

# Module 9 DC Machines

Lesson

38

D.C Generators

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## 38.1 Goals of the lesson

Students are expected to learn about the classification of d.c generators and their characteristics in this lesson. After going through this lesson they will be able to:

1. differentiate different types of d.c generators along with their schematic representations.
2. identify, looking at the circuit diagram of a given generator, the types of the generator i.e., whether the generator is shunt, separately excited or compound generator.
3. sketch the important characteristics (no load and load characteristics) of different types of generators.
4. identify various factors responsible for internal voltage drop.
5. understand the conditions to be fulfilled so as to build up voltage in a shunt generator.
6. predict the load characteristic of a shunt generator from its open circuit characteristic.
7. locate the shunt and series field coils in the machine and comment on their relative number of turns and cross sectional areas.

## 38.2 Generator types & Characteristics

D.C generators may be classified as (i) separately excited generator, (ii) shunt generator, and (iii) series generator and (iv) compound generator.

In a separately excited generator field winding is energised from a separate voltage source in order to produce flux in the machine. So long the machine operates in unsaturated condition the flux produced will be proportional to the field current. In order to implement shunt connection, the field winding is connected in parallel with the armature. It will be shown that subject to fulfillment of certain conditions, the machine may have sufficient field current developed on its own by virtue of its shunt connection.

In series d.c machine, there is one field winding wound over the main poles with fewer turns and large cross sectional area. Series winding is meant to be connected in series with the armature and naturally to be designed for rated armature current. Obviously there will be practically no voltage or very small voltage due to residual field under no load condition ( $I_a = 0$ ). However, field gets strengthened as load will develop rated voltage across the armature with reverse polarity, is connected and terminal voltage increases. Variation in load resistance causes the terminal voltage to vary. Terminal voltage will start falling, when saturation sets in and armature reaction effect becomes pronounced at large load current. Hence, series generators are not used for delivering power at constant voltage. Series generator found application in boosting up voltage in d.c transmission system.

A compound generator has two separate field coils wound over the field poles. The coil having large number of turns and thinner cross sectional area is called the *shunt field coil* and the other coil having few number of turns and large cross sectional area is called the *series field coil*. Series coil is generally connected in series with the armature while the shunt field coil is connected in parallel with the armature. If series coil is left alone without any connection, then it becomes a shunt machine with the other coil connected in parallel. Placement of field coils for shunt, series and compound generators are shown in figure 38.1. Will develop rated voltage across the armature with reverse polarity.

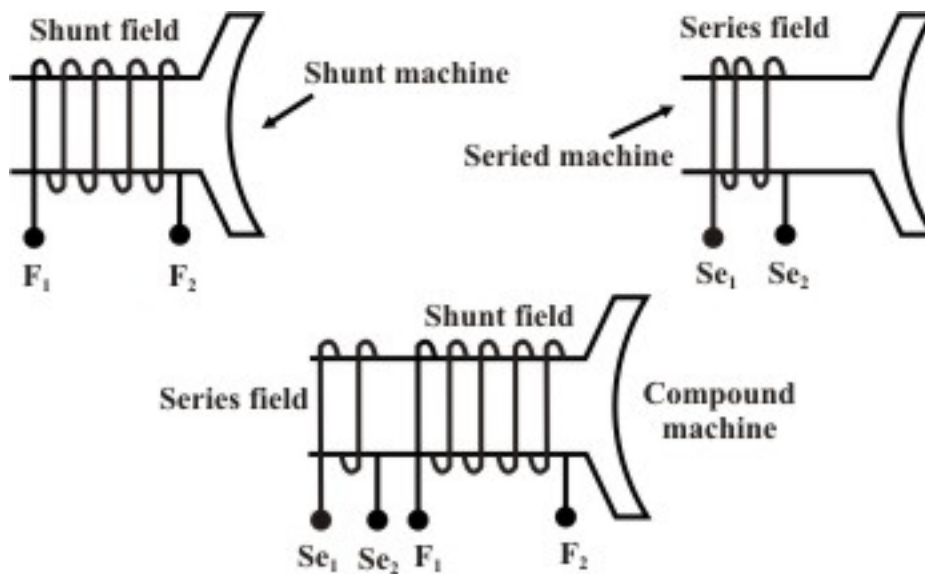


Figure 38.1: Field coils for different d.c machines.

### 38.2.1 Characteristics of a separately excited generator

#### No load or Open circuit characteristic

In this type of generator field winding is excited from a separate source, hence field current is independent of armature terminal voltage as shown on figure (38.2). The generator is driven by a prime mover at rated speed, say  $n$  rps. With switch  $S$  in opened condition, field is excited via a *potential divider* connection from a separate d.c source and field current is gradually increased. The field current will establish the flux per pole  $\phi$ . The voltmeter  $V$  connected across the armature terminals of the machine will record the generated emf ( $E_G = \frac{pZ}{a} \phi n = k\phi n$ ). Remember  $\frac{pZ}{a}$  is a constant ( $k$ ) of the machine. As field current is increased,  $E_G$  will increase.  $E_G$  versus  $I_f$  plot at constant speed  $n$  is shown in figure (38.3a).

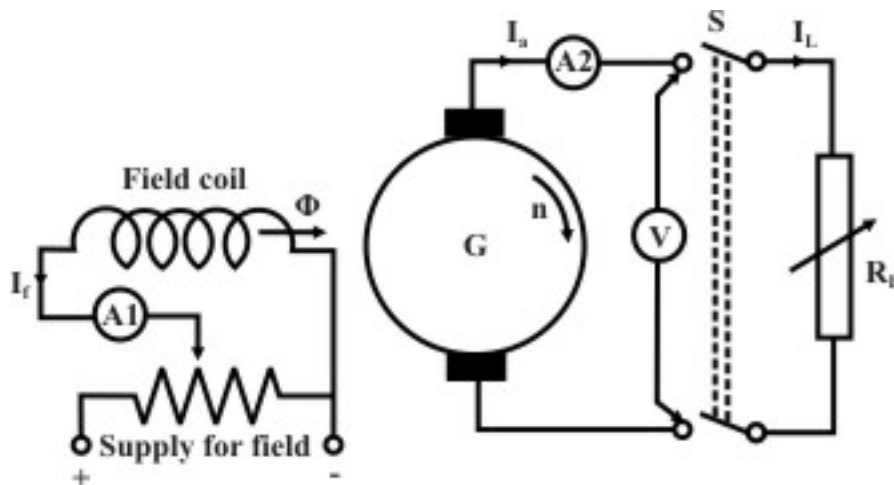


Figure 38.2: Connection of separately excited generator.

It may be noted that even when there is no field current, a small voltage (OD) is generated due to residual flux. If field current is increased,  $\phi$  increases linearly initially and O.C.C follows a straight line. However, when *saturation* sets in,  $\phi$  practically becomes constant and hence  $E_g$  too becomes constant. In other words, O.C.C follows the  $B-H$  characteristic, hence this characteristic is sometimes also called the *magnetisation* characteristic of the machine.

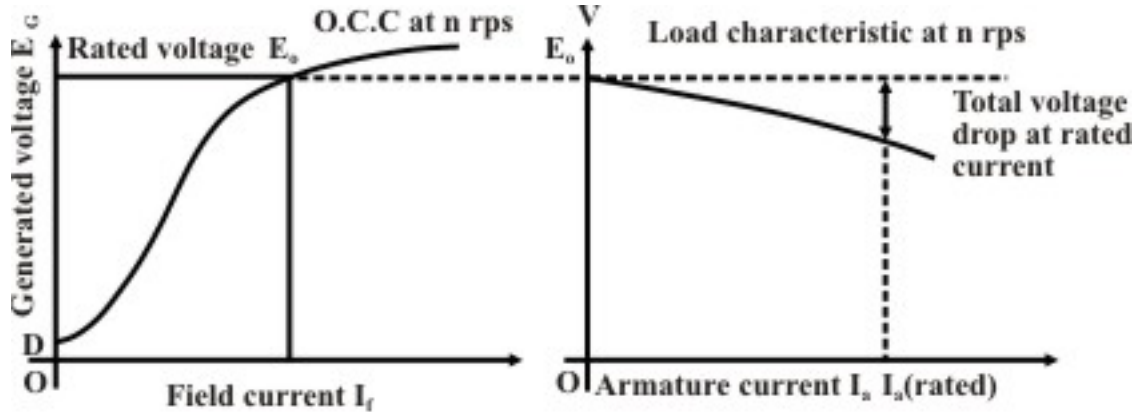


Figure 38.3: No load & Load characteristics of a separately excited generator.

It is important to note that if O.C.C is known at a certain speed  $n_1$ , O.C.C at another speed  $n_2$  can easily be predicted. It is because for a constant field current, ratio of the generated voltages becomes the ratio of the speeds as shown below.

$$\begin{aligned} \frac{E_{G2}}{E_{G1}} &= \frac{\text{Gen. voltage at } n_2}{\text{Gen. voltage at } n_1} \\ &= \frac{k\phi n_2}{k\phi n_1} \quad \because \text{voltage is calculated at same field current} \\ \therefore \frac{E_{G2}}{E_{G1}} &= \frac{n_2}{n_1} \Big|_{i_f = \text{constant}} \\ \text{or, } E_{G2} &= \frac{n_2}{n_1} E_{G1} \end{aligned}$$

Therefore points on O.C.C at  $n_2$  can be obtained by multiplying ordinates of O.C.C at  $n_1$  with the ratio  $\frac{n_2}{n_1}$ . O.C.C at two different speeds are shown in the following figure (38.4).

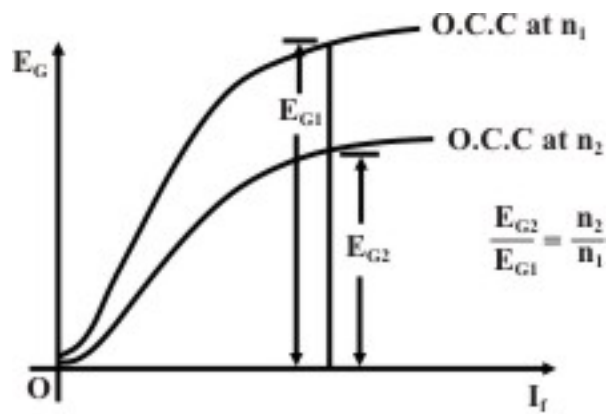


Figure 38.4: O.C.C at different speeds.

### Load characteristic of separately excited generator

Load characteristic essentially describes how the terminal voltage of the armature of a generator changes for varying armature current  $I_a$ . First at rated speed, rated voltage is generated across the armature terminals with no load resistance connected across it (i.e., with S opened) by adjusting the field current. So for  $I_a = 0$ ,  $V = E_o$  should be the first point on the load characteristic. Now with S is closed and by decreasing  $R_L$  from infinitely large value, we can increase  $I_a$  gradually and note the voltmeter reading. Voltmeter reads the terminal voltage and is expected to decrease due to various drops such as armature resistance drop and brush voltage drop. In an uncompensated generator, armature reaction effect causes additional voltage drop. While noting down the readings of the ammeter A2 and the voltmeter V, one must see that the speed remains constant at rated value. Hence the load characteristic will be *drooping* in nature as shown in figure (38.3b).

### 38.2.2 Characteristics of a shunt generator

We have seen in the previous section that one needs a separate d.c supply to generate d.c voltage. Is it possible to generate d.c voltage without using another d.c source? The answer is yes and for obvious reason such a generator is called *self excited* generator.

Field coil (F1, F2) along with a series external resistance is connected in parallel with the armature terminals (A1, A2) of the machine as shown in figure (38.5). Let us first qualitatively explain how such connection can produce sufficient voltage. Suppose there exists some residual field. Therefore, if the generator is driven at rated speed, we should expect a small voltage ( $k\phi_{res}n$ ) to be induced across the armature. But this small voltage will be directly applied across the field circuit since it is connected in parallel with the armature. Hence a small field current flows producing additional flux. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more generating more voltage. This more voltage will drive more field current generating more voltage. Both field current and armature generated voltage grow *cumulatively*.

This growth of voltage and the final value to which it will settle down can be understood by referring to (38.6) where two plots have been shown. One corresponds to the O.C.C at rated speed and obtained by connecting the generator in separately excited fashion as detailed in the preceding section. The other one is the V-I characteristic of the field circuit which is a straight line passing through origin and its slope represents the total field circuit resistance.

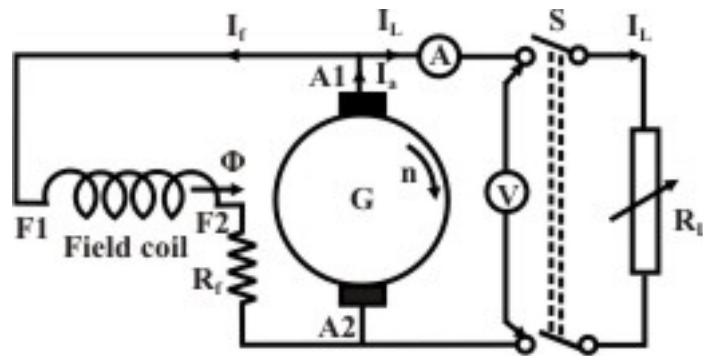


Figure 38.5: Shunt generator.

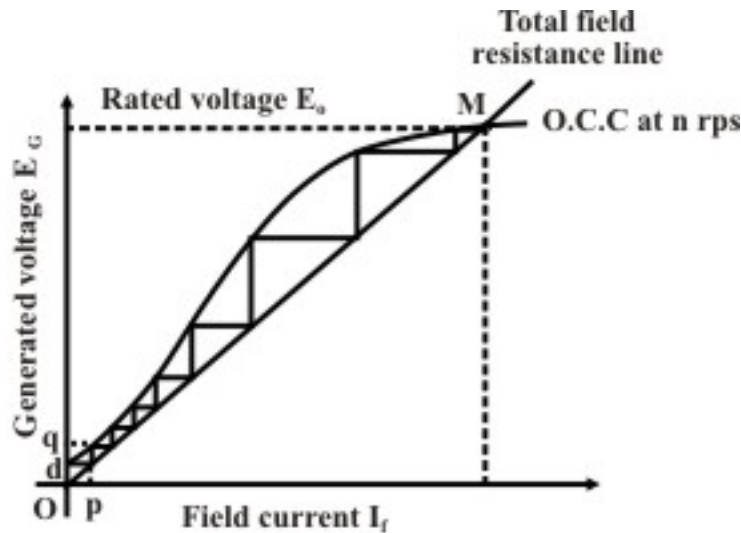


Figure 38.6: Voltage build up in shunt generator.

Initially voltage induced due to residual flux is obtained from O.C.C and given by  $O_d$ . The field current thus produced can be obtained from field circuit resistance line and given by  $O_p$ . In this way voltage build up process continues along the stair case. The final stable operating point ( $M$ ) will be the point of intersection between the O.C.C and the field resistance line. If field circuit resistance is increased, final voltage decreases as point of intersection shifts toward left. The field circuit resistance line which is tangential to the O.C.C is called the *critical* field resistance. If the field circuit resistance is more than the critical value, the machine will fail to excite and no voltage will be induced - refer to figure 38.7. The reason being no point of intersection is possible in this case.

Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover is reduced without changing  $R_f$ , the developed voltage will be less as because the O.C.C at lower speed will come down (refer to figure 38.8). If speed is further reduced to a certain critical speed ( $n_{cr}$ ), the present field resistance line will become tangential to the O.C.C at  $n_{cr}$ . For any speed below  $n_{cr}$ , no voltage built up is possible in a shunt generator.



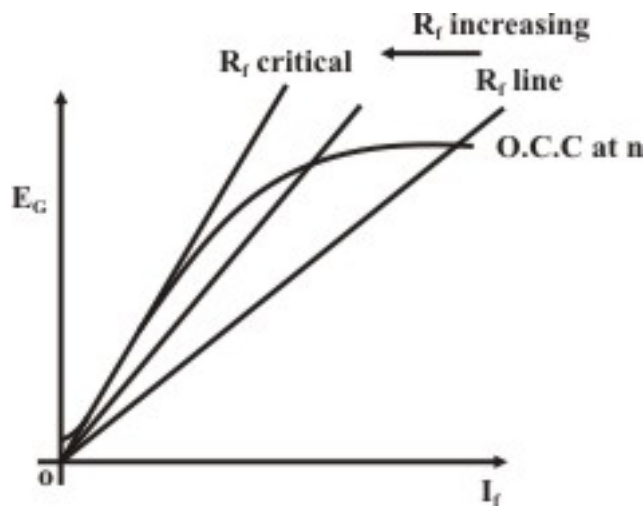


Figure 38.7: Critical field resistance.

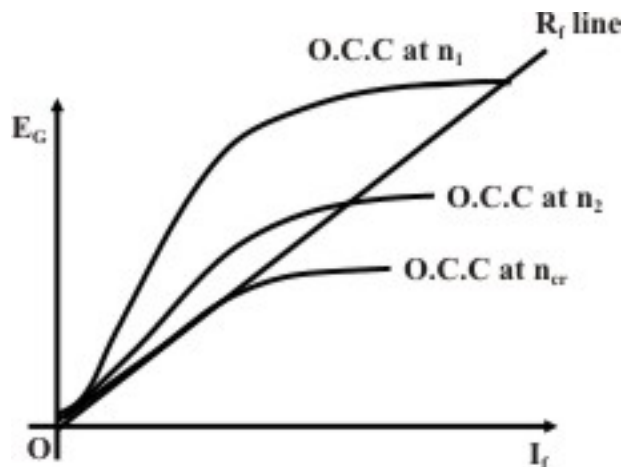


Figure 38.8: Critical speed.

A shunt generator driven by a prime mover, can not built up voltage if it fails to comply any of the conditions listed below.

1. The machine must have some *residual* field. To ensure this one can at the beginning excite the field separately with some constant current. Now removal of this current will leave some amount of residual field.
2. Field winding connection should be such that the residual flux is strengthened by the field current in the coil. If due to this, no voltage is being built up, reverse the field terminal connection.
3. Total field circuit resistance must be less than the critical field resistance.

### 38.2.3 Load characteristic of shunt generator

With switch S in open condition, the generator is practically under no load condition as field current is pretty small. The voltmeter reading will be  $E_o$  as shown in figures (38.5) and (38.6). In other words,  $E_o$  and  $I_a = 0$  is the first point in the load characteristic. To load the machine S is closed and the load resistances decreased so that it delivers load current  $I_L$ . Unlike separately



3. Now draw a horizontal line NQ which intersects the field resistance line at Q.
4. Draw a vertical line PQ intersecting OCC at P.
5. Length PQ must be  $I_a r_a$  drop.
6. Knowing the value of  $r_a$ ,  $I_a = \frac{PQ}{r_a}$ , can be calculated.
7. The above steps are repeated, for other values of chosen  $V$ .
8. Plot of all these pair of  $[V, I_a]$  will give the load characteristic.

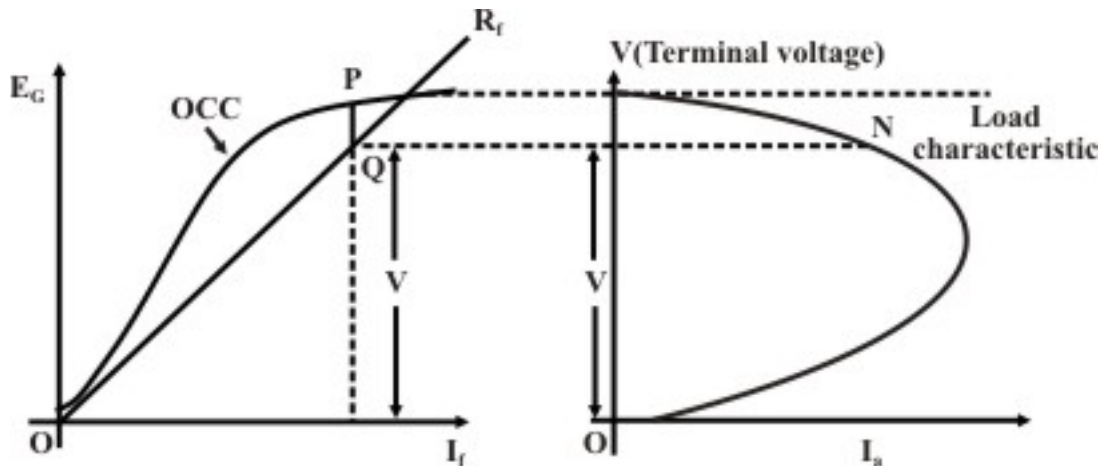


Figure 38.10: Finding  $I_a$  knowing  $V$ .

### Alternative method

In this method which is also graphical, we try to estimate the terminal voltage  $V$  for a given armature current  $I_a$ . Following steps may be adopted for the purpose.

1. Choose a particular value of armature current  $I_a$ .
2. Since armature resistance is known, calculate  $I_a r_a$ .
3. Mark a point K on the voltage axis of OCC such that  $OK = I_a r_a$ .
4. Draw a line parallel to  $R_f$  line and passing through point K. This line in general expected to intersect the OCC at two points G and H as shown in figure (38.11).
5. Draw two horizontal lines passing through G and H respectively.
6. Draw a vertical line in load characteristic plane at the chosen current  $I_a$ . This vertical line intersect the two horizontal lines drawn in the previous step at points P & Q respectively.
7. Thus we find the generator can deliver the chosen  $I_a$  at two different terminal voltages of  $V_p$  and  $V_q$ . So the load characteristic is a double valued function.
8. It should be noted that, there exists a line parallel to the  $R_f$  line which touches the OCC only at *one point* S as shown. For this we shall get a single terminal voltage as represented by the point T. The corresponding armature current ( $I_{a \max}$ ) is the maximum value which the generator is capable of delivering.

9. In fact it explains why the load characteristic takes a turn toward left after reaching a maximum current.

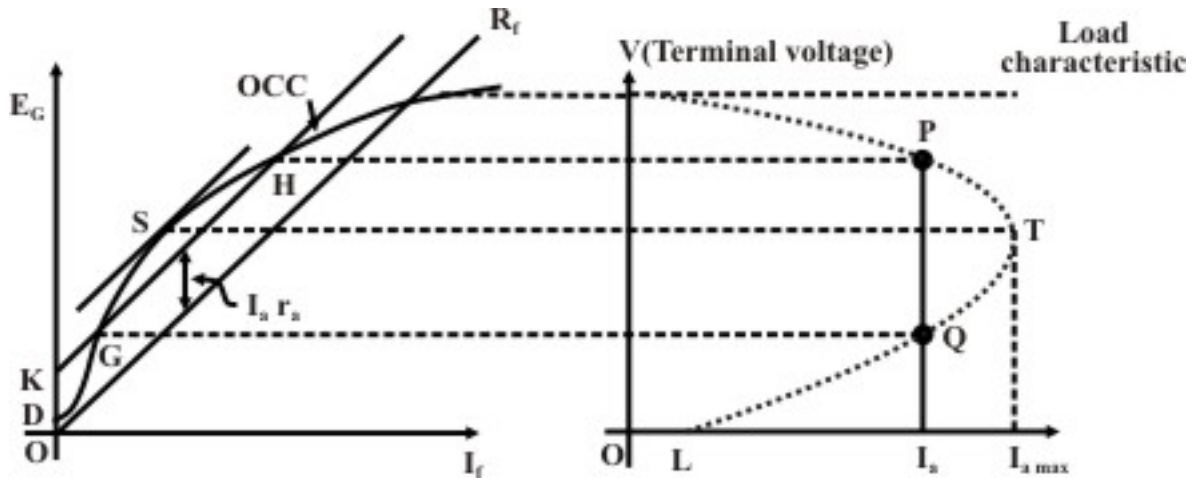


Figure 38.11: Finding  $I_a$  knowing  $V$ .

As we go on decreasing the load resistance, terminal voltage falls. Field being connected across the armature,  $\phi$  also falls reducing the generated voltage  $E_G$  which was not the case with separately excited generator where  $\phi$  produced was independent of the terminal voltage of the generator. Thus after reaching  $I_{a \max}$ , any further decrement in the load resistance causes  $E_G$  to fall substantially to make  $I_a < I_{a \max}$ . In fact, If we reduce  $R_L$  to the extent that  $R_L = 0$  (i.e., putting a short circuit across the terminals), field current becomes zero making  $E_G = \text{residual voltage} = OD$ . Therefore steady short circuit current of the generator will be pretty small and equal to  $\frac{OD}{r_a} = OL$ .

### 38.3 Compound generator

As introduced earlier, compound machines have both series and shunt field coils. On each pole these two coils are placed as shown in figure 38.1. Series field coil has low resistance, fewer numbers of turns with large cross sectional area and connected either in series with the armature or in series with the line. On the other hand shunt field coil has large number of turns, higher resistance, small cross sectional area and either connected in parallel across the armature or connected in parallel across the series combination of the armature and the series field. Depending on how the field coils are connected, compound motors are classified as *short shunt* and *long shunt* types as shown in figures 38.12 and 38.13

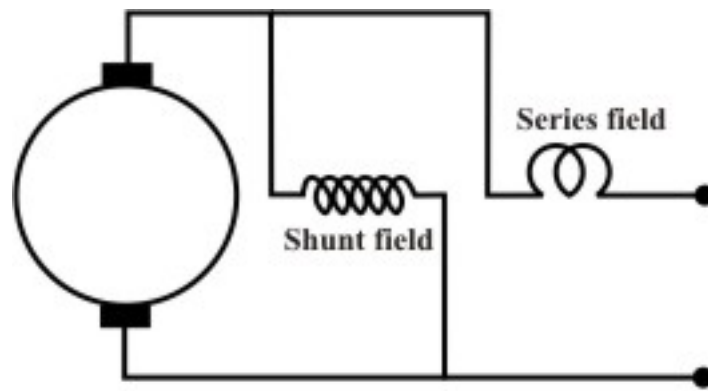


Figure 38.12: Short shunt connection.

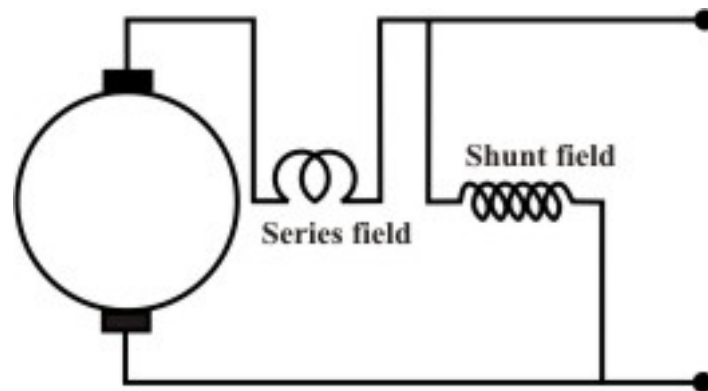


Figure 38.13: Long shunt connection.

Series field coil may be connected in such a way that the mmf produced by it aids the shunt field mmf-then the machine is said to be cumulative compound machine, otherwise if the series field mmf acts in opposition with the shunt field mmf – then the machine is said to be differential compound machine.

In a compound generator, series field coil current is load dependent. Therefore, for a cumulatively compound generator, with the increase of load, flux per pole increases. This in turn increases the generated emf and terminal voltage. Unlike a shunt motor, depending on the strength of the series field mmf, terminal voltage at full load current may be same or more than the no load voltage. When the terminal voltage at rated current is same that at no load condition, then it is called a level compound generator. If however, terminal voltage at rated current is more than the voltage at no load, it is called a over compound generator. The load characteristic of a cumulative compound generator will naturally be above the load characteristic of a shunt generator as depicted in figure 38.14. At load current higher than the rated current, terminal voltage starts decreasing due to saturation, armature reaction effect and more drop in armature and series field resistances.

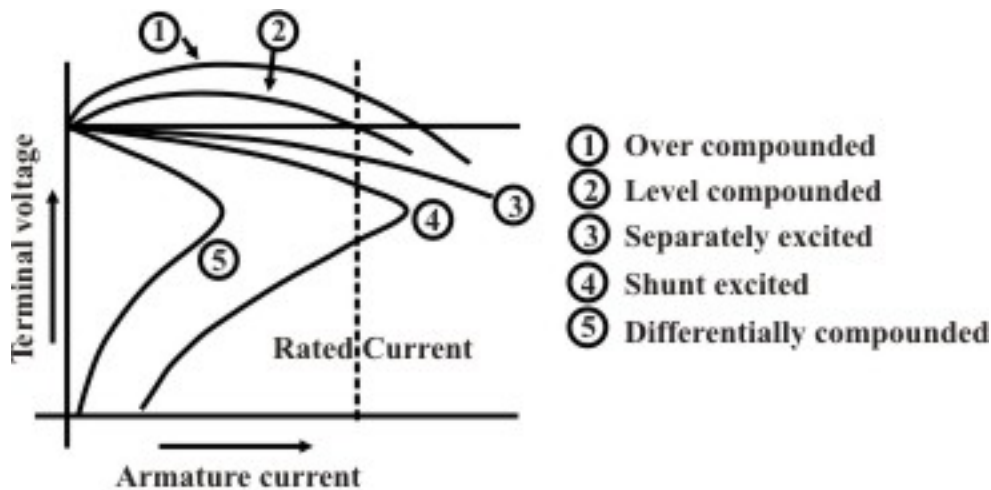


Figure 38.14: Load characteristics of d.c generators.

To understand the usefulness of the series coil in a compound machine let us undertake the following simple calculations. Suppose as a shunt generator (series coil not connected) 300 AT/pole is necessary to get no load terminal voltage of 220 V. Let the terminal voltage becomes 210 V at rated armature current of 20 A. To restore the terminal voltage to 220 V, shunt excitation needs to be raised such that AT/pole required is 380 at 20 A of rated current. As a level compound generator, the extra AT ( $380 - 300 = 80$ ) will be provided by series field. Therefore, number of series turns per pole will be  $80/20 = 4$ . Thus in a compound generator series field will automatically provide the extra AT to arrest the drop in terminal voltage which otherwise is inevitable for a shunt generator.

For the differentially compounded generator where series field mmf opposes the shunt field mmf the terminal voltage decreases fast with the increase in the load current.

### 38.4 Tick the correct answer

1. For building up of voltage in a d.c shunt generator,
  - (A) Field circuit resistance should be greater than a critical value.
  - (B) Field circuit resistance,  $R_f$  should  $\rightarrow 0$ .
  - (C) Field circuit resistance should be less than a critical value.
  - (D) Field circuit resistance,  $R_f$  should  $\rightarrow \infty$ .
  
2. This question is regarding the steady state armature current when dead short circuit occurs across the d.c generator terminals. Pick up the correct statement.
  - (A) For a shunt generator the short circuit armature current will be many times larger than the rated current of the armature.
  - (B) For a separately excited generator the short circuit armature current will be many times larger than the rated current of the armature.
  - (C) For a shunt generator the short circuit armature current will be many times lower than the rated current of the armature.
  - (D) For a separately excited generator the short circuit armature current will be many times lower than the rated current of the armature.

3. A shunt generator is found to develop rated voltage in the armature when driven at 1000 rpm in the clockwise direction. The generator is now first stopped and then run once again at 1000 rpm but in the anti-clock wise direction. The generator,
- (A) will develop rated voltage across the armature with same polarity as before.  
 (B) will develop rated voltage across the armature with reverse polarity.  
 (C) will develop a voltage lower than the rated value across the armature with reverse polarity.  
 (D) will fail to excite.
4. In relation to a compound d.c machine, choose the right statement from the following.
- (A) Shunt field coil is wound over stator poles and series field coil is wound over inter poles.  
 (B) Shunt field coil is wound over inter poles and series field coil is wound over stator poles.  
 (C) Both series field and shunt field coils are wound over the stator poles.  
 (D) Shunt field coil is wound over stator pole face and series field coil is wound over stator poles.
5. In relation to a compound d.c machine, choose the right statement from the following.
- (A) The resistance of the shunt field coil will be many times higher than the series field coil.  
 (B) The resistance of the shunt field coil and the series field coil are of the same order.  
 (C) The resistance of the series field coil will be many times higher than the shunt field coil.  
 (D) Either of (A), (B) and (C) is true statement.
6. In relation to a compound d.c machine, choose the right statement from the following
- (A) Both series and shunt field coils have comparable and number of turns and cross sectional areas.  
 (B) Shunt field coil has fewer number of turns and large cross sectional area compared to series field coil.  
 (C) Series field coil has fewer number of turns and large cross sectional area compared to shunt field coil.  
 (D) None of (A), (B) and (C) are correct statement.

### 38.5 Solve the following

1. (a) The O.C.C of a d.c generator having  $r_a = 0.8\Omega$  and driven at 500 rpm is given below:

Field current (A):	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
Armature voltage (V):	110	155	186	212	230	246	260	271

The voltage induced due to residual field may be neglected. The machine is now connected as shunt generator and driven at 500 rpm.

(i) What should be the field circuit resistance in order to have no load terminal voltage to be 230V? Also calculate the critical field resistance. (ii) What maximum current can be supplied to the load and at what terminal voltage? Assume the speed to remain constant at 500 rpm. (iii) What should be the range of variation of field circuit resistance in order to have a terminal voltage of 230V from no load to the full load condition, the full load armature current being 20A? The speed drops to 450 rpm at full load condition.

2. The OCC of a shunt generator running at 850 rpm is given below:

Field current (A):	0.8	1.6	2.4	3.2	4	4.8	5.6
Armature voltage (V):	28	55	75	82	100	108	115

(i) Find the open circuit induced emfs for field resistances of  $22\Omega$  and  $33\Omega$ . (ii) What should be the field resistance so that the open circuit induced emf at 850 rpm is 100 V. (iii) Find the critical speed for the field resistance found in (ii) and (iv) find the critical field resistance at 850 rpm.