ELECTRICAL MACHINES(EE 554)

Chapter-3 (DC Generator)

3.4 Types of DC generator:

The field winding of a DC generator has to be supplied by DC current in order to produced magnetic field. The supply of DC current to the field winding is known as “excitation”. The excitation can be provided by various ways and accordingly DC generators are classified as follow:

a) Separately excited DC generator
b) Self-excited DC generator

a) Separately excited DC generator:
It is the generator, whose field winding is excited by an independent external DC voltage source as shown in Fig.3.18. There is no electrical connection between field winding and armature winding. Fig.3.18(a) shows the connection diagram and 3.18(b) shows the circuit diagram of separately excited DC generator.

Here,
R_f = Resistance of field winding
I_f = Current through the field winding
E = Emf induced across the armature circuit
R_a = Resistance of armature circuit
V = Terminal voltage across the load
R_L = Load resistance
I_L = Load current

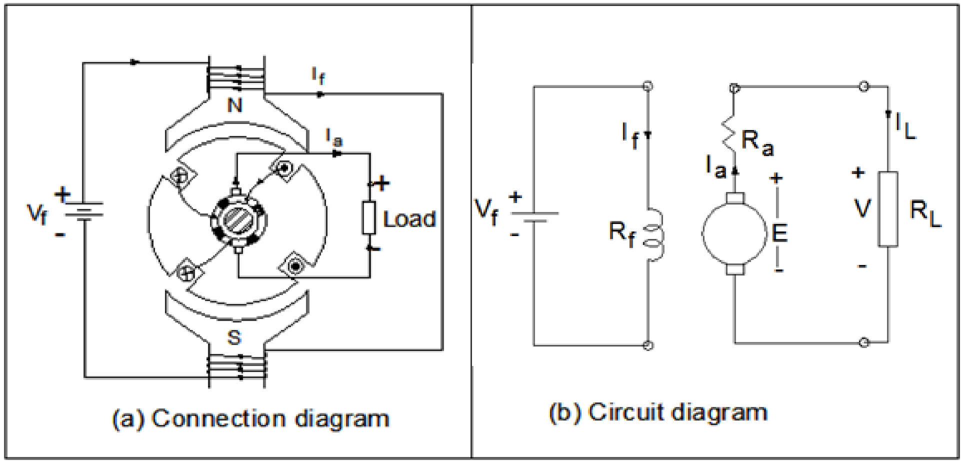


Fig.3.18 Separately excited DC generator

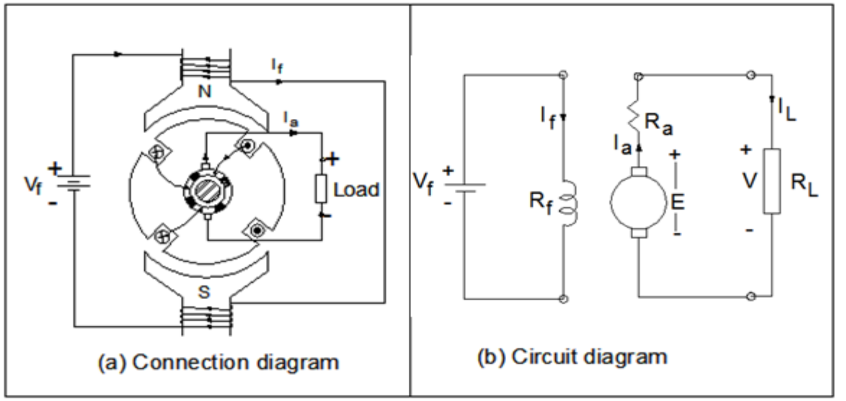
$$I_f = \frac{V_f}{R_f} \qquad \text{Here,} \quad I_a = I_L$$

Using Kirchoff's voltage law in armature and load circuit:

$$E - I_a.R_a - I_L.R_L = 0$$

[note that : $I_L.R_L = V$ = load terminal voltage]

Therefore, $\quad E - I_a.R_a = V \qquad (3.4)$



The terminal voltage is always less than the emf generated, because there will be some voltage drop in the armature resistance. Some voltage drop also takes place in the contact resistance between carbon brushes and commutator segments. Hence, the actual terminal voltage is given by:

$V = E - I_a.R_a$ – Voltage drop in the brushes. (3.5)

b) <u>Self excited DC generator</u>:

It is the generator, whose field winding is excited by the DC current generated by the armature of the machine itself. No external DC source is required for such generator. The field winding and armature winding have electrical connection. The inter-connection of field winding and armature winding can be connected in different ways and accordingly the self excited DC generators are classified into following types:

i) DC Shunt generator
ii) DC Series generator
iii) DC compound generator

i) <u>DC Shunt generator</u>:

In this type of generator, the field winding and armature winding are connected in parallel. In other word, the armature circuit is shunted by the field winding circuit. Fig.3.19 shows circuit diagram of DC shunt generator.

Field winding curreny $I_f = \dfrac{V_f}{R_f} = \dfrac{V}{R_f}$ (3.6)

Here, $I_a = I_L + I_f$ (3.7)

Terminal voltage across the load $V = E - I_a.R_a$ (3.8)

Load current $I_L = \dfrac{V}{R_L}$ (3.9)

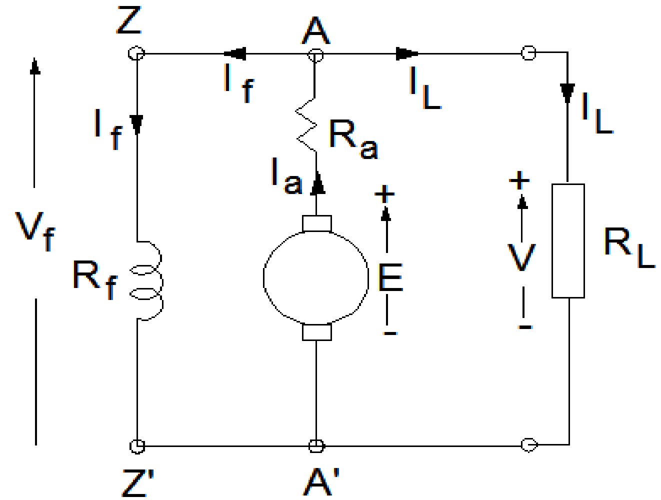
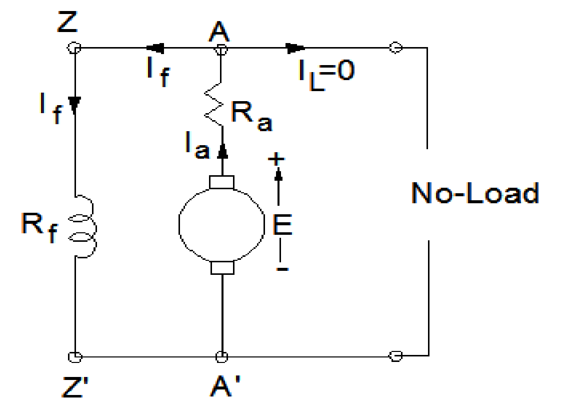


Fig.3.19 Circuit diagram of DC shunt generator

As the field winding current is much less with compare to armature current and load current, the field winding is made of thin wire and it will have higher resistance with compare to R_a.

A shunt generator must be started without load, otherwise the voltage will not build-up. If the shunt generator is started with load, all the current generated by armature at starting will flow through the load circuit and voltage build up can not take place.

At starting both armature current and field current are zero. However, there will be some magnetic flux in the air-gap of the machine due to the residual flux of the field pole. The magnitude of this residual flux will be very small. When the armature is rotated by external mechanical force, the armature will generate a small voltage due to residual flux. As the load terminal is open at the starting period, all the current generated by the armature will flow through the field winding. The field winding current at the beginning of voltage buil-up process is given by:



$$I_{f(0)} = \frac{E_{(0)}}{R_f} \qquad (3.10)$$

Where, $E_{(0)}$ = Emf generated by armature due to residual flux.

Now, the magnetic flux produced by the field poles will increase to to $I_{f(0)}$. Hence, the magnitude of emf will increase and accordingly more field current will flow. This process will keep on going and the magnitude of emf goes on increasing and finally the armature generates a steady constant voltage. Then the load can be connected. The detail of this voltage build-up process shall be discussed in the next section.

ii) DC series generator:

In this type of generator, the field winding is connected in series with the armature circuit as shown in Fig.3. 20.

Here, the same current passage through armature winding, field winding and load.

Therefore, $I_a = I_f = I_L$ (3.11)

The voltage build-up process is same as in shunt generator. However, it must be started with load. Otherwise, no current will flow through the field winding and voltage build-up can not take place.

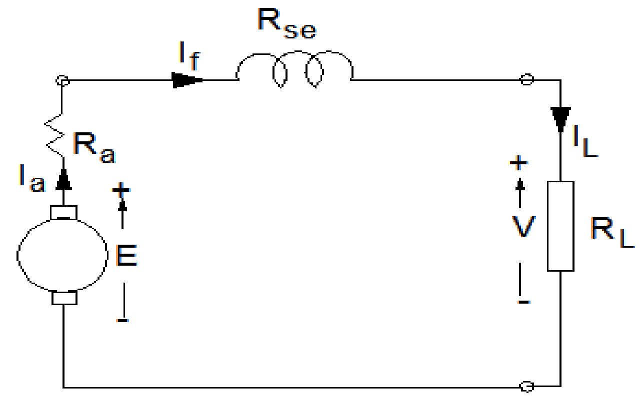


Fig.3.20 Circuit diagram of DC series generator

The load terminal voltage is given by: $V = E - I_a.R_a - I_f.R_{se}$ (3.12)

Here, the series field winding has to carry full load current, it is made of thick wire few number of turns.

iii) DC compound generator :

In this type of generator, there will be two sets of field windings. One set is connected in series with armature or load and another set is connected in parallel with the armature. Therefore, this type of generator will have a mixed type of characteristic lying between shunt and series characteristics. As the series winding has to carry full load current, it is made of thick wire with few turns. Whereas, the shunt field winding is made of thin wire with many numbers of turns. Because, the shunt field winding has to carry only small value of excitation current (I_f). The compound generator had been further classified into following two types:

a) Long shunt compound generator

b) Short shunt compound generator

Fig.3.21(a) and Fig.3.21(b) shows the circuit diagrams of long shunt DC generator and short shunt generator respectively.

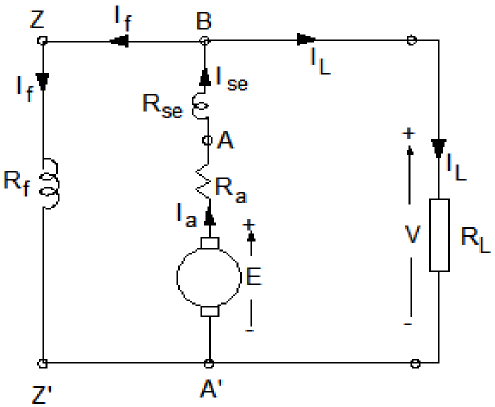


Fig.3.21(a)Long shunt compound generator

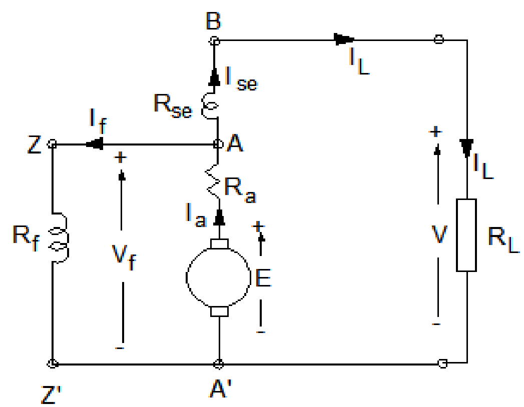
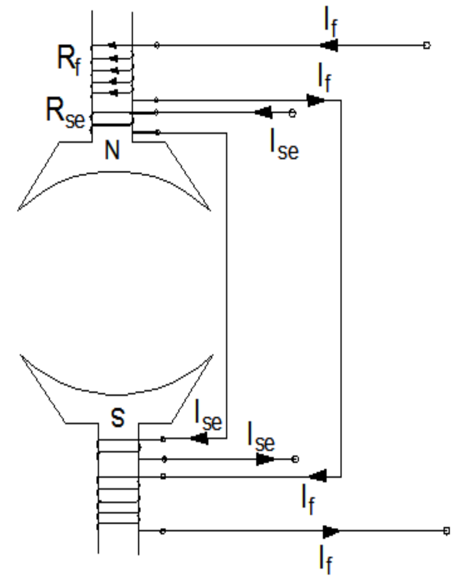


Fig.3.21(b) Short shunt compound generator



For long shunt generator:

$$I_f = \frac{V}{R_f} \qquad (3.13) \qquad\qquad V = E - I_a R_a - I_a R_{se} \qquad (3.14)$$

For short shunt generator:

$$I_f = \frac{V_f}{R_f} = \frac{E - I_a R_a}{R_f} \quad \text{and} \quad V_f = V + I_{se.} R_{se} \qquad (3.15)$$

$$V = E - I_a R_a - I_L R_{se} \qquad (3.16)$$

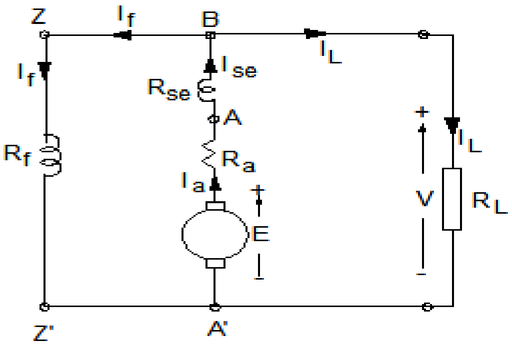
Illustrative Example :

A DC compound generator delivers 50A to the load at 500V. The armature, series field and field windings resistances are 0.05 Ω, 0.03 Ω and 250 Ω respectively. The voltage drop in carbon brush is 1 V per brush. Calculate the generated emf a) for long shunt compound b) Short shunt compound

Solution:

Given parameters : Ra = 0.05 ohm, R_{se} = 0.03 ohm and R_f = 250 ohms

a) Long shunt compound:



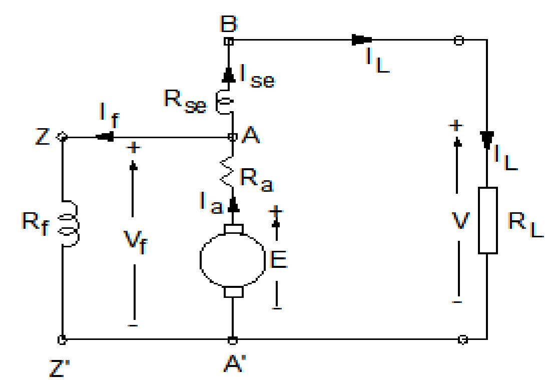
Voltage across the load V = 500 V

$$\text{Shunt field current } I_f = \frac{V}{R_f} = \frac{500}{250} = 2A \qquad I_L = 50\text{ A}$$

$\therefore$ $I_a = I_L + I_f = 50 + 2 = 52$ A

Then emf induced E = V + I_a (R_a+R_{se}) + drop in brushes = 500 + 52×(0.05+0.03) +1×2 = <u>506.16 V</u>

b) Short shunt compound:



Voltage across the shunt field winding:

V_f = V +$I_L R_{se}$= 500 + 50×0.03 = 501.5 V

$$I_f = \frac{V_f}{R_f} = \frac{501.5}{250} = 2.006A$$

$\therefore$ $I_a = I_L + I_f = 50 + 2.006 = 52.006$ A

Then Emf E = $V_f + I_a R_a$ + drop in brushes = 501.5 + 52.006×0.05 +1×2 = <u>506.1 V</u>

3.5 Characteristics of DC generator:

Different types of DC generators have different characteristic and accordingly they are suitable for different applications. The followings are the main characteristics of DC generator.

i) No-load characteristic (or open circuit characteristic or OCC curve)
ii) Load characteristic (or external characteristic)

3.5.1 No-load characteristic of DC generator:

No-load characteristics is a curve showing the values of emf generated across the armature at different values of field current at no-load and constant speed. The no-load characteristic of separately excited, shunt, series and compound DC generators are similar. The characteristic curve can be obtained practically as shown in Fig.3.22.

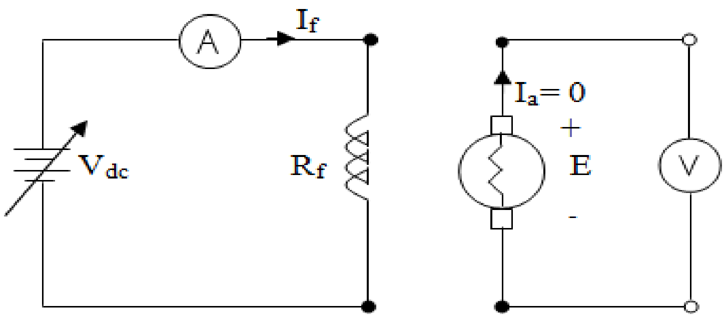


Fig.3.22 Circuit diagram for OCC curve

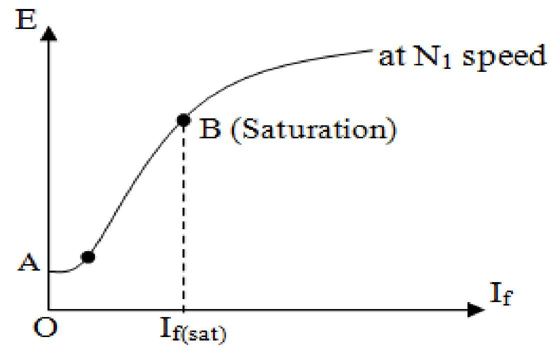


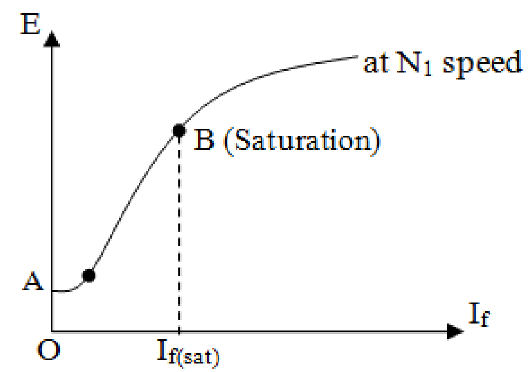
Fig.3.23 OCC curve of DC generator

The field winding is disconnected temporally for test purpose. The armature of the generator is rotated at a constant rated speed by some prime mover and the magnitudes of emf induced at different values of field current are measured. The resulting curve is shown in Fig.3.23.

The magnitude of emf induced across the armature is given by:

$$E = \frac{Z\phi.N}{60} \times \frac{P}{A}$$ And $\phi \propto I_f$ Since, the armature is driven at constant speed, $E \propto I_f$

When the field current is zero, there will be some residual flux in the air gap of the machine. Therefore, some emf (OA) will induce across the armature even the field current is zero. When in the field current increases, the magnetic flux (ϕ) increases proportionately and the emf (E) increases accordingly up the point 'B'. The point 'B' of the saturation point corresponding to field current 'I_{fsat}'. If the field current is further increased above I_{fsat}, the magnetic flux will not increase proportionately. The magnetic flux will increase by very small value with compare to increase in field current and accordingly the emf induce (E) will also increase by very small amount as shown in Fig.3.23. Fig.3.23 shows the OCC curve at rated speed N_1. The OCC curves at different speeds are shown in Fig.3.24.



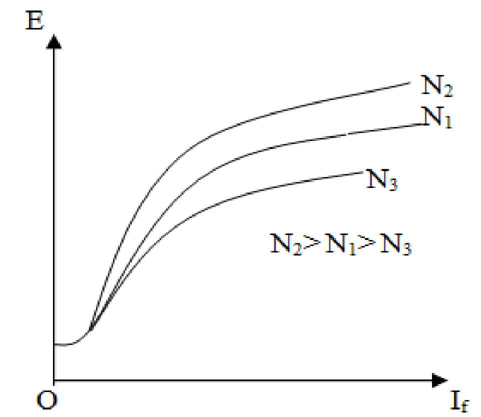
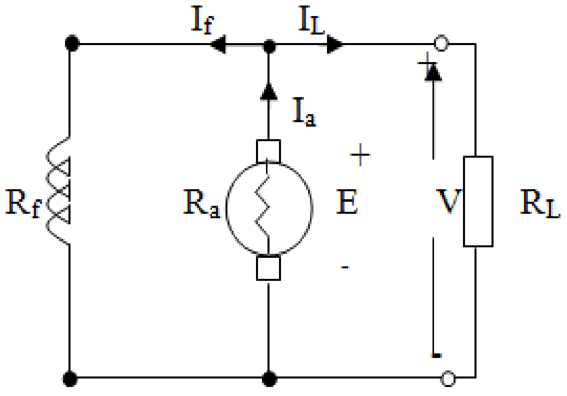


Fig.3.24 OCC curves at different speeds

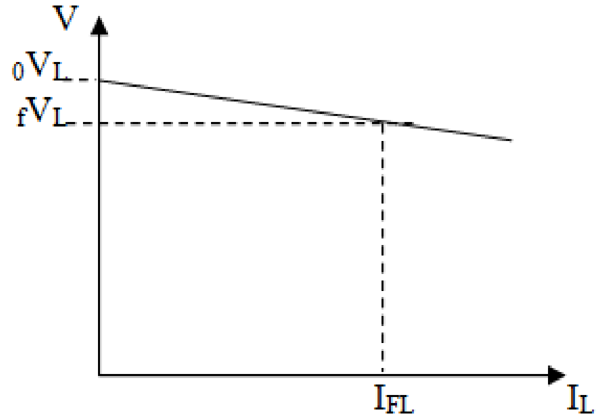
3.5.2 Load characteristic of DC generator:

Load characteristic is the curve showing the load terminal voltage at different values of load current. The different types of DC generators have different load characteristics.

Shunt generator: Let us consider a DC shunt generator as shown in Fig.3.25. When the generator is operated at full load, the field current (I_f) is very small with compare to the load current (I_L).When there is no load, the armature current ($I_a = I_f$) is very small with compare to full load current. Therefore, the voltage drop in armature resistance is very small and hence, terminal voltage is nearly equal to emf induced (i.e. V≈ E).



(a) Circuit diagram

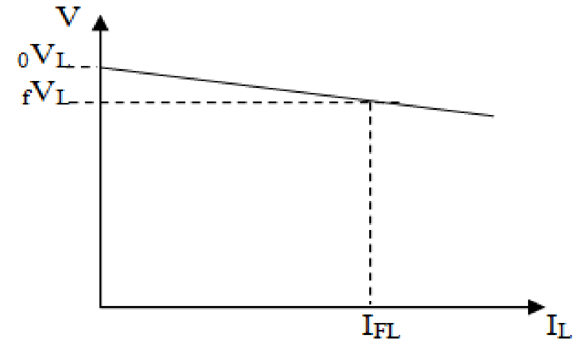


(b) Load Characteristics

Fig.3.25 Load characteristic of DC shunt generator

When the generator is loaded, the armature current ($I_a = I_f + I_L$) increases, then the load terminal voltage ($V = E - I_a . R_a$) decreases. The magnitude of load terminal voltage at different values of load current is shown in the Fig.3.21(b), which is known as load characteristic.

Let $_0V_L$ = load terminal voltage at no-load
$_fV_L$ = load terminal voltage at full-load



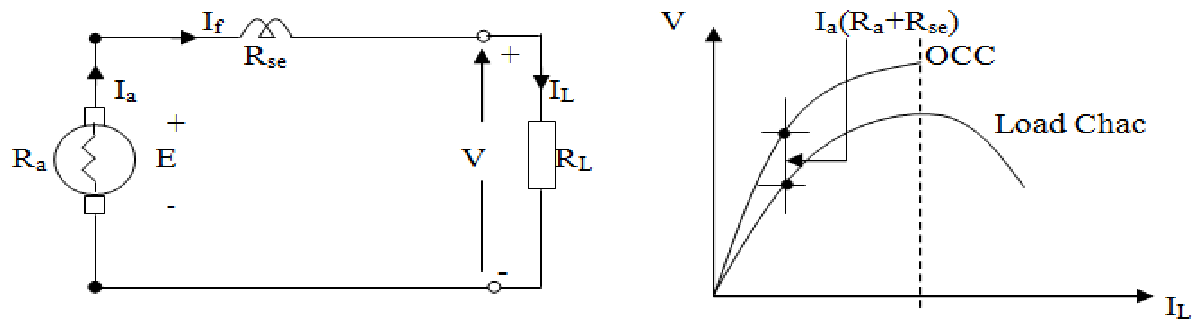
The total voltage drop from no-load to full-load = $_0V_L$ - $_fV_L$

Voltage regulation of generator is defined as change in load terminal voltage (from no-load to full-load) expressed as percentage of no-load terminal voltage.

$$\text{Hence Voltage Regulation (\%)} = \frac{_0V_L - {_fV_L}}{_0V_L} \times 100 \qquad (3.15)$$

<u>Series generator</u>:

Let us consider a DC series generator as shown in Fig.3.26. Here, the filed winding, armature winding and load are connected in series. Therefore, all of them carry the same current.



(a) Circuit diagram of DC series generator (b) Load Characteristic curve

Fig.3.26 Load characteristic of DC series generator

When the load current (I_L) increases, the armature current as well as the field current increases. Therefore, the voltage drop $I_a(R_a+R_{se})$ increases. But, at the same time, the air gap flux increases due to increase in I_f. Therefore, magnitude emf induced 'E' increases. Before the magnetic saturation, the increase in emf dominates the armature voltage drop. Therefore, load terminal voltage increases with load current up to the saturation as shown in Fig.3.26(b). Load characteristic curve is just below the OCC curve by an amount of armature voltage drop. Hence, a series generator has a rising voltage characteristic. However at over-load condition, the load terminal voltage starts decreasing due to excessive demagnetizing effect of armature reaction and saturation effect.

Compound generator: We have seen that a shunt generator has a dropping voltage characteristic and a series generator has a rising voltage characteristic. Since a compound generator has shunt as well as series field winding, a compound generator has a characteristic lying between shunt and series generators. A shunt generator may be modified into a compound generator to supply substantially constant voltage by adding few turns of field winding in series with load or armature. As the load current increases, the current through the series field winding also increases there by increasing the air gap flux. Hence, the emf induced in armature increases. By adjusting the number of series turns, the load terminal voltage can be controlled in different ways and accordingly different type of load characteristics can be obtained as shown in Fig.3.27.

i) If the series field amp-turns are such as to produce the full load terminal voltage equal to the no-load terminal voltage, then such generator is called as flat-compounded generator.

ii) If the series field amp-turns are such as to produce the full load terminal voltage greater than the no-load terminal voltage, then such generator is called as over-compounded generator.

iii) If the series field amp-turns are such as to produce the full load terminal voltage less than the no-load terminal voltage, then such generator is called as under-compounded generator.

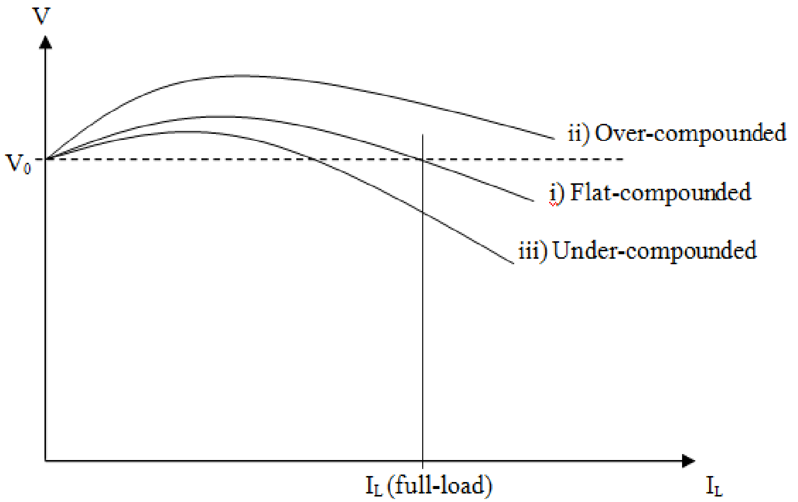
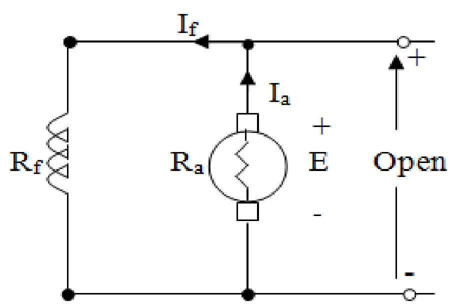


Fig.3.27 Characteristics of compound generator

3.6 Voltage Build-Up Process in DC generator:

Before loading a DC shunt generator, it should be allowed to build-up its voltage up to its rated value. Usually, there is always some residual magnetic flux produced by the field pole even in the absence of field current. Therefore at starting, when the armature is rotated at its rated speed by its prime-mover, a small amount of emf will induce across the armature due to this residual flux. As the load is not connected during this voltage build-up process, this emf forces current through the field winding. Hence, the air-gap flux will increases, provided the field circuit is correctly connected to the armature, otherwise this current may wipe off the residual flux. Because of this increase in air-gap flux, the magnitude of emf induced across the armature increases. Because of this increase in emf, field current will increase and air-gap flux will increase. This process goes on repeating until the emf reaches a final steady value. Now the question is when the emf reaches final steady value and what will be this final value. These facts can be explained with the help of OCC curve as shown in Fig.3.28.



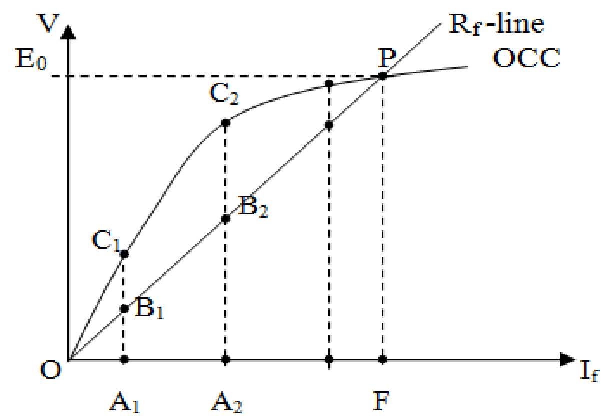
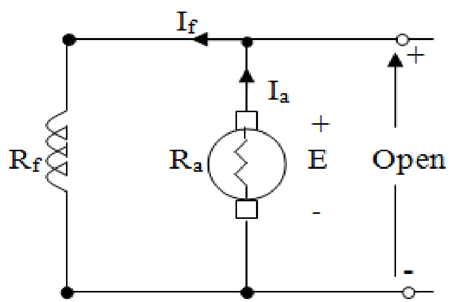
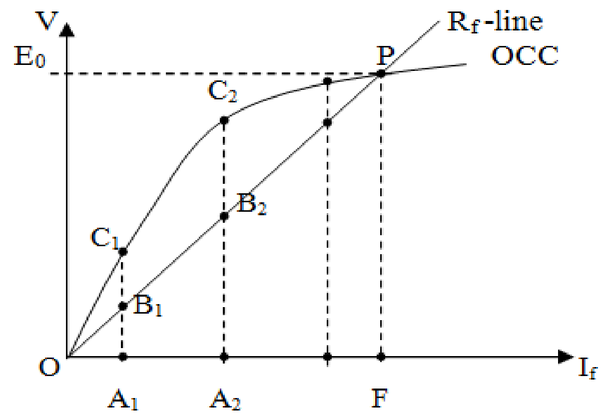


Fig.3.28 Voltage build-up in a DC shunt generator

Fig.3.28 shows the OCC curve and the plot of R_f line in a common current and voltage axis. The voltage build-up process follows the path of OCC. Let us consider an instant when the field current had increased to OA_2.





At this instant, Emf generated $E = A_2C_2$ Ohmic voltage drop in $R_f = A_2B_2$

B_2C_2 = Opposing self induced emf in the field coil due to changing current $I_f = L_f \frac{dI_f}{dt}$

As the voltage build-up process proceed on, the ohmic voltage drop goes on increasing and self induced emf goes on decreasing.

When the voltage build-up process reaches the point of intersection between OCC curve and the R_f line at point ‘P’, the total emf (E) is equal to the ohmic voltage drop in R_f and self induced emf $L_f.dI_f/dt$ has decreased to zero. That means I_f becomes constant or I_f is no more increasing. Hence, the voltage biuld-up process stops at point ‘P’ and steady emf generated is equal to E_0 as shown in Fig.3.28.

From the above explanation, it is clear that the instant ‘P’ depends upon the nature of OCC curve and the value field winding resistance ‘R_f’. Fig.3.29 shows the voltage build-up process at different values of field winding resistance.

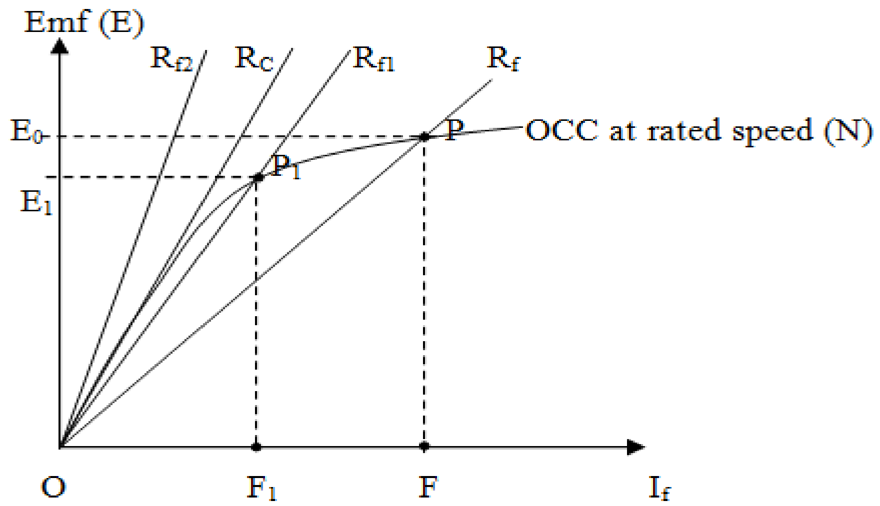


Fig.3.29 Voltage build-up with different values of field winding resistance

When the field winding resistance is equal to R_f, the maximum voltage build up is equal to $E_{0.}$

If the field winding resistance is increased to R_{f1}, the resistance line shifts up as shown in Fig.3.29. Now the new point of intersection is P_1 and the maximum voltage build up is equal to E_1 , which is less than E_0.

If the field winding resistance is increased to a large value (say to R_{f2}), then there is no intersection between OCC curve and R_{f2} line. Therefore, the generator can not build up the voltage with value of field winding resistance.

The maximum value of field winding resistance at which the generator just can build-up its voltage is R_C, which is just tangent to the OCC curve. Above this value of resistance, the generator cannot build-up the voltage. This value of resistance is known as “Critical resistance”.

Fig.3.30 shows the voltage build-up at different speed for a given value of field winding resistance.

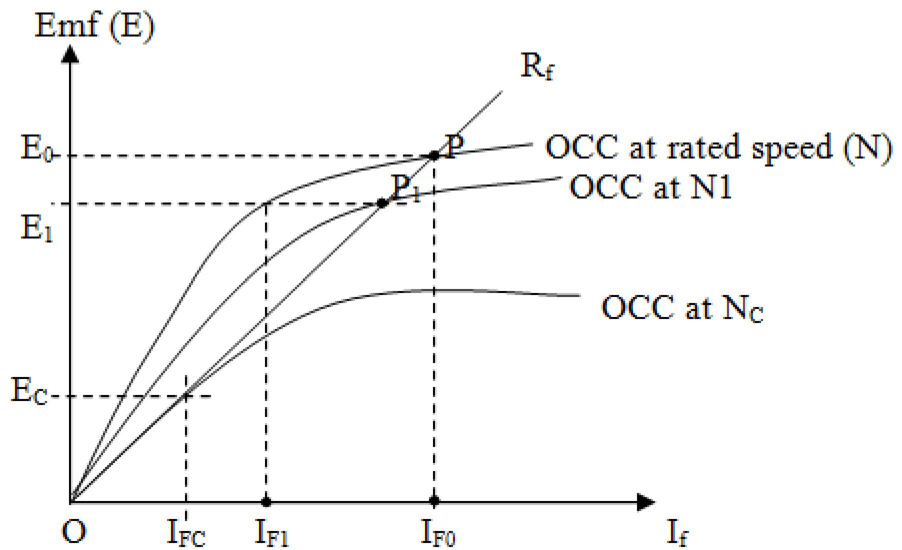


Fig.3.30 Voltage build-up with different speed

If the generator is allowed to build-up the voltage at lower speed N_1, then the new point of inter-section is P_1 and the maximum voltage build up is equal to E_1, which is less than E_0. If the generator is allowed to build-up the voltage at further lower speed N_C, the OCC curve is just tangent to the given value of R_f line. The generator will be just able to build-up its voltage at this speed. However, the maximum value of emf will be very small and equal to E_C. This speed is known as critical speed. Below the critical speed, the generator cannot build-up the voltage.

Losses in DC Generators:

There are mainly three types of losses in DC generator.

i) Copper losses:

- Armature copper loss ($I_a^2 R_a$)
- Field copper loss $\rightarrow I_{sh}^2 R_{sh}$ & $I_{Se}^2 R_{se}$

ii) Magnetic losses: (Iron loss or core loss)

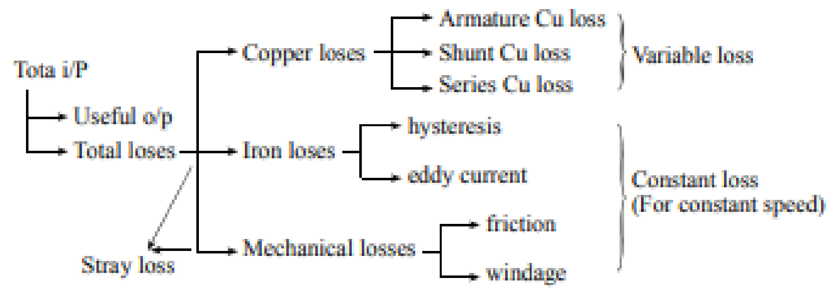
$\rightarrow$ hysteresis loss

$\rightarrow$ eddy current loss

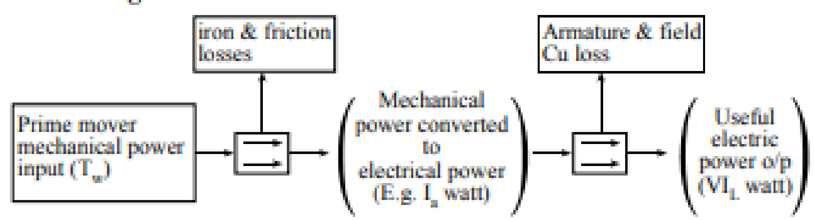
iii) Mechanical losses:

$\rightarrow$ Friction loss at bearings & commutator

$\rightarrow$ air-friction (windage) loss of rotating armature.



Power Stage



Efficiency of DC Generators:

i) Mechanical efficiency = $\frac{\text{Total electric power genrated in armature}}{\text{mechanical power supplied}}$

$$\Rightarrow \quad \eta_m = \frac{E_f I_a}{\text{O/P of driving engine}}$$

ii) Electrical efficiency = $\frac{\text{Watts availabel in load circuit}}{\text{total watts generated}}$

$$\Rightarrow \quad \eta_e = \frac{VI_2}{E_g I_a}$$

iii) Overall efficiency = $\frac{\text{Watts available in load ckt}}{\text{mechanical power i/P}}$

$$\Rightarrow \quad \eta = \frac{\text{O/P}}{\text{I/P}} = \frac{\text{O/P }(VI_2)}{\text{O/P }(VI_L) + \text{losses}} = \frac{\text{i/P - losses}}{\text{i/P}}$$

Mechanical power i/P = BHP of prime mover × 735.5
↓
Brake horse power

Voltage Regulation of DC generator

Let $_0V_L$ = load terminal voltage at no-load
$_fV_L$ = load terminal voltage at full-load

The total voltage drop from no-load to full-load
= $_0V_L$ - $_fV_L$

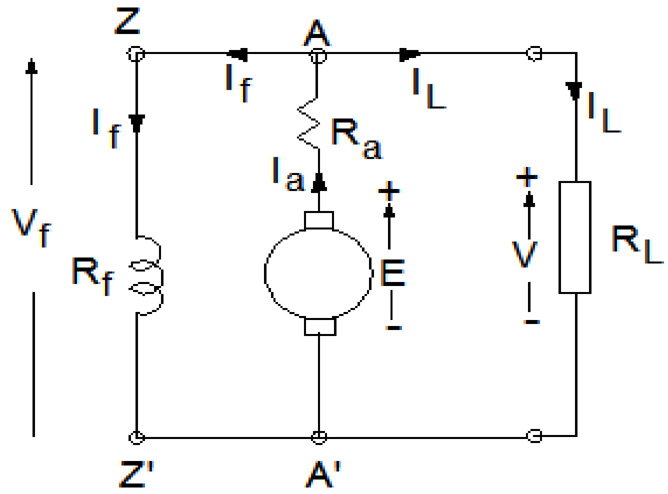
Voltage regulation of dc generator is defined as change in load terminal voltage (from no-load to full-load) expressed as percentage of no-load terminal voltage.

Hence, Voltage Regulation (%)

$$= \frac{0VL - fVL}{0VL} \times 100$$

Illustrative Example 3.5

A DC shunt generator generates 500V at no-load. The armature and field windings resistances are 0.05 Ω and 250 Ω respectively. When the generator delivers 30 A to the load, Calculate the terminal voltage and voltage regulation.



Solution:

At no-load V=E= 500V

At loaded condition:

$$I_f = \frac{V}{R_f} = \frac{E-V}{R_f} = \frac{500-V}{R_f}$$

And $I_a = I_L + I_f = 30 + \frac{500-V}{250}$

Then load terminal voltage:

$$V = E - Ia.Ra = 500 - (30 + \frac{500-V}{250}) \times 0.05$$

Or $250V = 500\times250 - (30\times250 + 500 - V) \times 0.05$

Or $250V = 125000 - (375 + 25 - 0.05V)$

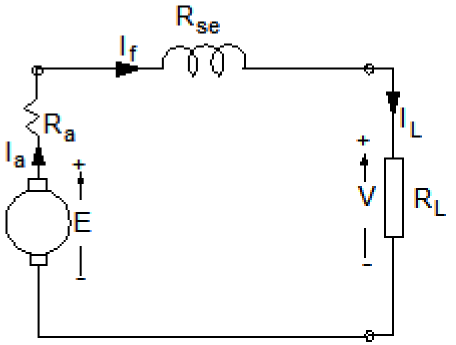
Or $250V - 0.05V = 125000 - 400$

Or $249.95V = 124600$

Or $V = 498.5$ V

Illustrative Example 3.6

A DC series generator has armature and field windings resistances of 0.5 Ω and 0.3 Ω respectively. When the generator delivers 5 A to the load, the load terminal voltage is 250V. Calculate the terminal voltage when the load current is 25A. Assume that the speed is constant



Solution:

Given that V = 250V, R_a = 0.5 ohm and R_{se} = 0.3 ohm

For Series generator $E = \frac{Z\phi.N}{60} \times \frac{P}{A}$

For constant speed $E \propto \phi \propto I_f = I_a = I_L$

When load current I_{L1} = 5 A, $E_1 = V_1 + I_{L1}.(R_a + R_{se}) = 250 + 5(0.5 + 0.3) = 254V$

$E_1 \propto I_{L1}$ and $E_2 \propto I_{L2}$

$$\therefore \quad \frac{E_2}{E_1} = \frac{I_{L2}}{I_{L1}} \quad \text{OR} \quad E_2 = \frac{I_{L2}}{I_{L1}} \times E_1 = \frac{25}{5} \times 254 = 1270V$$

$\therefore \quad V_2 = E_2 - I_{L2}(Ra + Rse) = 1270 - 25(0.8) = 1250V$