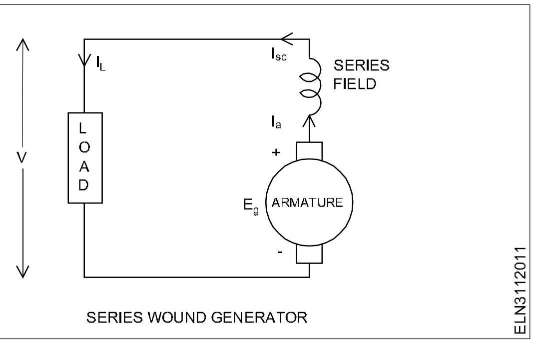
Characteristics of DC generator

Objectives: At the end of this lesson you shall be able to
- **explain the characteristic of DC series generator**
- **explain the characteristic of DC shunt generator**
- **explain the characteristic of DC compound generator**
- **explain the operation of paralleling of DC shunt generators**
- **explain the effect of armature reaction and remedies**
- **explain losses and efficiency of DC generators**
- **explain the routine and maintenance of DC generator.**

Characeteristics of series generator

In these types of generators the field windings, armature windings and external load circuit all are connected in series as shown in Figure 1.

Fig 1



SERIES WOUND GENERATOR

Therefore, the same current flows through armature winding, field winding and the load. Let, $I = I_a = I_{sc} = I_L$ Here, I_a = armature current I_{sc} = series field current I_L = load current There are generally three most important characteristics of series wound DC generator which show the relation between various quantities such as series field current or excitation current, generated voltage, terminal voltage and load current.

Magentic or open circuit characteristic of series wound DC generator

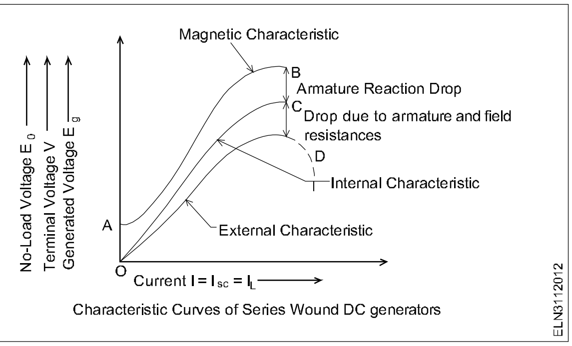
The curve which shows the relation between no load voltage and the field excitation current is called magnetic or open circuit characteristic curve. As during no load, the load terminals are open circuited, there will be no field current in the field since, the armature, field and load are series conected and these three make a closed loop of circuit. So, this curve can be obtained practically by separating the field winding and exciting the DC generator by an external source.

Here in the diagram below AB curve is showing the magnetic characteristic of sereis wound DC generator. The linearity of the curve will continue till the saturation of the poles. After that there will be no further significant change of terminal voltage of DC generator for increasing field current. Due to residual magnetism there will be a small initial voltage across the armature that is why the curve started from a point A which is a little above the origin O.

Internal characteristic of series wound DC generator

The internal characteristic curve gives the relation between voltage generated in the armature and the load current. This curve is obtained by subtracting the drop due to the demagnetizing effect of armature reaction from the no load voltage. So, the actual generated voltage (E_g) will be less than the no load voltage (E_0). That is why the curve is slightly dropping from the open circuit characteristic curve. Here in the diagram below OC curve is showing the internal characteristic or total characteristic of the series wound DC generator. (Fig 2)

Fig 2



Characteristic Curves of Series Wound DC generators

External characteristic of series wound DC generator

The external characteristic curve shows the variation of terminal voltage (V) with the load current (I_L). Terminal voltage of this type of generator is obtained by subtracting ohmic drop due to armature resistance (R_a) and series field resistance (R_{sc}) from the actually generated voltage (E_g). Terminal voltage $V = E_g - I (R_a + R_{sc})$ The external characteristic curve lies below the internal characeristic curve because the value of terminal voltage is less than the generated voltage. Here in the Figure 2 OD curve is showing the external characteristic of the series wound DC generator

Characteristic curves of series wound DC generators

It can be observed from the characteristics of series wound DC generator, that with the increase in load (load is increased when load current increases) the terminal voltage of the machine increases. But after reaching its maximum value it starts to decrease due to excessive demagnetizing effect of armature reaction. This phenomenon is shown in the figure by the dotted line.

Dotted portion of the characteristic gives approximately constant current irrespective of the external load resistance. This is because if load is increased, the field current is increased as field is series connected with load. Similarly if load is increased, armature current is increased as the armature is also series connected with load. But due to saturation, there will be no further significance raise of magnetic field strength hence any further increase in induced voltage. But due to increased armature current the affect of armature reaction increases significantly which causes significant fall in load voltage. If load voltage falls, the load current is also decreased proportionally since current is proportional to voltage as per ohm's law. So increasing load tends to increase the load current, but decreasing load voltage, tends to decrease load current. Due to these two simultaneous effects, there will be no significant change in load current in dotted portion of external characteristics of series wound DC generator. That is why series DC generator is called constant current DC generator.

The external/load characteristic of a shunt generator: The external/load characteristic is important for judging the suitability of a generator for a particular purpose. When the DC shunt generator is loaded, it is found that the terminal voltage drops with increase in the load current. In a shunt generator, the field current appears to be constant, and, hence, `V' also should remain constant and be independent of the load. But, it is not so practically. There are two main reasons for the drop in terminal voltage. They are :

- armature resistance drop (directly)
- armature reaction drop (indirectly).

Because of the above two reasons, the terminal voltage is reduced. This in turn affects the field current also. The decreased field current reduces the field flux which further reduces the induced emf.

Armature resistance drop: According to formula

Terminal voltage = Induced emf – armature voltage drop

$V = E - I_a R_a$

where I_a is the armature current

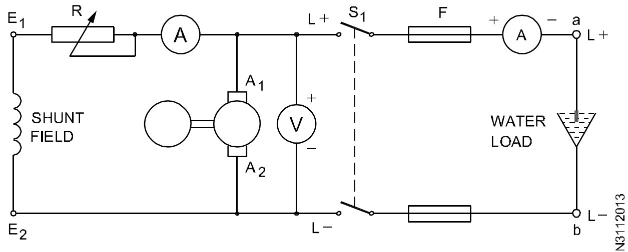
and R_a is the armature circuit resistance.

As such, when the load current is increased, more voltage is dropped in the armature circuit. Hence, the terminal voltage `V' decreases, under load condition.

Armature reaction drop: Due to the demagnetising effect of armature reaction, the main pole flux is weakened, and the induced emf (E) will be reduced in its magnitude.

The external characteristic gives the relation between terminal voltage and load current. Fig 3 gives the circuit diagram to determine this characteristic. The generator is first built up to its rated voltage. Then it is loaded in suitable steps up to full load. The terminal voltage and the corresponding load currents are noted for each step.

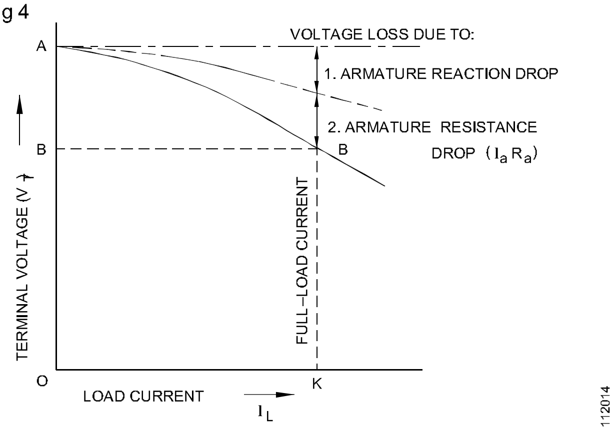
Fig 3



DC SHUNT GENERATOR

In this experiment, the field current has to be kept constant. This is due to the fact that when terminal potential decreases on load, the field which is connected across the armature will have a decreased current. This effect, if allowed, will reduce the field flux, thereby, decreasing the induced voltage. This effect cumulatively reduces the terminal voltage further. From the obtained values of the terminal voltage V_T and load current IL, the external characteristic curve is plotted as shown in Fig 4, keeping in V_T on `Y' axis and I_L on X axis. From the curve it will be observed that the no-load voltage OA is maximum, and it falls to OB when loaded, to indicate that the full load current value is OK as noted in the name-plate of the generator.

Fig 4

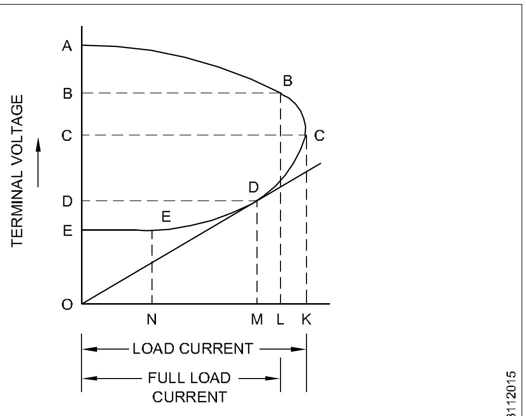


EXTERNAL CHARACTERISTIC CURVE OF DC SHUNT GENERATOR

Fall of voltage from no load to full load, which is due to armature reaction, and the armature voltage drop are found to be not appreciable. Normally the generators are designed to deliver full load current I_L, and the fall of voltage will be about 5 to 8 percent of the no-load voltage which can be regarded as negligible. If the load current is further increased by decreasing the load resistance, the curve reaches a point `C' as shown in Fig 5. At this point, the terminal voltage falls to OC which will be an appreciable fall when compared to the no-load terminal voltage. At this point `C', though the load current is maximum (OK), the terminal voltage will be much less than the no-load voltage.

However, when the load resistance is further decreased the load current decreases to OM and V_T is reduced to `OD', that means the load current cannot be increased beyond OK and the point `C' is called the breakdown point. It is the maximum possible current that a generator can supply. Beyond this point `C', the curve drops rapidly with decrease in the load resistance, indicating that the load current is also decreasing, instead of increasing. At point `E' the generator is virtually short-circuited, and all the voltage induced is dropped to near zero due to IaRa drop and armature reaction. Rather, we can say OE is the residual voltage of the generator. Practically all the generators operate only on the portion `AB' of the curve where the efficiency of the generator is maximum.

Fig 5



EXTERNAL CHARACTERISTIC CURVE (FULL CURVE)

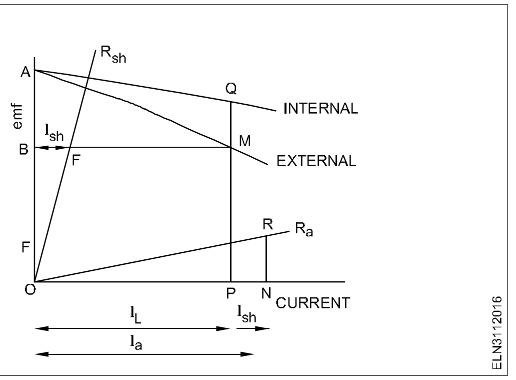
Internal characteristic: The internal characteristic gives the relation between induced voltage and the armature current. In a shunt generator,

$I_a = I_L + I_{sh} \qquad E = V_T + I_a R_a$

$$I_{sh} = \frac{V_T}{R_{sh}}$$

So, E/I_a curve can be obtained from the external characteristic shown in Fig 4. By plotting `$I_{sh}$' horizontally against `V', we get Rsh line which is a straight line through the origin, but because of the high resistance of the shunt field it has a very steep gradient as shown in Fig 6. Also draw the armature resistance(R_a) line by plotting the drop in voltage against the armature current as shown in Fig 4. Take any point `M' on the external characteristic (Fig 4) and draw the perpendicular `MP'. Then for the given terminal voltage the load current I_L = OP. Draw 'MB' horizontally, then BF = I_{sh}, and mark off PN = BF in the 'X' axis.

Fig 6



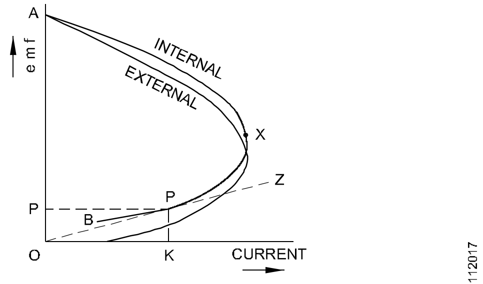
Then ON = OP + PN = $(I_L + I_{sh}) = I_a$.

Draw a line vertically from N to meet the armature resistance line Ra at `R'. Then, the vertical line `RN' is equal to the drop in the armature and, therefore, if the line PM is extended further to point `Q', making MQ = RN, the total length `PQ' is the sum of the terminal voltage and total armature drop, which is equal to the emf generated. Thus a point `Q' on the internal characteristic is obtained, and the total (internal) characteristic can be drawn by joining points A and Q.

If the load resistance is decreased, then the curve turns back as in Fig 7. If the load resistance is too small, then the generator is short-circuited and there is no generated emf due to heavy demagnetisation of the main poles.

Load critical resistance: It is defined as the minimum value of load resistance with which the generator builds up voltage, and, just below this value of load resistance the DC shunt generator will fail to build up its voltage when started with the load. When the DC shunt generator is started with the load, the terminal voltage may not raise beyond about 10V, the reason is the load resistance is so low, as if the generator is short-circuited. In Fig 7 the tangent line `OZ' to the internal characteristic APB is drawn. Its slope will give the value of the load critical resistance. As the DC shunt generator will not build up emf when made to build up with load below this value of resistance, it is called the load critical resistance.

Fig 7



INTERNAL & EXTERNAL CHARACTERISTIC CURVE

Load critical resistance in ohms =

$$\frac{\text{Voltage at point 'P'}}{\text{Load current at point 'P' (amps)}} = \frac{OP}{OK}$$

There are thus two critical resistances for a shunt generator, one for the field circuit and the other for the load external circuit.

Applications of DC shunt generator: According to the load characteristic of the DC shunt generator, the drop in voltage from no load to full load is not appreciable, up to its rated value of load current. Hence, it can be called a constant voltage generator. Therefore, it can be used for constant loads like:

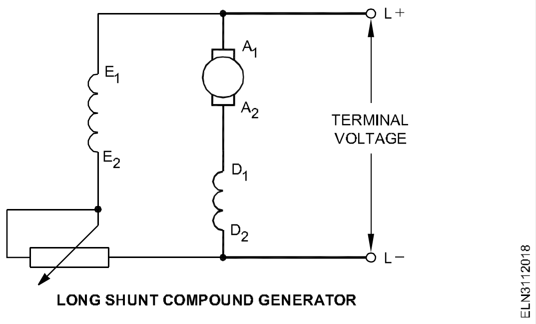
- centrifugal pump
- lighting load
- fans

- battery charging and electroplating.

Compound generator: Combination of shunt field and series field within one generator provides two sources of excitation, and such a generator is called a compound generator.

Long shunt compound generator: When the shunt field is connected in parallel with the series combination of the armature and the series field, the generator is said to be connected as a long shunt compound generator which is shown in Fig 8.

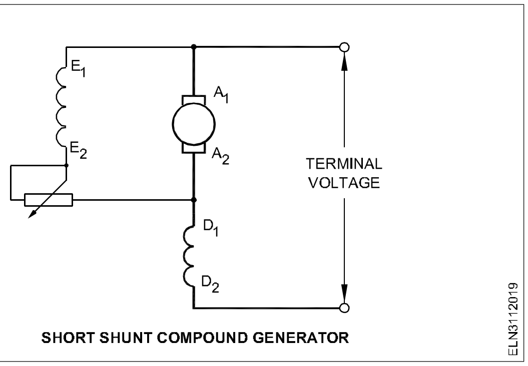
Fig 8



LONG SHUNT COMPOUND GENERATOR

Short shunt compound generator: When the shunt field is connected in parallel with only the armature, the generator is said to be connected as a short shunt compound generator which is shown in Fig 9.

Fig 9



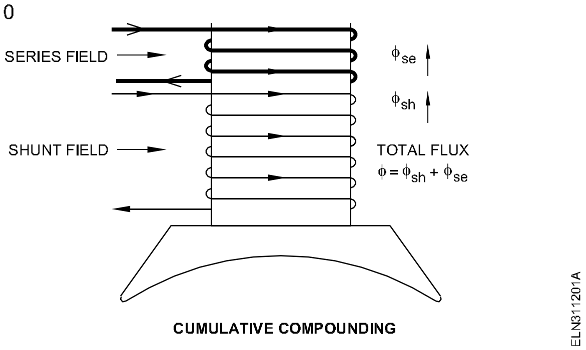
SHORT SHUNT COMPOUND GENERATOR

Cumulative compound generator: The shunt field excitation flux is usually more or less steady, and is affected only slightly as the terminal voltage fluctuates. The flux of the series field is quite variable because its ampere-turns depend upon the load current. When the load current is zero, it produces less flux (long shunt) or no flux (short shunt) and when the load current is high, it creates a good amount of flux. How much flux it must develop depends upon the extent to which it must compensate for the voltage drop. In a compound machine, the series field is wound directly over the shunt field with proper separation by insulations.

The series field coils may be connected to `assist' or `aid' the shunt field, as shown in Fig 10. Then this machine is said to be a cumulative (increasing by successive additions) compound generator. The ampere turns of the series field determines the amount of compounding.

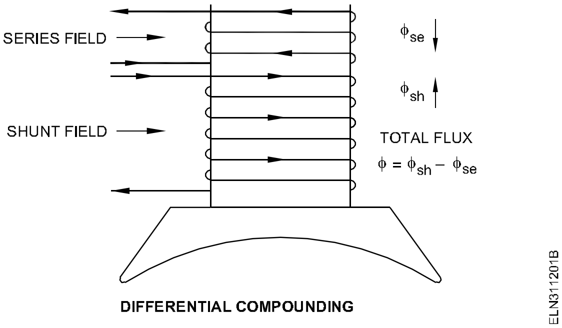
Differentially compounded generator: If the flux produced by the series field opposes the shunt field flux as shown in Fig 11, then the action is called `bucking' and the machine is said to be a differential (decreasing by successive subtractions) compound generator.

Fig 10



CUMULATIVE COMPOUNDING

Fig 11

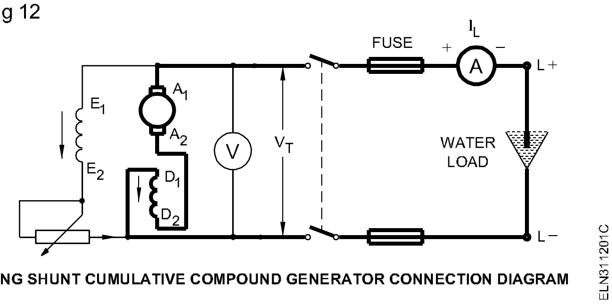


DIFFERENTIAL COMPOUNDING

External characteristics of DC compound generator

Cumulative compound generator: Fig 12 shows the connection diagram for a long shunt cumulative compound generator. In such a connection, the series field aids the shunt field and the total flux is equal to the sum of both the fluxes. By taking a set of readings for different load currents I_L and the corresponding terminal voltage V_T, we can draw a graph showing the relation between V_T and I_L. This curve is called the external characteristic curve.

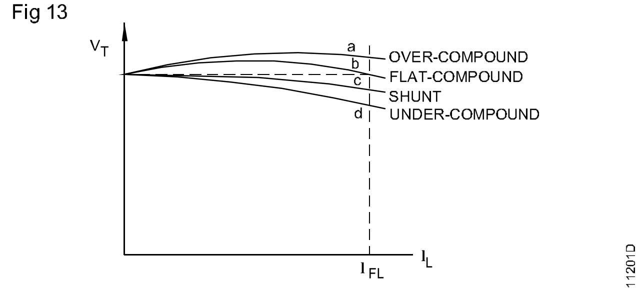
Fig 12



LONG SHUNT CUMULATIVE COMPOUND GENERATOR CONNECTION DIAGRAM

If the shape of the curve is as shown in curve `C' of Figure 13, then it will be the same as the curve shown for the shunt generator, and this generator could be used for constant voltage loads. If the shape of the curve is as shown in curve `a' of Fig 13, it shows that the terminal voltage goes on increasing with an increase of the load current. It is due to the reason that the series ampere-turns produce more flux than the flux required to over come the IaRa drop and the armature reaction. Such a machine is called an over-compounded generator, and this generator could be used for supplying load to long distance distribution lines so that the voltage drop in the line could be compensated by increased voltage.

Fig 13



EXTERNAL CHARACTERISTICS OF COMULATIVE COMPOUND DC GENERATORS

If the shape of the curve is as shown in curve `b' of Fig 13, it shows that the series ampere-turns at light load are producing more flux than required to overcome the I_aR_a drop but at full load the series field flux is just sufficient to overcome the I_aR_a drop and armature reaction. Such a machine is called a flat (level) compounded generator, and this generator could be used for supplying power to constant loads requiring specified terminal voltage.

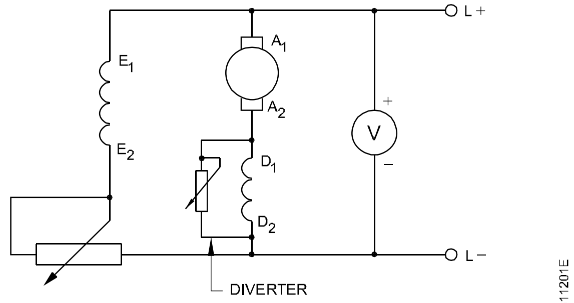
If the shape of the curve is as shown in curve `D', it shows that the series ampere-turns are not sufficient to overcome the drop in the terminal voltage due to the I_aR_a drop and the armature reaction but still they are aiding the shunt field. Such a machine is called an under-compounded generator, and this generator may be used for electroplating or lighting.

Degree of compoundings in a cumulative compound generator: The level of compounding in a generator can be altered by the amount of the series field current. Hence to adjust the series field current, a diverter may be connected as shown in Fig 14.

Differential compound generator: If the series field terminals are interchanged as shown in Fig 15, then the curve obtained may be as shown in Fig 16. In such a connection, the series field opposes the shunt field, and the generator becomes a differential compound generator. The total flux produced will be equal to the shunt field flux minus the series field flux. From the curve, it is clear that the terminal voltage drastically reduces with increase in the load current. It is due to the reason that series ampere-turns produce flux which are opposing or bucking the shunt field flux. This characteristic may be used in welding work, where the potential difference between the electrode and the job before striking an arc is in the order of, say 100V, and when the arc strikes it falls to, say 40 to 50 V, to maintain the flow of current.

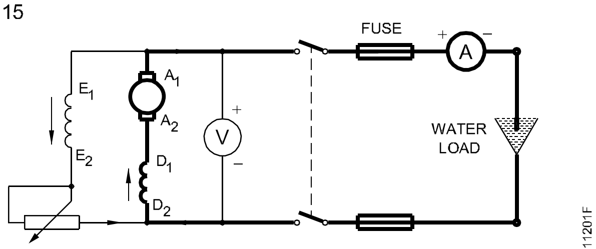
Application of a compound generator: Table 1 gives the different types of compound generators and their application in industry.

Fig 14



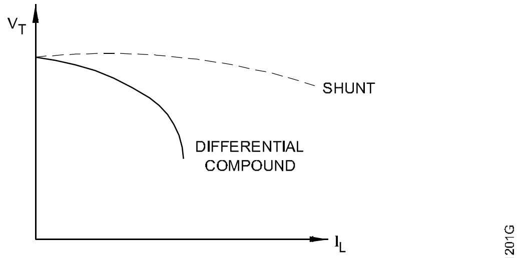
SERIES FIELD DIVERTER IN COMPOUND GENERATOR

Fig 15



CUMULATIVE COMPOUND GENERATOR CIRCUIT

Fig 16



EXTERNAL CHARACTERISTIC OF DIFFERENTIAL COMPOUND DC GENERATOR

Table 1

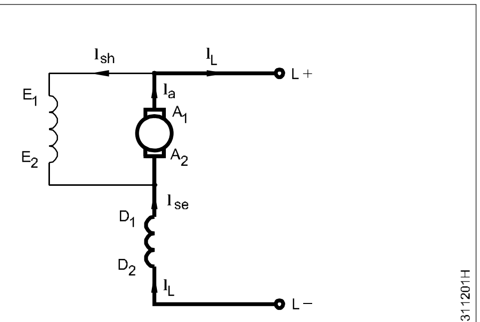
Sl.No.	Type of compound generator	Uses
1	Cumulative compound generator	
	a. Over-compounded	Used where the load is at a considerable distance from the generator as in railways, street lights etc.
	b. Flat or level compound	Used where the load is nearby, such as lighting loads and power loads of small buildings or lathes which require constant voltage.
	c. Under-compounded	Used for electroplating, lighting, etc.
2	Differential compound generator	Used for arc welding generators.

Numerical problems pertaining to DC generator: When the generator is loaded, there will be voltage drops in the armature resistance and series field resistance. To calculate the induced emf from the available data, the following steps should be adopted.

$Eg = V + I_aR_a + I_{se}R_{se}$

In the case of a short shunt compound generator shown in Fig 17, $I_{se} = I_L$ and $I_a = I_L + I_{sh}$.

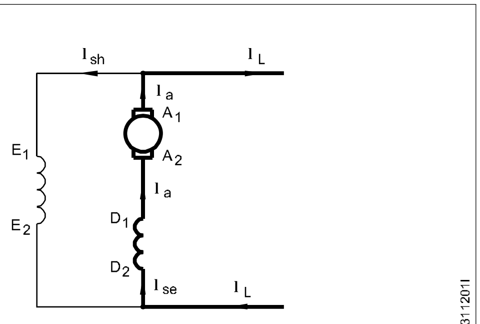
Fig 17



SHORT SHUNT COMPOUND GENERATOR

In the case of a long shunt compound generator shown in Fig 18 $I_{se} = I_a$ and $Ia = I_L + I_{sh} = I_{se}$

Fig 18



LONG SHUNT COMPOUND GENERATOR

where I_a = armature current in amps

I_{sh} = shunt field current in amps

I_{se} = series field current in amps

I_L = load current in amps.

Example: A long-shunt compound generator delivers a load current of 100 A at 400 V, and has armature, series field and shunt field resistances of 0.1 ohm, 0.03 ohm and 200 ohm respectively. Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.

Solution

Generator circuit is shown in Fig 19.

I_{sh} = 400/200 = 2 A

Current through armature and series winding is the same. Hence $I_a = I_{se}$ = 100 + 2 = 102 A.

Voltage drop in series field winding $= I_{se}R_{se}$ = 102 x 0.03 = 3.06 V

Armature voltage drop I_aR_a = 102 x 0.1 = 10.2 V.

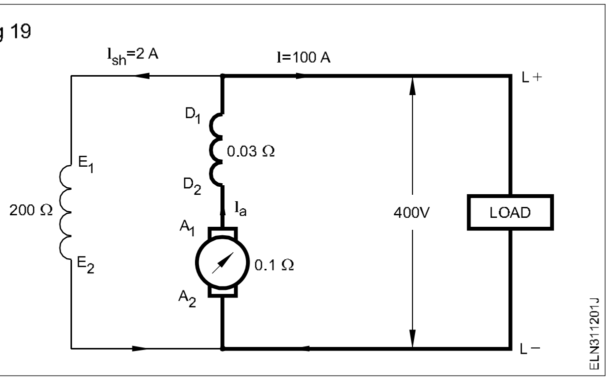
Assuming 2 brushes,

drop at brushes = 2 x 1 = 2 V.

Now, $E_g = V + I_aR_a$ + series drop + brush drop

= 400 + 10.2 + 3.06 + 2 = 415.26 V

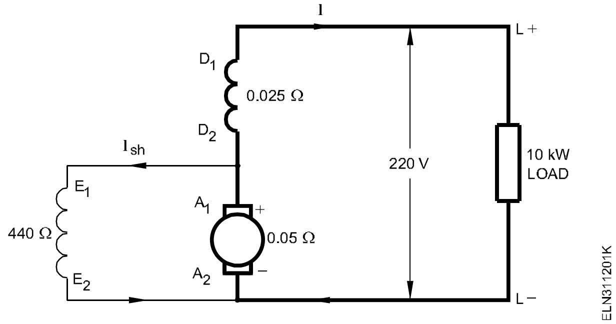
Fig 19



Example: A 10 kW compound generator works on full load with a terminal voltage of 220 V. The armature, series and shunt windings have resistances of 0.05 ohm, 0.025 ohm and 440 ohms respectively. Calculate the total emf generated in the armature when the machine is connected as short shunt.

Solution: Generator circuit is shown in Fig 20.

Fig 20



$$\text{Load current} = \frac{\text{Load in watts}}{\text{Ter min a voltage}} = \frac{10,000}{220} = 45.45A.$$

Voltage drop in series windings = 45.45 x 0.025 = 1.14 V.

Voltage across shunt winding = 220 + 1.14 = 221.14 V

I_{sh} = 221.14/440 = 0.503 A

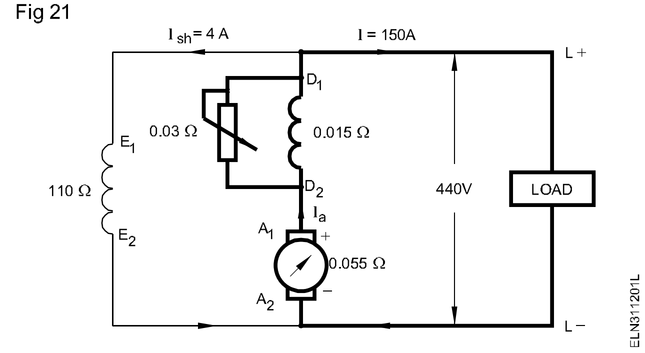
I_a = 45.45 + 0.503 = 45.953 A

I_aR_a = 45.953 x 0.05 = 2.297 V.

Generator emf = Terminal voltage + voltage drop in armature + voltage drop in series field = 220 + 2.297 + 1.14 = 223.44 V.

Example: In a long-shunt compound generator, as shown in Fig 21, the terminal voltage is 440 V when the generator delivers 150 A. Determine (i) induced emf (ii) total power generated and (iii) distribution of this power given that shunt field, series field, divertor and armature resistances are 110 ohms, 0.015 ohm, 0.03 ohm and 0.055 ohm respectively.

Fig 21



Solution

$I_{sh} = 440/110 = 4A;$

$I_a = 150 + 4 = 154$ A

Since the series field resistance and divertor resistance are in parallel (Fig 14), their combined resistance is = 0.03 x 0.015/0.045 = 0.01 ohm.

Total armature circuit resistance is = 0.055 + 0.01 = 0.065 ohm.

voltage drop across the series field and armature = 154 x 0.065 = 10.01V.

(i) Voltage generated by armature E_g = 440 + 10.01 = 450.01 V, say 450 V

(ii) Total power generated by armature = $E_g I_a$ = 450 x 154 = 69,300 W.

(iii) Power lost in armature = $I_a^2 R_a = 154^2 \times 0.055$ = 1304.4 W.

Power lost in the series field and divertor = $154^2 \times 0.01$

= 237.2 W

Power dissipated in shunt winding = VI_{sh} = 440 x 4

= 1760 W

Power delivered to load = 440 x 150

= 66000 W.

Parallel operation of DC generators

Parallel Operation of DC Generators: In a dc power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator.

The necessity of parallel operation

1 **Continuity of service:** If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down.

The supply can be obtained from a number of small units operating in parallel, then in case of failure of one unit, the continuity of supply can be maintained by other healthy units.

2 **Efficiency:** Generators run most efficiently when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

3 **Maintenance and repair:** If generators are operated in parallel, the routine or emergency operations can be performed by isolating the affected generator while load is being supplied by other units. This leads to both safety and economy.

4 **Increasing plant capacity:** When added capacity is required, the new unit can be simply paralleled with the old units to increase the plant capacity.

Conditions for paralleling of DC Generators

1 Output voltage must be same

2 Polarities must be same

Connecting Shunt Generators in Parallel: The generators in a power plant are connected in parallel through bus-bars. The bus-bars are heavy thick copper bars and they act as +ve and -ve terminals. The positive terminals of the generators are .connected to the +ve side of bus-bars and negative terminals to the negative side of bus-bars. Fig. 22 shows shunt generator 1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this generator, the second shunt generator 2 is connected in parallel with the first to meet the increased load demand.

Operation of paralleling of DC Generator

1 The prime mover of generator 2 is brought up to the rated speed. Now switch S_4 in the field circuit of the generator 2 is closed.

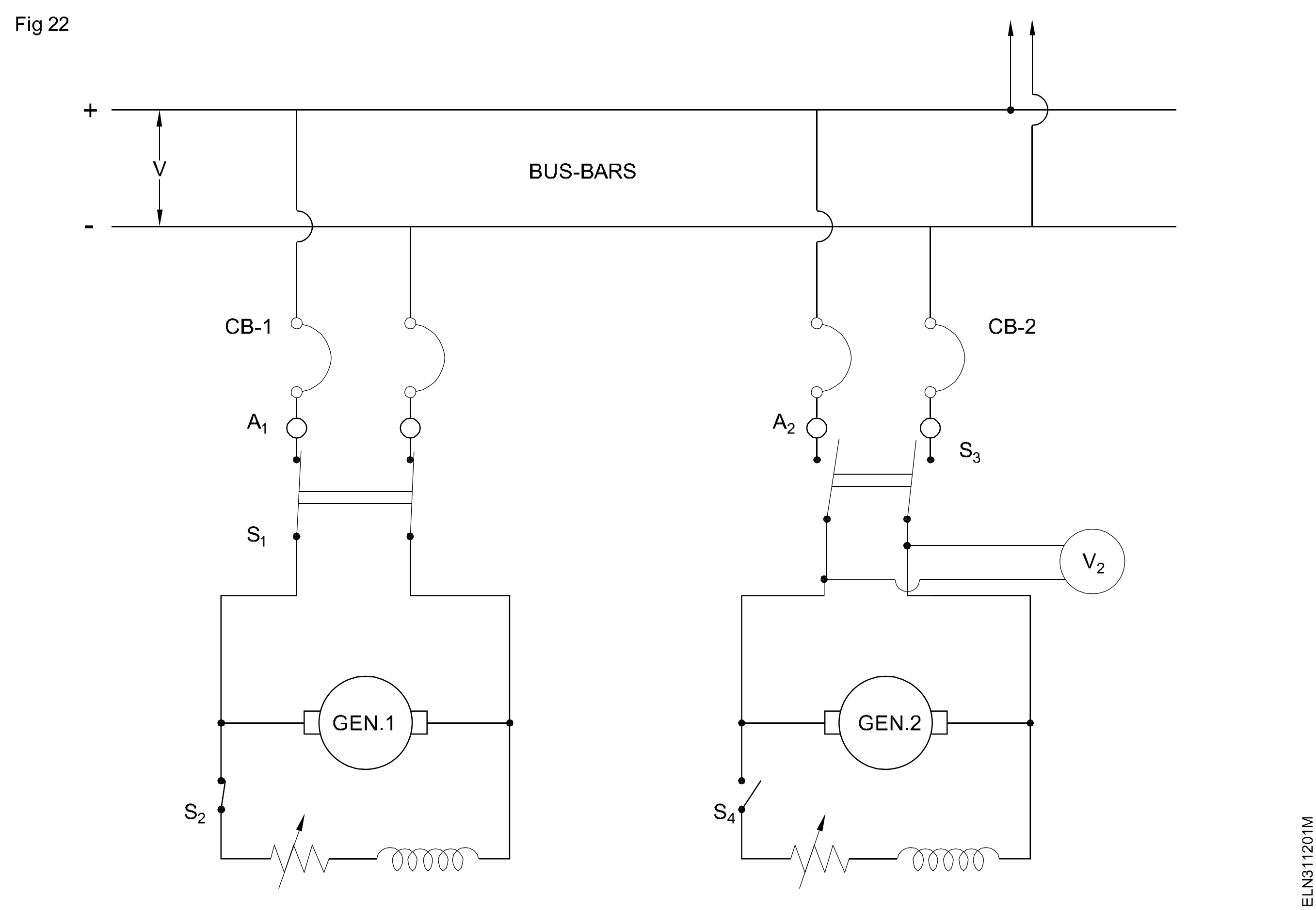
2 Next circuit breaker CB_2 is closed and the excitation of generator 2 is adjusted till it generates voltage equal to the bus-bars voltage. This is indicated by voltmeter V_2.

3 Now the generator 2 is ready to be paralleled with generator 1. The main switch S_3 is closed, thus putting generator 2 in parallel with generator 1. Note the generator 2 is not suplying any load because its generated emf is equal to bus-bars voltage. The generator is said to be "floating" (i.e. not supplying any load) on the bus-bars (Fig 22).

4 If generator 2 is to deliver any current then its generated voltage E should be greater than the bus-bars voltage V. In that case, current supplied by it I = (E-V)/Ra is the resistance of the armature circuit. By increasing the field current (and hence induced emf E), the generator 2 can be made to supply proper amount of load.

5 The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if generator 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the generator 1 to zero (This will be indicated by ammeter A_1) open CB_1 and then open the main switch S_1

Fig 22



Load Sharing: The load may be shifted from one generator to another merely by adjusting the field excitation. The load sharing of two generators which have unequal no-load voltages. Let E_1, E_2 = no-load voltages of the two generators R_1, R_2 = their armature resistances

Thus current output of the generators depends upon the values of E_1 and E_2. These values may be changed by field rheostats. The common terminal voltage (or bus-bars voltage) will depend upon (i) the emfs of individual generators and (ii) the total load current supplied. It is generally desired to keep the busbars voltage constant. This can be achieved by adjusting the field excitations of the generators operating in parallel.

Armature reaction

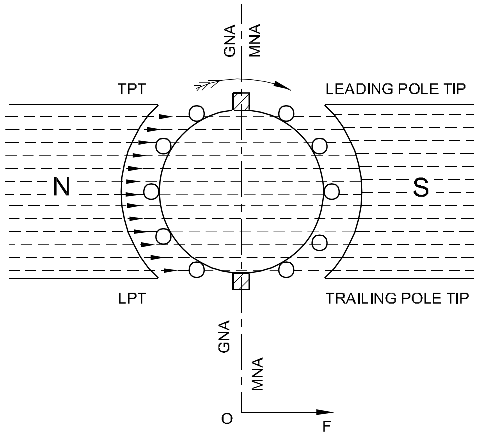
When armature conductors carry a lower load current, the mmf set up by the armature conductors interact with the main field flux in such a way that the field of the main field flux gets distorted and this is called cross-magnetizing effect.

However, the effect could be nullified by shifting the brush position of the generator by a small angle in the direction of rotation.

When the generator is loaded further, the pole tips get saturated which results in demagnetising the main field flux, thereby reducing the induced emf. This effect is called demagnetising effect, and can be explained further.

Fig 23 shows the flux distribution by the main field flux only. Since there is no current in the armature conductors, the flux is uniform. The GNA (Geometrical Neutral Axis) and MNA (Magnetic Neutral Axis) are coincident with each other.

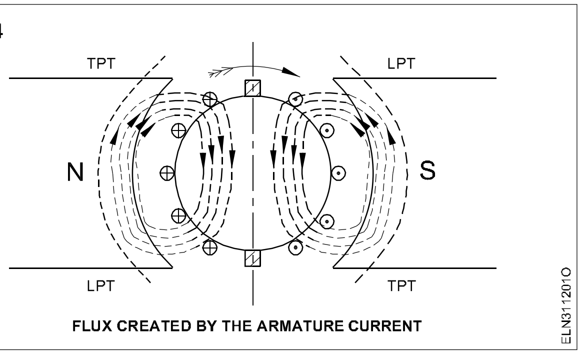
Fig 23



MAIN MAGNETIC FIELD OF A TWO - POLE DC MACHINE

Fig 24 shows the flux set up by the armature conductors alone. The current direction is marked as a plus sign(+), under the N.pole and dot (•) under the south pole as shown in the figure. The strength of this armature field (mmf) depends upon the armature current which, in turn, depends upon the load current.

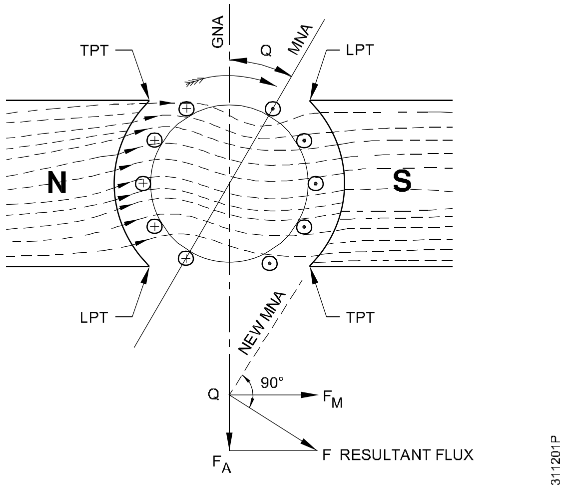
Fig 24



FLUX CREATED BY THE ARMATURE CURRENT

Cross-magnetising effect: Fig 25 shows the flux distribution by the combined effect of the main field and the armature mmf. The resulting field is found to have strengthened at the trailing pole tips and weakened at the leading pole tips. Due to this cross-magnetizing effect, the magnetic neutral axis (MNA) is shifted from the geometrical neutral axis (GNA) by an angle Q in the direction of rotation.

Fig 25



CROSS - MAGNETISING EFFECT

The effect of the main field flux (FF) and the armature flux (F_A) are shown by vectors in Fig 25. The magnetic neutral axis (MNA) should be at right angle to the resultant flux (F).

Remedy: The effect of the cross-magnetisation can be neutralized by shifting the brushes from GNA to MNA with the help of the rocker arm. Of course the amount of shifting depends upon the magnitude of the armature current. At the correct position of the brush, the induced emf will be maximum and the spark at the sides of brushes will be minimum.

Demagnetising effect: The uneven distribution of magnetic flux at heavy armature current results in a demagnetizing effect because strengthening on the trailing pole tip is only up to saturation of that tip. After saturation the flux cannot increase at the trailing tips equally with the decrease in flux at the leading pole tips which causes the demagnetising effect, and hence, the induced emf reduces under heavy load condition.

Remedy: To compensate the demagnetizing effect of the reduced induced emf, the ampere-turns are increased in the field winding itself to strengthen the main field for small machines. But, for large machines, the demagnetizing effect can be neutralized by providing compensating winding in the main pole-faces as shown in Fig 26, and connecting this compensating winding in series with armature as shown in Fig 27, which is for a compound machine.

Fig 26

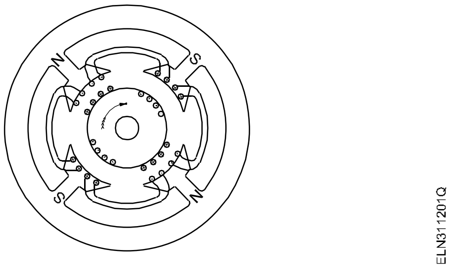
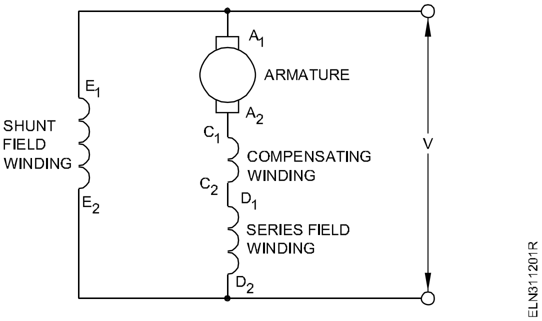


Fig 27



Compensating winding: The demagnetizing effect due to armature reaction in large machines, which are subjected to fluctuation of load, can be neutralized by this winding.

This winding carries an equal current in the opposite direction to the current in armature conductors. So the flux set up by them is also in the opposite direction and of equal magnitude to that of the armature flux. Hence they neutralize each other, and thereby, the demagnetising effect is nullified at any load, even at fluctuating loads.

Commutation

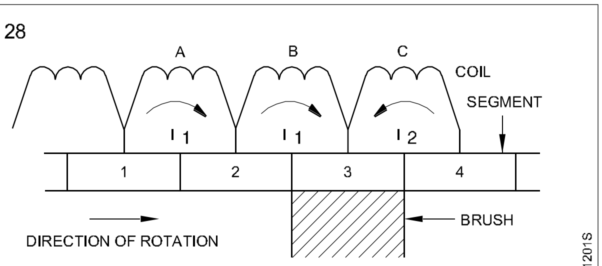
When a DC generator is loaded, the current flows through the armature winding, commutator and brushes to the external circuit. During this process, whenever a brush spans the two commutator segments, the winding element connected to those commutator segments is short-circuited. The changes in current direction, which take place in the winding element, just before, during and after the short circuit is called commutation.

If the change in the current direction is gradual, then a smooth commutation takes place. On the other hand a sudden change in current in the winding element is called rough commutation which results in heavy sparking at the sides of brushes. If rough commutation is allowed to continue, the brushes and commutator get spoiled ultimately due to the excess heat produced by the sparks.

These changes in current are explained through the following figures. Fig 28 shows the current in the coil B flows in a clockwise direction, and the brush collects I_1

amps from the left side winding and I_2 amps from the right side winding.

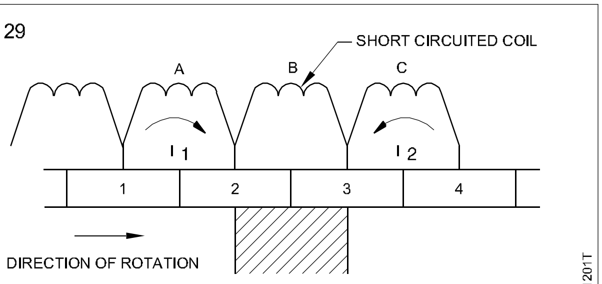
Fig 28



CURRENT COLLECTION - SEGMENT 3 IN CONTACT WITH THE BRUSH

Fig 29 shows that the brush short-circuits segments 2 and 3, and hence, coil B is short-circuited. Current I_1 in the left side winding passes to the brush through coil A, and the right side winding current passes through coil C. No current is in coil B as it is short-circuited.

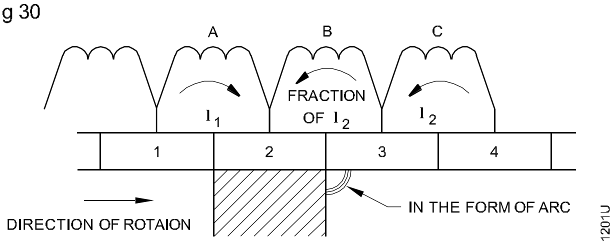
Fig 29



CURRENT COLLECTION-SEGMENTS 2 & 3 ARE IN CONTACT WITH THE BRUSH

Fig 30 shows that the brush contacts segment 2 only, and the current in the left side winding passes to the brush through coil A. On the other hand the current in the right hand side (I_2) should now pass through coil B via segment 2 to the brush.

Fig 30



CURRENT COLLECTION - SEGMENT 2 IN CONTACT WITH THE BRUSH

At this instant, the current in coil B, has to change its direction from clockwise to anticlockwise, but even though it changes it would not attain the full value of current after the short circuit. Therefore, a major portion of current I_2 from the right side passes to the brush through an arc from segment 3. This is due to the fact that the sudden change of current direction in coil B induces a statically induced (reactance) emf equal to $\frac{\varnothing}{t}$ or $\frac{I}{t}$

where Ø is the flux created by the current I in amps, and 't' represents the time of short circuit in seconds.

Further, the induced emf can also be calculated by knowing the reactance of the coil under commutation which depends upon the self-inductance of the coil, and the mutual inductance of the neighbouring coils.

For example, a2-pole, 2-brush DC generator delivers 100 amps to a load when running at 1440 r.p.m., and has 24 segments in its commutator. Then to find the statically induced emf in the winding element soon after the short-circuit, we have the current from the left side of the brush - 50 amps and the current from the right side of the brush - 50 amps.

Hence the change of current is from 50 amps in the clockwise direction to zero, then to 50 amps in the anticlockwise direction amounting to 100 amps.

Time taken for one revolution

$$= \frac{60}{1440} = 0.04166 \text{ seconds}$$

Time taken for short circuit

$$= \frac{0.04166 \text{ seconds}}{24 \text{ segments}} = 0.001736 \text{ seconds}$$

which is equal to time reqd. to pass one segment

Hence the statically induced emf

$$= \frac{I}{t} = \frac{100}{0.001730} = 57{,}603\text{V} .$$

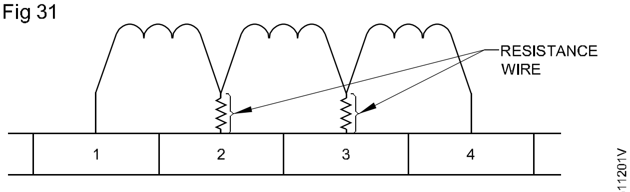
This induced emf will obey Lenz's law, and oppose the change in the current. Hence the current from the right hand side as shown in Fig 30 would not be able to pass through coil B, and hence it jumps to the brush in the form of an arc. This is called rough commutation.

Remedies for rough commutation by providing interpoles

To avoid sparks in the brush position, the following methods are used which effectively change the rough commutation to smooth commutation.

- Resistance wires are introduced between the end connection of the coil to the commutator, as shown in Fig 31. This increased resistance helps the current to change its direction smoothly, increasing the timing and reducing the statically induced emf.

Fig 31

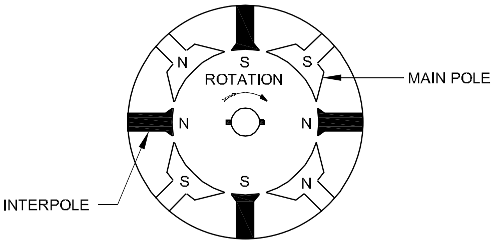


COMMUTATION WITH RESISTANCE WIRES

- High resistance brushes are used. Hence the contact resistance variation allows the current to change its direction smoothly, thereby reducing the statically induced emf.
- Small field poles called inter-poles are provided in between the main poles as shown in Fig 32. These inter-poles have their polarity the same as the next pole

ahead in the direction of rotation of the, generators. Further, their winding is connected in series with the armature so that they carry the same current as that of the armature.

Fig 32

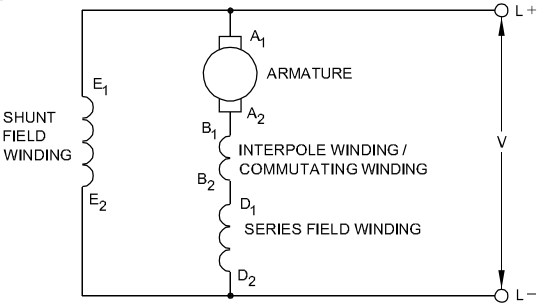


COMMUTATION WITH INTERPOLES

These inter-poles produce an emf opposite in direction to the statically induced emf, and have a magnitude depending upon the current. Thereby, the effect of statically induced emf is nullified.

These inter-poles are wound with less number of turns having thick gauge wire. Fig 33 shows the connection of inter-pole winding in a DC compound machine.

Fig 33



CONNECTION OF INTERPOLE WINDING IN A DC MACHINE

Losses and efficiency of DC machines

It is convenient to determine the efficiency of a rotating machine by determining the losses than by direct loading. Further it is not possible to arrange actual load for large and medium sized machines. By knowing the losses, the machine efficiency can be found by

$$\eta = \frac{\text{output}}{\text{output} + \text{losses}} \left(\text{For generators}\right)$$

$$\eta = \frac{\text{input - losses}}{\text{input}} \left(\text{For motors}\right)$$

In the process of energy conversion in rotating machines - current, flux and rotation are involved which cause losses in conductors, ferromagnetic materials and mechanical losses respectively. Various losses occurring in a DC machine are listed below (FIg 34 shows losses of DC machine.

Total losses can be broadly divided into two types

1 Constant losses

2 Variable losses

These losses can be further divided as

1 Constant losses - i) Core loss or iron loss

a Hysteresis loss

b Eddy current loss

ii Mechanical loss

a Windage loss

b Friction loss - brush friction loss and Bearing friction loss.

2 Variable losses - i) copper loss (I^2R)

a Armature copper loss

b Field copper loss

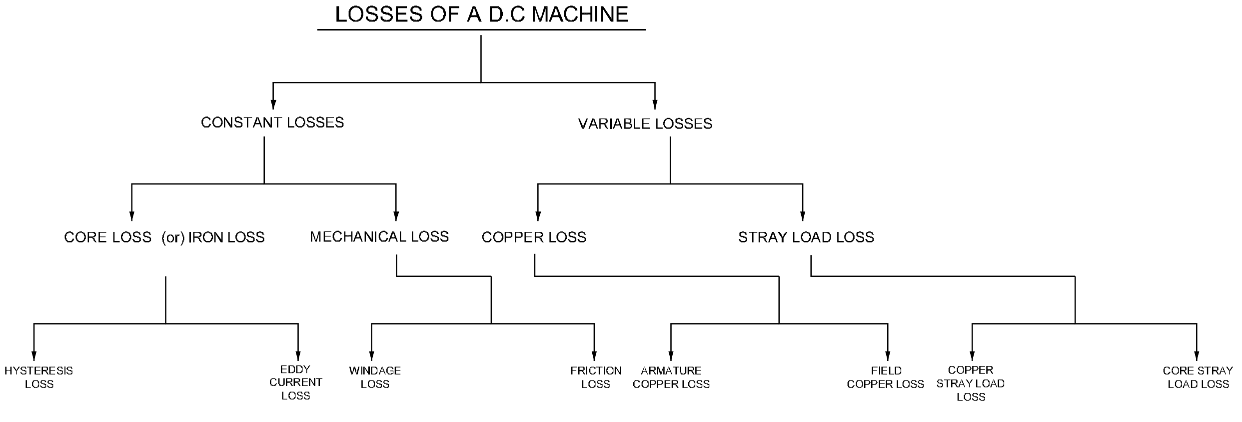
c Brush contact loss

ii Stray load loss

a Copper stray load loss

b Core stray load loss

Fig 34



Core loss or iron loss occurs in the armature core is due to the rotation of armature core in the magnetic flux produced by the field system. Iron loss consists of a) Hysteresis loss and b) Eddy current loss.

a) **Hysteresis loss:** This loss is due to the reversal of magnetization of armature core as the core passes under north and south poles alternatively. This loss depends on the volume and grade of iron, maximum value of flux density BM and frequency. Hysteresis loss W_h is given by Steinmetz formula.

$W_h = K_h B_m 1.6\ f\ v$ joule/sec. or watt

where K_h = Constant of proportionalitiy - depends on core material.

B_m = Maximum flux density in wb/m^2

F = Frequency in hertz

V = Volume of the armature core in m^3

b) Eddy Current loss: Eddy currents are the currents set up by the induced emf in the armature core when the core cuts the magnetic flux. The loss occurring due to the flow of eddy current is known as eddy current loss. To reduce this loss, the core is laminated, stacked and riveted. These laminations are insulated from each other by a thin coating of varnish. The effect of lamination is to reduce the current path because of increased resistance due to reduced cross section area of laminated core. Thus the magnitude of eddy current is reduced resulting in the reduction of eddy current loss.

Eddy Current loss W_e is given by

$W_e = K_e B^2_m f^2 t^2 v$ Watt

Where K_e = Constant of Proportionality

B_m = Maximum flux density in Wb/m^2

f = Frequency in Hz.

t = Thickness of the lamination in meters

v = Volume of the armature core in m^3.

ii Mechanical loss: these losses include losses due to windage, brush friction and bearing friction losses.

2) Variable losses: Variable losses consist of (i) Copper loss:

Armature copper loss ($I_a^2 r_a$) loss: This loss occurs in the armature windings because of the resistance of armature windings, when the current flows through them. The loss occurring is termed as copper loss or $I_a^2 r_a$ loss. This loss varies with the varying load.

b) Field contact drop: This is due the contact resistance between the brush and the commutator. This loss remains constant with load.

c) Brush contact drop: This is due the contact resistance between the brush and the commutator. This loss remains constant with load.

ii) Stray load loss: The additional losses which vary with the load but cannot be related to current in a simple manner are called stray load loss. Stray load losses are.

i) Copper stray load loss : The loss occuring in the conductor due to skin effect and loss due to the eddy currents in the conductor. Set up by the flux passing through them are called copper stray load loss.

ii) Core stray load loss: When the load current flows through the armature conductors, the flux density distribution gets distorted in the teeth and core. The flux density decreases at one end of the flux density wave and increases at the other. Since the core loss is proportional to the square of the flux density, the decrease in flux density will be less than the increase due to the increase in flux density, resulting in a net increase in the core loss predominantly in the teeth, known as stray load loss in the core.

Further under highly saturated conditions of teeth, flux leaks through the frame and end shields causing eddy current loss in them. This loss is a component of stray load loss. Stray load loss is difficult to calculate accurately and therefore it is taken as 1 % of the output of DC machine.

Efficiency of a DC generator

Power flow in a DC generator is shown in Figure 35.

$$= \frac{\text{output}}{\text{output} + \text{losses}} = \frac{VI}{VI + I_a^2 r_a + W_e}$$

where w_e is constant loss

Condition for maximum efficiency

Generator output = VI

Generator input = output+losses

$= VI + I^2 a R_a + W_e$

$= VI + (I + I_{sh})^2 R_a + W_e \quad \therefore I_a = (I + I_{sh})$

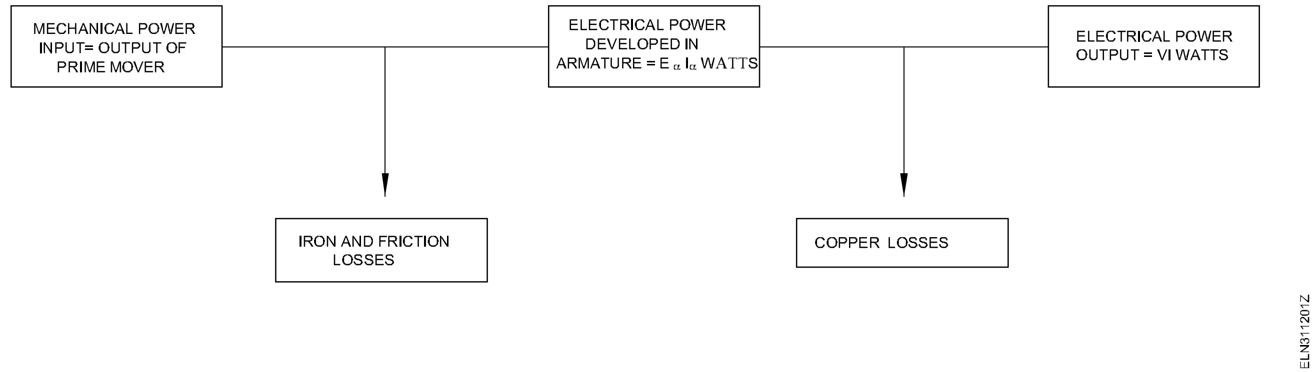
However, if I_{sh} is negligible as compared to load current $I_a = I$ (approx.)

$$\because \eta = \frac{\text{output}}{\text{input}} = \frac{VI}{VI + I^2 a R_a + W_e} = \frac{VI}{VI + I^2 R_a + W_e}$$

Efficiency is maximum when variable loss = constant loss.

The load current corresponding to maximum efficiency is given by the relation.

Fig 35



$$I^2R_a = We$$

$$I = \sqrt{\frac{W_e}{R_a}}$$

Efficiency of DC motor

The power flow in a DC motor is shown in Figure 36

$$\text{Efficiency of a DC motor} = \frac{\text{input} - \text{losses}}{\text{input}}$$

$$= \frac{VI - I_a^2 r_a - w_c}{VI}$$

The condition for maximum power developed

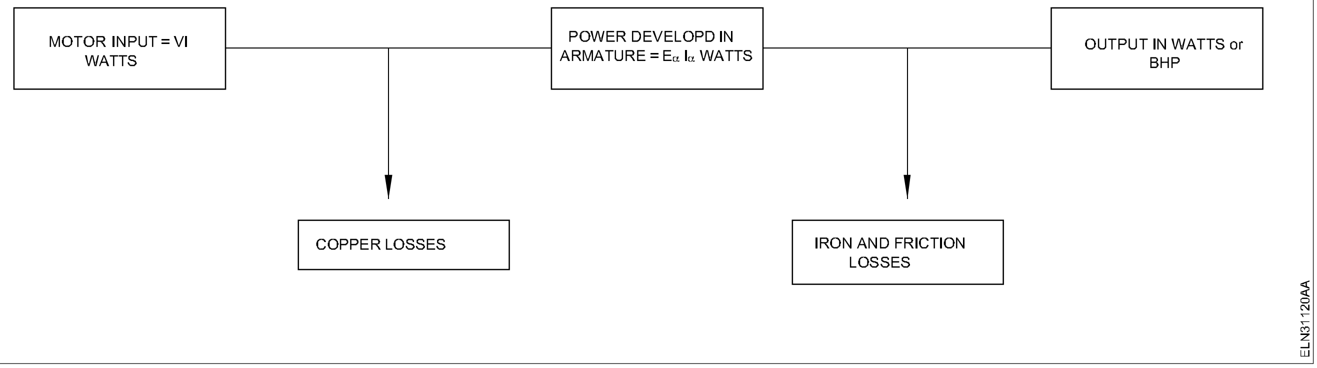
$$E_b = \frac{V}{2} = I_a r_a$$

This is shown in equation

The condition for maximum efficiency is variable loss = constant loss

$$I^2 r_a = w_e$$

Fig 36



Losses in a DC generator and DC motor

A DC generator converts mechanical power into electrical power and a DC motor converts electrical power into mechanical power. Thus, for a dc generator, input power is in the form of mechanical and the output power is in the form of electrical. On the other hand, for a dc motor, input power is in the form of electrical and output power is in the form of mechanical. In a practical machine, whole of the input power cannot be converted into output power as some power is lost in the conversion process. This causes the efficiency of the machine to be reduced. Efficiency is the ratio of output power to the input power. Thus, in order to design rotating dc machines (or andy electrical machine) with higher efficiency, it is important to study the losses occurring in them. Various losses in a rotating DC machine (DC generator or DC motor) can be characterised as follows:

Losses in a rotating DC machine

- **Copper losses**
  - Armature Cu loss
  - Field Cu loss
  - Loss due to brush contact resistance
- **Iron losses**
  - Hysteresis loss
  - Eddy current loss

- **Mechanical losses**
  - Friction loss
  - Windage loss

The above tree categorizes various types of losses that occur in a dc generator or a dc motor. Each of these is explained in details below.

Copper Losses

These losses occur in armature and field copper windings. Copper losses consist of Armature copper loss, Field copper loss and loss due to brush contact resistance.

Armature copper loss = $I_a{}^2R_a$ (where, $I_a{}^2R_a$ (where, I_a = Armature current and R_a = Armature resistance)

This loss contributes about 30 to 40% to full load losses. The armature copper loss is variable and depends upon the amount of loading of the machine.

Field copper loss = $I_f{}^2R_f$ (where, I_f = field current and R_f = field resistance) In the case of a shunt wounded field, field copper loss is practically constant. It contributes about 20 to 30% to full load losses.

Brush contact resistance also contributes to the copper losses. Generally, this loss is included into armature copper loss.

Iron losses (Core losses)

As the armature core is made of iron and it rotates in a magnetic field, a small current gets induced in the core itself too. Due to this current, eddy current loss and hysteresis loss occur in the armature iron core. Iron losses are also called as Core losses or magnetic losses.

Hysteresis loss is due to the reversal of magnetization of the armature core. When the core passes under one pair of poles, it undergoes one complete cycle of magnetic reversal. The frequency of magnetic reversal is given by, f=P.N/120 (where, P = no. of poles and N = Speed in rpm)

The loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. Hysteresis loss is given by, Steinmetz formula: $W_h = \eta B_{max}{}^{1.6} fV$ (watts), η = Steinmetz hysteresis constant V = volume of the core in m^3

Eddy current loss: When the armature core rotates in the magnetic field, an emf is also induced in the core (just like it induces in armature conductors), according to the Faraday's law of electromagnetic induction. Though this induced emf is small, it causes a large current to folw in the body due to the low resistance of the core. This current is known as eddy current. The powe loss due to this current is known as eddy current loss.

Mechanical losses

Mechanical losses consist of the losses due to friction in bearings and commutator. Air friction loss of rotating armature also contributes to these. These losses are about 10 to 20% of full load losses.

Stray losses

In addition to the losses stated above, there may be small losses present which are called as stray losses or miscellaneous losses. These losses are difficult to account. They are usually due to inaccuracies in the designing and modeling of the machine. Most of the times, stray losses are assumed to be 1% of the full load.

Power flow diagram

The most convenient method to understand these losses in a dc generator or a dc motor is using the power flow diagram. The diagram visualizes the amount of power that has been lost in various types of losses and the amount of power which has been actually converted into the output. Following are the typical flow diagrams for a dc generator and a dc motor. (Fig 37 & 38)

Fig 37

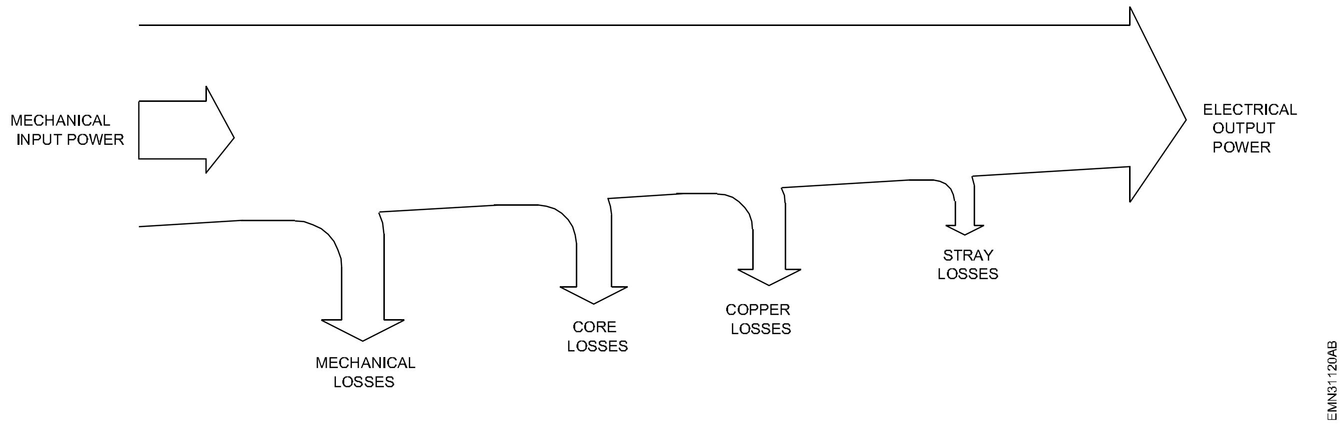
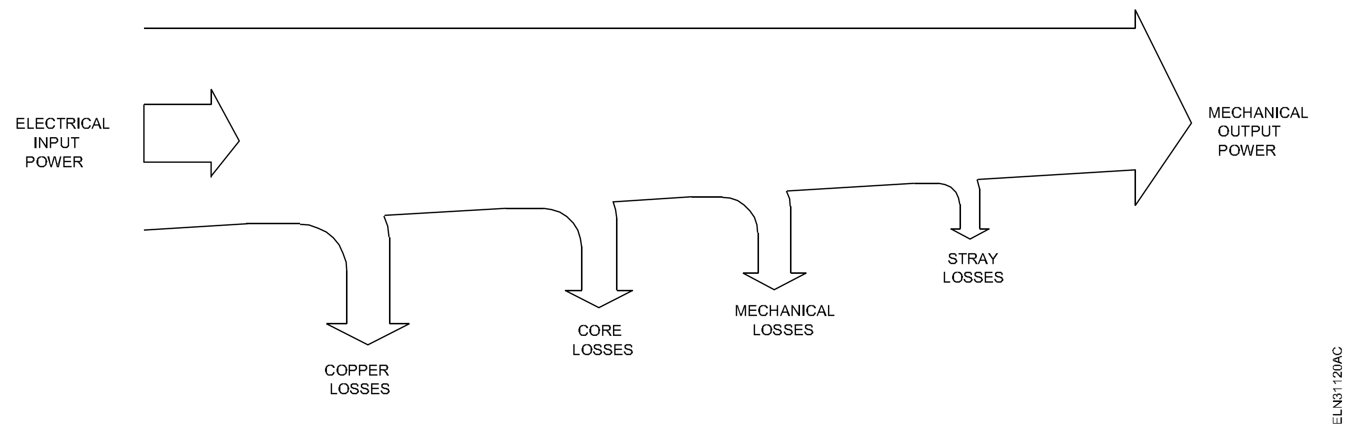


Fig 38



Efficiency of DC generator

Efficiency is simply defined as the ratio of output power to the input power. Let R = total resistance of the armature circuit (including the brush contact resistance, at series winding resistance, inter-pole winding resistance and compensating winding resistance). The efficiency of DC generator is explained in the line diagram Fig 39

I is the output current

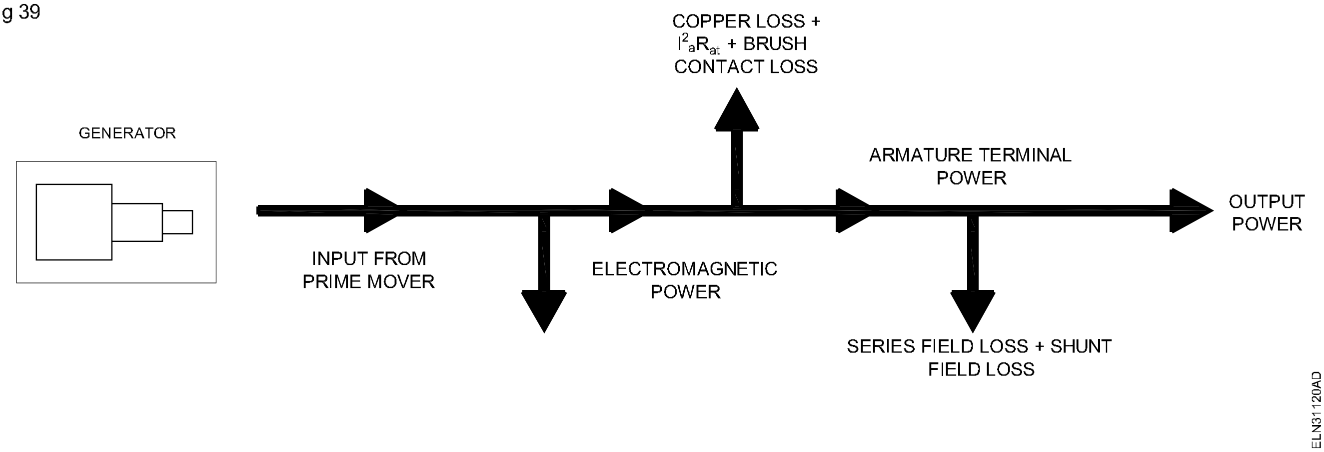
I_{sh} is the current through the shunt field

I_a is the armature current = $I + I_{sh}$

V is the terminal voltage.

Total copper loss in the armature circuit = $I_a{}^2 R_{at}$

Fig 39



Power loss in the shunt circuit = V_{Ish} (this includes the loss in the shunt regulating resistance).

Mechanical losses = friction loss of bearings + friction loss at a commutator + windage loss.

Stray loss = mechanical loss + core loss

The sum of the shunt field copper loss and stray losses may be considered as a combined fixed (constant) loss that does not vary with the load current I.

Therefore, the constant losses (in shunt and compound generators) = stray loss + shunt field copper losses.

Generator efficiency is given by the equation shown below.

$$\eta_G = \frac{\text{Generator output}}{\text{Generator output} + \text{losses}}$$

$$\eta_G = \frac{VI}{VI + I_a^2 R_{at} + V_{BD} I_a + P_k}$$

$$I_a = I + I_{sh}$$