Experiment No: 4

Characteristics of Separately Excited DC motor

1 Aim

To study the variation of speed with
• Armature Voltage
• Field Current
and to obtain the performance characteristics (T-ω) of a separately excited (S.E.) DC motor.

2 Theory

2.1 Basic Theory of Electromagnetic Power Conversion:

Electric machines convert electrical energy to mechanical energy and vice-versa, as shown in Fig.1. In the motoring mode, the electric power is converted into mechanical work. All the machines have a stationary part called the stator and a rotating part, called a rotor. They are separated by an air gap thus allowing the rotor to rotate freely on its shaft, supported by bearings. The stator is firmly fixed to a foundation to prevent it from turning. Both stator and rotor are made up of high permeability ferromagnetic material and the length of the air gap (is of the order of 0.5-1mm) is kept as small as possible so that the ampere turns required to establish the flux crossing the airgap as shown in fig. 2 is very small. If rotor and stator are perfectly round, the air gap is uniform and the magnetic reluctance (similar to resistance in electric circuits) in the path of flux lines crossing the air gap is uniform. Machines with such structures are called non-salient pole machines (Fig.2 a). Sometimes, the machines are purposely designed to have saliency so that the magnetic reluctance is unequal along various paths as shown in Fig.2(b). Such saliency results in what is called, the 'reluctance torque', which may be the primary or a significant means of producing torque. You should also note that to reduce eddy-current losses, the stator and rotor are constructed by laminations of silicon steel (these sheets are insulated from each other by a layer of thin varnish). These laminations are stacked together, perpendicular to the shaft axis. Slots may be cut into these laminations to place the conductors.
There are two basic principles that govern the operation of electric machines:
• A current carrying conductor placed in a magnetic field experiences a force.
• A voltage is induced in the conductor moving in a magnetic field.
Consider a conductor of length L meters shown in fig.3 (a) which is carrying a current 'i' Amperes and is subjected to an externally established magnetic field of a uniform flux density B wb/m^2 in perpendicular to the conductor length. A force 'F' is exerted on the conductor. The magnitude of this force is given by F = B I L Nm. The direction of the force is perpendicular to the directions of both 'I' and 'B'. The direction of this force can be obtained by superimposing the flux lines due to the conductor current as shown in Fig. 3 (b). The flux lines add up on the right side of the conductor and subtract on the left side as shown in Fig.3(c). Therefore, the force 'F' acts from higher concentration of flux lines to the lower concentration, i.e, from right to left.
In the fig. 4, conductor of length L meters is moving to the right at a speed V meters/sec. The B field is uniform and is perpendicular, into the plane of paper. The magnitude of induced emf is Volts is given by e= B L V. The polarity of the induced emf can be established as follows: Due to the conductor motion, the force on the charges within the conductor can be written as f=q(V X B). Due to orthogonality of V and B, the force on the positive charge is upward. Thus, the upper end will have a positive potential with respect to the lower end.

Now, consider two bar magnets pivoted at their center on the same shaft. There will be a torque, proportional to the angular displacement of the bar magnets, which will act to align them. This physical picture is useful in analysing the torque production in machines.

Currents in the machine windings create magnetic flux in the air gap between the stator and rotor. The flux path gets completed through the stator and rotor iron. This condition corresponds to the appearance of magnetic poles on both the stator and the rotor, centered on their respective magnetic axis as shown in Fig.5. Torque is produced by the tendency of these two magnetic fields to align. The resulting torque is proportional to the product of the amplitudes of the stator mmf (F_s) and rotor mmf (F_r), and sine of the angle δ_{sr} measured from the axis of stator mmf wave to that of the rotor. Therefore the generalized expression for torque is given by

$$T_e \propto F_s \;\; F_r \;\; \sin\delta_{sr} \tag{1}$$

In a typical machine most of the flux produced by the stator and rotor windings crosses the air gap and links both windings. This flux is termed the mutual flux, directly analogous to the mutual or magnetizing flux in a transformer. However, some of the flux produced by the rotor and stator windings does not cross the air gap. This is analogous to the leakage flux in a transformer. Only the mutual flux is of direct concern in torque production (the leakage fluxes do affect machine performance). From Fig 5(b), we can also write $F_s \;\; \sin\delta_{sr} = F_{sr} \;\; \sin\delta_r$ and $F_r \;\; \sin\delta_{sr} = F_{sr} \;\; \sin\delta_s$. Substituting these values in equ.(1), the generalized expression for torque can also be written as

$$T_e \propto F_{sr}\, F_r \; \sin\delta_r \quad or \quad T_e \propto F_s\, F_{sr} \; \sin\delta_s \tag{2}$$

A steady torque is developed only when both the fields are stationary with respect to each. **Hence, it can be concluded that the essential condition for the machine to develop steady torque is that stator field and rotor field should be stationary with respect to each other**.

2.2 DC Machine

The stator of a dc machine has projected poles (salient poles) and a coil is wound on these poles as shown in Fig.6 . When excited by dc current air-gap flux distribution created by this winding is symmetric about the center line of the field poles. **The field produced by the stator current is stationary with respect to stator. This axis is called the field axis or direct (d) axis**.

The rotor of dc machine has slots which contain a winding. This winding handles electric power for conversion to (or from) mechanical power at the shaft. In addition, there is a commutator affixed to the rotor. The commutator on its outer surface contains copper segments, which are electrically insulated from each other by means of mica. The coils of the rotor (armature) winding are connected to these commutator segments. A set of **stationary carbon brushes (these brushes are fitted to the stator) are placed on the rotating commutator**. It should be noted that the wear due to mechanical contact between the commutator and the brushes requires regular maintenance, which is the main drawback of these machines.

2.2.1 Principle of Operation of dc Machines:

Consider a two pole dc machine as shown in Fig.7 (a). The voltage induced in the rotor coil rotating in a uniform field established by the stator is alternating. The air gap flux distribution and the voltage induced in the coil are shown in Fig.7 (b) and (c) respectively. Consider a coil a-b is placed on diametrically opposite slots of the rotor. The two ends of this coil are two commutator segments which are **rotating**. Coil a is connected to segment C_a and coil b to segment C_b. Let B_1 and B_2 be the two

carbon brushes. These brushes are **stationary**. For counterclockwise motion of the rotor the terminal under north pole is positive with respect to the terminal under south pole. Therefore B_1 is always connected to positive end of the coil and B_2 to the negative end of the coil. Therefore even though the voltage induced in the coil is alternating, the voltage at the brush terminals is unidirectional as shown in fig. 7(d). The rectified voltage across the brushes has a large ripple (magnitude is not constant, it is varying). In a actual machine a large number of turns are placed in several slots around the periphery of the rotor. By connecting these in series through the commutator segments a reasonably constant dc voltage is obtained. The magnitude of the voltage induced in the armature is proportional to ($\phi \times \omega$) where ϕ is the airgap flux and ω is the speed of rotation.
Current reversal in a turn by commutator and brushes is shown in Fig. 8. In fig. 8(a) the end 'a' touches the brush B_1. The current flows from a to b. As this coil rotates, at a particular position it gets short circuited (refer fig.8b). The angle between the d-axis and this position is 90^o. As the coil rotates from this position, end 'a' now touches brush B_2. The current now flows from 'b' to 'a' as shown in fig.8(c). Hence, **the commutator and brushes rectify the alternating voltage induced in the armature to dc. This combination is also known as mechanical rectifier. Though the current flowing in the armature conductors is ac, the current flowing in/out of carbon brushes is dc. The change over from positive to negative value takes place at a particular axis. The angle between this axis and the d-axis is always 90^o. Therefore, this axis is known as q-axis or the quadrature axis. Since, the armature mmf (F_a) is along this axis, the angle δ_{sr} is always 90^o.**

It is often convenient to discuss a dc machine in terms of its equivalent circuit shown in Fig. 9(a) which shows the conversion between electrical and mechanical power or vice-versa. Field produced by the stator is represented by current I_F flowing in the coil. At steady state the equation relating this current and applied voltage to the field coil is $V_f = I_F\ R_F$, where R_F is resistance of the field coil. In figure 9(b) armature current I_a is entering the positive brush and produces electromagnetic torque to rotate the rotor at a speed ω. Due to this rotation a voltage is induced in the armature. This voltage is proportional to the air gap field and the speed of rotation. If ϕ is the air gap flux, and ω ' is the speed of rotation, the expression for the voltage induced in the armature is given by $E = K\ \phi\ \omega$, where 'k' is a constant. If R_a is the armature resistance and I_a is the armature current flowing into the positive carbon brush as shown in Fig.9(b) (the machine is operated as motor), the relationship between the steady state voltage induced in the armature E and the armature terminal voltage V_a is

$$V_a = E + I_a R_a \quad or \quad I_a = \frac{V_a - E}{R_a} \tag{3}$$

In case I_a is leaving the positive brush as shown fig. 9(c) (machine is operated as generator. The rotor is being driven by the prime mover), the relationship between the steady state voltage induced in the armature E and the armature terminal voltage V_a is

$$V_a = E - I_a R_a \quad or \quad I_a = \frac{E - V_a}{R_a} \tag{4}$$

The following points may be noted from these two equations:

- during motoring operation, armature current flows in opposition to the voltage induced in the armature (also known as speed voltage). Hence E for motoring operation is called as **back emf** denoted by E_b.
- when operated as generator, voltage induced in the armature is forcing the current to leave the positive brush. Hence E for generator operation is called as **induced emf** and is denoted by E.

For motoring action: Multiplying equation 3 by I_a, we get $V_a I_a = I_a^2 R_a + E_b I_a$
The first term in the above equation is the power input to the armature, second term is the power lost as heat in the armature resistance and last term is power developed in the armature. This developed power should be equal to the mechanical output power ($T_e \times \omega$) if friction is neglected.

In case of generator action: Multiplying equation 4 by I_a, we get $EI_a = I_a^2 R_a + V_a I_a$
The first term in the above equation is the power developed in the armature, second term is the power lost as heat in the armature resistance and last term is power supplied to the load.
In Fig.9a, the field winding is connected to a separate voltage source. Hence, this motor is known as separately excited (S.E.) dc motor. In these machines the required field current is a very small fraction of the rated current (could be around 2-3% of the current flowing in the armature circuit at full load). Hence, the field winding has a large number of turns with a thin conductor.
One of the unique features of this motor which has helped to maintain its supremacy over other electric drive systems, is its ability to provide a smooth and wide range of speed control with relative ease. This is because the mmf (magneto-motive force) produced by field coil and that produced by armature coil are always at quadrature, and hence they can be controlled independently. As shown in Fig.10, field mmf (F_s) is taken along the x-axis (also known as direct or d-axis) and the armature mmf (F_a) is along the y-axis (quadrature or q-axis). Since the angle between F_s and F_r is always 90^o, torque T_e is proportional to ($F_s F_a$). Now, F_s and F_a are proportional to field current (I_F) and armature current (I_a) respectively. Hence, the expression for Torque can be written as:

$$T_e \propto I_F I_a.$$

Since the angle between I_F and I_a is always 90^o, the ratio ($\frac{T_e}{I_a}$) is maximum. This is another important feature of the DC machine (in other machines, additional control is required to achieve this feature). Generally, it is assumed that the magnetic circuit is linear. Therefore, Φ is proportional to I_F. Hence, the torque expression becomes T_e = K ΦI_a, where K is constant.

2.3 Speed Control

The other basic equations governing the steady-state operation of the DC motor are:
$V_a = I_a R_a + E_b$, $E_b = K\phi\omega$, and $I_F = \frac{V_F}{R_F}$
Alternate method of deriving the expression for torque is as follows:
Multiplying the first equation by I_a we get, $V_a I_a = I_a^2\ R_a + E_b\ I_a$
First term in the above equation is the power input to the armature, second term is the power lost as heat in the armature resistance and the last term is the power developed in the armature. This power should be equal to the mechanical power ($T_e\ \omega$) if mechanical losses (friction & windage) are neglected.
Equating $E_b\ I_a = (\ K\ \phi\ \omega)\ I_a = T_e\ \omega$
Therefore $T_e = K\ \phi\ I_a$
Substituting for I_a in terms of torque and flux, the relationship between T_e and ω is given by:
$$\omega = \frac{V_a}{K\phi} - \frac{T_e R_a}{(K\phi)^2}$$
If armature terminal voltage V_a & airgap flux ϕ are held constant, the above equation becomes:
$$\omega = A + B\ T_e,$$
where A and B are constants. This is an equation of a straight line wherein, A is the y-axis intercept and (-B) is the slope. The y-axis intercept represents the no-load speed which depends only on the terminal voltage and air gap flux. The variation of speed with torque is shown in Fig.11. Generally, the drop in speed with increase in torque is small (it is desirable that the speed of rotation is independent of load coupled to the motor shaft). Therefore if V_a and ϕ are held constant, the speed of a separately excited dc motor will remain almost constant and it is independent of torque applied to the shaft.

Hence in order to vary the speed of rotation over a wide range, the no-load speed (magnitude of 'A') should be varied. This can be achieved by the following methods:
• By controlling the voltage applied to the armature terminals of the machine
• By controlling the flux produced by the field winding

2.3.1 Armature Voltage control:

The schematic diagram for this control technique is shown in Fig.12(a). In this method, the field current (hence ϕ) is held constant at its rated value and V_a is varied. The speed-torque characteristics for this method are shown in Fig.12(b). These characteristics are drawn for various values of V_a and fixed value of ϕ. This method of speed control is used for speed below the rated value. In addition, the following point may be noted:

* Since ϕ is held constant, the speed of rotation changes linearly with V_a. Motor will draw a constant armature current I_a from the source if it is driving a constant torque load ($T_e = K\phi I_a$). Under this working condition, the power (P) drawn by the motor varies linearly with the speed. This mode of operation is known as **constant flux** or **constant torque mode.** The variation of the various quantities with speed is shown in Fig.12(c).

2.3.2 Field Control:

The schematic diagram for this control technique is shown in Fig.12(d). In this method, the armature voltage is held constant at its rated value and the field current is reduced. The speed of the motor changes in inverse proportion to ϕ. The $T - \omega$ characteristics for this method are shown in Fig.12(b). These characteristics are drawn for various values of ϕ and fixed value of V_a. It should be noted that the reduction in speed with torque is higher compared to that in the previous method. This method of speed control is used for speed above the rated value. In addition, the following point may be noted:

* non-linear inverse speed control of motor speed. This method also changes the value of developed torque for a given armature current. If the armature current is held constant at the rated value, the input power and therefore output power remains approximately constant (assuming that frictional and windage losses remain constant). Hence, this operating zone is known as either **constant hp (horse-power)** or **field weakening zone**. Generally the maximum speed of rotation is kept within 150% of the rated value.

2.4 Variable Voltage DC Source:

Both armature voltage and field control methods require a variable voltage dc source. If a fixed-voltage dc power supply is available, voltage applied to the armature or field circuits can be varied by connecting a variable resistance in series with these circuits. However, this results in increased losses, heat and poor efficiency Nowadays, power electronic controllers are increasingly being used to obtain variable dc (or ac) voltage supply from ac source. The advantages are smooth & flexible control, and high efficiency (one such example is elegant, light weight miniature size fan regulator. This regulator is mounted inside the switch board, while 'old' fan regulator is mounted on the switch board. Apart from larger size, the old regulators dissipate heat at low speed of operation).

Fig.4 shows the output voltage waveform of a full wave diode bridge. If the input voltage to the bridge is $V_m \sin \omega t$, then the average value of the output voltage is given by:

$$V_{av} = \frac{2V_m}{\pi}$$

From the output voltage waveform, it can be observed that the waveform is continuous and the instantaneous value is always finite and positive. Hence the average value of the output voltage depends only on the peak value of the input voltage. An autotransformer is now required to vary the output dc voltage by varying the peak input voltage.
The average value of the output voltage can also be reduced if the instantaneous value of the output voltage is made either zero or negative. This is possible by using power semiconductor devices other than diodes (e.g. thyristors). This results in the reduction of size and cost, and improvement in efficiency. However, the applied voltage to the armature is continuously pulsating. In order to reduce the pulsation in the current drawn by the motor, (developed torque depends not on the applied voltage but on armature current and flux) an inductor is connected in series with the armature. Since the current flowing through the inductor is dc, the average voltage drop across it is zero at steady state. However, the current becomes almost constant (property of an inductor- current can not change instantaneously).

2.5 Starting:

From the basic equation governing the steady state operation of dc motor, we have the following:

$$I_a = \frac{(V_a - K\phi\omega)}{R_a}, \qquad \text{and} \qquad T_e = K\phi I_a$$

The torque developed at starting is determined by the product of total flux and armature ampere-turns. This torque is utilized partly in overcoming friction, partly in accelerating the armature, and partly in accelerating the load. The value of starting torque required from a motor will then depend very largely on the load. At standstill there is no back emf, so that to circulate full load current in the armature a very small voltage is required. Neglecting the effect of armature inductance, the voltage that must be applied to the armature at starting depends only on armature resistance. Since, this resistance is very small, a large current will flow if the rated voltage is directly applied to the armature (for the given machine whose parameters are given below, this current is approximately $\frac{180}{2} = 90A$, while the full load rated current is of the order of 10.5 A!). The starting current can be limited to a safe value by the following methods:

- including external resistance only in the armature circuit so that machine develops necessary starting torque. As the motor speeds up, the back emf is generated and the current falls. Generally a large resistance is necessary to limit the starting current. If this resistance is left in the circuit, the steady state speed would be very low and in addition there would be waste of power in the resistance. It is therefore becomes necessary to cut out the whole of the resistance so that rated speed is obtained.
- applying a low voltage by using a variable dc power supply. This voltage is increased as the machine accelerates.

The developed torque and the rate at which back emf is generated depends on the air gap flux. In order to have faster acceleration rated voltage is applied to the field winding while starting.

Note to TAs/RAs: There is a dc machine which is cut open. Show the following to students:
- carbon brushes, commutator, stator poles, rotor coil, stator and rotor laminations
- rotate the rotor and show that carbon brushes are stationary while commutator is rotating.

3 Procedure:

There are three machines mounted on the stand, out of which two of them are dc machines. Note the name plate ratings of these machines and use one of them as a dc motor and the other as a separately excited dc generator. The parameters are:
- 1.5 kW dc machine: $R_a = 2.04\Omega$, $R_F = 415\Omega$, Friction & windage loss at 1500 rpm = 53 W.
- 1.1 kW dc machine: $R_a = 2.1\Omega$, $R_F = 415\Omega$, Friction & windage loss at 1500 rpm = 53 W.

3.1 Precaution:

* **Always start the motor by applying a low input voltage (V_a) to the armature, else the power electronic controller may get damaged due to heavy inrush current. Also, apply the rated voltage to the field winding of the motor. In case the drive has tripped, bring back the voltage control knob on the power controller feeding armature of the dc motor to 'zero position' and then press the 'green' button.**

3.2 Armature Voltage control:

A. Connect the circuit as shown in Fig.14. In this experiment the motor is loaded by loading the generator. Put off all switches of the lamp load and open the main switch 'S' connected between the load and the armature of the DC generator. Also, **open switches S_1, S_2 and S_3**. These are on machine stand.

B. Switch on the AC supply to the power electronic controller supplying power to the field winding of the motor. Using the knob on the controller, apply the rated voltage to the field winding.

C. Switch on the AC supply to the power electronic controller supplying power to the armature of the motor. Using the knob on the controller, slowly increase the voltage to the armature till the rated value. Also, apply the rated voltage to the field winding of the generator (the output terminals are at the rear side of the controller feeding the armature of the motor). Note down the meter readings, speed and direction of rotation.

E. Close switch S and load the generator in steps till it reaches full load. For each load keep the input voltage to the armature constant & note down all the meter readings and speed. **You may find that beyond a certain load, it is not possible to keep the armature input voltage constant. Do not increase the load beyond this point**. Switch off the load and open S.

F. Now apply 85% of the rated voltage to the armature and repeat the above step. Do not switch off the supply.

3.3 Field Control:

A. Using the power electronic controller apply the rated voltage to the armature of the DC motor.

B. Using the power electronic controller suppling power to the field of the DC motor, reduce the field current to 0.4 A.

C. Close S and load the generator in steps till full load. For each load keep the input voltage to the armature and field current constant, and note down all the meter readings and speed. **You may find that beyond a certain load, it is not possible to keep the armature input voltage constant. Do not increase the load beyond this point**. Switch off the load and open S.

D. Now reduce the field current to 0.38A with armature voltage unchanged at its rated value. Repeat the above step.

E. Reduce the voltage applied to the armature to zero.

3.4 Reversal of Direction of Rotation

A. Without disturbing other parts of the circuit interchange the supply terminals to the armature of motor. Apply the rated voltage to the field winding of the motor, and slowly increase the voltage to the armature till the rated value. Note down the speed and direction of rotation.

E. Reduce the voltage applied to the armature of the motor to zero and put off the supply to both the power electronic controllers.

3.5 Plotting of $T - \omega$ Characteristics:

* Using the plot of efficiency vs output power of the generator, for each output determine the input to the generator.

* Assuming 100% coupling efficiency, the above input power is the output of the motor. Knowing the speed of the motor, determine the torque. Plot T-ω characteristics.

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4 Questions to be answered:

* The condition to develop steady torque is that the relative speed between the two fields (in this case F_s and F_a) should be zero. In other words, the two fields should be stationary w.r.t each other. In dc motor, the speed of F_s is zero (stator coil is stationary and it is excited by dc current), while the armature is rotating. Explain how is the above condition satisfied?

* Explain why the full field and reduced armature voltage is applied to dc motor while starting.

* Whether the speed is independent of the direction of rotation? If it isn't what could be the reason?

* What may happen if the field circuit gets open circuited during motoring?

* Which type of motor is most suitable for electric traction?

* What are the limitations of S.E. dc motor?

* Why is it mentioned in section-2.1.2 that the maximum speed of operation is about 150% of the rated speed?

* In dc series motor the field winding is connected in series with the armature. Can a separately excited motor be converted to series motor by connecting the field in series? Justify your answer.

* Of the two machines which one did you choose to operate as motor? Justify your answer.

* Assume that a given machine has the following name plate ratings:

  220 V, 9 A, 1.5 HP, 1500 rpm dc motor

  What do these numbers imply?

* In separately excited dc machine, the field winding carries a constant current. Hence, it dissipates power. Suggest a method to eliminate this power loss.

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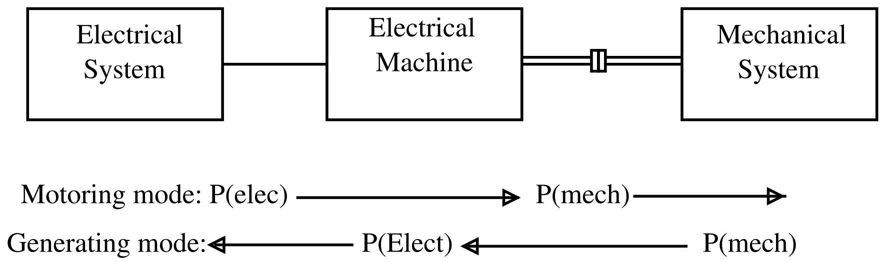


Fig :1 Electrical machine as an energy converter

Fig: 2 Structure of machines

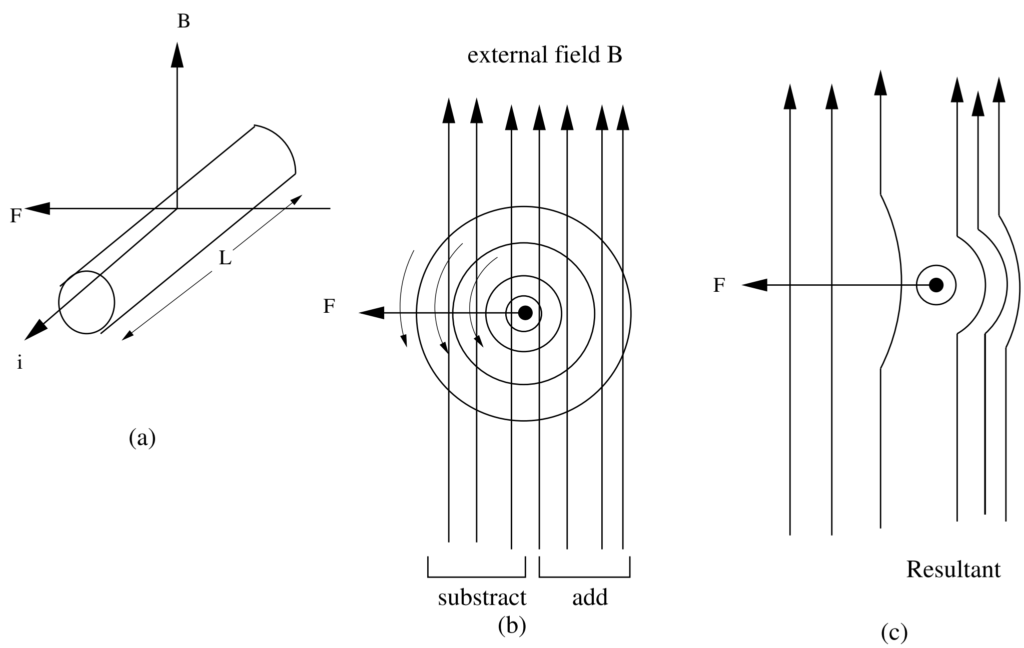


Figure: 3. Electric force on a current crrying conductor in a magnetic field.

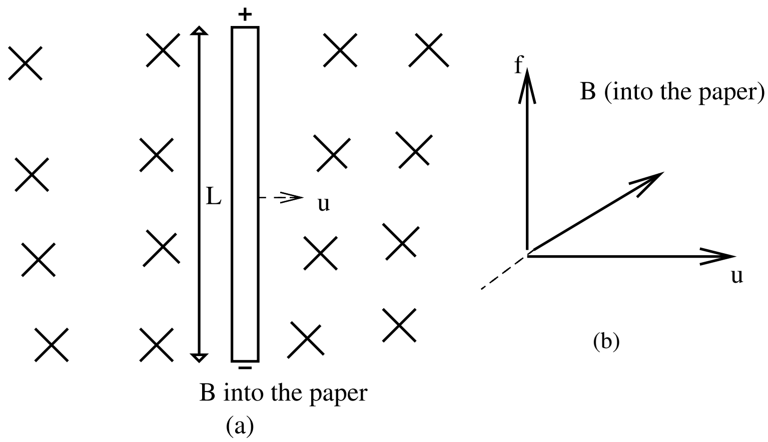


Figure: 4 Conductor moving in a magnetic field

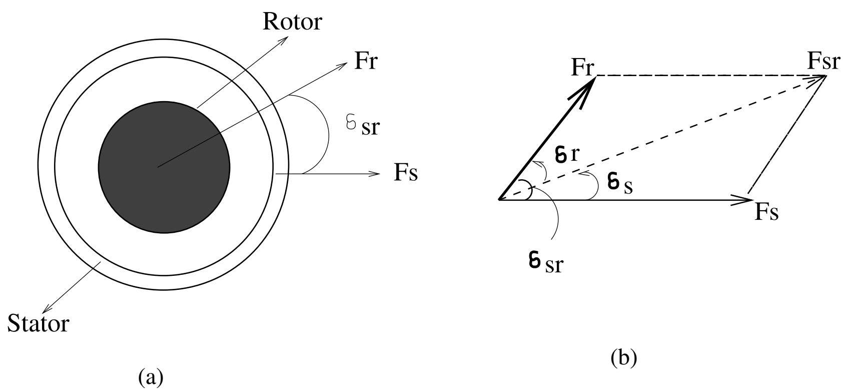


Fig 5: Simplified 2 pole machine and vector diagram of mmf waves.

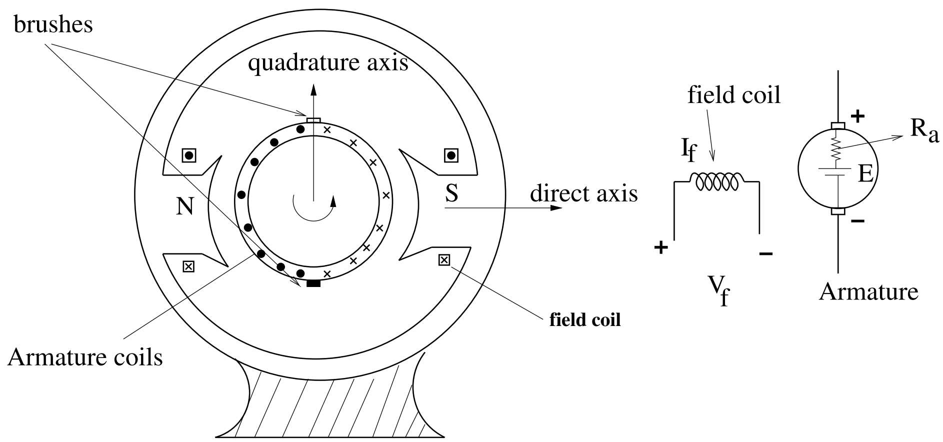


Fig: 6. Schematic representation of a dc machine

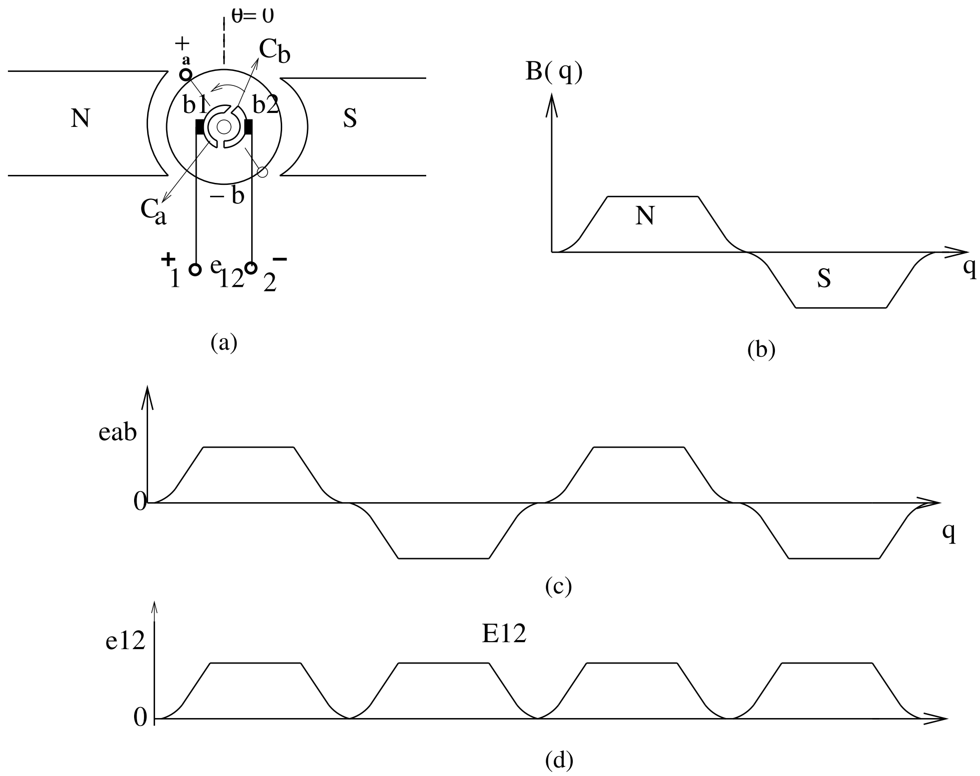


Fig: 7 Voltage rectification by commutators and brushes

(a)DC machine with commutator segments

(b)Flux density distribution in air gap (c)Singleturn machine

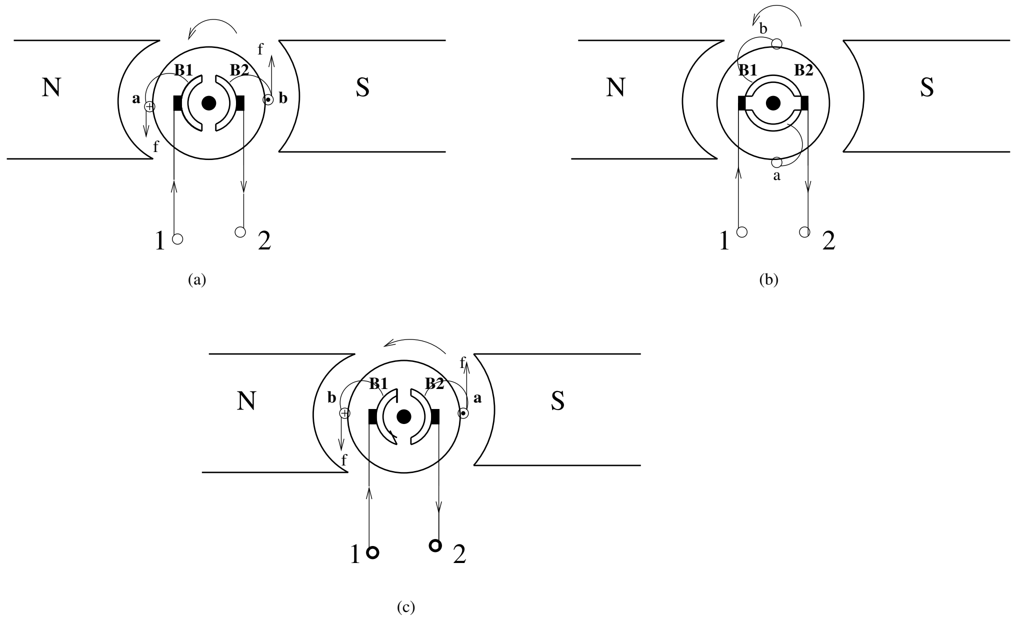
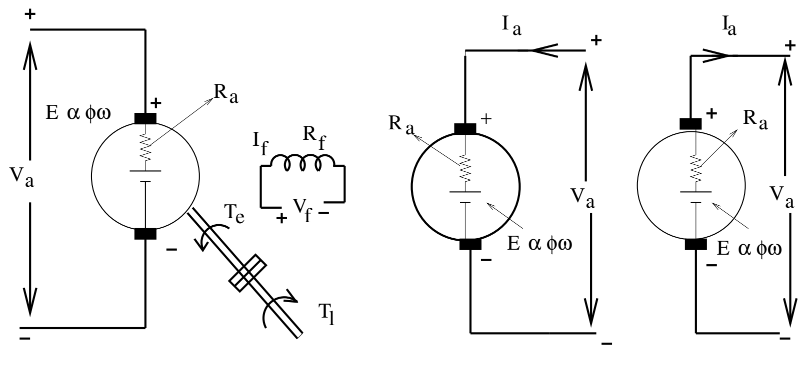


Fig: 8 Current reversal in a turn by commutators and brushes.



(a) (b) (c)

Fig 9:Equivalent circuit of DC machine.

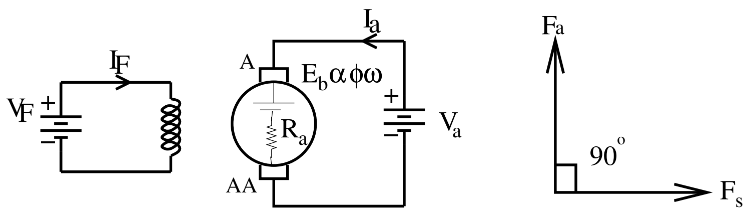


Fig 10 Separately Exicited DC Motor

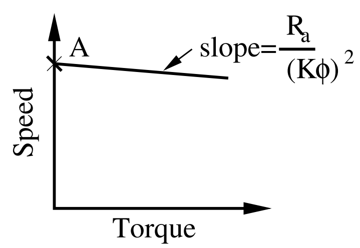


Fig.11 T$-\omega$ characteristics of Separately Excited DC Motor

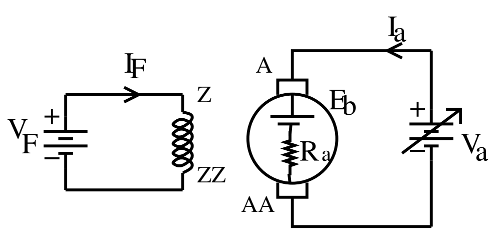


Fig.12 (a) Schematic diagram for armature voltage control

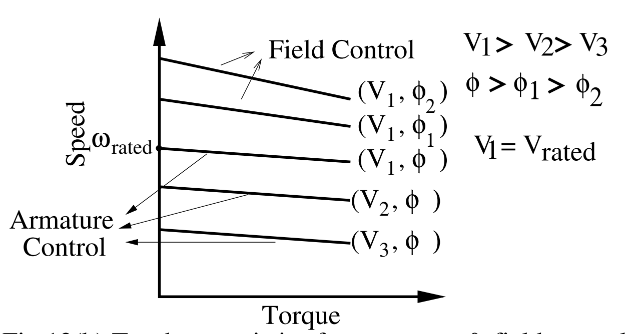


Fig.12(b) Tω characteristics for armature & field control

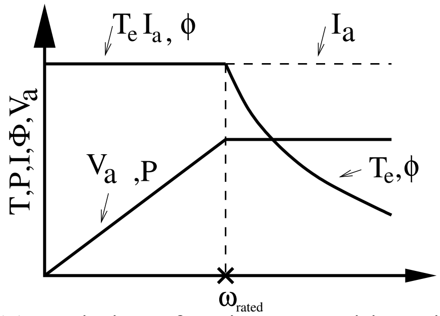


Fig.12(c) Variation of various quantities with speed

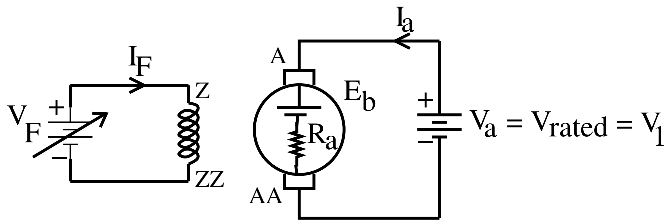


Fig. 12(d) Schematic diagram for field control

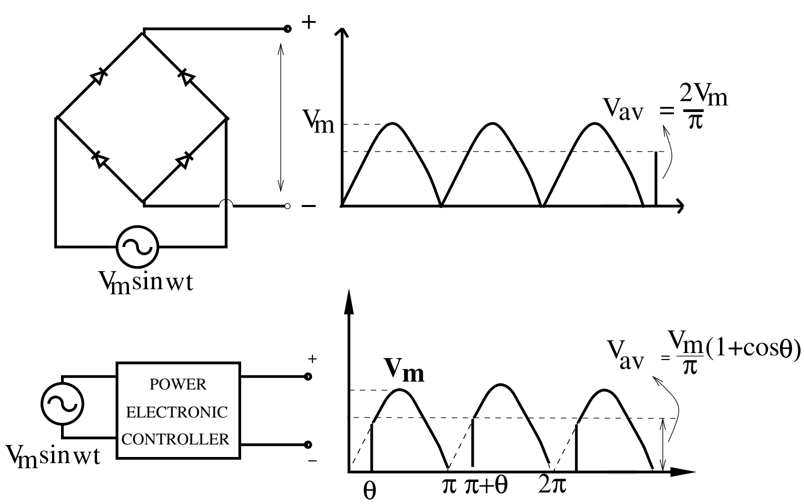


Fig.13 Output voltage waveform of Power Electronic controller

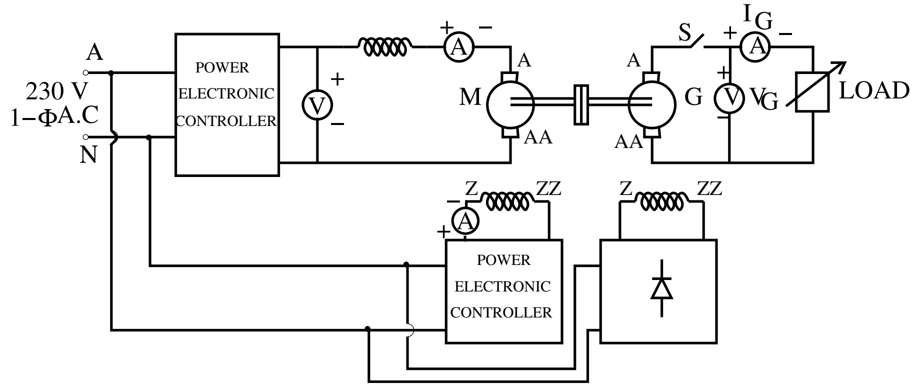


Fig.14 Circuit diagram for speed control of Separately Excited DC Motor

Efficiency Vs Output power of D.C Generator

Date :