CHAPTER 8
GENERATOR OPERATION

In generator operation, a dc machine is driven by a prime mover and supplies an electrical load. This chapter explains the operating characteristics of dc generator and the affect them.

8.1 The Voltage Equation

In generator operation, we are interested in the voltage supplied at the output terminals. From KVL and the information of the previous chapters, the terminal voltage of a dc generator can be written:

$V = E_A - (\sum IR + V_b)$ (8.1a)

$= K_e n \Phi_r - (\sum IR + V_b)$ (8.1b)

$= E_{Aoc} - (\sum IR + V_b + \Delta E)$ (8.1c)

$= K_e n \Phi_m - (\sum IR + V_b + \Delta E)$ (8.1d)

Where $E_A = K_e n \Phi_r$ is the induced emf in the armature, and Φ_r is the actual (i.e. resultant) flux per pole; $E_{Aoc} = K_e n \Phi_m$ is the induced emf on open circuit (no armature current), and Φ_m is the flux per pole due to the main field. Φ_r may be somewhat less than Φ_m due to the demagnetizing effect of armature reaction (chapter 5); ΔE represents the corresponding reaction in induced emf ($\Delta E = E_{Aoc} - E_A$, section 5.3). The difference between the induced emf E_A and the terminal voltage V is the sum of series resistive drops $\sum IR$ (in the armature, series field wdg, commutating wdg, and compensating wdg) and the brush contact drop V_b. Eqn. 8.1d tells us that the terminal voltage is determined primarily by the speed n and the main field flux Φ_m, with some reduction due to series voltage drops and armature reaction.

8.2 Speed of Rotation

The speed is set at the prime mover, not the generator itself. Of course the generator is a mechanical load on the prime mover, and hence affects its operation :as the electrical load on the generator increases, the armature current I_A increases thus increasing the developed torque T_d=(K I_A Φ_r); if the prime mover torque does not increase to balance the increase in T_d, it will slow down (reducing E_A, hence V, hence I_A, hence T_d). However, in many applications, the prime mover is equipped with automatic control that maintains the speed almost constant (eg governor :as speed begins to fall, the governor enlarges the steam openings to the turbine).

8.3 Field Excitation

The main flux Φ_m is determined by the field mmf through the magnetization carves, or we say that E_{Aoc} is determined by the field excitation current through the OCC; see section 4.3. The shunt field excitation may be controlled by adding the variable resistance in series with the shunt field wdgs, and the series field excitation may be controlled by means of a small variable resistor (diverter)in parallel with the series field wdgs, see fig.8.2.

8.4 Voltage Drops

The series resistance drops $\sum IR$ and armature reaction drop ΔE increase with load (why?); the brush constant drop V_b is practically constant over the normal working range of I_A. The total drop is generally small (small wdg resistance, and small demagnetizing effect of armature reaction). For simplicity, we shall use the symbol ΔV for the total drop:

$\Delta V = \sum IR + V_b + \Delta E$ (8.2)

So that equs. 8.1c and 8.1d become:

$V = E_{Aoc} - \Delta V$ (8.3a)

$= K_e n \Phi_m - \Delta V$ (8.3b)

8.5 Definitions

We shall need the terms and concepts defined below in our description of generator operation and the factors that affect it.

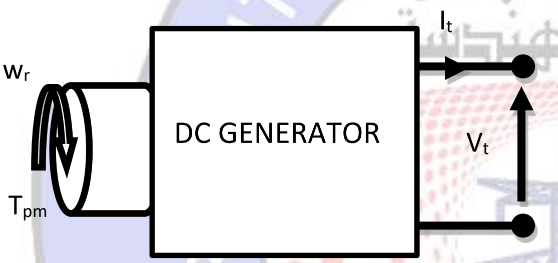


Fig. (8.1) Generator operation

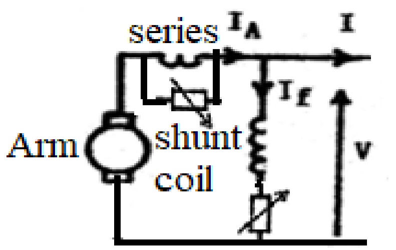
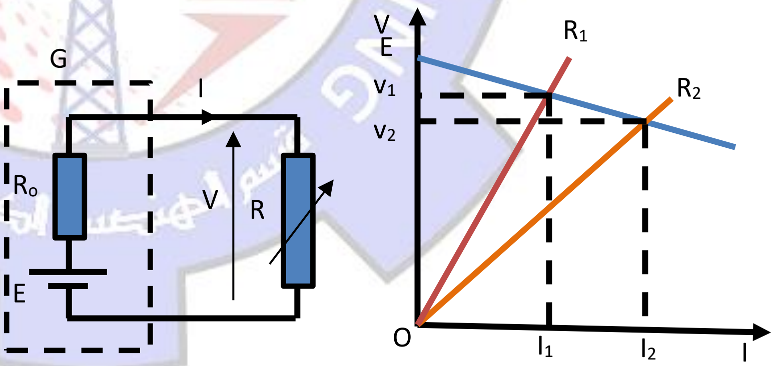


Fig. (8.2) DC machine with field control resistance

8.6 External Characteristic

The external characteristic of a dc generator is the curve relating terminal voltage V and terminal current I (i.e. load current). The curve shows now voltage change with load.

For a simple source circuit composed of constant emf E in series with constant internal resistance-see fig. 8.3a, the external characteristic is a straight line with negative slope, fig. 8.3b:



(a) circuit diagram (b) external characteristic
Fig. (8.3) Simple voltage source

$V = E - IR_0$ (8.4)

Comparing eqn. 8.4 with eqn. 8.1d we see that the external characteristic of a dc generator will be different from that of fig. 8.3b. We shall study the external characteristics of dc generators in section 8.3-8.6.

If a load resistance R_1 is connected across the terminals of the simple source of fig.3.3a, the terminal voltage and current will be:

$V_1 = \frac{E\,R_1}{R_o + R_1}$ and $I_1 = \frac{E}{R_o + R_1}$ (8.5)

The operating point (I_1, V_1) may also be found graphically by drawing the V-I characteristic of the load, and intersecting it with the characteristic of the source, fig. 8.3b; the intersection is the point that satisfies both characteristics at the same time. For the typical drooping characteristic shown, it is seen that decreasing the load resistance increases the load current and decreases the terminal voltage ($R_2 < R_1$, $I2 > I_1$, and $V_2 < V_1$).

Remark 1 :The graphical method can be used even when the external characteristic and the load V-I characteristic are nonlinear (not straight lines).

Remark 2 :The internal characteristic is the curve relating the emf and current. It is a horizontal line at E for the simple source of fig. 8.3a, but can be different in generators.

8.7 Voltage Control

A given external characteristic corresponds to a fixed speed and fixed settings of the field control resisters. If the setting of the field resisters is changed, Φ_m will also change (since the excitation currents are changed), and operation shifts to another curve. Therefore, the operating point may be moved from one curve to another by changing the field excitation, fig. 8.4. The terminal voltage may be kept approximately constant by automatic regulators that sense the terminal voltage and increase or decrease the excitation to keep the voltage at the set value.

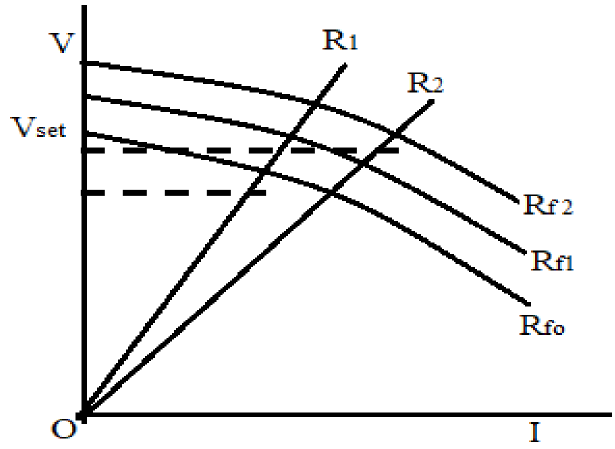


Fig. (8.4) Voltage control of DC generator with field control.

8.9 Voltage Regulation

The voltage regulation of a generator at a given load is defined by:

$$V_{reg} = \frac{V_{no} - V_{fl}}{V_{fl}} \quad (8.6)$$

It is a figure of merit that indicates how constant the terminal voltage is with load; a good voltage source should small voltage regulation. The voltage regulation of generators equipped with automatic voltage control is almost zero.

8.10 Separately Excited Generator

If the field current of a separately excited generator is kept constant, Φ_m and E_{Aoc} will be constant. The external characteristic is then as shown in fig. 8.5 :V is less than E_{Aoc} due to the armature circuit resistive drop I_AR_A (linear with current), the demagnetizing effect of armature reaction ΔE (nonlinear function of I_A), and the brush contact drop V_b (constant-not shown in figure). The curvature of the characteristic comes from ΔE. Compare with the simple source of fig. 8.3.

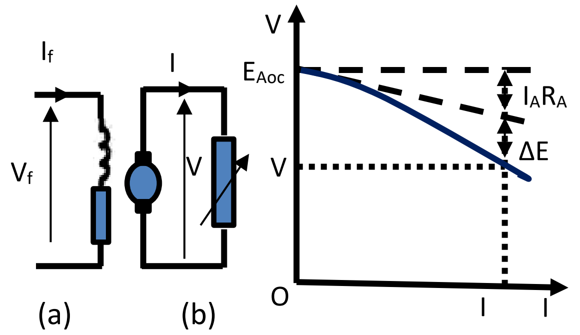


Fig. (8.5) Separately excited DC generator

8.11 Shunt Generator

The external characteristic of the shunt generator, fig. 8.6, is similar to that of the separately excited generator, but has an additional drop due to shunt field weakening:

$I_A\uparrow \rightarrow \Delta V\uparrow \rightarrow V\downarrow \rightarrow I_f\downarrow \rightarrow \Phi_m\downarrow \rightarrow E_{Aoc}\downarrow$

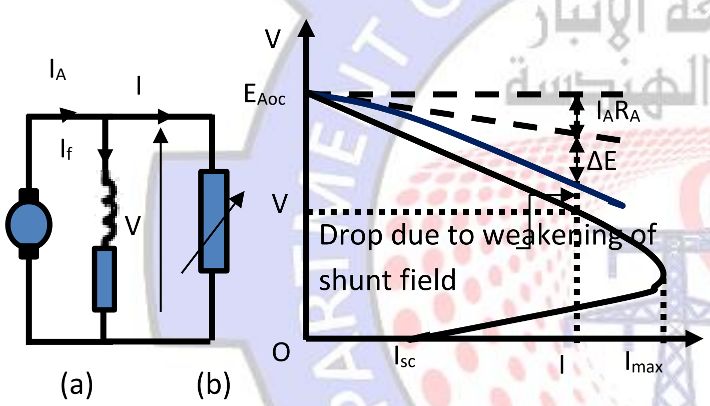


Fig. (8.6) Shunt excited DC generator

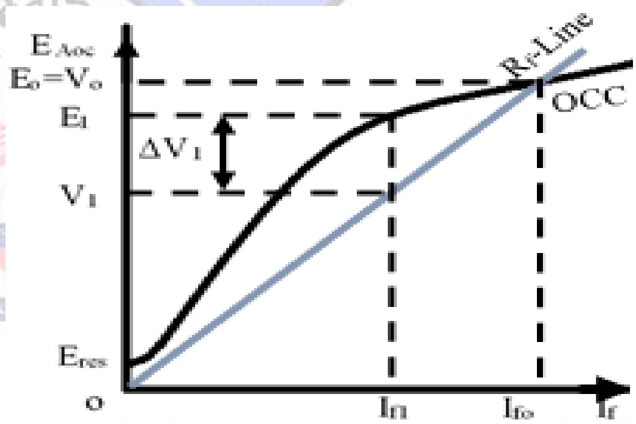


Fig. (8.7) Open Circuit Characteristics (OCC) of shunt excited DC generator.

To explain this process in more detail, we first draw the OCC as in fig. 8.7; note that the OCC is obtained with the shunt field wdg disconnected from the armature and fed from a separate source. Next, we draw the V-I characteristic for the shunt field resistance.

$$V = R_f I_f \qquad (8.7)$$

On the same graph. Now, for any field current If, the point (I_f, E_{Aoc}) must lie on the OCC, and the point (I_f, V) must lie on the R_f-line. At no-load the terminal current I is zero so that I_A is equal to 1_f which is small, so that we may neglect the drop ΔV; thus, the terminal voltage V is equal to the induced emf E_{Aoc}. This condition is satisfied only at the point of intersection of the R_f-line with the OCC; therefore, at no-load, we have:

$$I_f = I_{fo},\ E_{Aoc} = E_0,\ V = V_0, \text{ with } V_0 = E_0 \qquad (8.8)$$

Consider next the generator on load. I_A has increased so that the drop ΔV is now large enough to make V less than E_{Aoc}, eqn. 8.3a. Operation has to shift from the point of intersection :(I_f, E_{Aoc}) moves down the OCC, while (I_f, V) moves down the R_f-line. If will take up a position at which the difference between E_{Aoc} and V is equal to the drop ΔV:

$I_f = I_{f1}$, $EAoc = E_1$, $V = V_1$, with $V_1 = E_1 - \Delta V_1$ (8.9)

Comparing V_1 and $V_0 = (E_0)$, we see that the difference between them is the drop ΔV_1 plus an additional drop $(E_0 - E_1)$ due to the reduction of the induced emf E_{Aoc} from E_0 to E_1 corresponding to the reduction of the field current I_f from I_{f0} to I_{f1} as was stated at the beginning of this section.

At each value of load current, I, the field current I_f moves to a position that makes the difference between the OCC and the R_f-line equal to the drop ΔV that corresponds to that load current or, more precisely, to the armature current I_A. If you study the OCC and the R_f-line carefully, you will see that there is certain I_f at which the difference between them is maximum load current, I_{max} in fig.8.6; this is called the breakdown point.

The short circuit current of the shunt generator is inherently limited :at SC the terminal voltage V is zero so that $I_f = 0$; the emf is E_{res} (induced by the residual flux alone) which is very small. The resulting armature current is therefore small.

8.12 Voltage Build-Up

The preceding discussion helps us understand how the voltage of the shunt generator builds up. Assume that there is no load on the generator, and that there is an open switch in the field circuit so that $I_f=0$, $E_{Aoc}=E_{res}$, and $I_A=0$. If the switch is now closed, E_{res} is applied to R_f, and a small current If flows causing E_{Aoc} to climb up the OCC. But this increased value of E_{Aoc} is again applied to R_f and will increase I_f, which in turn increases E_{Aoc} some more. The process

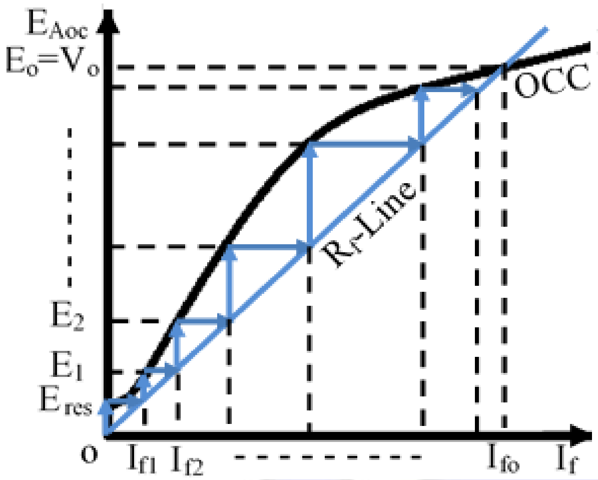


Figure 1.5 Voltage build-up

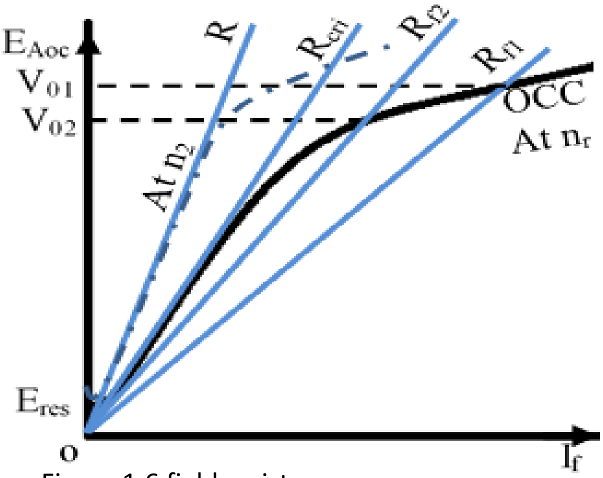


Figure 1.6 field resistance control

continues with (I_f, E_{Aoc}) climbing up the OCC and (I_f, V) climbing up the R_f-line until the two points coincide at the intersection point. We say that the shunt generator voltage V has 'build up' to V_0; what stops the build-up process from continuing indefinitely is the curvature of the OCC, i.e. saturation.

(Exercise :how does KVL apply to the circuit during build up?).

The process of voltage builds up requires the following conditions to succeed:

(1) There must be residual flux to start the process. A new generator, or one that has not been used for a long time, must be magnetized first. This is done by applying a separate dc source (for example a battery) to the field wdg for a short time; it is called 'flashing the field'.