In The Name of God The Most Compassionate, The Most Merciful

Electric Machines I

Table of Contents

Chapter 5
Direct Current (DC) Generators

Different Types of DC Generators

Base on the magnetic field production, DC generators are classified as

1. **Separately excited DC generators**: a separate voltage source (from the generator terminal) is required for field production.
2. **Shunt DC generators**: field winding is connected in parallel to the generator terminal (armature winding).
3. **Series DC generators**: field winding is connected in series with the armature winding.
4. **Cumulative compound DC generators**: both series and parallel field windings are used and their magnetic fields are added together. It is further divided as **long shunt** and **short shunt**.
5. **Differential compound DC generators**: both series and parallel field windings are used and their magnetic fields are subtracted from each other. It is divided as **long shunt** and **short shunt**.

Specifications of DC Generators

DC generators have the following specifications:

1. Nominal terminal **voltage**

2. Nominal **power** (nominal terminal current can be obtained from the first two items)

3. **Efficiency**

4. Nominal rotational **velocity**

5. **Voltage regulation** (VR)

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100$$

Prime movers

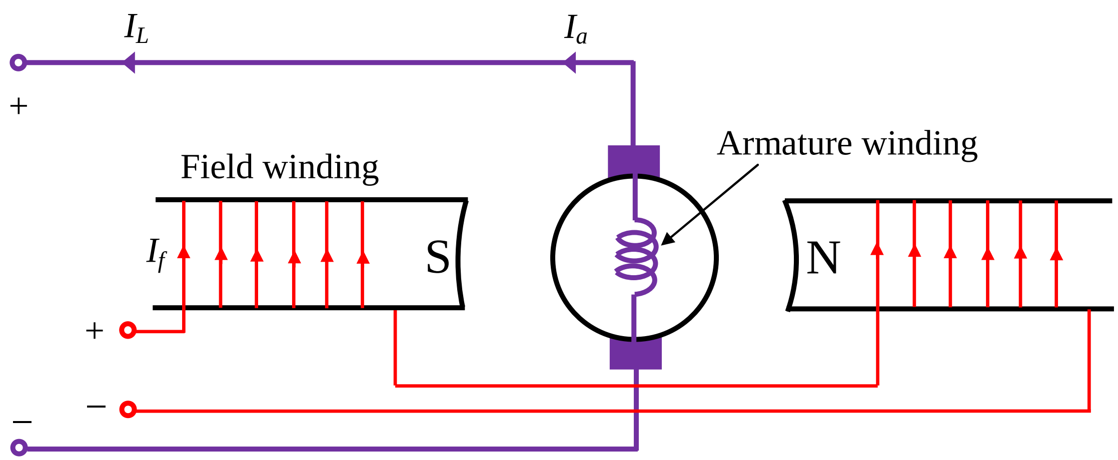
- The mechanical power to a DC generator can be provided by a prime mover.

- The prime movers can be
  1. **Steam turbines**
  2. **Gas turbines**
  3. **Hydro turbines**
  4. **Diesel engines**
  5. **Electric motors**

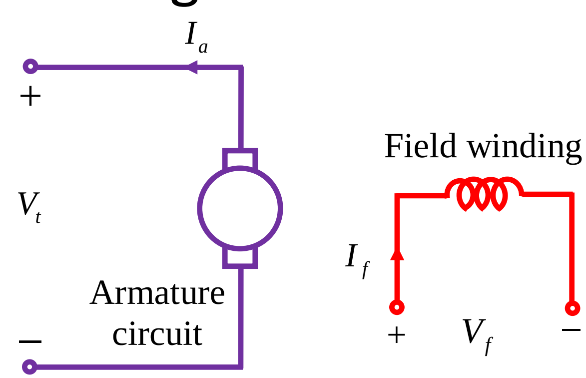
- In this chapter, it is assumed that the **rotational velocity** of the generators is **constant**, unless otherwise mentioned.

Separately Excited DC Generators

The schematic diagram of the separately excited dc generator:

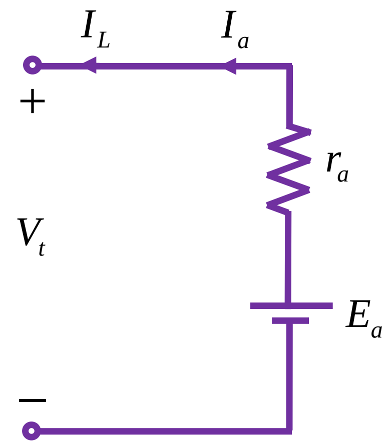


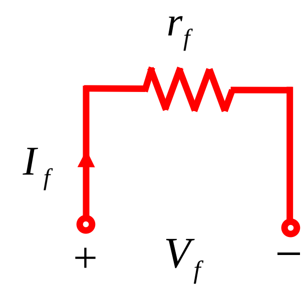
The simplified schematic diagram:



Separately Excited DC Generators

The equivalent circuit of the separately excited dc generator:





r_a is the armature winding resistance
r_f is the field winding resistance
I_a is the armature current
I_f is the field current
I_L is the load current
V_t is the generator terminal voltage (load voltage)
V_f is the field winding voltage
E_a is the induced voltage in the armature winding

$I_a = I_L$ $\quad$ $V_t = E_a - I_a r_a$ $\quad$ $E_a = k\phi\omega$ $\quad$ $V_f = I_f r_f$ $\quad$ $\phi \propto I_f$

Armature Induced Voltage

Induced voltage in a single loop is expressed as:

$$E = 2Bvl = 2B\omega r l = 2\frac{\phi}{A}\omega r l$$
$$= 2\frac{\phi}{2\pi r l / p}\omega r l = \frac{p}{\pi}\phi\omega$$

ω is the rotational velocity in rad/s
ϕ is the magnetic flux of each pole
p is the number of poles

The induced voltage in the armature winding having $\boldsymbol{N}$ turns and $\boldsymbol{a}$ parallel paths is obtained as:

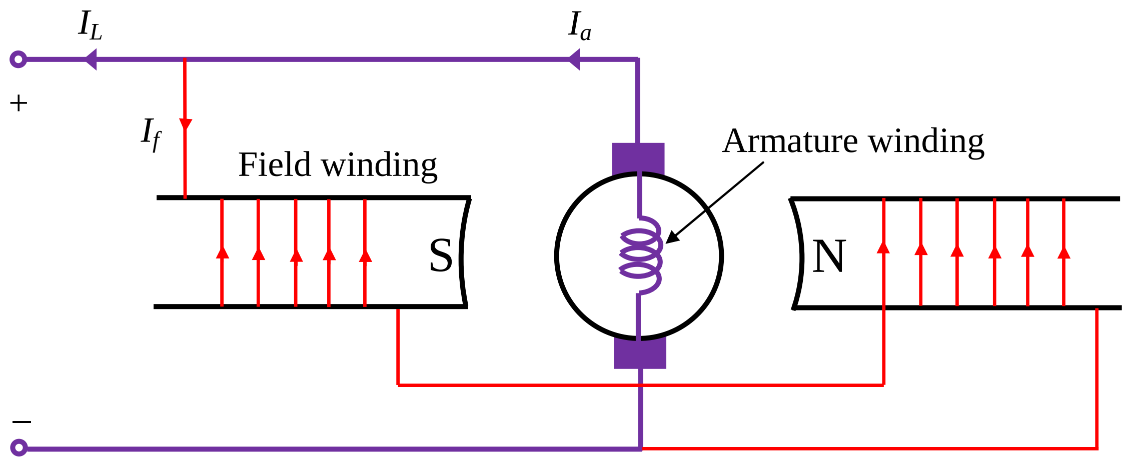
$$E_a = \frac{N}{a}E = \frac{Z}{2a}E = \frac{pZ}{2\pi a}\phi\omega$$

$$E_a = k\phi\omega \qquad k = \frac{pZ}{2\pi a}$$

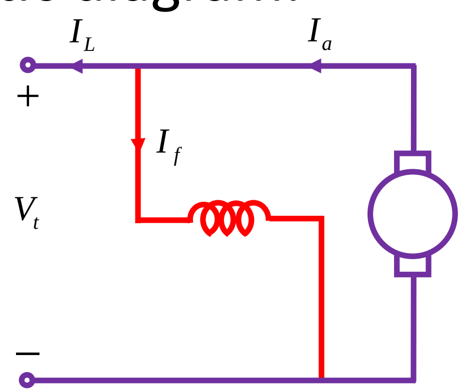
Z is the total number of conductors
N is the total number of turns
a is the number of parallel paths

Shunt DC Generators

The schematic diagram of the shunt dc generator:

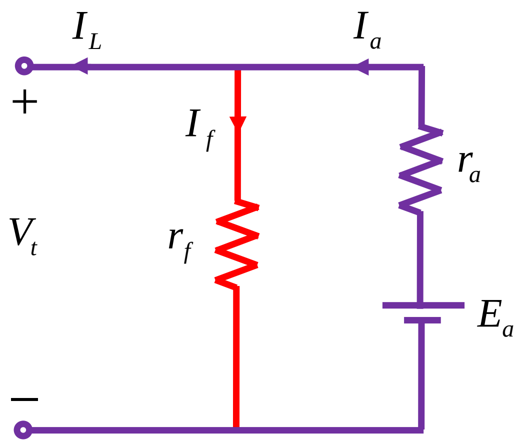


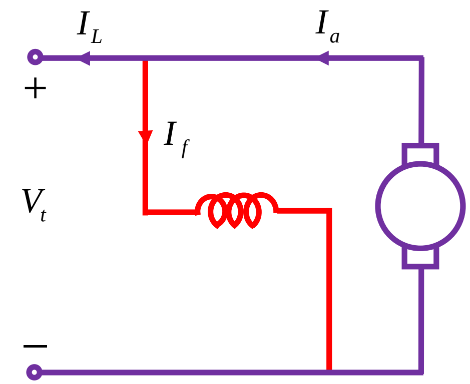
The simplified schematic diagram:



Shunt DC Generators

The equivalent circuit of the shunt dc generator:





$$I_a = I_L + I_f$$

$$I_f = \frac{V_t}{r_f}$$

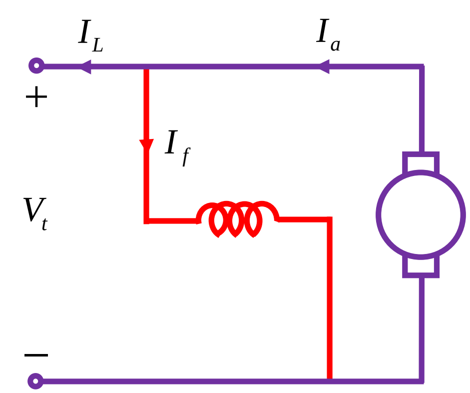
$$V_t = E_a - I_a r_a$$

$$E_a = k\phi\omega$$

$$\phi \propto I_f$$

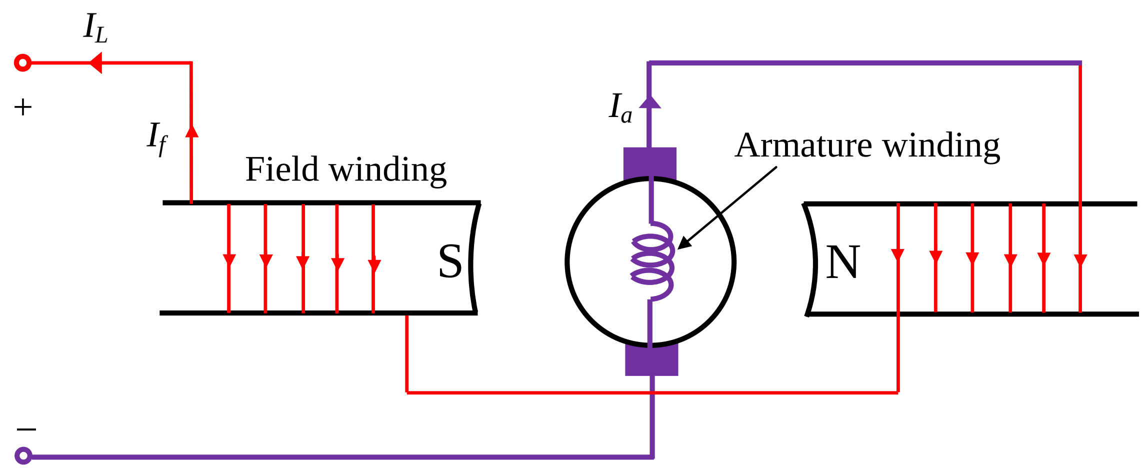
Voltage-Making of Shunt DC Generators

- Assume a shunt DC generator is rotated using a prime mover under no-load condition.
- In the starting point (when the rotational speed is still zero) the terminal voltage is zero;
- Therefore, the field current (I_f) is zero and no field can be produced.
- Consequently no emf is induced. $E_a = k\phi\omega$
- The question is how the terminal voltage can be made?
- Residual flux is behind the voltage-making.
- Residual flux produces a small emf. $E_a = k\phi_{res}\omega$
- Small emf causes small terminal voltage.
- Small terminal voltage flows small field current.
- Small field current increases the flux and so on.

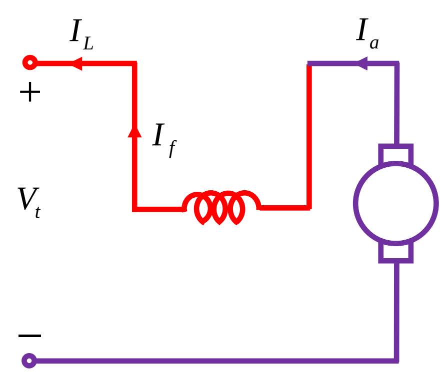


Series DC Generators

The schematic diagram of the series dc generator:

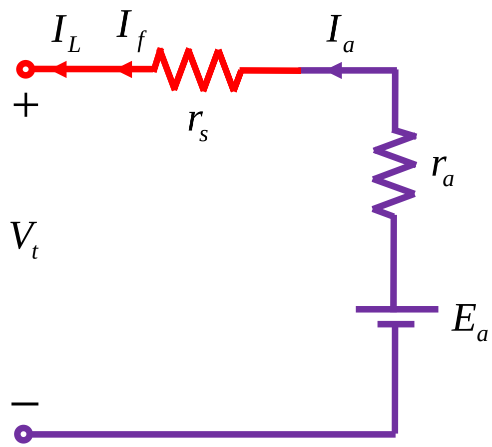


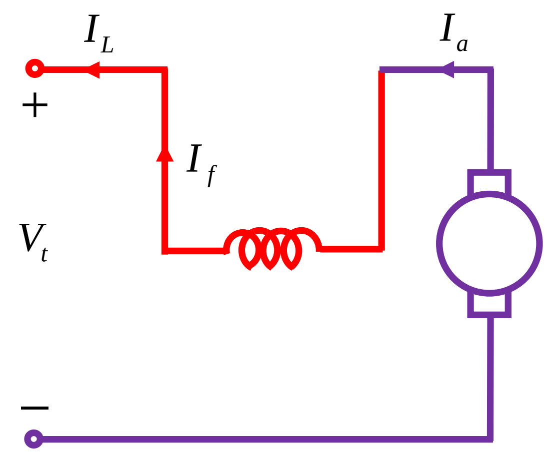
The simplified schematic diagram:



Series DC Generators

The equivalent circuit of the series dc generator:





$$I_a = I_f = I_L$$

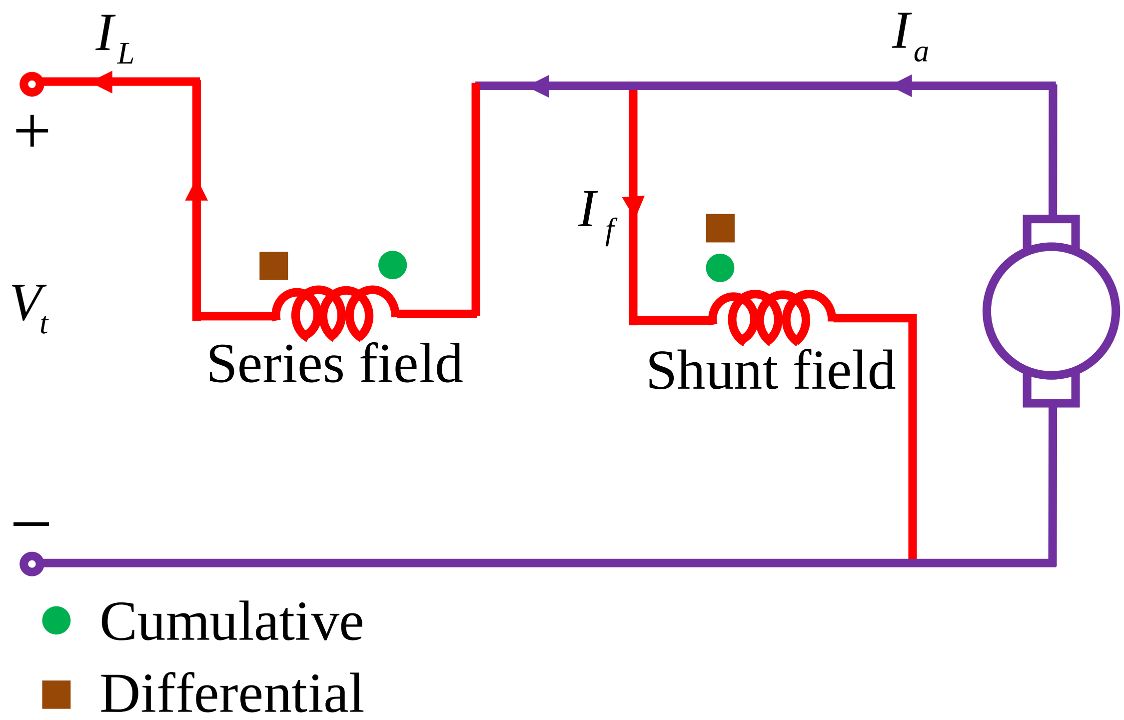
$$E_a = k\phi\omega$$

$$V_t = E_a - I_a(r_a + r_s)$$

$$\phi \propto I_f = I_a$$

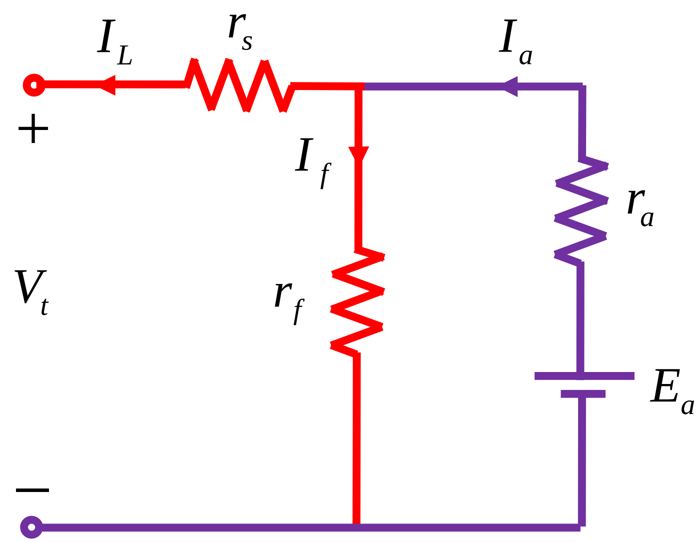
Compound DC Generators Short-shunt

The simplified schematic diagram of the short-shunt compound dc generator:



Compound DC Generators
Short-shunt

The equivalent circuit of the short-shunt compound dc generator:



$$I_L = I_a - I_f$$

$$E_a = k\phi\omega$$

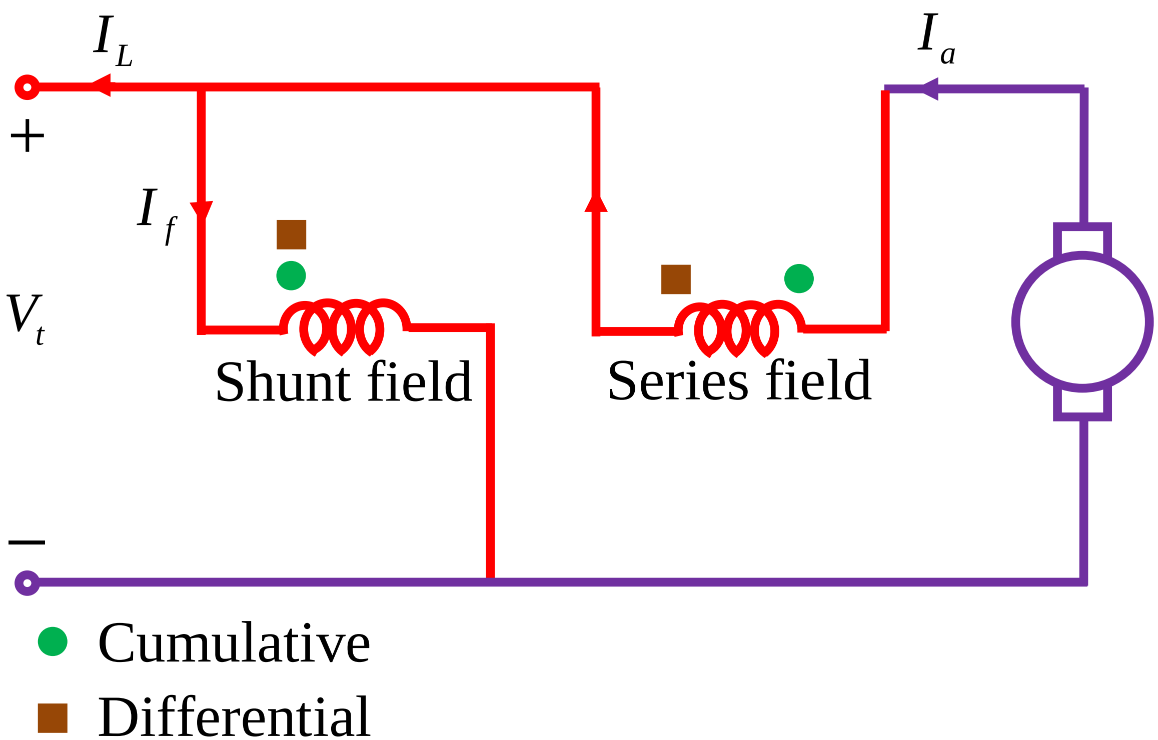
$$I_f = \frac{E_a - r_a I_a}{r_f}$$

$$V_t = E_a - r_a I_a - r_s I_L$$

$$\phi \propto \ k_{sh} I_f \pm k_s I_L \quad \begin{cases} + \ \text{Cumulative} \\ - \ \text{Differential} \end{cases}$$

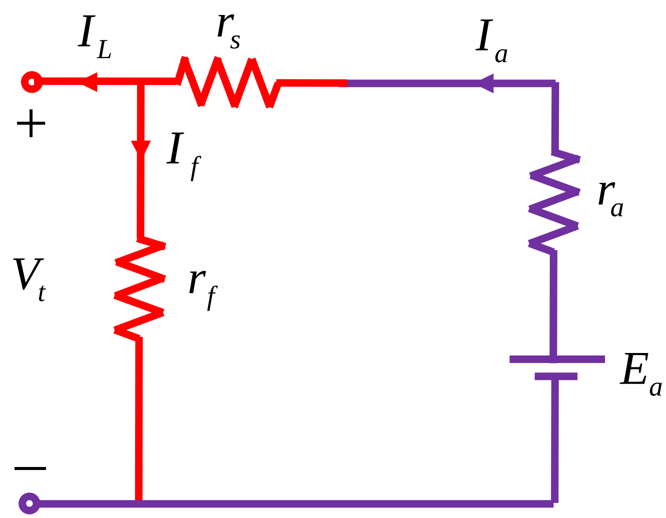
Compound DC Generators
Long-shunt

The simplified schematic diagram of the long-shunt compound dc generator:



Compound DC Generators
Long-shunt

The equivalent circuit of the long-shunt compound dc generator:



$$I_L = I_a - I_f$$

$$E_a = k\phi\omega$$

$$I_f = \frac{V_t}{r_f}$$

$$V_t = E_a - I_a(r_a + r_s)$$

$$\phi \propto k_{sh} I_f \pm k_s I_a \quad \begin{cases} + \text{ Cumulative} \\ - \text{ Differential} \end{cases}$$

Cumulative vs. Differential Compound DC Generators

- If the direction of the fields produced by the series and shunt field windings are the same, the generator is cumulative;
- Otherwise it is differential.

- Effective magneto-motive force (MMF) is calculated as

$$MMF_{effective} = N_f I_f \pm N_s I_s - ATD \qquad \begin{cases} + & \text{Cumulative} \\ - & \text{Differential} \end{cases}$$

where

N_f	The number of turns of shunt field winding
N_s	The number of turns of series field winding
ATD	Ampere turn demagnetizing

Power Flow in DC Generators

- In dc generators the input power is mechanical (torque multiplied by rotational speed) $P_{in} = P_{mech} = T\omega$

$$P_{\text{mech}} - P_{\text{mech-losses}} = E_a I_a$$

Input mechanical power → P_{mech}

Mechanical losses → $P_{\text{mech-losses}}$

- In dc generators the output power is electrical (voltage multiplied by current) $P_{out} = P_{elec} = P_L = V_t I_L$

$$E_a I_a - P_{\text{armature-losses}} - P_{\text{brush-losses}} - P_{\text{core-losses}} - P_{\text{field-losses}} = P_{elec}$$

Ohmic losses due to armature winding → $P_{\text{armature-losses}}$

Brushes losses → $P_{\text{brush-losses}}$

Core losses → $P_{\text{core-losses}}$

Ohmic losses due to field windings → $P_{\text{field-losses}}$

DC Generators

Example 1: Consider a separately excited DC generator with

$E_a = 151\ \text{V}$ $n = 1450\ \text{rpm}$ $I_f = 2.8\ \text{A}$

a) If the field current is reduced to 2.4 A, but the rotational velocity remains unchanged, calculate the **emf** (E_a).

b) If the field current is reduced to 2.1 A, and the rotational velocity is increased to 1600 rpm, calculate the **emf** (E_a).

c) If at the rotational velocity of 1200 rpm, the emf is 120 V, calculate **field current** (I_f).

d) If emf is 160 V and field current is 2.2 A, calculate the **rotational velocity** (n).

DC Generators

Solution 1: separately excited DC generator

$E_a = 151 \text{ V}$ $n = 1450 \text{ rpm}$ $I_f = 2.8 \text{ A}$

a) If the field current is reduced to 2.4 A, but the rotational velocity remains unchanged, calculate the **emf** (E_a).

$$E_a = \hat{k}\phi\omega \quad \Rightarrow \quad E_a = k I_f n$$

considering the linear core.

$$\frac{E_{a2}}{E_{a1}} = \frac{k I_{f2} n_2}{k I_{f1} n_1} \quad \Rightarrow \quad E_{a2} = E_{a1} \frac{I_{f2}}{I_{f1}} \frac{n_2}{n_1}$$

$$E_{a2} = 151 \times \frac{2.4}{2.8} \times \frac{1450}{1450} = 129.4 \text{ V}$$

DC Generators

Solution 1: separately excited DC generator

$E_a = 151 \text{ V}$ $n = 1450 \text{ rpm}$ $I_f = 2.8 \text{ A}$

b) If the field current is reduced to 2.1 A, and the rotational velocity is increased to 1600 rpm, calculate the **emf** (E_a).

$$E_{a2} = E_{a1} \frac{I_{f2}}{I_{f1}} \frac{n_2}{n_1}$$

⇒

$$E_{a2} = 151 \times \frac{2.1}{2.8} \times \frac{1600}{1450} = 125 \text{ V}$$

Note that **emf** is **directly** proportional with the **field current** and **rotational velocity**.

DC Generators

Solution 1: separately excited DC generator

$E_a = 151\ \text{V}$ $\quad\quad n = 1450\ \text{rpm}$ $\quad\quad I_f = 2.8\ \text{A}$

c) If at the rotational velocity of 1200 rpm, the emf is 120 V, calculate **field current** (I_f).

$$\frac{E_{a2}}{E_{a1}} = \frac{k\,I_{f2}\,n_2}{k\,I_{f1}\,n_1} \quad \Rightarrow \quad I_{f2} = I_{f1}\frac{E_{a2}}{E_{a1}}\frac{n_1}{n_2}$$

$$I_{f2} = 2.8 \times \frac{120}{151} \times \frac{1450}{1200} = 2.7\ \text{A}$$

Note that **field current** is **directly** proportional with the **emf** but **inversely** proportional with the **rotational velocity**.

DC Generators

Solution 1: separately excited DC generator

$E_a = 151\ \text{V}$ $n = 1450\ \text{rpm}$ $I_f = 2.8\ \text{A}$

d) If emf is 160 V and field current is 2.2 A, calculate the **rotational velocity** (n).

$$\frac{E_{a2}}{E_{a1}} = \frac{k\, I_{f2}\, n_2}{k\, I_{f1}\, n_1} \quad \Rightarrow \quad n_2 = n_1 \frac{E_{a2}}{E_{a1}} \frac{I_{f1}}{I_{f2}}$$

$$n_2 = 1450 \times \frac{160}{151} \times \frac{2.8}{2.2} = 1955\ \text{rpm}$$

Note that **rotational velocity** is **directly** proportional with the **emf** but **inversely** proportional with the **field current**.

DC Generators

Example 2: Consider a separately excited DC generator with the following values for nominal power, nominal terminal voltage and armature resistance: $P_n = 50 \text{ kW}$ $V_{tn} = 250 \text{ V}$ $r_a = 0.025 \ \Omega$

a) If the generator supplies the nominal load under the nominal voltage, calculate the **emf** (E_a) and the **armature current** (I_a).

b) If the voltage terminal remains 250 V but the load decreases to 40 kW, calculate the **emf** (E_a).

c) If the load is 40 kW and emf is 255 V, calculate the **terminal voltage**(V_t).

d) If the terminal voltage is 253 V and emf is 257 V, calculate **load power** (P_L).

DC Generators

Solution 2: a separately excited DC generator with

$$P_n = 50 \text{ kW} \qquad V_{tn} = 250 \text{ V} \qquad r_a = 0.025 \ \Omega$$

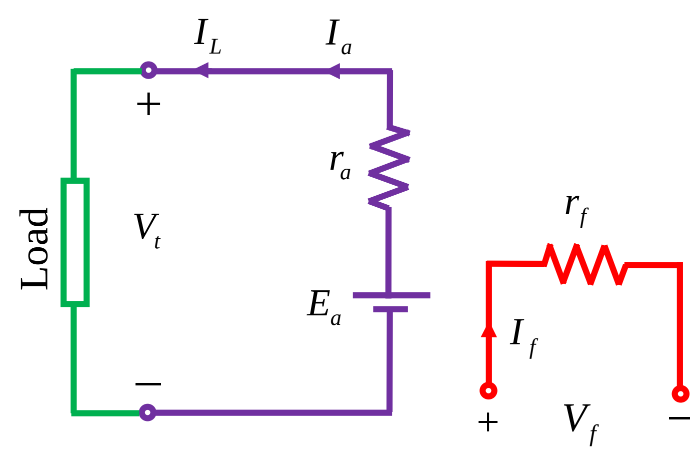
a) If the generator supplies the nominal load under the nominal voltage, calculate the **emf** (E_a) and the **armature current** (I_a).

$$V_t = V_{tn} = 250 \text{ V}$$

$$P_L = P_n = 50 \text{ kW}$$

$$I_L = I_a = \frac{50000}{250} = 200 \text{ A}$$

$$E_a = V_t + r_a I_a = 250 + 0.025 \times 200 = 255 \text{ V}$$



DC Generators

Solution 2: a separately excited DC generator with

$$P_n = 50 \text{ kW} \qquad V_{tn} = 250 \text{ V} \qquad r_a = 0.025 \ \Omega$$

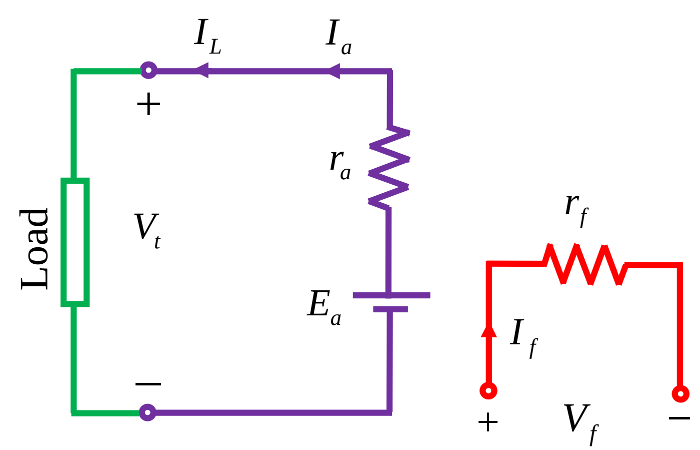
b) If the voltage terminal remains 250 V but the load decreases to 40 kW, calculate the **emf** (E_a).

$$V_t = 250 \text{ V}$$

$$P_L = 40 \text{ kW}$$

$$I_L = I_a = \frac{40000}{250} = 160 \text{ A}$$

$$E_a = V_t + r_a I_a = 250 + 0.025 \times 160 = 254 \text{ V}$$



DC Generators

Solution 2: a separately excited DC generator with

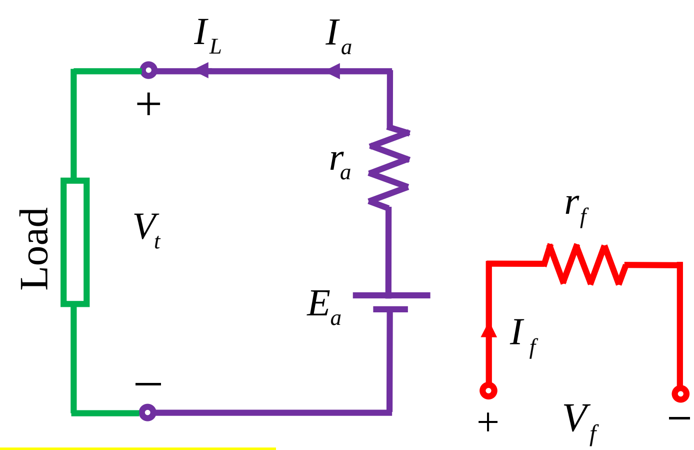
$$P_n = 50 \ \text{kW} \qquad V_{tn} = 250 \ \text{V} \qquad r_a = 0.025 \ \Omega$$

c) If the load is 40 kW and emf is 255 V, calculate the **terminal voltage**(V_t).

$$P_L = 40 \ \text{kW}$$

$$I_L = I_a = \frac{40000}{V_t}$$

$$E_a = 255 \ \text{V}$$



$$E_a = V_t + r_a I_a \Rightarrow 255 = V_t + 0.025\frac{40000}{V_t}$$

$$V_t^2 - 255V_t + 1000 = 0 \Rightarrow V_t = \begin{cases} 251 \ \text{V} & \text{(Accepted)} \\ 4 \ \text{V} & \text{(Not accepted)} \end{cases}$$

DC Generators

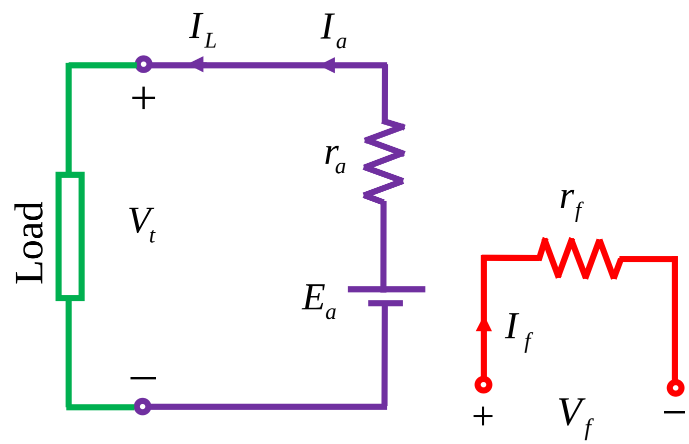
Solution 2: a separately excited DC generator with

$$P_n = 50 \ \text{kW} \qquad V_{tn} = 250 \ \text{V} \qquad r_a = 0.025 \ \Omega$$

d) If the terminal voltage is 253 V and emf is 257 V, calculate **load power** (P_L).

$$V_t = 253 \ \text{V}$$

$$E_a = 257 \ \text{V}$$



$$E_a = V_t + r_a I_a \Rightarrow I_L = I_a = \frac{E_a - V_t}{r_a}$$

$$\Rightarrow I_L = \frac{257 - 253}{0.025} = 160 \ \text{A}$$

$$P_L = V_t I_L = 253 \times 160 = 40480 \ \text{W}$$

DC Generators

Example 3: Consider a series DC generator with the following values for nominal power, nominal terminal voltage and series field resistance:

$$P_n = 10 \text{ kW} \qquad V_{tn} = 125 \text{ V} \qquad r_s = 0.05 \ \Omega$$

a) If the armature current is the nominal current and the terminal voltage is also nominal and emf is 137 V, calculate the **armature resistance** (r_a).

b) If the terminal voltage is nominal but the load is 75% of nominal load, calculate the **emf** (E_a).

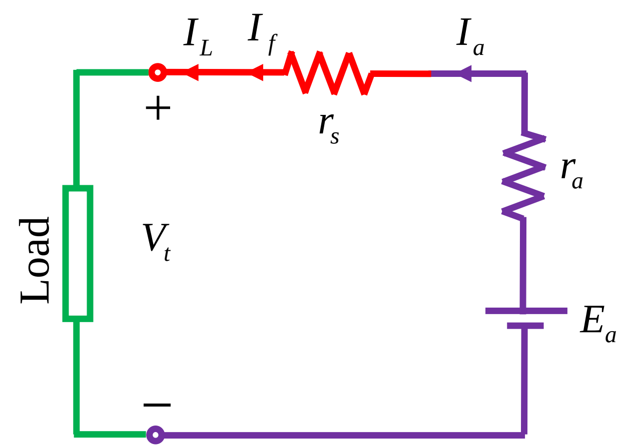
c) If the load is 8 kW and emf is 136 V, calculate the **terminal voltage** (V_t).

DC Generators

Solution 3: a series DC generator

$$P_n = 10 \text{ kW} \qquad V_{tn} = 125 \text{ V} \qquad r_s = 0.05 \ \Omega$$

a) If the armature current is the nominal current and the terminal voltage is also nominal and emf is 137 V, calculate the **armature resistance** (r_a).



$$I_{an} = \frac{P_n}{V_{tn}} = \frac{10000}{125} = 80 \text{ A}$$

$$r_a + r_s = \frac{E_a - V_t}{I_a} = \frac{137 - 125}{80} = 0.15 \ \Omega$$

$$r_a = 0.15 - r_s = 0.1 \ \Omega$$

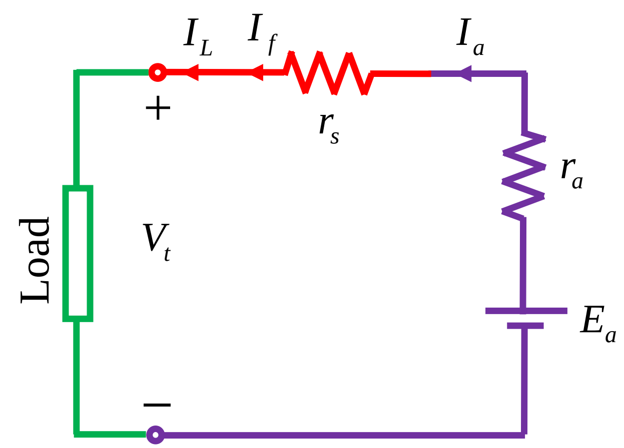
DC Generators

Solution 3: a series DC generator

$$P_n = 10 \text{ kW} \qquad V_{tn} = 125 \text{ V} \qquad r_s = 0.05 \ \Omega$$

b) If the terminal voltage is nominal but the load is 75% of nominal load, calculate the **emf** (E_a).

$$I_a = \frac{P_L}{V_t} = \frac{0.75\times 10000}{125} = 60 \text{ A}$$



$$E_a = V_t + I_a(r_a + r_s)$$

$$E_a = 125 + 60\times(0.1+0.05) = 134 \text{ V}$$

DC Generators

Solution 3: a series DC generator

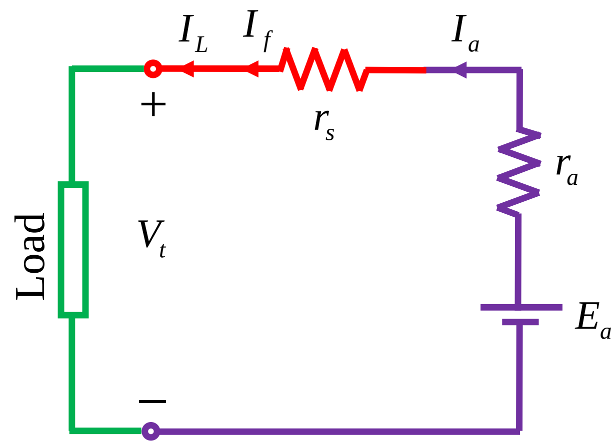
$$P_n = 10 \text{ kW} \qquad V_{tn} = 125 \text{ V} \qquad r_s = 0.05 \ \Omega$$

c) If the load is 8 kW and emf is 136 V, calculate the **terminal voltage** (V_t).

$$I_a = \frac{P_L}{V_t} = \frac{8000}{V_t}$$

$$E_a = V_t + I_a(r_a + r_s)$$

$$\Rightarrow 136 = V_t + \frac{8000}{V_t} \times 0.15$$



$$V_t^2 - 136V_t + 1200 = 0 \Rightarrow V_t = \begin{cases} 126.5 \text{ V} & \text{(Accepted)} \\ 9.5 \text{ V} & \text{(Not accepted)} \end{cases}$$

DC Generators

Example 4: Consider a shunt DC generator with the following values for nominal power, nominal terminal voltage armature resistance and field resistance:

$$P_n = 30 \ \text{kW} \qquad V_{tn} = 250 \ \text{V} \qquad r_a = 0.12 \ \Omega \qquad r_f = 40 \ \Omega$$

An electrical load under nominal voltage is connected to the generator and emf is 267 V. Calculate the **load power** and the **efficiency** of the machine.

DC Generators

Solution 4: Consider a shunt DC generator with

$$P_n = 30 \;\; \text{kW} \qquad V_{tn} = 250 \;\; \text{V} \qquad r_a = 0.12 \;\; \Omega \qquad r_f = 40 \;\; \Omega$$

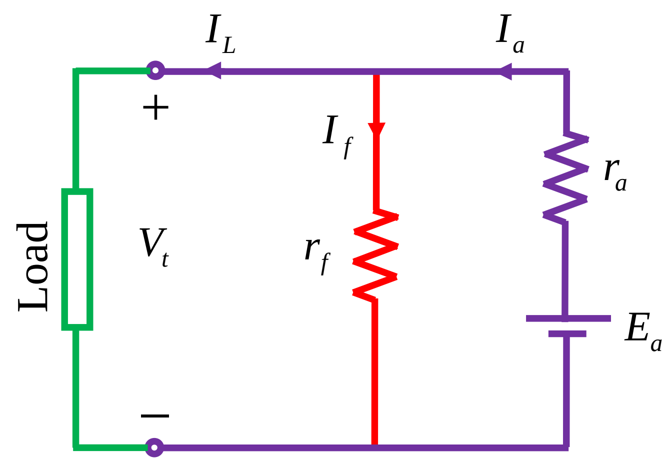
$$V_t = V_{tn} = 250 \;\; \text{V} \qquad E_a = 267 \;\; \text{V} \qquad P_L = ? \qquad \eta = ?$$

$$I_a = \frac{E_a - V_t}{r_a} = \frac{267 - 250}{0.12} = 141.7 \;\; \text{A}$$

$$I_f = \frac{V_t}{r_f} = \frac{250}{40} = 6.25 \;\; \text{A}$$

$$I_L = I_a - I_f = 135.45 \;\; \text{A}$$

$$P_L = V_t I_L = 250 \times 135.45 = 33862.5 \;\; \text{W}$$



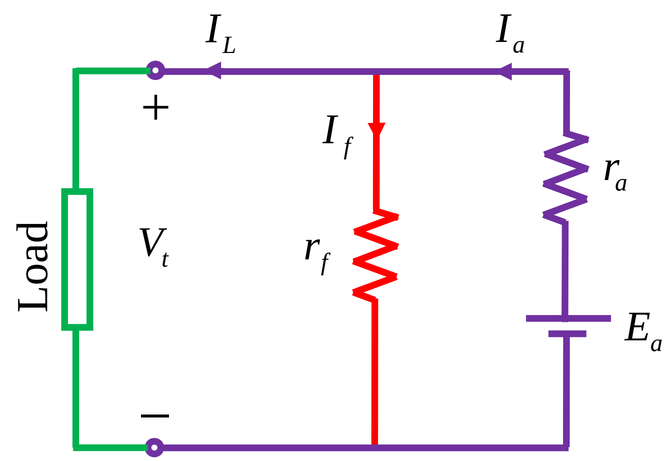
DC Generators

Solution 4: Consider a shunt DC generator with

$P_n = 30 \text{ kW}$ $V_{tn} = 250 \text{ V}$ $r_a = 0.12 \ \Omega$ $r_f = 40 \ \Omega$

$V_t = V_{tn} = 250 \text{ V}$ $E_a = 267 \text{ V}$ $P_L = ?$ $\eta = ?$

$$P_{out} = P_L = 33862.5 \text{ W}$$



Neglecting the mechanical losses, the input power is calculated as

$$P_{in} = E_a I_a = 267 \times 141.7 = 37833.9 \text{ W}$$

$$\eta_{\%} = \frac{P_{out}}{P_{in}} \times 100 = \frac{33862.5}{37833.9} = 89.5 \ \%$$

DC Generators

Example 5: Consider a cumulative long-shunt compound DC generator with the following values for nominal power, nominal terminal voltage series field resistance and shunt field resistance:

$P_n = 100 \text{ kW} \qquad V_{tn} = 600 \text{ V} \qquad r_s = 0.02 \ \Omega \qquad r_f = 200 \ \Omega$

At the nominal condition (load power and terminal voltage are nominal), the input power to the generator is 103.5 kW. Calculate the **armature resistance**.

DC Generators

Solution 5: Consider a cumulative long-shunt compound DC generator with

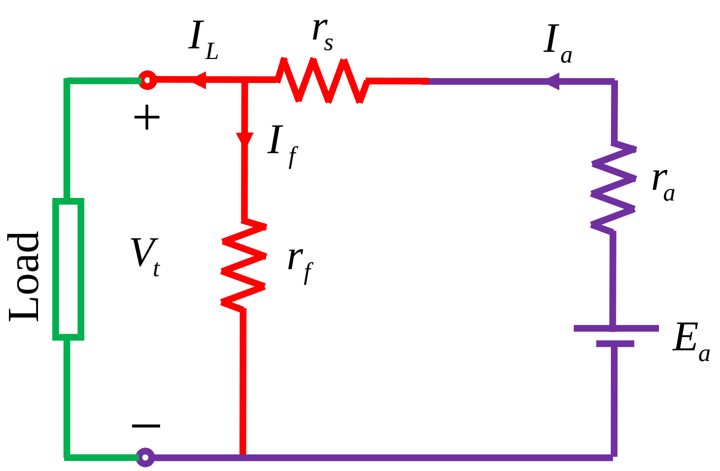
$P_n = 100\ \text{kW}$ $V_{tn} = 600\ \text{V}$ $r_s = 0.02\ \Omega$ $r_f = 200\ \Omega$

$P_L = P_n = 100\ \text{kW}$ $V_t = V_{tn} = 600\ \text{V}$ $P_{in} = 103.5\ \text{kW}$ $r_a = ?$

$$I_L = \frac{P_L}{V_t} = \frac{100000}{600} = 166.7\ \text{A}$$

$$I_f = \frac{V_t}{r_f} = \frac{600}{200} = 3\ \text{A}$$

$$I_a = I_L + I_f = 169.7\ \text{A}$$



DC Generators

Solution 5: Consider a cumulative long-shunt compound DC generator with

$P_n = 100\ \text{kW}$ $\quad V_{tn} = 600\ \text{V}$ $\quad r_s = 0.02\ \Omega$ $\quad r_f = 200\ \Omega$

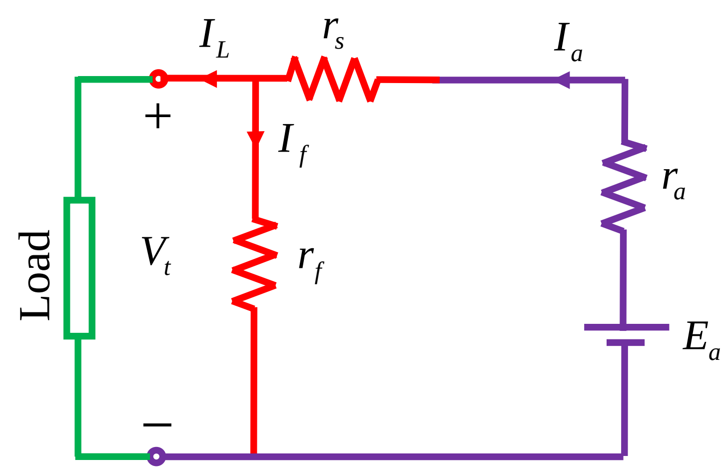
$P_L = P_n = 100\ \text{kW}$ $\quad V_t = V_{tn} = 600\ \text{V}$ $\quad P_{in} = 103.5\ \text{kW}$ $\quad r_a = ?$

$I_L = 166.7\ \text{A}$ $\quad I_f = 3\ \text{A}$ $\quad I_a = 169.7\ \text{A}$

$P_{in} = E_a I_a$ ⇒ $E_a = \dfrac{P_{in}}{I_a} = \dfrac{103500}{169.7} = 610\ \text{V}$

$$r_a + r_s = \frac{E_a - V_t}{I_a} = \frac{610-600}{169.7} = 0.059\ \Omega$$

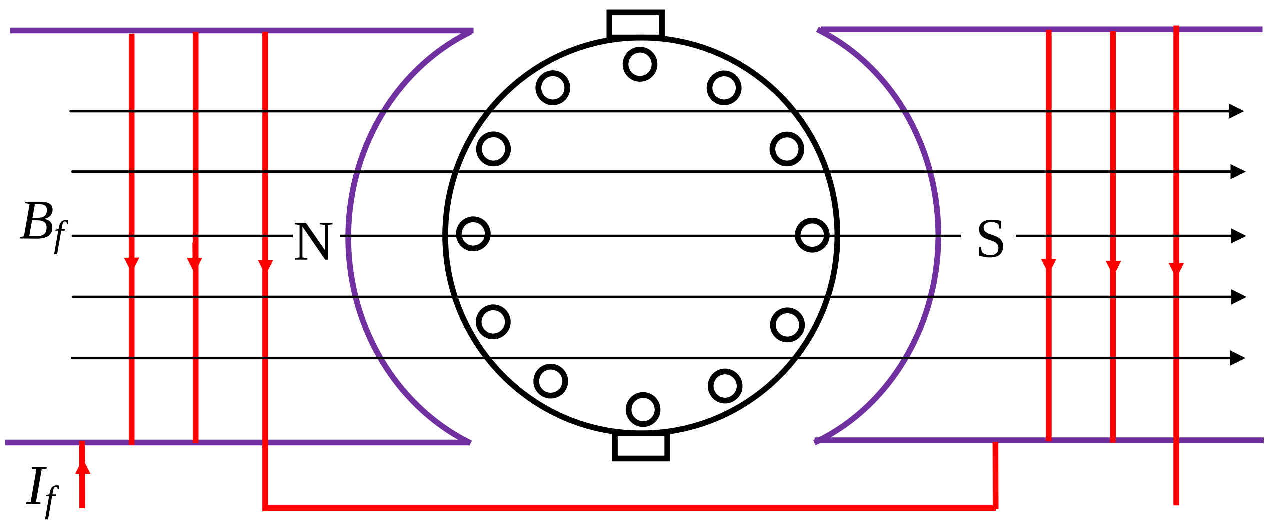
$$r_a = 0.059 - r_s = 0.039\ \Omega$$



Armature Reaction (AR)

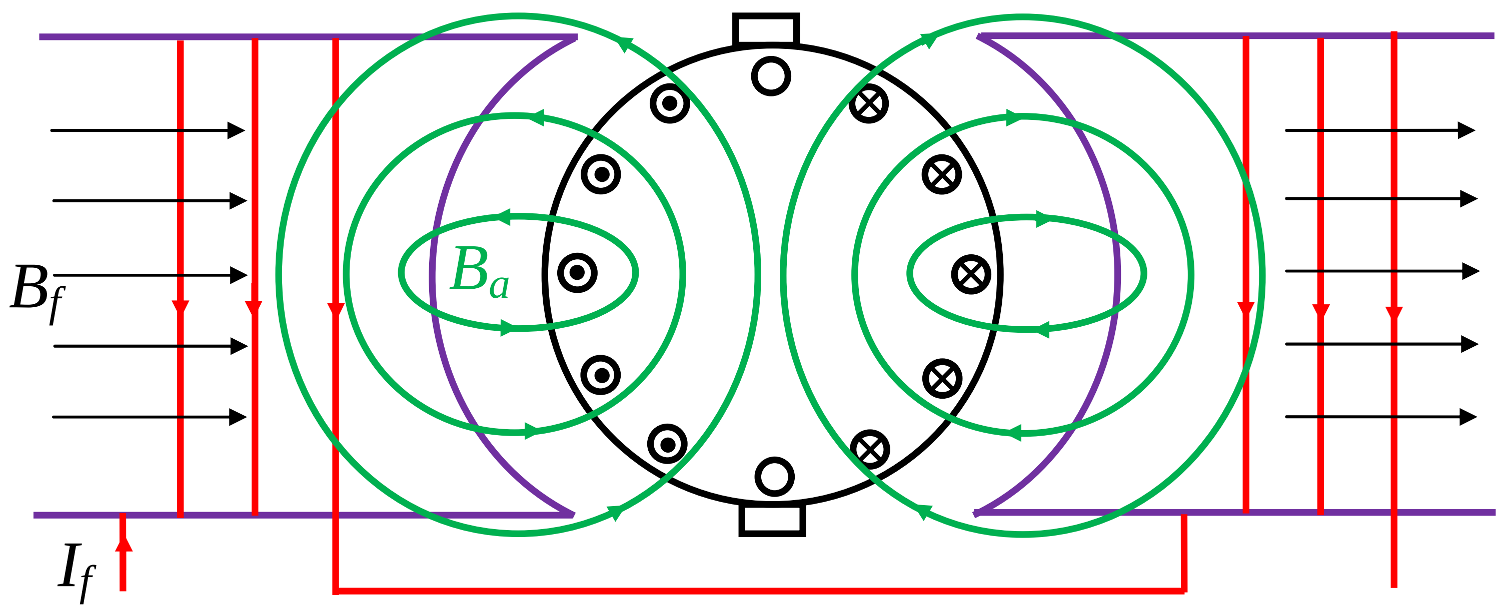
- The influence of the magnetic field due to armature current on the main field due to field winding current is called ***armature reaction***.

- Assume there is no current in the armature winding (no-load condition), therefore the field is only produced by the field winding current.

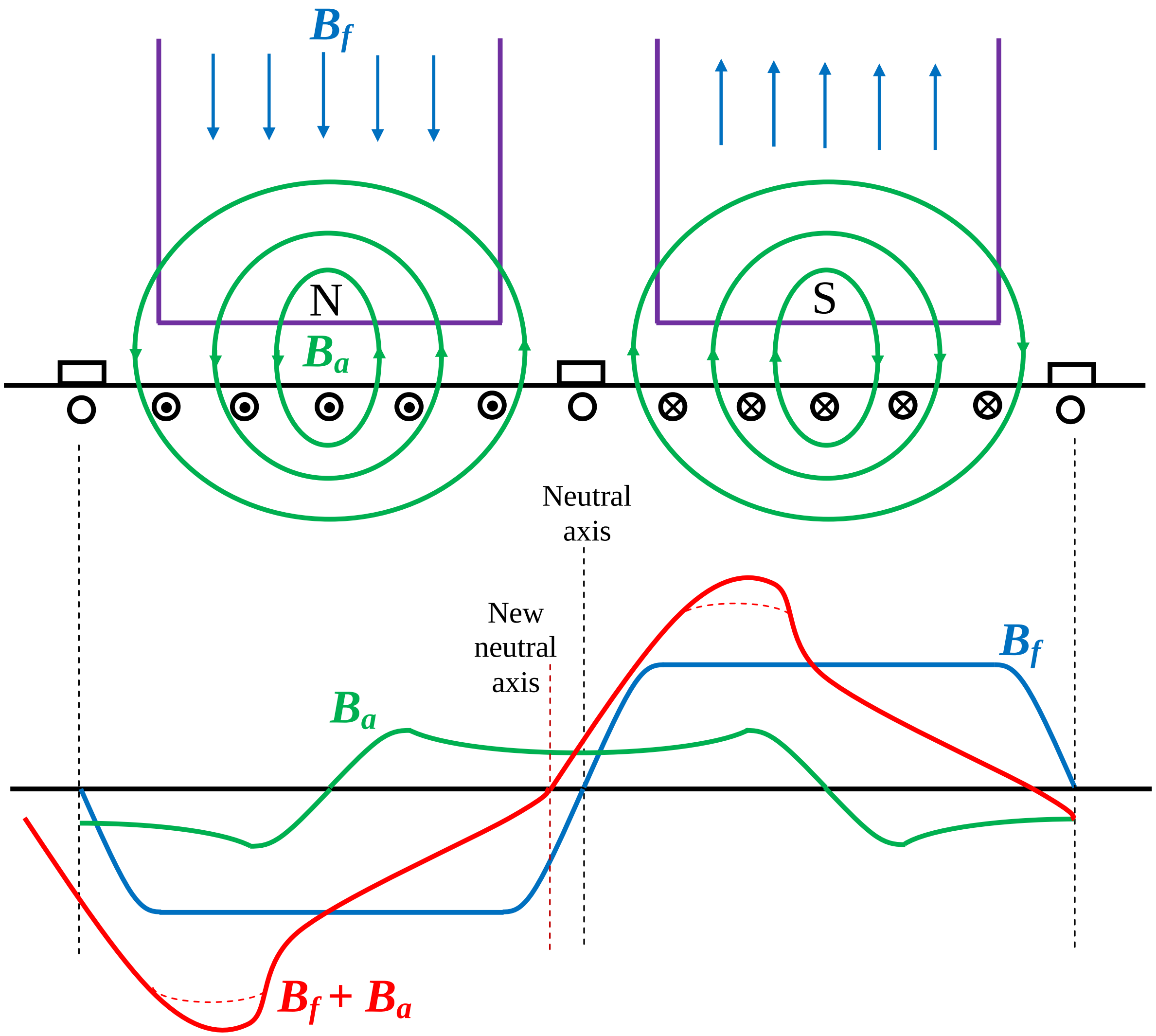


Armature Reaction (AR)

- Now assume armature winding carrying currents, therefore the field due to armature current interferes with that due to field winding current.



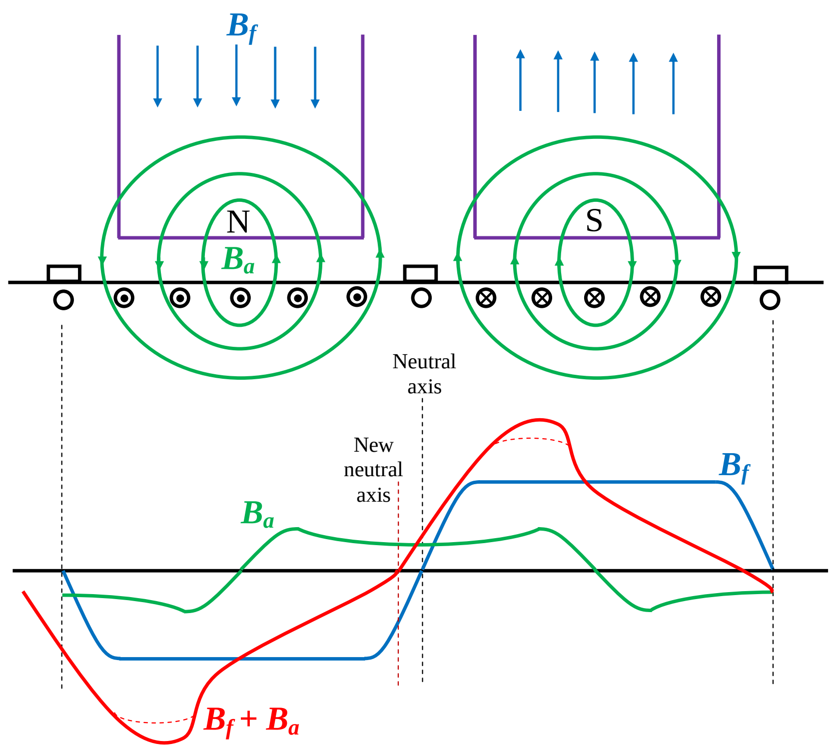
Armature Reaction (AR)



Armature Reaction (AR)

There are two armature reactions:

1. **Latitudinal armature reaction**: It means the neutral axis displacement. The displacement in the generating mode is in the direction of motion and in the motoring mode is in the opposite direction of motion.



2. **Longitudinal armature reaction**: The flux density under one edge of each pole increases and under the other edge decreases. The increase may saturate one edge of the pole and this effect is known as longitudinal AR or armature reaction demagnetization.

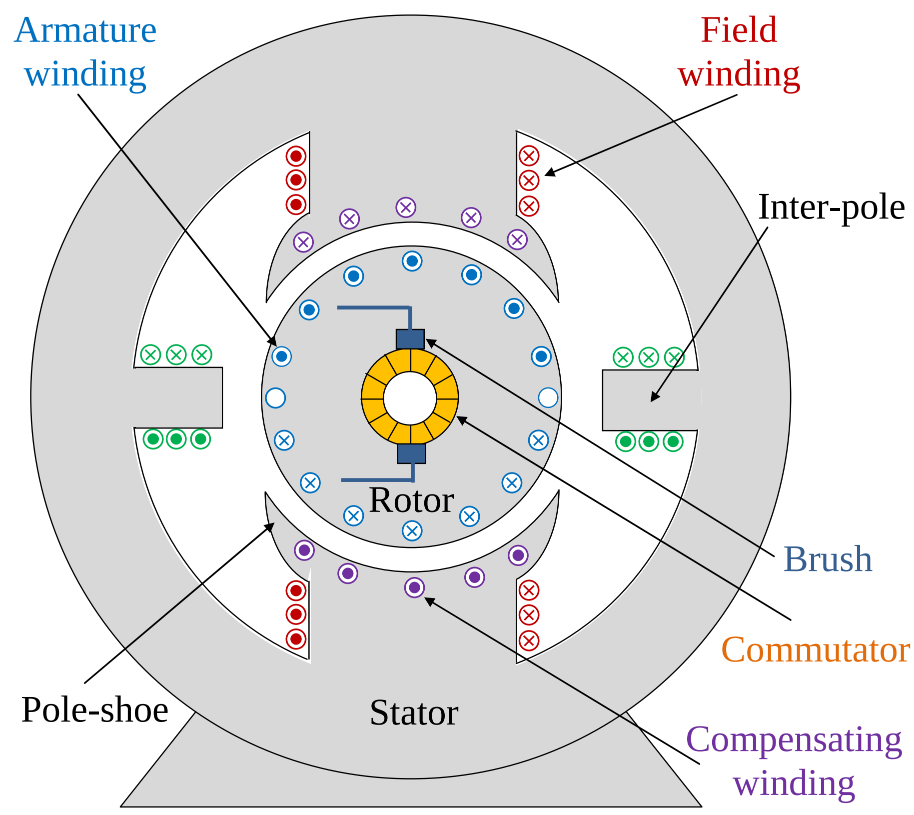
Methods to Improve Commutation

1. **Brushes displacement** (load dependent)

2. **Increase in the brush connection resistance** (higher ohmic loss)

3. Using **inter-poles** (higher cost)

4. Using **compensating windings** (higher cost)



Compensating Windings

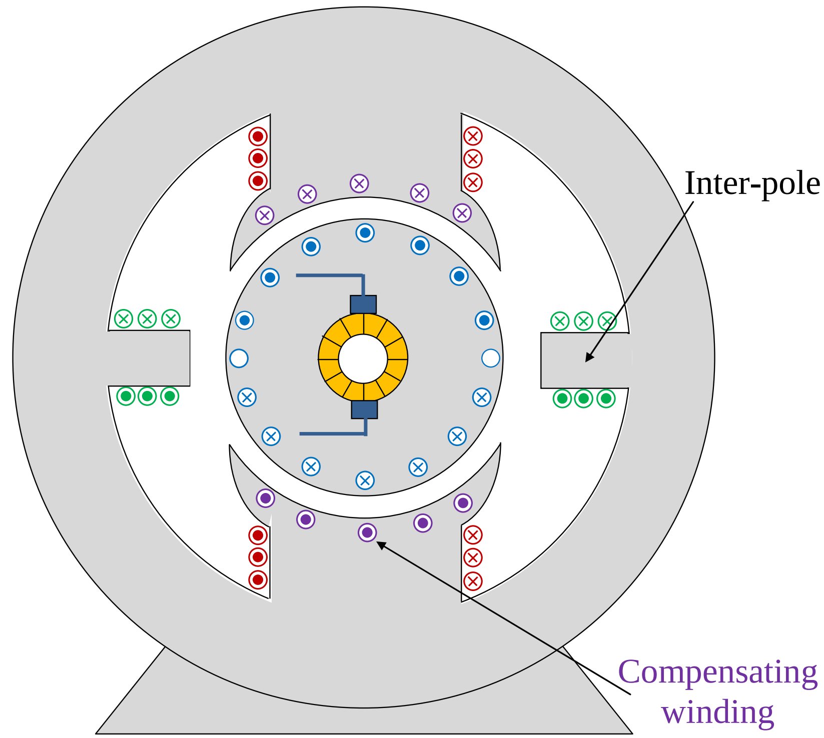
- Compensating windings **reduce** the **armature reaction**.

- The **armature current flows** in the **compensating windings**.

- **Ampere-turn** of compensating windings in each pole is expressed as:

$$AT_{cw} = \frac{Z_{cw}}{2} I_a \qquad (1)$$

Where Z_{cw} is the number of compensating conductors, I_a is the armature current.



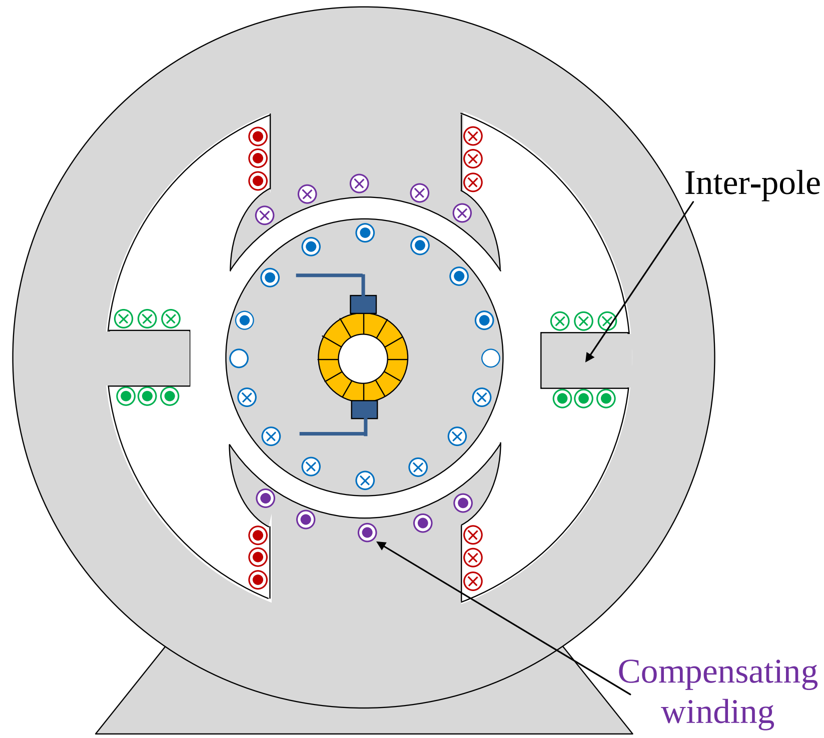
Compensating Windings

- The **ampere-turn of armature windings** under each pole is expressed as:

$$AT_a = \frac{\text{Pole arc}}{\text{Pole pitch}} MMF_a$$

$$AT_a = \frac{\text{Pole arc}}{\text{Pole pitch}} \frac{Z}{2p} \frac{I_a}{a} \qquad (2)$$

Where Z is the total armature conductors, a is the number of parallel paths and p is the number of poles.

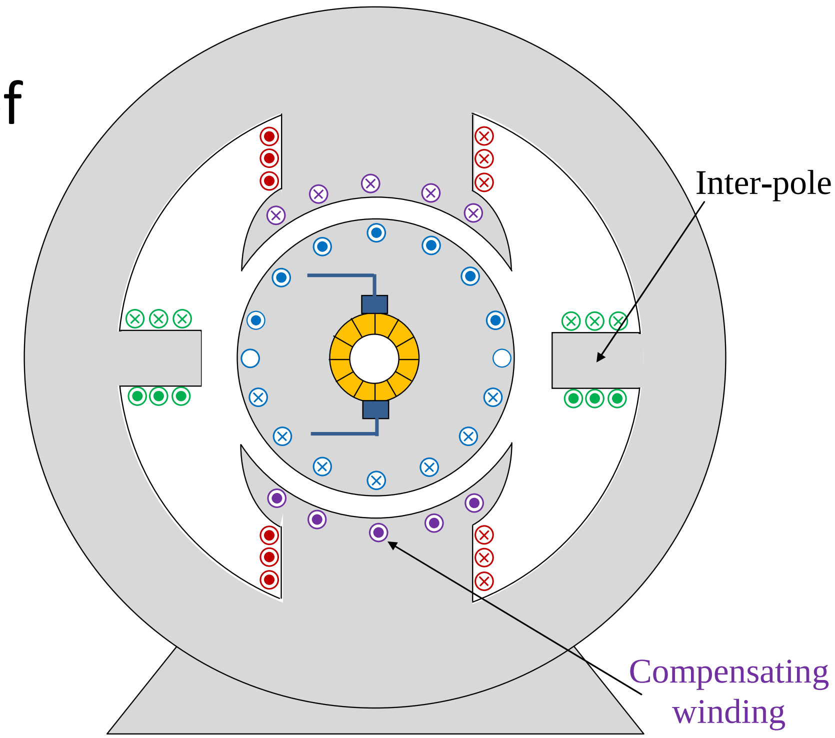


Compensating Windings

- To **minimize** the armature reaction, the ampere-turn of compensating windings should be equal to that of armature windings but in opposite direction.

$$AT_{cw} = \frac{Z_{cw}}{2} I_a \qquad (1)$$

$$AT_a = \frac{\text{Pole arc}}{\text{Pole pitch}} \frac{Z}{2p} \frac{I_a}{a} \qquad (2)$$



$$AT_{cw} = AT_a \Rightarrow Z_{cw} = \frac{\text{Pole arc}}{\text{Pole pitch}} \frac{Z}{a\,p}$$

Compensating Windings

Example: Consider a DC machine with 14 poles, 400 V, 2000 kW, having lap winding and 1100 conductors. Pole arc per pole pitch ratio is 0.7. Calculate the number of compensating conductors in each pole to have a uniform air-gap flux density under each pole.

$p = 14$ —Lap winding→ $a = 14$ $Z = 1100$

$$Z_{cw} = \frac{\text{Pole arc}}{\text{Pole pitch}} \frac{Z}{a\,p} \quad \Rightarrow \quad Z_{cw} = 0.7 \frac{1100}{14 \times 14} \approx 4$$

Inter-poles

Example: Consider a DC generator with 6 inter-poles, 600 V, 600 kW, having lap winding and 696 conductors. Calculate the number of turns of each inter-pole if the MMF of inter-poles is 1.25 times higher than that of armature.

Lap winding

$p = 6$ → $a = 6$ $\quad Z = 696$

$$MMF_{\text{inter-pole}} = 1.25 MMF_a$$

The current of inter-poles is the same as armature current (I_a).

$$\Rightarrow N_{\text{inter-pole}} I_a = 1.25 \frac{Z}{2p}\frac{I_a}{a} \Rightarrow N_{\text{inter-pole}} = 1.25 \frac{696}{2\times 6\times 6} \approx 12$$

Operating Characteristics of DC Generators

1. **No-load Characteristics (Magnetic Characteristics):** $E_a - I_f$

   No load terminal voltage vs. field current

   Generator speed is kept constant.

2. **Full-load Characteristics:** $V_t - I_f$

   Full-load terminal voltage vs. field current

   Generator speed and load current are kept constant.

3. **External Characteristics:** $V_t - I_L$

   Terminal voltage vs. load current

   Generator speed and field current are kept constant.

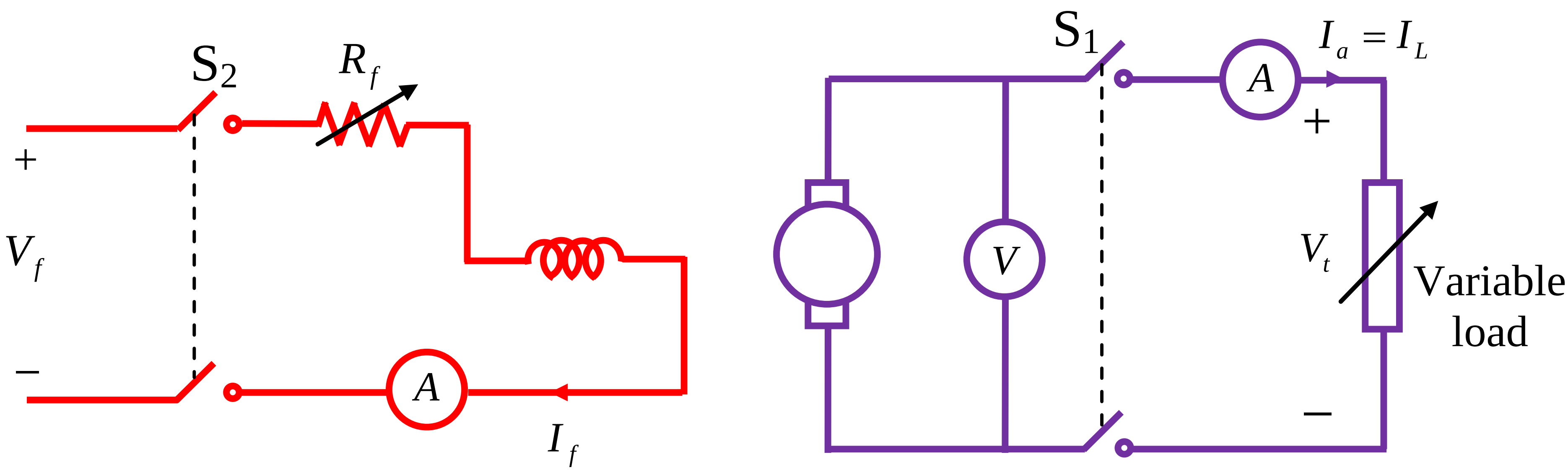
4. **Armature-reaction Characteristics** $I_f - I_L$

   Field current vs. load current

   Generator speed and terminal voltage are kept constant.

Operating Characteristics of Separately Excited DC Generators

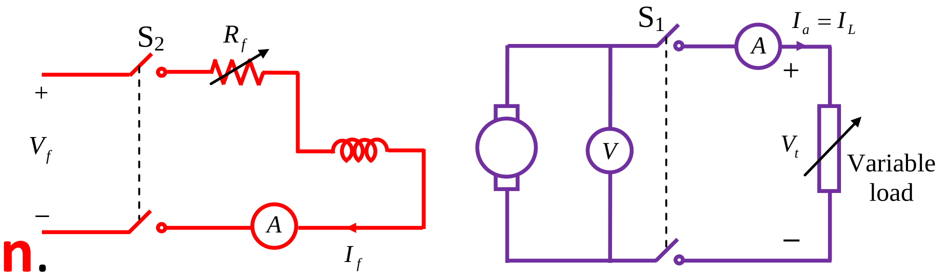
The following circuit is used to obtain the characteristics of a separately excited DC generator:



Operating Characteristics of Separately Excited DC Generators

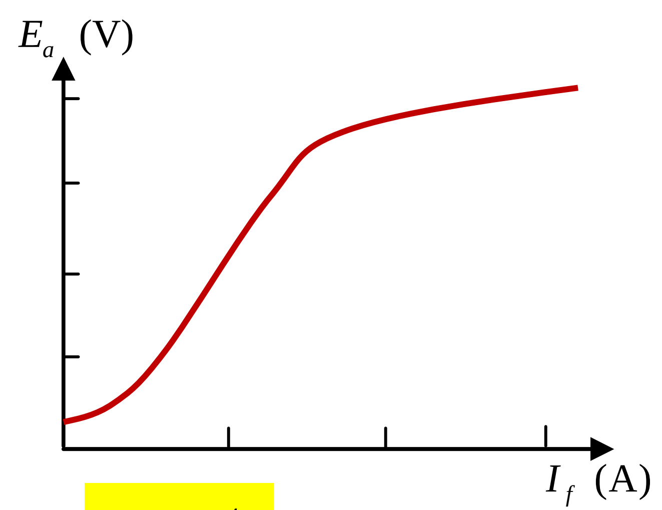
1. **No-load Characteristics (Magnetic Characteristics):** $E_a - I_f$

   No load terminal voltage vs. field current



Procedure:

- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- Due to the residual flux, a **small voltage** appears on the terminal.
- R_f is set to its **maximum** value and S_2 is **closed**.
- R_f is **gradually and monotonically decreased** and the terminal voltage and field current are recorded.



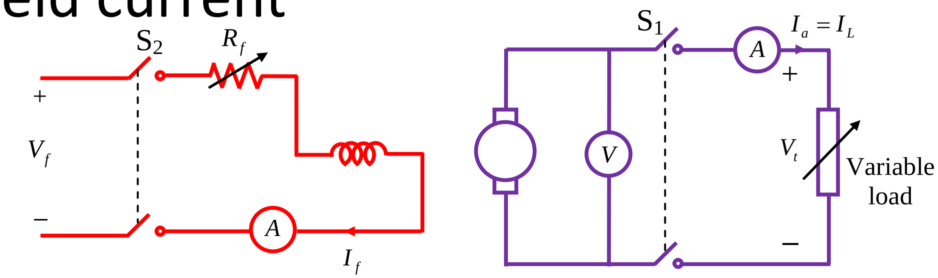
$n_r = cte$

Operating Characteristics of Separately Excited DC Generators

2. Full-load Characteristics:

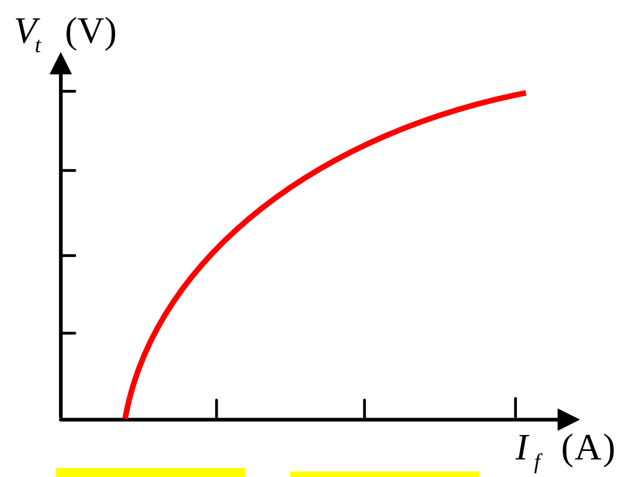
$V_t - I_f$

Full-load terminal voltage vs. field current



Procedure:

- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- Load resistance is set to its **minimum** (zero) and R_f is set to its **maximum** value.
- Switches S_1 and S_2 are **closed**.
- Load resistance is increased and R_f is **gradually decreased** so that the load current always remains at nominal value.
- The terminal voltage and field current are recorded.



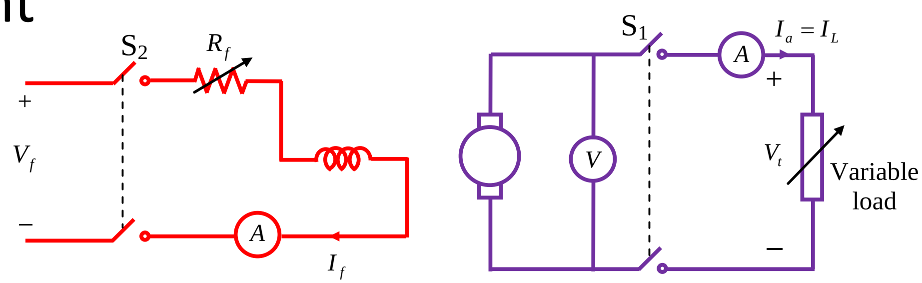
$n_r = cte$ $I_L = cte$

Operating Characteristics of Separately Excited DC Generators

3. External Characteristics:

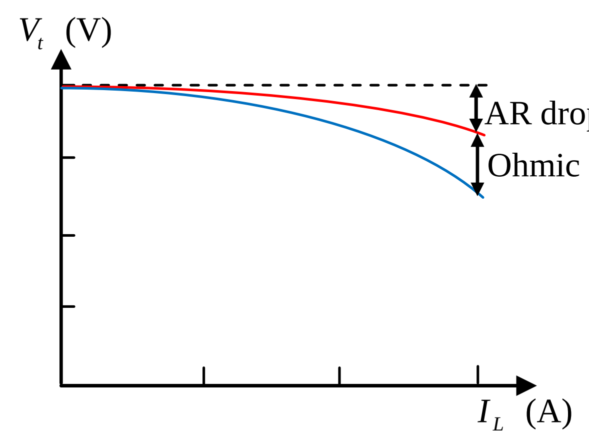
$V_t - I_L$

Terminal voltage vs. load current



Procedure:

- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- S_2 is **closed** and R_f is set so that to have nominal terminal voltage.
- Load resistance is set to its **maximum** value and S_1 is **closed**.
- Load resistance is decreased and field current is kept unchanged.
- The terminal voltage and load current are recorded.



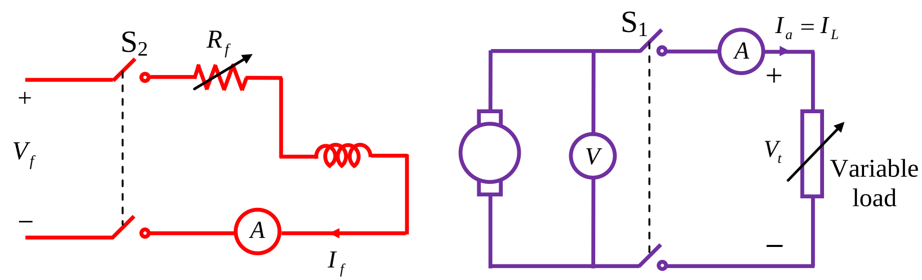
$n_r = cte$ $I_f = cte$

Operating Characteristics of Separately Excited DC Generators

4. Armature-reaction Characteristics

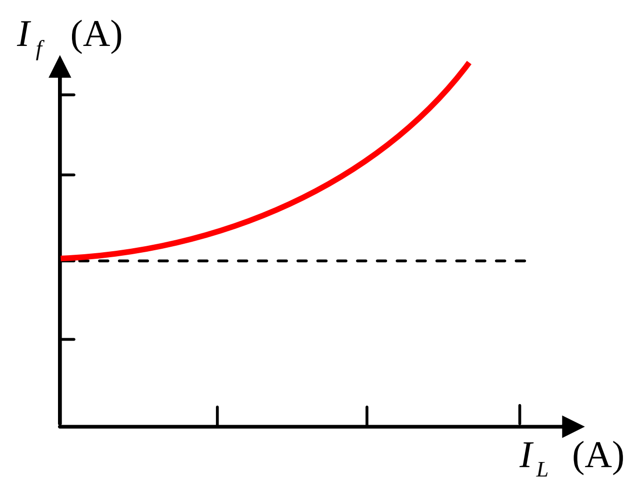
$I_f - I_L$

Field current vs. load current



Procedure:

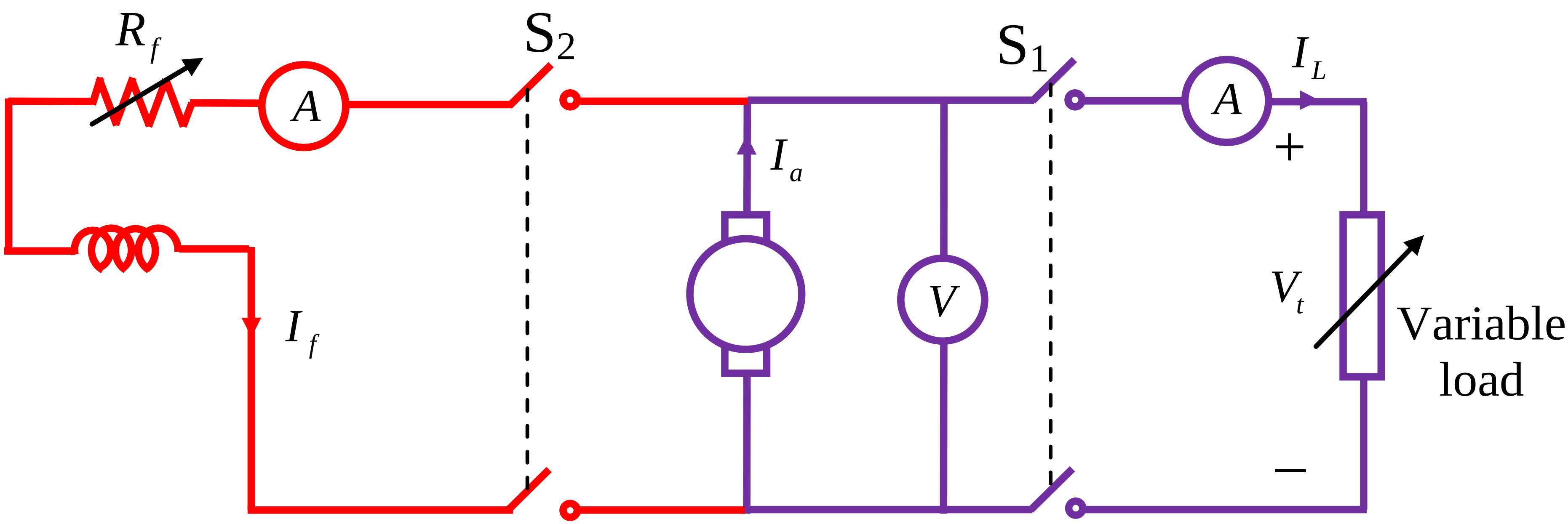
- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- S_2 is **closed** and R_f is set so that to have nominal terminal voltage.
- Load resistance is set to its **maximum** value and S_1 is **closed**.
- Load resistance is decreased and field current is increased to keep the terminal voltage unchanged (always nominal value).
- The load current and field current are recorded.



$n_r = cte$ $V_t = cte$

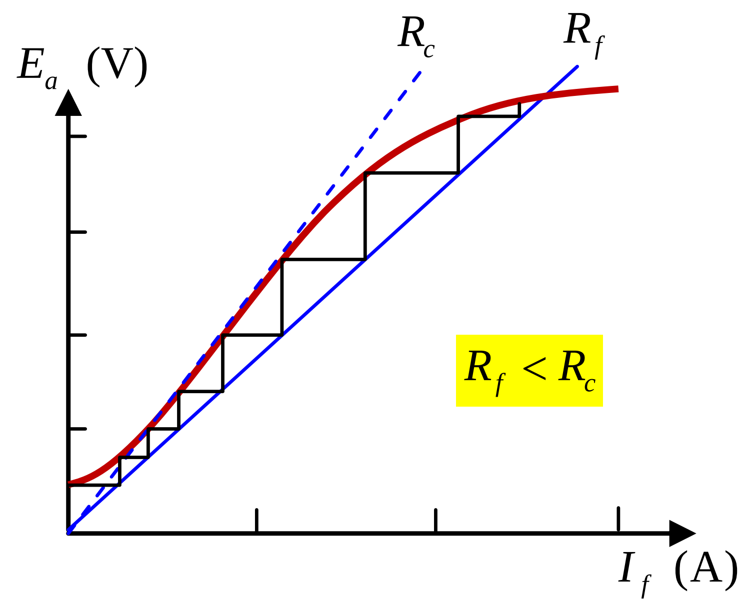
Operating Characteristics of Shunt DC Generators

The following circuit is used to obtain the characteristics of a shunt DC generator:



Starting of Shunt DC Generators

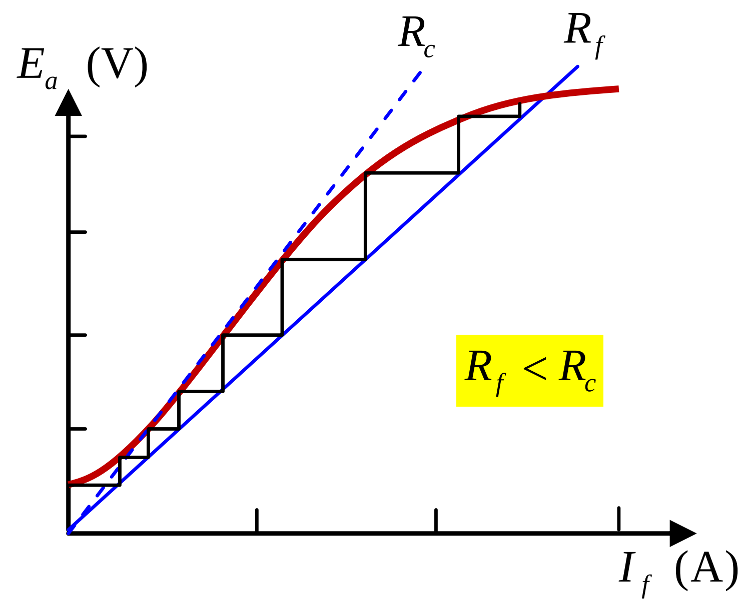
- Shunt DC generators use the terminal voltage to excite the field circuit.
- At starting situation there is a small terminal voltage due to residual flux which slightly excites the field circuit.
- The small voltage causes a small field current.
- The small field current in addition to residual flux increase the terminal voltage.
- It continues to reach to the normal operating point.



Starting of Shunt DC Generators

A shunt DC generator may not make voltage due to one of the following reasons:

1. **Lack of residual flux**. The shunt generator should be started in separately excited mode.
2. **The flux due to the field circuit is in opposite to the residual flux**.
3. **The field resistance is greater than critical resistance** (R_c).

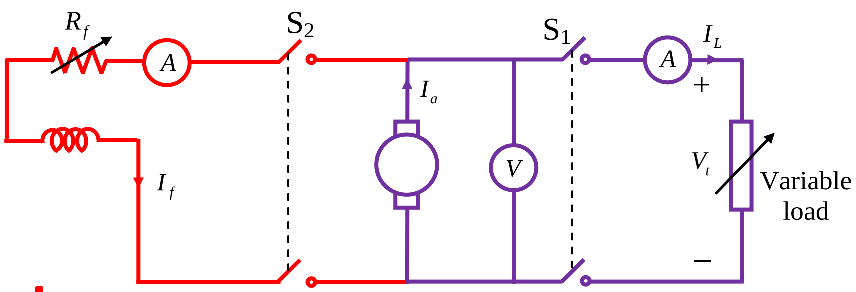


Operating Characteristics of Shunt DC Generators

1. **No-load Characteristics (Magnetic Characteristics):** $E_a - I_f$

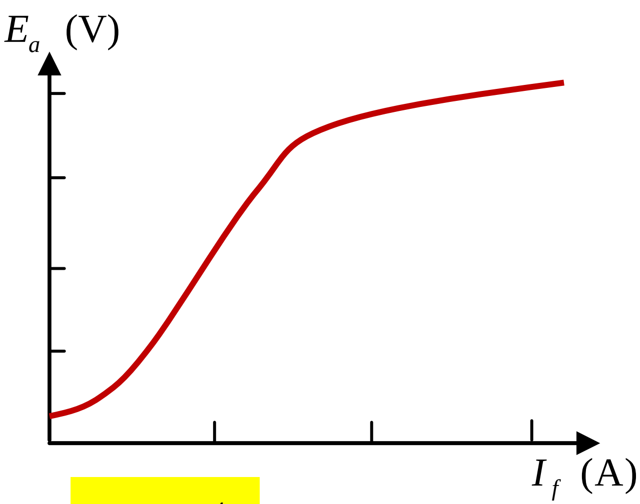
   No load terminal voltage vs. field current

Similar to separately excited



Procedure:

- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- Due to the residual flux, a **small voltage** appears on the terminal.
- R_f is set to its **maximum** value and S_2 is **closed**.
- R_f is **gradually and monotonically decreased** and the terminal voltage and field current are recorded.



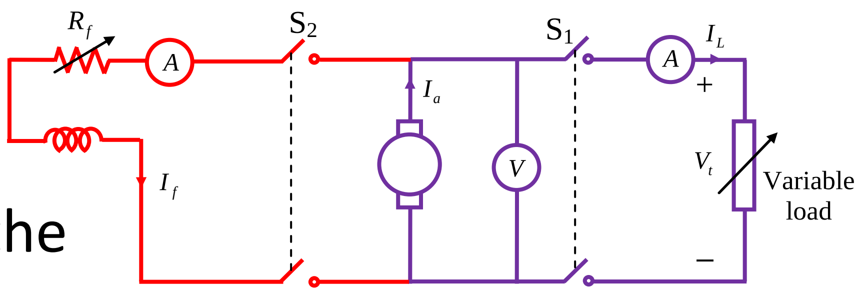
$n_r = cte$

Operating Characteristics of Shunt DC Generators

$V_t - I_f$

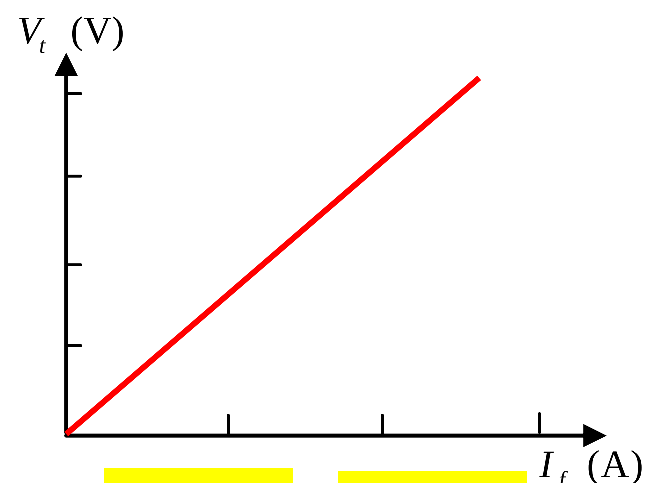
2. Full-load Characteristics:

Full-load terminal voltage vs. field current



Procedure:

- Since V_t and I_f are, respectively, the voltage and current of the field resistance, this characteristics is a line with slope of R_f .



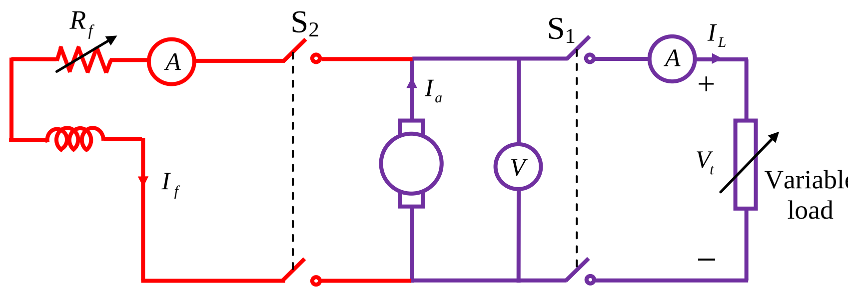
$n_r = cte$ $I_L = cte$

Operating Characteristics of Separately Excited DC Generators

3. External Characteristics:

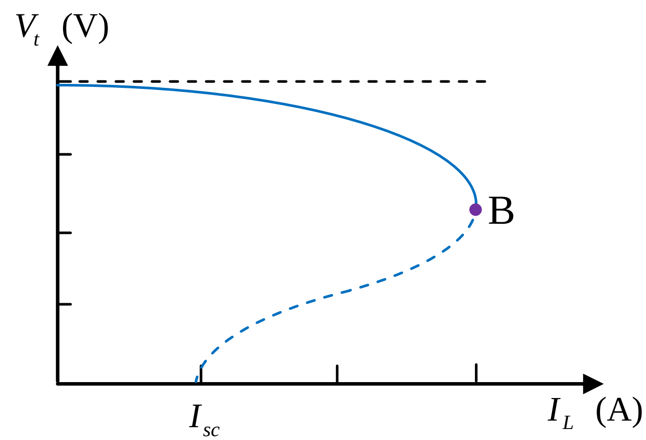
$V_t - I_L$

Terminal voltage vs. load current



Procedure:

- Switches S_1 and S_2 are both **open**.
- Generator is rotated at the **nominal speed**.
- S_2 is **closed** and R_f is set so that to have nominal terminal voltage.
- Load resistance is set to its **maximum** value and S_1 is **closed**.
- Load resistance is gradually decreased. Field current cannot be kept constant.
- The terminal voltage and load current are recorded.



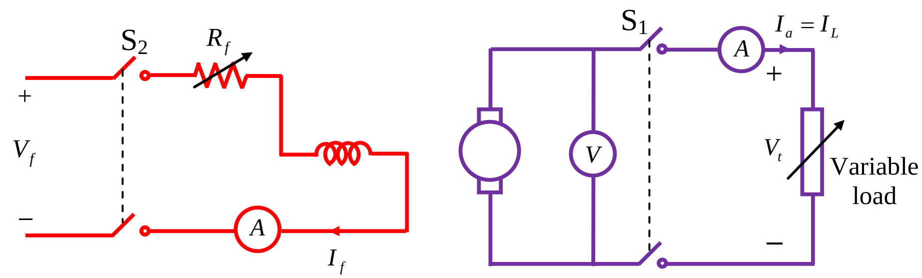
$n_r = cte$

Operating Characteristics of Shunt DC Generators

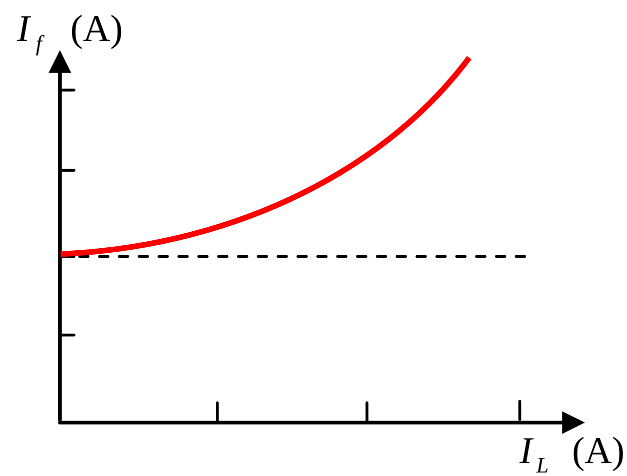
4. Armature-reaction Characteristics

$I_f - I_L$

Field current vs. load current



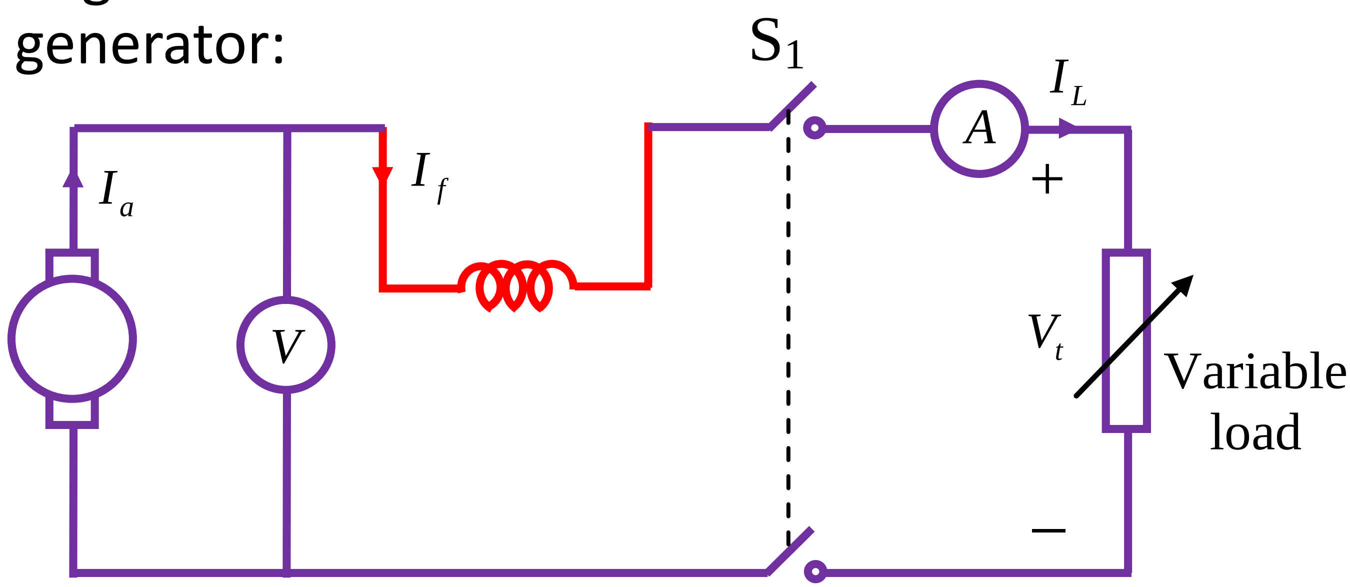
- The generator is connected as separately excited and this characteristics is obtained.



$n_r = cte$ $V_t = cte$

Operating Characteristics of Series DC Generators

The following circuit is used to obtain the characteristics of a series DC generator:



- **No-load characteristics** is **undefined** for this generator because at no-load the field current is zero.
- **Armature reaction characteristics** is **meaningless** here because $I_f = I_L$.

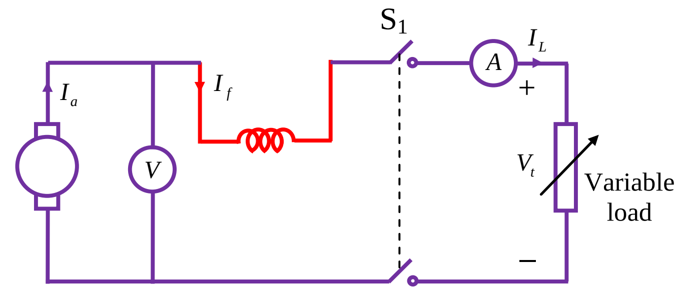
Operating Characteristics of Series DC Generators

Full-load and external Characteristics:

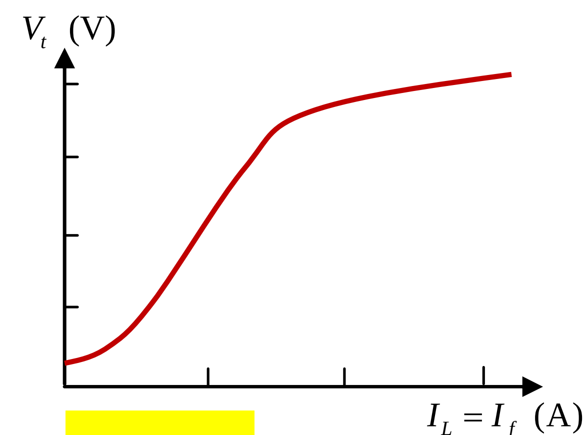
$V_t - I_f$ $V_t - I_L$

Full-load terminal voltage vs. field or load current

$I_f = I_L$



Since load and field currents are identical full-load and external characteristics are the same.



$n_r = cte$

Operating Characteristics of Compound DC Generators

1. **Cumulative compound**
   i. **Over Compound**: series field MMF is significantly greater than shunt field MMF.

   ii. **Flat compound**: series and shunt MMFs are so that the terminal voltage at full-load is the same as the terminal voltage at no-load.

   iii. **Under compound**: series field MMF is lower than shunt field MMF.

2. **Differential compound**

Operating Characteristics of Compound DC Generators