Experiment no. 3

Characteristics of DC Generators

1. Aim

To obtain :

- Open circuit and External characteristics of separately excited (S.E.) DC generator
- External characteristics of shunt generator

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 air gap 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 $\mathbf{F = B\,I\,L}\,N$. 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 $\mathbf{e = BLV}\ V$. 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 δ_r and F_r sin $\delta_{sr} = F_{sr}$ sin δ_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 $\boldsymbol{E = K \phi \omega}$, where '$\boldsymbol{K}$' 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

$$E I_a = I_a^2 R_a + V_a I_a$$

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.
Based on the method of excitation dc generators can be divided into two groups. Separately excited generators and self-excited generators. In a separately excited (S.E.) machine, the field winding is connected to a separate voltage source while, in a self excited generator field winding is connected across the armature terminals (provides its exciting current) . 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.

2.3 Magnetization Characteristics of a dc machine

The induced emf in the armature winding of a dc machine is directly proportional to flux and speed of rotation. Let us assume that the field winding is connected to a variable dc source that is capable of supplying a desired field current. If the armature terminals are left open and the armature is rotated at constant speed, then the induced emf in the armature is $E = K_1 \phi$, where K_1 is a constant. In other words the induced emf is directly proportional to the airgap flux. Flux depends on the magneto-motive force (MMF) provided by the current in the field winding. That is, $\phi = K_f I_F$, where K_f depends on the operating flux density. Therefore induced emf can now be written as $E = K_1 K_f I_f$. The magnetic circuit of a dc machine consists of both linear (airgap) and non-linear (magnetic material of the stator and rotor) parts. Hence, K_f changes (it decreases as the magnetic circuit gets saturated) with the change in flux density in the machine. The relationship between E and I_f can be determined by measuring the open circuit voltage (voltage across armature terminals) at different values of I_f at a constant speed. This curve is known as ***open circuit characteristics (O.C.C)***. This variation is shown in Fig.10. Since E is an indirect measure of air gap flux (at constant speed of rotation), the curve is similar to the B-H curve (or ϕ Vs I_f) of the magnetic material. For this reason, O.C.C. can also be referred to as the ***magnetization*** curve. It should be noted that E does not start at zero when the field current is zero but at some value (of the order of 8-10 V). This is due to ***residual magnetism***.

2.3.1 Armature Reaction

When there is no current in the armature winding (no-load condition), the flux produced by the field winding is uniformly distributed over the pole faces as shown in Fig.11(A). Let us assume that this two pole machine is driven by a prime mover in the clockwise direction (generator operation). The direction of the currents in the armature conductors under load is shown in Fig.11(B). The armature flux distribution due to armature mmf is also shown in this figure. Since both fluxes exist at the same time when the armature is loaded, the resultant flux gets ***distorted***. It can be seen that the armature flux opposes the flux in one half of the pole and aids in the other half. If the magnetic circuit is unsaturated the decrease in flux in one-half of the pole is accompanied by an equal increase in the flux in the other half. The net flux per pole, therefore, is the same under load as at no load. On the other hand, if the magnetic circuit is very close to saturation point under no-load, the increase in flux is smaller than the decrease in flux. In this case there is a net reduction in the total flux.

2.3.2 Separately excited dc generator

As the name suggests, a separately excited dc generator requires an independent dc external source for the field winding. The equivalent circuit representation under steady state condition is show in Fig.12. The equations under *steady-state* are:

$V_f = I_f\ R_t \qquad R_t = R_f + R_{ext} \qquad V_a = E + I_L\ R_a \qquad I_L = I_a$

When the field current is held constant and the armature is rotating at a constant speed, the induced emf in an ideal generator is independent of the armature current, as shown by the dotted line in Fig.13. As the load current I_L increases, the terminal voltage decreases as indicated by solid line. If the armature reaction is neglected, decrease in V_a should be linear and equal to the voltage drop across R_a and carbon brushes. However, if the generator is operated at the knee point in the magnetization curve, the armature reaction causes a further drop in terminal voltage.

2.3.3 Self Excited dc generator

In this generator, the field winding is connected across the armature. Hence, the terminal voltage is also the field voltage and the armature current is the sum of load and field currents. When the rotor of this machine is rotated, the residual flux in the field winding induces some voltage (E_r) in the armature winding as shown in Fig.14 . Since the field winding is connected across the armature, because of this induced emf a small current starts flowing in the field winding. If the field mmf due to this current aids the residual flux, total airgap flux increases. This increase in flux increases the induced emf which, in turn, increases the field current. This action is ***cumulative*** in nature.

If the field winding is connected in such a way that the flux produced by the field current opposes the residual flux, the generator fails to build up. This problem can be corrected by either reversing the direction of rotation or interchanging the field winding connections across the armature. The value of no-load voltage at the armature terminals depends on the field resistance (point of intersection of field resistance line with magnetization curve is the operating point). A decrease in the field resistance causes the generator to build up faster to a higher voltage.

The equivalent circuit representation under steady state condition is shown in Fig.15. The equations that govern the operation of a self excited generator under steady state are:

$I_a = I_L + I_f \qquad V_a = I_f\ (R_f + R_{ext}) = I_L\ R_L = E$ -$I_a\ R_a$

Under no load condition, the armature current is equal to the field current, which is a small fraction of load current. Therefore the terminal voltage under no-load condition is nearly equal to the induced emf (I_aR_a drop on no-load is very small). As the load current increases, the ***terminal voltage decreases*** due to the following reasons:

• $I_a\ R_a$ drop
• demagnetization effect of the armature reaction
• decrease in the field current due to the reduction in the terminal voltage (field current can be kept constant in separately excited generator, while in self excited generator this current falls with terminal voltage).

The variation of terminal voltage with load is shown in Fig.16.

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 prime mover (motor) and the other as a dc generator (You may have to justify your selection):
- 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 (prime mover) by applying a low input voltage (V_{in}) to the armature, else the power electronic controller may get damaged due to *heavy inrush current* (Treat this power electronic controller as a converter. Input to this controller is single phase AC and the output is DC. It should be noted that this experiment is on DC generator. A prime mover is required for a machine to operate as a generator. In this experiment DC motor is being used as a prime mover). 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 For Separately Excited DC generator:

A. • After noting down the **name plate details** of the dc machines. Connect the circuit diagram as shown in Fig.17. Keep the control knob (which is used for applying variable dc voltage to the field winding of the generator) on the field regulator of generator at 'zero output voltage' position. 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.
• Using the power electronic controller ***slowly increase*** the input to the prime mover. Speed of the **machine** set will increase. By controlling the input to the prime mover adjust the speed to the rated speed of the machine. Speed is measured using the tachometer provided.
• Using a multimeter note the voltage due to residual magnetism.
• Using the knob on the controller feeding the field winding of the generator, increase the input voltage **in steps** (field current will also increase) and for each case determine the open circuit voltage. Repeat this procedure till the open circuit voltage is **110% of the rated value. (The steps for OCC is thus finished. The remaining steps are for the loading test or external characteristics)**
• Now ***decrease*** the applied voltage to the field of the generator till the generated voltage is equal to its rated value.
• Close the main switch 'S' and load the generator in steps by switching ON the lamps and for each case ***adjust the prime mover input such that the speed remains constant*** . Note down load voltage and current, field voltage and current of the generator, armature current and voltage of the motor in a table. Repeat this procedure till the load current is equal to the rated current of the generator.
• Put off all the lamps, open the main switch S, reduce the prime mover input and put off the AC supply to the controllers.

B. Repeat the entire procedure in A for a speed of **80% of the rated speed** of the generator. Note down the readings in a separate table.

3.3 For Self Excited DC generator:

A. (Note that the OCC test has been performed for the seperatedly excited machine and is almost same for the self excited case, hence there is no need to repeat. The procedure below is for the loading test) •
   - Connect the circuit diagram as shown in Fig.18 (you need to connect the field winding across the armature instead of connecting it to a separate supply).
   - ***Slowly increase*** the input to the prime-mover. Speed of the set will increase. Observe the voltmeter connected across the terminals of the dc generator. Above a certain speed, the voltmeter reading starts increasing (**If this does not happen reduce the prime-mover input and switch off the supply. Interchange the field terminals of the generator and repeat the same procedure**). By controlling the input to the prime mover adjust the speed to **the rated speed of the machine**.
   - Close the main switch S. Load the generator **in steps** by switching ON the lamps and for each case ***adjust the prime mover input such that the speed remains constant***. Note down the load voltage and current, field current of the generator, armature current and voltage of the motor **in a table.** Repeat this procedure till the load current is equal to the rated current of the generator.
   - Put off all the lamps, open the main switch S, reduce the prime mover input and put off the AC supply to the controllers.

B. Repeat the entire procedure in A for a speed of **80% of the rated speed** of the generator. Note down the readings in a separate table.

1. ***Mention clearly the initial speed condition on the top of your observation tables.***
2. ***Calculate the voltage regulations and tabulate the values for all cases.***

4 Result

* ***Plot*** the variation of open circuit voltage with field current for the 2 speeds (same plot)

* ***Plot*** the variation of terminal voltage with load current for separately excited and self excited generators (on the same plot for the **rated** conditions)

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5 Questions to be answered in report:

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

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

220 V, 1.5 kW, 1500 rpm dc generator --What do these numbers imply?

C. There are motors without any rotor windings (e.g. stepper motor). Explain how the torque is produced in these machines (**Hint:** Go through very carefully the theory given in the first page).

D. How is the voltage induced in the armature (coil is rotating in a magnetic field) which is ac, converted to dc?

E. What is the effect of armature reaction?

F. 'Saturation of the magnetic material is a blessing in the case of self excited generator' Is this statement true? Justify your answer. (Hint: comment on the following:
- during voltage build up which is cumulative in nature.
- if the generator is operated in the linear region of the magnetization curve)

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

H. What may happen if load terminals are short circuited in (a) separately excited generator (b) self excited generator

I. You have been given the plot of efficiency vs input power of the prime mover. Explain how will you obtain the plot of efficiency vs output power of the generator. How will you obtain this plot in case the plot of efficiency vs input power of the prime mover is **not** available?

J. A DC **series** generator has armature resistance of 0.5 Ω and series field resistance of 0.03 Ω. It drives a load of 50 A. If it has 6 turns/coil and total 540 coils on the armature and is driven at 1500 rpm, calculate the t**erminal voltage** at the load. Assume 4 poles, lap type winding, flux per pole as 2mWb and total brush drop as 2V. Also determine the total **power loss** and **efficiency** of the machine.

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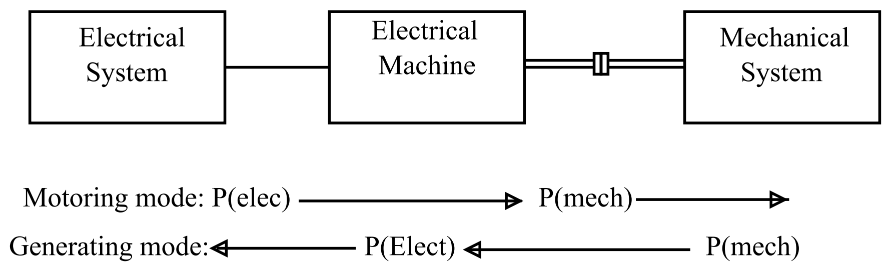

Fig. 1: Electrical machine as an energy converter

(a) **(b)**

Fig. 2: Structure of machines

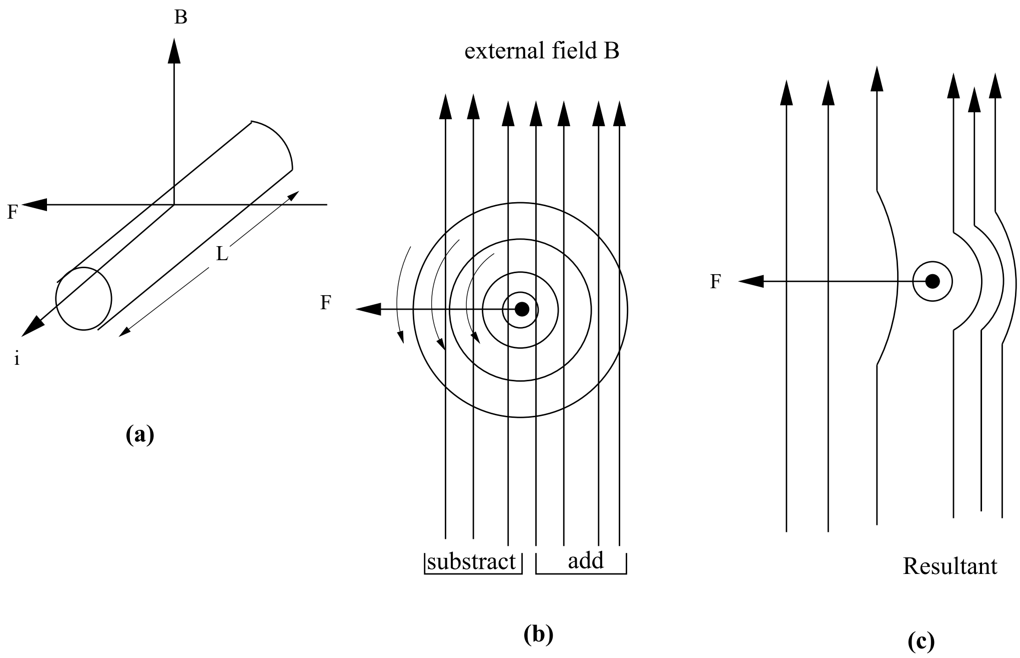

Fig. 3: Electric force on a current crrying conductor in a magnetic field

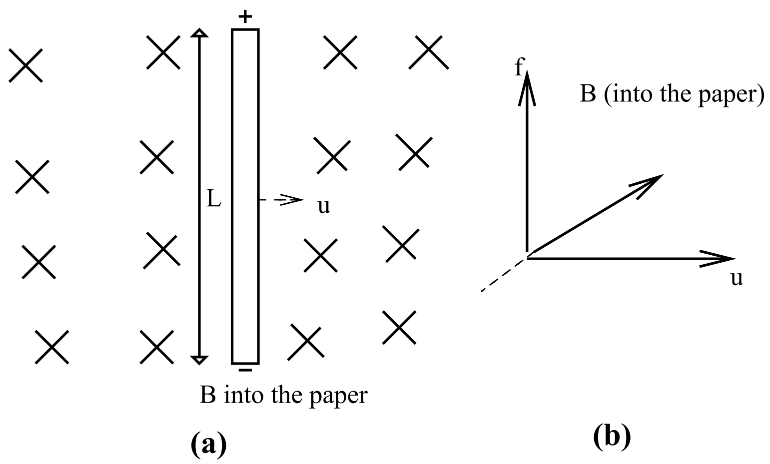

Fig. 4: Conductor moving in a magnetic field

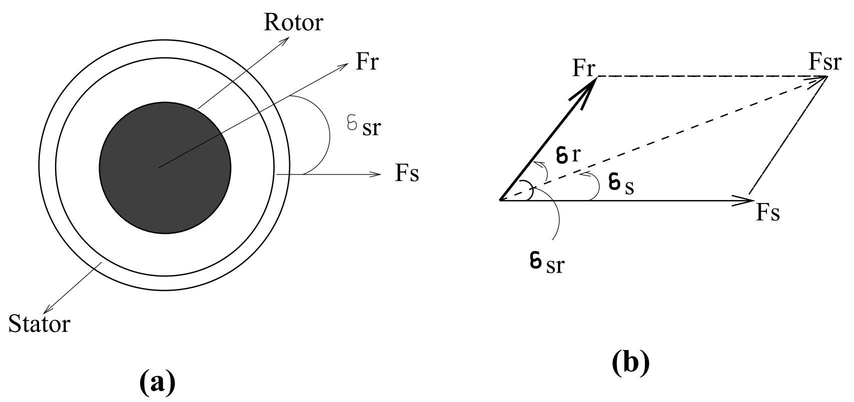

Fig. 5: Simplified 2 pole machine and vector diagram of mmf waves.

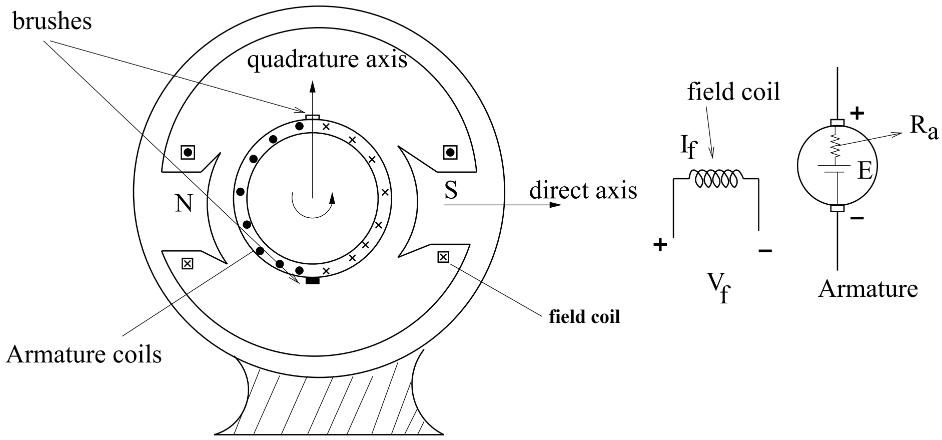

Fig. 6: Schematic representation of a dc machine

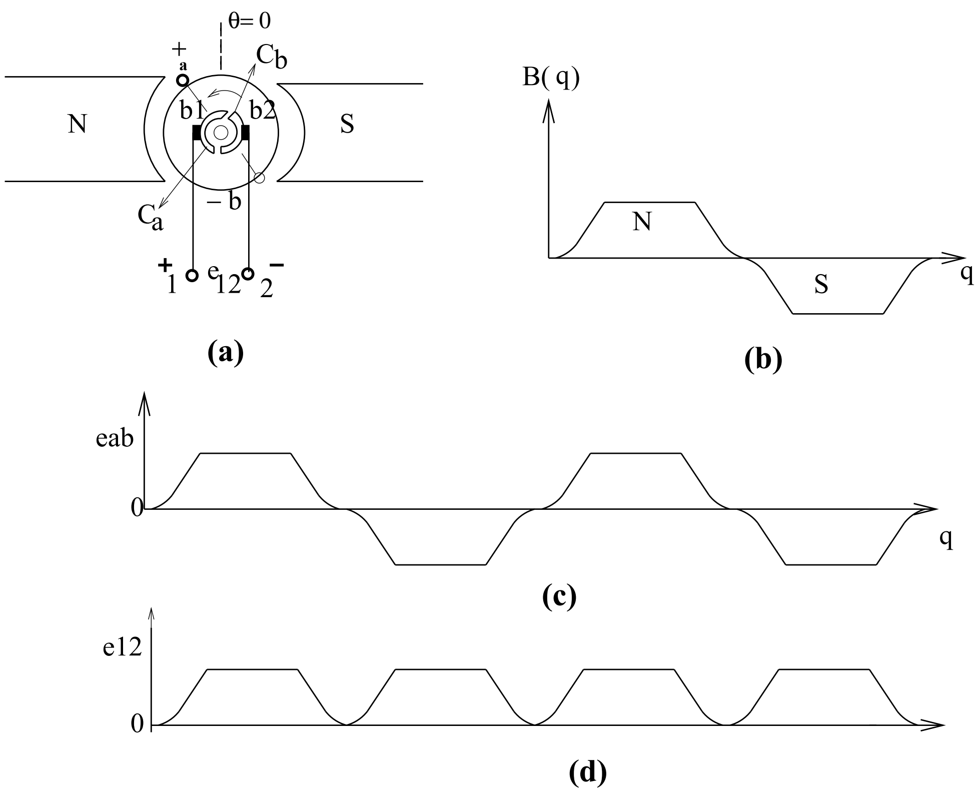

Fig. 7: Voltage rectification by commutators and brushes

(a)DC machine with commutator segments
(b)Flux density distribution in air gap
(c)(d)Singleturn machine voltage waveforms

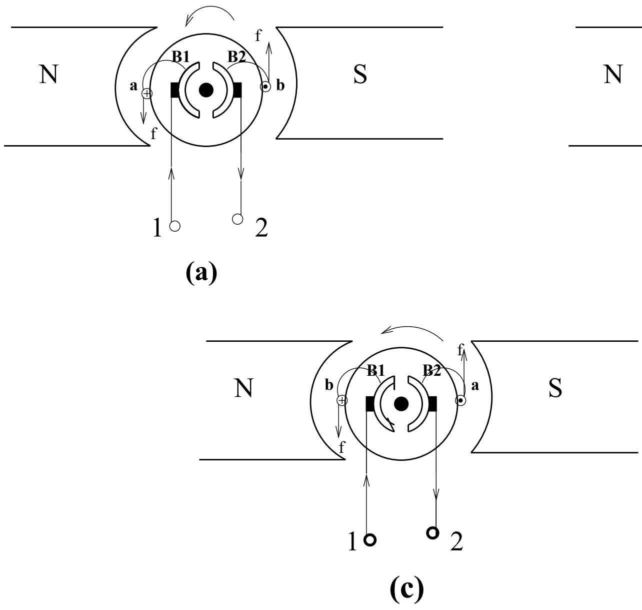

Fig. 8: Current reversal in a turn by commutators and brushes.

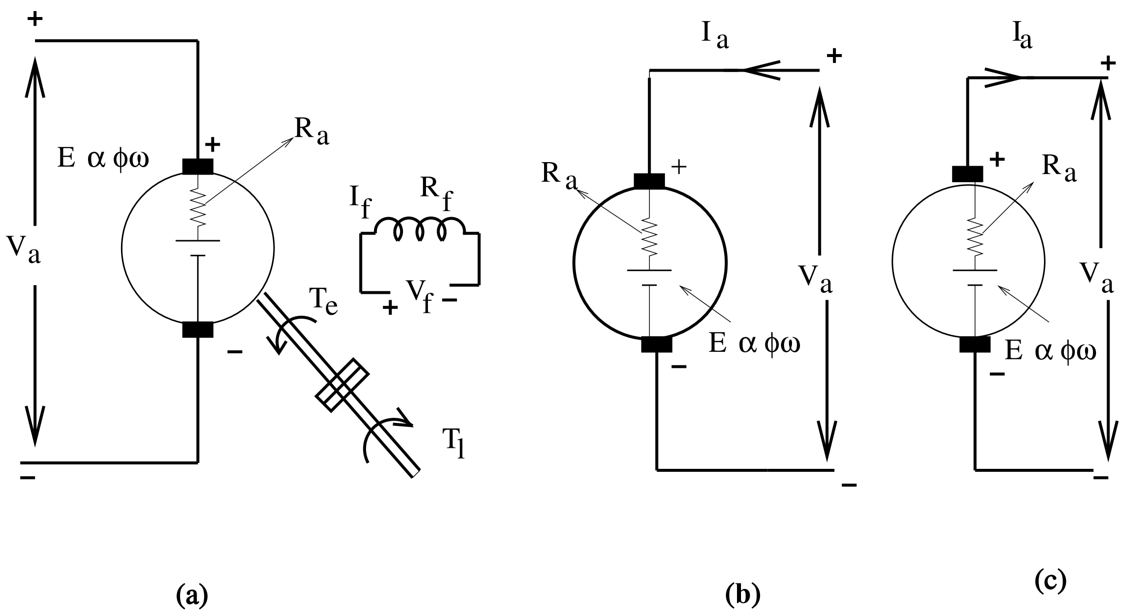

Fig. 9: Equivalent circuit of DC machine (a) General machine (b) dc motor (c) dc generator

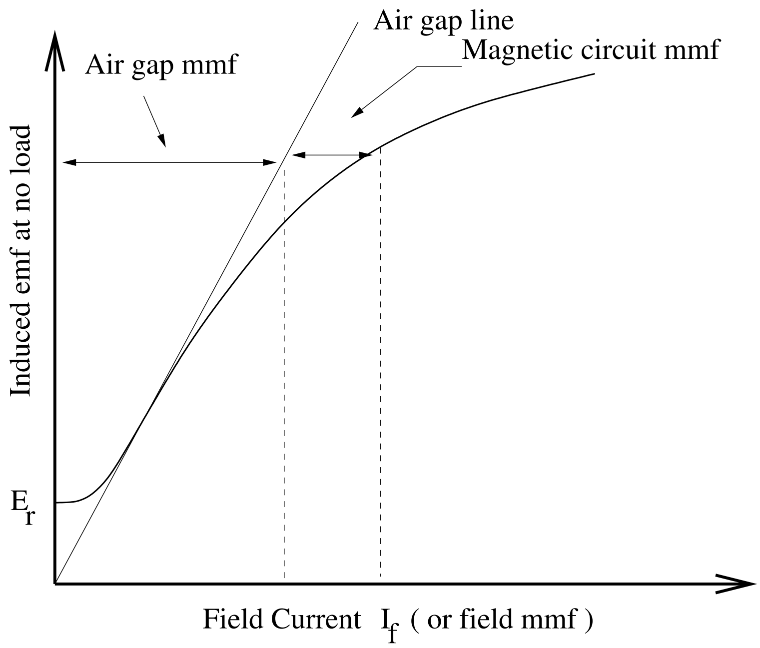

Fig.10: Magnetization (No−load) OCC characteristic of a dc machine.

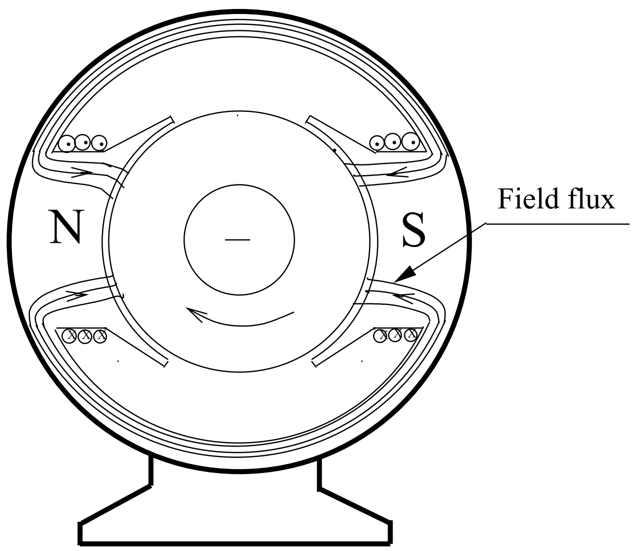

Figure A

Flux distribution due to field MMF only

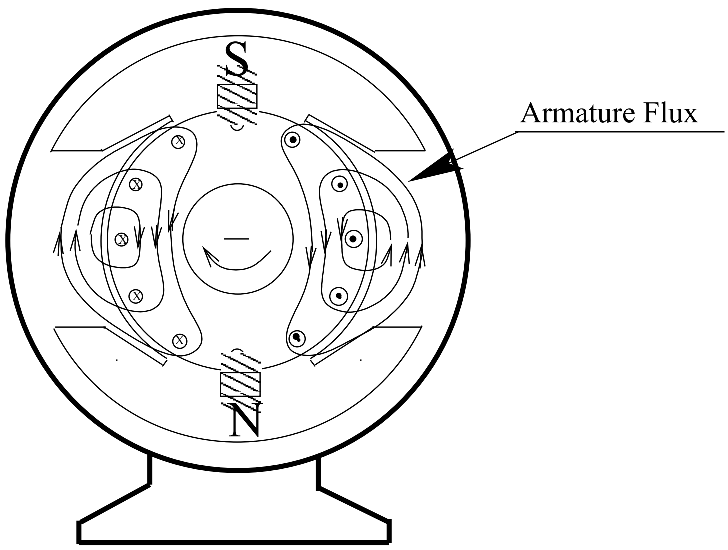

Figure B

Flux distribution due to armature MMF only

Fig. 11: Armature reaction in DC Generator

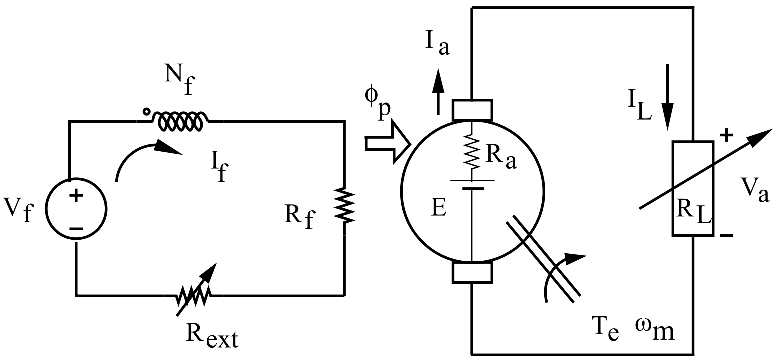

Fig.12 : An Equivalent circuit of a seperately excited dc generator

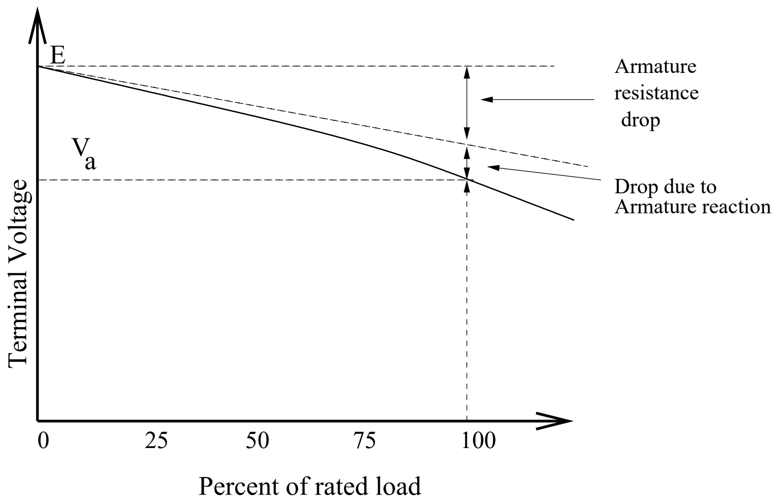

Fig. 13: The external characteristics of a seperately excited dc generator

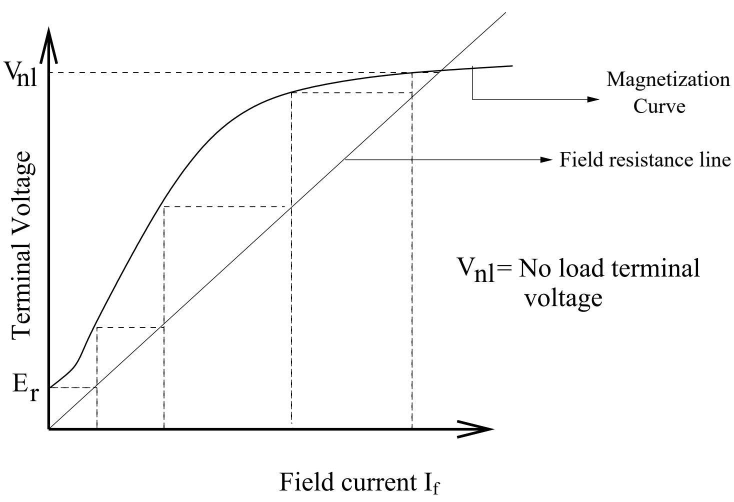

Fig. 14 : Voltage buildup in a self excited generator

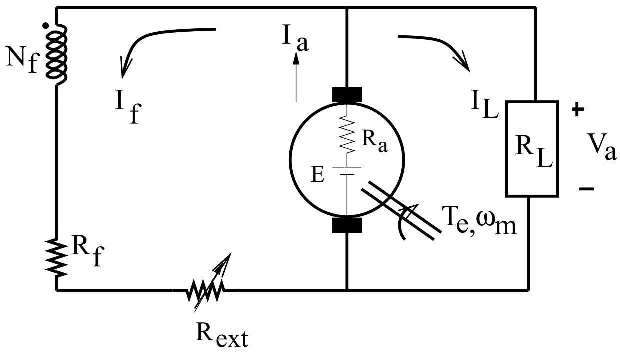

Fig. 15 : An Equivalent circuit of a Self Excited DC generator

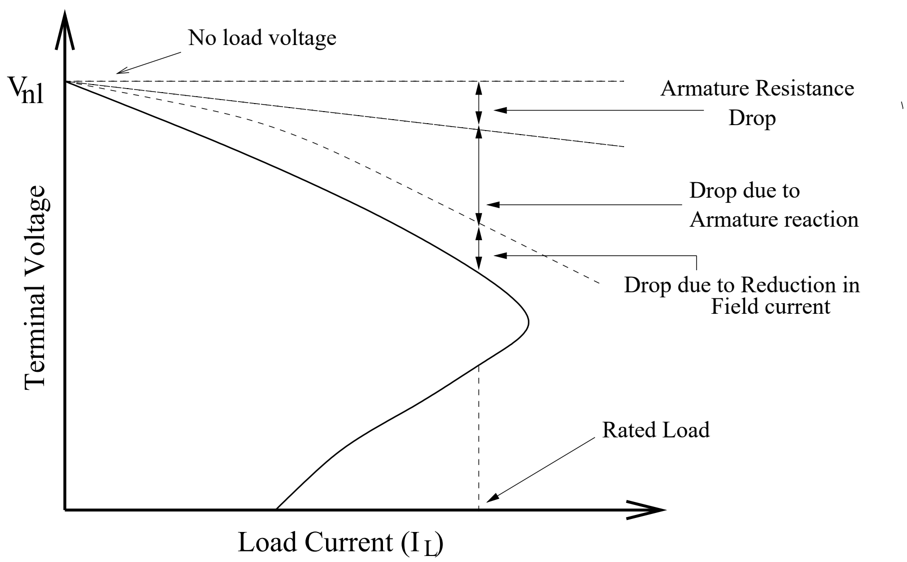

Fig.16 : External Characteristic of a Self Excited DC generator

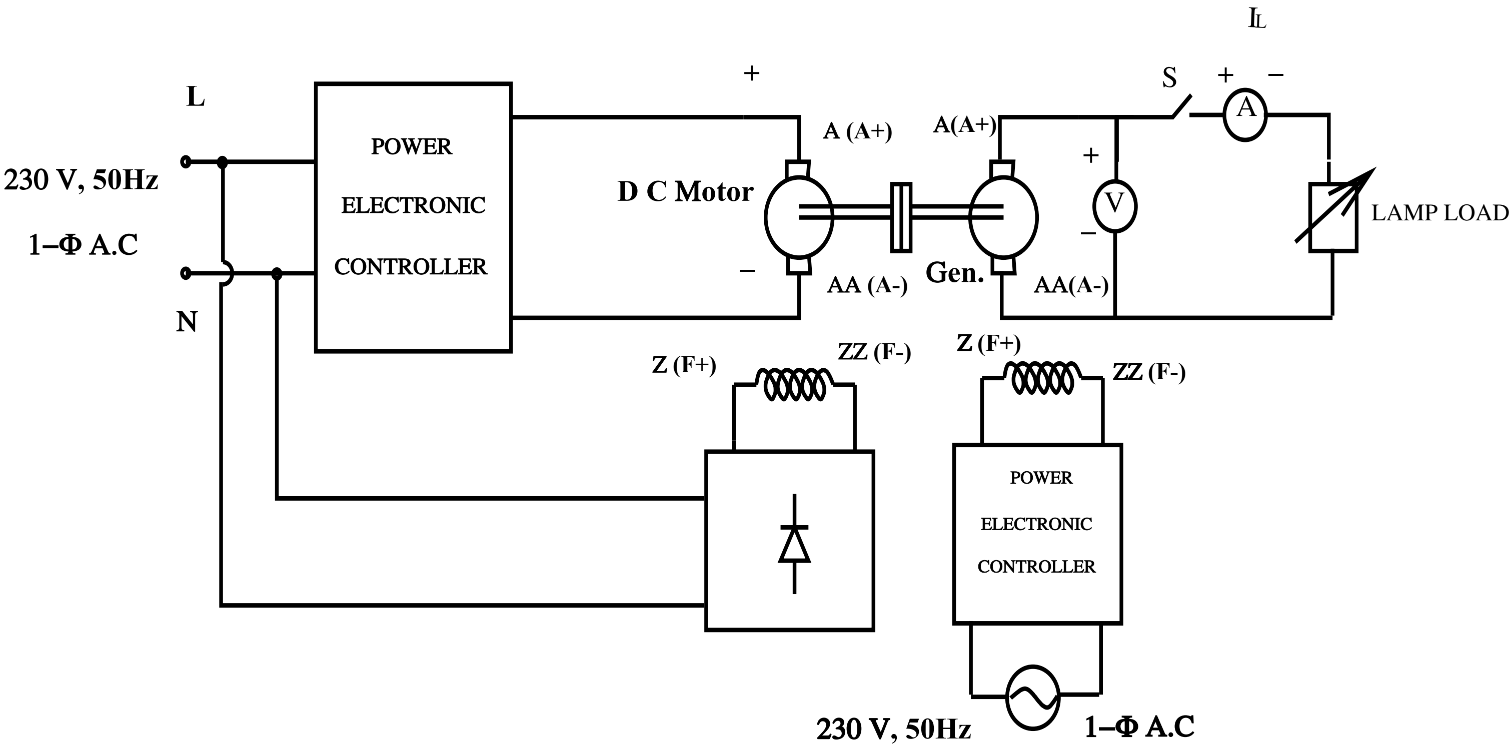

Fig.17 : Circuit diagram for seperately Excited DC Generator(for O.C.C. & Load test)
[A (A+) AA(A-) Z(F+) ZZ(F-)]

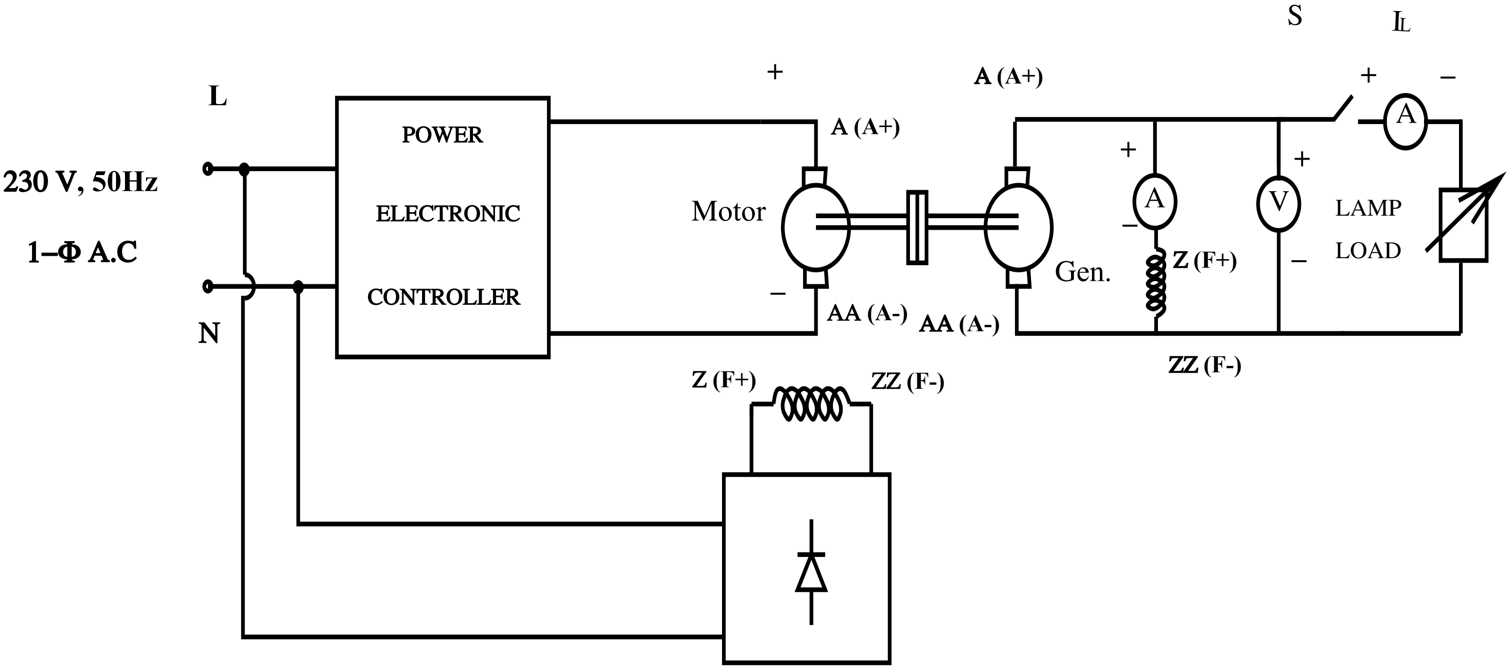

Fig. 18 : Circuit diagram for Self Excited DC Generator **[A (A+) AA(A-) Z(F+) ZZ(F-)]**

Efficiency Vs Input power of D.C Motor

Date :