Omega_L T_L = \Omega_m T_m \tag{3.12}$$

The block diagram from the transfer function given by Equations (3.7), (3.8), (3.9) and (3.10) is shown in Figure 3.5.

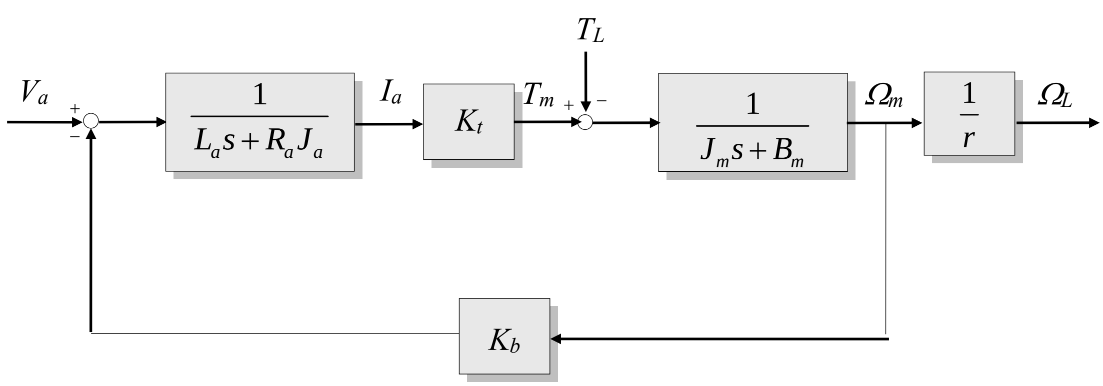


Figure 3.5 Block diagram of the unloaded DC motor.

Due to the presence of the additional rotating cogwheels of the gear, the mechanical coupling between the load and the motor is altered by the gear itself. The damping and inertia are not the same if measured at the input or at the output of the gear. Figure 3.6 reflects the effects of the cogwheels of the gear.

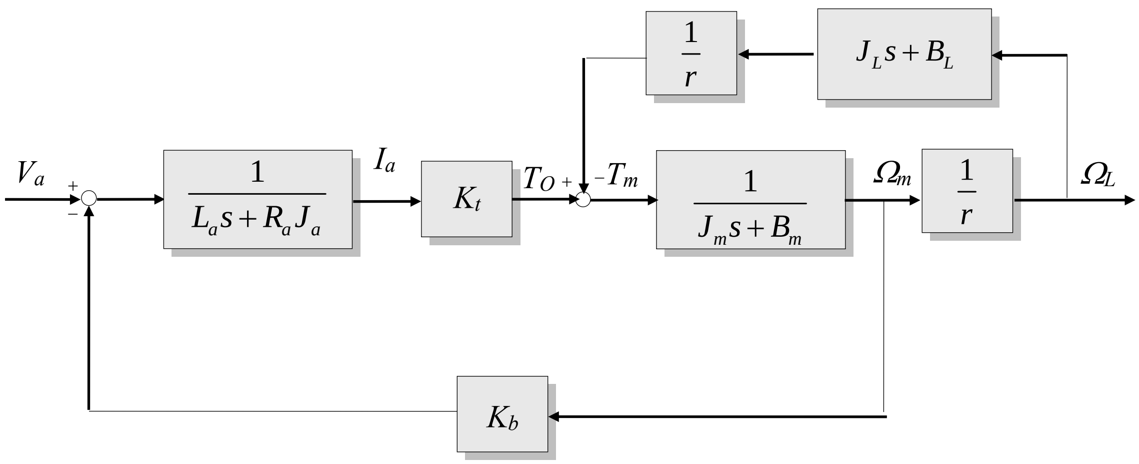


Figure 3.6 Block diagram of the DC motor with external load coupled by gears.

Then, the transfer function that relates the unloaded motor torque T_O with the motor angular velocity Ω_m can be calculated by

$$\begin{aligned}\frac{\Omega_m}{T_O} &= \frac{\frac{1}{J_m s + B_m}}{1 + \frac{1}{J_m s + B_m} \times \frac{1}{r^2}(J_L s + B_L)} \\ &= \frac{1}{(J_m + \frac{1}{r^2} J_L)s + B_m + \frac{1}{r^2} B_L}\end{aligned} \tag{3.13}$$

Defining the equivalent inertia moment J_e and the equivalent viscous friction coefficient B_e as

$$\begin{aligned}J_e &= J_m + \frac{1}{r^2} J_L \\ B_e &= B_m + \frac{1}{r^2} B_L\end{aligned} \tag{3.14}$$

Equation (3.13) can be rewritten as

$$\frac{\Omega_m}{T_O} = \frac{1}{J_e s + B_e} \tag{3.15}$$

The equivalent block diagram of the system is shown in Figure 3.5.

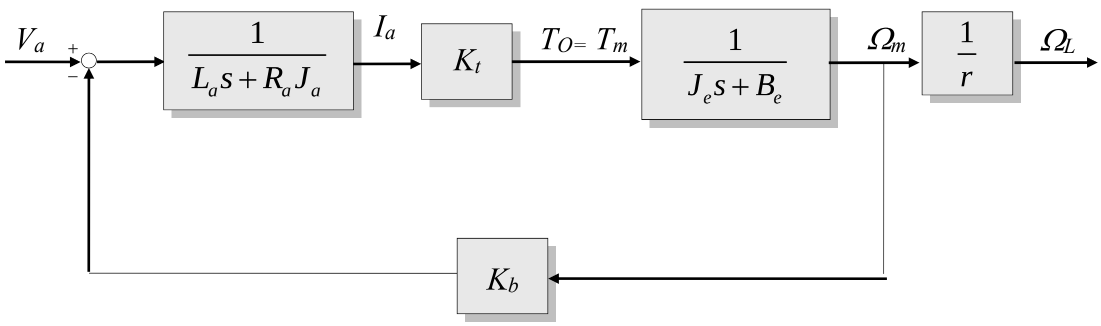


Figure 3.7 Equivalent block diagram of the DC motor with external load coupled by gears

The transfer function from v_a to ω_L of the system shown in Figure 3.5 is

$$\begin{aligned}\frac{\Omega_L}{V_a} &= \frac{1}{r} \cdot \frac{\dfrac{K_t}{(L_a s + R_a J_a)(J_e s + B_e)}}{1 + \dfrac{K_t K_b}{(L_a s + R_a J_a)(J_e s + B_e)}} \\ &= \frac{K_t}{r[(L_a s + R_a J_a)(J_e s + B_e) + K_t K_b]}\end{aligned} \tag{3.16}$$

Rewriting Equation (3.16) gives

$$\frac{\Omega_L}{V_a} = \frac{b_2}{s^2 + a_1 s + a_2} \tag{3.17a}$$

where

$$a_1 = \frac{L_a B_e + R_a J_a J_e}{L_a J_e} \tag{3.17b}$$

$$a_2 = \frac{R_a J_a B_e + K_t K_b}{L_a J_e} \tag{3.17c}$$

$$b_2 = \frac{K_t}{L_a J_e r} \tag{3.17d}$$

3.7 State Space Model of a DC Motor with the Load Coupled by Gears

Defining state variables as $x_1 = \omega_L$ and $x_2 = \dot{\omega}_L$ in Equation (3.17), we have the equation in state space

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}u \\ y &= \boldsymbol{C}\boldsymbol{x} \end{aligned} \tag{3.18a}$$

where the system matrices and the state vector are defined as

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 \\ -a_2 & -a_1 \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} 0 \\ b_2 \end{bmatrix}, \boldsymbol{C} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{and } \boldsymbol{x}^T = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{3.18b}$$

where $u = v_a$ is the control input and y is the output.

3.8 PID Controller for Comparison

3.8.1 Conventional PID Controller

A PID (Proportional-Integral-Derivative) controller is a widely used feedback control system in engineering and control theory. Its primary purpose is to continuously adjust a system's output to maintain the desired setpoint by minimizing the error between the desired and actual values. Here's a breakdown of the PID controller structure. A PID controller consists of three main components: Proportional, Integral, and Derivative. These components work together to produce a control signal that adjusts the process variable to achieve the desired setpoint.

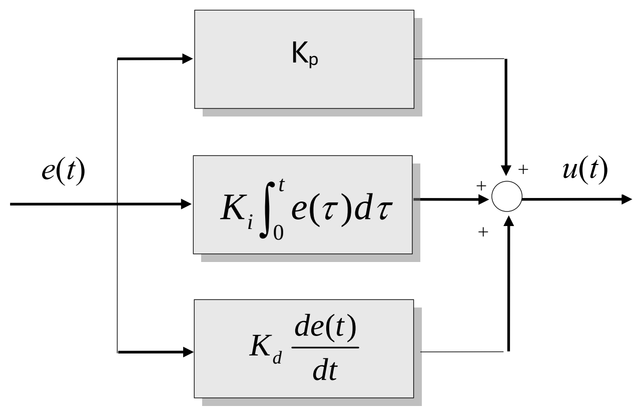


Figure 3.8 Structure of the PID controller

Mathematical description of the PID controller is given by

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (4.1a)$$

where k_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain.

Proportional Gain $(\boldsymbol{K_p})$: This parameter determines the proportion of the error signal contributing to the controller output. A higher $\boldsymbol{K_p}$ value results in a stronger response to the current error. Too high a $\boldsymbol{K_p}$can lead to oscillations or instability, while too low a value can result in a sluggish response.

Function: The proportional gain determines the response of the controller to the current error. It produces an output that is directly proportional to the error.

Effect: Increase K_p: Increases the response speed, but too high a K_p can cause the system to become unstable and oscillate. Decrease K_p: Reduces the response speed, making the system more stable but possibly leading to a larger steady-state error.

Mathematical representation:

$$P = K_p e(t) \tag{4.1b}$$

Behavior: Higher K_p: values result in a stronger corrective action for a given error.

Integral Gain ($\boldsymbol{K_i}$): The integral term considers the accumulation of past errors and amplifies them over time. It helps eliminate steady-state error by continuously adjusting the control signal. A higher $K_i$value helps reduce steady-state error but can lead to overshoot or instability if set too high.

Function: The integral gain determines the response based on the accumulation of past errors. It sums the error over time, which helps eliminate the residual steady-state error that a proportional-only controller cannot remove.

Effect: Increase (K_i): Reduces the steady-state error but can cause the system to become slower and potentially oscillatory if too high. Decrease (K_i): Reduces the risk of oscillation and overshoot but may leave a steady-state error.

Mathematical representation:

$$I = K_i \int_0^t e(\tau)\, d\tau \tag{4.1c}$$

Behavior: Higher K_i values result in more aggressive correction based on the accumulated error over time.

Derivative Gain ($\boldsymbol{K_d}$): The derivative term predicts the future behavior of the error based on its current rate of change. It helps dampen oscillations by counteracting rapid changes in the error signal. Increasing K_d enhances damping and reduces overshoot, but too high a value can lead to instability or sensitivity to noise.

Function: The derivative gain determines the response based on the rate of change of the error. It predicts future error based on its rate of change, providing a damping effect.

Effect:

Increase K_d: Improves system stability and reduces overshoot by damping the rate change of the error. However, too high a K_d can cause the system to become overly sensitive to noise.

Decrease K_d: Reduces the damping effect, which may lead to increased overshoot and potential oscillations.

Table 3.1 Roles of three terms

Element	Role
Proportional term (P)	Directly reacts to the present error
Integral term (I)	Accounts for accumulated past errors
Derivative (D)	Predicts and corrects for future errors

3.8.2 Tuning rules

The Ziegler-Nichols (Z-N) tuning method is a heuristic approach for tuning PID (Proportional-Integral-Derivative) controllers. It is particularly useful for achieving a good initial set of controller parameters. There are two primary Z-N methods: the Open-Loop (Process Reaction Curve) method and the Closed-Loop (Ultimate Gain) method.

(1) Ziegler-Nichols Open-Loop Method

This method involves applying a step change to the system and observing the output response to derive the process parameters. Here are the steps:

Perform a Step Test: Apply a step input to the process and record the output response.

Determine the Process Reaction Curve: Identify the following parameters from the curve:

- **L**: The time delay (dead time), which is the time it takes for the output to start responding after the step input.
- **T**: The time constant, which is the time it takes for the output to reach 63% of its final value after the initial response.
- **K**: The process gain, which is the ratio of the change in output to the change in input.

Calculate the PID Parameters: Use the identified parameters to calculate the PID gains using the Z-N open-loop formulas:

Table 3.2 Ziegler-Nichols Open-Loop Formula

Controller	K_p	T_i	T_d
P	$\frac{T}{L}$		
PI	$0.9\frac{T}{L}$	$3L$	
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

(2) Ziegler-Nichols Closed-Loop Method

This method involves increasing the proportional gain until the system output oscillates with a constant amplitude. The steps are as follows:

Step 1: Set the Initial PID Values: Start with $K_i = 0$ and K_d=0

Step 2: Increase Proportional Gain: Gradually increase the proportional gain Kp until the output oscillates with a constant amplitude. Record this gain as the Ultimate Gain Ku and the oscillation period as the Ultimate Period Tu.

Step 3: Calculate the PID Parameters: Use the Z-N closed-loop formulas to calculate the PID gains:

Table 3.3 Ziegler- Nichols closed-loop formulas

Controller	K_p	T_I	T_D
P	0.5 Ku	∞	0
PI	0.45Ku	$\frac{Tu}{1.2}$	0
PID	0.6Ku	$\frac{Tu}{2}$	$\frac{Tu}{8}$

(3) **Tyreus and Luyben method**

A modification to the above Ziegler-Nichols tuning parameters was made by Tyreus and Luyben.

The Tyreus-Luyben tuning method is another empirical approach for tuning PID controllers, particularly aimed at improving the performance of control systems compared to the Ziegler-Nichols method. It is often used for systems where Ziegler-Nichol's tuning might result in excessive oscillations or instability. The Tyreus-Luyben tuning rule is a method used to determine the proportional (P), integral (I), and derivative (D) gains of a PID controller. This method is similar to the Ziegler-Nichols tuning method but typically results in less aggressive controller settings, leading to a more stable system with less oscillation. The steps of the Tyreus-Luyben tuning method are as follows:

Step 1: Set initial conditions: Set the integral and derivative gains to zero (PI and PID controllers).

Step 2: Increase : Gradually increase the proportional gain Kp until the system output exhibits sustained oscillations. This gain is called the ultimate gain (Ku).

Step3: Determine the ultimate period (Tu): Measure the period of oscillation.

Table 3.4 Tyreus and Luyben tuning method

Controller	K_p	T_I	T_D
PI	$0.45K_u$	$\frac{Pu}{1.2}$	0
PID	$0.31K_u$	$2.2Pu$	$0.5P_u$

3.9 Nonlinear PID Controller

Linear PID controllers excel when operating within their design range. However, their performance can suffer significantly when dealing with changing or unpredictable process dynamics, especially for non-linear systems. Nonlinear PID (NPID) controllers offer an alternative, providing smoother operation and better handling of unexpected changes. However, the increased complexity of NPID controllers comes with a trade-off: more tuning parameters compared to linear PIDs. In this thesis, we use a simpler NPID controller design proposed by Jin and Son (2019) requiring only three tuning gains, similar to the conventional PID controller. This design incorporates a non-linear gain specifically affecting the integral term. The time-domain equation for this NPID controller is given by

$$u(t) = u_p(t) + u_i(t) + u_d(t) \tag{4.2a}$$

$$u_p(t) = k_p e(t) \tag{4.2b}$$

$$u_i(t) = k_i \int v(t)\,dt \tag{4.2c}$$

$$\frac{T_d}{N}\frac{du_d(t)}{dt} + u_d(t) = k_d\frac{de(t)}{dt} \tag{4.2d}$$

where u_p, u_i and u_d mean the proportional, integral and derivative actions, respectively and $v(t)$ is the scaled error of the integral term, and it is given by

$$v(t) = k(e)e(t) \tag{4.3}$$

$k(e)$ in Equation (4.3) denotes a nonlinear gain expressed by

The terms 'proportional' and 'derivative' are considered linear because they involve straightforward mathematical operations, such as multiplication and differentiation, that do not introduce variables raised to powers other than 1.

$$k(e) = \exp\left(-\frac{e^2}{2\sigma^2}\right) \tag{4.4}$$

where σ represents the largest change in the setpoint between steps. The transfer functions of the linear part of the NPID controller are

$$G_{pd}(s) = \frac{U_{pd}(s)}{E(s)} = K_p + K_d D(s) \tag{4.5a}$$

$$D(s) = \frac{s}{1 + \frac{T_d}{N} s} \tag{4.5b}$$

where $T_d = K_d/K_p$ is the derivative time and N is a user-defined parameter whose typical values are 5 to 30 (Åström et al., 1998). Note that if $N \to \infty$, $D(s)$ becomes the ideal differentiator. Also, the transfer function between v and u_i is as follows:

$$\frac{U_i(s)}{V(s)} = \frac{K_i}{s} \tag{4.6}$$

Figure 3.9 depicts the NPID control system. A disturbance signal, denoted by T_L, is applied to the input side of the system. In the block diagram, y_s is the setpoint, y is the output, e is the error between the setpoint and the output, v is the scaled error, u is the control input and Sat(.) is the input saturation. In an NPID controller, the integral term is often the primary candidate for nonlinear modification. This is because its function in eliminating steady-state error and addressing saturation or anti-windup concerns can be significantly enhanced through nonlinear techniques. Nonlinearity in the integral term can lead to improved performance and robustness.

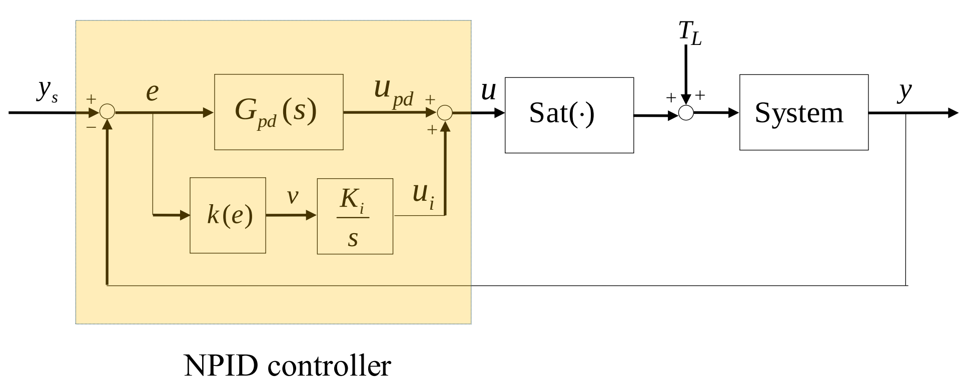


Figure 3.9 NPID control system.

3.10 Tuning of the Nonlinear PID Controller

Nonlinear PID controllers are designed to handle systems with nonlinearities more effectively than traditional linear PID controllers. Proper tuning of these controllers is essential for achieving optimal control performance.

Table 3.5 Comparison of Linear PID and NPID Controllers for Belt Drive Systems

Feature	Linear PID Controller	NPID Controller
Suitability for Nonlinear Systems	Less suitable	Well-suited
Adaptability to Changing Conditions	Limited	High
Robustness to Disturbances	Moderate	High
Overshoot	Can be significant	Often reduced
Settling Time	Can be long	Often shorter
Rise Time	Can be slower	Often faster
Integrate Absolute Error (IAE)	Can be higher	Often lower
Computational Requirements	Lower	Higher
Sensitivity to Noise and Measurement Errors	Moderate	Can be higher
Overall Performance for Belt Drive Systems	Suitable for simple systems with minimal disturbances	Often preferred for complex systems with nonlinear characteristics and varying disturbances

3.10.1 Performance index

To evaluate the performance of a Nonlinear PID controller, the Integral of Absolute Error with control effort (IAEU) performance index is used. The goal is to minimize J to achieve a balance between reducing the error and minimizing the control effort, leading to an efficient and stable control system. This index is given by:

3.10.2 Objective function

Careful selection of an objective function is essential for achieving optimal system performance while minimizing control effort. This function, known as a performance index in control systems, is the cornerstone of optimization. Common performance indicators include Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Integral Square Error (ISE), and Integral Time Square Error (ITSE) (Tsai et al., 2021). These performance indices are explained in the following way (J.Jebakumar et al., 2014).

Integral Absolute Error (IAE) integrates the absolute error across time without adding weight tany of the in errors in system response.

$$IAE = \int_0^T |e(t)| dt \tag{4.7}$$

Integral Time Absolute Error (ITAE) is a performance metric that heavily penalizes errors that persist for extended periods. It calculates this by multiplying the absolute error at each point in time by the elapsed time and then summing these values over the entire response period.

$$ITAE = \int_0^T t\,|e(t)| dt \tag{4.8}$$

Integral Square Error (ISE) is a performance metric that calculates the sum of the squared error over time. This method emphasizes larger errors, as squaring the error magnifies its impact on the overall result.

$$ISE = \int_0^T e(t)^2 dt \tag{4.9}$$

Integral Time Square Error (ITSE) calculates the integral of the squared error multiplied by time. This metric emphasizes both larger errors and errors that persist over longer durations.

$$ITSE = \int_0^T te(t)^2 dt \tag{4.10}$$

This thesis employs the Integral of Absolute Error and Control Signal (IAEU) as the objective function to achieve satisfactory system behavior during transitions while preventing excessive control actions in response to sudden setpoint changes. The IAEU provides insights into both systems tracking performance and control effort.

$$J = \int_0^{\infty} \left(\left| e(t) \right| + w \left| \Delta u(t) \right| \right) dt \quad (4.11a)$$

where $e(t)$ is the error signal at time t, defined as $e(t) = y_r(t) - y(t)$, where $y_r(t)$ is the setpoint signal and $y(t)$ is the output signal. $\Delta u(t)$ is the change in the control input at time t, defined as

$$\Delta u(t) = u(t) - u_0 \quad (4.11b)$$

$$u_0 = (R_a B_0 + K_a K_b xL)/K_a \quad (4.11c)$$

where $R_a, B_0, K_a, K_b,$ and xL are constants or parameters specific to the system being controlled. w is a weighting factor that balances the importance of the error term and the control effort term. A performance index is a mathematical function that quantifies the deviation of a system's output from a desired setpoint. It provides a numerical measure of the control system's quality. Several performance indices are commonly used for tuning nonlinear PID controllers:

3.10.3 Genetic algorithm

Genetic Algorithms (GAs) are a stochastic optimization technique inspired by the process of natural selection**.** They iteratively improve a population of potential solutions by applying genetic operators such as reproduction, crossover, and mutation. Introduced by John Holland in the 1970s at the University of Michigan, GAs have gained prominence due to advancements in computational power. Unlike traditional methods, GAs begins without prior knowledge of the optimal solution and rely on environmental feedback to evolve superior candidates. GAs are metaheuristic optimization techniques inspired by natural selection. They employ a randomized search approach on coded parameters. GAs have become a popular choice for tackling complex control problems that defy analytical solutions, particularly when dealing with vast search spaces. The core principle of GAs mimics biological evolution. Fitter individuals are more likely to survive and reproduce, passing on their beneficial traits to offspring. This process is simulated through genetic operators like crossover and mutation, which combine and modify existing solutions to create new ones. By iteratively selecting and breeding the best solutions, GAs effectively explores the solution space and converge towards optimal or near-optimal outcomes. Crucially, GAs incorporates past successful solutions into the search process. This historical information guides the algorithm towards promising regions of the search space. The performance of GAs is significantly influenced by the carefully tuned parameters of mutation and crossover rates.

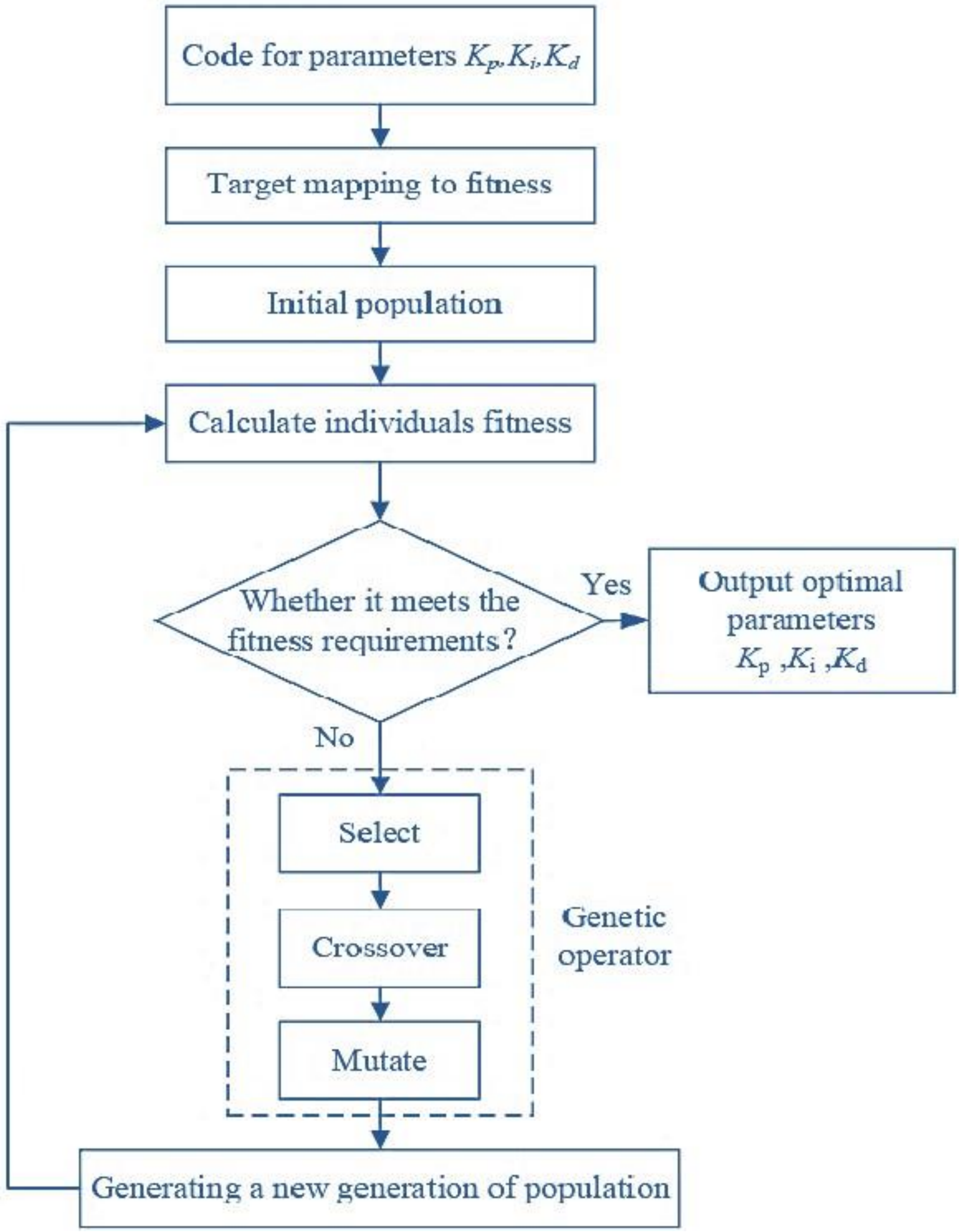


Figure 3.10 Genetic Algorithm based NPID controller(Korkmaz et al., 2012)

CHAPTER FOUR

SIMULATION AND DISCUSSION

In this chapter, we conduct a set of simulation works to examine the performance of the previously designed NPID controller and compare its performance with that of the PID controller.

4.1 System parameters

Table 4.1 shows the DC motor parameters and values with units. This table can serve as a valuable reference for understanding and analyzing the DC motor and load system.

Table 4.1 Parameters of the DC motor and external load coupled by gears

Parameter	Value	Unit
R_a	11.2	Ω
L_a	0.121	H
J_L	0.0.022	Kg-m^2
J_m	0.222	Kg-m^2
B_L	0.0005	Kg-m-sec/rad
B_m	0.0030	Kg-m-sec/rad
$r = n_2/n_1$	5	
Rated terminal voltage	240	V
K_a	1.28	N-m/rad
K_b	1.25	V-sec/rad
Motor speed, N	1750	rpm

4.2 Controller parameter Settings

4.2.1 PID controller

The PID controller for comparison was tuned using the Ziegler-Nichols method, which is a heuristic tuning method used to determine the optimal parameters for a PID controller. This method is particularly useful for systems where obtaining a model of the process is difficult. The Ziegler-Nichols method involves the following steps:

Step 1: Set the integral (K_P) and derivative (K_d) gains to zero.

Step 2: Increase the proportional gain (Kp) until the system output exhibits sustained oscillations. This gain is called the ultimate gain (Ku).

Step 3: Use Table 4.2 for setting parameters.

Table 4.2 Ziegler- Nichols method for the PID controller tuning

Controller	K_p	T_i	T_d
PID	$1.2\,T/L$	$2L$	$0.5L$

The tuned gains are summarized in Table 4.3. Note that $K_i = K_p/T_i$ and $K_d = K_pT_d$.

4.2.2 NPID controller

The NPID controller parameters were tuned by a GA such that minimizes the performance index defined in Equation (4.11). The tuned results are depicted in Table 4.3.

Table 4.3 Tuned PID and NPID controller gains

Controller	K_p	K_i	K_d
PID	17.400	57.000	0.870
NPID	6.425	2.375	0.403

4.3 Simulation of One-step Setpoint Changes

4.3.1 Simulation Scenario

To examine the setpoint tracking performance of the previously designed NPID controller, the following scenario was considered.

Scenario: The system is initially at the steady state of 1000rpm. A sudden setpoint change of 500 rpm is introduced, demanding a new desired output value (e.g., from 1000 rpm to 1500 rpm).

At this time, to quantitatively assess the performance of two methods, we measure metrics, such as the overshoot, rising time, settling time and IAE. IAE is defined by

$$IAE = \int_0^\infty | y_s(t) - y(t) | \, dt \tag{4.1}$$

where y_s is the setpoint and y is the output.

The maximum overshoot percentage (M_p) by which the system output exceeds the setpoint during transient response. It indicates how much the system overshoots before settling down. The rise time (t_r) denotes the time it takes for the system output to rise from 10% to 90% of the setpoint. It measures how quickly the system responds to a setpoint change. The settling time (t_s) denotes that the time it takes for the system output to remain within a specified percentage (usually ±2% or ±5%) of the setpoint. It measures how long it takes for the system to settle to its steady-state value. IAE measures the cumulative absolute deviation of the system output from the setpoint over time. It is an indication of overall tracking performance.

4.3.2 Setpoint tracking responses

Figure 4.1 presents the result of a simulation of the NPID controller under a one-step setpoint change scenario. Table 4.4 shows the setpoint tracking performance comparison of the two controllers. The response of the NPID controller was compared with that of the PID controller. Both controllers successfully drive the system output to the desired setpoint (around 1500 rpm). But the NPID controller exhibits a faster response with smaller overshoot, shorter settling time and smaller IAE compared to the PID controller. The control input of the NPID controller demonstrates smoother control action with less saturation.

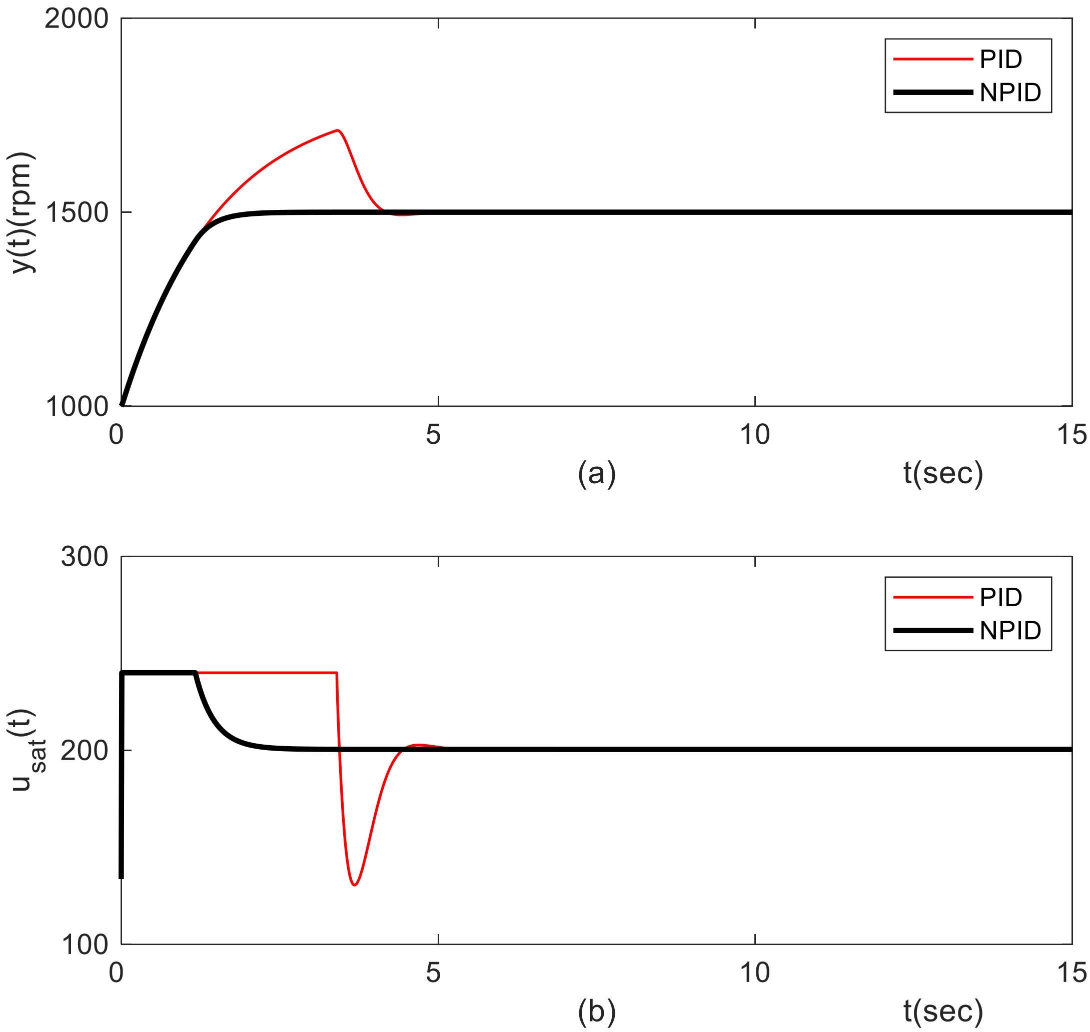


Figure 4.1 Responses of the PID and NPID controllers for one-step setpoint change (a) output, (b) control input

Table 4.4 Setpoint racking performance comparison of the two controllers

Controller	Performances			
	M_p (%)	t_r (sec)	t_s (sec)	*IAE*
PID	42.1586	1.1661	3.9872	633.7995
NPID	0.0036	1.1833	1.4989	328.2017

As seen in Table 4.4, the M_p of the PID controller is very large at 42.2%, while the M_p of the NPID controller is very small at 0.004%. The NPID controller has an extremely low overshoot, indicating that it closely follows the setpoint without exceeding it. Interpretation of the NPID controller significantly reduces the maximum overshoot compared to the PID controller, which is beneficial for systems where overshoot can be undesirable. The PID controller has a slightly shorter rise time compared to that of the PID controller. The PID controller takes longer to settling time within the acceptable range of 4 seconds around the setpoint. However, the NPID controller settles much faster compared to the PID controller. Interpretation of the NPID controller has a significantly shorter settling time (1.5 seconds), meaning it reaches and stays within the desired range around the setpoint more quickly than the PID controller. The NPID controller has a lower IAE value of 328, indicating better tracking performance with less cumulative error.

Overall, the NPID controller shows superior performance compared to the PID controller in terms of overshoot, settling time, and integral of absolute error, with only a marginal difference in rise time. This suggests that the NPID controller is more effective in tracking the setpoint with less error and faster response.

4.4 Simulation of Multi-step Setpoint Changes

4.4.1 Simulation Scenario

To examine the multi-step setpoint tracking performance of the NPID controller, the following two scenarios were considered.

Scenario 1: When the system was initially at rest, a sudden setpoint change of 500 rpm was introduced at 0 second. Then the setpoint was changed to 1000 and 1500 rpm at 15 and 30 seconds, respectively with the increment of 500rpm.

Scenario 2: When the system was initially at the steady state of 1500rpm, a sudden setpoint decrease of 500 rpm was introduced at 0 second. Then the setpoint was changed to 500 and 0 rpm at 15 and 30 seconds, respectively with the reduction of 500rpm.

4.4.2 multi-step setpoint tracking responses

Figure 4.2 shows the simulation results performed according to Scenario 1 and the response drawn. Figure 4.2(a) shows the output responses of the PID and NPID controllers for multi-step setpoint change and Figure 4.2(b) shows the control inputs of the two controllers.

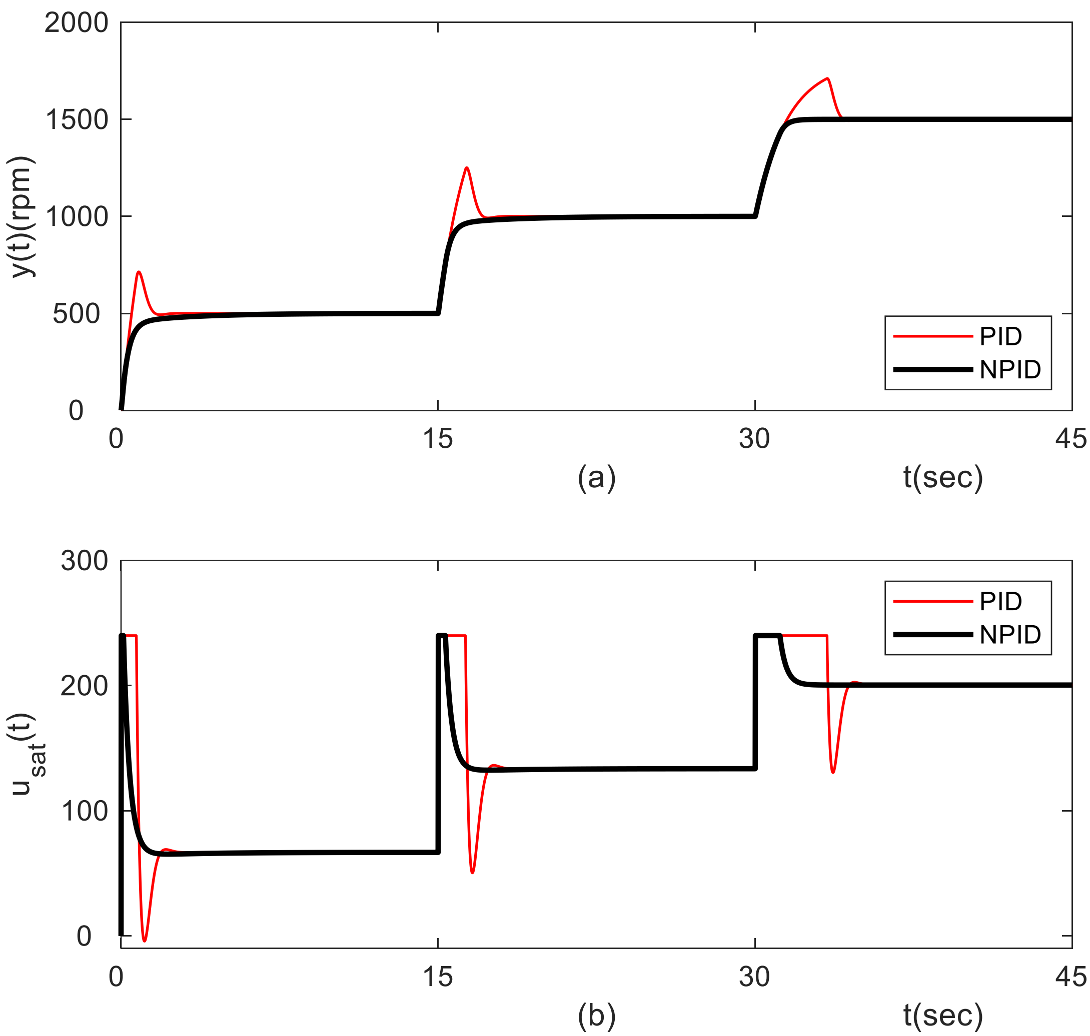


Figure 4.2 Responses of the PID and NPID controllers for multi-step setpoint change (a) output, (b) control input

It can be shown in Figure 4.2 that the output response of the NPID controller exhibits a smoother response with less overshoot compared to the PID controller. The NPID controller achieves faster settling times at each step change, indicating a more responsive control action. The PID controller shows significant oscillations and overshoot, particularly noticeable after each step-up change in the setpoint.

Figure 4.3 shows the simulation results performed according to Scenario 2 and the response drawn.

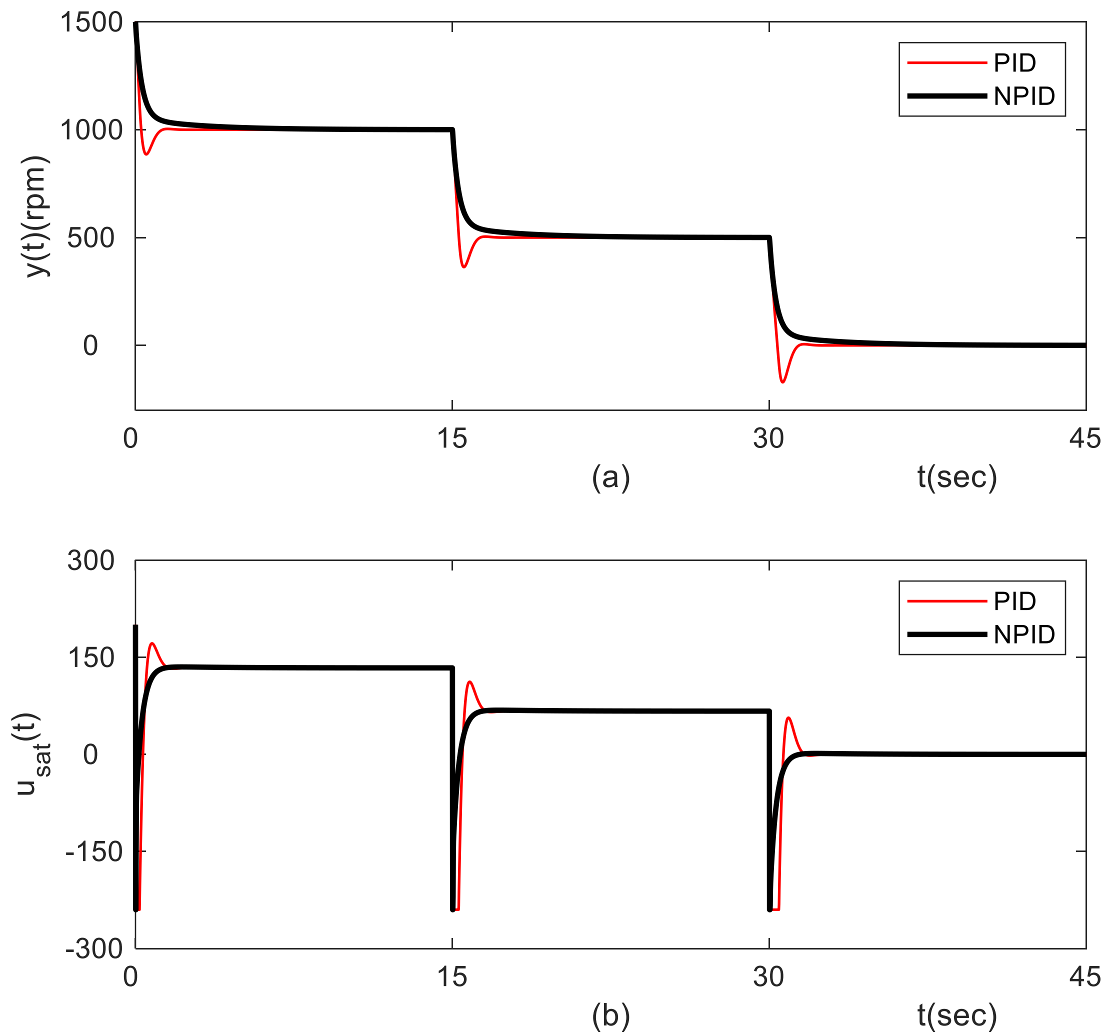


Figure 4.3 Responses of the PID and NPID controllers for multi-step setpoint change (a) output, (b) control input

Figure 4.3(a) shows the output response $y(t)$ of the stepdown system controlled by both the PID and NPID controllers. The system is subjected to a series of stepdown changes in the setpoint. Figure 4.3(b) shows the control input $u(t)$of the step-up system for both controllers. The control input from the NPID controller demonstrates smoother transitions and fewer abrupt changes compared to the PID controller. The PID controller's control input shows sharp spikes, indicating a more aggressive control action, which may lead to wear and tear on the actuators. The NPID controller maintains a more consistent and stable control effort, which can be advantageous in systems where actuator longevity and smooth operation are crucial. The NPID controller exhibits a smoother response with less overshoot compared to the PID controller.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This thesis has considered the design of the NPID controller for controlling speed of a dc motor with gear train and external load. The performance of the controllers was validated through simulations. From the comparative simulation results, one can conclude that the two controllers demonstrated nearly the same dynamic behavior under nominal condition. However, simulation results show that the NPID realized a good dynamic behavior of the motor with a rapid rise time, a settling time, overshoot and had better performance than the PID controller. But the comparison between the speed control of a dc motor by the NPID showed clearly that, the NPID controller gives better performance than the PID controller against parameter variations.

Key findings from the study include:

NPID controllers generally outperform linear PID controllers, particularly for complex systems characterized by nonlinearity and fluctuating disturbances.

NPID controllers are better suited to handle the inherent nonlinearities and uncertainties commonly found in belt drive systems, resulting in enhanced control performance.

NPID controllers can effectively minimize overshoot, settling time, and rise time, leading to more responsive and precise system behavior.

However, NPID controllers may necessitate greater computational resources and can be more susceptible to noise and measurement errors.

1. The proposed NPID algorithm significantly outperforms conventional methods in terms of computational efficiency.
2. A proportional controller (k_p) reduces rise time and can eliminate steady-state error.
3. An integral controller (k_i) eliminates steady-state error and can degrade transient response.
4. A derivative controller (k_d) improves stability, reduces overshoot, and enhances transient response.
5. The NPID approach using normalized values achieves high accuracy.
6. MATLAB is a powerful and user-friendly tool for simulating the entire project.

5.2 Recommendation

Based on the demonstrated superior performance of the Nonlinear PID (NPID) controller in comparison to the PID controller, particularly in terms of rapid rise time, settling time, overshoot, and robustness against parameter variations, we strongly recommend its implementation in the belt drive systems of the Kesem Sugar Factory.

The NPID controller's ability to effectively handle nonlinear dynamics and provide precise control offers several significant advantages:

Improved Efficiency: The NPID controller's faster response time and reduced overshoot can lead to more efficient operation of the belt drive systems, reducing energy consumption and increasing productivity.

Enhanced Quality: Precise control can contribute to a higher quality of the final sugar product by ensuring consistent and accurate material handling.

Increased Reliability: The NPID controller's robustness to parameter variations can improve system reliability and reduce downtime caused by unexpected changes in operating conditions.

Reduced Maintenance Costs: By minimizing system disturbances and optimizing control performance, the NPID controller can help prolong the lifespan of components and reduce maintenance costs

For simple belt drive systems with minimal disturbances and linear characteristics**,** linear PID controllers can be a viable option due to their simplicity and lower computational demands.

However, for more complex systems with nonlinear characteristics, varying disturbances, or stringent performance requirements, NPID controllers are strongly recommended.

When implementing NPID controllers, careful attention should be paid to the design of the adaptive gain scheduling mechanism to ensure stability and robustness.

To mitigate the potential drawbacks of NPID controllers**,** techniques such as noise filtering, robust control design, and advanced adaptive algorithms can be employed.

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