Basics of DC Machines

By Kiran Daware

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Chapter 1

Basics of DC Machines

1.1 Introduction:

Around 1820, Hans Christian Oersted discovered the generation of magnetic field around a current carrying conductor by observing the deflection of a compass needle. This was the first known mechanical movement due to electricity, which further led to the invention of electric motors. About a decade later, Michael Faraday discovered that electric current is generated whenever a conductor is placed in a varying magnetic field. This discovery became the foundation for the development of electric generators. The era of electrical machines started with the inventions of DC motors and DC generators.

A DC motor is an electrical machine which converts DC electrical energy into rotational mechanical energy. That is when a DC electric current is given to a DC motor, its shaft rotates. On the other hand, when the shaft of a DC generator rotates, an electric current is induced in the conductors of the generator. The fact is, a DC motor can also act as a DC generator when its shaft is rotated and vice versa. Therefore, **DC motors and DC generators can be collectively termed as DC machines**. In this module, you will learn about the construction and working principle of DC machines.

1.2 Construction of a DC machine:

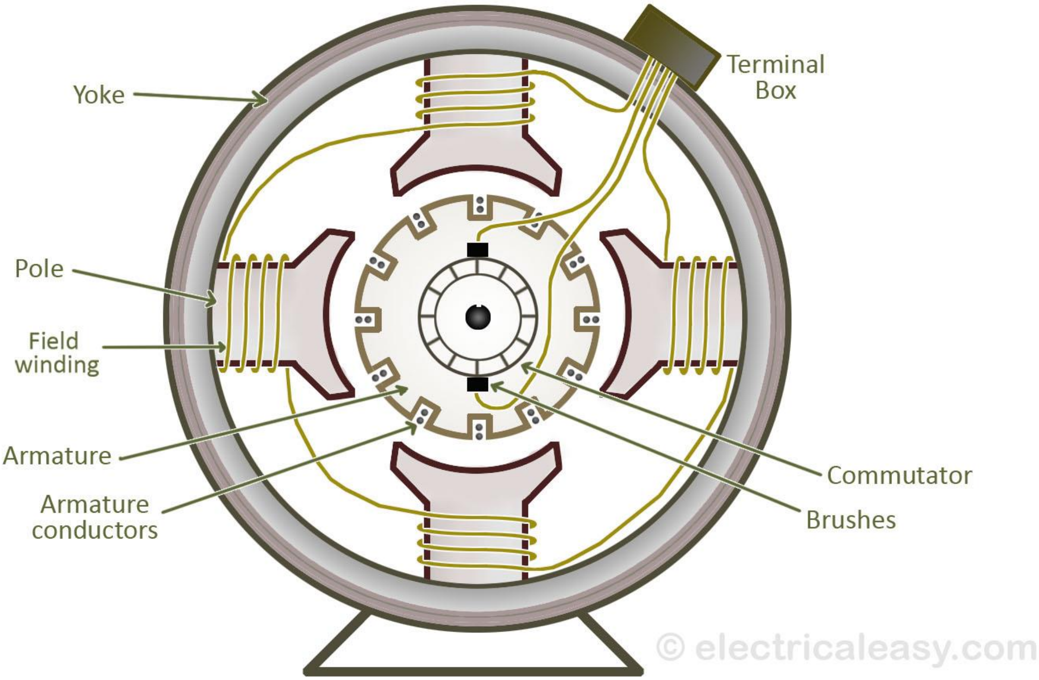


Figure 1.1 Construction of a DC Machine

Figure 1.1 shows constructional details of a simple 4 pole DC machine. The assembly consists of a stator and a rotor. Basic components of a DC machine are briefly explained below.

Figure 1.2 Stator of a DC machine

- **Yoke:** The outer frame of a DC machine is called as a yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly, but also carries the magnetic flux produced by the field winding.

- **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in the air gap uniformly.

- **Field winding:** They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

- **Armature Core:** Armature core is the rotor of the machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. The armature is keyed to the shaft.

- **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils. Both, lap and wave winding, are explained in a later chapter.

- **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a DC generator, is to collect the current generated in armature

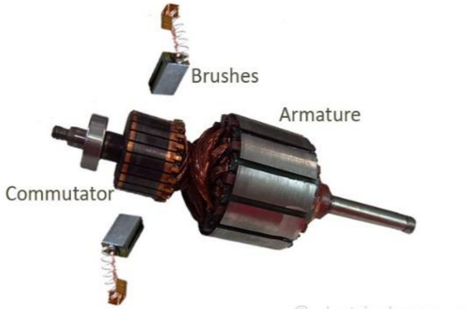


Figure 1.3

conductors. Whereas, in case of a DC motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other by mica insulation. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

1.3 Working principle of a DC Generator

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. And if the conductor is provided with the closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of the induced current is given by Fleming's right hand rule.

Fleming's right hand rule: *The thumb, first finger and second finger of the right hand are held perpendicular to each other. If the thumb is pointed in the direction of motion of the conductor and the first finger is pointed in the direction of the magnetic field (north to south), the second finger represents the direction of induced current.*

1.4 Need of the split ring commutator:

According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor on the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating.

If you look at the figure 1.4, you will know how the direction of the induced current is alternating in an armature conductor. But with a split

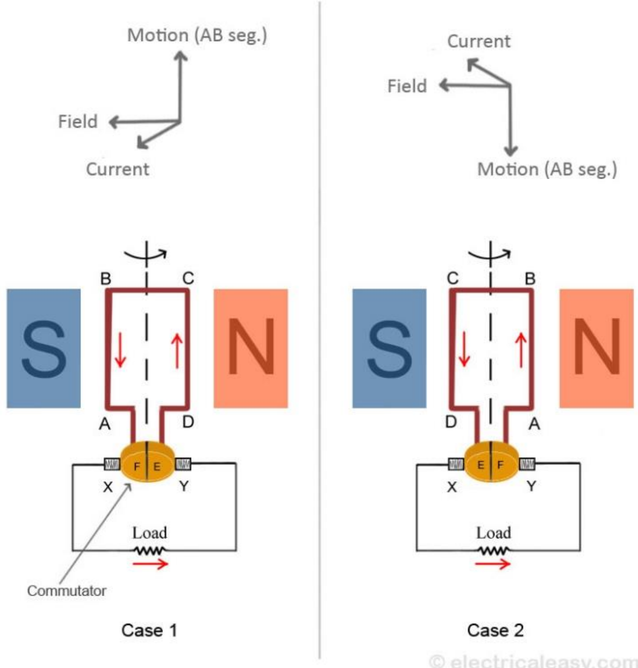


Figure 1.4

ring commutator, connections of the armature conductors also get reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

1.5 Working principle of a DC Motor:

"Whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force." The magnitude of this force is given as; $F=BIL$, where B = Magnetic flux density, I = Current, L = length of the conductor within the magnetic field. The direction of this force experienced by the conductor is given by Fleming's left hand rule.

Fleming's left hand rule: *The thumb, first finger and second finger of the right hand are held perpendicular to each other. If the first finger is pointed in the direction of the magnetic field and the second finger is pointed in the direction of the current, then the thumb represents the direction of force experienced by the conductor.*

Figure 1.5 helps in understanding the working principle of DC motor. When the armature winding is connected across a DC supply, a current set up in the winding. The magnetic field may be provided by energizing field coils or by using permanent magnets. In the presence of magnetic field, current carrying armature conductors experience force in opposite directions at the opposite sides. Hence, a torque is experienced by the armature which causes the armature to rotate.

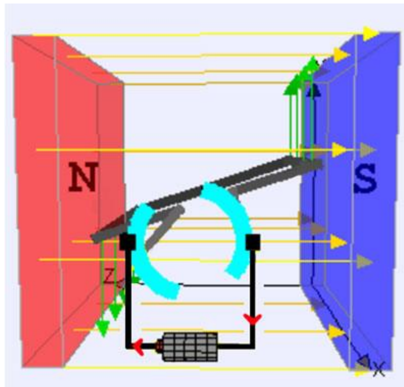


Figure 1.5

A split ring commutator is necessary to achieve unidirectional torque (just like it helps in achieving unidirectional current in DC generators).

1.6 Back EMF:

According to the fundamental laws of nature, no energy conversion is possible until there is something to oppose the conversion. In case of generators, this opposition is provided by magnetic drag and in case of DC motors, there is back emf (Eb).

When the armature of the motor is rotating, the armature conductors also cut the magnetic flux lines. Due to this, generation action occurs. Hence, an electrodynamically induced emf is

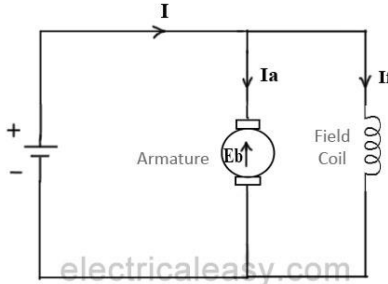


Figure 1.6

generated in the conductors which is opposite to the direction of the provided armature current.

The applied voltage has to force the current through the armature conductors against back emf. Under normal running conditions, back emf (Eb) is always less than the applied voltage (V). Due to the presence of back emf, the net voltage across the armature circuit is given as:

V = Eb + Ia.Ra

(Where, V = applied voltage, Eb = Back emf, Ia = armature current, Ra = armature resistance.)

Significance of back emf:

Magnitude of back emf is directly proportional to speed of the motor. Consider the load on a DC motor is suddenly reduced. In this case, required torque will be small as compared to the current torque. Speed of the motor will start increasing due to the excess torque. Hence, being proportional to the speed, magnitude of the back emf will also increase. With increasing back emf armature current will start decreasing. Torque is proportional to the armature current, it will also decrease until it becomes sufficient for the load. Thus, the speed of the motor will regulate.

On the other hand, if a DC motor is suddenly loaded, the load will cause decrease in the speed. Due to decrease in speed, back emf will also decrease, allowing more armature current. Increased armature current will increase the torque to satisfy the load requirement. Hence, the presence of the back emf makes a DC motor 'self-regulating'.

1.7 Classification of DC Machines:

DC machines are usually classified on the basis of their field excitation method. This makes two broad categories of dc machines; (i) Separately excited and (ii) Self-excited.

- **Separately excited:** In separately excited dc machines, field winding is supplied from a separate power source. That is, field winding is electrically separated from the armature circuit. This type of dc machines is not commonly used.

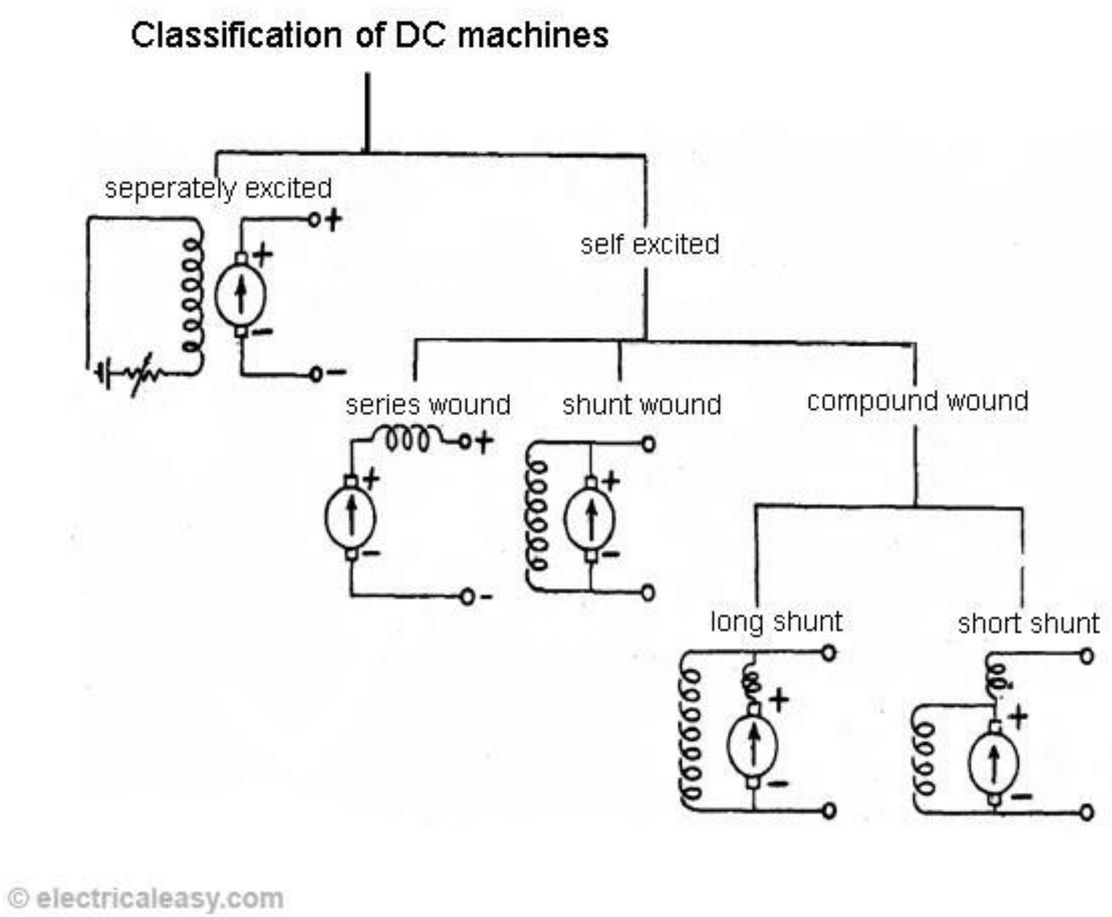


Figure 1.7 Classification of DC machines

- **Self excited:** In this type, field winding and armature winding are interconnected in various ways to achieve wide range of performance characteristics. Depending on that, self-excited machines can be further classified as –

    - Series wound – In this type, field winding is connected in series with the armature winding. Therefore, the field winding carries whole load current (armature current). That is why series winding is designed with few turns of thick wire and the resistance is kept very low (about 0.5 Ohm).

    - Shunt wound – Here, field winding is connected in parallel with the armature winding. Shunt winding is made with large number of turns and the resistance is kept very high (about 100 Ohm). It takes only small current which is less than 5% of the rated armature current.

    - Compound wound – In this type, there are two sets of field winding. One is connected in series and the other is connected in parallel with the armature winding. Compound wound machines are further divided as
        - Short shunt – field winding is connected in parallel with only the armature winding
        - Long shunt – field winding is connected in parallel with the combination of series field winding and armature winding

1.8 Armature winding:

To learn how practical armatures are wound, it is essential to know the following terminologies –

- **Pole pitch:** It is defined as the number of armature slots per pole. For example, if there are 36 armature slots and 4 poles, the pole pitch will be 36/4=9.

- **Coil:** A coil has two sides which rest in distinct armature slots. A coil may be single turn or multi-turn coil. A single turn coil has only one conductor per coil side but a multi-turn coil may have many conductors per coil side. All the coils are connected in series and the junctions of consecutive coils are terminated on the respective commutator segments.

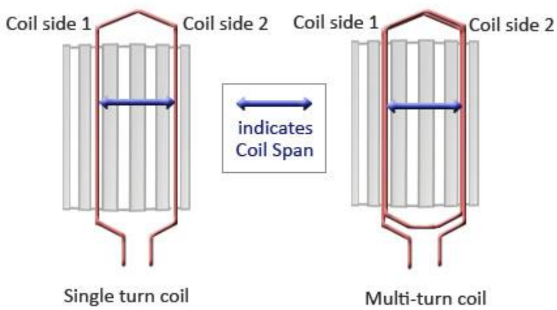
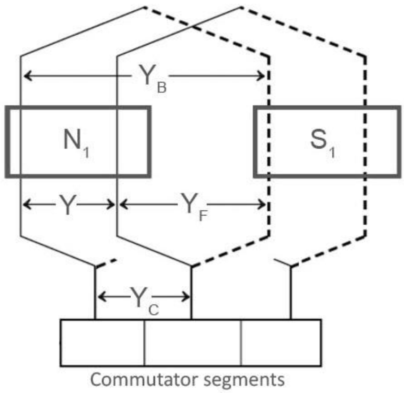


Figure 1.8

- **Coil span:** It is nothing but the spacing between the two coil sides in terms of the number of armature slots. If coil span is equal to the pole pitch, then the winding is called to be full pitched. In this case, the coil sides lie exactly under the opposite poles and maximum emf is induced in the coil. Example - for a full pitched coil with coil span of 9, if one coil side is placed in slot no. 3 then the other coil side must be placed in slot no. 12. If the coil span is less than the pole pitch, then the winding is called to be fractional pitched. In this case, the net emf generated in the coil is less than that would be in a full pitched coil. This is due to the phase difference between the generated emfs in the two coil sides. Still, fractional pitch windings may be sometimes used for substantial saving in copper at the end connections and for improving commutation.

- **Winding pitch (Y):** It is the distance between the beginnings of two consecutive coils measured in terms of armature conductors.



Lap Winding

Figure 1.9

- **Back pitch (Y_B):** Back pitch is defined as the distance by which a coil advances on the back of the armature. It is measured in terms of armature conductors.

- **Front pitch (Y_F):** It is defined as the distance, measured in terms of armature conductors, between the second conductor of one coil and the first conductor of the next coil. OR it is the distance between the two coil sides that are connected to the same commutator segment.
- **Commutator pitch (Y_C):** It is the distance between the two commutator segments to which the two end of the same coil are connected. It is measured in terms of commutator segments.

- **Single layer and double layer winding:** When only one conductor or coil side is placed in an armature slot then the winding is called single layer winding. It is not very commonly used. On the other hand, in double layer winding, each armature slot carries two conductors forming two layers of winding. One coil side lies in the upper layer while the other coil side of the same coil lies in the lower layer in a different armature slot.

- **Simplex and multiplex winding:** If there is only one set of closed winding, then the winding is called as simplex winding. If there are two sets of closed winding then it is called as duplex winding and so on.

Lap winding:

A type of armature winding in which successive coils overlap each other is called as lap winding. For a simplex lap winding, the commutator pitch is 1. That means, the two ends of a coil are connected to adjacent commutator segments. For a duplex lap winding, commutator pitch is 2. The winding may be progressive or retrogressive. A progressive winding progresses in the direction in which the coil is wound. The opposite way is retrogressive.

In simplex lap winding, number of parallel paths is equal to the number of poles. When brushes of the same polarity are connected together, then the current flowing paths between the opposite brushes are called as parallel paths.

Wave winding:

In wave winding, the end of one coil is connected to the beginning of a coil which lie under the same polarity of field pole as that of the first coil. In other words, all the coils which carry emf in the same direction at a time are connected in series. Hence, a simplex wave winding makes only two parallel paths.

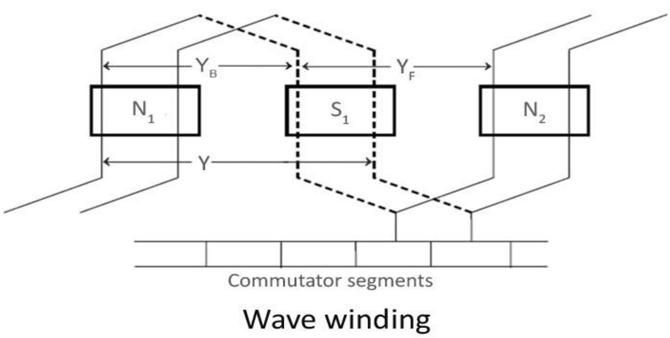


Figure 1.10

Brush positions:

The brush positions can be determined by finding the direction of induced emf in the various armature conductors. By applying the Fleming's right hand rule, the direction of induced emf in any conductor can be found. A positive brush is placed on a commutator segment at which direction of induced emf in both the terminated conductors is positive. Whereas, a negative brush is placed where direction of induced emf in both the terminated conductors in negative.

Dummy coils:

For obtaining specific performance characteristics of the machine, each machine has to be designed with the specific type of winding and with the specific number of armature conductors. Sometimes, an armature may not be available with the number of slots according the design requirements. In such cases, an armature with more slots is taken and the winding is placed, according to the requirement, omitting few armature slots. But, this will disturb the mechanical balance of the armature and make the machine unstable while running. Dummy coils are placed in the empty slots to provide mechanical balance to the armature. They are just like the other armature coils, except that they are not connected to any commutator segments. Dummy coils are electrically insulated from the armature circuit.

1.9 EMF equation and Torque equation:

In a DC machine, regardless of a motor or generator, generation of emf and torque occur at the same time. For example, in a DC motor, there will be induced voltage in the form of back emf in the armature conductors when the motor is running. The same emf equation can be used to calculate the generated emf in a dc generator and back emf in dc motor. In the same way, the same torque equation can be used to calculate the electromagnetic torque developed in a dc motor and a dc generator.

EMF equation:

Let us assume a dc generator, in which –

P = number of field poles
Z = total number of armature conductors
ϕ = flux produced per pole (in Wb)
A = number of parallel paths in the armature
N = rotational speed of the armature (in RPM)

Now,

Average emf generated per conductor is given by $\frac{d\Phi}{dt}$ (Volts) ...(eq. 1)

Flux cut by one conductor in one revolution = $d\Phi = P\Phi$ ....(Weber),

Number of revolutions per second = N/60

Therefore, time for one revolution = $dt = 60/N$ (Seconds)

Therefore,

from eq. 1, emf generated per conductor = $\frac{d\Phi}{dt} = \frac{P\Phi N}{60}$ (Volts)...(eq. 2)

The net generated emf across the generator terminals is the emf generated in any one of the parallel paths. Eq. 2 gives the emf generated in one conductor only and all the conductors are connected in series forming the parallel paths.

Hence, the net generated emf across the armature terminals (Eg) is given as –

$$Eg = \frac{P\Phi N}{60}\frac{Z}{A} \quad \text{(Volts)}$$

- For a simplex lap wound generator, number of parallel paths is equal to the number of poles. Therefore, $Eg = \frac{P\Phi N}{60}\frac{Z}{P}$
- For a simplex wave wound generator, there are only two parallel paths. Therefore, $Eg = \frac{P\Phi NZ}{120}$

Torque equation:

Whenever the armature conductors carry current in presence of the field flux, they experience a force. But the force is opposite in direction at the opposite sides of the armature, which gives rise to electromagnetic torque. Torque is given by the product of the force and the radius at which this force acts.

Torque T = F × r (N-m) ….where, F = force and r = radius of the armature.

Work done by this force in once revolution,

Work done = Force × distance = F × 2πr (2πr = circumference of the armature).

Net power developed in the armature

$$= \frac{work\ done}{time} = \frac{force \times \text{circumference} \times no.\ of\ revolutions}{time} = \frac{F \times 2\pi r \times N}{60} \quad \text{(Joules per second)}$$

But, F × r = T and 2πN/60 = angular velocity ω in radians per second.

Rearranging the above equation, the net power developed P = T × ω (Joules per second)

Armature torque:

Let, the torque developed in the armature be denoted as Ta.

Then the power developed in the armature Pa = Ta × ω = Ta × 2πN/60

We know, the power developed in the armature is actually converted from the electrical power.

That is, mechanical power = electrical power

$$Ta \times 2\pi N/60 = Eb.Ia$$

Eb is the back emf generated in the armature and it is calculated from the same emf equation as that of dc generators. Therefore, $Eb = \frac{P\Phi N}{60}\frac{Z}{A}$

Therefore, $Ta \times 2\pi N/60 = \frac{P\Phi N}{60}\frac{Z}{A} \times Ia$

$$Ta = \frac{PZ}{2\pi A} \times \Phi . Ia \quad \text{(N-m)}$$

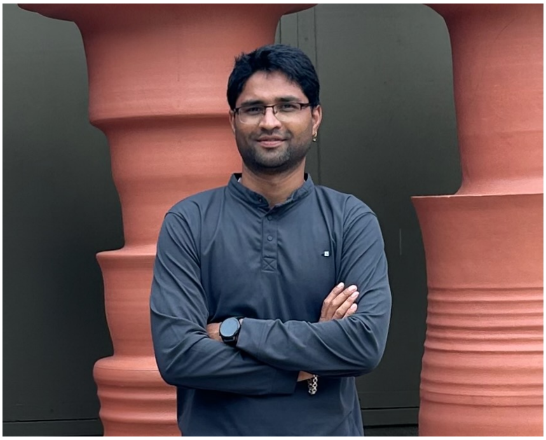
In the above equation, $\frac{PZ}{2\pi A}$ is practically constant for a DC machine. Therefore, armature torque is directly proportional to the product of the flux and the armature current. i.e. Ta ∝ $\Phi . Ia$

Shaft torque:

The total developed armature torque is not available at the shaft. Due to iron and friction losses in the machine, some of the armature torque is lost and hence, the shaft torque is always less than the armature torque. Unlike armature torque, the shaft torque is calculated from the output power available at the shaft. It is denoted by Tsh.

$$Tsh = \frac{Output\ in\ watts}{2\pi N/60} \quad \text{(N-m)}$$

About the Author



Hi, I'm Kiran Daware. I hold a Bachelor's degree in Electrical Engineering from Shivaji University, Kolhapur, India. I am the founder of electricaleasy.com - a popular technical blog for electrical engineering students. I write to simplify complex electrical concepts, helping students understand the basics in easy and practical terms. My goal is to make learning electrical engineering an enjoyable and accessible journey for everyone.

Apart from electrical engineering, I'm also exploring various other fields that interest me. To learn more about me and my journey, feel free to visit my personal portfolio at dkiran.net.