A Comparative Analysis of different Controllers considering uncertainty for the Robust Position Control of DC Motor

A Thesis

Submitted towards the partial fulfillment of

the requirements for the award of degree of

Master of Engineering

in

Electronics Instrumentation and Control Engineering

Submitted by

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Certificate

This is to certify that the work presented in this thesis entitled **" A Comparative Analysis of different Controllers considering uncertainty for the Robust Position Control of DC Motor"** submitted in the partial fulfillment of the requirement for the award of the degree of **Master of Engineering** in **Electronics Instrumentation and Control Engineering** at **Thapar University, Patiala,** is an original record under the supervision and guidance of **Ms. Gagandeep Kaur, Assistant Professor** and **Dr. Yaduvir Singh, Associate Professor**. The matter embodied in this report has not been submitted anywhere for the award of any degree.

Date: 12/7/11

(FARHAD ASLAM)

Place: Thapar University, Patiala

I CERTIFIED THAT THE ABOVE STATEMENT MADE BY THE STUDENT IS CORRECT TO THE BEST OF OUR KNOWLEDGE AND BELIEF.

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Date: 12/7/11 **(FARHAD ASLAM)**

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Abstract

Growing need of industry for higher productivity is placing new demands on mechanisms connected with electrical motors. They lead to different problems in work operation due to fast dynamics and instability. The stability of the system is essential to work at desired set targets. The non- linear effects caused by a motor frequently reduce stability, which reduces the controller's ability to maintain speed or position at set points. Hence all the industrial process applications require robust position control of dc motor. It is more important to know how the mechanism, or in other words the load on the motor behaves. A non- linear load and also disturbance control method for dc motor is developed and implemented in the thesis.

The aim of this thesis is to design a robust position control of dc motor by selecting different controllers like P, PI, PID and their tuning methods. The model of a dc motor is considered as a third order system with incorporating uncertainty. Comparison of the different kinds of tuning methods of parameter for PID controller are analyzed in the thesis. One is the controller design by Zeigler and Nichols method, second is the auto tuning of the controller in basic design mode and third is in the extended design mode. It was found that the proposed PID parameters adjustment in the basic and extended design mode is far better than the P, PI and Zeigler and Nichols method. The proposed method could be applied to the higher order system also.

The dc motor is such a drive which is perhaps more often used in all industrial processes including electrical, mechanical, construction, petroleum industry, power sectors, development sites, paper industry, beverages industry, etc. so the controlled stable operation of this drive attracts the researchers always, still keeping more and more future scope in it.

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List of Abbreviations

AC	Alternating Current
C- EMF	Counter- Electromotive Force
DC	Direct Current
DCS	Distributed Control System
DDC	Direct Digital Control
DOF	Degree of Freedom
EMF	Electromotive Force
P	Proportional
PI	Proportional- Integral
PID	Proportional- Integral- Derivative
RPM	Revolutions per minute
SEPEX	Separately Excited
SRM	Switched Reluctance Motor
UK	United Kingdom
US	United States
Z- N	Zeigler & Nichols

Chapter 1

Introduction

1.1 Objective of the thesis

In most of the industrial processes like electrical, mechanical, construction, petroleum industry, iron & steel industry, power sectors, development sites, paper industry, beverages industry, etc. the need for higher productivity is placing new demands on mechanisms connected with electrical motors. They lead to different problems in work operation due to fast dynamics and instability. That is why control is needed by the system to achieve stability and to work at desired set targets. The robust speed and position control of electrical motors is of utmost importance due to various non linear effects like load and disturbance that affected the motor to deviate from its normal operation. The main objective of the work is to control the non- linear load and disturbance to be widely implemented in machine automation.

1.2 Methodology used

In brief, the methodology employed goes along as follows: first, the modeling of a DC motor is done through different steps like reperesent the DC motor circuit diagram, its system equations, calculating transfer function. Second, the control algorithms are converted to model block using MATLAB/SIMULINK. In this work, the conventional controllers like P, PI, PID and their tuning method is employed. The different kinds of tuning methods of parameter for PID controller are compared and analyzed. One is the controller design by Zeigler and Nichols method, second is the auto tuning of the PID controller in basic design mode and third is in the extended design mode.

1.3 Literature Review

The followings are the few books and papers that were referred to, in the process of undertaking this project. For the undertaking of this project, thorough reading of dc motor and analog controller is required before the project can commences. Hence a comprehensive research for resources are required and the following are some of the literatures that has somehow contributed to my understanding of the control system and the tuning method for controller parameters in specific.

Books

[1] Steven T.Karris, 'Introduction to Simulink with Engineering Applications', Orchard Publications,www.orchardpublications.com

[2] Tan Kiong Howe, May 2003, Thesis, B.E (Hons.), ‘Evaluation of the transient response of a DC motor using MATLAB/SIMULINK’, University of Queensland.

[3] Math Works, 2001, Introduction to MATLAB, the Math Works, Inc.

[4] J. J. D’Azzo and C. H. Houpis, Linear control system analysis and design, McGraw-Hill, New York, 1995.

[5] S. J. Chapman, Electric machinery fundamentals, 3rd ed., WCB/McGraw-Hill, New York, 1998.

Journals

[1] O. Dwyer, .PI And PID Controller Tuning Rules for Time Delay Process: A Summary. Part 1: PI Controller Tuning Rules, Proceedings of Irish Signals and Systems Conference, June1999

[2] M. Chow and A. Menozzi, “on the comparison of emerging and conventional techniques for DC motor control,” Proc. IECON, pp. 1008- 1013, 1992.

[3] S. Li and R. Challoo, Restructuring electric machinery course with an integrative approach and computer- assisted teaching methodology, IEEE Trans Educ. 49 (2006), 16_28.

From the reading of the above and not inclusive, it is found that the conventional tuning of controllers like Zeigler and Nichols method are not guaranteed to find the global optimum solution to problem, but they are generally good at finding acceptably good solutions to problems in a more slow manner.

However in this thesis, PID controller is still used as the preferred controller for the robust position control of DC motor but the tuning method used is different. In this work, auto tuning of parameters of PID controller is implemented. First is the Basic Design mode and second is the Extended Design mode.It is found that the these tuning method is far more superior than the conventional tuning and stability is achieved in a very fast and quick time.The proposed method could be applied to the higher order system also.

1.4 Thesis Layout

The present thesis is organized in six chapters. Some of these chapters are based on developments from former chapters, but in general, all of them can be read independently as self contained entities.

Chapter 1 presents the objective of the work, the methodology used in this work and the resource from which this work can be practically implemented.

Chapter 2 reveals the various aspects of the DC motor.

Chapter 3 describes the detail of different Controllers used and their tuning methods.

Chapter 4 presents the system equations and their modeling.

Chapter 5 shows the model, simulation, results and comparisons.

With respect to the conclusion of the thesis, they are presented in brief at the end of each chapter and the most important concepts are summarized in Chapter 6.

Chapter 2

DC Motor

2.1 History & Background

At the most basic level, **electric motors** exist to convert electrical energy into mechanical energy. This is done by way of two interacting magnetic fields -- one stationary, and another attached to a part that can move. A number of types of electric motors exist, but mostly used DC motors in some form or another. DC motors have the potential for very high torque capabilities (although this is generally a function of the physical size of the motor), are easy to miniaturize, and can be "throttled" via adjusting their supply voltage. DC motors are also not only the simplest, but the oldest electric motors.

The basic principles of electromagnetic induction were discovered in the early 1800's by Oersted, Gauss, and Faraday. By 1820, Hans Christian Oersted and Andre Marie Ampere had discovered that an electric current produces a magnetic field. The next 15 years saw a flurry of cross-Atlantic experimentation and innovation, leading finally to a simple DC rotary motor. A number of men were involved in the work, so proper credit for the first DC motor is really a function of just how broadly you choose to define the word "motor."

Michael Faraday (U.K.)

Fabled experimenter Michael Faraday decided to confirm or refute a number of speculations surrounding Oersted's and Ampere's results. Faraday set to work devising an experiment to demonstrate whether or not a current- carrying wire produced a circular magnetic field around it, and in October of 1821 succeeded in demonstrating this.

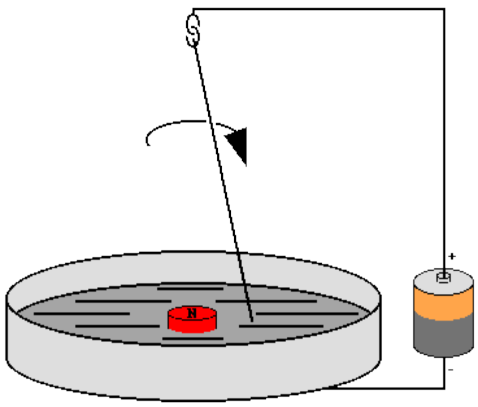

Fig. 2.1 Faraday's Electric Motor

Faraday took a dish of mercury and placed a fixed magnet in the middle; above this, he dangled a freely moving wire (the free end of the wire was long enough to dip into the mercury). When he connected a battery to form a circuit, the current- carrying wire circled around the magnet. Faraday then reversed the setup, this time with a fixed wire and a dangling magnet -- again the free part circled around the fixed part. This was the first demonstration of the conversion of electrical energy into motion, and as a result, Faraday is often credited with the invention of the electric motor. Bear in mind, though, that Faraday's electric motor is really just a lab demonstration, as you can't harness it for useful work.

Joseph Henry (U.S.)

It took ten years, but by the summer of 1831 Joseph Henry had improved on Faraday's experimental motor. Henry built a simple device whose moving part was a straight electromagnet rocking on a horizontal axis. Its polarity was reversed automatically by its motion as pairs of wires projecting from its ends made connections alternately with two electrochemical cells. Two vertical permanent magnets alternately attracted and repelled the ends of the electromagnet, making it rock back and forth at 75 cycles per minute.

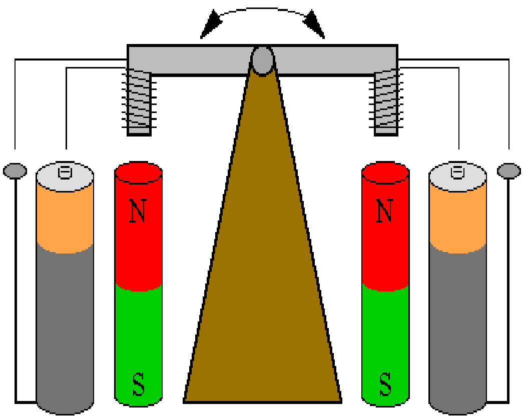

Fig. 2.2 Joseph Henry experimental setup

Henry considered his little machine to be merely a "philosophical toy," but nevertheless believed it was important as the first demonstration of continuous motion produced by magnetic attraction and repulsion. While being more mechanically useful than Faraday's motor, and being the first real use of electromagnets in a motor, it was still by and large a lab experiment.

William Sturgeon (U.K.)

Just a year after Henry's motor was demonstrated, William Sturgeon invented the commutator, and with it the first rotary electric motor -- in many ways a rotary analogue of Henry's oscillating motor. Sturgeon's motor, while still simple, was the first to provide continuous rotary motion and contained essentially all the elements of a modern DC motor. Note that Sturgeon used horseshoe electromagnets to produce both the moving and stationary magnetic fields (to be specific, he built a shunt wound DC motor).

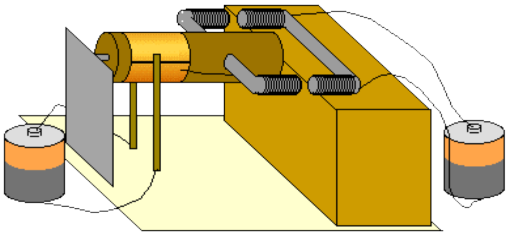

Fig. 2.3 William Sturgeon experimental setup

2.2   Principle of Operation

In any electric motor, operation is based on simple electromagnetism. A current- carrying conductor generates a magnetic field; when this is then placed in an external magnetic field, it will experience a force proportional to the current in the conductor, and to the strength of the external magnetic field. As you are well aware of from playing with magnets as a kid, opposite (North and South) polarities attract, while like polarities (North and North, South and South) repel. The internal configuration of a DC motor is designed to harness the magnetic interaction between a current- carrying conductor and an external magnetic field to generate rotational motion.

Let's start by looking at a simple 2-pole DC electric motor (here red represents a magnet or winding with a "North" polarization, while green represents a magnet or winding with a "South" polarization).

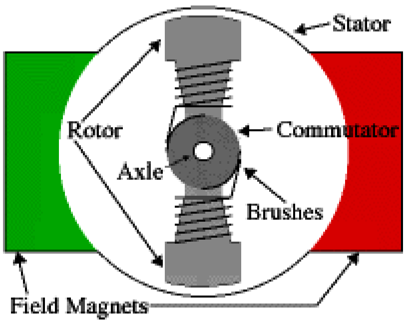

Fig. 2.4 Simple 2- pole DC electric motor

Every DC motor has six basic parts -- axle, rotor (a.k.a., armature), stator, commutator, field magnet(s), and brushes. In most common DC motors, the external magnetic field is produced by high-strength permanent magnets. The stator is the stationary part of the motor -- this includes the motor casing, as well as two or more permanent magnet pole pieces. The rotor (together with the axle and attached commutator) rotate with respect to the stator. The rotor consists of windings (generally on a core), the windings being electrically connected to the commutator. The above diagram shows a common motor layout -- with the rotor inside the stator (field) magnets.

The geometry of the brushes, commutator contacts, and rotor windings are such that when power is applied, the polarities of the energized winding and the stator magnet(s) are misaligned, and the rotor will rotate until it is almost aligned with the stator's field magnets. As the rotor reaches alignment, the brushes move to the next commutator contacts, and energize the next winding. Given our example two-pole motor, the rotation reverses the direction of current through the rotor winding, leading to a "flip" of the rotor's magnetic field, driving it to continue rotating.

In real life, though, DC motors will always have more than two poles (three is a very common number). In particular, this avoids "dead spots" in the commutator. You can imagine how with our example two-pole motor, if the rotor is exactly at the middle of its rotation (perfectly aligned with the field magnets), it will get "stuck" there. Meanwhile, with a two-pole motor, there is a moment where the commutator shorts out the power supply (i.e., both brushes touch both commutator contacts simultaneously). This would be bad for the power supply, waste energy, and damage motor components as well. Yet another disadvantage of such a simple motor is that it would exhibit a high amount of torque "ripple" (the amount of torque it could produce is cyclic with the position of the rotor).

So since most small DC motors are of a three-pole design.

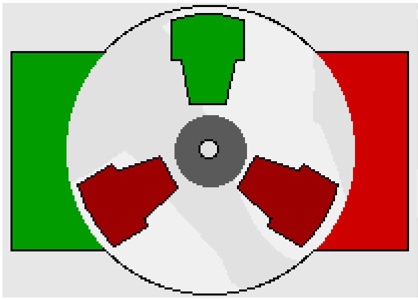

Fig. 2.5 Simple 3- pole DC electric motor

Here one pole is fully energized at a time (but two others are "partially" energized). As each brush transitions from one commutator contact to the next, one coil's field will rapidly collapse, as the next coil's field will rapidly charge up (this occurs within a few microsecond). We'll see more about the effects of this later, but in the meantime you can see that this is a direct result of the coil windings' series wiring:

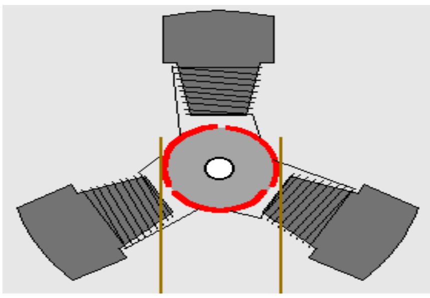

Fig. 2.6 3- pole DC motor with commutator contacts

There's probably no better way to see how an average DC motor is put together, than by just opening one up. Unfortunately this is tedious work, as well as requiring the destruction of a perfectly good motor. This is a basic 3-pole DC motor, with 2 brushes and three commutator contacts.

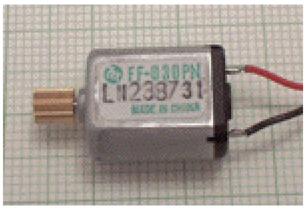

Fig. 2.7 3- pole iron core DC motor

The use of an iron core armature (as in the Mabuchi, above) is quite common, and has a number of advantages. First off, the iron core provides a strong, rigid support for the windings -- a particularly important consideration for high- torque motors. The core also conducts heat away from the rotor windings, allowing the motor to be driven harder than might otherwise be the case. Iron core construction is also relatively inexpensive compared with other construction types.

But iron core construction also has several disadvantages. The iron armature has a relatively high inertia which limits motor acceleration. This construction also results in high winding inductances which limit brush and commutator life.

In small motors, an alternative design is often used which features a 'coreless' armature winding. This design depends upon the coil wire itself for structural integrity. As a result, the armature is hollow, and the permanent magnet can be mounted inside the rotor coil. Coreless DC motors have much lower armature inductance than iron-core motors of comparable size, extending brush and commutator life.

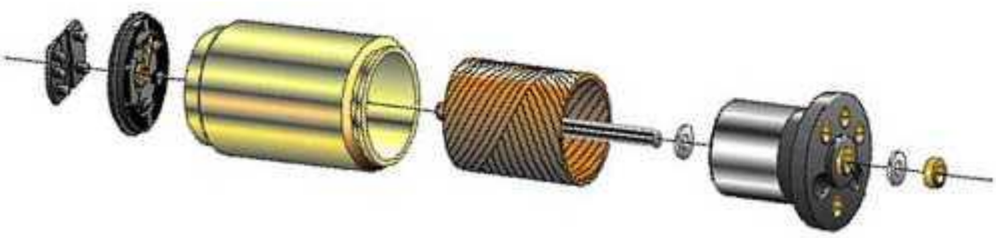

Fig. 2.8 MicroMo Electric motor

The coreless design also allows manufacturers to build smaller motors; meanwhile, due to the lack of iron in their rotors, coreless motors are somewhat prone to overheating. As a result, this design is generally used just in small, low-power motors. Users will most often see coreless DC motors in the form of pager motors.

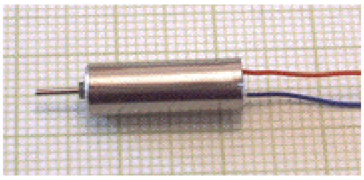

Fig. 2.9 3- pole Coreless DC motor

Again, disassembling a coreless motor can be instructive -- a 3-pole coreless DC motor.

2.3 Types of DC Motor

There are basically two categorization of DC Motor. One is based on their circuitry and other is based on their features & characteristics.

Based on Circuitry

There are three basic types of dc motors: (1) Series motors (2) shunt motors, and (3) compound motors. They differ largely in the method in which their field and armature coils are connected.

Series DC Motor

In the series motor, the field windings, consisting of a relatively few turns of heavy wire, are connected in series with the armature winding. Both a diagrammatic and a schematic illustration of a series motor is shown in figure 2.10. The same current flowing through the

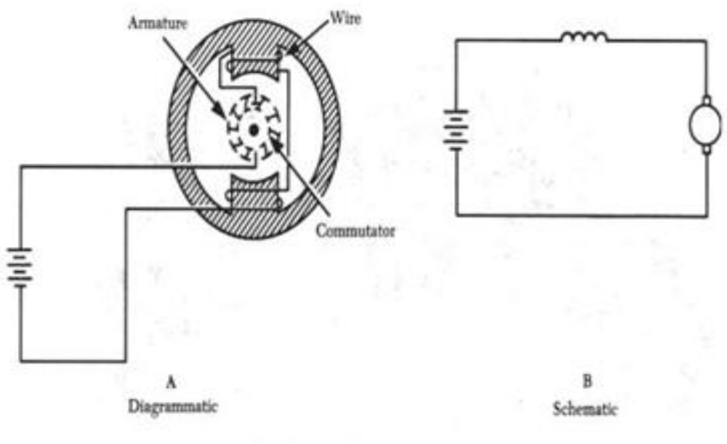

Fig. 2.10 Series motor

field winding also flows through the armature winding. Any increase in current, therefore, strengthens the magnetism of both the field and the armature.

Because of the low resistance in the windings, the series motor is able to draw a large current in starting. This starting current, in passing through both the field and armature windings, produces a high starting torque, which is the series motor's principal advantage.

The speed of a series motor is dependent upon the load. Any change in load is accompanied by a substantial change in speed. A series motor will run at high speed when it has a light load and at low speed with a heavy load. If the load is removed entirely, the motor may operate at such a high speed that the armature will fly apart. If high starting torque is needed under heavy load conditions, series motors have many applications. Series motors are often used in aircraft as engine starters and for raising and lowering landing gears, cowl flaps, and wing flaps.

Shunt DC Motor

In the shunt motor the field winding is connected in parallel or in shunt with the armature winding. (See figure 2.11) The resistance in the field winding is high. Since the field winding is connected directly across the power supply, the current through the field is constant. The field current does not vary with motor speed, as in the series motor and, therefore, the torque of the shunt motor will vary only with the current through the armature. The torque developed at starting is less than that developed by a series motor of equal size.

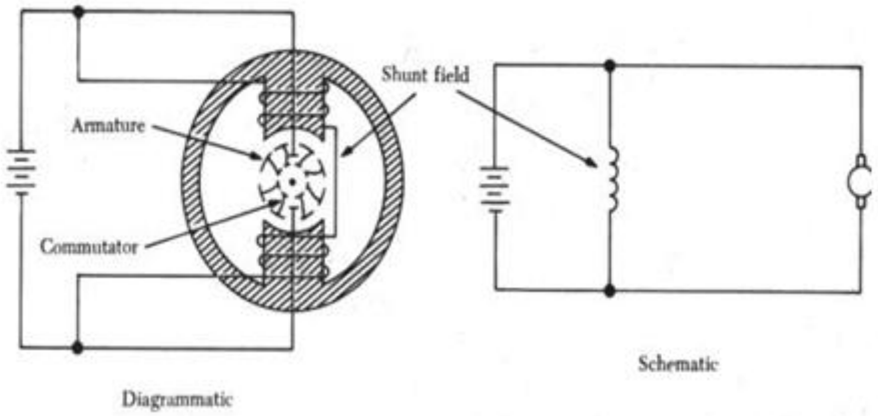

Fig. 2.11 Shunt motor

The speed of the shunt motor varies very little with changes in load. When all load is removed, it assumes a speed slightly higher than the loaded speed. This motor is particularly suitable for use when constant speed is desired and when high starting torque is not needed.

Compound DC Motor

The compound motor is a combination of the series and shunt motors. There are two windings in the field: a shunt winding and a series winding. A schematic of a compound motor is shown in figure 2.12.

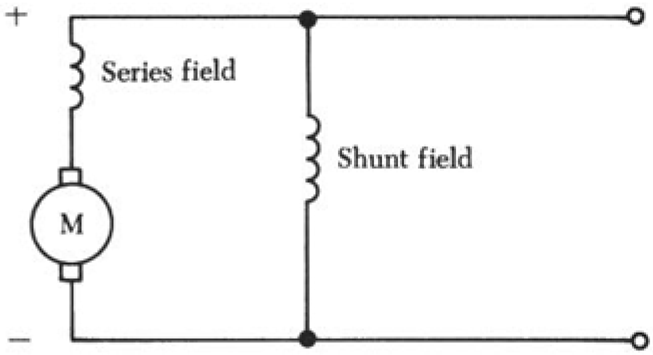

Fig. 2.12 Compound motor

The shunt winding is composed of many turns of fine wire and is connected in parallel with the armature winding. The series winding consists of a few turns of large wire and is connected in series with the armature winding. The starting torque is higher than in the shunt motor but lower than in the series motor. Variation of speed with load is less than in a series wound motor but greater than in a shunt motor. The compound motor is used whenever the combined characteristics of the series and shunt motors are desired.

Like the compound generator, the compound motor has both series and shunt field windings. The series winding may either aid the shunt wind (cumulative compound) or oppose the shunt winding (differential compound).

The starting and load characteristics of the cumulative compound motor are somewhere between those of the series and those of the shunt motor.

Because of the series field, the cumulative compound motor has a higher starting torque than a shunt motor. Cumulative compound motors are used in driving machines which are subject to sudden changes in load. They are also used where a high starting torque is desired, but a series motor cannot be used easily.

In the differential compound motor, an increase in load creates an increase in current and a decrease in total flux in this type of motor. These two tend to offset each other and the result is a practically constant speed. However, since an increase in load tends to decrease the field strength, the speed characteristic becomes unstable. Rarely is this type of motor used in aircraft systems.

A graph of the variation in speed with changes of load of the various types of dc motors is shown in figure 2.13.

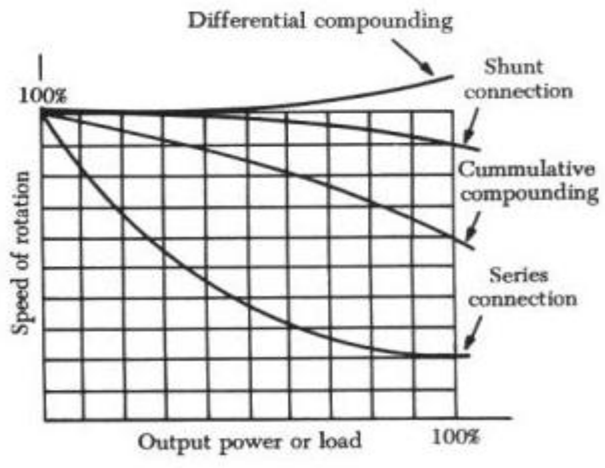

Fig. 2.13 Load characteristics of DC motors

Based on Characteristics

DC Motors differ from AC Motors, as they are powered by a direct current of Electricity, as opposed to an Alternating current. There are three main types of Direct Current motor, each with different features and characteristics. These are:

Stepper DC Motors

Brushless DC Motors

Brushed DC Motors

Although the main principle of these motors is the same (the stepper DC motor does differ however), they each have different uses and different operation methods.

In a strict sense, the Brushed and Brushless motor types (which are by far the most common of the DC motors) are not strictly completely DC dependant. Their operation depends on the fact that they contain a Commutator, which converts the DC supply that they are given into AC.

DC motors are generally used for more precision and power than AC motors, as they tend to be more controllable.

Stepper DC Motors

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a magnetically soft rotor with salient poles is controlled by a set of external magnets that are switched electronically. A stepper motor may also be thought of as a cross between a DC electric motor and a rotary solenoid. As each coil is energized in turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the stepper motor may not rotate continuously; instead, it "steps" — starts and then quickly stops again — from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards and it may change direction, stop, speed up or slow down arbitrarily at any time.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. This mode of operation is often called micro stepping. Computer controlled stepper motors are one of the most versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle in discrete steps with ease, and hence stepper motors are used for read/write head positioning in computer floppy diskette drives. They were used for the same purpose in pre-gigabyte era computer disk drives, where the precision and speed they offered was adequate for the correct positioning of the read/write head of a hard disk drive. As drive density increased, the precision and speed limitations of stepper motors made them obsolete for hard drives—the precision limitation made them unusable, and the speed limitation made them uncompetitive—thus newer hard disk drives use voice coil- based head actuator systems. (The term "voice coil" in this connection is historic; it refers to the structure in a typical (cone type) loudspeaker. This structure was used for a while to position the heads. Modern drives have a pivoted coil mount; the coil swings back and forth, something like a blade of a rotating fan. Nevertheless, like a voice coil, modern actuator coil conductors (the magnet wire) move perpendicular to the magnetic lines of force.)

Stepper motors were and still are often used in computer printers, optical scanners, and digital photocopiers to move the optical scanning element, the print head carriage (of dot matrix and inkjet printers), and the platen. Likewise, many computer plotters (which since the early 1990s have been replaced with large-format inkjet and laser printers) used rotary stepper motors for pen and platen movement; the typical alternatives here were either linear stepper motors or servomotors with complex closed-loop control systems.

So-called quartz analog wristwatches contain the smallest commonplace stepping motors; they have one coil, draw very little power, and have a permanent-magnet rotor. The same kind of motor drives battery-powered quartz clocks. Some of these watches, such as chronographs, contain more than one stepping motor.

Stepper motors were up scaled to be used in electric vehicles under the term SRM (Switched Reluctance Motor).

Brushless DC Motors

Brushless DC motors are extremely desirably as they completely eliminate the need for brushes. This increases their life, survival without maintenance, power output and efficiency dramatically.

Their basic working principle is to facilitate an external commutator, which will reverse the direction of the current depending on the position of the rotor.

As there are no brushes, maintenance levels are lowered dramatically, and as there is no friction caused by brushes, the efficiency of a brushless motor is typically between 85 and 90 percent (a brushed motor's efficiency is usually about 75 to 80 %). This makes them ideal for heavy duty use, and cost efficiency in the long term. They also run much cooler than AC and brushed motors, which greatly increases the life of the motors in context.

Brushed DC Motors

Brushed DC motors are the classic DC motors, which include a split ring commutator, and can be powered by any kind of DC battery. These motors are often considered to be limited, due to the need that brushes will always be in contact with the commutator ring, hence creating friction. Brushes also scratch the surface of the ring, which eventually will lead to replacement of the brushes and ring.

Although the brushes in these motors were originally made from copper wire (now obsolete), they are now made from carbon, which is a longer-lasting material, gives less friction, and is cheaper.

The advantages of Brushed DC motors are that their initial cost is extremely low, and that they have an extremely simple speed control system (Dynamo).

2.4 DC Motor Behavior

At a simplistic level, using DC motors is pretty straightforward -- you put power in, and get rotary motion out. Life, of course, is never this simple -- there are a number of subtleties of DC motor behavior that should be accounted for their design.

High speed output

This is the simplest trait to understand and treat -- most DC motors run at very high output speeds (generally thousands or tens of thousands of RPM). While this is fine for some BEAMbots (say, photopoppers or solarrollers), many BEAMbots (walkers, heads) require lower speeds -- you must put gears on your DC motor's output for these applications.

Back EMF

Just as putting voltage across a wire in a magnetic field can generate motion, moving a wire through a magnetic field can generate voltage. This means that as a DC motor's rotor spins, it generates voltage -- the output voltage is known as back EMF. Because of back EMF, a spark is created at the commutator as a motor's brushes switch from contact to contact. Meanwhile, back EMF can damage sensitive circuits when a motor is stopped suddenly.

Noise (ripple) on power lines

A number of things will cause a DC motor to put noise on its power lines: commutation noise (a function of brush / commutator design & construction), roughness in bearings (via back EMF), and gearing roughness (via back EMF, if the motor is part of a gearmotor) are three big contributors.

Even without these avoidable factors, any electric motor will put noise on its power lines by virtue of the fact that its current draw is not constant throughout its motion. Going back to our example two-pole motor, its current draw will be a function of the angle between its rotor coil and field magnets:

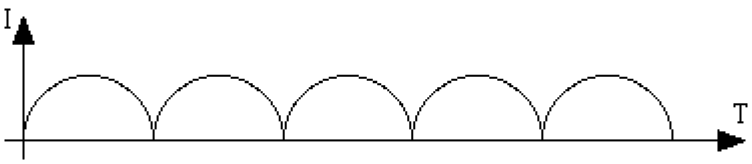

Fig. 2.14 Current output of 2- pole DC motor

Since most small DC motors have 3 coils, the coils' current curves will overlay each other:

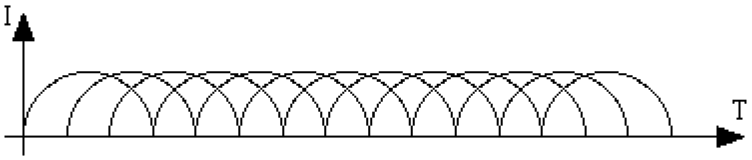

Fig. 2.15 Current output of 3- pole DC motor

Added together, this ideal motor's current will then look something like this:

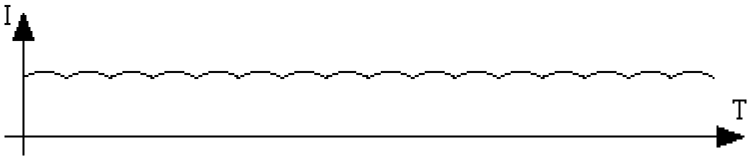

Fig. 2.16 Current output of ideal motor

Reality is a bit more complex than this, as even a high-quality motor will display a current transient at each commutation transition. Since each coil has inductance (by definition) and some capacitance, there will be a surge of current as the commutator's brushes first touch a coil's contact, and another as the brushes leave the contact (here, there's a slight spark as the coil's magnetic field collapses).

As a good example, consider an oscilloscope trace of the current through a Mabuchi FF-030PN motor supplied with 2 V (1ms per horizontal division, 0.05 mA per vertical division):

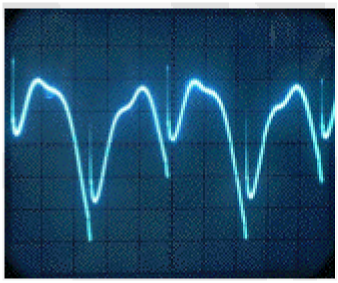

Fig. 2.17 Current output of MabuchiFF- 030 PN motor

In this case, the peak-to-peak current ripple is approximately 0.29 mA, while the average motor current is just under 31 mA. So under these conditions, the motor puts about less than 1% of current ripple onto its power lines (and as you can see from the "clean" traces, it outputs essentially no high-frequency current noise). Note that since this is a 3-pole motor, and each coil is energized in both directions over the course of a rotor rotation, one revolution of the rotor will correspond to six of the above curves (here, 6 x 2.4 ms = 0.0144 sec, corresponding to a motor rotation rate of just under 4200 RPM).

Motor power ripple can wreak havoc in Nv nets by destabilizing them inadvertently. Fortunately, this can be mitigated by putting a small capacitor across the motor's power lines (you'll only be able to filter out "spikey" transients this way, though -- you'll always see curves like the ones above being imposed on your power). On the flip side of this coin, motor power ripple can be put to good use -- as was shown above, ripple frequency can be used to measure motor speed, and its destabilizing tendencies can be used to reverse a motor without the need for discrete "back-up" sensors.

2.5 Brushed DC Motor

A **Brushed DC motor** is an internally commutated electric motor designed to be run from a DC power source.

2.5.1 DC Motor Rotation

The following diagram illustrate a simple, two-pole, brushed, DC motor.

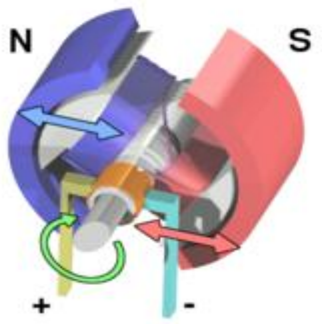

Fig. 2.18 Brushed DC motor rotation1

A simple DC electric motor, When the coil is powered, a magnetic field is generated around the armature. The left side of the armature is pushed away from the left magnet and drawn toward the right, causing rotation.

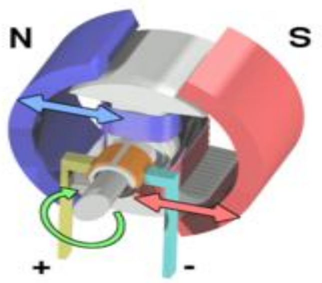

Fig. 2.19 Brushed DC motor rotation2

The armature continues to rotate.

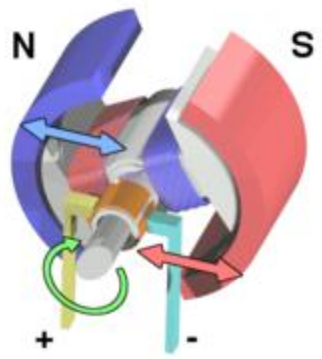

Fig. 2.20 Brushed DC motor rotation3

When the armature becomes horizontally aligned, the commutator reverses the direction of current through the coil, reversing the magnetic field. The process then repeats.

When a current passes through the coil wound around a soft iron core, the side of the positive pole is acted upon by an upwards force, while the other side is acted upon by a downward force. According to Fleming's left hand rule, the forces cause a turning effect on the coil, making it rotate. To make the motor rotate in a constant direction, "direct current" commutators make the current reverse in direction every half a cycle (in a two-pole motor) thus causing the motor to continue to rotate in the same direction.

A problem with the motor shown above is that when the plane of the coil is parallel to the magnetic field—i.e. when the rotor poles are 90 degrees from the stator poles—the torque is zero. In the pictures above, this occurs when the core of the coil is horizontal—the position it is just about to reach in the fig. 2.20. The motor would not be able to start in this position. However, once it was started, it would continue to rotate through this position by inertia.

There is a second problem with this simple pole design. At the zero-torque position, both commutator brushes are touching (bridging) both commutator plates, resulting in a short-circuit. The power leads are shorted together through the commutator plates, and the coil is also short-circuited through both brushes (the coil is shorted twice, once through each brush independently). Note that this problem is independent of the non-starting problem above; even if there were a high current in the coil at this position, there would still be zero torque. The problem here is that this short uselessly consumes power without producing any motion (nor even any coil current.) In a low-current battery-powered demonstration this short-circuiting is generally not considered harmful. (Here, low-current means that the battery is intrinsically limited to low current and will not overheat if loaded with a short circuit; this is usually the case for an AA alkaline cell but not the case for batteries like the Li-ion cells used in many laptop batteries in this first decade of the 21st century.) However, if a two-pole motor were designed to do actual work with several hundred watts of power output, this shorting could result in severe commutator overheating, brush damage, and potential welding of the brushes—if they were metallic—to the commutator. Carbon brushes, which are often used, would not weld. In any case, a short like this is very wasteful, drains batteries rapidly and, at a minimum, requires power supply components to be designed to much higher standards than would be needed just to run the motor without the shorting.

One simple solution is to put a gap between the commutator plates which is wider than the ends of the brushes. This increases the zero-torque range of angular positions but eliminates the shorting problem; if the motor is started spinning by an outside force it will continue spinning. With this modification, it can also be effectively turned off simply by stalling (stopping) it in a position in the zero-torque (i.e. commutator non-contacting) angle range. This design is sometimes seen in homebuilt hobby motors, e.g. for science fairs and such designs can be found in some published science project books. A clear downside of this simple solution is that the motor now coasts through a substantial arc of rotation twice per revolution and the torque is pulsed. This may work for electric fans or to keep a flywheel spinning but there are many applications, even where starting and stopping are not necessary, for which it is completely inadequate, such as driving the capstan of a tape transport, or any instance where to speed up and slow down often and quickly is a requirement. Another disadvantage is that, since the coils have a measure of self inductance, current flowing in them cannot suddenly stop. The current attempts to jump the opening gap between the commutator segment and the brush, causing arcing.

Unlike the demonstration motor above, DC motors are commonly designed with more than two poles, are able to start from any position, and do not have any position where current can flow without producing electromotive power by passing through some coil. Many common small brushed DC motors used in toys and small consumer appliances, the simplest mass-produced DC motors to be found, have three-pole armatures. The brushes can now bridge two adjacent commutator segments without causing a short circuit. These three-pole armatures also have the advantage that current from the brushes either flows through two coils in series or through just one coil. Starting with the current in an individual coil at half its nominal value (as a result of flowing through two coils in series), it rises to its nominal value and then falls to half this value. The sequence then continues with current in the reverse direction. This results in a closer step-wise approximation to the ideal sinusoidal coil current, producing a more even torque than the two-pole motor where the current in each coil is closer to a square wave. Since current changes are half those of a comparable two-pole motor, arcing at the brushes is consequently less.

If the shaft of a DC motor is turned by an external force, the motor will act like a generator and produce an Electromotive force (EMF). During normal operation, the spinning of the motor produces a voltage, known as the counter-EMF (CEMF) or back EMF, because it opposes the applied voltage on the motor. The back EMF is the reason that the motor when free-running does not appear to have the same low electrical resistance as the wire contained in its winding. This is the same EMF that is produced when the motor is used as a generator (for example when an electrical load, such as a light bulb, is placed across the terminals of the motor and the motor shaft is driven with an external torque). Therefore, the total voltage drop across a motor consists of the CEMF voltage drop, and the parasitic voltage drop resulting from the internal resistance of the armature's windings. The current through a motor is given by the following equation:

$$I = \frac{V_{applied} - V_{cemf}}{R_{armature}}$$

The mechanical power produced by the motor is given by:

$$P = I \cdot V_{cemf}$$

As an unloaded DC motor spins, it generates a backwards-flowing electromotive force that resists the current being applied to the motor. The current through the motor drops as the rotational speed increases, and a free-spinning motor has very little current. It is only when a load is applied to the motor that slows the rotor that the current draw through the motor increases.

"In an experiment of this kind made on a motor with separately excited magnets, the following figures were obtained:

Revolutions per minute	0	50	100	160	180	195
Amperes	20	16.2	12.2	7.8	6.1	5.1

Apparently, if the motor had been helped on to run at 261.5 revolutions per minute, the current would have been reduced to zero. In the last result obtained, the current of 5.1 amperes was absorbed in driving the armature against its own friction at the speed of 195 revolutions per minute."

2.5.2 The Commutating Plane

In a dynamo, a plane through the centers of the contact areas where a pair of brushes touch the commutator and parallel to the axis of rotation of the armature is referred to as the *commutating plane*. In this diagram the commutating plane is shown for just one of the brushes, assuming the other brush made contact on the other side of the commutator with radial symmetry, 180 degrees from the brush shown in fig. 2.21.

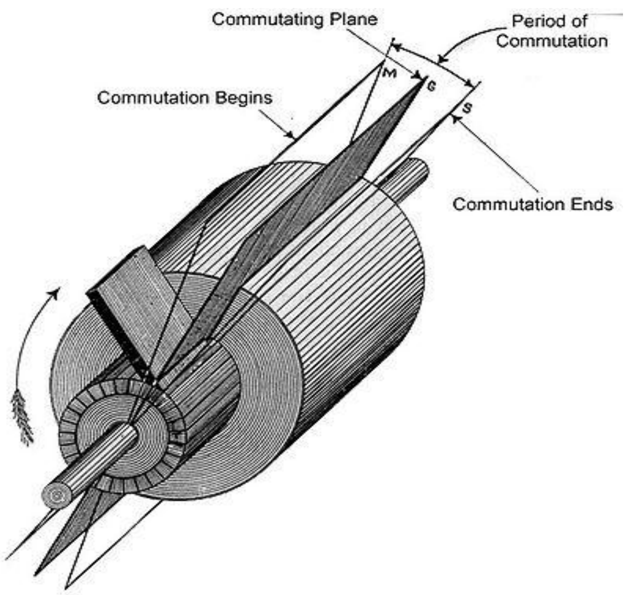

Fig. 2.21 The Commutating plane

2.5.3 DC Motor Design variations

DC motors are commonly constructed with wound rotors and either wound or permanent magnet stators.

Wound stators

The field coils have traditionally existed in four basic formats: separately-excited (sepex), series-wound, shunt-wound, and a combination of the latter two; compound-wound. In a series wound motor, the field coils are connected electrically in series with the armature coils (via the brushes). In a shunt wound motor, the field coils are connected in parallel, or "shunted" to the armature coils. In a separately-excited (sepex) motor the field coils are supplied from an independent source, such as a motor-generator and the field current is unaffected by changes in the armature current. The sepex system was sometimes used in DC traction motors to facilitate control of wheelslip.

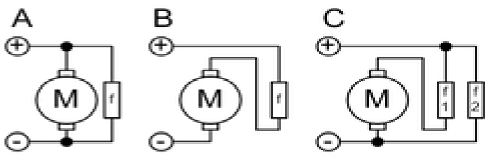

Fig. 2.22 A: Shunt B: Series C: Compound f: field coil

Permanent- magnet motors

Permanent magnet types have some performance advantages over direct-current excited synchronous types, and have become predominant in fractional horsepower applications. They are smaller, lighter, more efficient and reliable than other singly-fed electric machines.

Originally all large industrial DC motors used wound field or rotor magnets. Permanent magnets have traditionally only been useful on small motors because it was difficult to find a material capable of retaining a high-strength field. Only recently have advances in materials technology allowed the creation of high-intensity permanent magnets, such as neodymium magnets, allowing the development of compact, high-power motors without the extra real-estate of field coils and excitation means.

Axial field motors

Traditionally, the field has been applied radially- in and away from the rotation axis of the motor. However some designs have the field flowing along the axis of the motor, with the rotor cutting the field lines as it rotates. This allows for much stronger magnetic fields, particularly if halbach arrays are employed. This, in turn, gives the motor's power at lower speeds. However, the focused flux density cannot rise about the limited residual flux density of the permanent magnet despite high coercivity and like all electric machine, the flux density of magnetic core saturation is the design constraint.

2.5.4 DC Motor Starters

The counter-emf aids the armature resistance to limit the current through the armature. When power is first applied to a motor, the armature does not rotate. At that instant the counter-emf is zero and the only factor limiting the armature current is the armature resistance. Usually the armature resistance of a motor is less than 1 Ω; therefore the current through the armature would be very large when the power is applied. This current can make an excessive voltage drop affecting other equipment in the circuit and even trip overload protective devices.

Therefore the need arises for an additional resistance in series with the armature to limit the current until the motor rotation can build up the counter-emf. As the motor rotation builds up, the resistance is gradually cut out.

Manual- starting rheostat

When electrical and DC motor technology was first developed, much of the equipment was constantly tended by an operator trained in the management of motor systems. The very first motor management systems were almost completely manual, with an attendant starting and stopping the motors, cleaning the equipment, repairing any mechanical failures, and so forth.

The first DC motor-starters were also completely manual, as shown in this image. Normally it took the operator about ten seconds to slowly advance the rheostat across the contacts to gradually increase input power up to operating speed. There were two different classes of these rheostats, one used for starting only, and one for starting and speed regulation. The starting rheostat was less expensive, but had smaller resistance elements that would burn out if required to run a motor at a constant reduced speed.

This starter includes a no-voltage magnetic holding feature, which causes the rheostat to spring to the off position if power is lost, so that the motor does not later attempt to restart in the full-voltage position. It also has overcurrent protection that trips the lever to the off position if excessive current over a set amount is detected.

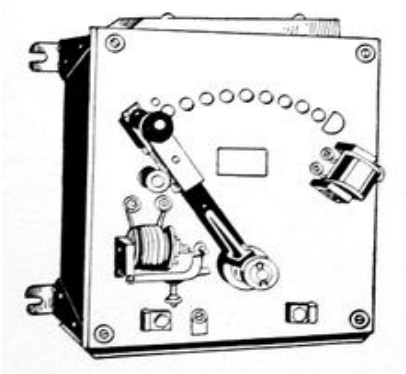

Fig. 2.23 DC motor manual starting rheostat with no Voltage and overload release features

Three- point starter

The incoming power is indicated as L1 and L2. The components within the broken lines form the three-point starter. As the name implies there are only three connections to the starter. The connections to the armature are indicated as A1 and A2. The ends of the field (excitement) coil are indicated as F1 and F2. In order to control the speed, a field rheostat is connected in series with the shunt field. One side of the line is connected to the arm of the starter (represented by an arrow in the diagram). The arm is spring-loaded so, it will return to the "Off" position when not held at any other position.

On the first step of the arm, full line voltage is applied across the shunt field. Since the field rheostat is normally set to minimum resistance, the speed of the motor will not be excessive; additionally, the motor will develop a large starting torque.

The starter also connects an electromagnet in series with the shunt field. It will hold the arm in position when the arm makes contact with the magnet. Meanwhile that voltage is applied to the shunt field, and the starting resistance limits the current to the armature. As the motor picks up speed counter-emf is built up; the arm is moved slowly to short.

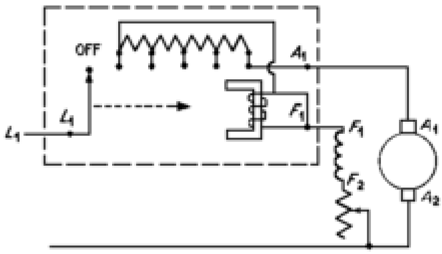

Fig. 2.24 Three point Starters

Four- point starter

The four-point starter eliminates the drawback of the three-point starter. In addition to the same three points that were in use with the three-point starter, the other side of the line, L1, is the fourth point brought to the starter when the arm is moved from the "Off" position. The coil of the holding magnet is connected across the line. The holding magnet and starting resistors function identical as in the three-point starter.

The possibility of accidentally opening the field circuit is quite remote. The four-point starter provides the no-voltage protection to the motor. If the power fails, the motor is disconnected from the line.

2.6 Torque Speed Characteristics

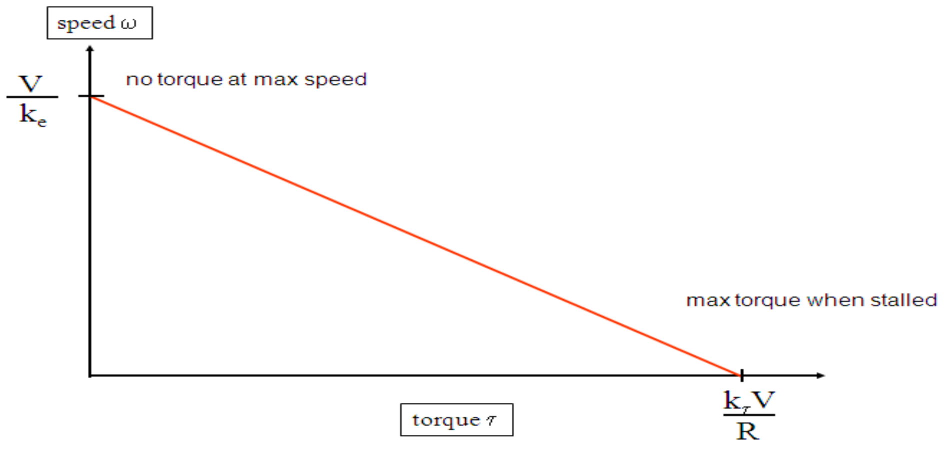

Fig. 2.25 Speed vs Torque at a fixed voltage

Linear mechanical power $P_m = F * V$

Rotational version of $P_m = T * w$

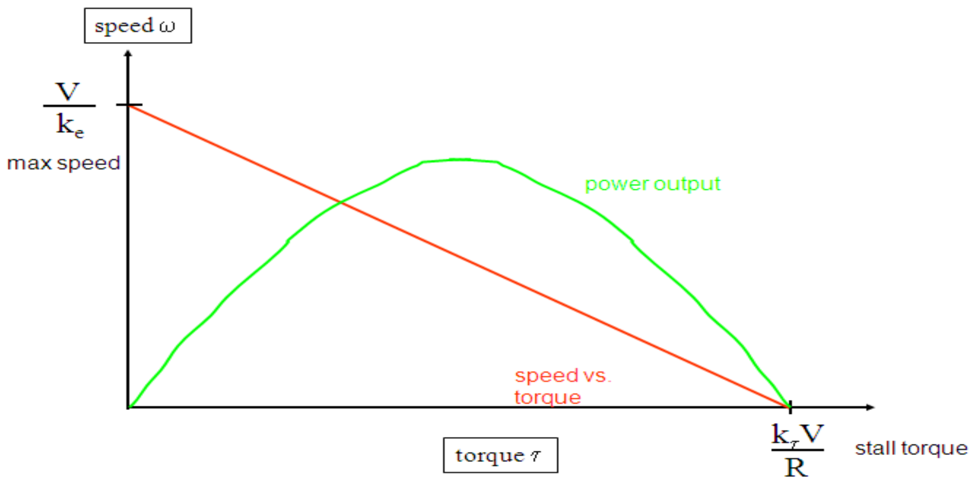

Fig. 2.26 Power output curve at a fixed voltage

2.7 Pros & Cons of DC Motor

The Brushed DC motor is one of the earliest motor designs. Today, it is the motor of choice in the majority of variable speed and torque control applications. It has also several other factors like simple design, excellent speed and position control, easy to control torque, cheap drive design that help dc motor to be used by the most of the process industries.

Pros

- Easy to understand design
- Easy to control speed
- Easy to control torque
- Simple, cheap drive design
- Low Initial Cost - $/Hp
- Simple & Efficient Operation
- Compact Size – cubic inches/Hp
- Long Life – 30,000 to 50,000 hours
- Low Noise
- No Exhaust Emissions
- Withstand high temporary overloads
- Automatic/Remote Start & Control

Cons

- Expensive to produce
- Can't reliably control at lowest speeds
- Physically larger
- High maintenance
- Dust
- Portability

2.8 Applications of DC Motor

- Industrial applications use dc motors because the speed-torque relationship can be varied to almost any useful form -- for both dc motor and regeneration applications in either direction of rotation. Continuous operation of dc motors is commonly available over a speed range of 8:1. Infinite range (smooth control down to zero speed) for short durations or reduced load is also common.
- Dc motors are often applied where they momentarily deliver three or more times their rated torque. In emergency situations, dc motors can supply over five times rated torque without stalling (power supply permitting).
- Dynamic braking (dc motor-generated energy is fed to a resistor grid) or regenerative braking (dc motor-generated energy is fed back into the dc motor supply) can be obtained with dc motors on applications requiring quick stops, thus eliminating the need for, or reducing the size of, a mechanical brake.
- Dc motors feature a speed, which can be controlled smoothly down to zero,

immediately followed by acceleration in the opposite direction -- without power circuit switching. And dc motors respond quickly to changes in control signals due to the dc motor's high ratio of torque to inertia.

- DC motors are used in many, if not most, modern machines. Obvious uses would be in rotating machines such as fans, turbines, drills, the wheels on electric cars, locomotives and conveyor belts. Also, in many vibrating or oscillating machines, a dc motor spins an irregular figure with more area on one side of the axle than the other, causing it to appear to be moving up and down.
- DC motors are also popular in robotics. They are used to turn the wheels of vehicular robots, and servo motors are used to turn arms and legs in humanoid robots. In flying robots, along with helicopters, a motor causes a propeller or wide, flat blades to spin and create lift force, allowing vertical motion.
- DC motors are replacing hydraulic cylinders in airplanes and military equipment.
- In industrial and manufacturing businesses, DC motors are used to turn saws and blades in cutting and slicing processes, and to spin gears and mixers (the latter very common in food manufacturing). Linear motors are often used to push products into containers horizontally.
- Many kitchen appliances also use DC motors. Food processors and grinders spin blades to chop and break up foods. Blenders use electric motors to mix liquids, and microwave ovens use motors to turn the tray food sits on. Toaster ovens also use electric motors to turn a conveyor to move food over heating elements.

Hence the different aspects of DC motors can be familiar and well understood.

Chapter 3

PID Controller

3.1 Introduction

PID controller consists of Proportional Action, Integral Action and Derivative Action. It is commonly refer to Ziegler-Nichols PID tuning parameters. It is by far the most common control algorithm. In this chapter, the basic concept of the PID controls will be explained.

PID controller's algorithm are mostly used in feedback loops. PID controllers can be implemented in many forms. It can be implemented as a stand-alone controller or as part of Direct Digital Control (DDC) package or even Distributed Control System (DCS). The later is a hierarchical distributed process control system which is widely used in process plants such as iron and steel or oil refining industries.

It is interesting to note that more than half of the industrial controllers in use today utilize PID or modified PID control schemes. Below is a simple diagram illustrating the schematic of the PID controller. Such set up is known as non interacting form or parallel form.

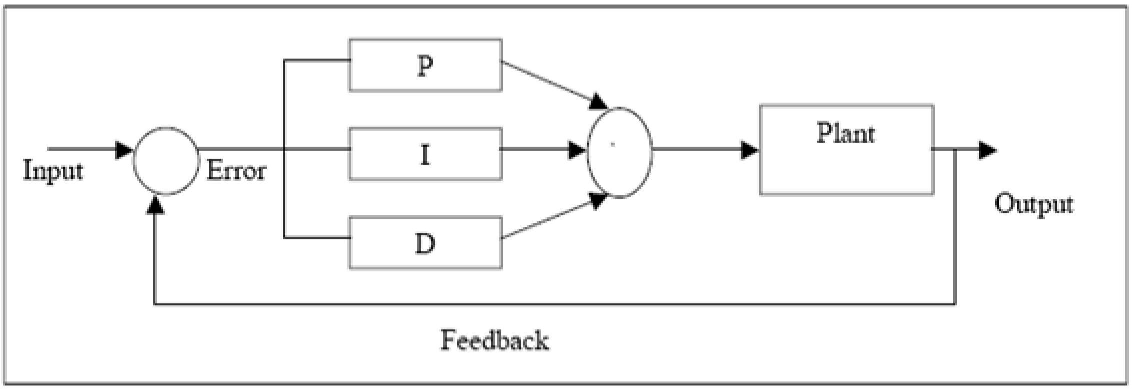

Fig. 3.1 Schematic of the PID Controller- Non Interacting form

3.2 PID Controller

In proportional control,

$$\mathbf{P_{term} = K_P * Error}$$

It uses proportion of the system error to control the system. In this action an offset is introduced in the system.

In Integral control,

$$\mathbf{I_{term} = K_I * \int Error\ dt}$$

It is proportional to the amount of error in the system. In this action, the I-action will introduce a lag in the system. This will eliminate the offset that was introduced earlier on by the P-action.

In Derivative control,

$$\mathbf{D_{term} = K_D * \frac{d\,(Error)}{dt}}$$

It is proportional to the rate of change of the error. In this action, the D-action will introduce a lead in the system. This will eliminate the lag in the system that was introduced by the I-action earlier on.

3.3 Continuous PID

The three controllers when combined together can be represented by the following transfer function.

$$\mathbf{G_c(s) = K\,(1 + 1/sT_i + sT_d)}$$

This can be illustrated below in the following block diagram

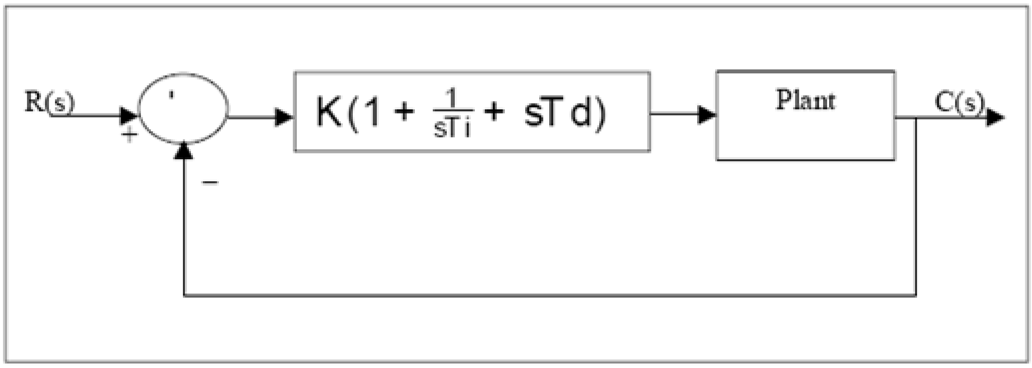

Fig. 3.2 Block diagram of Continuous PID Controller

What the PID controller does is basically is to act on the variable to be manipulated through a proper combination of the three control actions that is the P control action, I control action and D control action.

The P action is the control action that is proportional to the actuating error signal which is the difference between the input and the feedback signal. The I action is the control action which is proportional to the integral of the actuating error signal. Finally the D action is the control action which is proportional to the derivative of the actuating error signal. With the integration of all the three actions, the continuous PID can be realized.

This type of controller is widely used in industries all over the world. In fact a lot of research, studies and application have been discovered in the recent years.

3.4 Optimizing of PID Controller

There are different tuning methods for the parameters of PID controller will be used.

3.4.1 Zeigler & Nichols Method

For the system under study, Zeigler-Nichols tuning rule based on critical gain K*er* and critical period P*er will* be used. In this method, the integral time T_i will be set to infinity and the derivative time T_d to zero. This is used to get the initial PID setting of the system. This PID setting will then be further optimized using the Basic Design mode and Extended Design mode.

In this method, only the proportional control action will be used. The K_p will be increase to a critical value K*er* at which the system output will exhibit sustained oscillations. In this method, if the system output does not exhibit the sustained oscillations hence this method does not apply.

From the response below, the system under study is indeed oscillatory and hence the Z-N tuning rule based on critical gain K*er* and critical period P*er* can be applied.

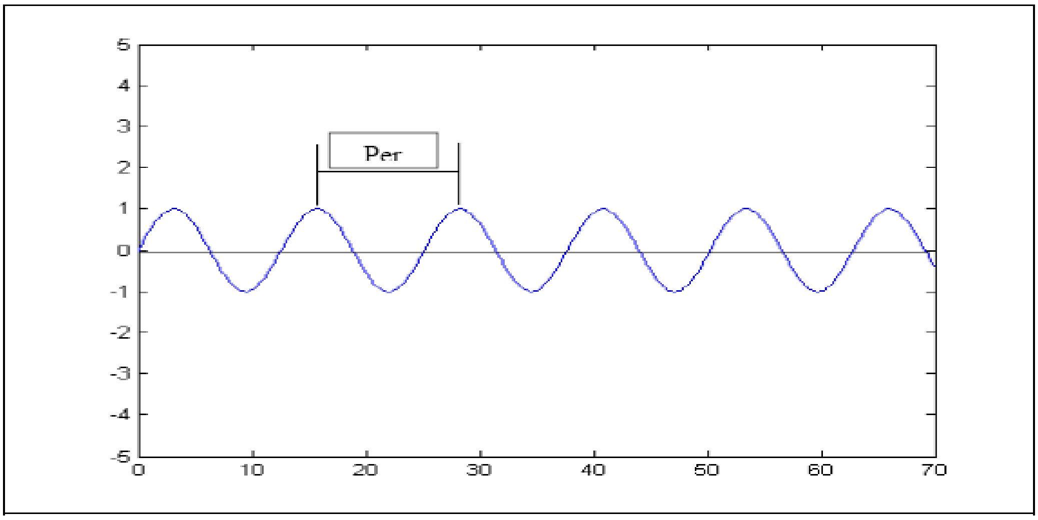

Fig. 3.3 Illustration of Sustained oscillation with period Per

The transfer function of the PID controller is

$$G_c(s) = K\,(1 + 1/sT_i + sT_d)$$

The objective is to achieve a unit-step response curve of the designed system that exhibits a maximum overshoot of 25 %. If the maximum overshoot is excessive says about greater than 40%, fine tuning should be done to reduce it to less than25%.

The system under study above has a following block diagram

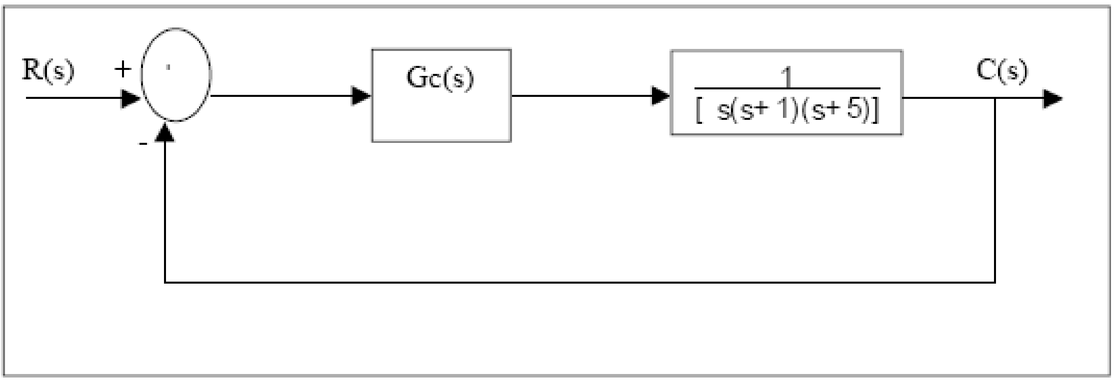

Fig. 3.4 Block diagram of Controller and Plant

Since the $T_i = \infty$ and $T_d = 0$, this can be reduced to the transfer function of

$$R(s)/C(s) = Kp/\ s(s+1)(s+5) + Kp$$

The value of Kp that makes the system marginally stable so that sustained oscillation occurs can be obtained by using the Routh's stability criterion. Since the characteristic equation for the closed-loop system is

s^3+ 6s^2+ 5s+ Kp= 0

From the Routh's Stability Criterion, the value of Kp that makes the system marginally stable can be determined.

The table below illustrates the Routh array.

s^3	1	5
s^2	6	Kp
s^1	(30-Kp)/6	0
s^o	Kp	0

Table 3.1 Routh Array

By observing the coefficient of the first column, the sustained oscillation will occur if Kp = 30.

Hence the critical gain K*er* is

$$K_{er} = 30$$

Thus with Kp set equal to Ker, the characteristic equation becomes

$$s^3 + 6s^2 + 5s + 30 = 0$$

The frequency of the sustained oscillation can be determined by substituting the s terms with *j*ω term. Hence the new equation becomes

$$(j\omega)^3 + 6(j\omega)^2 + 5(j\omega) + 30 = 0$$

This can be simplified to

$$6(5 - \omega)^2 + j\omega(5 - \omega) = 0$$

From the above simplification, the sustained oscillation can be reduced to

$$\omega^2 = 5$$

or $$\omega = \sqrt{5}$$

The period of the sustained oscillation can be calculated as

$$P_{er} = 2\pi/\sqrt{5}$$

$$= 2.8099$$

From Ziegler-Nichols frequency method of the second method, the table suggested tuning rule according to the formula shown. From these we are able to estimate the parameters of Kp, T_i and T_d.

Type of Controller	Kp	Ti	Td
P	0.5 Ker	∞	0
PI	0.45 Ker	(1/1.2) Per	0
PID	0.6 Ker	0.5 Per	0.125 Per

Table 3.2 Recommended PID Value Setting

Hence from the above table, the values of the PID parameters Kp, T_i and T_d will be Kp = 30

Ti = 0.5 X 2.8099

= 1.405

Td = 0.125 X 2.8099

= 0.351.

The transfer function of the PID controller with all the parameters putting in below equation

$$\mathbf{G_c(s) = K_p\,(1 + 1/sT_i + sT_d)}$$

From the above transfer function, we can see that the PID controller has pole at the origin and double zero at s = -1.4235. The block diagram of the control system with PID controller is as follows.

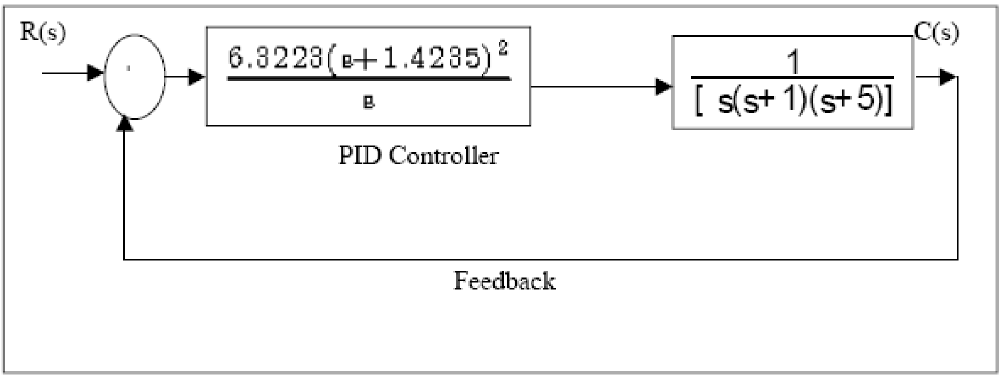

Fig. 3.5 Illustrated the Closed Loop Transfer Function.

3.4.2 Auto tuning of PID Controller

Auto tuning is basically used to tune PID gains automatically in a Simulink model containing a PID controller block. The PID tuner allows to achieve a good balance between performance and robustness. It automatically computes a linear model of the plant. The PID tuner considers the plant to be the combination of all blocks between the PID controller input and output. Thus, the plant includes all blocks in the control loop, other than the controller itself.

The main objectives of PID tuner are

1. **Closed- loop stability:** The closed-loop system output remains bounded for bounded input.
2. **Adequate performance:** The closed-loop system tracks reference changes and suppresses disturbances as rapidly as possible. The larger the loop bandwidth (the frequency of unity open-loop gain), the faster the controller responds to changes in the reference or disturbances in the loop.
3. **Adequate robustness:** The loop design has enough gain margin and phase margin to allow for modeling errors or variations in system dynamics.

3.4.3 Controllers Design with the PID Tuner

There are different steps to be followed while designing controllers with the PID Tuner ---

1. Prerequisites for PID Tuning
2. Opening the Tuner
3. Analyzing the Design in the PID Tuner
4. Refining the Design
5. Verifying the PID Design in Your Simulink Model

Prerequisites for PID Tuning

Before the use of PID Tuner, following is the must:

- Create a Simulink model containing a PID Controller or PID Controller (2DOF) block. The model can have one or more PID blocks, but tuning is done one PID block at a time. The plant (all blocks in the control loop other than the controller) can be linear or nonlinear. The plant can also be of any order, and have any time delays.
- Configure the PID block settings, such as controller type, controller form, time domain, sample time.

Opening the Tuner

To open the PID Tuner and view the initial compensator design:

1. Open the Simulink model by typing the model name at the MATLAB command prompt.
2. Double-click the PID Controller block to open the block dialog box.
3. In the block dialog box, click **Tune** to launch the PID Tuner.

   After launching the PID Tuner, the following actions occur:

   - The PID Tuner automatically linearizes the plant at the default operating point; The PID Tuner computes an initial compensator design using the algorithm described in PID Tuning Algorithm.
   - The PID Tuner displays the closed-loop step reference tracking response for the initial compensator design in the PID Tuner dialog box. For comparison,

the display also includes the closed-loop response for the gains specified in the PID Controller block, if that closed loop is stable, as shown in the following figure.

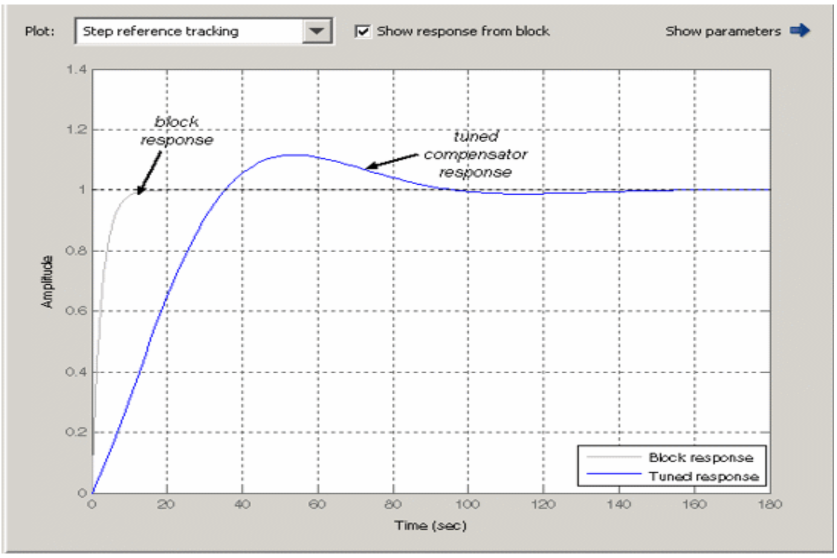

Fig. 3.6 PID Tuner frame

Analyzing the Design in the PID Tuner

To determine whether the compensator design meets the requirements, it can be analyzed the system response in any of these response plots:

- **Step reference tracking (default):** For evaluating how the controller tracks a reference signal.
- **Step disturbance rejection:** For evaluating how the controller rejects disturbances.
- **Open- loop Bode plot:** For evaluating open- loop frequency response.
- **Open- loop Nichols chart:** For evaluating open- loop frequency response.

Refining the Design

If the response of the initial controller design does not meet the requirements, it can interactively adjust the design. The PID Tuner gives two ways to refine the controller design:

- **Adjust response time (Basic Design mode):** Make the closed-loop response of the controlled system faster or slower.
- **Separately adjust loop bandwidth and phase margin (Extended Design mode):** The larger the loop bandwidth, the faster the controller responds to changes in the reference or disturbances in the loop. The larger the phase margin, the more robust the controller is against modeling errors or variations in plant dynamics.

Verifying the PID Design in Your Simulink Model

In the PID Tuner, tuning of compensator is done using a linear model of the plant. A good compensator design is first achieved in the PID Tuner. Then, verify that the tuned controller meets the design requirements when applied to the nonlinear plant in the Simulink model.

To verify the compensator design in the nonlinear Simulink model:

1. In the PID Tuner, click **Apply** to update the Simulink PID Controller block with the tuned PID parameters.
2. Simulate the Simulink model, and evaluate whether the simulation output meets the design requirements.

3.4.4 Analysis of the Classically Designed Controller

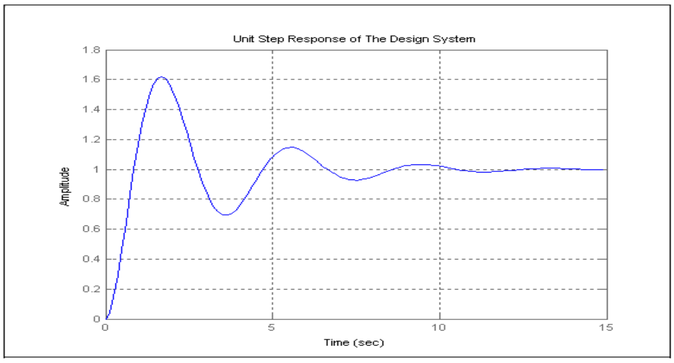

Fig. 3.7 Unit Step response of the Designed System.

From the above diagram, the response of the system can be analyzed. The zero and pole of the system can be calculated using the MATLAB function **tf2zp**. The response of the system can be analyzed via the following parameters:

- Delay time, t_d
- Rise time, t_r
- Peak time, t_p
- Maximum Overshoot, Mp
- Settling time, t_s

The **delay time**, t_d of the above system which is the time taken to reach 50% of the final response time is about 0.5 sec.

The **rise time**, t_r is the time taken to reach 5 to 95 % of the final value is about1.75 sec.

The **Peak time**, t_p is the time taken for the system to reach the first peak of overshoot is about 2.0 sec.

The **Maximum Overshoot**, Mp of the system is approximately 60%.

Finally the **Settling time**, t_s is about 10.2 sec. From the analysis above, the system has not been tuned to its optimum. Here we can improve the system by looking into the system zero and pole.

The system zeros and poles can be calculated using MATLAB function.

Hence the different parameters of control system are known and that parameters need to be controlled for better efficiency.

Chapter 4

Case Study

4.1 Modeling a DC Motor

To be modeling a DC Motor, simple circuit of its electrical diagram as shown in fig. 4.1 is considered. To be Modeling and Simulate the DC motor, the following steps are to be made step by step;

Step1: Represent the DC motor circuit diagram.

Step2: Represent system equations

Step3: Calculate the Transfer function

Step4: Convert to model block

Step5: Run the Simulation

Step6: Analysis

4.2 Closed-Loop System Consideration

To perform the simulation of the system, an appropriate model needs to be established. Therefore, a model based on the motor specifications needs to be obtained. Fig. 4.1 shows the DC motor circuit with Torque and Rotor Angle consideration.

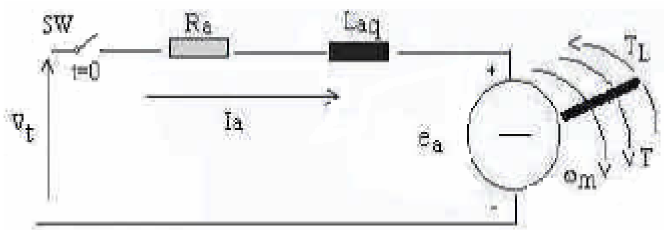

Fig. 4.1 Schematic diagram of a DC motor

4.3 System Equations

The motor torque **T** is related to the armature current, **i** , by a torque constant **K**;

$$T = K\,i \qquad (1)$$

The generated voltage, $\mathbf{e_a}$, is relative to angular velocity by;

$e_a = K\, w_m = K\, d\theta/dt$ (2)

From Fig. 4.1 we can write the following equations based on the Newton's law combined with the Kirchhoff's law:

$J\, d^2\theta/dt^2 + b\, d\theta/dt = K\, i$ (3)

$L\, di/dt + Ri = V - K\, d\theta/dt$ (4)

4.4 Transfer Function

Using the Laplace transform, equations (3) and (4) can be written as:

$J\, s^2\, \theta(s) + b\, s\, \theta(s) = K\, I(s)$ (5)

$L\, s\, I(s) + R\, I(s) = V(s) – K\, s\, \theta(s)$ (6)

Where *s* denotes the Laplace operator. From (6) we can express **I**(*s*):

$$I(s) = \frac{V(s) - K\, s\, \theta(s)}{R + Ls} \qquad (7)$$

and substitute it in (5) to obtain:

$$\mathrm{J\, s^2\, \theta(s) + b\, s\, \theta(s) = \frac{K\,(V(s) - K\, s\, \theta(s))}{R + Ls}} \qquad (8)$$

This equation for the DC motor is shown in the block diagram in Fig. 4.2. From equation (8), the transfer function from the input voltage, **V** (*s*), to the output angle, θ, directly follows:

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{K}{[\, s\{(R + Ls)(Js + b) + K^2\}]} \qquad (9)$$

Before any consideration of the above equations, we must know the constant values of data, K, J, b, V, L and R. This is very important to the application of DC motor which we will be used.

Speed N = 1220 rpm = 127.7 rad/sec

Motor inertia J = 1 $Kg.m^2$ V = 240V $i = armature\ current = 16.2\ A$

$E_O = V – i\, R_a$ = 230.3 V Power $P = E_O\, I_a$ = 3731 W = 5 HP

$I_f = V/\, R_f = 1$ where $R_f = 240\ \Omega$ $E_O = w\, L\, I_{f=}$ 127.7 rad/sec

Therefore for the max speed rpm of 1220, it can be calculate the torque constant K;

$$w_m = \frac{V}{K} = \frac{2\pi N}{60} \qquad (10)$$

K = 1.88 N. m/A

By using equation (3), for w = dθ/dt

$$K \times i = J\frac{dw}{dt} + bw \quad (11)$$

At the steady state (used as analyzed data), both **I** and **w** are stabilized;

$$J\frac{dw}{dt} = 0 \ \ and \ \ T = \frac{P}{w} = 29.2\ Nm$$

Therefore, the total equivalent damping **b** can be chosen the value of;

$$b = \frac{K \times i}{w} = 0.24\ N.m.s \quad L = mutual\ inductance = 1.8\ H$$

$$R = armature\ resistance\ = 0.6\ \Omega$$

By calculating and assuming the require data as above, the following value are assigned to be used for our desire DC Motor Model. **V**=240 V; **J**= 1 kg.m^2; **b** =0.24 N.m.s;

K =1.88 N. m/A; **R** =0.6 Ω; and **L** =1.8 H;

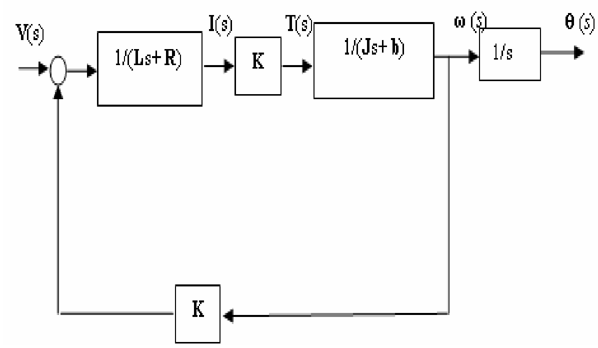

Fig. 4.2 A closed- loop system that representing the DC motor

Nominal values of desired DC motor model

Maximum speed of the motor (N) = 1200 r.p.m. or 127.7 rad/sec

Supply voltage (V) = 240 V

Back emf (E) = 230.3 V

Armature current (i) = 16.2 A

Power (P) = 3731 W or 5 HP

Field resistance (R_f) = 240 Ω

Armature resistance (R) = 0.6 Ω

Mutual inductance (L) = 1.8 H

Motor inertia (J) = 1 $Kg.m^2$

Motor torque (T) = 29.2 N. m

Motor torque constant (K) = 1.88 N. m/A

Damping coefficient (b) = 0.24 N. m. s.

So the desired value of DC motor parameter is obtained for a particular application.

Chapter 5

Simulations, Results & Comparisons

There are four cases in which uncertainty in the form of disturbance and load is considered to the system.

Our Design requirement

Maximum Overshoot = < 2%

Undershoot = 0

Rise time (t_r) = < 7 sec

Settling time (t_s) = < 12 sec

Case1: No Load and No Disturbance

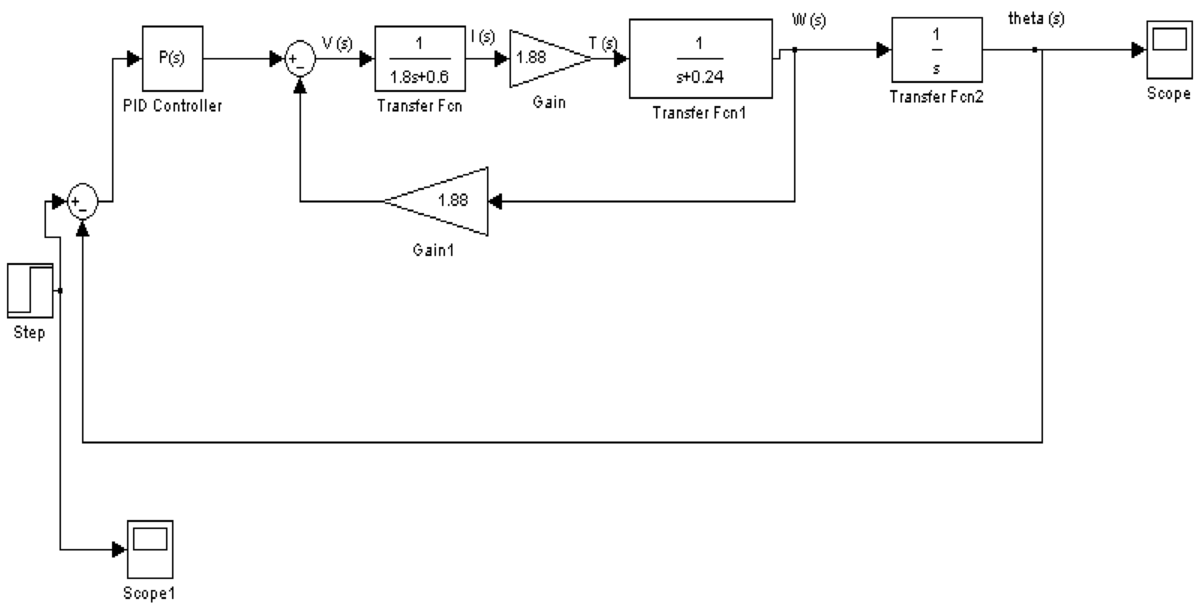

Fig. 5.1 Simulink diagram of dc motor model with controller

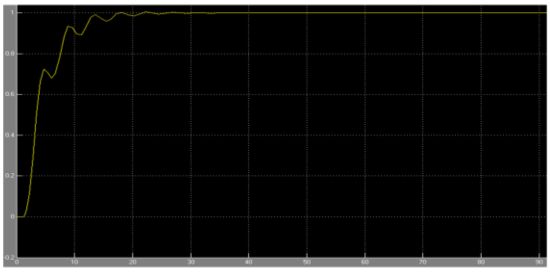

Fig. 5.2: System output with P controller

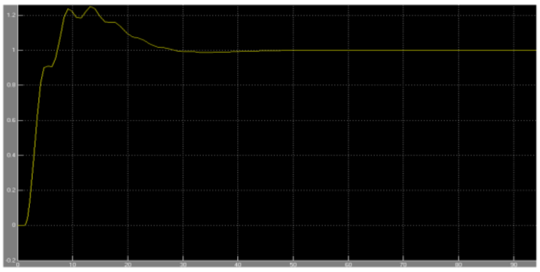

Fig. 5.3: System output with PI controller

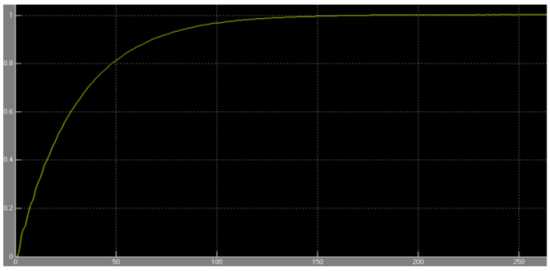

Fig. 5.4: System output with PID controller

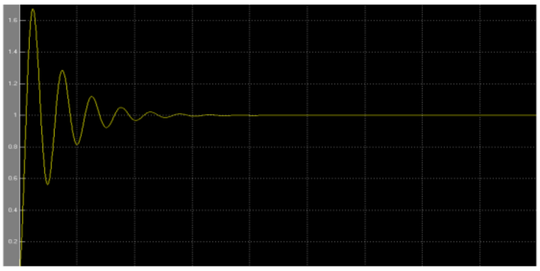

Fig. 5.5: System output with PID controller (Zeigler & Nichols method)

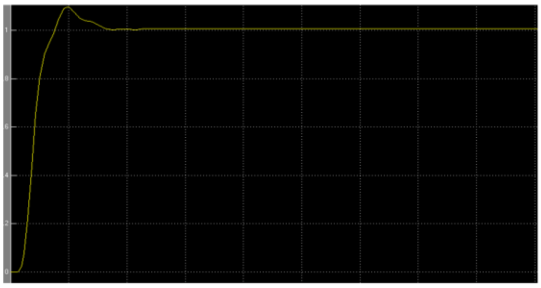

Fig. 5.6: System output with PID controller auto tuning (Basic Design mode)

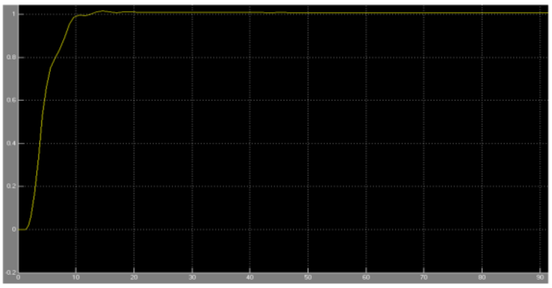

Fig. 5.7: System output with PID controller auto tuning (Extended Design mode)

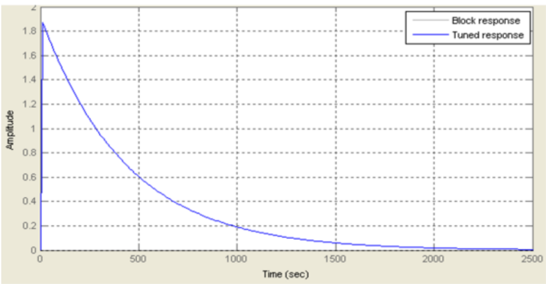

Fig. 5.8: Step disturbance rejection plot with PID controller auto tuning (Extended Design mode)

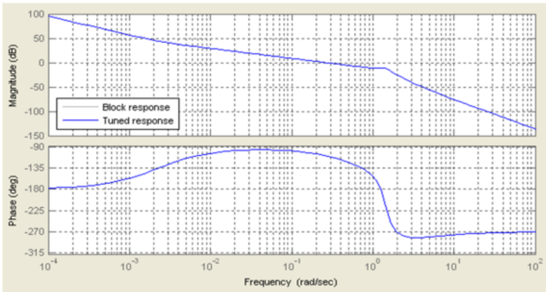

Fig. 5.9: Open- loop Bode plot with PID controller auto tuning (Extended Design mode)

Controller types	K_P	K_I	K_D	Rise time (t_r in sec)	Settling time (t_s in sec)	Over shoot (%)	Under shoot (%)	Gain margin(db@ rad/sec)	Phase margin (deg@rad/sec)
P	0.5	0	0	6.19	15.6	0.377	30	7.02@1.43	85.6@0.264
PI	0.5154	0.07252	0	2.68	23.9	25.2	8	6.41@1.4	60@0.303
PID	0.1	0.00001	1.001	70	130	0	0	-	-
PID (ZN)	0.0138	0.00123	0.038795	50	1500	65	33	-	-
PID(Basic)	0.73195	0.0029102	-1.5315	3.36	14.2	9.85	0	10.1@1.26	60@0.329
PID(Ext.)	0.5247	0.0023067	-1.0011	5.59	8.45	1.62	0	11@1.25	71@0.262

Table 5.1 Comparative analysis of different controllers under no load & no disturbance

Hence after implementation of auto tuning of PID controller in extended design mode, the system design requirement is achieved which is shown in table 5.1.

Case2: Load and No Disturbance

In this case uncertainty in the form of 2nd order load is considered.

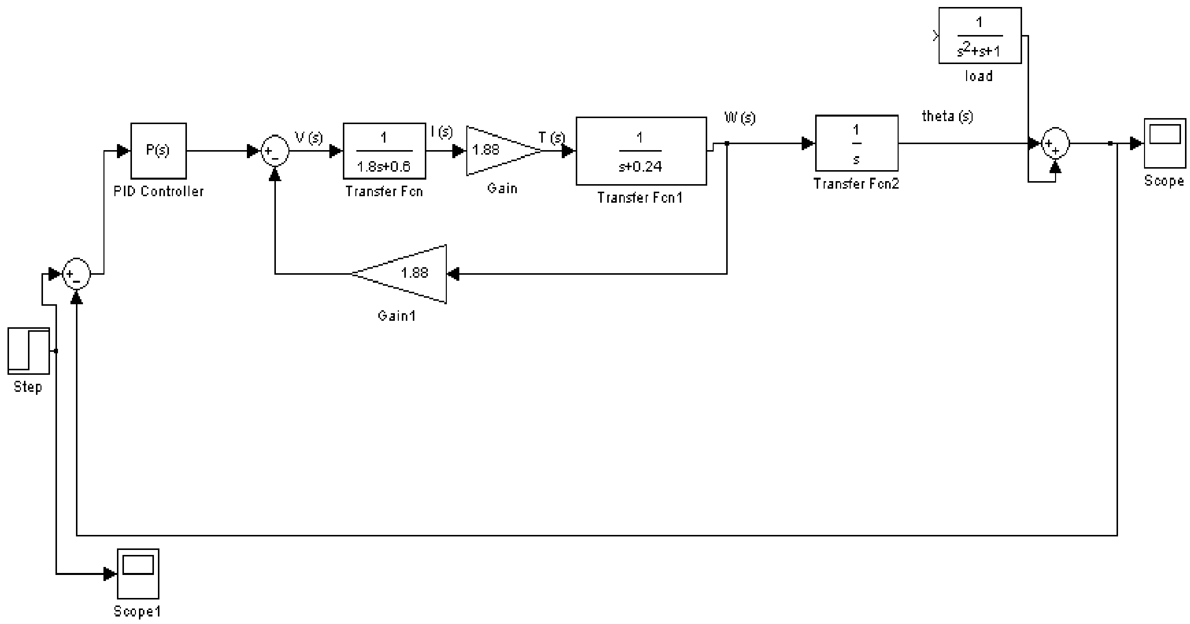

Fig. 5.10 Simulink diagram of dc motor model with controller

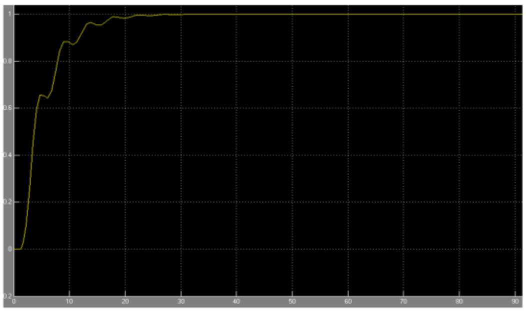

Fig. 5.11: System output with P controller

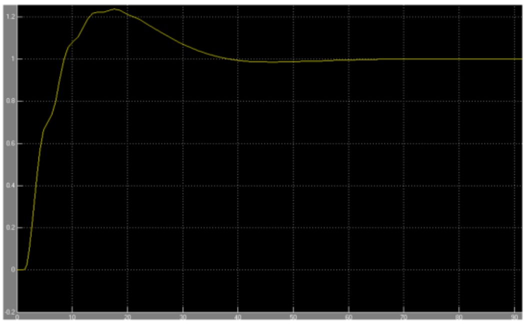

Fig. 5.12: System output with PI controller

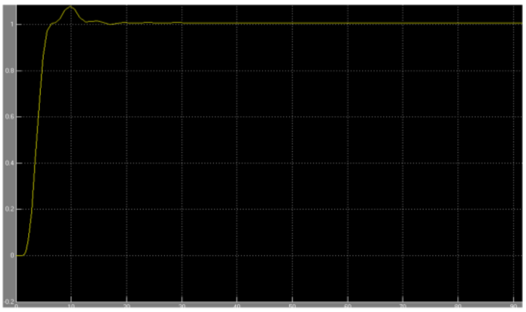

Fig. 5.13: System output with PID controller auto tuning (Basic Design mode)

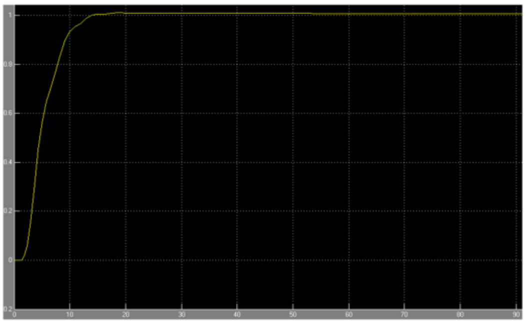

Fig. 5.14: System output with PID controller auto tuning (Extended Design mode)

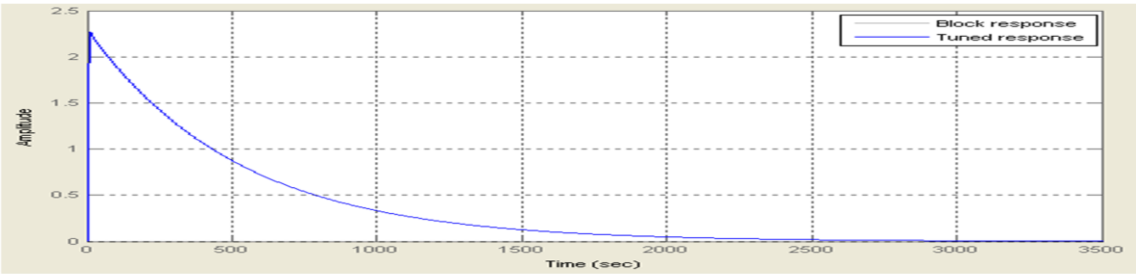

Fig. 5.15: Step disturbance rejection plot with PID controller auto tuning (Extended Design mode)

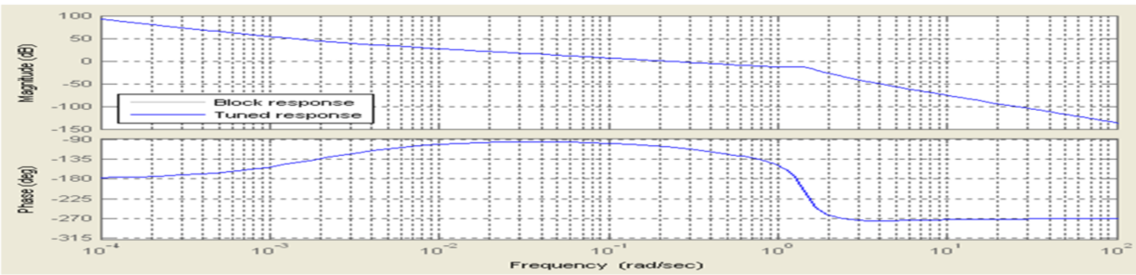

Fig. 5.16: Open- loop Bode plot with PID controller auto tuning (Extended Design mode)

Controller types	K_P	K_I	K_D	Rise time (t_r in sec)	Settling time (t_s in sec)	Over shoot (%)	Under shoot (%)	Gain margin(db@ rad/sec)	Phase margin (deg @rad/sec)
P	**0.43695**	**0**	**0**	**9.6**	**16.1**	**0.00758**	**32**	**8.19@1.43**	**86.2@0.229**
PI	**0.35952**	**0.037665**	**0**	**5.45**	**34**	**23.7**	**0**	**9.62@1.41**	**60@0.21**
PID(Basic)	**0.76098**	**0.0031897**	**-1.276**	**2.65**	**11**	**8.05**	**0**	**8.88@1.2**	**60@0.361**
PID(Ext.)	**0.43964**	**0.0019183**	**-1.103**	**6.53**	**11.6**	**1.12**	**0**	**13@1.28**	**73@0.278**

Table 5.2 Comparative analysis of different controllers under load & no disturbance

After consideration of 2nd order load, the design requirement meets in the extended design mode which is shown in table 5.2.

Case3: No Load and Disturbance

In this case uncertainty in the form of step disturbance of final value 0.5 is considered.

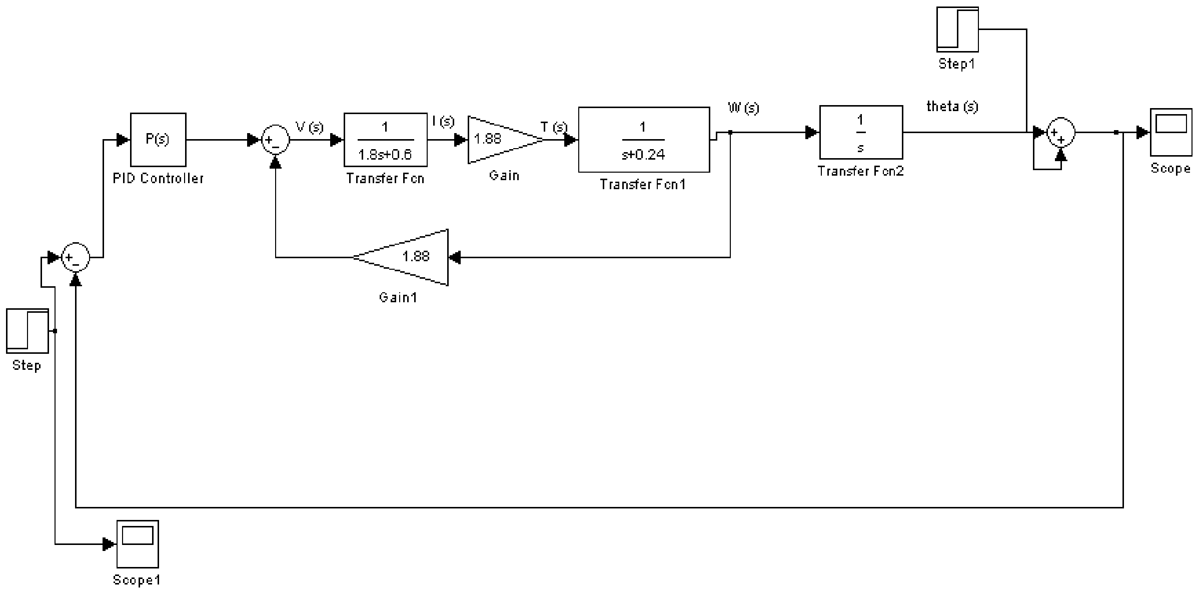

Fig. 5.17 Simulink diagram of dc motor model with controller

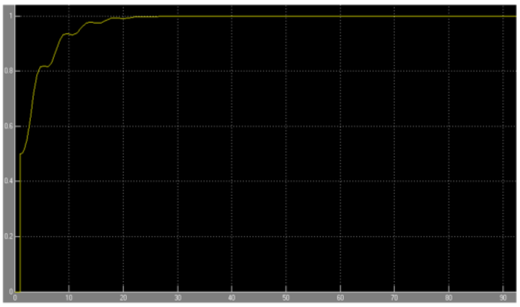

Fig. 5.18: System output with P controller

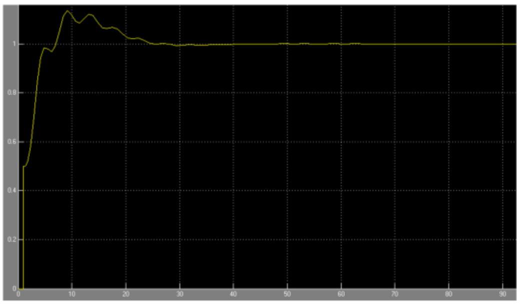

Fig. 5.19: System output with PI controller

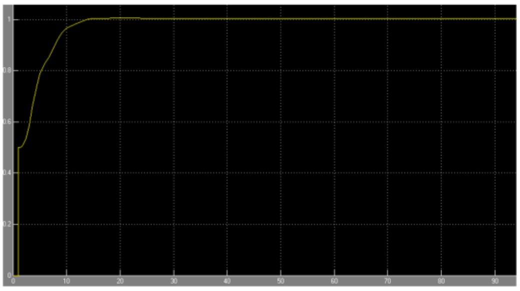

Fig. 5.20: System output with PID controller auto tuning (Basic Design mode)

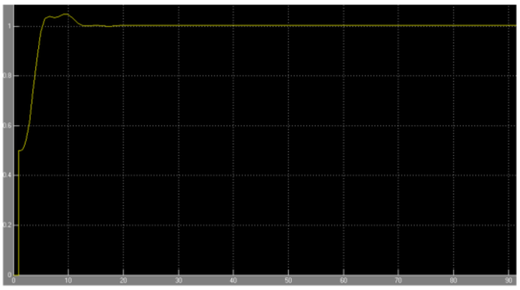

Fig. 5.21: System output with PID controller auto tuning (Extended Design mode)

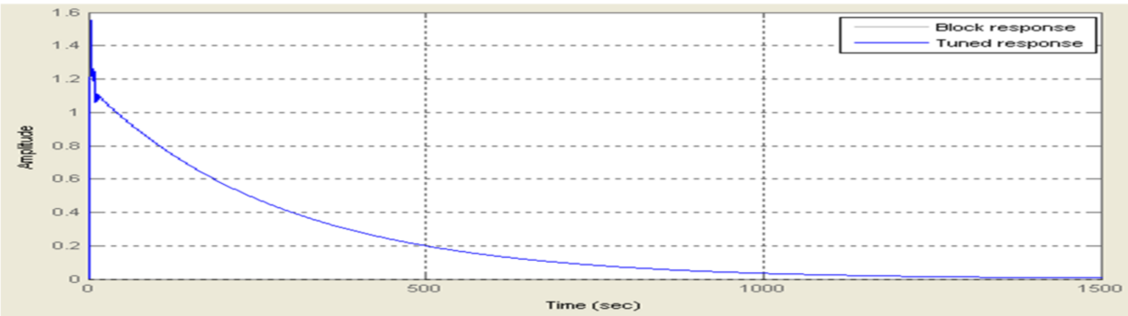

Fig. 5.22: Step disturbance rejection plot with PID controller auto tuning (Extended Design mode)

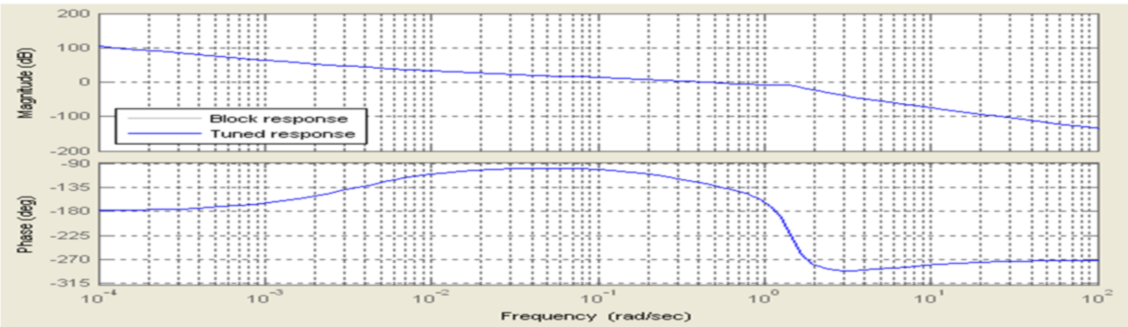

Fig. 5.23: Open- loop Bode plot with PID controller auto tuning (Extended Design mode)

Controller types	K_P	K_I	K_D	Rise time (t_r in sec)	Settling time (t_s in sec)	Over shoot (%)	Under shoot (%)	Gain margin(db@ rad/sec)	Phase margin (deg@rad/sec)
P	0.41817	0	0	9.75	19.1	0	20	8.57@1.43	86.4@0.218
PI	0.56269	0.084676	0	2.2	22.8	27.2	1	5.62@1.4	60@0.332
PID(Basic)	0.43964	0.0019183	-1.1032	6.53	11.6	1.12	0	13@1.28	73@0.218
PID(Ext.)	0.86883	0.0035009	-1.4425	2.37	10.9	9.9	0	8.39@1.18	55@0.396

Table 5.3 Comparative analysis of different controllers under no load & disturbance

Hence after the consideration of disturbance, the design requirement meets in the Basic design mode which is shown in table 5.3.

Case4: Load and Disturbance

In this case uncertainty in the form of step disturbance of final value 0.5 and a 2nd order load is incorporated.

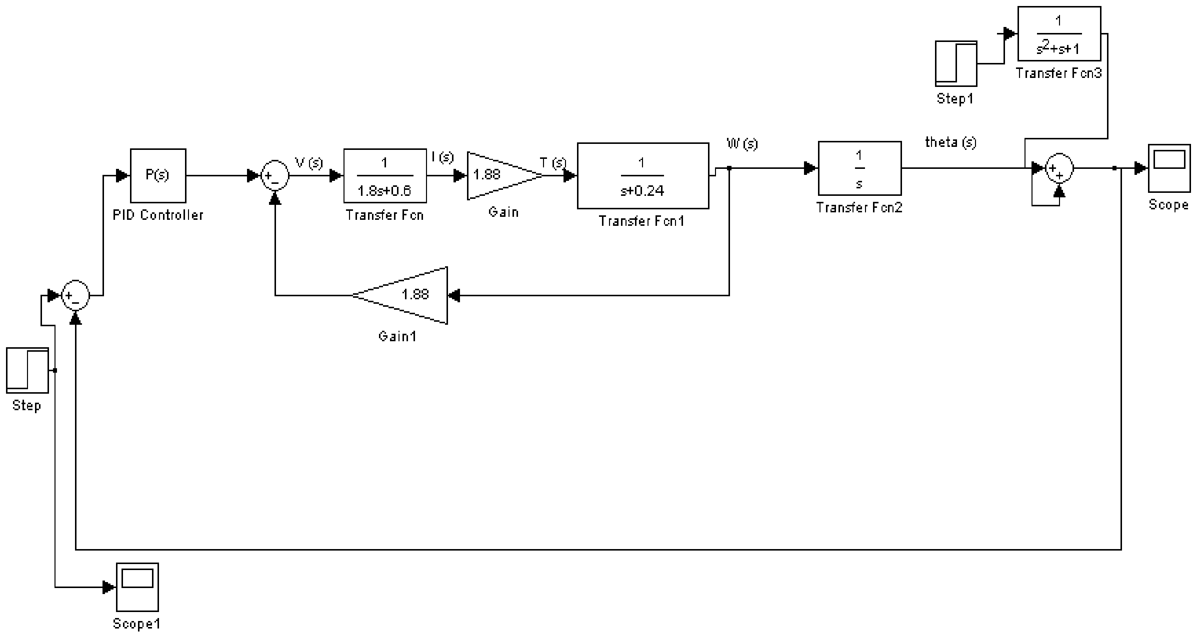

Fig. 5.24 Simulink diagram of dc motor model with controller

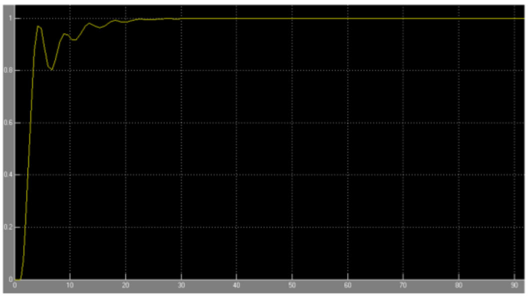

Fig. 5.25: System output with P controller

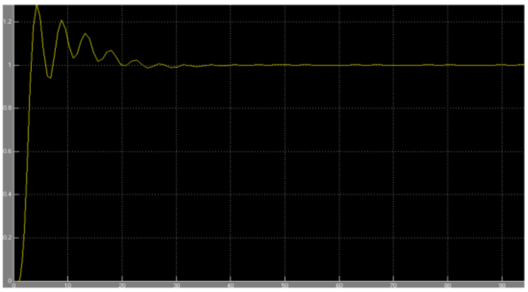

Fig. 5.26: System output with PI controller

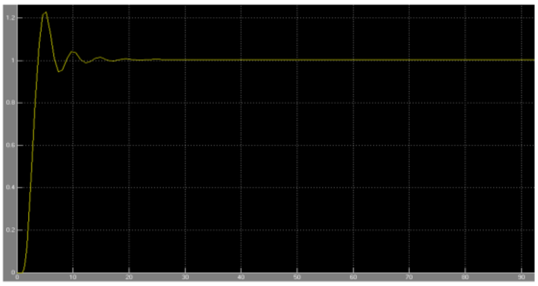

Fig. 5.27: System output with PID controller auto tuning (Basic Design mode)

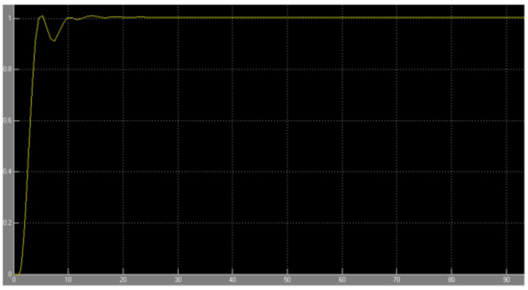

Fig. 5.28: System output with PID controller auto tuning (Extended Design mode)

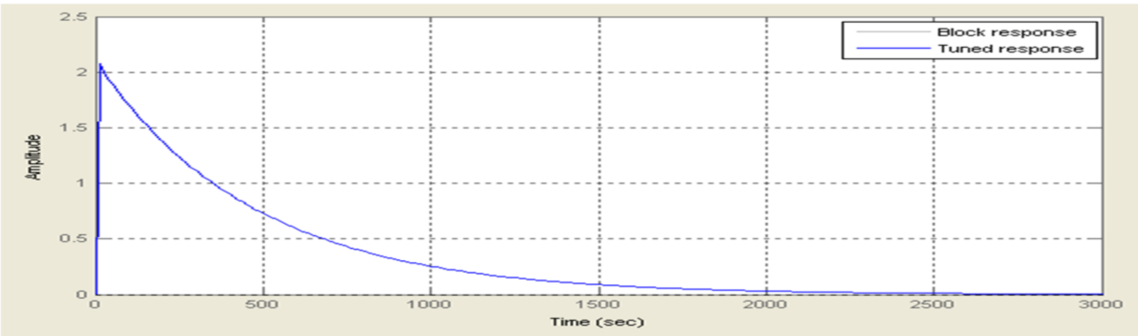

Fig. 5.29: Step disturbance rejection plot with PID controller auto tuning (Extended Design mode)

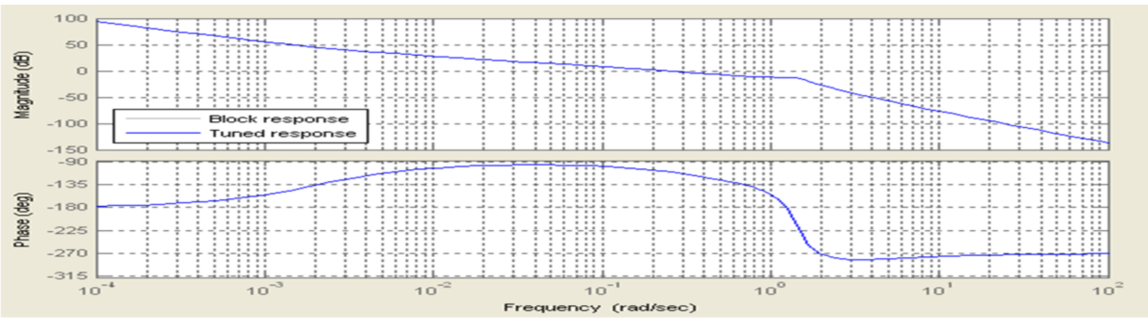

Fig. 5.30: Open- loop Bode plot with PID controller auto tuning (Extended Design mode)

Controller types	K_P	K_I	K_D	Rise time (t_r in sec)	Settling time (t_s in sec)	Over shoot (%)	Under shoot (%)	Gain margin(db@ rad/sec)	Phase margin (deg@rad/sec)
P	0.36613	0	0	10.4	20.3	0	20	9.73@1.43	86.9@0.19
PI	0.58763	0.091329	0	2.07	22.5	28.7	5	5.23@1.4	60@0.348
PID(Basic)	0.79159	0.0033399	-1.2026	2.47	10.7	24	3	8.23@1.21	60@0.378
PID(Ext.)	0.4814	0.0021039	-1.1276	5.9	9.46	1.47	3	12.3@1.24	71@0.239

Table 5.4 Comparative analysis of different controllers under load & disturbance

Hence after considering uncertainty in the form of both 2nd order load and step disturbance, the best controller performance is achieved in extended design mode which is shown in table 5.4.

Chapter 6

Conclusion & Future Scope

Electric machines are used to generate electrical power in power plants and provide mechanical work in industries. The DC machine is considered to be basic electric machines. The aim of this thesis is to introduce Technicians to the modeling of power components and to use computer simulation as a tool for conducting transient and control studies. Next to having an actual system to experiment on, simulation is often chosen by engineers to study transient and control performance or to test conceptual designs.

MATLAB/SIMULINK is used because of the short learning curve that most students require to start using it, its wide distribution, and its general-purpose nature. This will demonstrate the advantages of using MATLAB for analyzing power system steady state behavior and its capabilities for simulating transients in power systems and power electronics, including control system dynamic behavior.

This thesis has demonstrated the implementation of auto tuning of PID controller in MATLAB/SIMULINK, both in basic and extended design mode. This is easy to implement and requires a small amount of time. The controller showed robust performance of the system under different cases and optimization of our system is achieved which is less complex than other controllers and optimization technique. So controlled operation of this dc motor drive attracts the researchers always and by the use of advanced soft computing technique like genetic algorithm and memetic algorithm, still keeping more and more future scope in it.

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