
DC MACHINES AND TRANSFORMERS

Chapter 2 D.C. GENERATOR

Detailed Study Notes for Engineering Students

Topics covered

2.1 Working principle, construction and types of D.C. generator

2.2 Armature winding types – concept of lap and wave winding

2.3 E.m.f. equation

2.4 Generator characteristics, build-up of e.m.f., critical resistance and critical speed

2.5 Concept of flux distribution in D.C. machine

2.6 Armature reaction and remedial measures

2.7 Commutation method, concept of reactance voltage

2.8 Applications of different types of D.C. generator

2.9 Parallel operation of D.C. generators

Includes: solved numericals • diagrams • comparison tables • 15 MCQs with answer key • 10 long-answer questions

Contents

Section	Topic
2.1	Working principle, construction and types of D.C. generator
2.2	Armature winding types – lap and wave winding
2.3	E.m.f. equation (with numericals)
2.4	Generator characteristics; build-up of e.m.f.; critical resistance and critical speed (numericals)
2.5	Concept of flux distribution in D.C. machine
2.6	Armature reaction and remedial measures
2.7	Commutation and reactance voltage
2.8	Applications of D.C. generators
2.9	Parallel operation of D.C. generators
-	Quick revision: important formulae
-	Multiple Choice Questions (15) and Answer Key
-	Broad (long-answer) Questions (10)

How to use these notes

- Read each section first as a **concept** (paragraphs), then revise from the **lists and tables**.
- Redraw every figure at least twice – diagrams carry marks in university and board examinations.
- Solve each numerical yourself before looking at the solution; formulae are collected at the end for quick revision.
- Attempt the MCQs without looking at the key, then use the broad questions for answer-writing practice.

2.1 Working Principle, Construction and Types of D.C. Generator

2.1.1 Introduction

An **electric generator** is a rotating machine that converts **mechanical energy into electrical energy**. When the output is direct current (unidirectional and of constant polarity), the machine is called a **D.C. generator** or **dynamo**. The mechanical input is supplied by a *prime mover* such as a diesel engine, steam turbine, water turbine or an electric motor. Although a.c. is used for bulk generation and transmission, D.C. generators are still studied because the same machine, when supplied with d.c., works as a D.C. motor, and because d.c. supply is needed for electroplating, electrolysis, battery charging, excitation of alternators and speed-controlled drives.

2.1.2 Working Principle

The D.C. generator works on **Faraday's laws of electromagnetic induction**. According to these laws, whenever the magnetic flux linked with a coil changes, or a conductor cuts magnetic flux, an e.m.f. is induced in it. In a generator the field system produces a steady magnetic flux and the armature conductors are rotated through it, so the e.m.f. is **dynamically induced**.

Magnitude of induced e.m.f.: $e = B \cdot l \cdot v \cdot \sin \theta$ (volt)
where B = flux density (T), l = active length of conductor (m), v = velocity of conductor (m/s), θ = angle between B and v

The **direction** of the induced e.m.f. (and of the current if the circuit is closed) is given by **Fleming's right-hand rule**: *stretch the thumb, fore-finger and middle finger of the right hand mutually perpendicular to one another; if the fore-finger points in the direction of the magnetic field and the thumb in the direction of motion of the conductor, the middle finger gives the direction of the induced e.m.f.*

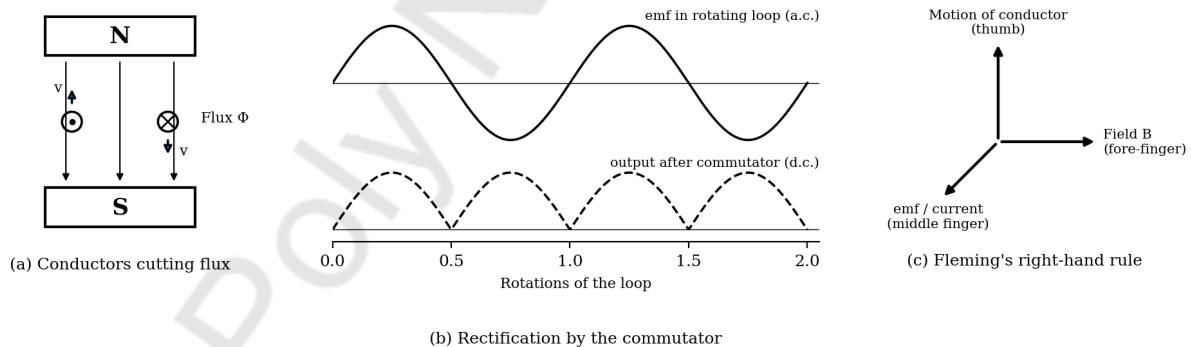


Fig. 2.1 (a) Conductors cutting flux, (b) alternating emf of a loop and rectified output, (c) Fleming's right-hand rule

Step-by-step working

1. The field winding is excited and produces a steady flux from the N pole to the S pole.
2. The armature, driven by the prime mover, rotates and its conductors cut the flux, so an alternating e.m.f. is induced in each conductor (the conductor under an N pole carries e.m.f. in one direction and, after half a revolution under an S pole, in the opposite direction).
3. The armature conductors are connected to the **commutator segments**. Carbon brushes rest on the commutator and are placed so that each brush always touches the segment connected to the conductors that are under the same polarity of pole.

4. Because the connections to the external circuit are reversed at the same instant as the e.m.f. in the coil reverses, the polarity of each brush remains fixed. The commutator therefore acts as a **mechanical rectifier**.
5. The external circuit thus receives a unidirectional (pulsating but practically steady, because of a large number of coils) voltage.

2.1.3 Construction of D.C. Generator

A D.C. machine consists of two main parts: the stationary part called the **stator** (field system: yoke, poles, field windings) and the rotating part called the **rotor** (armature, commutator, shaft). The cross-section of a four-pole machine is shown below.

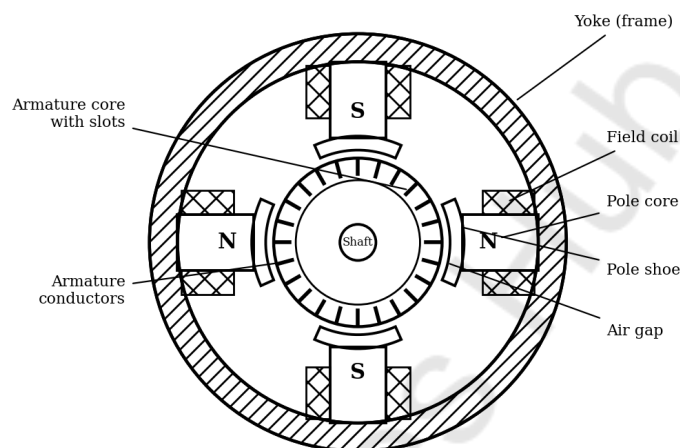


Fig. 2.2 Cross-section of a four-pole D.C. machine

The constructional parts, their materials and functions are summarised in the table that follows.

Part	Material used	Function / special features
Yoke (frame)	Cast iron for small machines; cast steel or rolled (fabricated) steel for large machines	Gives mechanical support to the poles; protects the machine; acts as the return path for the magnetic flux (carries half of pole flux).
Pole core and pole shoe	Thin laminations of annealed steel (or cast steel), riveted together and bolted to yoke	Pole core carries the field winding; pole shoe spreads the flux uniformly over the air gap, reduces air-gap reluctance and supports the field coil. Laminations reduce eddy-current loss caused by flux pulsation at the pole faces.
Field winding	Insulated copper wire or strip	Wound on pole cores to produce the working flux. <i>Shunt field</i> : many turns of thin wire. <i>Series field</i> : few turns of thick wire. Coils on adjacent poles are connected so that poles are alternately N and S.
Armature core	Laminated silicon-steel discs, (about 0.35–0.5 mm thick) insulated by varnish, keyed to the shaft	Houses the armature winding in slots on its periphery and provides low-reluctance path for flux. Lamination reduces eddy-current loss; silicon steel gives low hysteresis loss. Ventilating ducts are provided for cooling.
Armature winding	Insulated copper conductors placed in slots	Rotating conductors in which e.m.f. is induced; connected as lap or wave winding to the commutator.

Part	Material used	Function / special features
Commutator	Hard-drawn, wedge-shaped copper segments insulated from each other and from the shaft by mica	Collects current from the armature conductors and converts the induced a.c. into d.c. in the external circuit. Mica between segments is undercut to keep brushes in contact with copper.
Brushes and brush-holders	Carbon, graphite or copper-carbon (electro-graphite)	Brushes slide over the commutator and carry current between armature and external circuit; spring-loaded brush-holders hold constant pressure. Carbon gives good contact, self-lubrication and a high contact resistance that helps commutation.
Shaft, bearings, end-covers, fan	Mild steel shaft; ball/roller bearings; cast iron or steel end shields	Shaft transmits torque from prime mover; bearings reduce friction; end-covers protect the winding; fan gives forced ventilation.

2.1.4 Types of D.C. Generators

D.C. generators are classified according to the way in which their field winding is excited.

- **Separately excited generator** - the field winding is supplied from an independent external d.c. source (battery or another generator). The flux is independent of the load and armature current.
- **Self-excited generator** - the field winding is supplied by the generator's own armature. A small residual magnetism in the poles starts the process. Self-excited generators are of three kinds:
 - **Shunt generator** - field winding (high resistance, many turns) connected in parallel with the armature.
 - **Series generator** - field winding (low resistance, few turns) connected in series with the armature and load.
 - **Compound generator** - has both shunt and series field windings. Depending on connection it is *long-shunt* or *short-shunt*, and depending on the relative direction of the series flux it is *cumulative* (series flux aids shunt flux) or *differential* (series flux opposes shunt flux).

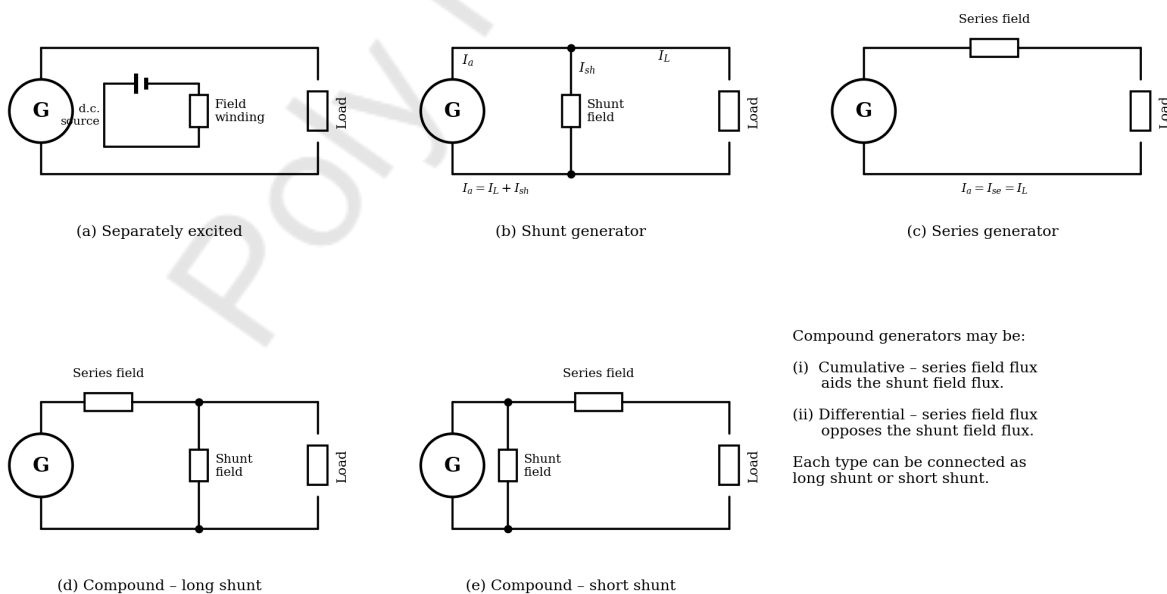


Fig. 2.3 Types of D.C. generators (circuit connections)

Current and voltage relations of each type

Type	Current relations	Voltage equation (E_g = generated e.m.f.; V = terminal voltage; V_b = brush drop, about 1 V per brush)
Separately excited	$I_a = I_L$	$V = E_g - I_a R_a - V_b$
Shunt	$I_{sh} = V/R_{sh}$ $I_a = I_L + I_{sh}$	$V = E_g - I_a R_a - V_b$
Series	$I_a = I_{se} = I_L$	$V = E_g - I_a (R_a + R_{se}) - V_b$
Long-shunt compound	$I_{sh} = V/R_{sh}$ $I_a = I_{se} = I_L + I_{sh}$	$V = E_g - I_a (R_a + R_{se}) - V_b$
Short-shunt compound	$I_{se} = I_L$ $I_{sh} = (V + I_L R_{se})/R_{sh}$ $I_a = I_L + I_{sh}$	$V = E_g - I_a R_a - I_L R_{se} - V_b$

Note: A generator with permanent-magnet poles is also possible for very small machines (e.g. tacho-generators); it needs no field winding.

2.2 Armature Winding Types - Concept of Lap and Wave Winding

The armature winding is the heart of a D.C. machine. It consists of a number of **coils** placed in the slots of the armature core and joined to the commutator segments. The way these coils are joined decides the number of **parallel paths** between the brushes, and therefore the voltage and current rating of the machine.

2.2.1 Important Terms

Term	Meaning
Conductor	A single length of wire lying in the magnetic field in which e.m.f. is induced.
Turn	Two conductors connected at the far end (one turn = 2 conductors).
Coil	One or more turns; each coil has two <i>coil sides</i> and two ends connected to commutator segments. A winding with C coils has C commutator segments (single-turn coils: $Z = 2C$).
Pole pitch	Peripheral distance between the centres of two adjacent poles = Z/P conductors (or S/P slots).
Coil span (pitch)	Distance between the two sides of a coil, measured in conductors/slots. Full-pitch coil span = one pole pitch.
Back pitch (Y_B)	Distance in conductors between the two sides of the same coil (measured at the back, i.e. non-commutator end).
Front pitch (Y_F)	Distance between the second conductor of one coil and the first conductor of the next coil connected to it (at commutator end).
Resultant pitch (Y_R)	Distance between the starting conductors of two consecutive coils in series. Lap: $Y_R = Y_B - Y_F$; Wave: $Y_R = Y_B + Y_F$.
Commutator pitch (Y_C)	Number of commutator segments between the two ends of a coil.
Progressive / retrogressive	If the winding advances in the direction of the rotation of armature it is progressive; otherwise retrogressive.

2.2.2 Lap Winding

In **lap winding** the two ends of a coil are connected to **adjacent commutator segments**, so the winding 'laps back' over the previous coil. It is mainly used for machines of **large current and low voltage**.

- Back and front pitches are both odd and of opposite sign (progressive: $Y_B > Y_F$).
- $Y_B - Y_F = \pm 2$ (simplex) and $Y_C = \pm 1$.
- For a progressive winding: $Y_B = (Z/P) + 1$, $Y_F = Y_B - 2$; for a retrogressive winding: $Y_B = (Z/P) - 1$, $Y_F = Y_B + 2$.
- The number of parallel paths $A = P$ (simplex), $A = 2P$ (duplex) and so on; the number of brushes = number of poles.
- **Equalizer rings** are provided to connect points of equal potential, preventing circulating currents due to unequal pole fluxes and so protecting the brushes from sparking.

2.2.3 Wave Winding

In **wave winding** the two ends of a coil are connected to commutator segments that are about **one pair of poles apart**, so the winding progresses like a wave around the armature. It is used for machines of **high voltage and low current**.

- Y_B and Y_F are both odd and have the same sign; they may be equal.
- Average pitch $Y_{av} = (Z \pm 2)/P$, $Y_R = Y_B + Y_F = 2Y_C$ and $Y_C = (C \pm 1)/(P/2)$. The $\pm$ sign makes the winding progressive or retrogressive and ensures the winding closes after going once round the armature.
- For simplex wave winding the number of parallel paths is always $A = 2$, whatever the number of poles; two brushes are sufficient (more may be used for current collection).
- No equalizer rings are needed, since the conductors in each path are distributed under all poles. **Dummy coils** are sometimes added to keep the winding mechanically symmetrical.

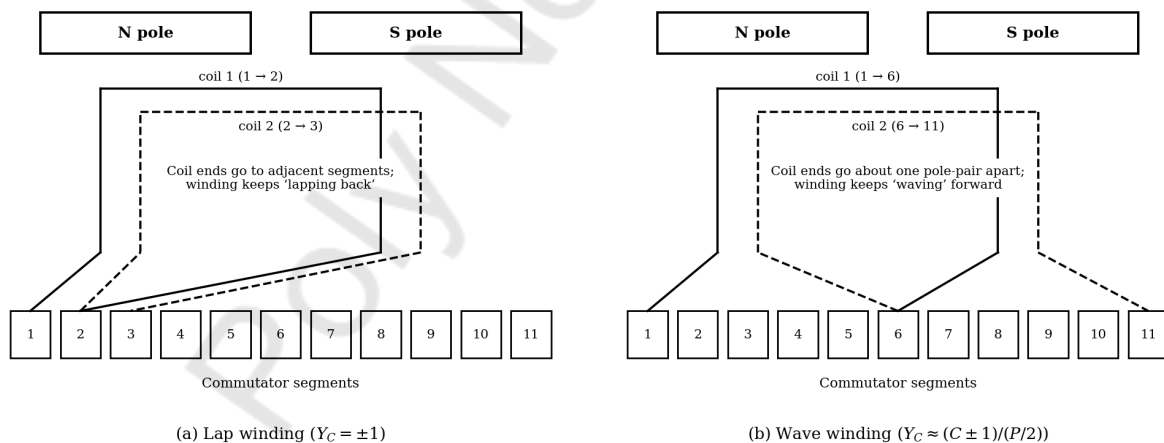


Fig. 2.4 Developed schematic of lap and wave coil connections

Comparison of lap and wave winding

Point of comparison	Lap winding	Wave winding
Coil ends joined to	Adjacent commutator segments	Segments about one pole-pair apart
Number of parallel paths (A)	$A = P$ (simplex)	$A = 2$ (simplex)
Number of brushes	Equal to number of poles (P)	Two (or P, if desired)
Number of conductors per path	Z/P	$Z/2$
Current per path	I_a/P	$I_a/2$
Suitable for	Low voltage, high current machines	High voltage, low current machines
Equalizer rings	Necessary	Not required
Commutator pitch	$Y_C = \pm 1$	$Y_C = (C \pm 1)/(P/2)$
Cost / copper	Needs more conductors of larger cross-section for the same voltage	Needs fewer conductors per path for the same voltage, so cheaper

Example 2.1 - Winding pitches

A 4-pole, simplex lap winding has 16 conductors in the armature. Find Y_B , Y_F and Y_C .

Solution: $Y_B = Z/P + 1 = 16/4 + 1 = 5$; $Y_F = Y_B - 2 = 3$; $Y_C = +1$.

Example 2.2 - Wave winding pitches

A 4-pole simplex wave winding has 22 conductors and 11 commutator segments. Find the pitches.

Solution: $Y_C = (C \pm 1)/(P/2) = (11 - 1)/2 = 5$; $Y_R = 2Y_C = 10$; $Y_B = Y_F = 5$ (both odd, as required).

2.3 E.m.f. Equation of a D.C. Generator

The e.m.f. equation gives the magnitude of the e.m.f. generated between the brushes in terms of the machine constants and operating conditions.

Notation

- Φ = flux per pole (Wb)
- Z = total number of armature conductors
- P = number of poles
- A = number of parallel paths (lap: $A = P$; wave: $A = 2$)
- N = speed of armature in revolutions per minute (r.p.m.)

Derivation

1. Flux cut by **one conductor** in **one revolution** = $d\Phi = P \cdot \Phi$ (Wb).
2. Time taken for one revolution = $60/N$ seconds.
3. Average e.m.f. induced in one conductor = $d\Phi/dt = P\Phi/(60/N) = \mathbf{P\Phi N/60}$ volt.
4. The number of conductors connected in series in each parallel path = Z/A . The e.m.f. between brushes equals the e.m.f. of one parallel path.

$$\mathbf{E_g = (P \Phi N / 60) \times (Z / A) = \Phi Z N P / (60 A) \text{ volt}}$$

- **Lap winding** ($A = P$): $E_g = \Phi Z N / 60$

- **Wave winding** ($A = 2$): $E_g = \Phi Z N P / 120$
- In terms of angular speed $\omega = 2\pi N/60$: $E_g = (ZP/2\pi A) \Phi \omega = K_a \Phi \omega$
- For a given machine Z , P and A are fixed, so $E_g \propto \Phi N$ ($E_g = K\Phi N$, with $K = ZP/60A$).

Related relations

- Terminal voltage of generator: $V = E_g - I_a R_a - (\text{brush contact drop})$.
- Power developed in the armature (electrical equivalent of mechanical power converted) = $E_g I_a$.
- Power output = $V I_L$.
- Armature copper loss = $I_a^2 R_a$; shunt field copper loss = $V I_{sh}$.

Losses in D.C. generator	Details
Copper losses	Armature copper loss (about 30–40% of full-load loss), field copper loss (20–30%), brush contact loss
Iron (core) losses	Hysteresis loss and eddy-current loss in armature core and teeth (constant for constant speed and flux)
Mechanical losses	Friction (bearings, brushes) and windage loss
Stray load losses	Small additional losses due to flux distortion, leakage etc.

Efficiency: $\eta = (\text{Output} / \text{Input}) \times 100 = (V I_L) / (V I_L + \text{total losses}) \times 100$.

Example 2.3 - E.m.f. of lap- and wave-wound armature

A 4-pole generator has 400 armature conductors and a flux of 0.02 Wb per pole. Find the generated e.m.f. at 1000 r.p.m. if the armature is (i) lap wound, (ii) wave wound.

(i) Lap: $A = P = 4 \rightarrow E_g = \Phi Z N P / 60A = (0.02 \times 400 \times 1000 \times 4) / (60 \times 4) = \mathbf{133.3 \text{ V}}$

(ii) Wave: $A = 2 \rightarrow E_g = (0.02 \times 400 \times 1000 \times 4) / (60 \times 2) = \mathbf{266.7 \text{ V}}$

The wave winding gives twice the voltage of the lap winding for the same conductors, as it has half the number of parallel paths (note: the lap winding then carries twice the current).

Example 2.4 - Shunt generator voltage equation

A 250 V shunt generator supplies a load current of 50 A. Armature resistance = 0.05 Ω , shunt field resistance = 100 Ω , brush drop = 1 V per brush. Find the generated e.m.f.

$I_{sh} = V/R_{sh} = 250/100 = 2.5 \text{ A}$; $I_a = I_L + I_{sh} = 50 + 2.5 = 52.5 \text{ A}$

$E_g = V + I_a R_a + \text{brush drop} = 250 + (52.5 \times 0.05) + 2 = \mathbf{254.6 \text{ V}}$

2.4 Generator Characteristics

The performance of a generator is judged from its **characteristics**, which are graphs showing the relation between two quantities. Three characteristics are important.

Characteristic	Plot between	Conditions kept constant	Use
Open-circuit characteristic (O.C.C. / magnetisation curve)	Generated e.m.f. E_0 versus field current I_f	Speed constant, armature on no load	Shows magnetic behaviour of the machine; used to determine critical resistance, critical speed and voltage build-up
Internal (total) characteristic	Generated e.m.f. E_g versus armature current I_a	Speed and field resistance constant	Shows e.m.f. actually generated after armature-reaction effect

Characteristic	Plot between	Conditions kept constant	Use
External characteristic	Terminal voltage V versus load current I_L	Speed and field-circuit resistance constant	Shows how terminal voltage varies with load; used to select the generator for an application

2.4.1 Open-Circuit Characteristic (O.C.C.)

The O.C.C. is obtained by running the generator at **constant rated speed on no load** and varying the field current in steps from zero upward. For all types of generator (even self-excited ones) the field winding is **separately excited** during the test, so that the field current can be varied independently; a field rheostat in potentiometer connection (or a variable d.c. source) is used. The e.m.f. is read by a voltmeter across the armature.

- **Initial point:** even with $I_f = 0$ a small e.m.f. (about 2–3% of rated voltage) is induced because of **residual magnetism** of the poles.
- **Linear region:** flux is proportional to field current because iron has low reluctance.
- **Knee:** the curve bends as the iron begins to saturate.
- **Saturation:** a large increase in I_f gives only a small increase in e.m.f.
- Since $E_g \propto \Phi N$, the O.C.C. at another speed can be obtained by multiplying the e.m.f. at each I_f by the ratio of speeds: $E_2 = E_1 \times (N_2/N_1)$.

2.4.2 External Characteristics (Concept Only)

The external characteristic is drawn between terminal voltage and load current. The terminal voltage falls with load because of the armature resistance drop ($I_a R_a$), the demagnetising effect of armature reaction, and, in shunt machines, the reduction of field current caused by the falling voltage.

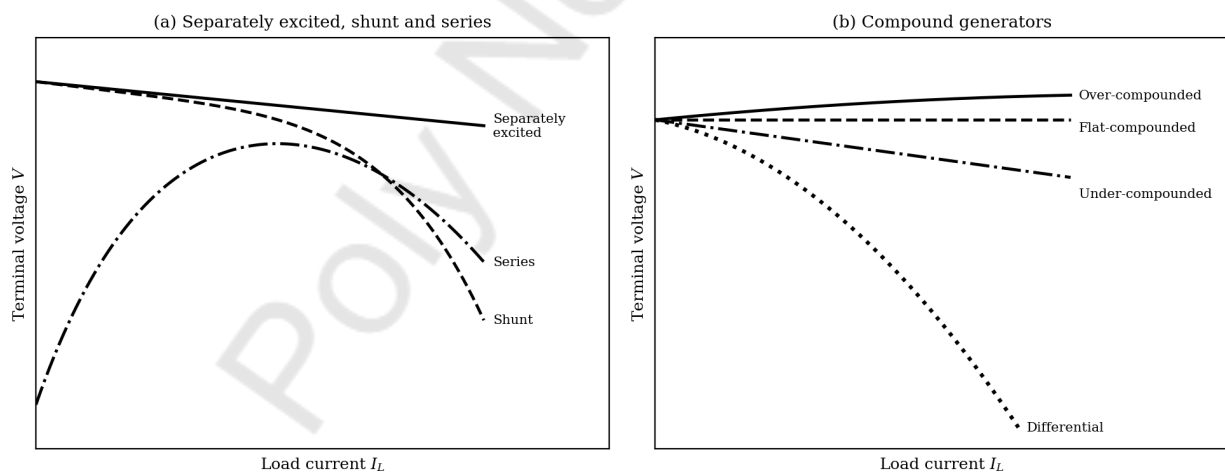


Fig. 2.5 External characteristics of D.C. generators (concept)

Generator	Shape of external characteristic	Reason
Separately excited	Slight drop in voltage as load increases	Only $I_a R_a$ drop and armature reaction reduce the voltage; field current is independent of load. Gives the best voltage regulation among non-compounded types.
Shunt	Voltage falls more than in separately excited machine; at heavy overload the curve bends back and voltage falls sharply (short-circuit current is small)	Fall in terminal voltage reduces field current, which reduces flux and e.m.f. further – cumulative effect.

Generator	Shape of external characteristic	Reason
Series	Voltage is nearly zero (residual) at no load, rises with load, reaches maximum and then drops	Load current is the field current: flux and e.m.f. rise with load; at saturation armature reaction and $I_a(R_a + R_{se})$ drop dominate.
Cumulative compound	Over-compounded: voltage rises with load; flat (level)-compounded: voltage practically constant; under-compounded: voltage falls slightly	Series flux aids shunt flux and compensates the drops. The degree of compounding is decided by the number of series turns.
Differential compound	Voltage falls rapidly with load (nearly constant-current type)	Series flux opposes shunt flux and reduces the resultant flux as load increases.

2.4.3 Methods of Building Up of E.m.f. in a Self-Excited Generator

A self-excited generator (shunt or compound) has no external source for its field. It builds up its voltage by itself, starting from the **residual magnetism** in the poles.

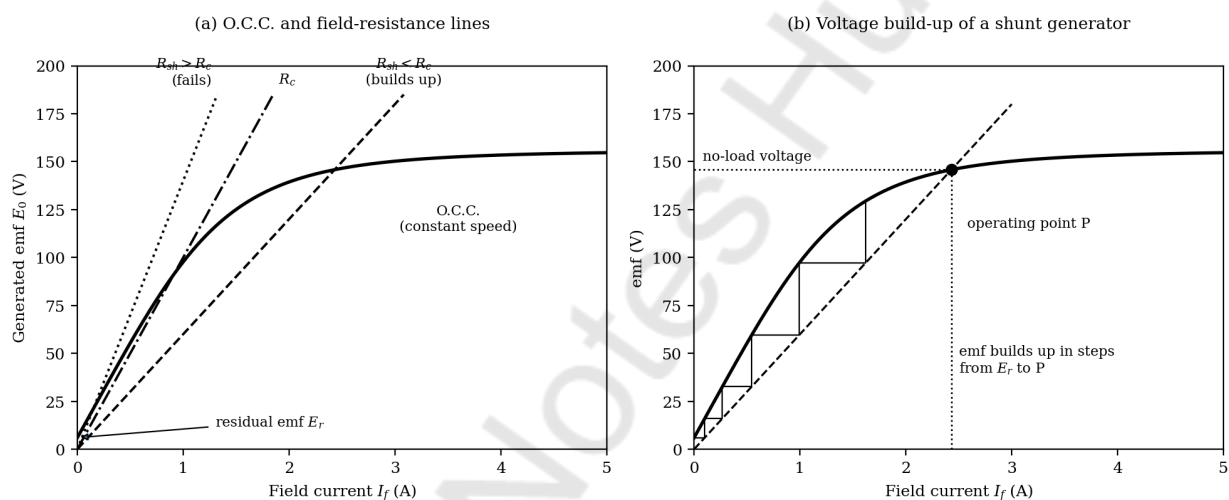


Fig. 2.6 (a) O.C.C. with field-resistance lines, (b) voltage build-up of a shunt generator

Process of build-up

1. When the armature is rotated, the residual flux induces a small e.m.f. E_r (a few volts) in the armature.
2. This e.m.f. drives a small current through the shunt field winding, which is connected across the armature.
3. If the field connections are correct, the field mmf adds to the residual flux, the flux increases and so does the e.m.f.
4. The increased e.m.f. circulates a still larger field current and the process goes on cumulatively.
5. Build-up stops at the point P where the **field-resistance line** ($V = I_f R_{sh}$) cuts the O.C.C.; at this point the e.m.f. generated is just enough to drive the field current. This is the no-load voltage of the generator.

Conditions required for build-up of voltage

- There must be some **residual magnetism** in the field poles.
- The field winding must be connected to the armature so that the field mmf **aids** the residual flux (correct polarity).
- The total field-circuit resistance must be **less than the critical resistance** for the speed of operation.
- The speed must be **greater than the critical speed** for the given field resistance.

- For a series generator the load resistance must be less than the critical load resistance (otherwise the machine does not excite).

Failure to build up - causes and remedies

Cause	Remedy
Residual magnetism lost or very weak	'Flash' the field from a battery/d.c. source for a short time, or run once as a motor
Field winding connected in wrong direction (opposes residual flux)	Reverse the field terminals (or reverse direction of rotation, after re-flashing)
Field circuit resistance greater than critical resistance	Cut out external (rheostat) resistance in the field circuit
Speed lower than critical speed	Increase the prime-mover speed
Open circuit in field winding or poor brush contact / brushes not on neutral axis	Check connections, clean the commutator, set brushes properly

2.4.4 Critical Resistance and Critical Speed

Critical field resistance (R_c)

The **critical resistance** of a shunt generator is the **maximum value of field-circuit resistance** (at a given speed) for which the generator will just build up its voltage. Graphically it is the **slope of the tangent** drawn to the initial, straight portion of the O.C.C. through the origin.

$$R_c = \Delta E / \Delta I_f \text{ (slope of the linear part of O.C.C.) in ohm}$$

- If $R_{sh} < R_c$: the field-resistance line cuts the O.C.C. at a high point - the generator **builds up**.
- If $R_{sh} = R_c$: the line coincides with the linear part of O.C.C. - build-up is unstable and indefinite.
- If $R_{sh} > R_c$: the line meets the O.C.C. close to the residual e.m.f. - the generator **fails to excite**.

Critical speed (N_c)

The **critical speed** is the **minimum speed** below which a shunt generator will not build up for a given field-circuit resistance. At speed N , e.m.f. for the same field current is proportional to N , so the slope of the linear part of O.C.C. - that is, R_c - is also proportional to speed.

$$R_c \propto N \Rightarrow R_{c2} / R_{c1} = N_2 / N_1 \Rightarrow N_c = N_1 \times (R_{sh} / R_{c1})$$

(R_{c1} = critical resistance at speed N_1 ; R_{sh} = actual field resistance)

Numerical 2.1 - Critical resistance

The linear portion of the O.C.C. of a shunt generator at 1000 r.p.m. gives 120 V for a field current of 1.2 A. Find the critical resistance at 1000 r.p.m. and also at 800 r.p.m.

Solution: R_c (1000 r.p.m.) = $\Delta E / \Delta I_f = 120 / 1.2 = 100 \Omega$

R_c (800 r.p.m.) = $100 \times (800 / 1000) = 80 \Omega$

Numerical 2.2 - Critical speed

The critical resistance of a shunt generator at 1000 r.p.m. is 40Ω . The field circuit resistance is 50Ω . Will it build up at 1000 r.p.m.? Find the minimum speed for build-up.

Solution: At 1000 r.p.m., $R_{sh} = 50 \Omega > R_c = 40 \Omega$, so the generator **will not build up**.

Critical speed $N_c = N_1 \times R_{sh} / R_{c1} = 1000 \times 50 / 40 = 1250 \text{ r.p.m.}$ The speed must exceed 1250 r.p.m. (or R_{sh} must be reduced below 40Ω).

Numerical 2.3 - From O.C.C. data

The O.C.C. of a shunt generator at 600 r.p.m. is:

I_f (A): 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 E_0 (V): 5, 55, 105, 135, 152, 163, 170.

The field resistance is 60 Ω . Find (i) the no-load voltage, (ii) critical resistance, (iii) critical speed.

(i) Field-resistance line: $V = 60 I_f$. At $I_f = 2.5$ A the line gives 150 V, which is less than the O.C.C. value (163 V); at 3.0 A the line gives 180 V, more than 170 V. So the intersection lies between 2.5 A and 3.0 A, where the O.C.C. is $E = 163 + 14(I_f - 2.5)$. Equating: $163 + 14(I_f - 2.5) = 60 I_f \rightarrow 128 = 46 I_f \rightarrow I_f = 2.78$ A, so no-load voltage = $60 \times 2.78 \approx \mathbf{167\text{ V}}$.

(ii) The O.C.C. is straight up to about 1.0 A, with slope $\Delta E/\Delta I_f = (105 - 55)/0.5 = \mathbf{100\ \Omega}$. So $R_c = 100\ \Omega$ at 600 r.p.m. ($R_{sh} = 60\ \Omega$ is less than R_c , so the machine builds up).

(iii) $N_c = N_1 \times R_{sh}/R_{c1} = 600 \times (60/100) = \mathbf{360\text{ r.p.m.}}$. Below 360 r.p.m. the generator will not excite with this field resistance.

Practice numericals

1. The critical resistance of a shunt generator at 1200 r.p.m. is 80 Ω and its field resistance is 60 Ω . Find the critical speed. [Ans: **900 r.p.m.**]
2. The O.C.C. of a generator at 800 r.p.m. has a linear portion giving 100 V at 1.25 A. Find R_c at 800 r.p.m. and at 1000 r.p.m. Will the generator build up at 1000 r.p.m. if $R_{sh} = 90\ \Omega$? [Ans: **80 Ω ; 100 Ω ; yes, 90 $\Omega < 100\ \Omega$]**

2.5 Concept of Flux Distribution in D.C. Machine

The flux in the air gap of a D.C. machine is produced by the field winding (the **main flux**) and, when the armature carries current, by the armature conductors (**armature flux**). The way this flux is distributed along the armature surface decides the e.m.f. wave in each conductor, the position of the brushes and the commutation behaviour.

No-load flux distribution

- At no load the armature current is zero, so the air-gap flux is produced by the main poles only.
- Under the pole face the air gap is uniform, so the flux density B is nearly **constant (flat-topped)** over the pole arc. At the pole tips, *fringing* makes the flux fall gradually.
- Between two adjacent poles (the **interpolar region**) the flux density is practically **zero**.
- The flux is symmetrical about the axis of each pole, and the poles are alternately N and S so that B changes sign from one pole to the next.

Neutral axes

Term	Definition	Role
Geometrical neutral axis (GNA)	The axis passing through the armature centre and exactly midway between two adjacent main poles (the interpolar axis)	Fixed by the geometry of the machine
Magnetic neutral axis (MNA)	The axis perpendicular to the direction of the resultant air-gap flux - conductors lying on it cut no flux, so e.m.f. induced is zero	Position depends on load; ideal position for brushes (zero e.m.f. in the coil short-circuited by brushes)
Interpolar zone	Region between pole tips where flux density is $\sim$ zero	Commutation takes place here

At no load GNA and MNA coincide, and the brushes, kept at GNA, collect the maximum e.m.f. On load the armature current produces its own flux which distorts the main flux, the MNA moves away from the GNA and the situation changes - this is called **armature reaction** (next section).

The e.m.f. induced in a coil is directly related to the shape of the flux density wave: because B is flat over the pole arc, the e.m.f. in a conductor is almost constant while it passes under the pole and falls to zero in the interpolar zone. The commutator and the large number of coils sum these to give practically steady d.c.

2.6 Armature Reaction in D.C. Machine and Remedial Measures (Concept Only)

Armature reaction is the effect of the magnetic field set up by the armature current on the distribution and magnitude of the main field flux. When the armature carries current, its conductors produce an mmf directed along the brush axis (i.e. at 90° electrical to the main field, if brushes are on GNA) – the **cross-magnetising** mmf. The resultant air-gap flux is the combination of the two.

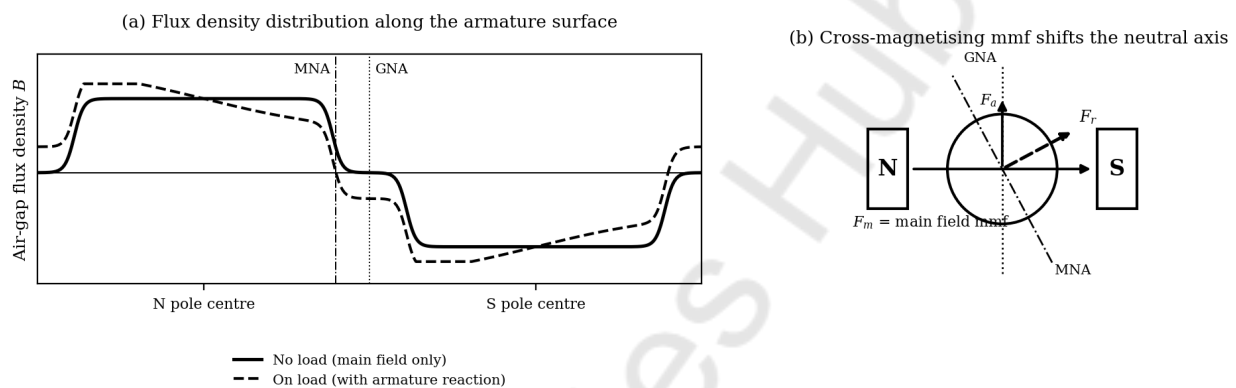


Fig. 2.7 (a) Flux density distribution on no load and on load, (b) cross-magnetising armature mmf and shift of the neutral axis

2.6.1 Effects of Armature Reaction

1. **Distortion of the main flux (cross-magnetising effect):** at each pole the flux density is increased under one pole tip and decreased under the other. Hence the flux wave is distorted.
2. **Shifting of the magnetic neutral axis (MNA):** the MNA moves in the **direction of rotation** for a generator (and against the direction of rotation for a motor). Brushes which were on GNA are now no longer at the point of zero e.m.f.
3. **Weakening (demagnetisation) of the main flux:** because of magnetic saturation at the strengthened pole tip, the increase of flux there is less than the decrease at the weakened tip, so the total flux per pole falls slightly. Result: generated e.m.f. and terminal voltage decrease.
4. **Poor commutation and sparking:** because the coil short-circuited by the brush is no longer in the zero-flux zone, an e.m.f. is induced in it and large circulating current produces sparks at the brushes.
5. **Demagnetising effect when brushes are shifted:** if the brushes are shifted forward to the new MNA (angle θ), the armature mmf can be resolved into a *cross-magnetising* component and a *demagnetising* component (due to conductors in the angle 2θ), which directly opposes the main field.

2.6.2 Remedial Measures

Method	How it works	Remarks
Brush shift	Brushes are moved forward (generator) to the new MNA, i.e. in the direction of rotation	Simple but not satisfactory - the correct shift changes with load; increases demagnetisation; used only in small machines
Interpoles (commutating poles)	Small narrow poles placed between the main poles and connected in series with the armature . Polarity: for a generator, same as the main pole <i>ahead</i> in the direction of rotation; for a motor, same as the pole behind	Neutralise armature cross-magnetising mmf in the interpolar zone and produce a commutating e.m.f.; effective for all loads because their strength follows armature current; used in nearly all machines above about 1 kW
Compensating winding	Conductors embedded in slots in the pole faces, connected in series with the armature so that current in them is opposite in direction to that in armature conductors under the pole	Cancels armature reaction under the pole face and prevents flux distortion; costly, so used only in large machines and machines with sudden load changes or heavy overloads
High-reluctance pole tips	Pole shoe with slots, or increased air gap at the pole tips, or saturated tips	Reduces cross flux; but needs more field mmf, so increases cost

2.7 Commutation Method and Concept of Reactance Voltage

2.7.1 Commutation

The armature coils are connected in parallel paths. When a coil moves from one parallel path to the next, the current in it must **reverse** from $+I_c$ to $-I_c$. This reversal of current in a coil, while it is short-circuited by a brush, is called **commutation**. The time during which the coil is short-circuited is the **commutation period T_c** .

$$T_c = (b - m) / v_c \text{ seconds}$$

b = brush width (m), m = thickness of mica insulation (m), v_c = peripheral velocity of commutator (m/s)

Coil current $I_c = I_a/A$ (lap: I_a/P ; wave: $I_a/2$)

T_c is very short (typically about 0.5 to 2 ms), so the current reversal is very rapid and any inductance in the coil opposes it.

Types of commutation (shown in Fig. 2.8)

- **Ideal (linear) commutation:** current reverses uniformly from $+I_c$ to $-I_c$ and is zero at mid-period; no sparking; brush current density is uniform.
- **Under-commutation (delayed):** the current reversal lags and reaches $-I_c$ late; the remaining current is forced to flow as a spark when the brush leaves the segment - the most common problem; sparking at the trailing brush edge.
- **Over-commutation:** the reversal is too fast - the current overshoots and sparking occurs at the leading edge of the brush (rare, usually from excessive interpole strength).

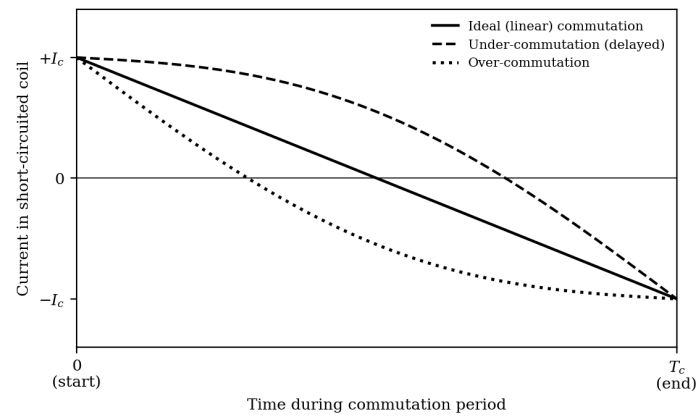


Fig. 2.8 Current in the coil under commutation

2.7.2 Reactance Voltage

The coil under commutation has self-inductance L . As its current changes, a **self-induced e.m.f.** $e = L \, di/dt$ appears. By Lenz's law it opposes the change of current, i.e. it opposes the reversal. This e.m.f. is called the **reactance voltage**. In addition, the mutual induction between the coils being commutated at the same time contributes.

Average reactance voltage, $e_r = L \times (2 I_c / T_c)$ volt

The reactance voltage sends a circulating current through the coil and brush contact in the same direction as the original current, so the reversal is **delayed**; at the end of T_c the current has not reached $-I_c$, which gives rise to sparking, brush burning, pitting of the commutator and heating. The reactance voltage is higher for larger current, higher speed (smaller T_c) and larger inductance.

2.7.3 Methods of Improving Commutation

Method	Principle	Details
Resistance commutation	Use of high-resistance carbon brushes	Contact resistance between brush and segment grows as the segment leaves, which forces the current to reverse quickly; improves commutation, though loss increases a little
E.m.f. (voltage) commutation - interpoles	A commutating e.m.f. is induced in the short-circuited coil, opposite to the reactance voltage	Interpoles in series with armature give e.m.f. proportional to armature current, so commutating e.m.f. adjusts automatically with load; in addition they neutralise cross-magnetising armature reaction. Most widely used method.
Brush shift	Brushes advanced to a position where the coil cuts flux of next pole	Gives the required commutating e.m.f.; needs readjustment with load; seldom used
Compensating winding	Removes armature reaction under poles	Used in addition to interpoles in heavy-duty machines
Good maintenance	-	Proper brush pressure, brush set on neutral axis, clean commutator, mica properly undercut, correct brush grade

Numerical 2.4 - Reactance voltage

A 4-pole lap-wound generator delivers an armature current of 200 A. The commutator peripheral speed is 15 m/s, brush width 10 mm, mica thickness 1 mm and coil inductance 0.05 mH. Find the average reactance voltage.

Coil current: $I_c = I_a / A = 200/4 = 50$ A (lap: $A = P = 4$).

Commutation period: $T_c = (b - m)/v_c = (10 - 1) \times 10^{-3}/15 = 0.6$ ms.

$e_r = L \times 2I_c/T_c = (0.05 \times 10^{-3} \times 100)/(0.6 \times 10^{-3}) = 8.33$ V

2.8 Applications of Different Types of D.C. Generator

Type of generator	Characteristic property	Typical applications
Separately excited	Voltage can be varied over wide range by changing field current; stable operation; voltage almost independent of load	Ward-Leonard speed-control systems, testing laboratories, electroplating/electrolysis with variable voltage, supply to d.c. motors requiring wide voltage range
Shunt	Nearly constant voltage (drooping slightly) from no load to full load; voltage adjustable by field rheostat	Battery charging, general lighting and power supply, excitation of alternators (exciters), small d.c. supply systems
Series	Voltage rises with load; poor regulation at no load	Series arc lighting (constant current), boosters in d.c. feeders to compensate line drop, supply to series motors during regenerative braking in traction
Cumulative compound - over-compounded	Voltage rises with load	Supply to distant loads through long feeders (compensates line drop); traction work
Cumulative compound - flat (level) compounded	Constant terminal voltage at all loads	Lighting and power supply in factories, hotels, offices, lifts and cranes, d.c. supply of power plants
Differential compound	Voltage drops rapidly with load; nearly constant-current	Arc welding machines, and in other circuits where current should stay constant

2.9 Parallel Operation of D.C. Generators

In large installations, several generators are connected in **parallel** to common bus-bars so that they together supply the load. All the positive terminals are joined to the positive bus-bar and all the negative terminals to the negative bus-bar.

Advantages of parallel operation

- **Continuity of supply:** if one machine breaks down, the others continue to supply the load.
- **Efficiency:** as the load varies, machines can be switched on or off so that those in service run near full load, where efficiency is the highest.
- **Maintenance:** any machine can be taken out for repair or inspection without interrupting the supply.
- **Future expansion:** additional generators can be added as the load grows.
- **Flexibility:** small units of different ratings can be used, and the total capital is spread over time.

Conditions for paralleling a generator with bus-bars

- The **polarity** of the incoming generator must be the same as that of the bus-bars.

- Its **terminal voltage** must be equal to the bus-bar voltage before the switch is closed.
- For proper sharing of load, the generators should have **similar drooping external characteristics** (equal percentage voltage drop from no load to full load).

2.9.1 Parallel Operation of Shunt Generators

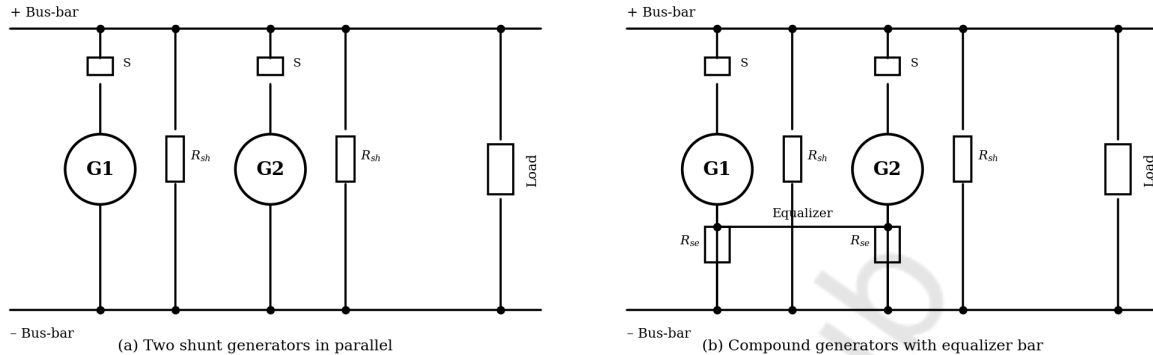


Fig. 2.9 Parallel operation: (a) shunt generators, (b) compound generators with equalizer

Procedure for connecting generator G2 to bus-bars already supplied by G1

1. Start the prime mover of G2 and bring it to rated speed, keeping the main switch S_2 open.
2. Close the field circuit and adjust the field rheostat of G2 until the voltmeter shows a voltage equal to the bus-bar voltage with the correct polarity (verified by a voltmeter/ lamp).
3. Close the main switch S_2 . The generator is now 'floating' on the bus-bars and delivers no current.
4. Increase the field current of G2 (field rheostat) and, if needed, the speed of the prime mover, to make G2 take a share of the load; simultaneously reduce the field excitation of G1 so that the bus-bar voltage is maintained.
5. Adjust the two rheostats until the load is shared in proportion to the ratings of the machines.

Load sharing

When two shunt generators with e.m.f.s E_1 , E_2 and armature resistances R_1 , R_2 run in parallel (field currents neglected), the bus-bar voltage is $V = E_1 - I_1 R_1 = E_2 - I_2 R_2$ with $I_1 + I_2 = I_L$. The load sharing can be changed by altering the field currents (and hence e.m.f.s). Since the shunt generator has a drooping characteristic, if one machine tends to take more load its terminal voltage falls and the other machine takes up more – the operation is **stable**.

2.9.2 Parallel Operation of Series and Compound Generators

Series generators have a rising characteristic, so parallel operation is **unstable**. If one machine takes slightly more current, its series field becomes stronger, its e.m.f. rises and it takes still more current, while the other falls and may even run as a motor (reverse current). The same applies to compound generators because of their series windings.

This is prevented by using an **equalizer connection** (equalizer bar): a thick conductor connecting the armature ends of the series windings (the points of the same polarity) of all machines together. Then the series field currents are forced to be equal in proportion, so any increase in the current of one machine is shared by all series fields and the load is divided in proportion to the ratings. The series windings of the machines should have resistances in the inverse ratio of their ratings.

- Shunt generators – no equalizer needed.
- Series and compound generators – equalizer bar must be connected **before** closing the main switch of the incoming machine.
- For over-compounded generators, the equalizer bar improves stability in parallel operation.

Numerical 2.5 - Load sharing of shunt generators

Two shunt generators in parallel supply a total load of 100 A. Generator 1 has e.m.f. 220 V and armature resistance 0.1 Ω ; generator 2 has e.m.f. 225 V and armature resistance 0.2 Ω . Neglect field currents. Find the current delivered by each and the bus-bar voltage.

Solution: $I_1 + I_2 = 100$ A and $V = 220 - 0.1I_1 = 225 - 0.2I_2$.

Put $I_2 = 100 - I_1$: $220 - 0.1I_1 = 225 - 0.2(100 - I_1) = 205 + 0.2I_1 \rightarrow 15 = 0.3I_1$.

$I_1 = 50$ A, $I_2 = 50$ A and bus-bar voltage $V = 220 - 0.1 \times 50 = 215$ V.

Quick Revision - Important Formulae

Topic	Formula
Induced e.m.f. in a conductor	$e = B l v \sin \theta$
Generated e.m.f. of D.C. generator	$E_g = \Phi Z N P / (60 A)$; lap: $\Phi ZN/60$; wave: $\Phi ZNP/120$
Terminal voltage	$V = E_g - I_a R_a - V_{\text{brush}}$
Shunt generator currents	$I_{\text{sh}} = V/R_{\text{sh}}$; $I_a = I_L + I_{\text{sh}}$
Series generator	$I_a = I_{\text{se}} = I_L$; $E_g = V + I_a(R_a + R_{\text{se}}) + V_b$
Short-shunt compound	$I_{\text{se}} = I_L$; $I_{\text{sh}} = (V + I_L R_{\text{se}})/R_{\text{sh}}$; $I_a = I_L + I_{\text{sh}}$
Long-shunt compound	$I_{\text{sh}} = V/R_{\text{sh}}$; $I_a = I_L + I_{\text{sh}}$; $E_g = V + I_a(R_a + R_{\text{se}}) + V_b$
Lap winding pitches	$Y_B = Z/P \pm 1$; $Y_F = Y_B \mp 2$; $Y_C = \pm 1$; $A = P$
Wave winding pitches	$Y_{\text{av}} = (Z \pm 2)/P$; $Y_C = (C \pm 1)/(P/2)$; $A = 2$
O.C.C. at another speed	$E_2 = E_1(N_2/N_1)$ at the same I_f
Critical resistance	$R_c = \Delta E/\Delta I_f$; $R_c \propto N$
Critical speed	$N_c = N_1(R_{\text{sh}}/R_{c1})$
Commutation period	$T_c = (b - m)/v_c$
Reactance voltage	$e_r = L(2I_c/T_c)$
Efficiency	$\eta = V I_L / (V I_L + \text{losses}) \times 100\%$

Multiple Choice Questions (15)

Choose the correct option. The answer key is given after the questions.

1. A D.C. generator works on the principle of
 - (a) statically induced e.m.f.
 - (b) mutually induced e.m.f.
 - (c) dynamically induced e.m.f.
 - (d) self-induced e.m.f. only
2. The function of the commutator in a D.C. generator is to
 - (a) convert the alternating e.m.f. induced in the armature into unidirectional voltage at the brushes
 - (b) increase the generated voltage
 - (c) reduce the armature reaction
 - (d) provide cooling of the armature
3. The armature core of a D.C. machine is made of laminated
 - (a) cast iron
 - (b) silicon steel
 - (c) aluminium
 - (d) copper
4. In a simplex lap winding of a P-pole machine the number of parallel paths is
 - (a) 2
 - (b) $P/2$
 - (c) P
 - (d) $2P$
5. In a simplex wave winding the number of parallel paths is
 - (a) equal to the number of poles
 - (b) always 2
 - (c) always 4
 - (d) half the number of poles
6. A 6-pole lap-wound generator has 600 conductors and a flux of 0.04 Wb per pole. The e.m.f. generated at 1000 r.p.m. is
 - (a) 200 V
 - (b) 400 V
 - (c) 800 V
 - (d) 1200 V
7. A 4-pole wave-wound generator has 500 conductors, flux 0.03 Wb per pole and runs at 1200 r.p.m. The generated e.m.f. is
 - (a) 300 V
 - (b) 450 V
 - (c) 600 V
 - (d) 1200 V
8. The open-circuit characteristic (O.C.C.) of a D.C. generator is a plot of
 - (a) terminal voltage versus load current
 - (b) generated e.m.f. versus field current at constant speed
 - (c) generated e.m.f. versus armature current
 - (d) field current versus speed

9. Which one of the following is **not** a condition for the voltage build-up of a shunt generator?
- Residual magnetism in the poles
 - Field mmf aiding the residual flux
 - Speed above the critical speed
 - Field resistance greater than the critical resistance
10. The critical resistance of a shunt generator is the
- minimum field resistance for build-up
 - maximum field resistance for which the generator will just build up (slope of the linear part of O.C.C.)
 - armature resistance at rated load
 - load resistance at rated voltage
11. If the speed of a shunt generator is halved, its critical field resistance becomes
- double
 - unchanged
 - half
 - one-fourth
12. Armature reaction in a D.C. generator causes
- distortion of the main flux and a slight reduction in its magnitude
 - an increase of main flux
 - no change in the flux
 - reduction of friction
13. Interpoles of a D.C. generator are connected
- in parallel with the armature
 - in series with the armature
 - in series with the shunt field
 - across the supply
14. The reactance voltage in a coil undergoing commutation is due to
- armature resistance
 - the self-inductance of the coil ($L \frac{di}{dt}$)
 - brush contact resistance
 - armature reaction flux only
15. To ensure stable parallel operation of compound generators, which connection is essential?
- Equalizer connection
 - Series resistance in the shunt field
 - Interpole in each machine
 - Opposite polarity connection

Answer Key

Q.	Ans.	Q.	Ans.	Q.	Ans.
1	(c)	6	(b)	11	(c)
2	(a)	7	(c)	12	(a)
3	(b)	8	(b)	13	(b)
4	(c)	9	(d)	14	(b)
5	(b)	10	(b)	15	(a)

Hints: Q6: $E = \Phi ZN/60$ (lap) = $0.04 \times 600 \times 1000/60 = 400$ V. Q7: $E = \Phi ZNP/(60A) = 0.03 \times 500 \times 1200 \times 4/(60 \times 2) = 600$ V. Q11: $R_c \propto N$.

Broad (Long-Answer) Questions (10)

1. Explain the working principle of a D.C. generator. With a neat sketch describe the construction of a D.C. machine and state the material and function of each part.
2. Classify D.C. generators according to the method of excitation. Draw the circuit diagram of each type and write the current and voltage equations of the shunt, series, long-shunt and short-shunt compound generators.
3. Explain lap winding and wave winding. Define back pitch, front pitch, resultant pitch and commutator pitch, and compare the two windings in tabular form. A 4-pole simplex lap winding has 16 conductors - find Y_B , Y_F and Y_C .
4. Derive the e.m.f. equation of a D.C. generator. A 4-pole lap-wound armature has 728 conductors and flux of 30 mWb per pole running at 1500 r.p.m. Calculate the generated e.m.f. and the speed at which the same armature, if wave wound, would give the same e.m.f. **[Ans: 546 V; 750 r.p.m.]**
5. Explain how the O.C.C. of a D.C. generator is obtained. Describe the external characteristics of separately excited, shunt, series and compound generators with the help of sketches and give reasons for their shapes.
6. Explain the process of voltage build-up in a self-excited shunt generator. State the conditions necessary for build-up and the causes and remedies if a generator fails to excite.
7. Define critical resistance and critical speed. Show that $R_c \propto N$. The O.C.C. of a shunt generator at 1000 r.p.m. is linear up to 120 V at 1.5 A and the field resistance is 64 Ω . Find the critical resistance and the critical speed. **[Ans: $R_c = 80 \Omega$; $N_c = 800$ r.p.m.]**
8. What is meant by flux distribution in a D.C. machine? Define GNA and MNA. Explain armature reaction, its effects on the main flux and on commutation, and describe the remedial measures (interpoles and compensating windings).
9. What is commutation? Explain the reactance voltage and the types of commutation (linear, under- and over-commutation). Describe the methods of improving commutation. Find T_c and the reactance voltage if $b = 12$ mm, $m = 1$ mm, $v_c = 20$ m/s, $I_c = 40$ A and $L = 0.06$ mH. **[Ans: $T_c = 0.55$ ms; $e_r = 8.73$ V]**
10. State the advantages of running D.C. generators in parallel and the conditions for paralleling. Explain the procedure of paralleling shunt generators and the need of an equalizer connection for series/compound generators. List the applications of each type of D.C. generator.