Chapter 7 – Electromagnetic Principles Applied to Motors.

7.1 Introduction

In this chapter, we will be looking at a few types a motors and we will also show how they can be controlled by circuits formed by transistors, power supplies and associated control signals.

We hope to provide you with a clear, qualitative, understanding of the motors (and generators). Knowing how these machines actually work qualitatively will help you to cope with more advanced study of electrical machines in future.

You might have come across using Fleming's right-hand and left-hand rules to explain generator and motor actions. However, these are rules to aid your memory; they are not fundamental laws (or principles); they do not provide the understanding we seek. Moreover, there is no fun remembering these rules. So, this is the last time you will come across the name Fleming in this chapter.

We will also refrain from mentioning Faraday's Law and Lenz's Law, as far as possible. These laws were derived from observations made by Faraday and Lenz in the many experiments they performed, before human knew the atomic structure of matters. For that reason, they are actually manifestations of the Lorentz Force Law which came later and which we will introduce to you and making sure you know how to apply it. You must believe that you can follow the materials. All we ask from you is to put in the effort, exercise your imagination and ask questions to clarify your doubts.

This chapter is written in the form of tutorial style. You will need to attend the lectures and fill up missing information on the many diagrams and watch short videos to see how the principles we are going to present you can really work! You will discover that you can predict the result correctly even before the videos are run.

7.2 Preliminary Overview of Electrical Machines

Electrical machines can be pictured as consisting of a rotor structure with its magnetic field and a stator structure with its magnetic field. Each of these magnetic field can be pictured as a set of north and south poles. Just as a compass needle tries to align with the earth's magnetic field, the rotor and stator fields attempt to align. Therefore, in a motor, the stator field rotates ahead of the rotor field, pulling on it. Conversely, in a generator, the rotor does the work on the stator.

We need not concern ourselves with the statements made in the above paragraph for the time being. They will become clearer as we proceed further into this chapter.

7.3 Forces and Torques in Magnetic Field Systems

The 2 basic principles resulting in the production of forces (and torques) are

i. interaction between magnetic fields and current-carrying conductors.

ii. alignment of flux lines.

7.4 Discussion on Point (i)

A moving charged particle experiences a force when it travels in a region where there is a magnetic field. The direction and magnitude of the force it experiences is governed by the Lorentz Force Law (part of it only as we are not concerned with forces due to electric fields in the motors and generators that we are dealing with).

Lorentz Force Law (qualitative understanding only)

A charged particle of charge magnitude $+q$ travelling at a velocity $\vec{v}$ in the presence of magnetic field $\vec{B}$ will experience a force $\vec{F}$ as shown in Figure 7.1 . Note that the the operation is a vector multiplication (a.k.a vector cross product).

$$\vec{F} = q\vec{v} \times \vec{B}$$

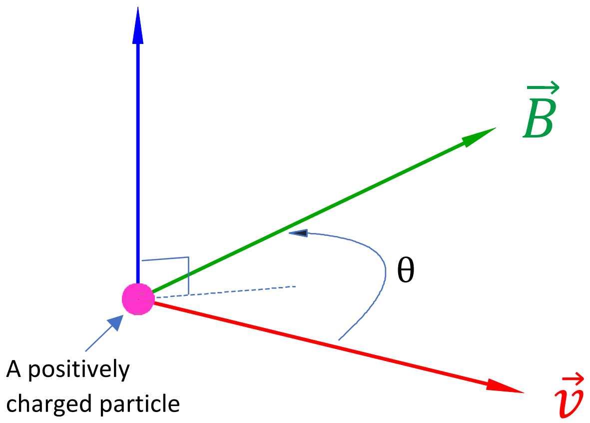


Figure 7.1 – Force on a moving positive charge in the presence of magnetic field.

The direction of $\vec{F}$ is perpendicular to the plane that contains $\vec{v}$ and $\vec{B}$. The lecturer will demonstrate to you how to obtain the direction during the lecture. You may also consult books or youtube (https://www.youtube.com/watch?v=9LTiXFafSZk) on how the perform vector cross product. We concern ourselves with the directions in our discussions to follow. That said, the magnitudes can be calculated by using the following equation.

$$F = qvB\ sin\theta$$

7.4.1 A step by step introduction to motor action.

Determine the direction of the force experienced by the moving charge in the following situations.

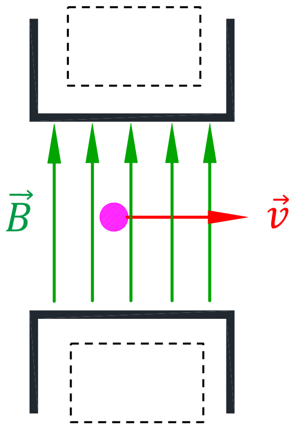


Figure 7.2 - Direction of force is __________ the paper.

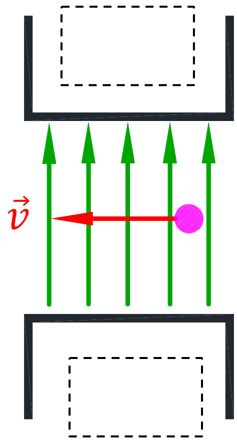


Figure 7.3 - Direction of force is __________ the paper.

Figure 7.4 shows the situation when a train of charges moves in the region of magnetic field. Each of the charges will experience a force into the paper (or into the screen if you are attending lecture).

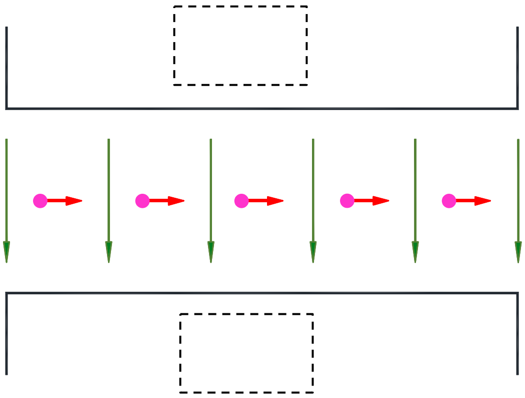


Figure 7.4 - A train of charges moving in a magnetic field.

What if the charges are confined within a stiff rod which is free to move, as shown in Figure 7.5?

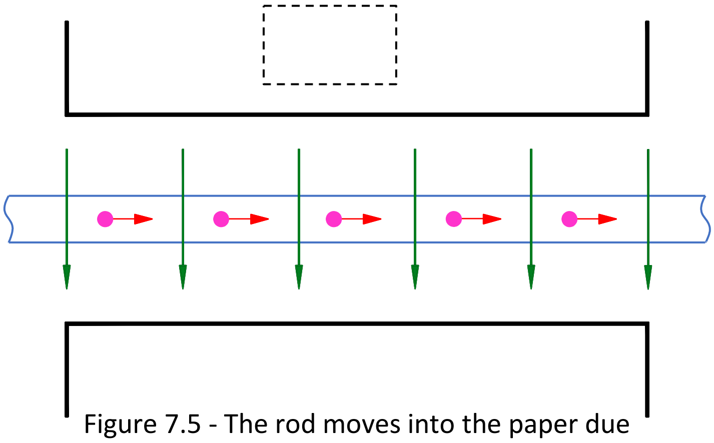


Figure 7.5 - The rod moves into the paper due to the force exerted by the moving charges.

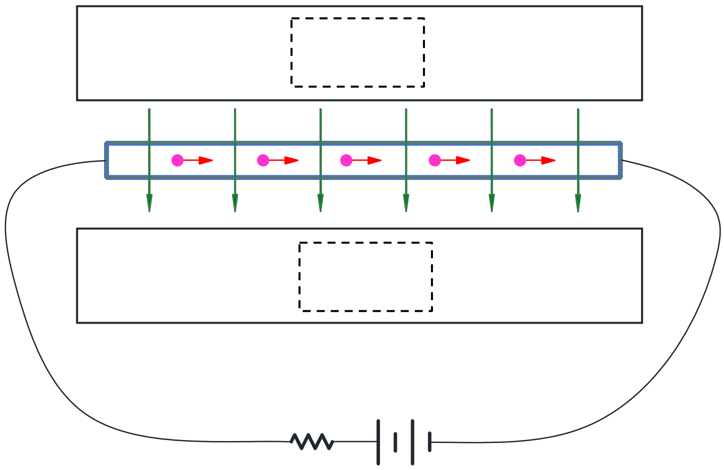


Figure 7.6 - Current flowing in a rod made from electrical conductor.

Figure 7.6 shows one possible arrangement to create the situation in Figure 7.5. This is a simple motor and forms the basis of the various motors which make use of principle (i) stated in section 7.3. It can be shown that the force on the rod is given by the equation

$F = BIL$ where B is the magnetic field density, I, the current magnitude and L, the rod length.

<u>Is that all?</u>

We seem to be getting work done from nothing. Who is doing the work of moving the rod? Is it the magnetic field? or the DC Supply? or the combination of the two?

To answer, let us look at the magnetic field first. According to the law of mechanics, any work done by a force has to be in the direction of the force. As the Lorentz force is always perpendicular to the motion of the charges, there is no work done by the magnetic field. Otherwise, we will just need magnets to produce energy.

So it has to be the DC supply doing the work, but how?

Let us use a little imagination here. As the rod, which carries the charges, 'moves into' the paper, the charges has another velocity component which is in the direction 'into the paper'. In which case, they will experience a force to the left (check it out using Lorentz Force Law). Therefore, for current to continue flowing from left to right, the DC supply has to do the work of continuously pushing the charges to the right. The work done is by electrostatic force from the DC supply (or batteries).

We conclude that in a motor, electrical power is converted to mechanical power.

If we make the current higher (by reducing the resistor value or increasing the DC supply voltage), a larger current will flow. The rod will experience a greater force and moves into the paper faster. This result in larger left-directed forces on the charges which oppose their motion due to the electrostatic forces from the DC supply. This explains the back emf part in the circuit model of a DC motor.

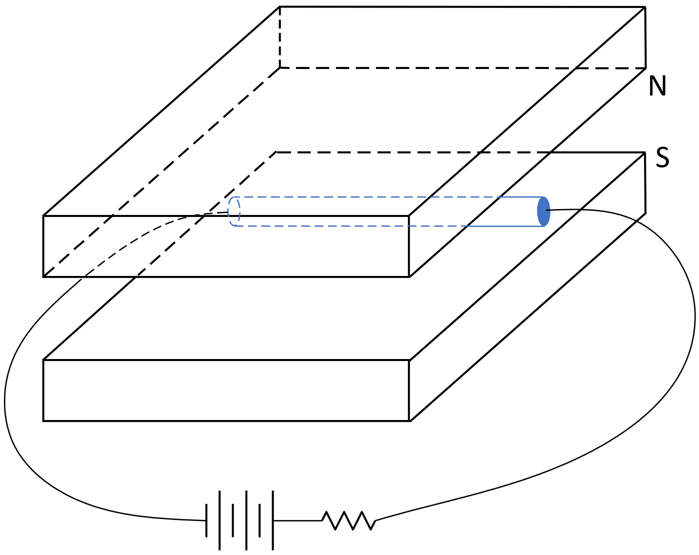


Figure 7.7- Arrangement of a simple linear motor. The mechanical detail is not shown. Obviously, the rod has to rest on a smooth surface, or rails.

Which direction does the rod move in Figure 7.7? ________________

As the rod moves, which end of the rod is more positive? left / right

The link to a video that demonstrates a simple linear DC motor

https://www.youtube.com/watch?v=UT2e_Fy2rM4

You have already learnt enough to be able to tell if the magnetic is pointing upwards or downwards. What is your answer?

7.4.2 DC Motor (practical applications of the principles we discussed so far).

In a rotary DC motor, the same principles apply. The video link below provides a nice introduction to a more practical motor than we have discussed. Now that you have a good grasp of the basic principles presented in the last section, you will find that you are able to predict the direction of rotation confidently even before it is shown.

https://www.youtube.com/watch?v=LAtPHANEfQo&feature=youtu.be

7.4.3 Generator

We will see how a generator work using the ______________________.

Again, we will use a simplest arrangement. Figure 7.8 is obtained by taking away the wires and the DC supply from Figure 7.7. The rod is moved at a velocity $\vec{v}$ in the direction indicated while the $\vec{B}$ field is pointing down as indicated.

Consider a positive charge q residing inside the rod. This charge is carried by the rod and moves together with the rod. Now apply Lorentz Force Law to this charge.

Will it experience a force? yes / no

If so, in which direction is the force acting on the charge? left / right

The conclusion is that positive charges move to the left (actually, in metallic conductor, the electrons move to the right, leaving the unmovable positive ions on the left end). Therefore, we can tell straightaway the electromotive force generated is positive at the left end.

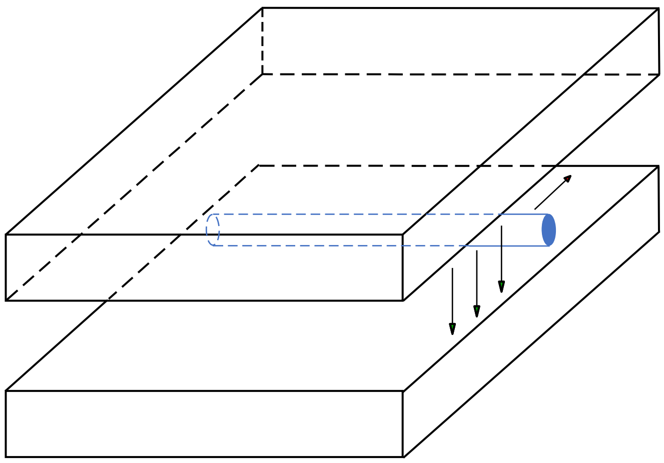


Figure 7.8- Arrangement of a simple linear generator.

If we measure the two ends of the rod with a voltmeter set to DC, we will be able to read a voltage.

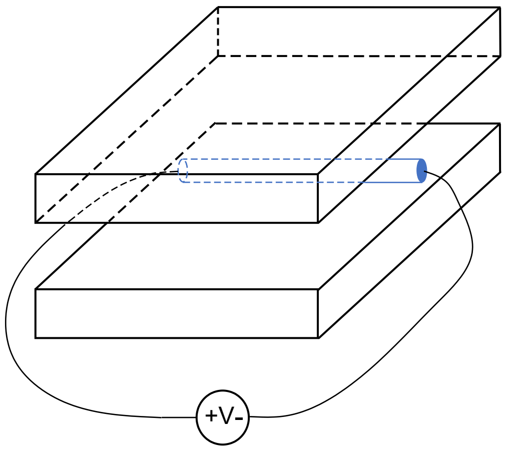


Figure 7.9 – Measuring the emf generated.

If we now connect a resistor to the generator as shown in Figure 7.10, the electromotive force (emf) generated will deliver a current to the resistor. If you series an LED to the resistor, it might lits up. That is, electrical energy has been converted to heat energy and light energy.

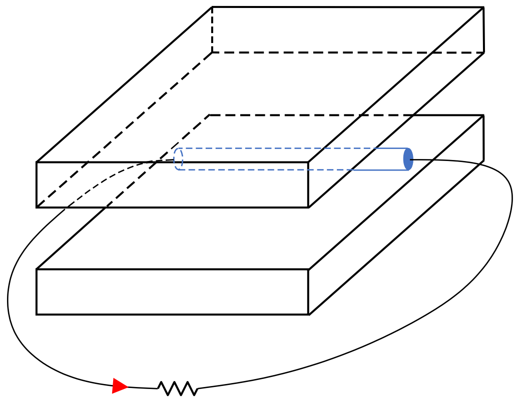


Figure 7.10 – Generator delivers current when the circuit is closed.

<u>Where does the power come from? Who is doing the work?</u>

It seems that by just moving a metallic rod in a magnetic field, one is able to generate electricity. So you may be led to think that making the rod light and slide it on a smooth surface against very low friction, you can generate electricity without much effort. If you has some engineering sense, you should suspect this claim.

How to refute this idea that something cannot be coming from nothing? By now you should be able to guess the answer; use _______________ Law.

An opposing force to original backward motion of the rod.

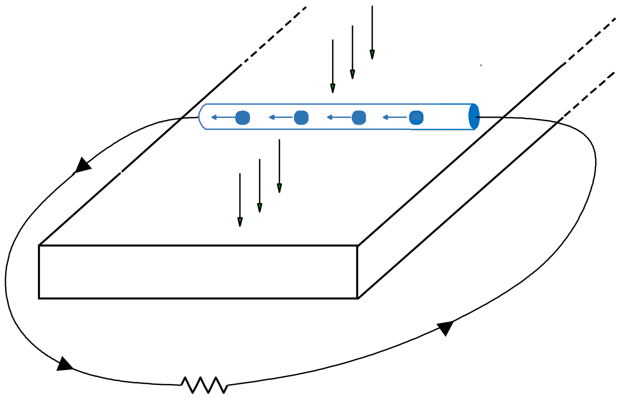


Figure 7.11 – Charges moving inside the rod that constitutes the current experience another force component directed against the direction in which the rod is moved.

The upper magnet pole of Figure 7.10 has been removed in Figure 7.11 for clarity. As the charges move inside the rod, they experience another force component which cause them to move forward. However, they are confined to the rod. As a result these charges will push against the surface of the rod, in the forward direction. That is, the rod is resisting the original force that is moving it backwards.

So, you have to put in more force (and therefore doing more work) to move the rod backward when current starts to flow. The higher the current, the higher is the opposing force. The higher the opposing force, the more mechanical work one has to put in if the current is to be maintained.

We conclude that in a generator, mechanical work done is used to produce electricity.

A youtube video link on DC Generator:

https://www.youtube.com/watch?v=mq2zjmS8UMI

Concluding remarks on point (i) principles.

If you haven't yet noticed, it is quite amazing that forces derived from moving charges in magnetic fields are all there is in DC machines. The qualitative understanding you have now will enable you to answer question such as “Is it possible to construct an electrical generator without copper wires?” In principle you can. Magneto plasma-dynamic generators where ionised gaseous material and plasma are used as conductors is one example.

We will see how electronic circuits can be used to drive DC motors in the next section.

However, not all electrical motors work on principle (i) - force derived from moving charges in a magnetic field. Stepper motor is one good example, it works on principle (ii) – alignment of flux lines. We will discuss stepper motors in a later section.

7.5 DC Motor Drives System

The drive controller converts an AC or DC voltage to an adjustable DC voltage that is then applied to the DC motor armature. Regulation characteristics of the controller allow the motor to run at the desired speed set by reference input. Additional circuits can help protect the controller, motor and driven machine from the line voltage transients, overloads and various circuit faults.

The DC motor converts the adjustable voltage DC from the drive controller to rotating mechanical energy. Motor shaft rotation and direction are proportional to the magnitude and polarity of adjustable voltage applied to the motor. Normally, the motor shaft is coupled to a gear reducer or other transmission device that is then coupled to the driven machine.

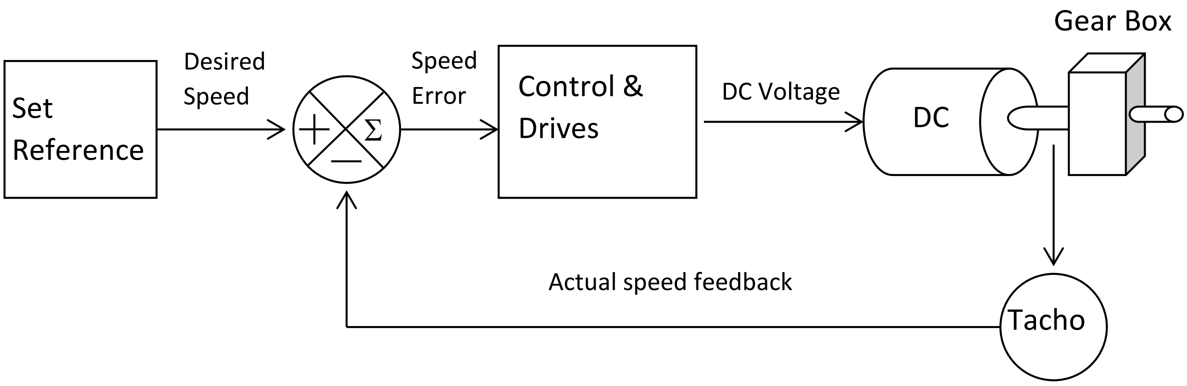


Figure 7.12 – DC Drive Control System

The DC motor in a typical drive control system can be of the shunt wound or permanent magnet type. In adjustable speed DC drive applications the motor armature is connected to an adjustable voltage supply. The motor field (if not of the permanent magnet type) is connected to either a fixed or adjustable voltage supply.

The tachometer-generator (feedback device) converts actual speed to an electrical signal that is summed with the desired reference signal. The output of the summing junction provides an error signal to the controller and a speed correction is made.

7.6 Model of DC Motor operating under steady-state

When the mechanical load of a motor changes or when the voltage source driving the motor changes, the speed of the motor will change (assume there is no closed-loop a.k.a. feedback control). How the speed changes is conveyed in the form of steady-state characteristics, which indicate how the motor behaves when the transients due to the above factors have passed and the motor is once again become steady in a new speed.

Fortunately, the steady-state operation of a DC motor can be predicted using a simple model (a.k.a. equivalent circuit) shown in Figure 7.13.

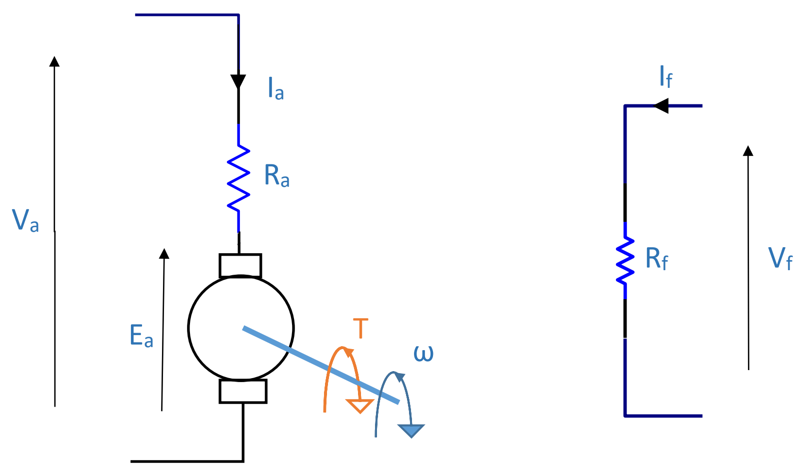


Figure 7.13

Name of Symbols

V_a Armature voltage

E_a Back emf

I_a Armature current

R_a Armature resistance

T Torque developed (Nm)

ω Angular speed (rad/s or rads^{-1})

V_f Field voltage

I_f Field current

R_f Field coil resistance

Circuit equations

From Figure 7.13, the following basic equations can be developed.

$V_a = I_a R_a + E_a$ & $I_f = {}^{V_f}/_{R_f}$

Fundamental relations

$E_a = K_e \omega$ where K_e is called the emf constant and is given in Volts per rads^{-1} (V/rads^{-1}).

$T = K_t I_a$ where k_t is called the torque constant and is given in Nm per Ampere (Nm/A).

k_e and k_t have the same numerical values (only when they are expressed in the units given above).

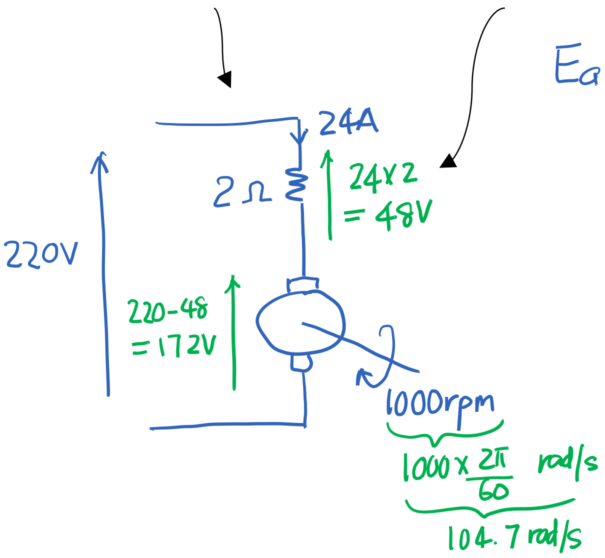
You may relish on the fact that these 2 simple equations and 2 relations allow us to predict all aspects of behaviour of a DC motor when it is running in steady-state. The only thing that can give you trouble is that rotational speed is often expressed in revolution per minute (rpm) which use the symbol N, rather than in ω.

Example 7-1

What can you do with just the following statement about a DC motor? (That is, what can you infer from the statement?)

"A separately excited DC motor is rated at 220 V, 24 A, 1000 rpm with an armature resistance of 2 Ω."

Answer: I will sketch the equivalent circuit, fill in the information and proceed to work on the circuit. (The circuit is drawn and information provided in the problem statement are in done in BLUE). Working out in GREEN.



$E_a = k_e \omega \Rightarrow k_e = \dfrac{172\,V}{104.7\ rad/s}$

$= 1.64\ V/rad/s$

$\Rightarrow k_t = 1.64\ Nm/A$

Rated torque $T = k_t I_a$

$= 1.64 \times 24$

$= 39.4\ Nm$

Rated output power $= T\omega$

$= 39.4 \times 104.7\ W$

$= 4.125\ kW$

7.7 Discussion on Point (ii) of section 7.3 – Alignment of Flux Lines

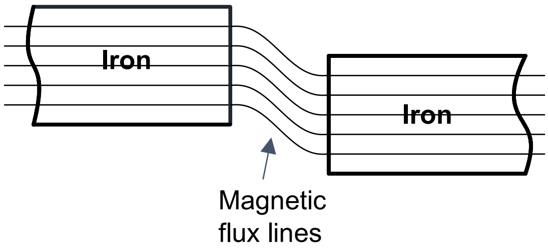


Figure 7.15 – Forces on magnetic material due to Maxwell stress.

A general principle formulated by Maxwell is that forces on magnetic bodies are transmitted across the gap between them by stress in the flux lines. The flux lines can be considered to have an 'elastic band' property, with the tendency to shorten lengthwise. Thus, in Figure 7.15, the iron pieces experience a force tending to align them such as to reduce the reluctance of the system, minimising the stored energy in the magnetic field.

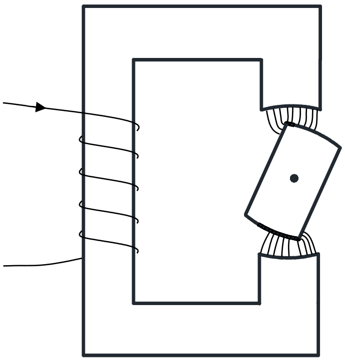


Figure 7.16 – A simple machine to illustrate flux alignment.

Figure 7.16 shows a simple machine with a fixed ferromagnetic core excited by a current in the field winding to produce flux. The magnetic flux are produced by the current in the winding. The rotor will eventually aligned itself to the core due to the torque from the 'stretched elastic' flux lines.

Does it matter if the current is injected in the other direction? Yes / No

The machine shown in Figure 7.16 is not a motor per se as continuous rotation of the rotor is not possible. However, it forms the basis of motors using the flux alignment principle, as shown in the next section.

7.8 Variable-reluctance stepping motor

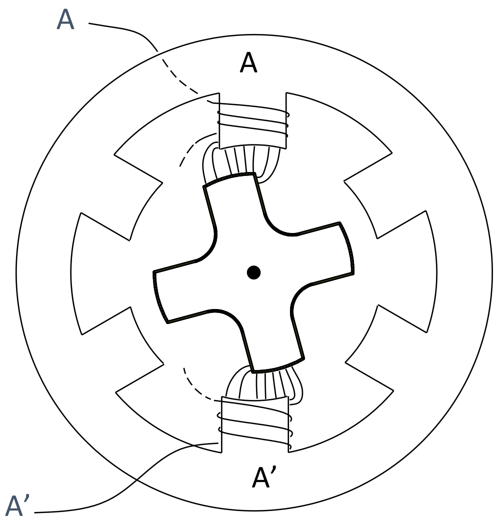


Figure 7.17 – Variable-reluctance stepping motor.

Figure 7.17 shows a simplified diagram of a variable-reluctance (VR) stepping motor. The stator is made from a stack of steel laminations, and has 6 equally spaced projecting poles, each carrying a separate winding. Winding A-A' is shown in Figure 7.17, windings B-B' and C-C' are not shown, making up 3 phases in the stator.

The rotor, which may be solid or laminated, has 4 projecting teeth, of the same width as the stator teeth. There is a very small air-gap (typically 0.2 mm or less) between the rotor and the stator teeth. When there is no current in all the 3 phases, the rotor will be free to rotate.

When phase A is energised, the rotor will aligned itself to the phase A poles as shown in Figure 7.18. One of the teeth of the rotor is highlighted in the diagram so that its movement can be tracked.

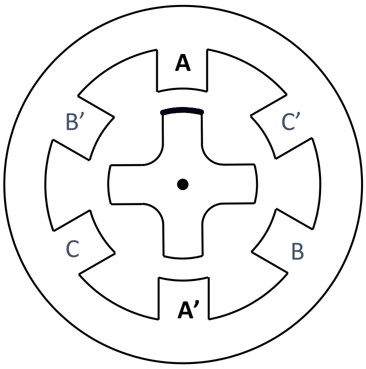


Figure 7.18 – Phase A is energised.

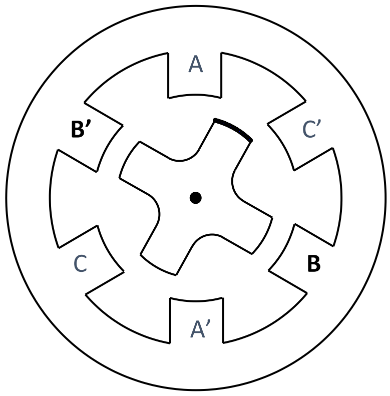


Figure 7.19 – Phase B is energised.
Phase A switched-off

In Figure 7.19, when phase A is switched-off, and phase B is switched-on instead, the second pair of rotor poles will be pulled into alignment with the stator poles of phase B. The step angle is 30° in the clockwise direction.

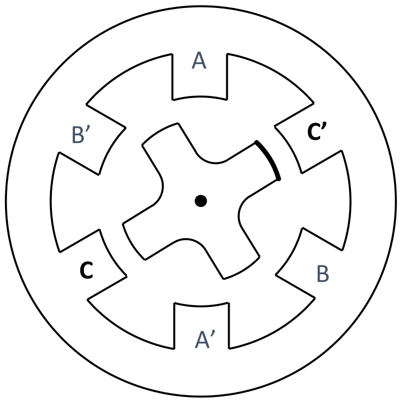


Figure 7.20 – Phase C is energised. Phase B switched-off.

The rotor rotates another 30° clockwise when phase B is switched-off, and phase C is switched-on. At this stage, the highlighted pole pair is aligned again to the stator, but this time they are aligned to phase C stator poles, as shown in Figure 7.20.

By repetitively switching on the stator phases in the sequence ABCA… , the rotor will rotate clockwise in 30° steps.

If the switching sequence is changed to ACBA… , the rotor will rotate anticlockwise.

This mode of operation is known as 'one-phase-on', and is the simplest way of making the motor step. Note that the direction of the energising current does not affect the operation as the rotor will aligned equally well regardless of the direction of current. That is, regardless of whether a particular pole is north or south.

'one-phase on' mode does not make use of the magnetic core effectively as 2 pairs of stator poles are inactive at any time. This is a waste of the magnetic material. A better alternative is the '2-phase on' mode. In this mode, AC-CB-BA-AC-….. sequence will again cause the rotor to rotate clockwise in 30^o steps. The rotor will experience higher torque in this mode as there are 2 phases 'pulling' at rotor poles. The alignment force is not doubled, however, as the alignment forces from the 2 poles are at an angle (15^o in this case) to the rotor poles.

There is also a half-step mode if AC-C-CB-B-BA-A-AC-…. sequence is employed. In this case, the rotor steps at 15^o. The drawback for this mode is the alignment forces are not uniform in each step.

We will see how electronic circuits can be used to drive this stepper motor in the next section.

Video on Variable Reluctance (VR) stepper motor (the 2nd part of the video explains the hybrid stepper motor which is not discussed in this module).

https://www.youtube.com/watch?v=eyqwLiowZiU