CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

There are solutions for every problem which we come across in our day to day life. Accidents are common in human life and due to accidents human bones are fractured. These fractures may be a minor crack or even they need a replacement. The branch of surgery dealing with the study of bone fracture is orthopaedics and the surgical practice of reducing and stabilizing fractured bones using mechanical connectors such as metal plates, rods, wires or screws is termed as Osteosynthesis. In Osteosynthesis low power electric motors are used to make joints in the fractured bones. Depending on the nature of fracture, a metal plate or screws will be attached with the fractured bone. These plates are screwed with metal screws. This thesis is mainly focused on the effective control of the permanent magnet direct current motors (PMDC) which are used for screw fixation in the orthopaedic surgeries.

1.2 BACKGROUND OF THE STUDY

1.2.1 Orthopaedic Surgical Simulators

Generally novice surgeons used to practice Osteosynthesis phenomenon in synthetic bones rather than live patients. This is because if carried out in live patients, the over tightening of screws may result in
additional bone fracture. The trainee surgeons undergo this practice with the help of a simulator in three phases namely screw insertion, tightening and stripping. The amount of torque required for screw fixation depends on the type and geometry of screw and the bone density. Each phase need different torque and it should be applied such that optimal screw fixation is obtained.

During 1990’s, research and case studies were presented in the area of orthopaedic surgeries, with focus on orthopaedic drilling tools. Allota et al (1996) studied the control of penetration for orthopaedic surgery and pointed out that the performance of the drilling tool is limited by lack of sensing means to discriminate the hard and soft tissue layers. A fuzzy logic based drilling system (Allota et al 1997) capable of detecting the layers of bone tissue and automatic feed stop according to the surgeon’s specification was proposed in their work. Baker et al (1996a and 1996b) submitted a case study focusing the design characteristics of a mechatronic drill system for ear surgery. In this system, the drill is controlled with respect to the tissue characterization. The PMDC motor is used in this system to produce the drill rotation along with various sensing components to measure axial force and torque on the drill and its displacement. A two level fuzzy logic lattice learning scheme was developed by Kaburlasos et al (1997 & 1998). They estimated the thickness of stapes bone using a force/torque pair of drilling profiles.

Many researchers focused on the drilling system with respect to mechanical parameters, which includes the size of the drill bit, the penetration depth, temperature rise etc. Matthews & Hirsch (1972); Lavelle & Wedgwood (1980); Eriksson & Albrektsson (1984a and 1984b); Abouzgia & Symington (1996); Natali & Ingle et al (1996); Toews & Bailey et al (1999); Bachus & Rondina et al (2000); Nicky Bertollo & William Robert Walsh (2011) concentrated on the conversion of mechanical energy into thermal
energy during the drilling process. The study was carried out on the aspects of transients in temperature rise of adjacent bone and soft tissues during the drilling process. Krause et al (1982) investigated on combined feed rates and the depth of cuts for the cutting burs. Their study concluded that the temperature rise in bone due to an increase in rotational speed was dependent upon the particular bur. The temperature decreases when the feed rate increases, whereas it increases with increase in depth of cut.

Mustafa et al (1995) investigated the effect of force on drill speed and the energy consumed during the drilling process. The investigations were made for a wide range of speed and load. Their findings concluded that the average operating speed changes with the force applied and the energy consumed decreases with speed and force as the drilling time is reduced. Abouzqia & Symington (1996) fitted a speedometer to a surgical drill and monitored the rotational speed during the drilling process. They focused on the temperature rise for a wide range of speed and force. With this experimental set up they determined the effect of the speed and force on the temperature rise and suggested high drilling speed and torque to reduce the temperature rise. Reingewirtz et al (1997) analyzed the influence of parameters such as drilling speed and drilling load applied on the bone during drilling. The drilling time will be reduced with increase in speed of rotation and is inversely proportional to the square of the load. The amount of temperature rise depends on drill geometry and diameter, rotational speed, feed rate, axial thrust force and initial drill bit temperature. The outcome of these studies pointed that the speed control and duration of the drilling also plays a vital role in deciding the temperature rise.

measurement at the drill bit has been described in their study. The heat generated in the drill bit is proportional to the drilling speed and they experimentally verified the temperature variations for various speed, with different feed rate chosen arbitrarily.

Allan et al (2005) devised an in-vitro experiment to simulate preparation for Osteosynthesis using different drills with different degrees of wear. According to them the amount of wear of drill bit is directly proportional to the significant difference in the temperature. Their study justified that the large rise in temperature impairs bone regeneration and contributes to failure of internal fixation. They also advised to discard the drills after a single use, as the cost of the drill is low. A new drilling system for bone grafting was suggested by Eduardo Anitua et al (2007). The new drilling procedure based on the biologic criteria using a very low drill speed of 1000 to 1500 rpm recommended by them reduces the severity of the damage of the host tissue.

Augustin et al (2008) combined the drill speed with the drill diameter and used external cooling agent to reduce the temperature rise below the critical level. They inferred that the increase in drill diameter and drill speed increases the bone temperature. With the use of external cooling agent, increase in feed rate decreases the bone temperature. Aksakal et al (2011) observed that the increase in drill speed causes rise in temperature whereas it decreases with increase in feed rate and applied drill force. A statistical and histopathological analysis was made by them on the temperature changes in both male and female bovine tibias. Their work concluded that the maximum value of temperature depends on drill tip angle and bone mineral density. Increase of these factors increases the maximum value of temperature rise.

Burak Oezdoganlar et al (2011); Yoed Rabin et al (2012) investigated the thermal exposure of bone during the drilling process. An
experimental investigation was made to study the effect of spindle speed, feed rate and depth of drilling on the temperature distribution during drilling of the cortical section of the bovine femur. In the experimental analysis of temperature rise, the thermocouples are used to measure the bone temperature. But fixing of the thermocouples in the immediate vicinity of the drilled hole is tedious. Yung-Chuan Chen et al (2013) developed a method of analysis to measure the temperature rise in the immediate vicinity of the drilled hole and also presented the finite element simulations of the temperature rise during bone drilling. It has been concluded in their study that the cause for the temperature rise in the bone is high drilling speed even for a constant drill feeding rate in their study.

In early 2000 robot assisted surgeries came into existence. Ming-Dar Tsai et al (2007), proposed a haptic simulator, which computes the drilling forces and torques based on reliable metal removing theorem. Olga Sourina et al (2007) developed a software simulator which helps in understanding of the complex 3-dimensional relationships between bones and implants. This software allows for better and more precise surgery by letting the surgeon practice the surgery in a virtual environment. Boiadjiev (2007) recommended automatic drilling system for orthopaedic surgery using a robotized drilling module.

A mechatronic screw driver was proposed by Thomas et al (2008). Their system controls the tapping depth and also prevents over-tightening of screws. They investigated the effect of various parameters in the synthetic bone and sheep tibia. Bone drilling process currently depends on surgeon’s manual skill. Ann Majewicz et al (2010) designed a haptic simulator for the screw insertion in osteosynthesis process. They developed a one degree of freedom friction based haptic device and evaluated the system by sensing the
vertical motion of the screw and device calibration based on measurements in human bone.

A modular drilling system with fuzzy logic controller was proposed by Shih-Tseng Lee et al (2001). They developed and tested the system on the aspects of current consumed by the DC motor of the drill. Inaccurate penetration in the bone may harm the soft tissues. This problem was addressed and a new micro Vibrated robot was designed and proposed by Supawat Sarakankosol (2011). The robot developed by them senses the torque based on current and controls the depth of penetration. Kazimir Zagurski (2012) discussed the features of automatic bone drilling and the problems associated with it. The approach was focused on increasing the safety conditions in robotized drilling system. Wen-Yo Lee & Ching-Long Shih (2013) attempted to solve the problems associated with bone drilling. They physically realized a DC motor drilling system which can drill with a constant drilling force and can automatically stop drilling at the moment of breaking through of the bone. This system controls both the drilling motor and feed rate. It uses an algorithm that detects the breakthrough of the bone using the threshold information of the thrust force, the trend of the drilling torque and the feed rate as well. For validation, the results of the algorithm were compared with experimental values in their study.

1.2.2 PMDC Motor

Ismail Altas (2007) developed the MATLAB/Simulink model of the PMDC motor and simulated its characteristics. The simulation was carried out by using the dynamic model of the PMDC motor proposed for a light tracking servo system. The transfer function model of the PMDC motor was suggested and its step response has been analyzed in his study. Chandrasekaran & Thiyagarajah (2011) modeled the PMDC motor for solar
powered pumping systems. Sankar & Rama Reddy (2011) presented the
digital simulation of the PMDC motor.

1.2.3 Chopper Controlled PMDC Motor Drives

Castagnet & Nicloai (1999) proposed a cost effective microcontroller based chopper controlled drive for speed control of PMDC motor drives for home appliances. Ismail Altas (2007) presented a novel control scheme for PMDC Motor. This control scheme consist of PWM based DC-DC chopper controlled by general predictive controller. The performance of the scheme is compared with its counterpart PI controller based system in their work. A fuzzy based transient analysis of chopper controlled drive was presented by Norul Islam et al (2011). They modeled a closed loop scheme with current and speed feedback loops for a chopper controlled generator coupled to a separately excited DC motor. A flexible chopper controlled system using H-bridge was proposed by Shakil Seeraji et al (2011). They varied the pulse width of the PWM signal which in turn varies the voltage fed to the PMDC motor. A microcontroller based adjustable closed loop speed controller was designed and proposed by Ettomi et al (2003). Huangsheng Xu et al (2007) enhanced the dynamic response of the microcontroller scheme proposed with a current control loop. The closed loop chopper controlled drive systems discussed so far utilize a traditional P, PI and PID controller system or a fuzzy logic based controller or a neural network based controller. The simulation studies of these schemes show that they have very high peak overshoot, poor steady state and transient state responses.

1.2.4 Controllers

Automatic control system may have traditional or modern controllers. The function of these controllers is to regulate the process of the system and to obtain the desired output. It is known that the conventional
controllers include P, PI, PD or PID controllers. For traditional controllers, the mathematical model of the process is required to design them whereas the modern controllers viz., fuzzy, neuro and neuro-fuzzy controllers do not require the same.

1.2.4.1 Traditional Controllers

Most of the industrial control processes are nonlinear in nature and thus the mathematical model to describe them becomes complicated. Ziegler & Nicholas (1942) studied that the nonlinear process can be satisfactorily controlled by optimal tuning of the PID controller. Their work formed the platform for the wide application of conventional controllers in the field of automatic control systems.

The traditional PID controller can be implemented as P, PI, PD or PID controller. Depending on the nature of the system the type of controller can be chosen. P controller utilizes the proportional gain. However, it has the disadvantages of increased peak overshoot apart from introducing steady state error. The use of PI Controller in a closed loop system eliminates the steady state error in the system but it may cause some oscillations when large value of integral gain is used. The PID controller on the other hand tries to reduce the oscillations with the help of small derivative gain.

Most of the PMDC motors are used for position control applications. The feedback of the speed and position sensor is processed through the PI or PID controllers and the desired position is obtained. Sharaf et al (2007) proposed a novel control strategy using PID algorithm for the control of PMDC motor which is powered from photovoltaic cell. Nitai Pal et al (2012) dealt with the closed loop speed control of DC motors used in rock drilling and mud pump applications. In this application PID controller is used to regulate the speed of the motor. Ba-Hai Nguyen et al (2009) proposed
a novel robust control techniques using PD controller for the effective speed control of DC motors.

1.2.4.2 Modern Controllers

It is known that, modern controllers don’t use the mathematical model. They are developed using knowledge based approach where the past performance of the system is taken into account. The controllers are trained and tuned based on the previous response of the system. Fuzzy Logic Controller (FLC) is a rule based decision making system used for process control and used mainly for imprecise data processing. They are knowledge based systems. Based on the type of response required, the rules are framed. Arpit Goel et al (2012) studied the various fuzzy techniques used for the control of PMDC motors. Moussavi et al (2012) studied and analyzed the combination of adaptive and fuzzy controller for PMDC motors.

Iracleous & Alexandridis (1995) proposed a new approach for tuning the PI controller for effective speed control of series connected DC motor system. They tuned the parameters of the PI controller system using the fuzzy logic approach. Rui Zhang et al (2009) simulated a fuzzy self-tuned PID control strategy for DC motors in order to control the speed of the motor effectively. Essam Natsheh & Khalid Buragga (2010) compared the performance of fuzzy tuned PID controller with traditional PID controller and concluded that the fuzzy tuned PID controller results in improved steady state and transient state performance of the DC motor drives.

1.2.5 Conclusion

From all the aforesaid studies, it is clear that drilling speed, feed rate and drill bit geometry are the parameters which cause the temperature rise in bones during the drilling process. This Thesis focuses on the speed control
of the drill as the other parameters such as feed rate and drill bit geometry are treated as constant. It has been done so because the feed rate varies from surgeon to surgeon (Hillery & Shuaib 1999), and the drill geometry is determined by the bone density. The chopper controlled drive for the PMDC motor is simulated with traditional PI Controller system and its performance have been enhanced using Anti-Windup schemes.

A fuzzy tuned Anti-Windup scheme and an Intelligent Emotional Controller called Brain Emotional Learning Based Intelligent Controller (BELBIC) have been proposed for the further improvement in performance of the conventional PI controller scheme. These two controllers’ schemes are built with the combination of traditional and knowledge based controllers. The controllers are used to generate the appropriate command for PWM signal required by the chopper. Depending on the type of surgery the speed is set and by varying the output voltage of the chopper, the desired speed is obtained in the motor based on the PWM signal generated. The proposed drive has an inner current control loop to switch ON / OFF the motor and an outer speed control loop to control the speed.

1.3 OSTEOSYNTHESIS – AN OVERVIEW

Broken pieces of a fractured bone must be set back into appropriate place and should be held together to heal correctly. This process of setting of the bones is termed as reduction. The reduction process is of two types’ viz., external reduction and internal reduction. Setting of the broken pieces without surgery is called closed or external reduction, whereas when setting is assisted with surgery, it is termed as open or internal reduction. During internal or open reduction mechanical devices like glue, pins, plates, rods or screws will be used to hold the broken pieces together. This procedure of healing the bone fracture with mechanical device is labeled as osteosynthesis.
Hip and wrist fractures are most usual fractures cured by osteosynthesis. Wrist fractures are most common in youngsters. In this case, if the fracture is severely misaligned, then osteosynthesis is recommended. The hip fracture can occur in three areas, the femoral neck, and the intertrochanteric area and at the sub trochanteric area. The femoral neck is a narrow area where the ball and socket of the joint meet. The portion of the hip directly beneath the ball and socket portion is the intertrochanteric area and the lower portion of the hip which reaches the upper leg is sub trochanteric area. When fracture occurs in femoral neck, surgical screws are used to stabilize the fracture. Other than the femoral neck, if fracture occurs elsewhere, the fracture is repaired by using plates and screws.

1.3.1 Surgical Pins

In osteosynthesis phenomenon, surgical pins are used to connect bones involving joints. These pins are made of non-magnetic materials such as stainless steel or titanium. Based on the type of injury, placement and degree of stabilization, the screws may be removed after healing or they may be left in place. Now-a-days biodegradable pins and anchors are developed. These pins are currently made from polymer materials or magnesium alloys, which will dissolve as the bone gets healed. The main advantage of using these screws is they cause less irritation to the surrounding tissues.

1.3.2 Bone Drill

The purpose of bone drill is to create the holes to attach the surgical pins and screws attach to. By proper drilling and screwing the broken bones can be brought together and the fracture can be cured. The bone drills are made of surgical-grade materials. The diameter of the bone drills vary from 1.5 mm to 6mm according to the American Iron and Steel Institute (AISI) standards. During pin installation, surgeons may require to ream a hole to fit
the pin properly. The bone drill performs this function with ease. The bone drills fitted to hand power tools helps by reducing the time of screw or pin fixation. The bone drill is electrically powered and has a motor operating at higher speed. The advantages of electric bone drill are rapid operation and capability of creating a precise sized hole in the bone.

1.3.3 Bone Screw

Bone Screws are usually made of non-reactive materials. They are implanted into the bone to protect the unfractured bone segments from moving around. The screw secures the broken pieces of bone together to allow it to heal properly.

1.3.4 Drilling Procedure

Usually, the surgical bones were clamped to the work table and then drilled. The novice surgeons are allowed to practice with minimum of two holes for a particular speed and feed rate. During the high speed drilling, wedging of the drill-bit may occur due to the chips not clearing along the flutes. This wedging may result in fracture of drill-bits. The speeds used for drilling ranges from 300 to 2000 rpm (Toews et al 1999; Hiilery & Shuaib 1999). Normally used feed rate is ranged from 40 to 60 mm/min and is chosen arbitrarily.

1.4 ORTHOPAEDIC SURGICAL TRAINING

During the surgical training, novice surgeons should fix the fractures on synthetic bones using surgical tools and implants. A typical type of fractured bone is shown in Figure 1.1.
Figure 1.1 Synthetic bones with fracture

The trainee surgeons will be provided with good quality synthetic bones which are made from the materials with different densities and textures on the surface and inside to simulate real bones. Students need to reduce the fracture and fix it internally using implants that can be selected from hundreds of different plates, screws, nails and wires. The trainee surgeons use different surgical instruments to drill the holes, measure the length, and insert the implants etc. Figure 1.2 shows the stabilizing of fractured pelvis by insertion of screws. The training lab doesn’t need a real human body or anesthesia and assisting nurses. The trainees will be allowed to work independently.

Figure 1.2 Insertion of Screws to stabilize a fractured pelvis
1.4.1 **Computer Assisted Surgical Simulators**

Orthopaedic surgery necessitates understanding of complex 3-dimensional structure of bones. They also associate with the relationship of bones with nerves, blood vessels and other vital structure. The teaching and learning process of orthopaedic surgeries requires spatial skills, needs more time and practice. The use of computers in the training session reduces the time required for learning, presents a visual effect for the novice surgeons to understand the concepts easily and saves cost and equipment. They also help practitioners to simulate more complex problems and to plan the operations according to the degree of complexity. The simulators provide virtual environment including the operation room, human body parts reconstructed from Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) scans, surgical instruments and implants, real sounds imposed into the scene and force feedback and collision detection.

The simulator utilizes a software module, which deals with the models of bone, surgical instruments and they consist of fractured and unfractured bones. Selecting a proper bone (ex: pelvis bone, femur, foot and ankle etc.), a fracture can be made on it. Depending on the bone selected and fracture made, depth for screw insertion, screw thickness, and length of the screw will be simulated using the software. From the simulated data the trainee surgeons can practice drilling and screw insertion. The motor used for drilling is PMDC Motor. Based on the data simulated the surgeons need to control the operation of the motor. This thesis aims at designing a closed loop control technique for the effective control of the PMDC motor used in this orthopaedic drilling system.
1.5  PMDC MOTORS

Earlier in the 19th century PMDC Motors were introduced. The magnetic materials used were steel and tungsten steel which have poor magnetic property. Hence, electromagnetic field excited motors became popular. The advance in magnetic materials such as rare earth magnet resulted in improved steady state performance and power density of the motor. Because of these advances and better performances PMDC motors found a wide application in medical instruments, automobiles, computer peripherals, robots etc. Some of the benefits that PMDC motors possess are:

1. Higher efficiency since no loss in field circuit
2. Linear torque speed characteristics
3. Higher magnetic flux density in air gap and so better dynamic performance
4. Compact size
5. Simplified construction
6. Free from maintenance
7. Wide operating speed range
8. Ability to adapt a range of power sources

1.5.1  Construction

The use of permanent magnets in PMDC motors makes them to be compact in size, lighter and more efficient. These motors are constructed as brushed and brushless motors. The brushed motor uses a rotating armature winding and a stationary field permanent magnet, whereas the brushless motor uses a stationary armature which is commutated externally by an
electronic control and rotating permanent magnets. In orthopaedic surgical simulators permanent magnet brushed DC motors are used.

1.5.2 Brushed DC Motor

A brushed DC motor consists of a rotating armature and stationary field made of permanent magnets. The armature windings are mounted on a rotating shaft and the shaft also carries the commutator. The commutator periodically reverses the flow of current in the windings and rotates the shaft. The external electric power is fed to the windings through the one or more pair of brushes that bear on the commutator. The rotating armature has a one or more coils of wire wound around a laminated magnetically through soft ferromagnetic core. Current from the brushes flows through the commutator and one winding of the armature, making it a temporary magnet. The magnetic field produced by the armature interacts with the stationary magnetic field produced by the permanent magnet. The force between the two magnetic fields tends to rotate the motor shaft. The rotor keeps rotating as long as power is applied through the brushes. Figure 1.3 shows the electric circuit diagram of PMDC motor.

![Figure 1.3 Electric Circuit Diagram of PMDC Motor](image)

Figure 1.3 Electric Circuit Diagram of PMDC Motor
1.5.3 Armature

The armature of the PMDC motor is similar to conventional DC motors. It consists of winding slots, commutator segments and brushes. PMDC motors are free from armature reaction, as the field caused by armature windings doesn’t affects the main field flux produced by permanent magnets.

1.5.4 Field Magnets

The field permanent magnets may be of surface-mounted or interior-mounted. Surface-mounted magnets are less expensive but are not suited for high speeds. Interior-mounted are also called as flux concentrating machines. They overcome the shortcoming of surfaced mounted machines in terms of air gap flux density, harmonics shielding and structural integrity. During 19th century, magnets were made of iron but nowadays they are made from alloys of copper, silver and gold made superior magnets. In 1932, Alnico an alloy of AL, Fe NI and Co was developed for permanent magnet field excitation. Alnico magnets are used in motors having ratings in the range of 1 kW to 150 kW. The other magnetic materials that have been developed recently are neodymium-iron-boron alloy, ceramic and rare earth magnets. Rare earth magnets are alloys of samarium-cobalt. They are the highest performing magnetic materials but are expensive. The neodymium-iron-boron alloy performs 30% better than samarium cobalt alloys, but they have poor corrosion resistance. Protective coatings have been developed to overcome this deficiency. Ceramic magnets are alloys of barium ferrite and strontium ferrite. They possess much higher coercive forces than alnico and their ability to resist demagnetization are better. Ceramic magnets are used for fractional kilowatt rating motors.
1.5.5 **Commutator**

The commutator is fixed to the shaft of the armature, and rotates while maintaining contact with the brushes. This means the direction of the current running through the electromagnetic coils, also known as the polarity, reverses with every half-turn of the armature. This keeps the armature turning in the same direction, instead of oscillating back and forth.

1.5.6 **Brushes**

Brushes are spring-loaded carbon contacts. The springs hold the brushes in contact with the commutator.

1.5.7 **Mathematical Model**

The high torque output and quiet operation characteristics of PMDC motor makes them to use in orthopaedic surgeries and surgical simulators. For an applied voltage of $V_a$ volts, the motor draws a current of $I_a$ amps and develops a back emf of $V_c$ volts. The equivalent circuit of the PMDC motor is shown in Figure 1.4. Using it the electrical and mechanical characteristics of the motor are derived and verified by Ismail Atlas (2007); Shankar & Rama Reddy (2011).

![Equivalent Circuit model](image)

*Figure 1.4 Equivalent Circuit model*
In the equivalent circuit model $V_a$ is the armature supply voltage, $L_a$ is armature inductance, $R_a$ is armature resistance with an induced voltage $V_c$. The induced voltage $V_c$ opposes the supply voltage $V_a$ and is due to the rotation of the electrical coil through the fixed flux lines of the permanent magnets. This voltage is referred to as the back emf. The equations governing the mathematical model are derived as follows:

$$V_a = V_c + I_a R_a + L_a \frac{dI_a}{dt} \quad (1.1)$$

$$V_c = K_1 \omega_a \quad (1.2)$$

$$T_E = T_L + B \omega_a + J_{eq} \frac{d \omega}{dt} \quad (1.3)$$

$$T_E = K_2 I_a \quad (1.4)$$

Where,

- $V_a$ - armature supply voltage in V
- $V_c$ - induced voltage in V
- $R_a$ - armature resistance in Ohms
- $L_a$ - armature inductance in H
- $I_a$ - armature current in A
- $K_1$ - voltage constant in volts sec/rads
- $\omega_a$ - angular speed in rads/sec
- $T_E$ - electromagnetic torque developed in Nm
- $T_L$ - load torque in Nm
- $J_{eq}$ – Total Moment of Inertia of motor and load in kg.m$^2$
- $B$ - Damping Coefficient in Nms
- $K_2$ - torque constant in Nm/A
The differential equations governing the motor model are arrived from the electrical and mechanical characteristics as

\[
\frac{dI_a}{dt} = -\frac{R_a}{L_a} I_a - \frac{K_1}{L_a} \dot{\theta}_a s + \frac{V_a}{L_a}
\]

(1.5)

\[
\frac{d\dot{\theta}_a}{dt} = \frac{K_2}{J_{eq}} I_a - \frac{B}{J_{eq}} \dot{\theta}_a - \frac{T_l}{J_{eq}}
\]

(1.6)

From the Equations (1.5) and (1.6) the state space model of the motor system is derived as

\[
\frac{d}{dt} \begin{pmatrix} I_a \\ \dot{\theta}_a \end{pmatrix} = \begin{pmatrix} \frac{-R_a}{L_a} - \frac{K_1}{L_a} \\ \frac{K_2}{J_{eq}} - \frac{B}{J_{eq}} \end{pmatrix} \begin{pmatrix} I_a \\ \dot{\theta}_a \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} \frac{1}{L_a} V_a + \begin{pmatrix} 0 \\ 0 \end{pmatrix} \frac{1}{J_{eq}} T_l
\]

(1.7)

\[
\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I_a \\ \dot{\theta}_a \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V_a \\ T_l \end{pmatrix}
\]

(1.8)

Where,

\[
Y_1 = \frac{d}{dt}(I_a) \quad \text{and} \quad Y_2 = \frac{d}{dt}(\dot{\theta}_a)
\]

From the above expressions the following block diagram representation is obtained. Figure 1.5 shows the block diagram representation of PMDC motor.

![Figure 1.5 Block Diagram Representation](image-url)
1.5.8 Characteristics

The speed torque characteristics of a PMDC motor is linear. As torque increases, the speed decreases linearly. The rated torque is defined for continuous duty cycle operation. High speed PMDC motors can also be made for low duty cycle and short time operation. Lower the duty cycle, higher is the torque capacity. But the temperature increase in the windings may resist the over load capacity. For motor carrying high current, the performance can be affected by brushes and commutator. The use of proper heat sink increases the load capacity.

![Characteristics of PMDC Motor](image)

(a) Performance Characteristics

Figure 1.6 (Continued)
Figure 1.6 Characteristics of PMDC Motor

The elimination of armature reaction is due to high reluctance caused by the constant field of permanent magnets. It permits a linear operation over the entire speed torque range. With a constant armature voltage, when the torque increases the speed decreases. As shown in Figure 1.6(b), as the applied voltage increases, the speed torque curve shift upwards. In PMDC motors, speed is proportional to voltage and torque is proportional to current. In the figure 1.6(b), $I_{FL}$ refers to full load current, whereas $I_1$, $I_2$, $I_3$ and $I_4$ are stalling currents with respect to voltages $V_1$, $V_2$, $V_3$ and $V_4$ respectively.

The equivalent circuit parameters of the PMDC motor taken into consideration are determined as given in Table 1.1. The motor capacity is 52W, 9V, 4990 rpm.
Table 1.1 Specifications of PMDC Motor

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Output Power ($P_o$)</td>
<td>52W</td>
</tr>
<tr>
<td>2.</td>
<td>Input Voltage ($V_a$)</td>
<td>9V</td>
</tr>
<tr>
<td>3.</td>
<td>No-Load Speed ($N_o$)</td>
<td>4990 rpm</td>
</tr>
<tr>
<td>4.</td>
<td>Armature Resistance ($R_a$)</td>
<td>1 Ω</td>
</tr>
<tr>
<td>5.</td>
<td>Armature Inductance ($L_a$)</td>
<td>0.13 mH</td>
</tr>
<tr>
<td>6.</td>
<td>Moment of Inertia (J)</td>
<td>$4.8e^{-6}$ kg-m$^2$</td>
</tr>
<tr>
<td>7.</td>
<td>Damping Coefficient (B)</td>
<td>$6.04e^{-6}$ N-m/rads/sec</td>
</tr>
<tr>
<td>8.</td>
<td>Voltage Constant ($K_1$)</td>
<td>$1.7e^{-2}$ volts/rads/sec</td>
</tr>
<tr>
<td>9.</td>
<td>Torque Constant ($K_2$)</td>
<td>$1.68e^{-2}$ N-m/A</td>
</tr>
</tbody>
</table>

Using the above parameters and from the mathematical model the speed torque characteristics of the motor has been simulated. The simulation model used to study the characteristics has been illustrated in Figure 1.7.
To study and analyze the performance of the motor, the torque versus speed characteristics has been simulated for various supply voltages and plotted as shown in Figures 1.8 (a), 1.8 (b), and 1.8 (c).

(a) **Input voltage of 3V**

(b) **Input voltage of 6V**

*Figure 1.8 (Continued)*
(c) Input Voltage of 9V

(d) Various Input Voltage Levels

Figure 1.8 Simulated Torque Speed Characteristics

Figure 1.8(d) depicts the comparison of simulated torque speed characteristics for various voltage levels. The simulated result indicates that the torque speed characteristic of the motor is linear in nature.
1.5.9 Speed Control

The flux of the PMDC motor remains constant and so speed cannot be controlled by using flux control method. The only way to control the speed is by using armature voltage control method. This can be achieved by inserting a resistor in series with the armature. But there will be a drop in the resistor and also energy loss occurs in the resistor. The speed of a PMDC motor can also be controlled by varying the applied voltage \( V_a \). The variation of speed is achieved by using choppers. Usually closed loop chopper control technique is employed based on the application. The duty cycle of the chopper is varied which in-turn varies the voltage applied to the armature, resulting in varied speed of the armature in a wide range. The armature voltage control method is used in systems where speed control below base speed is required. In this Thesis, a speed control loop is employed for controlling the speed of the PMDC motor.

1.6 CONVENTIONAL CONTROLLERS – AN OVERVIEW

The traditional controller tries to minimize the error between the measured and desired outputs. After World War II, electrical systems with PID controllers were developed. These PID Controllers were used to control and maintain the processes. They were designed and implemented using current error, past error and rate of change of error. Today’s process industries have wide application of PID controllers to control temperature, pressure, flow rate, tank level, speed and current etc. The use of PID controllers provides accurate control under different process conditions. Basically PID control algorithm is a simple equation that the controller uses to evaluate the controlled variables.
The working of a PID controller can be described as for instance, if speed is the controlled variable, then it is measured and feedback to the controller. Based on the set value and the current value, the error is generated. The error value is examined with the PID algorithm. Finally, the controller issues the necessary commands and alters the process inputs such that the error is eliminated. The phenomenon of PID control is iterative in nature. The PID algorithms provide straightforward correlations between the process and responses. Along with these advantages, the other features are they are easy to use and tune. The structure of the PID controller can be P, PI, PD or PID. The values of three parameters proportional, integral and derivative constants are chosen as numerical values in order to tune the controller. The reaction of the proportional constant is based on the current error, the integral constant’s reaction is based according to the total of recent errors, and the reaction of derivative constant is the rate at which the errors have been changed.

1.6.1 P Controller

The P controller utilizes the gain $K_p$ and produces the output value which is proportional to the current error value. Adjusting the gain value $K_p$ will adjust the response of the controller. The P controller is governed by the Equation 1.9.

$$P_{out} = K_p e(t)$$  \hspace{1cm} (1.9)

1.6.2 PI Controller

In a PI Controller, with the proportional band ($K_p$) the controller produces the output proportional to the error and the integral action produces the output proportional to the amount of time the error is present. Due to the proportional controller offset will be present and increasing the $K_p$ value will
make the loop go unstable. The integral action eliminates the offset. The absence of integral term prevents the system from reaching the target value and so PI controllers are used commonly. The PI controller is governed by the Equation 1.10.

\[ P_{out} = K_p e(t) + K_i \int e(t) \] (1.10)

1.7 CHOPPER CONTROLLED PMDC MOTOR DRIVE SYSTEM

In general, the PMDC motor drive system consists of a chopper with any conventional controller. The chopper provides variable voltage based on the speed requirement. The chopper drive employs controller in order to keep the motor speed at any desired set-speed under changing load conditions. The controller processes the error between the set and actual speed of the motor and generates the appropriate command for driving the switches. The starting current of the DC motors will be high due to the absence of back emf. This may cause damage to the armature windings, which can be avoided by employing a current controller in the drive system.

In general PMDC motor drive system, the function of current controller is to limit the value of current within its rated value. Due to the addition of current controller, the motor input voltage \( V_a \), depends both on the speed and current controllers. It should be ensured that \( V_a \) is applied in such a way that the motor during positive and negative torque, does not draw more than the rated current. So, an inner current loop hence current controller is required. The chopper works on PWM technique and produces variable DC output voltage, without any time delay. Hence it can be represented by a simple gain function \( K_3 \) in the block diagram as shown in Figure 1.9.
Figure 1.9 Block diagram of Chopper Driven PMDC Motor System

The speed and current limiter functions of the speed and current controllers depend on the motor-load parameters $R_a$, $L_a$ and $J_{eq}$. $K_3$ is the gain of the chopper circuit; $K_4$ and $K_6$ are current and speed controller gains respectively. The speed and current filter constants are denoted by $K_7$ and $K_5$ respectively. The block diagram illustrated in Figure 1.9 is a general block diagram. Depending on the applications, the controllers are selected and the gains are fixed. In this study, the current control loop employs a current controller in order to ON/OFF the chopper switch. The speed control loop employs conventional or proposed modern controllers, which governs the entire operation of the chopper drive system.
1.8 OBJECTIVE OF THE THESIS

The aim of the study is to develop an efficient closed loop chopper controlled drive for PMDC motors used in orthopaedic surgeries and surgical simulators and it can be listed as follows:

1. Developing a simulation model for the chopper drive employing a traditional PI controller and to analyze its performance using MATLAB / Simulink.

2. Analyzing the various anti-windup schemes to enhance the performance of the drive.

3. Simulating a Fuzzy Tuned AWPI Controller based chopper drive and analyzing its performance.

4. Developing and simulating a BELBIC based chopper drive and validating the simulation results through an experimental setup.

5. Comparing the performance of the traditional controller based drive with various proposed modern controller schemes.

6. Demonstrating the superiority of the proposed schemes.
1.9 APPROACH FLOW DIAGRAM

CERTAIN INVESTIGATIONS ON CHOPPER CONTROLLED DRIVE FOR PMDC MOTORS USED IN ORTHOPAEDIC SURGERIES

- Study of Mathematical Model and Simulation of Characteristics of PMDC Motor
- Development of Closed Loop Chopper Control Drive for PMDC Motor with Inner Current Control Loop and Outer Speed Control Loop for Drilling and Screwing Modes
- Simulation and Analysis of Chopper drive with conventional PI controller

Enhancing the Performance of Chopper Drive using following techniques
1. Anti-Windup Schemes
2. Fuzzy Tuned Anti-Windup Schemes
3. BELBIC Scheme

- Design and Simulation of following AWPI Schemes
  - Back Calculation AWPI Scheme
  - Conditional Integration AWPI Scheme
  - Dead Zone AWPI Scheme
  - AWPI with tracking

- Simulation of Fuzzy Tuned AWPI Controller Scheme
- Simulation of BELBIC Based Chopper Controller Scheme
- Performance Analysis of the Fuzzy Tuned Anti-Windup Scheme based chopper drive
- Performance Analysis of the BELBIC based Chopper Drive

- Performance Analysis of the Anti-Windup Schemes based chopper drive
- Hardware Implementation BELBIC Based Chopper Controller Scheme
- Validation of experimental Setup

Performance Comparison and Analysis of the aforesaid controller schemes with conventional PI controller scheme based chopper drive

Inferences and Conclusions

Figure 1.10 Approach Flow diagram
1.10 ORGANIZATION OF THE THESIS

The remaining chapters of the Thesis are organized as follows:

Chapter 2 describes the simulation study of the closed loop chopper controlled drive employing traditional P and PI controller scheme. It also highlights the disadvantages of the schemes.

Chapter 3 illustrates the phenomenon of integral wind-up problem and the simulation studies of the chopper drive with the following anti-windup schemes viz., back calculation, conditional integration anti-windup, dead zone and tracking anti-windup.

Chapter 4 depicts the simulation of the fuzzy tuned AWPI controller based chopper controlled scheme. The simulation studies have been done and the performance of the scheme has been analyzed.

Chapter 5 elucidates the BELBIC based chopper controlled scheme. This is followed by the explanation of simulation and experimental results.

Chapter 6 compares the performance of the traditional controller schemes with the various proposed controller schemes. Superiority of the proposed schemes on the aspect of control system is demonstrated.

Chapter 7 summarizes the work presented in the Thesis. The main contribution of the Thesis is highlighted and suggestions are made for future work.