## 3. SYSTEM DESCRIPTION

**3.1 DC MOTOR AND ITS OPERATION**

A direct current (DC) motor is an electromechanical device that converts DC electrical energy into mechanical energy. When direct current is applied to the motor, it produces a mechanical rotary action of the motor’s shaft which connected to a machine or other mechanical device to perform some sort of work. In other words, the DC motor converts electric power into mechanical works. Direct current motors have variable characteristics and are used in variable speed drives. DC motor is possible to obtain speed control over wide range and it is also can provide a high starting torque. DC motors are used for many applications in industry. Some of the application where the load on the DC motor varies over a speed range and may demand high speed control accuracy and good dynamic responses. It is very important to make a controller to control the speed of DC motor in desired speed. Nowadays in this modern technology the control of DC motor is a common practice so that it makes the implementation of DC motor of controller speed is important. DC motor is widely used in speed control system in many applications which needs high control requirement such as rolling mill, fuel pump control and double-hulled tanker. Thus, it is very important to control the speed to achieve good production and also it is more precise and reliable.

DC motors are devices that convert electrical energy (dc) to mechanical energy. A motor works on the principle that **a current-carrying conductor placed in a magnetic field experiences a force.** This force is due to the interaction between magnetic field due to the current carrying conductor and the magnetic field that existed. A motor can derive its electrical energy from either a dc source or from an ac source. They can therefore be referred to as either dc motors or ac motors. The magnetic field of the motors can be derived from either a permanent magnet or from an electromagnet.

**3.1.1 PRINCIPLE OF OPERATION OF A PERMANENT MAGNET DC MOTOR**

A rectangular coil free to rotate about a fixed axis is placed inside a magnetic field produced by a permanent magnet as shown in figure 3.1.



Figure 3.1. Basic circuit for a dc motor operation principle

A dc current is fed into the coil through carbon brushes bearing on a commutator, which consists of a metal ring split into two halves separated by insulation. As current flows through the coil a magnetic field is set up around the coil which interacts with the magnetic field due to the permanent magnet. This causes a force F to be exerted on the conductor, whose direction can be determined by the Fleming’s Left hand rule. This causes a torque and the coil rotates. When the coil has rotated through 900 the negative and positive terminals if the supply interchange the commutator halves thus, reversing the current direction. This prevents the coil from rotating in the opposite direction, thus it rotates continuously in one direction.

**3.1.2 SPEED CONTROL OF A DC MOTOR**

**3.1.2.1 BACK EMF, Eb**

When the armature of a dc motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field due to the permanent magnet, thus an emf is induced in them as in a generator. The induced emf acts in opposite direction to the direction of the applied voltage, Vt (Lenz’s Law). The induced emf is known as back emf or counter emf, Eb. The back emf is given by;

Eb= …(3.1)

Where,

P= Number of poles of the permanent magnet,

∅= Flux per pole in Wb,

Z= total number of armature conductors,

N= speed of the motor in RPM

A= number of parallel paths

The back emf is always smaller than the applied voltage, although the difference is small when the motor is running under normal conditions.

The net voltage across the armature circuit is,

Va=Vt-Eb. …(3.2)

If Ra is the armature resistance, then, Ia= …(3.3)

Since Vt and Ra are usually fixed, the value of Eb determines the current Ia drawn by the motor. If the speed of the motor is high, then Eb= ,is large hence the motor draws less armature current and vice versa.

Vt=Eb + IaRa (Motor voltage equation) …(3.4)

Eb= Vt - IaRa

Thus,

= Vt – IaRa …(3.5)

Or N=

Or N= …(3.6)

Where K=

Armature torque = = …(3.7)

**3.1.2.2 SPEED CONTROL OF A DC MOTOR**

There are three main methods of controlling the speed of a dc motor, namely:

1. By varying the flux per pole (∅). This is called flux control method.
2. By varying the resistance in the armature circuit. This is called armature control method.
3. By varying the applied voltage. This is called voltage control method.

**3.1.2.3 EQUIVALENT CIRCUIT OF A DC MOTOR**

In a dc motor, the field flux ∅f is established by the stator, either by means of a permanent magnet where the field flux ∅f remains constant or by means of a field winding where the field current If controls the flux ∅f . The rotor carries in its slots the armature winding, which handles the electrical power.

The interaction of the field flux ∅f and the armature current ia produces the electromagnetic torque;

Tem=kt∅fia …(3.8)

Where kt is the torque constant of the motor.

A back emf is produced in the armature circuit by the rotation of the armature conductors of a speed 𝜔m in the presence of a field flux ∅f:

ea =ke∅f 𝜔m …(3.9)

where ke is the voltage constant of the dc motor.

The interaction between Tem with the load torque determines how the motor speed

builds up.

𝑇𝑒𝑚=𝐽+𝐵ωm+Tωl(t) …(3.10)

Where J and B are the total equivalent inertia and the damping respectively, of the motor-load combination and T 𝜔L is the equivalent working torque of the load.



Figure 3. 2. Equivalent Circuit of Permanent Magnet dc Motor

A controllable voltage source Vt is applied to the armature terminals to establish ia. Thus the armature current is determined by Vt, the induced emf ea, the armature resistance Ra, and the armature winding inductance La.

Vt = ea+Raia+La  …(3.11)

**3.1.2.4 FOUR QUADRANT OPERATION OF A DC MOTOR**

DC machines act as generators while braking. To consider braking, it’s assumed that the flux ∅f is kept constant and the motor is initially driving a load at speed 𝜔m. to reduce speed, the armature voltage Vt is reduced below ea so that the armature current ia reverses in direction. The electromagnetic torque Tem reverses in direction and the kinetic energy associated with the motor load inertia is converted into electrical energy by the dc machine. this energy must somehow be absorbed by the source Vt or be dissipated by a resistor.

During braking operation, the polarity of ea does not change since the direction of rotation has not changed. As the rotor slows down, ea decreases in magnitude. The generation stops when the rotor comes to a standstill and all the inertial energy has been exhausted.

The direction of rotation of the motor is reversed by reversing the polarity of the terminal voltage Vt. A dc motor can therefore operate in either direction and its electromagnetic torque can be reversed for braking, as shown by the four quadrants of the torque-speed plane in figure 3.3



Figure 3. 3. Four Quadrant Operation

In permanent magnet dc motors, permanent magnets on the stator produce a constant field flux ∅f and thus we have;

Tem=kTIa …(3.12)

Ea=kE𝜔m …(3.13)

Vt=Ea + RaIa …(3.14)

The steady state speed can thus be obtained as a function of Tem for a given value of Vt.

𝜔m =(𝑉𝑡− 𝑇𝑒𝑚) …(3.15)

The speed of a load with an arbitrary torque-speed characteristics can hence be controlled by controlling Vt in a permanent magnet dc motor.

**3.1.2.5 ADJUSTABLE SPEED DRIVES**

A switch mode dc-dc converter can be used to control the speed of a dc motor. Figure 3.4 is a two quadrant converter which can be used when reversing the direction of the motor rotation is not needed but braking is required.



Figure 3.4 Two Quadrant Converter

For a single quadrant operation where speed is to remain unidirectional and there is no need for braking, the step down converter of figure 3.5 can be used.  Figure3.5 Single Quadrant Converter

**3.1.2.6 CONTROL OF ADJUSTABLE SPEED DRIVES**

Figure 3.6 shows a block diagram of a dc motor operating in closed loop to deliver controlled speed.

The speed transducer converts the mechanical energy (speed) into an electrical signal. The electrical signal is fed to the controller as a feedback. The controller compares the feedback signal to the reference signal (speed) and produces a PWM signal of appropriate duty cycle. The PWM signal is used to control the switch of the power electronics converter. This controls the terminal voltage Vt and hence, the speed.



Figure 3 6 Block Diagram of a dc Motor speed controller in a closed loop system

**3.2 CHOPPER AND ITs OPERATION**

**3.2.1 INTRODUCTION**

In hybrid electric vehicles (HEVs), power electronics are used in two formats: series hybrid and parallel hybrid. The difference between a series hybrid and a parallel hybrid is the relationship of the electric motor to the [internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine) (ICE). Devices used in electric vehicles consist mostly of dc/dc converters for battery charging and dc/ac converters to power the propulsion motor. Electric trains use power electronic devices to obtain power, as well as for vector control using pulse width modulation (PWM) rectifiers. The trains obtain their power from power lines. Another new usage for power electronics is in elevator systems. These systems may use Thyristors, inverters, permanent magnet motors, or various hybrid systems that incorporate PWM systems and standard motors.

**3.2.2 CHOPPERS**

In electronics, a **chopper** circuit is used to refer to numerous types of electronic switching devices and circuits used in power control and signal applications. A chopper is a switching device that converts fixed DC input to a variable DC output voltage directly. Essentially, a chopper is an electronic switch that is used to interrupt one signal under the control of another. In power electronics applications, since the switching element is either fully on or fully off, its losses are low, then the circuit can provide high efficiency. However, the current supplied to the load is discontinuous and may require smoothing or a high switching frequency to avoid undesirable effects. In signal processing circuits, use of a chopper stabilizes a system against drift of electronic components; the original signal can be recovered after amplification or other processing by a synchronous demodulator that essentially un-does the “chopping” process.

**3.2.3 CLASSIFICATION OF CHOPPERS**

Choppers may be classified on several bases.

On basis of input and output voltage levels:

* Step-down chopper class A
* Step-up chopper class B
* class C(combination of A&B) class D
* class E
* class B \*explanation of class A, C,D,E chopper

On basis of circuit operation:

* First quadrant
* Two quadrant
* Four quadrant

On basis of commutation method:

* Voltage commutated
* Current commutated
* Load commutated
* Impulse commutated

**3.2.4 APPLICATIONS OF CHOPPERS**

Most modern uses also use alternative nomenclature which helps to clarify which particular type of circuit is being discussed. These include:

* switched mode power supplies, including DC to DC converters.
* Speed controllers for DC motors
* Class D Electronic amplifiers
* Switched capacitor filters
* Variable-frequency drives
* D.C. motor speed control
* D.C. voltage boosting
* Battery-operated electric cars
* Battery-operated appliances.

**3.2.5** **CONTROL STRATEGIES**

For all the chopper configurations operating from a fixed DC input voltage, the average value of the output volt-age is controlled by periodic opening and closing of the switches used in the chopper circuit. The average output voltage can be controlled by different techniques namely: Pulse-width modulation Frequency modulation Variable frequency, variable pulse width CLC control. In pulse-width modulation the switches are turned on at a constant chopping frequency. The total time period of one cycle of output waveform is constant. The average output voltage is directly proportional to the ON time of chopper. The ratio of ON time to total time is defined as duty cycle. It can be varied between 0 and 1 or between 0 and 100%. Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a technique used to encode a message into a pulsing signal. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible. Typically switching has to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies. In frequency modulation, pulses of a fixed amplitude and duration are generated and the average value of output is adjusted by changing how often the pulses are generated. Variable pulse width and frequency combines both changes in the pulse width and repetition rate.

**3.2.6 CHOPPER AMPLIFIERS**

One classic use for a chopper circuit and where the term is still in use is in chopper amplifiers. These are DC amplifiers. Some types of signals that need amplifying can be so small that an incredibly high gain is required, but very high gain DC amplifiers are much harder to build with low off-set and 1/ *f* noise, and reasonable stability and bandwidth. It’s much easier to build an AC amplifier instead. A chopper circuit is used to break up the input signal so that it can be processed as if it were an AC signal, then integrated back to a DC signal at the out-put. In this way, extremely small DC signals can be amplified. This approach is often used in electronic instrumentation where stability and accuracy are essential; for example, it is possible using these techniques to construct Pico voltmeters and Hall sensors. The input off set voltage of amplifiers becomes important when trying to amplify small signals with very high gain. Because this technique creates a very low input off-set voltage amplifier, and because this input off-set voltage does not change much with time and temperature, these techniques are also called “zero-drift” amplifiers (because there is no drift in input off-set voltage with time and temperature). Related techniques that also give these zero-drift advantages are auto-zero and chopper-stabilized amplifiers. Auto-zero amplifiers use a secondary auxiliary amplifier to correct the input off-set voltage of a main amplifier. Chopper-stabilized amplifiers use a combination of auto-zero and chopper techniques to give some excellent DC precision specifications. Some example chopper and auto-zero amplifiers are LTC2050, MAX4238/MAX4239and OPA333.

**3.3 P, PI, PID CONTROLLERS**

**3.3.1 INTRODUCTION**

This report is written to analyze the recitation that was presented on 02.04.2013. The recitation was presented by Sena TEMEL, Semih YAĞLI and Semih GÖREN. It was mainly about P, P-D, P-I and P-I-D controllers, their digital versus continuous time realizations and their characteristics including sampling period effects on the response of digital ones. Moreover, position and velocity form of P-I-D control was modeled on the ‘Gate’ project. Apart from these topics, P-I-D tuning methods such as manual tuning, Ziegler-Nichols tuning, Cohen-Coon tuning and MATLAB tuning method were discussed. Transient performances of P, P-D, P-I and P-I-D controllers were explained in detail. Modeling a discrete time P-I-D controller to control a continuous time plant was explained over a MATLAB code introducing the effect of sampling time and the choice of s\*-domain to z-domain transformation method on MATLAB. It was explained how to remove poles that cause instability in discrete time by adding a new pole. Finally, it was shown how one could control the speed and position of the vehicle using discrete time P-I-D controller on the ‘Gate’ project.

**3.3.2 P- CONTROLLER**

P controller is mostly used in first order processes with single energy storage to stabilize the unstable process. The main usage of the P controller is to decrease the steady state error of the system. As the proportional gain factor K increases, the steady state error of the system decreases. However, despite the reduction, P control can never manage to eliminate the steady state error of the system. As we increase the proportional gain, it provides smaller amplitude and phase margin, faster dynamics satisfying wider frequency band and larger sensitivity to the noise. We can use this controller only when our system is tolerable to a constant steady state error. In addition, it can be easily concluded that applying P controller decreases the rise time and after a certain value of reduction on the steady state error, increasing K only leads to overshoot of the system response. P control also causes oscillation if sufficiently aggressive in the presence of lags and/or dead time. The more lags (higher order), the more problem it leads. Plus, it directly amplifies process noise.

**3.3.3 P-I CONTROLLER**

P-I controller is mainly used to eliminate the steady state error resulting from P controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. This controller is mostly used in areas where speed of the system is not an issue. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I guarantees set point overshoot.

**3.3.4 P-D CONTROLLER**

The aim of using P-D controller is to increase the stability of the system by improving control since it has an ability to predict the future error of the system response. In order to avoid effects of the sudden change in the value of the error signal, the derivative is taken from the output response of the system variable instead of the error signal. Therefore, D mode is designed to be proportional to the change of the output variable to prevent the sudden changes occurring in the control output resulting from sudden changes in the error signal. In addition D directly amplifies process noise therefore D-only control is not used.

**3.3.5 P-I-D CONTROLLER**

P-I-D controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. The necessity of using a derivative gain component in addition to the PI controller is to eliminate the overshoot and the oscillations occurring in the output response of the system. One of the main advantages of the P-I-D controller is that it can be used with higher order processes including more than single energy storage.

**3.4 THE DISCRETE KALMAN FILTER**

The Kalman filter is among the most notable innovations of the 20th century. This algorithm recursively estimates the state variables in a noisy linear dynamical system as new observations are measured and as the system evolves in time. It optimally updates the estimates of the system variables, for example, the position and velocity of a projectile, by minimizing the mean-squared estimation error of the current state as noisy measurements are received. Each update provides the latest unbiased estimate of the system variables together with a measure on the uncertainty of those estimates in the form of a covariance matrix. Since the updating process is fairly general and relatively easy to compute, the Kalman filter can often be implemented in real time.

The Kalman filter is used to reduce the noise while reading (i,e, the speed of the motor) data from the real time system