DESIGN AND SIMULATION OF LEAKAGE CURRENT IN SMART POWER MODULE (SPM) MOTOR DRIVE APPLICATION

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LIST OF SYMBOLS AND ABBREAVIATIONS

DC	Direct Current
AC	Alternating Current
SPM	Smart Power Module
RPM	Rounds Per Minute
EMI	Electromagnetic Interference
EMF	Electromagnetic Field
PM	Permanent Magnet
IGBT	Insulated Gate Bipolar Transistor
RMS	Root Mean Square
BLDC	Brushless Dc Motors
PWM	Pulse-Width Modulation
VCE	Collector-To-Emitter Voltage
N.C	Normal Condition
S.F.C	Single Fault Condition
FDT	Fairchild Design Tools
IEC	International Electrotechnical Commission
EMDS	Electric Motor Drive Systems
HVAC	Heating And Air Conditioning
HVIC	High-Voltage Integrated Circuit
PT	Punch Through
NPT	Non Punch Through
BJT	Bipolar Junction Transistor
PMSM	Permanent Magnet Synchronous Motors

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CHAPTER I

INTRODUCTION

1.1 General Background of Electric Motor

An electric motor is an electric machine that converts electrical energy into mechanical energy. In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force within the motor. In certain applications, such as in the transportation industry with traction motors, electric motors can operate in both motoring and generating or braking modes to also produce electrical energy from mechanical energy [1].

Found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives, electric motors can be powered by direct current (DC) sources, such as from batteries, motor vehicles or rectifiers, or by alternating current (AC) sources, such as from the power grid, inverters or generators. Small motors may be found in electric watches. General-purpose motors with highly standardized dimensions and characteristics provide convenient mechanical power for industrial use. The largest of electric motors are used for ship propulsion, pipeline compression and pumped-storage applications with ratings reaching 100 megawatts. Electric motors may be classified by electric power source type, internal construction, application, type of motion output, and so on [1]. Devices such as magnetic solenoids and loudspeakers that convert electricity into motion but do not generate usable mechanical power are respectively referred to as actuators and transducers. Electric motors are used to produce linear force or torque (rotary).

Perhaps the first electric motors were simple electrostatic devices created by the Scottish monk Andrew Gordon in the 1740s [3]. The theoretical principle behind production of mechanical force by the interactions of an electric current and a magnetic field, Ampère's force law, was discovered later by André-Marie Ampère in 1820. The conversion of electrical energy into mechanical energy by electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821. A free-hanging wire was dipped into a pool of mercury, on which a permanent magnet (PM) was placed. When a current was passed through the wire, the wire rotated around the magnet, showing that the current gave rise to a close circular magnetic field around the wire [4]. This motor is often demonstrated in physics experiments, brine substituting for toxic mercury. Though Barlow's wheel was an early refinement to this Faraday demonstration, these and similar homopolar motors were to remain unsuited to practical application until late in the century.

In 1827, Hungarian physicist Ányos Jedlik started experimenting with electromagnetic coils. After Jedlik solved the technical problems of the continuous rotation with the invention of commutator, he called his early devices as "electromagnetic self-rotors". Although they were used only for instructional purposes, in 1828 Jedlik demonstrated the first device to contain the three main components of practical DC motors: the stator, rotor and commutator. The device employed no permanent magnets, as the magnetic fields of both the stationary and revolving components were produced solely by the currents flowing through their windings [5][6][7].

Figure 1.1: Various electric motors, compared to 9 V battery

1.2 Universal Motor

The universal motor is a type of electric motor that can operate on both AC and DC power. They are commutated series-wound motors or shunt-wound motors where the stator's field coils are connected in series or parallel with the rotor windings through a commutator. This type of electric motor can operate well on AC because the current in both the field coils and the armature (and the resultant magnetic fields) will alternate (reverse polarity) synchronously with the supply. Hence the resulting mechanical force will occur in a consistent direction of rotation, independent of the direction of applied voltage, but determined by the commutator and polarity of the field coils.

Universal motors have high starting torque, run at high speed and are lightweight and are commonly used in portable and domestic equipment [8]. They're also relatively easy to control, electromechanically using tapped coils or electronically. However, the commutator has brushes that wear, so they are much less often used for equipment that is in continuous use. In addition, partly because of the commutator universal motors are typically very noisy [8].

1.2.1 Properties of Universal Motor

When used with AC power these types of motors are able to run at a rotation frequency well above that of the mains supply, and because most electric motor properties improve with speed, this means they can be lightweight and powerful [8]. However, universal motors are usually relatively inefficient- around 30% for smaller motors and up to 70-75% for larger ones [8].

One useful property of having the field windings in series with the rotor windings is that as the speed increases the back EMF naturally reduces the voltage across, and current through the field windings, giving field weakening at high speeds. This means that the motor does not inherently have a maximum speed for any particular applied voltage. Universal motors can be and are generally run at high speeds, 4000-16000 rpm, and can go over 20,000 rpm [8]. By way of contrast, induction motors cannot turn a shaft faster than allowed by the power line frequency.

Universal motors's armatures typically have far more coils and plates than a DC motor, and hence less windings per coil. This reduces the inductance. Motor damage may occur from over-speeding (running at a rotational speed in excess of design limits) if the unit is operated with no significant mechanical load. On larger motors, sudden loss of load is to be avoided, and the possibility of such an occurrence is incorporated into the motor's protection and control schemes. In some smaller applications, a fan blade attached to the shaft often acts as an artificial load to limit the motor speed to a safe level, as well as a means to circulate cooling airflow over the armature and field windings.

An advantage of the universal motor is that AC supplies may be used on motors which have some characteristics more common in DC motors, specifically high starting torque and very compact design if high running speeds are used.

A negative aspect is the maintenance and short life problems caused by the commutator, as well as EMI issues due to any sparking. Because of the relatively high maintenance commutator brushes, universal motors are used in devices such as food mixers and power tools which are used only intermittently and often have high starting-torque demands. Continuous speed control of a universal motor running on AC is easily obtained by use of a thyristor circuit, while multiple taps on the field coil provide (imprecise) stepped speed control. Household blenders that advertise many speeds frequently combine a field coil with several taps and a diode that can be inserted in series with the motor (causing the motor to run on half-wave rectified AC).

Series wound electric motors respond to increased load by slowing down; the current increases and the torque rises in proportional to the square of the current since the same current flows in both the armature and the field windings. If the motor is stalled, the current is limited only by the total resistance of the windings and the torque can be very high, and there is a danger of the windings becoming overheated. 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 low; therefore the current through the armature would be very large when the power is applied. Therefore the need can arise 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.

The output speed torque characteristic is the most notable characteristic of series wound motors. The speed being almost entirely dependent on the torque required to drive the load. This suits large inertial loads as the speed will drop until the motor slowly starts to rotate and these motors have a very high stalling torque.

Not all series wound motors can operate well on AC current. Motors intended for AC generally require laminated field cores. As the speed increases, the inductance of the rotor means that the ideal commutating point changes. Small motors typically have fixed commutation. While some larger universal motors have rotatable commutation, this is rare. Instead larger universal motors often have compensation windings in series with the motor, or sometimes inductively coupled, and placed at ninety electrical degrees to the main field axis. These reduce the reactance of the armature, and improve the commutation [8].

1.2.2 Applications of Universal Motor

Operating at normal power line frequencies, universal motors are often found in a range less than 1000 watts. Universal motors also form the basis of the traditional railway traction motor in electric railways. In this application, the use of AC to power a motor originally designed to run on DC would lead to efficiency losses due to eddy current heating of their magnetic components, particularly the motor field pole-pieces that, for DC, would have used solid (un-laminated) iron. Although the heating effects are reduced by using laminated pole-pieces, as used for the cores of transformers and by the use of laminations of high permeability electrical steel, one solution available at the start of the 20th century was for the motors to be operated from very low frequency AC supplies, with 25 and 16 2⁄3 Hz (the latter subsequently redesignated 16.7 Hz) operation being common. Because they used universal motors, locomotives using this design could operate from a third rail or overhead wire powered by DC. As well, considering that steam engines directly powered many alternators, their relatively low speeds favored low frequencies because comparatively few stator poles were needed.

In the past, repulsion-start wound-rotor motors provided high starting torque, but with added complexity. Their rotors were similar to those of universal motors, but their brushes were connected only to each other. Transformer action induced current into the rotor. Brush position relative to field poles meant that starting torque was developed by rotor repulsion from the field poles. A centrifugal mechanism, when close to running speed, connected all commutator bars together to create the equivalent of a squirrel-cage rotor. As well, when close to operating speed, better motors lifted the brushes out of contact.

Their high speed makes them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high speed and light weight are desirable. They are also commonly used in portable power tools, such as drills, sanders, circular and jig saws, where the motor's characteristics work well. Many vacuum cleaner and weed trimmer motors exceed 10,000 RPM, while many Dremel and similar miniature grinders exceed 30,000 RPM.

Universal motors also lend themselves to electronic speed control and, as such, are an ideal choice for domestic washing machines. The motor can be used to agitate the drum (both forwards and in reverse) by switching the field winding with respect to the armature. The motor can also be run up to the high speeds required for the spin cycle.

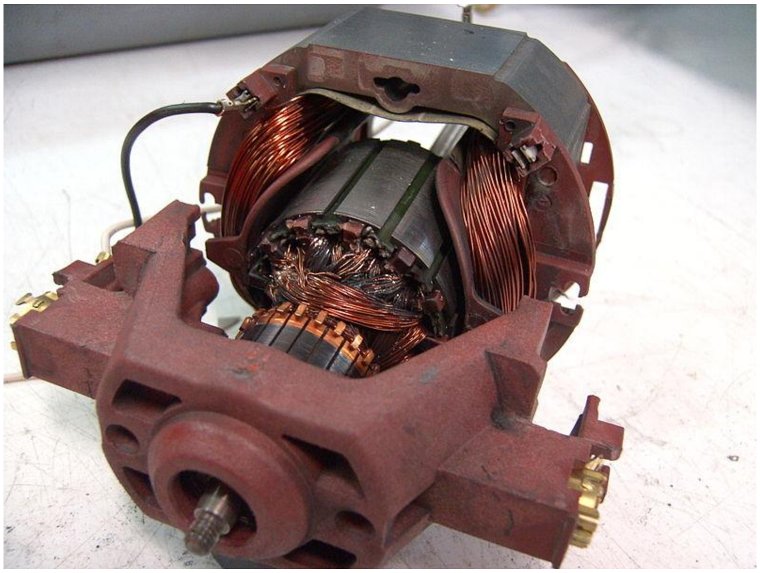

Figure 1.2 : Universal motor of a vacuum cleaner

1.3 DC Motor

A DC motor is a mechanically commutated electric motor powered from direct current (DC). The stator is stationary in space by definition and therefore the current in the rotor is switched by the commutator to also be stationary in space. This is how the relative angle between the stator and rotor magnetic flux is maintained near 90 degrees, which generates the maximum torque [9].

DC motors have a rotating armature winding (winding in which a voltage is induced) but non-rotating armature magnetic field and a static field winding (winding that produce the main magnetic flux) or permanent magnet. Different connections of the field and armature winding provide different inherent speed/torque regulation characteristics. The speed of a DC motor can be controlled by changing the voltage applied to the armature or by changing the field current. The introduction of variable resistance in the armature circuit or field circuit allowed speed control. Modern DC motors are often controlled by power electronics systems called DC drives.

The introduction of DC motors to run machinery eliminated the need for local steam or internal combustion engines, and line shaft drive systems. DC motors can operate directly from rechargeable batteries, providing the motive power for the first electric vehicles. Today DC motors are still found in applications as small as toys and disk drives, or in large sizes to operate steel rolling mills and paper machines.

1.3.1 Brush DC Motor

The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary magnets (permanent or electromagnets), and rotating electrical magnets.

Advantages of a brushed DC motor include low initial cost, high reliability, and simple control of motor speed. Disadvantages are high maintenance and low life-span for high intensity uses. Maintenance involves regularly replacing the brushes and springs which carry the electric current, as well as cleaning or replacing the commutator. These components are necessary for transferring electrical power from outside the motor to the spinning wire windings of the rotor inside the motor [10]. Brushes are made of conductors.

1.3.2 Brushless DC Motor

Typical brushless DC motors use a rotating permanent magnet in the rotor, and stationary electrical current/coil magnets on the motor housing for the stator, but the symmetrical opposite is also possible. A motor controller converts DC to AC. This design is simpler than that of brushed motors because it eliminates the complication of transferring power from outside the motor to the spinning rotor. Advantages of brushless motors include long life span, little or no maintenance, and high efficiency.

Disadvantages include high initial cost, and more complicated motor speed controllers. Some such brushless motors are sometimes referred to as "synchronous motors" although they have no external power supply to be synchronized with, as would be the case with normal AC synchronous motors [10].

1.3.3 Permanent magnet stators

A PM motor does not have a field winding on the stator frame, instead relying on PMs to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. PM fields (stators) are convenient in miniature motors to eliminate the power consumption of the field winding. Most larger DC motors are of the "dynamo" type, which have stator windings. Historically, PMs could not be made to retain high flux if they were disassembled; field windings were more practical to obtain the needed amount of flux. However, large PMs are costly, as well as dangerous and difficult to assemble; this favors wound fields for large machines.

To minimize overall weight and size, miniature PM motors may use high energy magnets made with neodymium or other strategic elements; most such are neodymium-iron-boron alloy. With their higher flux density, electric machines with high-energy PMs are at least competitive with all optimally designed singly fed synchronous and induction electric machines. Miniature motors resemble the structure in the illustration, except that they have at least three rotor poles (to ensure starting, regardless of rotor position) and their outer housing is a steel tube that magnetically links the exteriors of the curved field magnets [10].

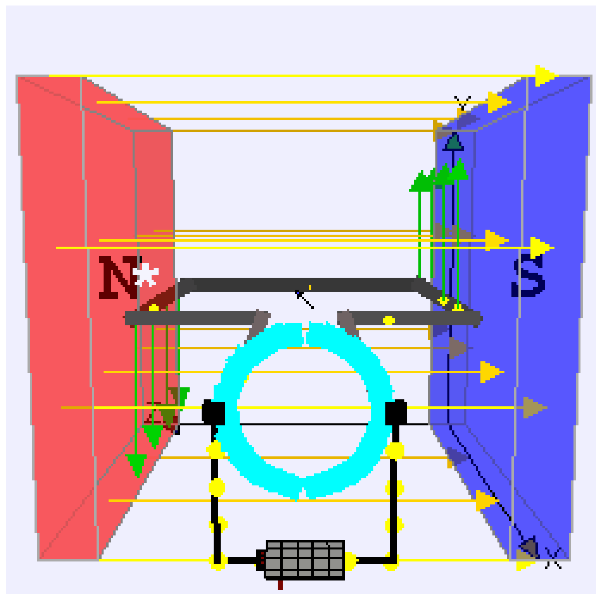

Figure 1.3: A brushed DC electric motor

1.4 Smart Power Module (SPM)

Motors are the major source of energy consumption in appliances. In motoring action, the electrical system makes current flow through conductors that are placed in the magnetic field. A force is produced on each conductor. If the conductors are placed on a structure free to rotate, an electromagnetic torque will be produced, tending to make the rotating structure rotate at some speed. If the conductors rotate in a magnetic field, a voltage will also be induced in each conductor and that does can increased the energy consumption. Since governmental and agency regulations continue to mandate reduced energy consumption, inverter technology is being increasingly accepted and used by a wide range of users in the design of their products. Power modules for inverterized motor drive applications are also part of a current trend due to the advantages that offer such as space-savings and ease of assembly [1].

Integrated power modules seem to be the solution chosen by most researchers, designers or producers in the field of motor drive applications [2]. Fairchild Semiconductor has developed a series of SPM® devices for a highly efficient integrated solution. They concentrate on the development of an intelligent integrated power module using the new concept of building structure and advanced packaging technology that is the means of achieving an excellent, cost-effective solution. The first and second series of Motion-SPM in DIP package and Mini-DIP package have been successfully introduced into the market [1]-[2]. Since then, a great number of SPM inverter systems have been implemented and continue to run successfully, which validates the very good results of SPM reliability.

Now, Fairchild Semiconductor has taken the next step with the development of low power and cost effective SPM families in µMini-DIP SPM package, which are quite specialized for IGBT inverter application range of less than 7kW. Within such an operating power, one of the most important requirements in the system is more compactness and easier mass production process with high quality and reliability resulting in more cost-effectiveness comparing to discrete inverter solutions.

These modules have been fully developed as an answer to the strong demands particularly in home appliances applications such as air-conditioners, washing machines and refrigerators, requiring higher efficiency and higher performance characteristics [1].

Figure 1.4: Smart Power Module

1.5 Problem Statement

The terms “energy-saving” and “quiet-running” are becoming very important in the world of variable speed motor drives. Inverter technology is being increasingly accepted and used by a wide range of users in the design of their products. For low-power motor control, there are increasing demands for compactness, built-in control, and lower overall-cost. An important consideration, in justifying the use of inverters in these applications, is to optimize the total-cost-performance ratio of the drive system. In order to meet these needs, Fairchild Semiconductor have designed and developed a new series of compact, highly functional and very efficient power semiconductor devices called the “SPM (Smart Power Module)”.

SPM-inverters are a very viable alternative to conventional ones for low-power motor drives due to their attractive characteristics, specifically for appliances such as washing machines, air-conditioners and fan. Besides that, motor often encountered with problems such as leakage current, less efficiency, electromagnetic interference (EMI), and acoustic noise. Indirectly, this will reduce the motor efficiency. Therefore, many researchers have given a lot off efforts in developing a motor drive to overcome these problems. Based on the abovementioned problems, this project will focus on the problem in order to increase the efficiency of the motor drives by using SPM.

1.6 Objectives and Scopes

1.6.1 Objective

The main purpose of this project is to design and simulate the circuit that using SPM to get the result whether it can increase the motor efficiency for home appliances application or not. There are two major topics that need to understand while doing this project which is comparison between IGBT and MOSFET devices and comparison between conventional motor and BLDC motor in terms of leakage current.

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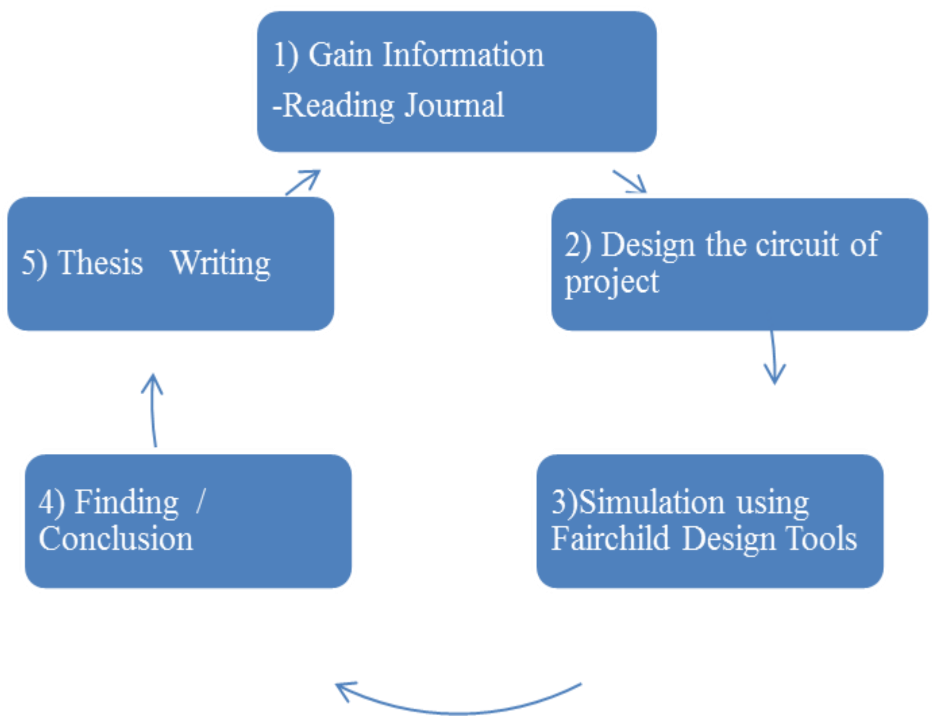

Figure 1.5: Flow Diagram

1.6.2 Scope of Work

The purpose of this project is to get a comparison between the usage of Smart Power Module (SPM) in motor drives application and without using SPM. Based on the studied in [7], SPM can reduce Electromagnetic Interference (EMI), leakage current, acoustic noise and increase efficiency of the motor and inverter. But, in this project only focus on how to increase the efficiency of motor in air conditioner application.

This project also requires knowledge in software skills. The scope of work in this project is as follows:-

Design the circuit parameter and demonstrate simulation via Fairchild Design Tools software.

i. Construct and build SPM circuit to perform a simulation.
ii. Simulate the switching loss of SPM by using Microsoft Excel.
iii. Analyzing and comparing the results from simulation and manual calculation.

1.6.3 Thesis Overview

This thesis contains 5 chapters with appendices at the end. Each of the chapters represents of enough information for better understanding due on this project.

Chapter 1

Briefly explain the scope and objective for this project to achieve and a general view of electrical motor and smart power module.

Chapter 2

Introduces the basic concept and definition of direct current motor (DC motor), motor efficiency, brushless DC motor (BLDC) and also brief description on insulated gate bipolar transistor (IGBT).

Chapter 3

Describe about methodology for smart power module setup and design using Fairchild Design Tools (FDT) and calculation via Microsoft Excel software.

Chapter 4

Step for smart power module simulation via FDT, switching loss calculation by using Microsoft Excel software.

Chapter 5

A brief conclusion, discussed and compare a result obtain from FDT, Microsoft Excel and testing.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

In this chapter, the review on the research is done for a past semester. The review included motor efficiency and also insulated gate bipolar transistor (IGBT). These research are been done through the journals, DC motor books and from the competence person who has a great knowledge in this subject.

2.2 What Is Leakage Current?

Leakage current[4] is the current that flows through the protective ground conductor to ground. In the absence of a grounding connection, it is the current that could flow from any conductive part or the surface of non-conductive parts to ground if a conductive path was available (such as a human body). There are always extraneous currents flowing in the safety ground conductor.

2.2.1 Why Is It Important?

Electrical equipment commonly includes a grounding system to provide protection against a shock hazard if there is an insulation failure. The grounding system usually consists of a grounding conductor that bonds the equipment to the service ground (earth). If there is acatastrophic failure of the insulation between the hot (power) line and touchable conductive parts, the voltage is shunted to ground. The resulting current flow will cause a fuse to blow or open a circuit breaker; preventing a shock hazard. Obviously, a possible shock hazard exists if the grounding connection is interrupted, either intentionally or accidentally. The shock hazard may be greater than supposed because of the leakage currents.

Even if there is no insulation failure, interruption of the leakage currents flowing through the ground conductor could pose a shock hazard to someone touching the ungrounded equipment and ground (or other grounded equipment) at the same time. This possibility is of much more concern in medical applications, where a patient may be the recipient of the shock. A fatal shock could result if the patient is in a weakened condition or unconscious, or if the leakage current is applied to internal organs through patient contacts. The double insulation provided in non-grounded equipment provides protection by using two separate layers of insulation. The protection in this case is ensured because both layers of insulation are unlikely to fail. However, the conditions that produce leakage currents are still present, and must be considered.

2.2.2 What Causes Leakage Current?

There are two types of leakage current: ac leakage and dc leakage. Dc leakage current usually applies only to end-product equipment, not to power supplies. Ac leakage current is caused by a parallel combination of capacitance and dc resistance between a voltage source (ac line) and the grounded conductive parts of the equipment. The leakage caused by the dc resistance usually is insignificant compared to the ac impedance of various parallel capacitances.

The capacitance may be intentional (such as in EMI[3] filter capacitors) or unintentional. Some examples of unintentional capacitances are spacings on printed wiring boards, insulations between semiconductors and grounded heatsinks, and the primary-to-secondary capacitance of isolating transformers within the power supply.

2.2.3 What Is A Safe Level

For non-medical equipment, the safe levels have been determined by an international organization and documented in the IEC 950 safety standard. Most countries around the world
have adopted this standard. The limits are defined in Table 1.

Table 2.1 : IEC 950 Safety Standards

Equipment	**Type**	**Max. Leakage Current**
Double insulated	All	0.25mA
Grounded	Hand Held	0.75mA
	Movable (other than hand-helded)	3.5mA
	Stationary (Permanently connected)	3.5mA

Medical equipment leakage current limits are much lower. The requirements are summarized in Table 2. Because of the lower values of allowable leakage current in medical power supplies, it is important to substantially reduce the capacitances that cause leakage currents. This poses a
special design problem for the power supply and especially EMI filters. For example, line-toground capacitors are an important part of the EMI
filter's ability to perform properly. Reducing their value can severely reduce the filter's effectiveness. Condor's medical designs and patented EMI filtering techniques have overcome these problems.

Table 2.2 : IEC601-1, UL2601-1 Safety Standards

Medical Device Category	Type B		Type BF		Type CF	
Conditions	N.C.	S.F.C.	N.C.	S.F.C.	N.C.	S.F.C.
Earth Leakage Current, Portable	0.5[1]	1.0	0.5[1]	1.0	0.5[1]	1.0
Earth Leakage Current, Fixed	2.5	5.0	2.5	5.0	2.5	5.0
Enclosure Leakage Current	0.1	0.5	0.1	0.5	0.1	0.5
Patient Leakage Current	0.1	0.5	0.1	0.5	0.01	0.05

2.3 Direct Current Motor (DC Motor)

2.3.1 Principle of DC Motor

This DC or Direct Current Motor works on the principal, when a current carrying conductor is placed in a magnetic field, it experiences a torque and has a tendency to move. This is known as motoring action. If the direction of electric current in the wire is reversed, the direction of rotation also reverses. When magnetic field and electric field interact they produce a mechanical force, and based on that the working principle of dc motor established. The direction of rotation of a this motor is given by Fleming's left hand rule, which states that if the index finger, middle finger and thumb of your left hand are extended mutually perpendicular to each other and if the index finger represents the direction of magnetic field, middle finger indicates the direction of electric current, then the thumb represents the direction in which force is experienced by the shaft of the dc motor [12].

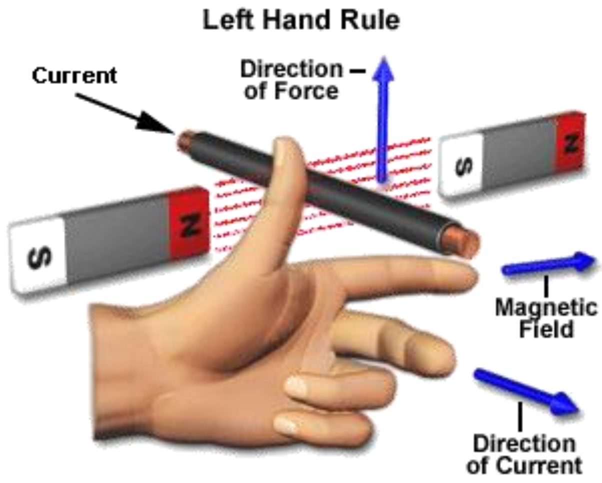

Figure 2.1: Fleming left hand rule

Structurally and construction wise a Direct Current Motor is exactly similar to a D.C. Generator, but electrically it is just the opposite. Here we unlike a generator we supply electrical energy to the input port and derive mechanical energy from the output port. We can represent it by the block diagram shown below.

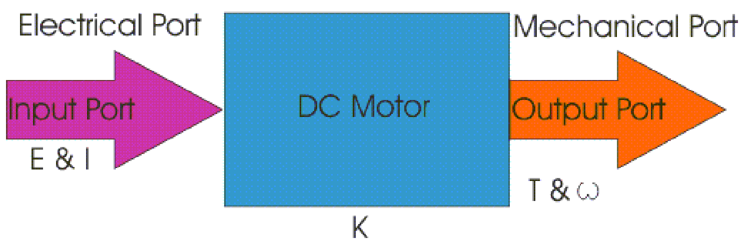

Figure 2.2: Principles of DC motor

Here in a DC motor, the supply voltage E and current I is given to the electrical port or the input port and we derive the mechanical output i.e. torque T and speed ω from the mechanical port or output port. The input and output port variables of the Direct Current Motor are related by the parameter K.

$$\therefore T = K.I \ \& \ E = K.\omega$$

So from the picture above we can well understand that motor is just the opposite phenomena of a D.C. Generator, and we can derive both motoring and generating operation from the same machine by simply reversing the ports [12].

2.3.2 Detailed Description of a DC Motor

The direct current motor is represented by the circle in the center, on which is mounted the brushes, where we connect the external terminals, from where supply voltage is given. On the mechanical terminal we have a shaft coming out of the Motor, and connected to the armature, and the armature-shaft is coupled to the mechanical load. On the supply terminals we represent the armature resistance Ra in series. Now, let the input voltage E, is applied across the brushes. Electric current which flows through the rotor armature via brushes, in presence of the magnetic field, produces a torque Tg. Due to this torque Tg the dc motor armature rotates. As the armature conductors are carrying currents and the armature rotates inside the stator magnetic field, it also produces an emf Eb in the manner very similar to that of a generator. The generated Emf Eb is directed opposite to the supplied voltage and is known as the back Emf, as it counters the forward voltage [12].

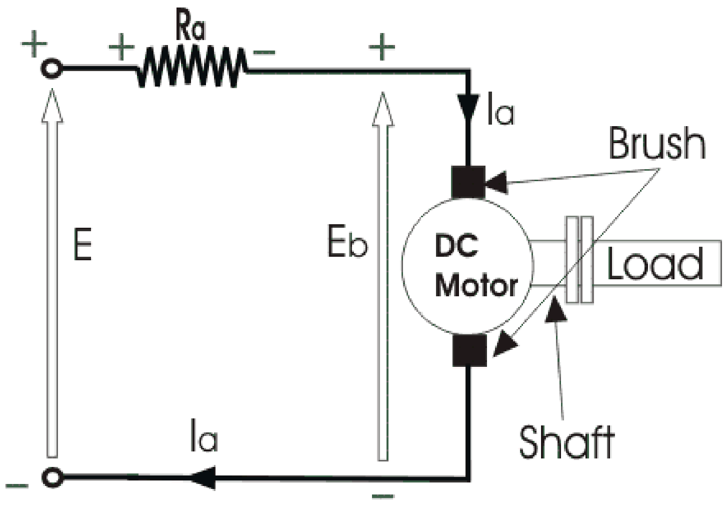

Figure 2.3: Electric current flow in DC motor

The back emf like in case of a generator is represented by

$$E_b = \frac{P.\varphi.Z.N}{60.A} \text{-----------------------------}(1)$$

Where,

P = no of poles

φ = flux per pole

Z= No. of conductors

A = No. of parallel paths

and N is the speed of the DC Motor.

So from the above equation we can see Eb is proportional to speed 'N'. That is whenever a Direct Current Motor rotates, it results in the generation of back Emf. Now lets represent the rotor speed by ω in rad/sec. So Eb is proportional to ω.

So when the speed of the motor is reduced by the application of load, Eb decreases. Thus the voltage difference between supply voltage and back emf increases that means E − Eb increases. Due to this increased voltage difference, armature current will increase and therefore torque and hence speed increases. Thus a DC Motor is capable of maintaining the same speed under variable load.

Now armature current Ia is represented by

$$I_a = \frac{E - E_b}{R_a}$$

Now at starting,speed ω = 0 so at starting Eb = 0.

$$\therefore I_a = \frac{E}{R_a} \text{-----------------------------}(2)$$

Now since the armature winding resistance Ra is small, this motor has a very high starting current in the absence of back Emf. As a result we need to use a starter for starting a DC Motor.

Now as the motor continues to rotate, the back Emf starts being generated and gradually the current decreases as the motor picks up speed [12].

2.3.3 Working or Operating Principle of DC Motor

A DC Motor in simple words is a device that converts direct current(electrical energy) into mechanical energy. It's of vital importance for the industry today, and is equally important for engineers to look into the working principle of DC motor in details that has been discussed in this article. In order to understand the operating principle of dc motor we need to first look into its constructional feature [12].

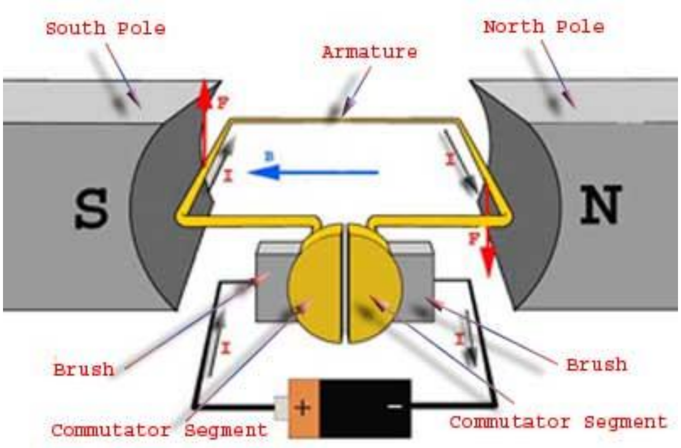

Figure 2.4: basic construction of a dc motor

The very basic construction of a dc motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet as shown in the diagram below.

Now to go into the details of the operating Principle of dc motor its important that we have a clear understanding of Fleming's left hand rule to determine the direction of force acting on the armature conductors of dc motor.

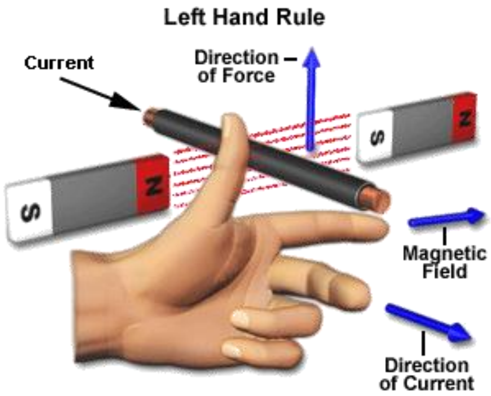

Figure 2.5: Fleming left hand rule

Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left hand in such a way that the current carrying conductor is placed in a magnetic field (represented by the index finger) is perpendicular to the direction of current (represented by the middle finger), then the conductor experiences a force in the direction (represented by the thumb) mutually perpendicular to both the direction of field and the current in the conductor [12].

For clear understanding the principle of DC motor we have to determine the magnitude of the force, by considering the diagram below.

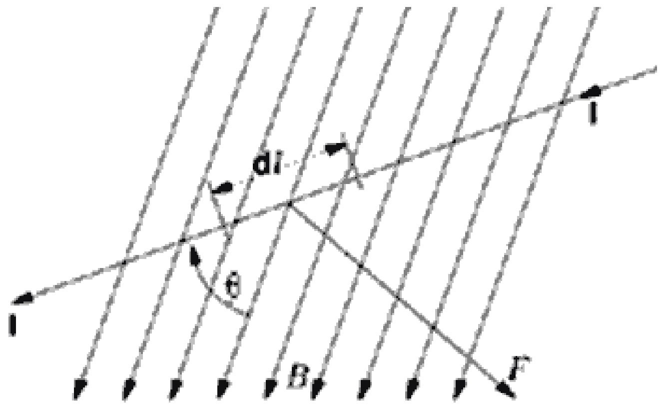

Figure 2.6: Principle of DC motor

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