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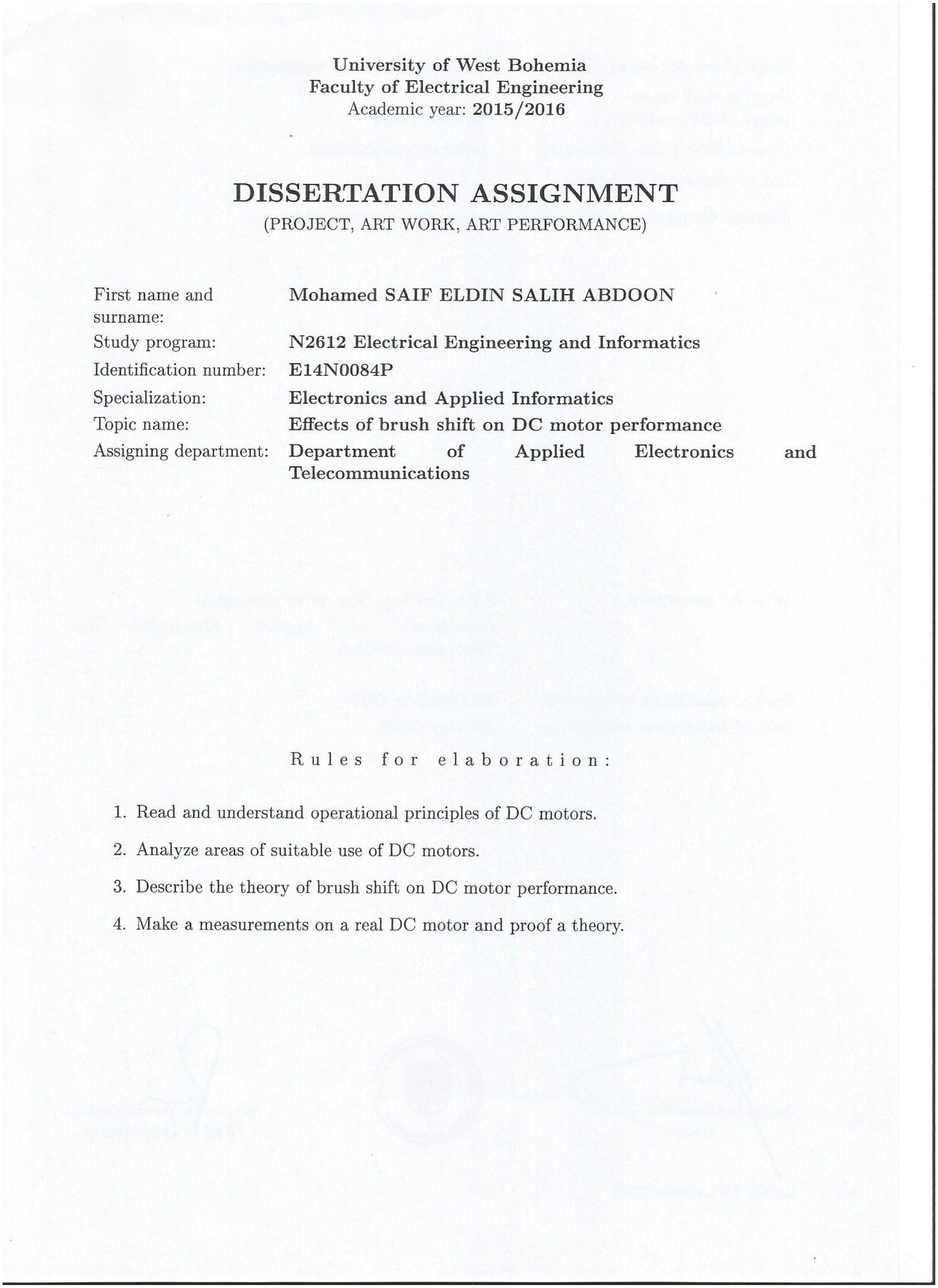
FACULTY OF ELECTRICAL ENGINEERING

Department of Applied Electronics and Telecommunications

Master's Thesis

Effects of brush shift on DC motor performance

Mohamed Abdoon 2016



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3. Describe the theory of brush shift on DC motor performance.
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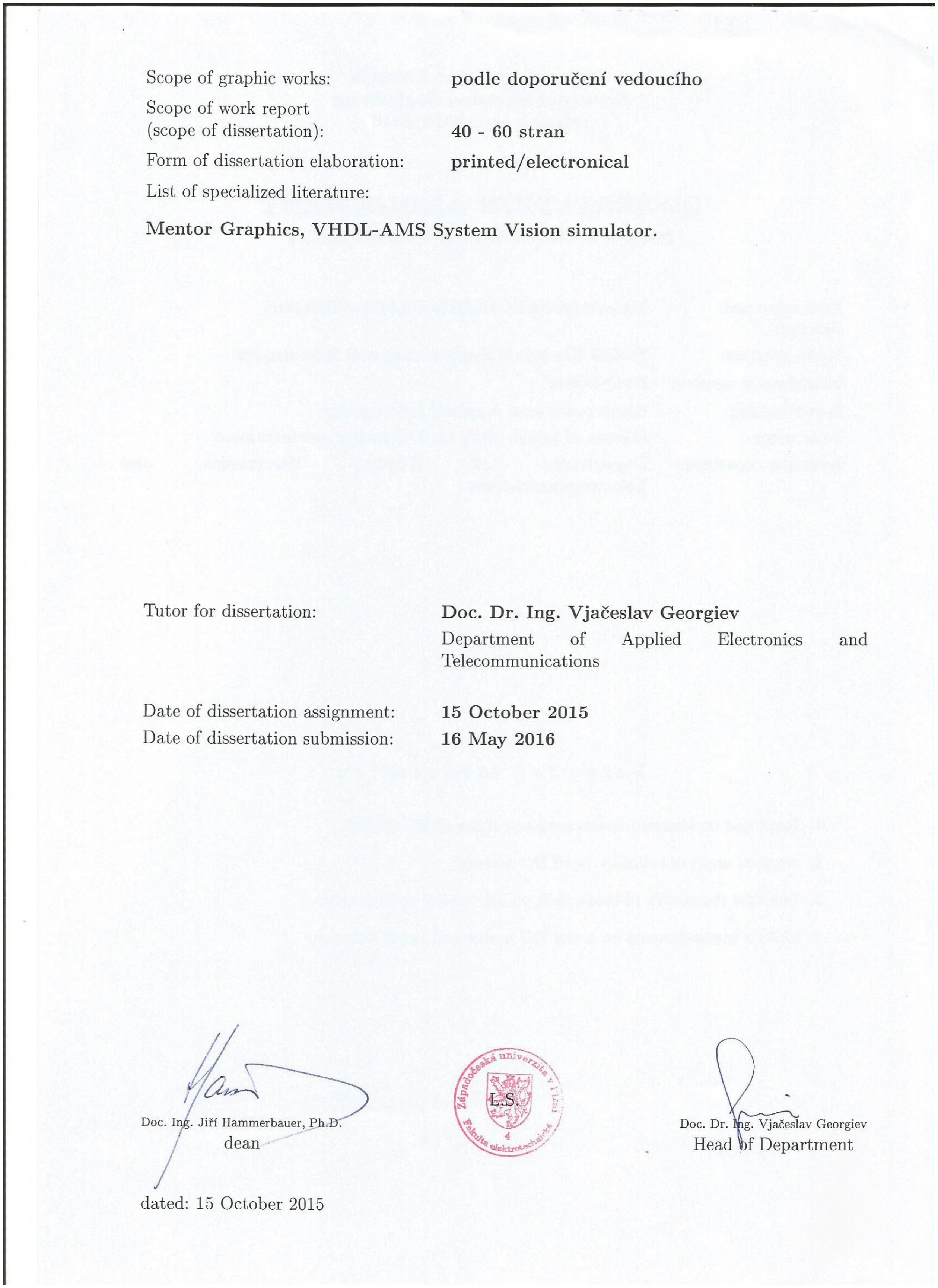

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Abstract

This thesis focuses on the effects of brush shifting on the performance of brushed DC motors. It begins by explaining the basic operating principles of electric machines and compares them to one another. The thesis then shows the implementation of a simulation model on Ansys Maxwell in order to validate the theory presented regarding armature reaction and demonstrates the possibilities of predicting motor characteristics via simulation. Finally the thesis presents measurements and results performed on an experimental setup to prove and validate the claim of improving motor performance using brush shifting.

Key words

DC motor, commutator, armature, magnetic field, PMDC, Ansys

Declaration

I declare that this Master’s thesis has been written only by myself using the literature provided at the references section.

I also declare that the software used for writing, preparing and simulating the tasks in this Master’s thesis is legal.

…………………………….

Signature

Acknowledgment

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List of abbreviations

2D	2 Dimensional
3D	3 Dimensional
AC	Alternating Current
AT	Ampere Turn
BEMF	Back Electro-Motive Force
BLDC	Brushless Direct Current
DC	Direct Current
DUT	Device Under Test
EMF	Electro-Motive Force
EMI	Electro-Magnetic Interference
GHz	Giga Hertz
GNA	Geometric Neutral Axis
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
MMF	Magneto Motive Force
MNA	Magnetic Neutral Axis
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PM	Permanent Magnet
PMDC	Permanent Magnet Direct Current
PMSM	Permanent Magnet Synchronous Machine
RAM	Random Access Memory
RMxprt	Rotational Machine Expert
RPM	Round Per Minute

1 Introduction

Electric machines have been around since the early 1800s, their invention were as a result of the developments of ideas from several scientists over the years which begun by the invention of the electromagnet by William Sturgeon.

Today, electric machines have found their way into every application where the conversion between electrical to mechanical energy or vise versa needs to take place. They are found in electronics, household appliances and automotive components. As we will explore in this thesis, there are several different types of electric machines, each of which has its advantages and disadvantages.

Today most research publication goes into the design and operation of Brushless DC motors (BLDC). This is in part due to industry trends which prefer the use of BLDC motors in several applications where precise control is required and potential cost reduction is achievable.

However, BLDC motors did not manage to completely obsolete other types of brushed motors despite their advantages due to the added complexity of the drive electronics required for BLDC.

In this thesis we will focus on Permanent Magnet DC motors (PMDC), since they do not receive the same level of depth of analysis that goes into BLDC motors, this is due to the fact that PMDC motors are very easy in principle to operate as will be explained in the following chapter, where as BLDC motors require deeper analysis in order to reach an operating state.

The proposed research and investigation in this thesis will aim to verify the feasibility of brush shifting to correct for the effects of armature reaction in PMDC motors. The idea of brush shifting to adjust the motor characteristics has not been investigated in depth in literature regarding the theory of electric machines, instead most references suggest the addition of interpoles or compensating windings to correct the effects of armature reaction, both of which are not realistically possible to achieve in PMDC motors due to packaging and cost restraints.

1.2 Principles of electromagnetism

In order to gain an understanding for how electric machines work, an understanding of electromagnetism is required, it is also required in order to understand the commutation effects due to the magnetic fields created by either the stator or rotor. Electromagnetism is one of the fundamental forces found in nature, from the word it can be understood that it relates magnetic energy and electrical energy together, its principles are used in many aspects of engineering from power transformers to electric machines to switch relays and many others [1]. By the end of this section the reader will gain understanding of the basic principles that underlay the operation of electric machines.

When an electric current flows through a conductor a magnetic field is formed around this wire. The term magnetic field describes the region around the wire or magnet where its effect and properties of attraction or repulsion could be observed.

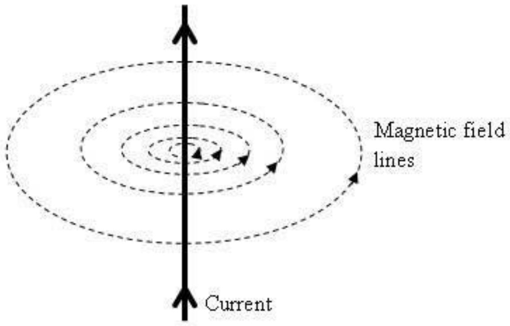


Figure 1 Generation of magnetic field

If an iron core were to be added, or a conductor loopes around it, then the resultant magnetic field is much stronger and effectivelty creates what is known as an electromagnet. Another form of electromagent is known as a solenoid described in [2]. The magnetic field resulting from such a construction is a vector, its direction can be found be aplying the right hand rule. Figure 2 shows an illustration of how to apply the right hand rule also known as the thumb rule.

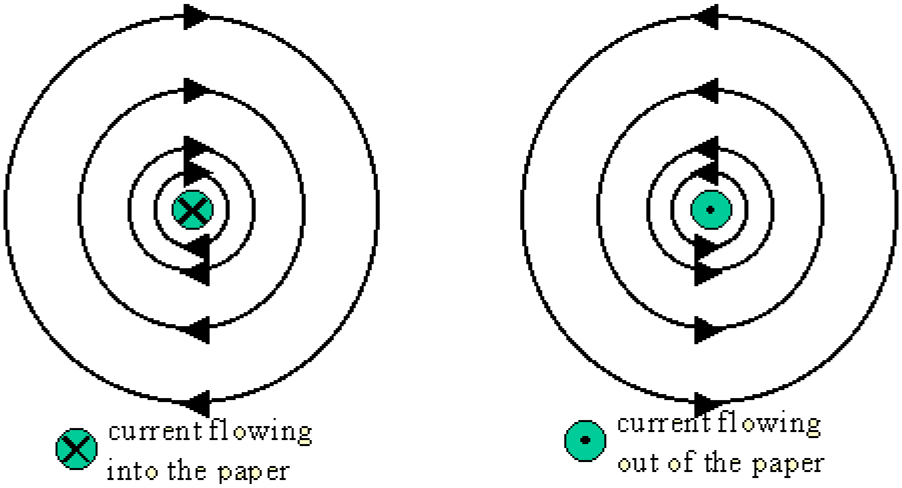


Figure 2 illustration of the right hand (thumb) rule

Additionally however a magnetic field could also be created by using a permanent magnet. The magnetic field B has the unit Tesla [T]. The magnetic flux through a certain surface is then defined as the surface integral of the normal component of the magnetic field B through that surface, and it has the unit Weber [Wb]. In simpler words the magnetic flux shows how many lines of force are present within a certain magnetic field. Therefore the amount of flux φ per unit area, assuming the surface area S can be written as

$$d\varphi = B \cdot dS$$ **Equation 1**

1.2.1 Lorentz force

The understanding of Lorentz force is crucial to the understanding of how the Electromotive Force (EMF) is generated, which is the principle that underlies the operation of electric machines.

Lorentz force is known as the force exhibited on a charged particle ***v*** when it moves through an electric field E and magnetic field B, it is expressed as

$$F = qE + qv \times B$$ **Equation 2**

In electric machines the electric field’s contribution could be omitted and we can modify this equation to express the electric current instead of the electric charge the resulting equation is described below

$$F = I\, l \times B$$ **Equation 3**

The equation presented above underlies the basic principle of the generation of force in Newtons [N] acting upon a wire of length l carrying current I. This wire could be a part of many wires that form the armature of a DC motor. It is also visible that there is a relationship of proportionality between force, current, length and magnetic field. Hence, the higher the current the greater the force exerted on that wire. It is also important to note that the above equation assumes perpendicularity between the direction of flux and direction of motion of the wire. Therefore, this equation is modified to include angles which are not perpendicular i.e. 90°.

$$F = B\, l\, v \sin \Theta \qquad \textbf{Equation 4}$$

Where: v is the velocity at which the conductor or wire cuts the magnetic field in [m/s]

From the above derived equation, we understand that the rotational movement of a conductor through a magnetic field results in an EMF that reaches a maximum and then goes back to a minimum point of zero.

The next step is to express the torque based on equation 3. Since torque is the product of the tangential force multiplied by the length of the conductor, we can deduce the following formula

$$T = 2rFN = 2rBIlN \qquad \textbf{Equation 5}$$

Where: T is the torque in Newton meter [N.m]

r is the distance between the axis of rotation and the conductor in meters [m]

N is the number of turns

1.2.2 Faraday’s law

Faraday’s law also known as the law of magnetic induction, is a law that describes how a voltage can be induced in a coil of wire when it experiences a change in the surrounding magnetic field. The formula is shown below

$$E = N\frac{d\varphi}{dt} \qquad \textbf{Equation 6}$$

This effect can also be observed when a coil is moved in a magnetic field. However this equation must be modified in order to obey Lenz’s law, which states that an induced current on a wire which results from a varying magnetic field will travel in the opposite direction to the original current. Therefore the equation becomes as shown below

$$E = -N\frac{d\varphi}{dt} \qquad \textbf{Equation 7}$$

It can be clearly understood from the equation above that by increasing the number of turns N we therefore increase the amount of resultant EMF.

2 Types of electric machines

Electric machines are divided into two main groups known as alternating current machines and direct current machines. This definition by itself can be a source of confusion since all electric machines are built upon the principles of alternating current. However, in our classification we will consider DC machines as ones which are able to operate directly from a DC power supply, while we consider AC machines ones which are not operable when supplied by DC voltages directly. The main difference between them is the fact that alternating current machines are electrically commutated whilst direct current machines are mechanically commutated, with the exception of brushless direct current motors BLDC.

This chapter will explain in some detail the principles of operation of a few different types of electric machines, their control methods and required driving circuits. However, since this thesis focuses on DC machines they will be explained in greater detail in this chapter.

Figure 3 outlines some of the most relevant electric machines.

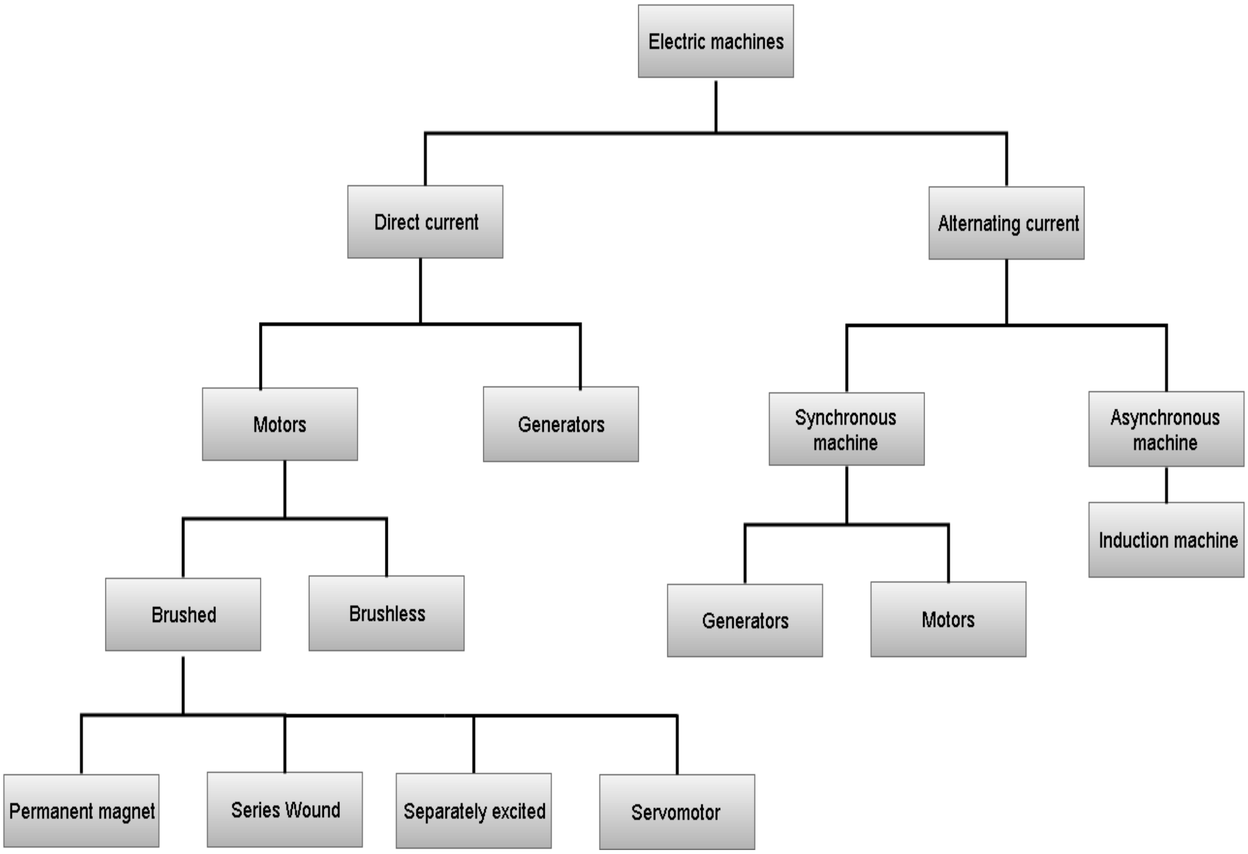


Figure 3 Common classification of electric machines

2.1 Permanent magnet brushed DC motors (PMDC)

As the name suggests the PMDC motor incorporates a permanent magnet in its design. The permanent magnets are used in order to generate the stator field, which interacts with the rotor field created by the armature to produce a rotational movement.

The PMDC motor is of special interest for our thesis, nevertheless PMDC motors are one of the most commonly found motors in low power applications, mainly due to their cost advantage, light weight and as will be explained further, their ease of operation. In addition PMDC motors do not exhibit the field circuit copper losses due to the fact that they do not need an external excitation circuit as will be described in the following sections.

The operating process is very simple, DC voltage is applied to the motor terminals and is delivered to the armature coils via the commutator and brushes, the commutator reverses the polarity of the current through the coil in order to continue the rotation of the rotor. The commutator is essential to the operation of a PMDC motor due to the fact that if the direction of current through the rotor continues to be in the same direction, there will be no EMF force generated when the main field has no perpendicular component to the rotor. The following figure is an illustration of how a PMDC motor is constructed.

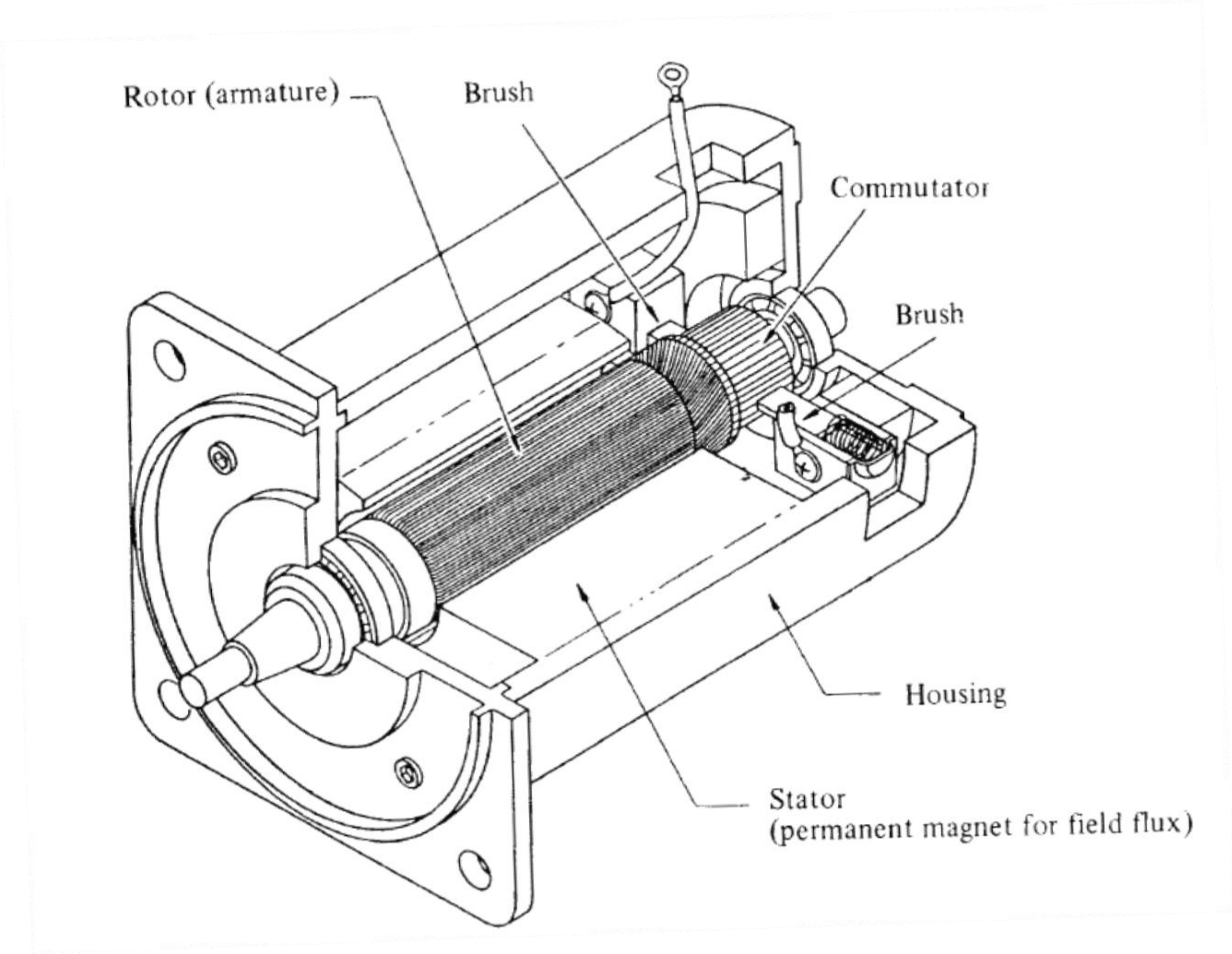


Figure 4 Illustrative construction of a permanent magnet brushed DC motor [3]

The speed is therefore controlled by adjusting the voltage, since the characteristic curves in the case of PMDC motors are very linear.

The torque developed by a PMDC motor follows the following formula

$$T = K_T I_a \qquad \textbf{Equation 8}$$

Where: K_T is the motor constant in [Nm/A]

I_a is the armature current

The torque constant has the unit Nm/A and can be calculated as

$$K_T = \frac{z}{2\pi}\varphi \qquad \textbf{Equation 9}$$

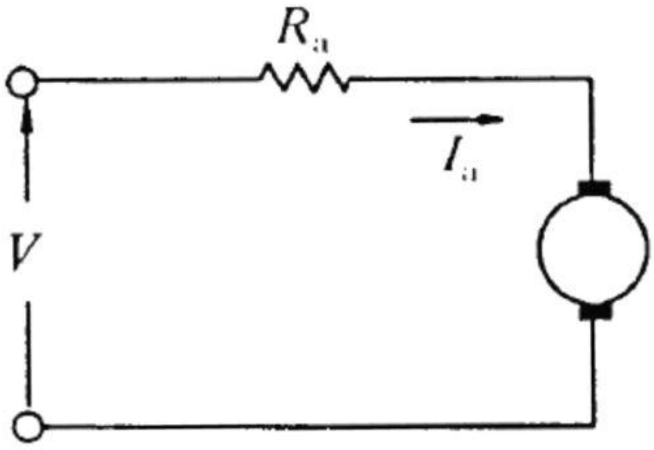


Figure 5 Equivalent circuit of PMDC motor

By analyzing the equivalent circuit of the PMDC motor, we can derive the voltage equation which relates to its operation.

The voltage could be expressed by the formula

$$V = R_a I_a + K_E n$$ **Equation 10**

Where: R_a is the armature resistance

K_E is the back EMF constant

n is the rotational speed

As we have described in 1.2.2 when a current carrying conductor is moved in an electric field, a voltage is induced and the direction of this voltage opposes the direction of the original source of voltage. This phenomenon is known as back EMF, which means that during normal operation the motor also acts as a generator. An important point to consider is, that since the back EMF opposes the direction of the supply the net sum voltage applied to the armature is going to be as shown below

$$V_{sum=}V_{supply}-V_{BEMF}$$ **Equation 11**

Back EMF has several advantages in the operation of DC machines such as speed regulation, regenerative braking and determining the speed of the armature. These applications will be explored in the next sections.

An important consideration while discussing PMDC motors is that their stator field is always constant. Due to this fact PMDC motors react quickly to the change in applied voltage, therefore their operation is relatively easy to control as will be shown in the following section.

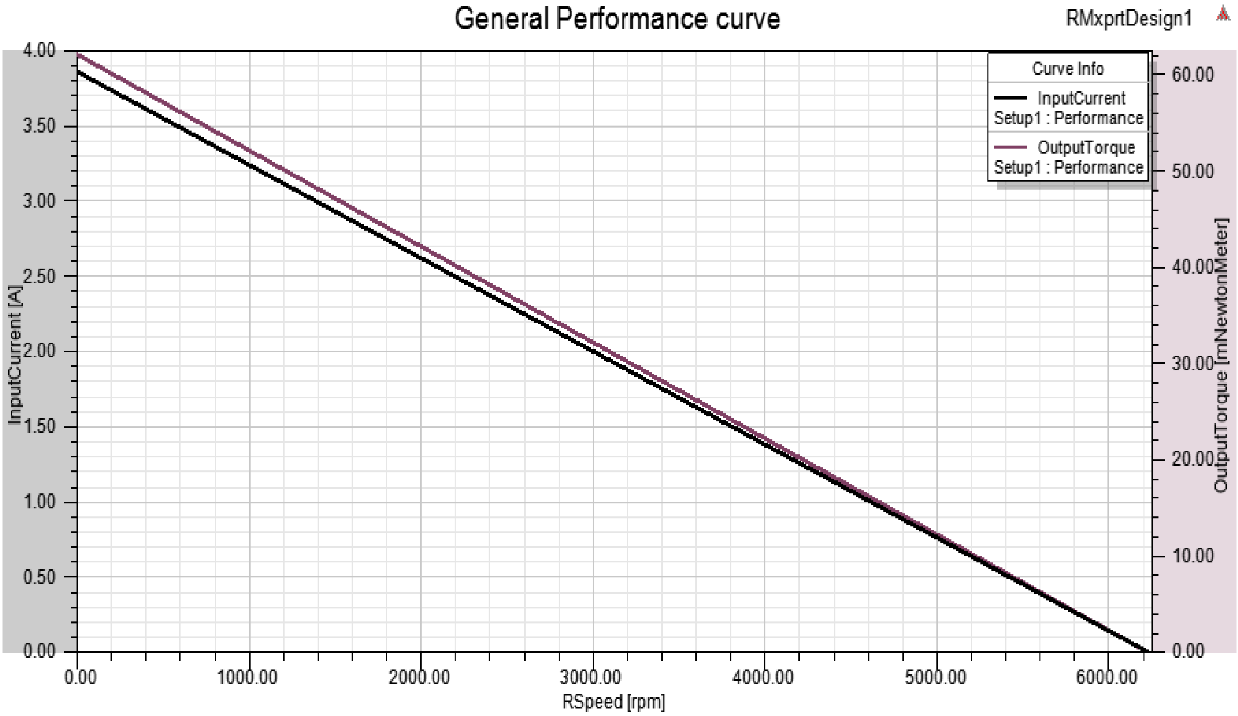


Figure 6 Example of performance curves of PMDC motor

The above figure shows the performance curve of a PMDC motor. The starting torque of the motor can be given by the formula

$$T_s = \frac{K_T V}{R_a} \qquad \textbf{Equation 12}$$

Where: T_s is the starting torque

Additionally the maximum speed which can be achieved by the motor when no load is applied can be calculated by

$$n_o = \frac{V}{K_E} \qquad \textbf{Equation 13}$$

Where: n_o is the no load speed

2.1.2 Control and drive circuit

As mentioned previously a PMDC motor requires a constant DC voltage or a voltage in the form of a Pulse Width Modulation (PWM) signal across its terminals to start rotating. The direction of the rotation can be reversed by reversing the polarities of the applied voltage and furthermore, the speed can be controlled by adjusting the voltage applied to the terminals.

However, in applications which require speed control, varying the magnitude and polarity of the DC supply is not always possible since the main supply could be shared with other systems in a network. Therefore in most cases a set of relays or an H-bridge controlled by a microcontroller is required in order to switch direction and to control the speed of the motor is used. A typical H-bridge is shown in the figure below

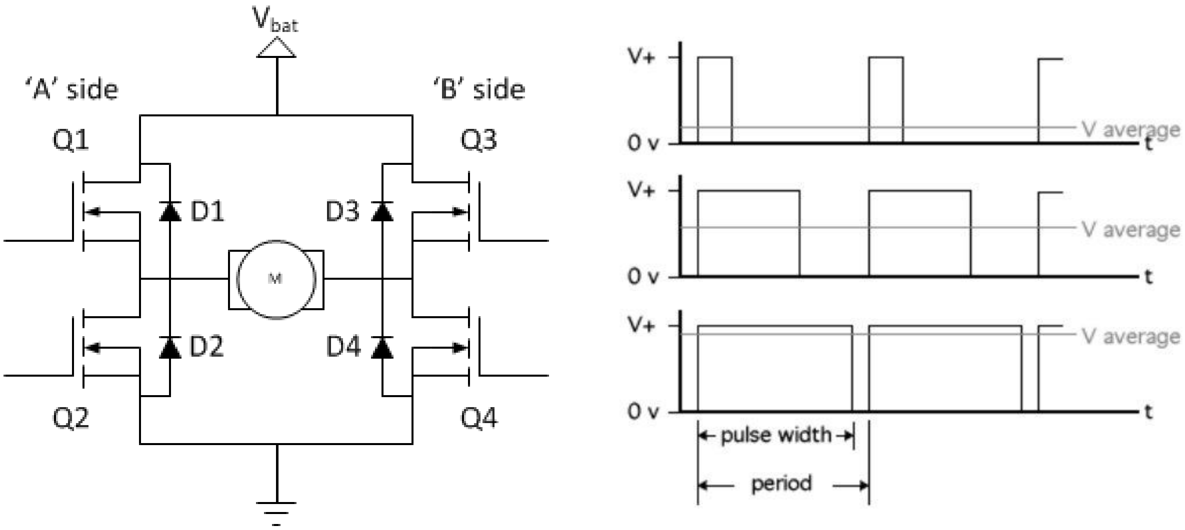


Figure 7 H-Bridge control circuit (left) and PWM signal (right) [4]

Depending on the application and the voltage levels involved, the switching elements may be switched from MOSFETs (shown above) to Insulated Gate Bipolar Transistors (IGBT). Depending on the duty cycle of the PWM signal, the average voltage seen by the motor at it terminals changes proportionally.

A question that might arise is, why does the motor keep spinning even when there is no voltage applied to the terminals during the off time. This is mainly due to the inductance of the motor and the inertia of the rotor.

One of the main advantages of PMDC motors is the compactness of their design, as a result, they can be used in small appliances were packaging and low supply voltage are priority. However, a disadvantage of PMDC motors is the fact that they might overheat due to excessive loading or due to the ambient surrounding temperature. Both these factors contribute to the demagnetization of the permanent magnets, where in the case of excessive loading could lead to higher current going through the armature therefore creating a stronger magnetic field, this magnetic field if exceeds a certain threshold will start to permanently demagnetize the magnets. Therefore, special care needs to be applied in order not to exceed the maximum current rating of the motor in order not to reach the irreversible state of magnet demagnetization. This is one of the main reasons why PMDC motors are not commonly used in application where high power output is required.

2.2 Wound brushed DC motors

The main distinction between the other different types of brushed DC motors and PMDC motors is the construction and generation of the stator field. Whilst, the PMDC motor uses permanent magnets to generate the stator field, other types use the principle of the electromagnet as described in section 1.2. The stator could be constructed in different configurations as will be described in the following sections.

2.2.1 Shunt Wound brushed DC motors

In the shunt wound brushed DC motor the field windings which wrap around the stator core are connected in parallel or shunted to the armature.

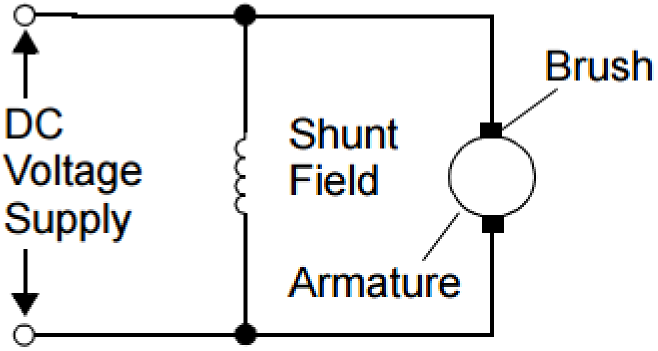


Figure 8 Schematic illustration of the connection of shunt wound DC machine

Both the stator and the armature are supplied from the same source, the amount of flux φ can be adjusted by adding a variable resistor in series with the stator coils, this method is used to control the speed of the wound DC motor and follows the formula below

$$n \propto \frac{V - I_a R_a}{\varphi}$$ **Equation 14**

Another method to control the speed of wound DC motors is by adding a variable resistor with the armature coils, thus increasing the total value of R_a. Adjusting these parameters also changes the amount of generated torque which follows the equation below

$$T \propto \varphi I_a$$ **Equation 15**

The most important characteristic of shunt wound DC motors is that, the speed of the motor is actually self regulated. This self regulation is achieved due to the effect of back EMF as previously shown in equation 11, therefore, if a load is applied to the motor the speed is suddenly decreased, this decrease in speed results in a corresponding decrease of the back EMF which leads to an increase of *Vsum* which in turn increases the amount of armature current thus increasing the torque. The final value of speed would be slightly lower than the initial speed before the load was applied to the motor.

2.2.2 Series Wound brushed DC motors

In a series wound DC motor, the armature and the stator windings are connected in series. One of the main advantages of the series wound DC motor is very high starting torque.

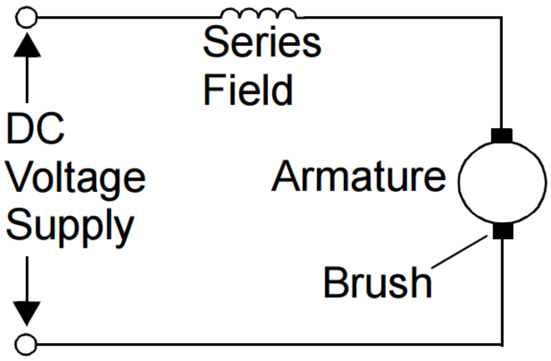


Figure 9 Schematic illustration of series wound DC machine

The high starting torque is a result of the connection topology, since there is no back EMF at start, therefore the full supply voltage is available to the armature and this leads to a high generated flux on the stator field, which is considered as the main advantage of series wound DC motors. Therefore in this case we can deduce the following relationship

$$\varphi \propto I_a \propto I_s \quad \textbf{Equation 16}$$

Where: I_s is the stator current

However, the main disadvantage of series wound DC machines is the fact that their speed depends on the load in such a way that, the higher the load the lower the speed. This is due to the fact that when load is applied the current through the stator increases so much that it starts to saturate the magnetic core of the stator. In addition to the aforementioned, the series motor’s speed would increase uncontrollably if the load were to be removed from the shaft, this is known as ‘running away’ and could lead to the destruction of the motor if safety provisions are not taken into account such as speed sensor or centrifugal switch. The damage is usually as a result of the centrifugal forces, which act upon the armature coils of the motor and usually lead to the coils being removed from their original slots.

2.2.3 Compound DC motors

A compound DC motor is a motor that incorporates in its design the features of both shunt and series DC motors. Compound DC motors are usually used in applications where a compromise between both is required. The compound motor delivers torque similarly to the series DC motor as well as provides speed control similarly to the shunt DC motor.

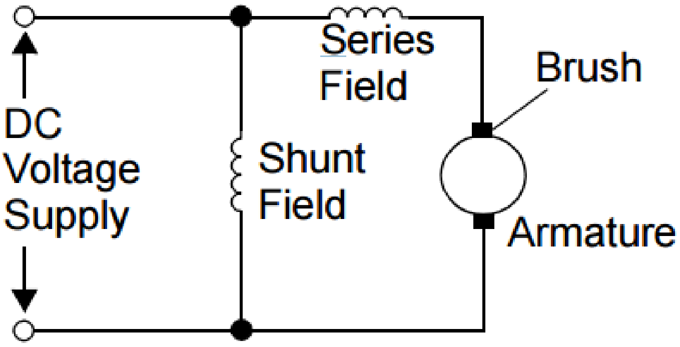


Figure 10 Schematic illustration of a compound DC motor

As could be visible from the above schematic, the current through the motor could be calculated as the sum of current through the shunt field in addition to the current through the series field. Speed regulation is achieved due to the fact that, if a load is placed on the motor shaft the current through the armature and series coil would increase this in turn means that the current through the shunt coils would decrease, thus decreasing the speed of the motor, and the motor torque would adjust by increasing. The runaway phenomenon could occur in one condition only if the shunt current decreases to zero and the series field are shorted. The following graph shows the speed in relation to the produced torque of the Compound, Series and Shunt motors.

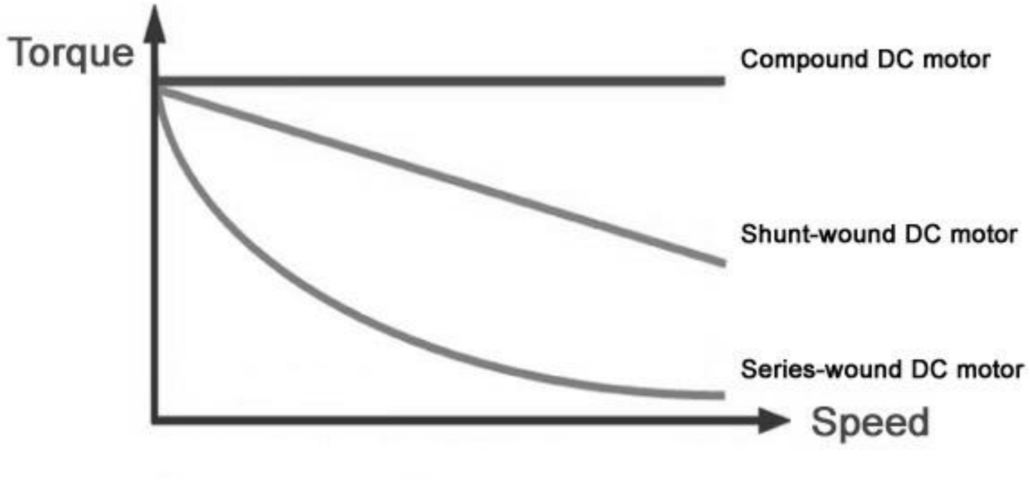


Figure 11 Torque in relation to speed

2.3 Brushless DC motors (BLDC)

BLDC motors are generally considered state of the art in the field of electric drives, this is due to several reasons chief amongst which are the significantly higher efficiency both thermal and electrical in comparison with classical excited motors. BLDC motors also offer a certain amount of flexibility to system designers in such a way that allows them to define different commutation strategies i.e. sinusoidal or trapezoidal, with sensor or sensor-less all in the aim of reducing system cost and achieving target requirements. In addition to the aforementioned they are more reliable, compact and much quieter.

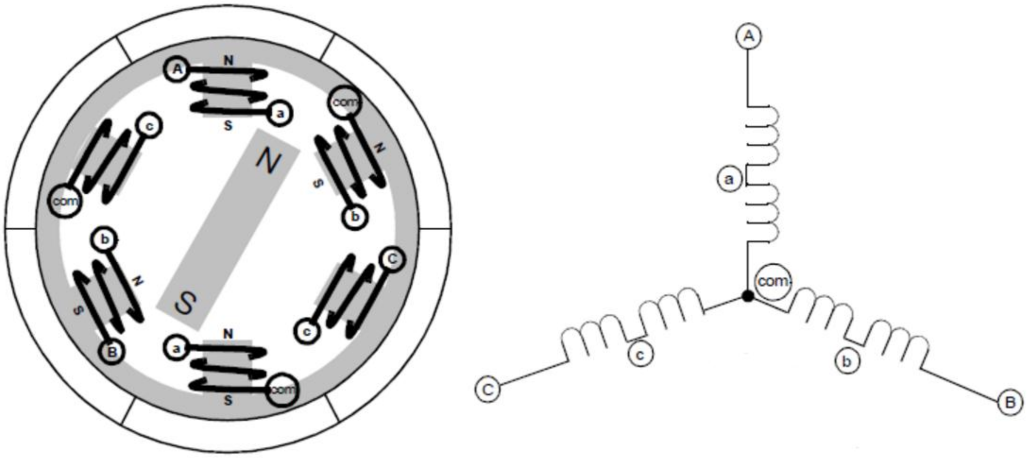


Figure 12 Simplified BLDC motor construction [5]

In general brushed motors are known as mechanically commutated whilst brushless motors are known as electrically commutated, this terminology in a sense explains the principle of operation for both machines. As we have discussed in section 2.1 the PMDC motor uses a commutator in order to switch the direction of current through the coil to keep the rotor spinning in the desired direction. However in a BLDC motor the commutation is achieved electrically by using power switches instead of a commutator.

BLDC motors can be separated into two types known as trapezoidal and sinusoidal which in some cases could be known as Permanent Magnet Synchronous Motor (PMSM). These definitions are based on the winding of the stator coils, and the shape of the produced back EMF. The sharp transition in the design between the stator coils and the magnets create an air gap, which is the main reason behind the trapezoidal shape of the back EMF. On the other hand sinusoidally wound motors usually contain skewed magnets which tend to smooth the shape of the waveform. Therefore, the result is a sinusoidal looking waveform. However, trapezoidally wound motors usually have higher power density than the sinusoidally wound motors, due to the higher density of the stator coils.

2.3.1 Control strategies for BLDC

The critical factor when discussing BLDC motors is the control strategy used to operate the motor, unlike traditional brushed DC motors for example which are self commutated, a BLDC motor will not start to rotate once a DC voltage is applied to its terminals. Generally, there are two different types of BLDC motor control strategies known as scalar control and vector control.

In the case of the scalar control we assume control over the magnitude of voltage and the frequency. On the other hand, vector control uses space vectors for controlling the motor currents which in turn adjust the output torque of the motor. A common method of scalar control is known as six step commutation, which results in the trapezoidal waveform which could be seen in figure 13. As could be seen from the following figure the energizing sequence is 120 degrees apart, and the current flows through two of the phase at one time while the third phase is left completely off.

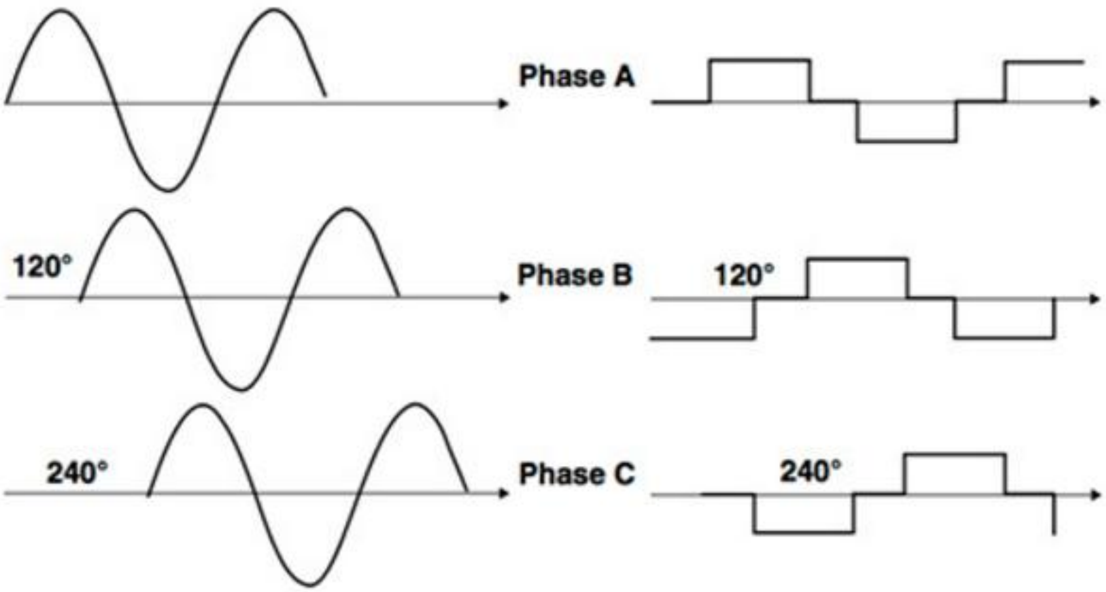


Figure 13 Sinusoidal commutation (left) compared to six-step commutation (right)

It is important to note however, that the switching of the phases is timed very precisely otherwise, this might negatively influence the behavior of the motor by providing uneven torque delivery. Therefore, in order to achieve precise switching some rotor position sensing must be provided, whether by means of sensors such as hall sensors and encoders or by back EMF sensing techniques.

The main advantage of six-step commutation is the simplicity of such a control scheme, which means that there are fewer demands on the processor and therefore the system cost is significantly reduced. However, as mentioned above uneven torque delivery or torque ripple, is highly undesired in an application where smoothness and precise position control is required for e.g. in an electric steering system moreover, torque ripple often causes noise sometimes audible and reduces the life of the motor due to the uneven stress on the motor components.

All of the aforementioned drawbacks could be improved by sinusoidal commutation, where all three phases are energized at the same time however, with a 120 degree phase shift. This overlapping of the phases minimizes greatly the effect of the torque ripple and increases the overall torque output of the motor. This dynamic improvement however increases the demand on the processing power and more over, higher rotor position precision is required.

2.4 AC machines

AC machines are by far the most widely used in applications which require higher speed output and where AC line power is readily available. As could be seen from figure 3, AC machines are generally classified into synchronous and non synchronous machines. Since this thesis focuses mainly on DC motors only a brief overview of AC machines will be presented.

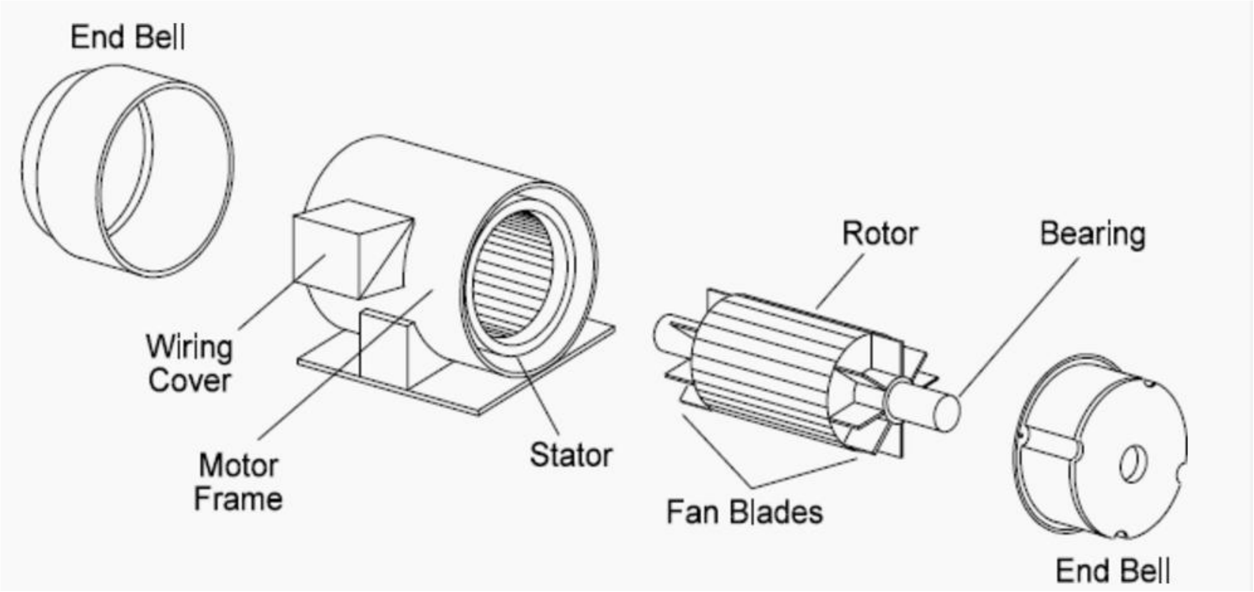


Figure 14 Construction of an induction machine [6]

2.4.1 Synchronous machines

The term synchronous machine indicates that, the rotating speed of the shaft is proportional to the frequency of current in the armature, and that the generated magnetic fields of the armature and stator rotate at the same speed which is known as synchronous speed. Synchronous machines are considered very reliable and are used as generators or in applications where steady rotational speed is required.

If we look at synchronous motors, they generally contain a three phase AC stator, and a rotor that is supplied by DC power which then produces a fixed magnetic field. The rotating magnetic field of the stator coils also known as synchronous speed can be given by

$$N_s = \frac{120f}{P}$$ **Equation 17**

Where: N_s is the synchronous speed

f is the frequency provided by the stator’s supply

P is the number of stator poles

However, when a synchronous motor is powered from a standstill, the inertia of the rotor is too high to start following the stator field in what is so called magnetic lock. Therefore, a synchronous machine is not self-starting but needs to be initially brought up to synchronous speed or close, and then the fields attract each other and remain in synchronous speed or magnetic lock.

It is important to note however that as the load is increased beyond a certain value the rotor would start to lag behind the stator field

2.4.2 Asynchronous machines

Machines which operate at speeds different to synchronous speed are known as asynchronous machines. Asynchronous motors are sometimes referred to as induction machines which indicates that an AC current is induced to the rotor as a result of Faraday’s law discussed in section 1.2.2.

Induction motors have two main different rotor types known as wound type or squirrel cage type. The main difference between them lies in the fact that wound type rotors uses coils of wire instead of conductor bars which are used in the squirrel cage type.

2.5 DC Electric machine operation modes

In this thesis the terms motor and generator are often used and applied alternatively. This is due to the fact that an electric machine can operate as a generator when there is an external driving force applied to the shaft. In this section, we explain the different operation modes including generation, regeneration and braking. These operational modes are of importance since in many practical applications an electric machine could be used to drive a certain load, however also required to charge a battery, such an example exists in the form of an electric car.

2.5.1 Generation

We have previously discussed the generation of EMF, therefore as an electric machine revolves whilst keeping the supply terminals open, an EMF force appears across its terminals. Two main parameters influence the magnitude of the generation namely, the rotational speed n and the back EMF constant K_E. Once a load in the form of an external resistance R_{ext} is connected across the terminals, a current would flow through the load. However, the amount of voltage appearing at the supply terminals is lower than the magnitude of EMF due to the voltage drops across the armature. The voltage appearing at the terminals could be obtained from the following equation

$$V = nK_E \frac{R_{ext}}{R_{ext}+R_a}$$ **Equation 18**

However, care should be taken to include the voltage drop depending on the brush material used. Additionally, the regenerated power could be found by

$$P = VI_a$$ **Equation 19**

2.5.2 Regeneration

In this case we assume a motor is connected directly to a DC supply, provided the DC supply is able to absorb current i.e. a source which is able to operate at least in two quadrants.

If the shaft spins with enough speed, current returns to the power source, this mode of operation is commonly referred to as generation. The no load speed of the motor is determined by equation 13, however if the motor shaft is to be driven in such a way that it exceeds the no load speed, the back EMF will be greater than the power supply voltage. In this condition the machine starts to regenerate and provides current to the power source as shown in Figure 15.

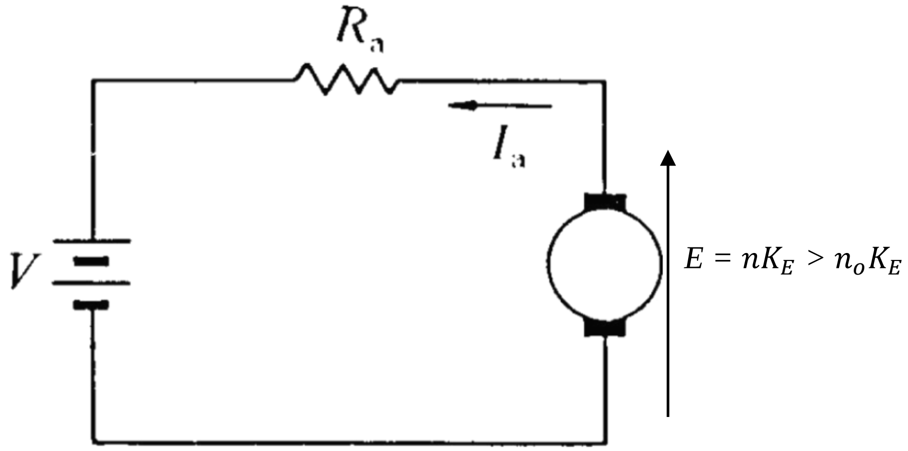


Figure 15 Schematic illustration showing current flow in regeneration mode

The current I_a can be calculated using the formula

$$I_a = \frac{BEMF-V}{R_a}$$ **Equation 20**

2.5.3 Braking

Braking is generally referred to when the machine operates in a direction opposing the direction of rotation of the shaft. For instance, when a counter clockwise torque is applied to a motor which attempts to rotate in the clockwise direction, the polarity of the back EMF also reverses and a larger current flows through. The current could be found using the following formula

$$I_a = \frac{V+|BEMF|}{R_a} \qquad \textbf{Equation 21}$$

Machine braking is a very effective method of braking and is commonly used. However, care must be taken in order not to exceed the maximum rated current in order to prevent demagnetization due to large currents.

2.6 Comparison between electric machines

In this section of the thesis we attempt to make a comparison between the common types of electric machines used in the industry and highlight both advantages and disadvantages of every machine type.

In general, DC machines such as PMDC and other types of brushed variants are amongst the simplest electric machines when it comes to regulation and simplicity of control, in fact in many applications they are connected directly to a battery. Such an example is the battery powered hair trimmer. However, for high power outputs in the range of tens of kilowatts the relevance of DC machines starts to decrease if compared with other machine types. This is due to the fact that mechanical commutation methods usually result in losses and requires maintenance over lifetime.

AC machines on the other hand offer high density power outputs with good efficiency. In the case of the induction machine they are able to self start and are cheaper to produce than the equivalent power rated synchronous machine, induction machines are also commonly used to power electric vehicles. Whereas synchronous machines are designed to operate where a constant speed is required and no load variation is expected on the shaft. Due to their cost which includes the addition of another machine in order to bring it to synchronous speed, they are rarely used in applications with less than 20 kilowatts. However, they are also used at power stations to correct the power factor where they are run in the no load state.

The choice of electric machine type therefore depends on several factors, which include cost, space, complexity and life time requirements. Below is a table which summarizes the advantages and disadvantages of the machines discussed previously.

Type	Advantages	Disadvantages	Application
PMDC	1. Easily controlled 2. Proven technology 3. No need for external excitation	1. Brush wear 2. EMI due to sparking 3. Risk of demagnetization	1. Car seats 2. Small appliances
BLDC & PMSM	1. Precise control 2. High efficiency and low EMI	1. Complex algorithms 2. Higher cost of drive electronics and magnet cost	1. Cooling fans 2. Electric vehicles
AC Asynchronous (Induction)	1. Robust 2. Low maintenance	1. High power 2. Complex control	1. Electric pumps 2. Fans
AC Synchronous	1. Constant speed, independent on load 2. High Efficiency	1. Not self starting 2. Higher cost	1. Conveyor belts 2. Voltage regulation

Table 1 Comparison between common electric machine types

3 Armature reaction in PMDC motors

The phenomenon of armature reaction is the main topic of this thesis, in this chapter it will be introduced and explained in detail.

Armature reaction is a phenomenon that occurs in electrical machines, where the main field generated by stator coils or by permanent magnets is distorted as a result of the magnetic field generated by currents through the armature coils. This distortion of the main field could severely affect the performance of the motor, and could cause unwanted effects such as accelerated brush wear, increased EMI and lower efficiency due to higher current consumption at specific load points.

In order to establish a clear understanding of armature reaction, it is necessary to understand a few terms related to electrical machines, which describe the so called neutral axis where the brushes are normally placed within a PMDC motor.

3.1 The importance of Magnetic Neutral Axis (MNA)

As discussed previously in chapter 1, EMF is produced when a current carrying coil cuts the path of flux lines generated by a magnetic field. However, in an electric machine there exists an axis where there is no EMF produced because the conductors of the armature move in parallel to lines of flux generated by the stator field or permanent magnets. The magnetic neutral axis lies within this region.

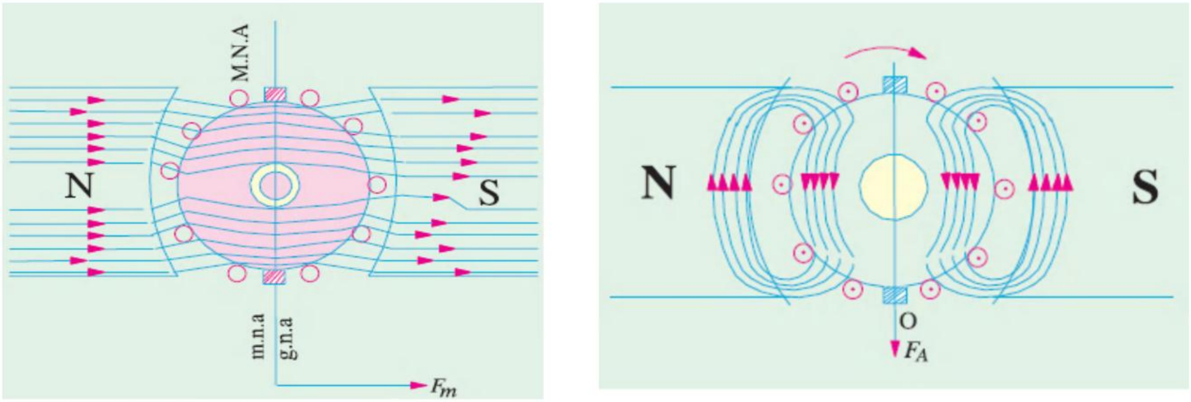


Figure 16 Illustration of MNA and GNA (left) armature field (right) [7]

Therefore, MNA is simply the axis where no EMF is produced due to the armature conductors moving in parallel to the lines of flux. The brushes are usually placed along the

MNA, therefore the MNA is of high importance in the operation of electrical machines as it is the optimal position where the switching of the direction of current takes place.

In figure 16, an unpowered DC machine is represented, i.e. there is no voltage applied to the armature coils via the commutator and brushes, it could be visible that the magnetic flux lines are symmetric in respect with the center of the North (N) and South (S) poles as illustrated by the vector F_m. However, in figure 16 (right side) the so called armature field is shown, and its direction could be defined based on Fleming's right hand rule. It is very important to note that the generated flux is symmetrical around the brush axis as illustrated by the vector F_A.

So far we have seen the fields generated by the armature field and the stator field separately however, in operation the two fields exist simultaneously in order to produce a mechanical force or to generate electricity. Figure 17 shows how those fields look like once they interact together.

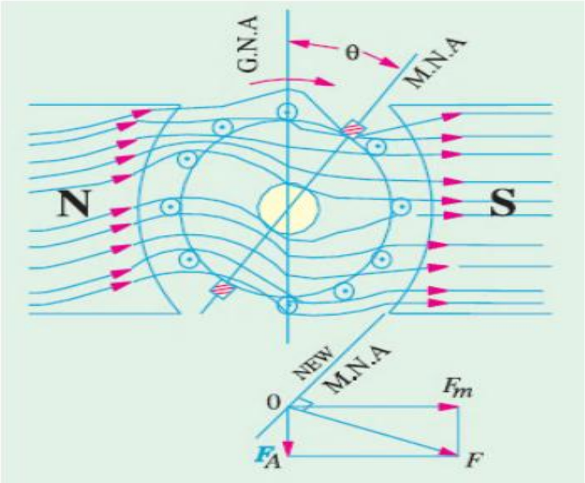


Figure 17 The interaction between Stator and rotor magnetic fields [7]

As could be seen from the figure above, the generated armature field effectively distorts the main field generated by the stator or PM. This leads to a shift in the position of MNA, which could be found by adding the vectors OF_m and OF_A which in turn results in the vector OF. We must keep in mind that the position of the MNA is always perpendicular to the resultant vector OF.

It can also be observed that there is a concentration and de-concentration of flux around the edges of the poles. Generally, the pole tip that is met first by the armature is known as the leading pole tip, where we find the flux de-concentrated and the corresponding tip on the other side is known as the trailing pole tip, where the flux is concentrated as a result of armature reaction.

3.2 The concept of demagnetization and cross magnetization

In the previous section at figure17, we have observed the overall flux distribution due to armature reaction. The resulted distorted flux lines are contributed by the stator field and the armature field. In this section we try to further analyze the armature field, since not only does it change the direction of the stator lines but it also weakens them.

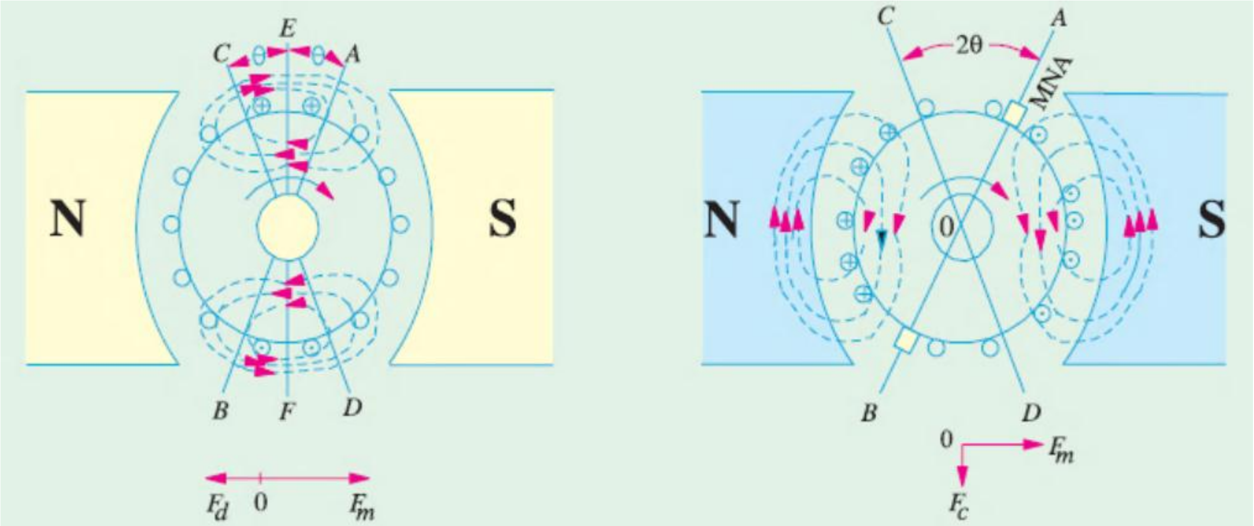


Figure 18 Shows demagnetization effects (left) and cross magnetization (right) [7]

Let us first consider the above figure on the left, here we define two critical areas AOC and BOD where O defines the origin point, or the center of the armature. In this case the armature conductors which carry current generate a flux which has an effective direction from right to left represented by the vector F_d. Referring back to figure 16, we know that the stator field generates flux which has a direction from left to right i.e. from North to South pole represented by the vector F_m. Thus, the conductors which lie in the areas AOC and BOD create flux that opposes or acts against the main flux. This effect is known as the demagnetization effect which weakens the net total magnetic field generated by PMs in the case of a PMDC motor.

Considering the figure on the right, we define areas AOD and COB where O also defines the origin point. The conductors within these areas carry current which generate flux with a downward direction, represented by the vector F_c whilst the main field is represented by vector

F_m. We observe that the direction of the vector F_c is perpendicular to F_m, this is what greatly contributes to the distortion in flux shown in figure 17.

3.3 The effect of winding methods on armature reaction

In order to calculate the effect of armature reaction, an understanding of the winding methods used for armature coils must be developed. The choice of winding method depends on several factors which include operating current, available space and cost.

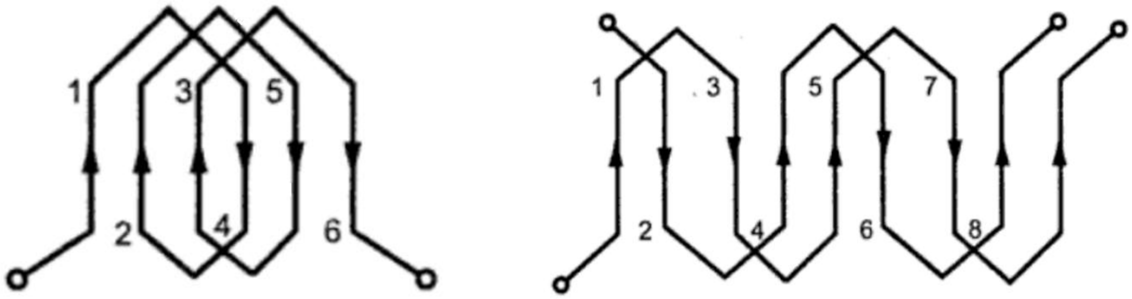


Figure 19 comparison between lap winding (left) and Wave winding (right)

3.3.1 Lap Winding

The name Lap winding is inspired by how the coil laps back with the succeeding coil. The winding starts from one commutator segment and is lapped back to the second commutator segment where it is joined with the succeeding coil. The lap winding method is specifically advantageous for high current machines due to the parallel paths which are formed.

3.3.2 Wave Winding

In the case of wave winding, the coils form a wave like pattern with the main difference to lap winding method being, that wave winding minimizes overlapping. Therefore wave winding is preferred for lower current applications.

3.4 Calculation of armature reaction

The calculation of armature reaction is usually split into two parts, namely the cross-magnetizing component and the demagnetizing component, both effects have been described previously in section 3.2. The calculation of these components require the knowledge of the winding method used for the armature coils, the number of armature conductors and how many poles are present within the machine.

The unit used for the calculations is known as Ampere-Turn (AT), which is a unit for measuring Magneto Motive Force (M.M.F), which is usually used to describe the MMF of a current carrying coil.

The demagnetizing amp-turns per pole can be calculated by the following formula:

$$dAT = \frac{\Theta_m IZ}{360}$$ **Equation 22**

Where: I is the armature current in Amperes

$I = \frac{I_a}{2}$ for wave winding configuration

$I = \frac{I_a}{P}$ for lap winding configuration

Z is the number of armature conductors

Θ_m is the brush shift in degrees from the GNA

The cross magnetizing ampere-turns per pole can be calculated using:

$$cAT = ZI\left[\frac{1}{2P} - \frac{\Theta_m}{360}\right]$$ **Equation 23**

Where: P is the number of poles

3.5 The effect of armature reaction on commutation

As discussed previously, the function of a commutator in a DC machine is to reverse the direction of current through the coils in order to maintain the rotation of the motor. Figure 20 shows the current through the armature, where T is the time when two commutator segments are short circuited by the brush. In this section we explore the effects of armature reaction on commutation and how adjusting the brush position i.e. brush shift improves the commutation procedure.

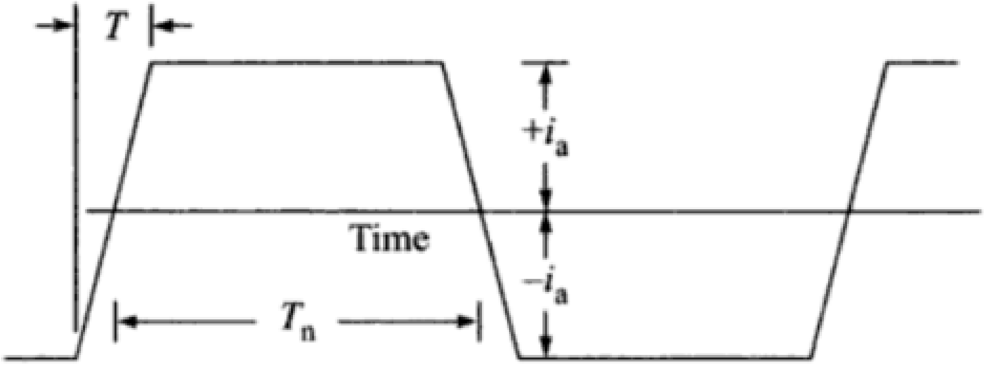


Figure 20 Armature current graph illustrating current reversal [8]

In an ideal case, commutation would occur without the creation of sparks. Sparks appear because the coil which is undergoing commutation is short circuited by the brush, therefore sparks are generated when the brush moves away from the specific commutator segment that belongs to the coil. Again, ideally the commutation process i.e. current reversal would be completed within that time period before the brush moves away from the commutator segment.

In practice however, commutation process experiences a delay due to the inductance of the coil itself and armature reaction, which affects the commutation process by distorting flux lines close to the GNA, which in turn generates an EMF through the coil. The difference between the ideal and actual real current is shown in the graph below.

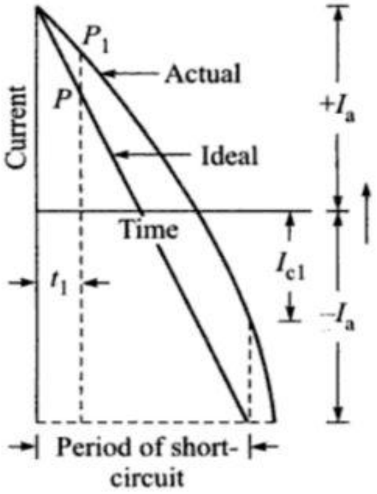


Figure 21 Actual current graph in comparison to ideal [8]

The self induced EMF resulting from the inductance of the coil can be calculated as

$$EMF_l = -\frac{L\,2I_a}{T}\ [\mathrm{v}]$$ **Equation 24**

Where: L is the inductance of the coil

3.6 Reducing the effects of armature reaction

Due, to the aforementioned, we can therefore conclude that the effect of armature reaction should be minimized in order to enhance the efficiency and lifetime of the machine. In the next section we identify a few methods for minimizing the effects of armature reaction.

3.6.1 Increasing the resistance of the brushes

An effective way of reducing the effects of armature reaction is by increasing the resistance of the brushes. [9] Is a paper which explains in detail the effects of resistance commutation, and presented detailed analysis of the equations related to it. A common material instead of Copper is Carbon-graphite, since the resistance is determined by the following formula

$$R = \rho \frac{l}{A} \quad \textbf{Equation 25}$$

Where: ρ is the resistivity of the conductor

l is the length of the conductor

A is the cross-section or the surface area between the brush and commutator

In order to understand the principle of this method let us consider figure 22. The current flowing through the coil C would prefer the path of the lower resistance, i.e. through coil B if the brush has sufficiently high resistance, since the resistance of the path r_1 will be increasing due to the decrease in surface area as the brush moves away from commutator segment b, thus forcing the current to move into the desired direction which translates to less sparking since the coil C discharges most of the current contained within itself.

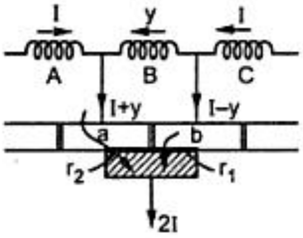


Figure 22 Illustration of current flow [7]

Therefore, resistance commutation is a good technique that is generally deployed within electric machines. In addition resistance commutation significantly reduces the wear on the commutator segments, which can significantly increase the lifetime of the machine. However, increased resistance causes voltage drops over the brushes, which could be an issue depending on the application of the machine therefore, an appropriate brush material and size should be chosen in order to find the most appropriate compromise. [10][11]

3.6.2 By adding interpoles and compensating windings

The idea behind using interpoles is to compensate for the cross-magnetizing effect of armature reaction. Interpoles and compensating windings are generally used for larger machines, since due to space and cost constraints they are not added to PMDC motors. The figure below shows how they are usually connected within an electric machine.

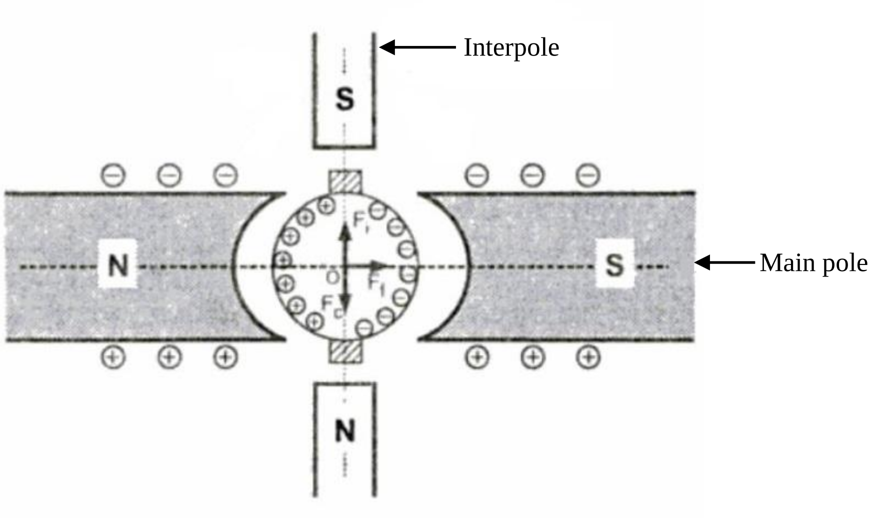


Figure 23 Graphical illustration showing the connection of interpoles [7]

Interpoles and compensating windings are connected in series with the armature, hence, depending on the armature current the field generated by them differs. They are placed on the GNA, which has an advantage of creating a reversing EMF that opposes the self induced EMF as a result of commutation. This leads to faster and more effective commutation.

3.6.3 By increasing reluctance at the pole tips (Chamfered poles)

Referring back to figure 17, it was visible that due to the cross-magnetizing effect of armature reaction, flux at the pole tips of the motor is severely affected. This could be improved by increasing the reluctance at the pole tips since the reluctance follows the formula

$$R = \frac{l}{\mu A}$$ **Equation 26**

Where: l is the length of the magnetic path

μ is the permeability of the material in this case it is air μ_o

A is the cross sectional area

The use of this method has an effect on the path of main field flux as well however, the improvement at the pole tips yields a far greater advantage, and therefore this method is commonly used. [12] Is a patent declaration which includes the invention report for a patent regarding magnet pole design addressing the issues of armature reaction.

3.6.4 Brush shift

Brush shifting is one of the simplest ways of minimizing the effects of armature reaction, since it does not require any additional components to be added to the machine, therefore it presents a cost saving advantage to the user. Figure 24 shows a brush shift from the GNA to the MNA.

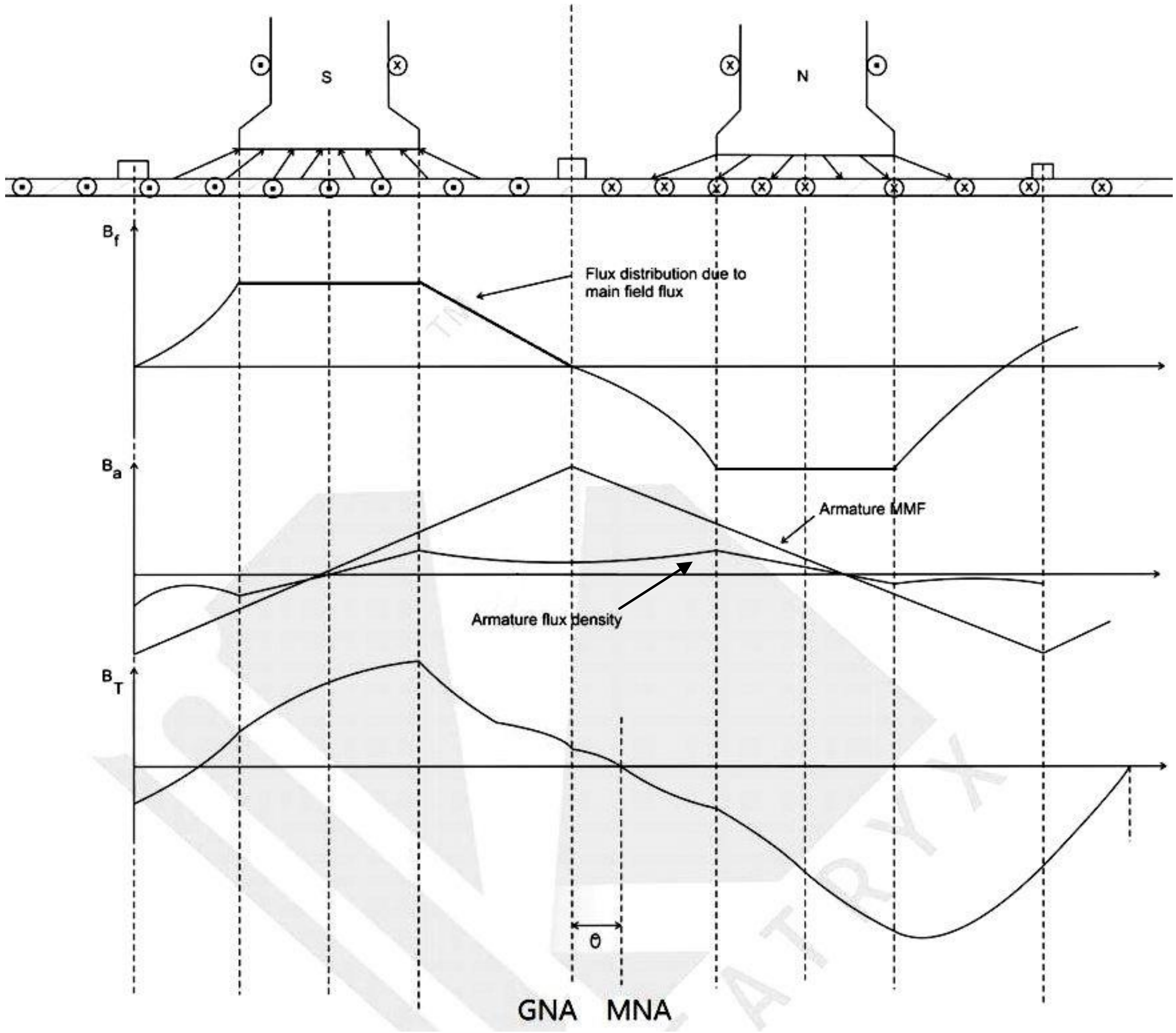


Figure 24 Illustration of brush shift [13]

The main advantage behind shifting the brush closer to the MNA is that the coil undergoing commutation falls under the influence of the field pole of opposite polarity. This could be observed in Figure 24 by comparing wave forms B_f and B_T, where the influence of the main pole of opposite polarity is that it creates an EMF that opposes the self induced EMF mentioned previously in section 3.5. Therefore, by careful positioning of the brushes on the MNA sparkless commutation could be achieved, due to the faster current reversal which in turn significantly increases the lifetime of the motor. [14]

Brush shifting has some limitations however, chief amongst which is the fact that the MNA position varies depending on the current through the armature. This means that if the load changes the brush position must be adjusted accordingly. In addition, brush shifting introduces a demagnetizing effect as could be seen from equation 22 in section 3.4. Another limitation depends on the desired operation of the machine, whether it is used as generator or motor, since in the case of the motor the MNA shifts opposite to the direction of rotation and in case of the generator it shifts within the direction of the rotation.

3.6.5 Increasing the strength of the stator field

It is very important to consider the amount of the MMF generated by the armature compared to the MMF generated by the stator. The stator's field should be significantly stronger than the field generated by the armature specifically under full load conditions, since the effect of both the cross magnetizing and de-magnetizing components could be less severe on the stator's field. This however, could be a difficult requirement, due to the cost of permanent magnets and the space constraints as well.

3.6.6 Discussion: Choice of methods for armature reaction reduction

In the previous sections, we presented a few methods of reducing the effects of armature reaction. In this section we compare them, evaluate their feasibility and argue why some are more suitable to implement than others depending on the type of machine and application.

Obviously, increasing the strength of the stator field is an effective method of reducing the effect of armature reaction since the deformation of the stator flux is the main root cause which results in negative effects such as worsened commutation and performance. However, keeping in mind that with increased stator strength comes additional cost and at least in the case of a motor, it leads to a stronger machine which is not always desired, since in many cases a simple PMDC motor is powered directly from the battery which means that the output torque could be too high. Therefore, machine designers choose in many cases either to live with the resulting worsened commutation or chose a different solution such as brush shifting specifically if the operation of the machine is unidirectional.

On the other hand resistance commutation is by far one of the most used methods of reducing the effects of armature reaction, however it serves only the purpose of improving commutation and has no influence on improving the magnetic distortion as a result of armature current.

Brush shifting therefore represents a suitable method for improving the effects of armature reaction as well as improving commutation, the main drawback of such method is the fact that it would need to be adjusted depending on the load on the machine. However, there are countless applications were the direction, load and speed of the machine are kept constant throughout the life time of the machine, and in such applications brush shifting represents a great opportunity to enhance and improve the performance of the machine. Generally, brush shift is suitable for machines which are operated uniderectionaly and in the case of varying loads a compromise brush shift angle could be chosen by the machine's designer in order to improve the performance throughout the complete load range. This means that a weaker machine given the appropriate brush shift could be used potentially in an application where a design of a new stronger motor would have been required.

In several applications however, machine designers choose to use a combination of methods to solve the complications of armature reaction. Such combination is the use of the appropriate brush shift in addition to the use of chamfered poles and resistance commutation. By implementing such solutions the designers benefit from the lower cost of the solution and the fact that those methods combined yield an improvement in performance as well as increased lifetime and durability which arises from the use of resistance commutation.

The following table summarizes the advantage and disadvantages of some of the methods discussed.

Type	Advantages	Disadvantages
Brush Shift	1. Relative ease of implementation and adjustment 2. No additional cost required	1. Limitations if used for machines with varying loads 2. Not suitable for machines which act as motor and generator
Resistance commutation	1. Increasing life of commutator due to polishing effect of carbon brush 2. Suitable for various loads	1. Increased voltage drop 2. Larger brushes required due to current density
Changing magnetic field strength	1. Ensures the stator's field is more immune against armature reaction 2. Increased motor performance	1. In the case of permanent magnets the cost is significantly higher 2. Increased performance is not always desired
Chamfered poles	1. Yields increased reluctance at pole tips	1. Applicable only for machines which incorporate magnetic poles
Interpoles	1. Very effective method for removing effects of armature reaction	1. Only suitable for use in larger machines due to space and const constraint

Table 2 Comparison between methods for armature reaction reduction

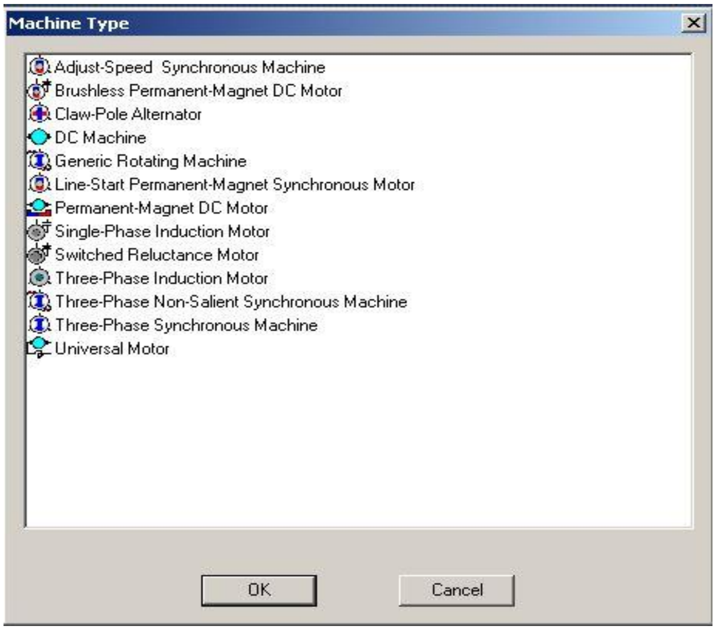
4 Motor simulation using Ansys RMxprt and Maxwell 2D

Ansys Rotational Machine Expert (RMxprt) is a template based interface for the simulation of electric machines. RMxprt was chosen as a simulation tool for this thesis due to several factors, since it offers a very intuitive way of designing, calculating, tuning and rapidly optimizing the parameters of electric machines during the design phase. The simulation model could then be used as a basis for further simulations on Maxwell 2D or Maxwell 3D, which then focuses on mechanical and electromagnetic characteristics of the machine.

RMxprt was also chosen in order to validate the feasibility of predicting and determining the amount of adequate brush shift in order to optimize the performance of the motor for the specific required operation window of the motor.

RMxprt uses classical analytic electric machine equations, which have been previously covered in previous sections, to evaluate motor performance and characteristics. The Graphical User Interface (GUI) allows editing and optimizing the model’s parameters and displays the corresponding changes immediately to the user.

As the name suggests RMxprt contains a library of rotational machines of wide variety which includes both AC machines and DC machines. However, most conviniently the libraries contain the accompanying power electronic drive circuits and the control elements, all of which are editable either by using Ansys Simplorer or Ansys Maxwell Circuit editor.



Adjust-Speed Synchronous Machine
Brushless Permanent-Magnet DC Motor
Claw-Pole Alternator
DC Machine
Generic Rotating Machine
Line-Start Permanent-Magnet Synchronous Motor
Permanent-Magnet DC Motor
Single-Phase Induction Motor
Switched Reluctance Motor
Three-Phase Induction Motor
Three-Phase Non-Salient Synchronous Machine
Three-Phase Synchronous Machine
Universal Motor

Figure 25 List of machines as viewed from RMxprt (GUI)

4.1 PMDC motor model

Building the model for the motor begins by choosing the type of machine and then specifying the motor parameters via RMxprt. Then the user starts defining the geometrical dimensions of the machine, followed by defining the material properties such as the type of steel used for the motor casing and the magnet types.

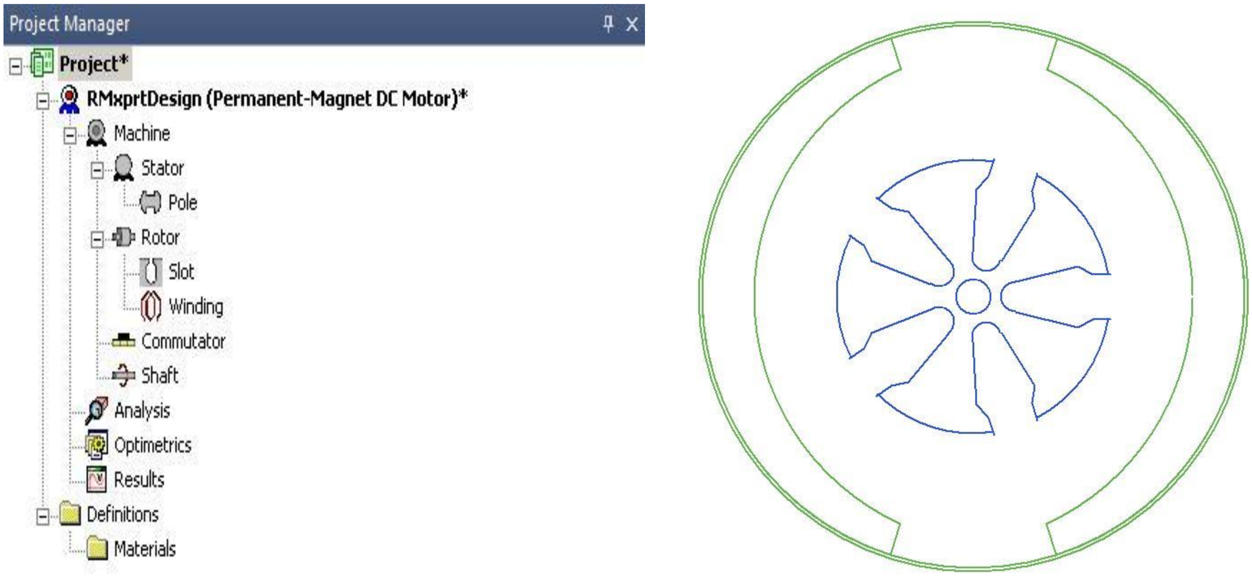


Figure 26 RMxprt model structure

As visible from the figure above the machine's components are structured in a hierarchical order, which adds to the ease of use for the user. In this section we will describe some of the most important design parameters that should be specified during the model setup since errors in these parameters could result in deviation of the performance analysis of the motor.

Under the machine tab, the number of poles and the target reference speed of the machine are specified. The chosen parameters are 2 poles and 6300 rpm.

Under the stator tab, mechanical dimensions were specified as 36 mm for the diameter and the length was 51 mm. The material chosen for the housing was silicon steel type M36, which is a material commonly used in rotational machines due to low core losses and improved eddy current circulation [15].

Under the pole tab properties regarding the permanent magnets are defined, usually machine designers consider properties such as remanence (B_r) which describes the strength of the magnetic field, coercivity (H_{cb}/H_{cj}) which describes the resistance of the material to become demagnetized, the energy product (BH_{max}) which describes the density of the magnetic flux per unit area, the curie temperature (T_c) which describes the limit at which the magnet loses its magnetic properties and the maximum operating temperature recommended by the magnet manufacturer (T_o). The chosen material was Y20 which has the following parameters [16]

Property	Value	Unit
Remanence (B_r)	350	[mT]
Coercivity (H_{cb}/H_{cj})	150	[kA/m]
Energy product (BH_{max})	18	[kJ/m^3]
Maximum operating temperature (T_o)	250	[°C]
Curie temperature	450	[°C]

Table 3 Properties of chosen magnet pole

In the rotor tab dimensions such as the length and diameter of the rotor were defined, the steel type of the rotor is chosen to be of the same material as the stator housing. The winding method was chosen to be lap winding. The user can also define the amount of skewing on the rotor which has an effect on cogging torque of the motor. Additionally the dimensions of slots could be either specifically designed by the user or the option of auto design could be chosen, since this thesis does not propose a new slot design the auto design feature was selected.

The definition of brush sift could be defined under the commutator tab, where the dimensions of the brush were set as 5mm width and 8.75 mm length. The amount of brush shift could be specified in the brush displacement in mechanical degrees where a positive value indicates a shift in the counter-clockwise direction while a negative value indicates a shift in the clock-wise direction. The commutator length was chosen to be 8.75 mm and diameter of 7 mm.

At this point RMxprt has generated the machine model based on our design specifications, the following step is to define the analysis type to be performed. The motor will be simulated with constant voltage and linearly varying load torque is applied in order to obtain the PMDC motor characteristics. The following table shows the defined load type and final machine parameters.

Operation type	Motor	-
Load type	Linear torque	[kA/m]
Rated output power	16	[W]
Rated voltage	12	[V]
Rated speed	6300	[rpm]
Operating temperature	75	[°C]

Table 4 Machine Parameters

4.2 RMxprt Simulation results

In this section of the thesis we will review the results and the performance curves obtained from the analytical simulations of RMxprt, whilst focusing on the effects of brush shifting on the motor's performance. This section of the thesis will perform as a base reference to chapter 5, where we compare our measurements on motors at the test bench with the results of the simulations presented here.

Below are the efficiency and performance curves generated by RMxprt simulations.

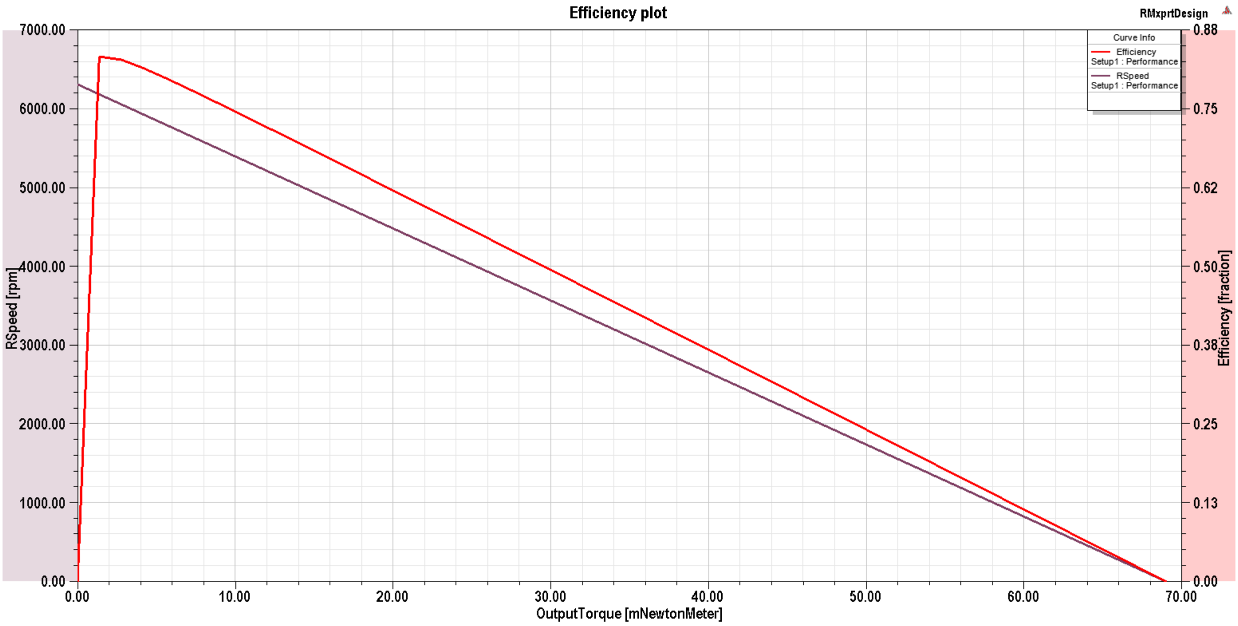


Figure 27 Efficiency curve obtained from RMxprt

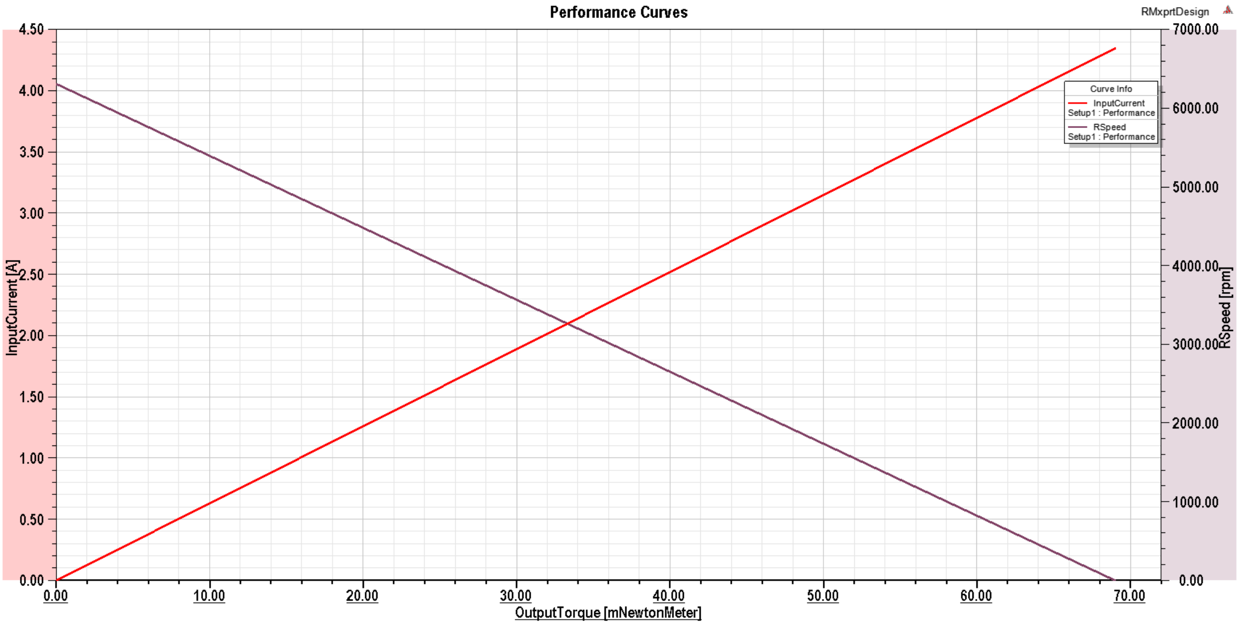


Figure 28 Performance curves obtained from RMxprt

4.2.1 Brush shift simulations

We must specify a method to validate and compare results, since the typical performance curve starts from no load condition to stalled rotor position i.e. zero speed. Therefore, we will specify load points and measure the rotor speed relative to the load. The chosen points will be 0 mNm i.e. no load, 10 mNm, 20 mNm and 30 mNm. The following curves which were obtained by simulating the model described in the previous section will be shown in appendix A. However, the results will be summarized in the tables below.

Brush offset	0 mNm		10 mNm		20 mNm		30 mNm	
	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]
0 degree	-	6304	0.63	5391	1.26	4478	1.89	3565
10 degree	-	6413	0.64	5468	1.28	4523	1.92	3578
20 degree	-	6746	0.68	5700	1.35	4654	2.02	3609

Table 5 Simulation results at specified load points

The results presented in the table above show an improvement in the performance of the motor, specifically in the rotor speed relative to the load torque, with different brush angles giving incremental improvements in the performance of the motor.

4.3 Magnetic and transient simulations on Maxwell 2D

Maxwell 2D uses Finite Element Analysis (FEA) based on the Maxwell equations to solve the electromagnetic problems in two dimensions. FEA methods usually separate the model into smaller bodies, these bodies are then interconnected by boundaries either surfaces or lines.

In this section of the thesis, we will briefly introduce the results of exporting the defined model via RMxprt to Maxwell 2D however since this thesis aims to verify the performance aspects of motors via RMxprt the results obtained from Maxwell 2D's simulations will not be discussed and compared in detail.

With a computer using Intel i3 core with 1.5 GHz frequency and 4GB RAM, it took approximately 8 hours to complete one simulation. Therefore, the time required to perform one 2D simulation is multiple times longer compared to RMxprt which requires less than 10 minutes to perform one simulation.

The figure below shows the field analysis of the model at time instant 0, where the transient analysis has not yet started. Therefore, it is visible that the fields are distributed ideally without deformation on the flux lines due to the fact that no current is flowing through the armature windings.

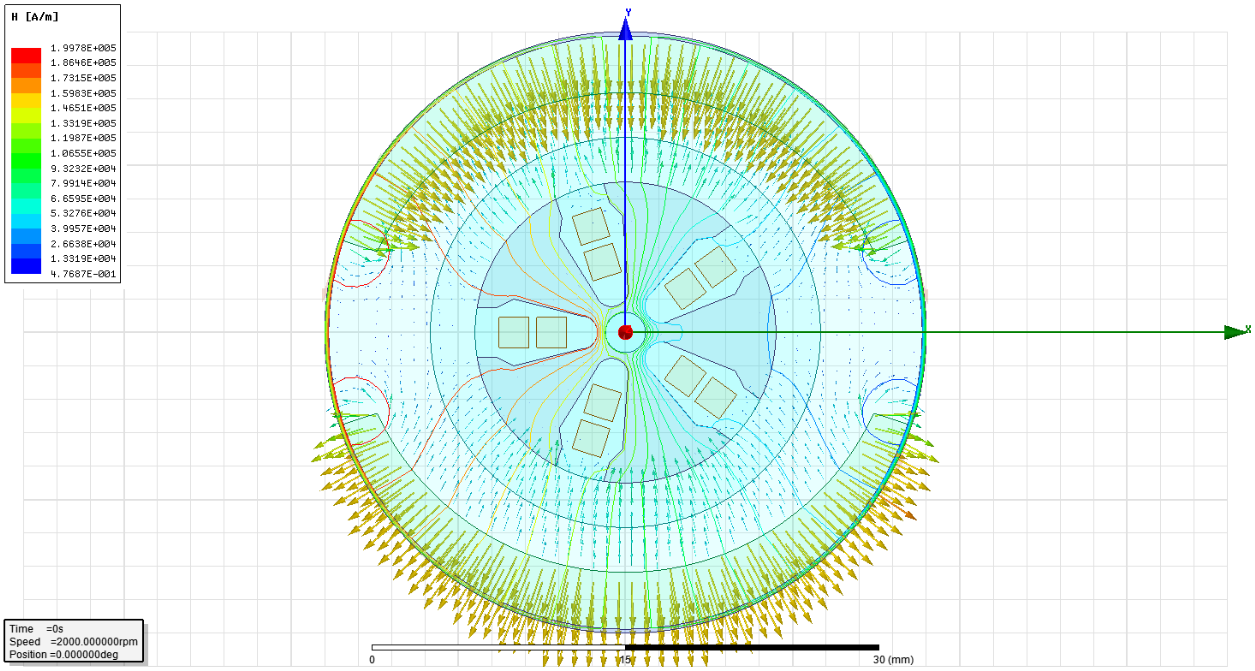


Figure 29 Field analysis showing flux lines and H-field and B-field at initial condition

Figure 30 clearly demonstrates the effects of armature reaction and how it distorts the shape of the main flux generated by the permanent magnets. The figure below is captured at time instant 0.5 s.

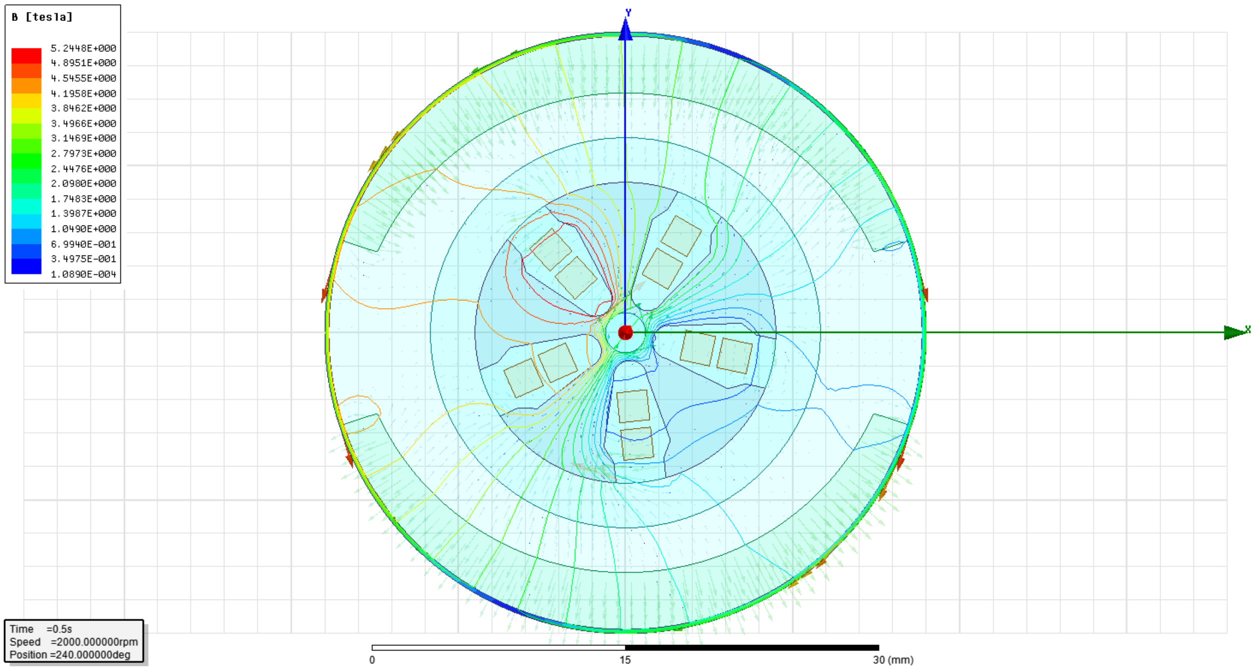


Figure 30 Field analysis showing flux lines and H-field and B-field at 0.5 S

As could be seen from the figure above the armature reaction leads to the concentration of the flux lines at the pole tips, a phenomenon which has previously been described in detail at section 3.1. Therefore, the direction of armature rotation could be clearly observed from the above figure, since there is a de-concentration of flux at the pole tip which is first met by the armature, and concentration of flux on the other side of the pole. This leads to the conclusion that the direction of rotation of the armature is in the clockwise direction, which further validates the simulation settings and parameters since the specified direction of rotation was clockwise.

Another important feature that is available via Maxwell 2D is the ability to view transient analysis of other parameters such as torque relative to time, winding currents and induced voltages. The following figure shows the output torque of the motor while rotating.

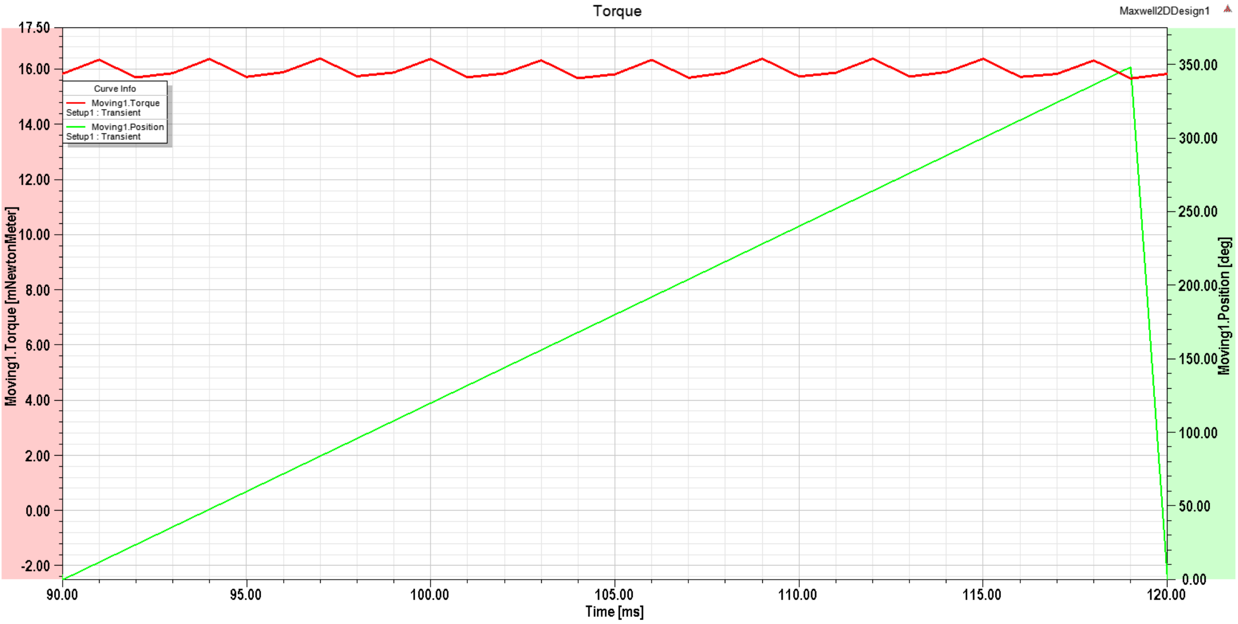


Figure 31 transient analysis of output torque produced by motor shaft

The observed variations in the torque output are known as torque ripple, which are as a result of the interaction between the stator magnetic field and the rotor slots. Therefore, since our motor consists of two stator poles and five rotor slots we observe a total of ten peak variations in the output torque of the motor per mechanical rotation.

5 Measurements and experimental setup

In this section of the thesis we perform measurements on the previously simulated motor to validate the simulation model and evaluate the effects of brush shifting on PMDC motor performance.

To calculate the performance of PMDC motor, one could measure the no load speed and current, the same procedure could then be applied for the stall condition. Following that a straight line could be drawn between the two measured points i.e. the no load and stall condition.

5.1 No load speed and current measurements

No load measurements were performed with no load connected to the motor shaft. The motor was supplied from a 12 V supply and the rotor speed was measured using a tachometer and the armature current was measured using current probes for minimal added resistance in series with the armature.

The measured no load current arises mainly due to mechanical friction. The mechanical friction arises due to the contact between the shaft and bearing and between the rotor construction i.e. windings and air therefore this friction torque increases also with the speed of rotation. It is important to note however, that the speed dependant friction torque is negligible compared to the rated output torque of the motor.

The tachometer uses an infrared beam that is reflected upon a reflective surface and the rotor speed is calculated based on that.

5.2 Torque measurements

There are several methods for performing torque measurements, most industrial test benches incorporate torque sensors within them to measure the torque output of the Device Under Test (DUT). The load is provided by another DC motor with at least 10 times greater stall torque.

An alternative measurement method makes use of the understanding of DC machines developed from the simulations and theory presented in the previous chapters of this thesis. The experimental setup used is shown in the following figure, while the test bench with tachometer, power supply and oscilloscope probe connections are shown in Appendix B.

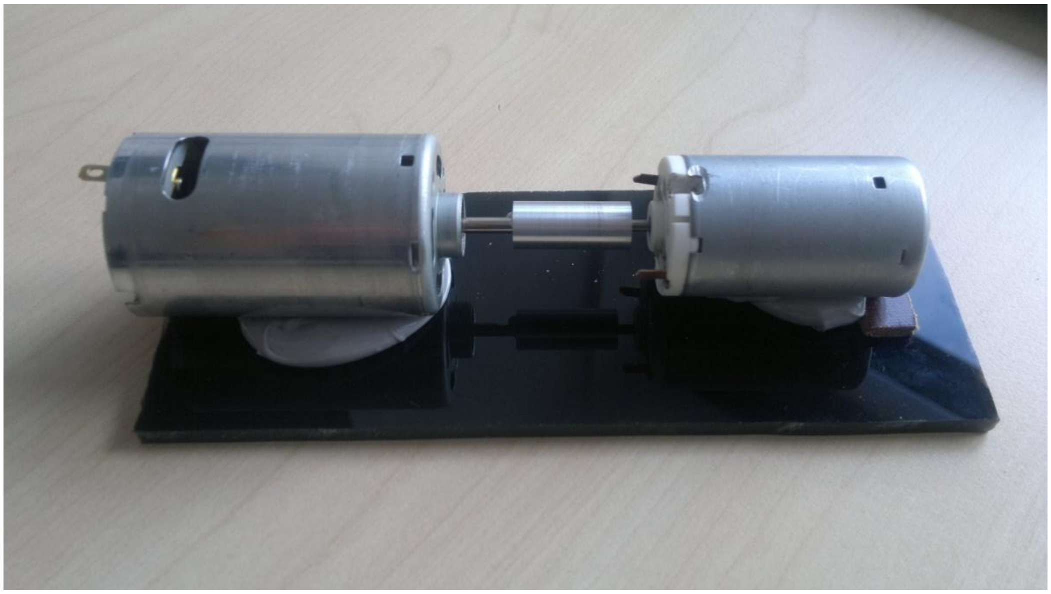


Figure 32 Motor test setup

The method uses two machines just as the previous method above however, one machine is used as a motor (DUT) and the other machine is used as a generator, the generator is then loaded by connecting a variable power resistor in parallel. The user then records parameters such as rotor speed, input current and voltage for the (DUT) and output current and voltage of the generator. The torque can then be calculating using the equation below

$$T = \frac{P}{\omega} \qquad \textbf{Equation 27}$$

Where: T is the output torque at the coupling in Newton meter [Nm]

P is the mechanical power at the coupling in watts [W]

ω is the rotational speed of the shaft in radians per second [rad/s]

The mechanical power at the coupling could be calculated by using the equation below, given the assumption that the coupling is ideal and exhibits no mechanical losses.

$$P = \frac{IP_M + OP_G}{2} \qquad \textbf{Equation 28}$$

Where: IP_M is the input power of the motor

OP_G is the output power of the generator

Both input power and output power must be carefully measured as deviations in measurements could lead to deviations in the calculated output torque, therefore the output and input voltages where measured at the terminals of the machines using an oscilloscope in order to account for the voltage drop across the cables from the power supply. It is also important to measure higher loads quickly in order to prevent the motor from overheating.

5.3 Discussion of results

The results of the measurements are summarized in the following figures and table. The results below compare the performance of the motor at different brush shift angles, specifically 0 degree offset and 20 degree offset.

Brush offset	0 mNm		10 mNm		20 mNm		30 mNm	
	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]	Current [A]	Speed [rpm]
0 degree	0.01	6300	0.67	5478	1.26	4428	1.80	3540
10 degree	0.16	6404	0.68	5530	1.19	4656	1.71	3783

Table 6 Measurement results at specified load points

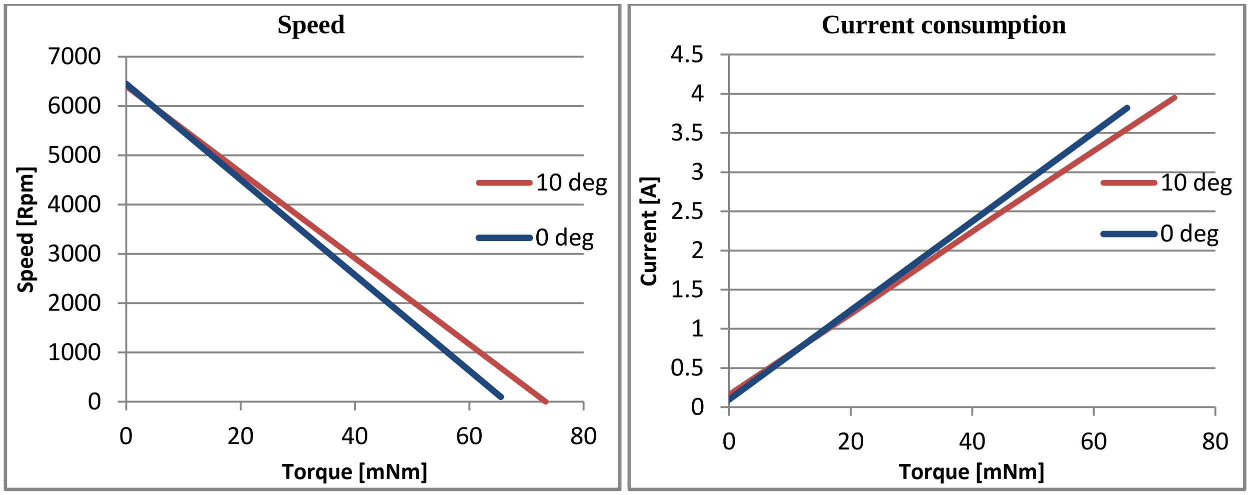


Figure 33 Performance curves at different brush angles

The results above show an improvement in the performance curves of the motor specifically at the load points. The measurements also show an improvement in the current consumption of the motor under load.

The comparison between measurements and simulation results show key differences mainly in the current consumption at load points. While in simulation the current consumption at load points increased incrementally by increasing the brush shift angle, the observed results from the measurements at the test bench indicate a reduction of current consumption at load point with brush shifting. The differences between simulation and measurements could be attributed to some mismatches between the idealized parameters in the defined model via RMxprt and the real motor.

However, the aforementioned fact that current consumption is reduced at load point, further validates the feasibility of using brush shifting to improve not only the performance aspect of the motor i.e. speed relative to load torque but the overall current consumption and efficiency of the motor while operation. In addition, the lowered current consumption indicates that there is less sparking at load point which would result in longer life time expectancy from the brushes.

Measured performance characteristics at the defined operation points (0 mNm, 10 mNm, 20 mNm and 30 mNm) have been found to be comparable with the results obtained from simulations whilst not completely overlapping. However, their progression i.e. increased performance at load point follows the results obtained from simulations using RMxprt.

6 Conclusions and future work

In this Master thesis we investigated the effects of brush shifting and its effect on PMDC motor performance in detail. We attempted to create a simple and intuitive guide to understand the effects of armature reaction and presented the methods commonly used to counter the effects of armature reaction.

In Chapter 1 we presented the main motivation behind this research and why it is still viable to investigate the performance and behavior of PMDC motors despite the rise of rivaling electric machine configurations such as BLDC. Then we gave an introduction to the fundamentals of electromagnetism which underlay the operation of every electric machine in existence.

Chapter 2 then presented an overview of different types of electric machines out of which a few main types which are commonly applied in industry and household applications were discussed and reviewed in detail. The chapter then proceeded by comparing and discussing the main advantages and disadvantages of the presented types taking into account several factors such as cost, design complexity, control schemes and several others.

In Chapter 3 the aim was to cover the theory behind the phenomena of armature reaction, whilst keeping the emphasis on how they affect PMDC in particular and DC motors in general. The chapter later reviewed the ways in which the effects of armature reaction are minimized and then concluded by a discussion outlining the advantages and disadvantages of each method in order to help the reader understand which methods are amongst the most relevant depending on the applications and which are the most prevalent in the industry.

Chapter 4 then starts by an introduction into RMxprt and Maxwell 2D both of which are simulation tools which were utilized in order to simulate motor characteristics. The chapter then proceeds by describing the motor model in detail and then presents the results of brush shifting via RMxprt. The second part of the chapter presented the magnetic and transient analysis via Maxwell 2D which enables the reader to validate and compare simulations of the motor with theory covered in previous chapters regarding armature reaction and its effects on the magnetic field.

Chapter 5 gives an introduction to the experimental setup and test bench that used in order to measure the motor characteristics and validate the effects of brush shifting. It begins by explaining the measurement procedures and then presents and compares the results of the measurements performed on the motor with the simulations from chapter 4. The chapter concluded by validating the feasibility of brush shift to improve motor performance and reduce current consumption at load points.

This Master thesis provides several topics for further investigation and study for example:

- Fully designing and implementing a machine model which includes more detailed material description for FEM analysis.
- Investigating whether armature reaction effects would be minimized using an alternative solution to the one proposed in this thesis that would still remain cost effective such as chamfered pole design.
- EMI tests to measure and validate the improvement when applying methods such as brush shifting and resistance commutation in reducing EMI.

Appendix A

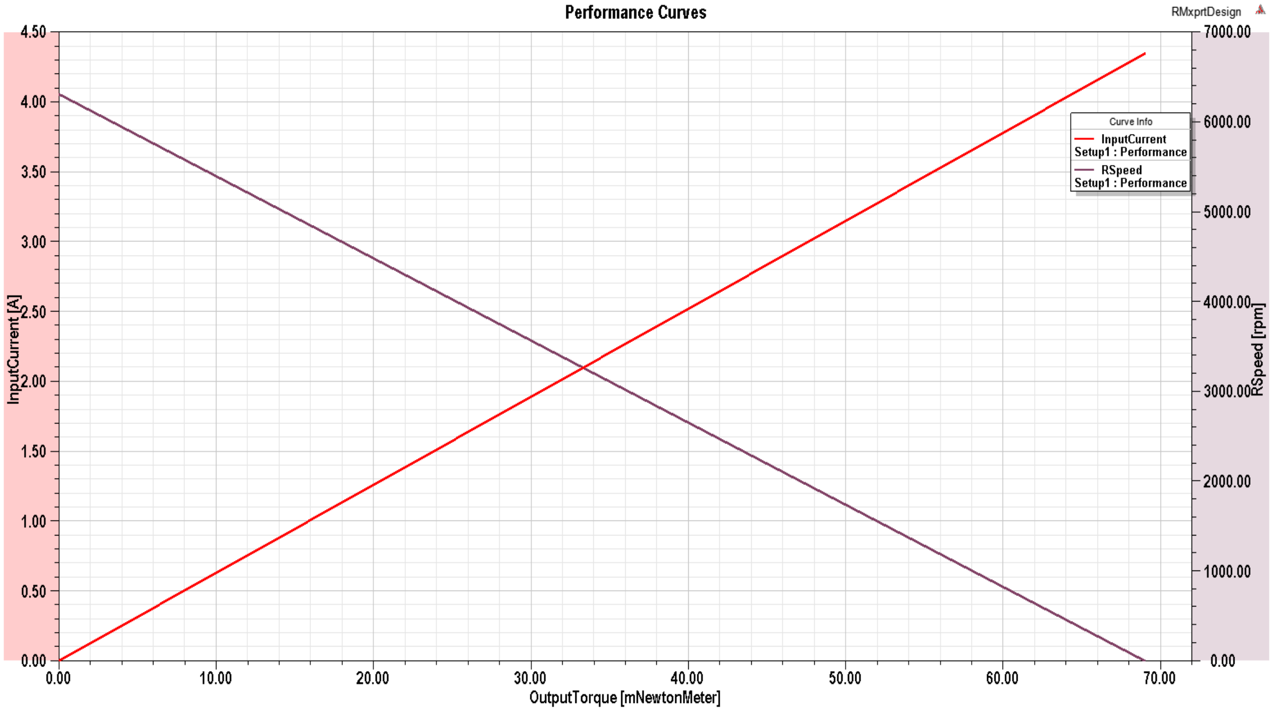


Figure A1 Performance curve with brush shift at 0°

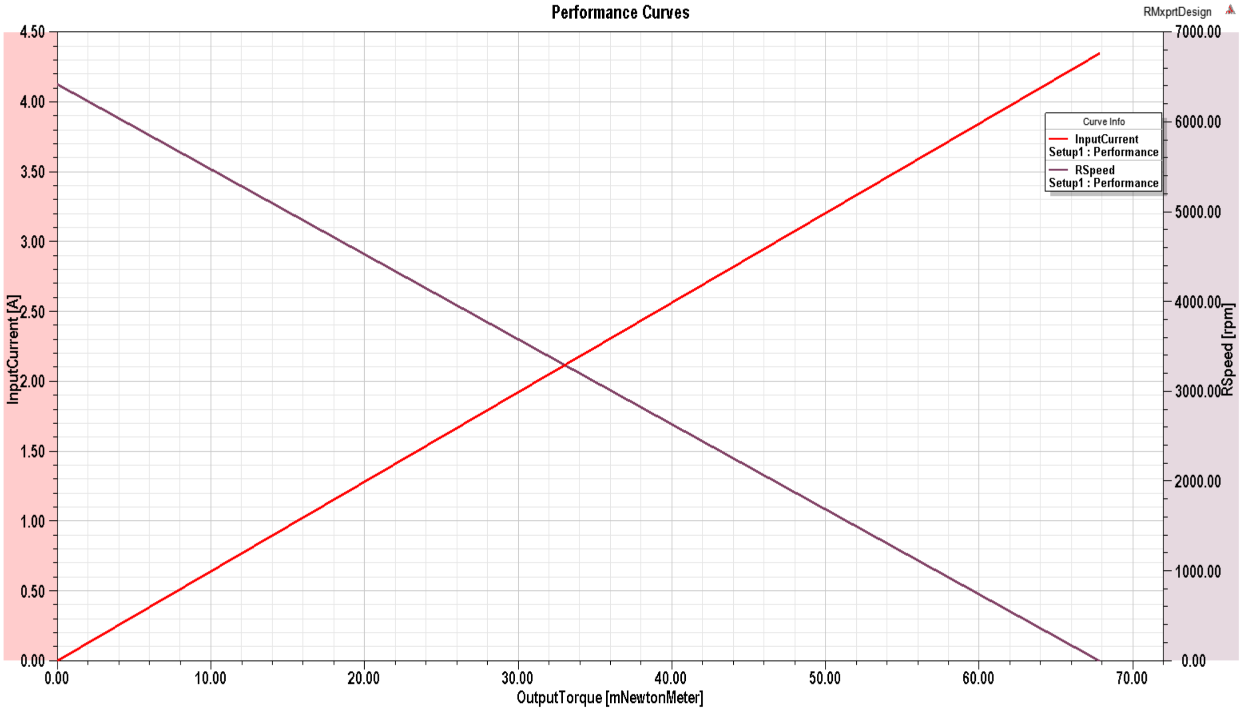


Figure A2 Performance curve with brush shift at 10°

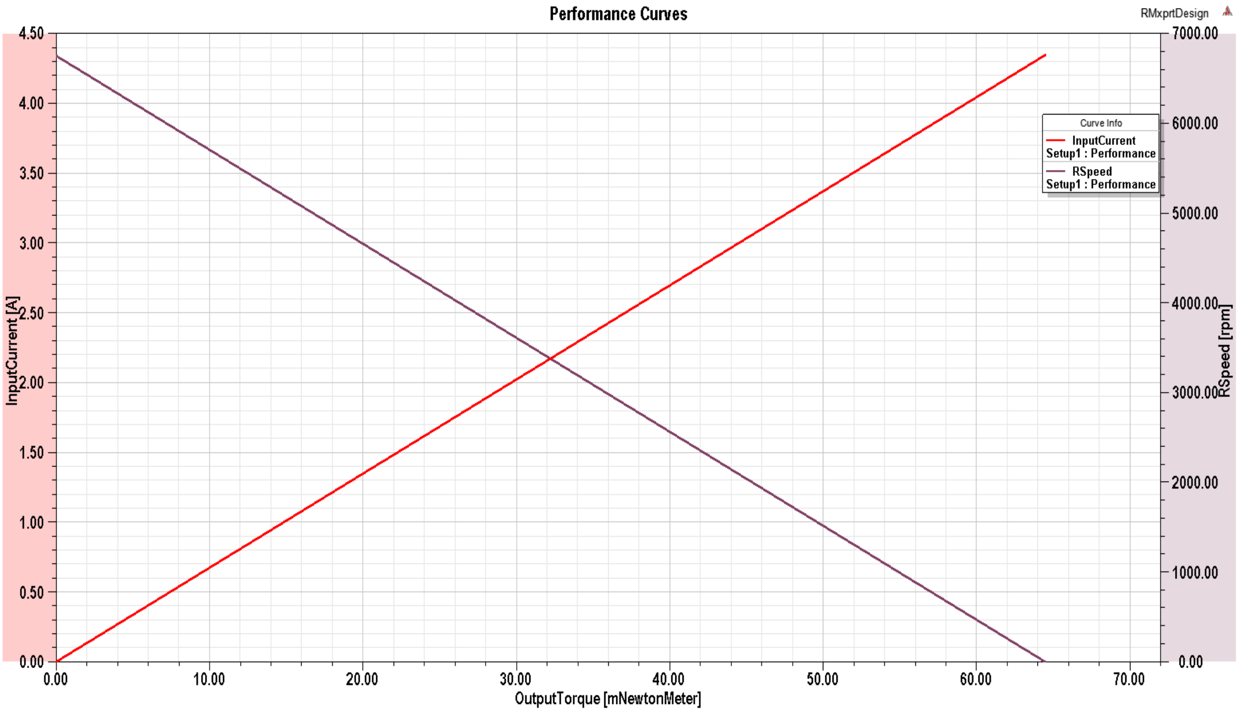


Figure A3 Performance curve with brush shift at 20°

Appendix B

Figure B1 Experimental setup at test bench with tachometer and oscilloscope probes

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[-]* Indicates the author did not cite the mentioned reference directly, but was instead used to develop general understanding of the topic and provide an additional source of information for the reader.

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