EEE 321

Electromechanical Energy Conversion – I

By

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CHAPTER 4

DC MOTORS AND GENERATORS

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Introduction

- DC **generators** are DC machines that convert mechanical energy to DC electric energy.
- DC **motors** are DC machines that convert DC electric energy to mechanical energy.
- The **difference** between a **DC motor** and a **DC generator** is the **<u>direction of power flow</u>**.

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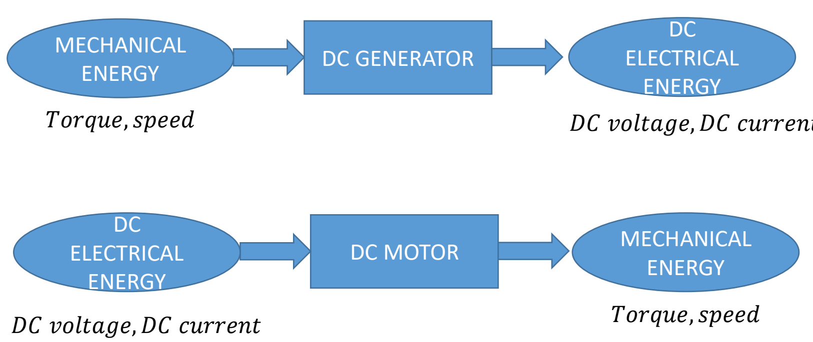
Introduction



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Speed Regulation

- **DC motors** are often compared by their **speed regulations**.
- **Speed regulation** is a measure of a DC motor that shows how the **speed of the motor** drops as **the load is increased**.
- **Speed regulation** (***SR***) of a motor is defined by

$$\boxed{SR = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \times 100\%}$$

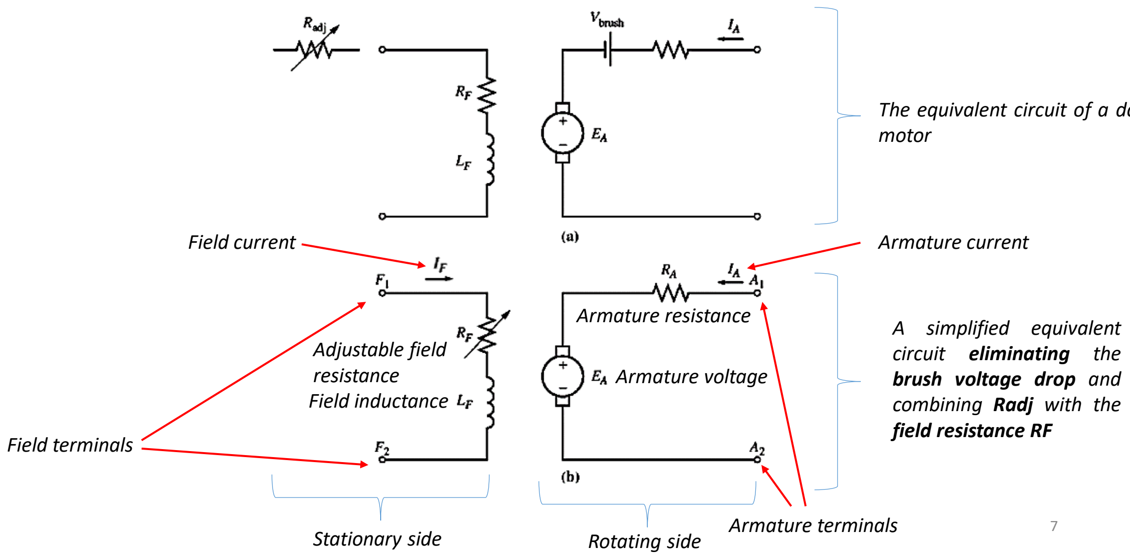
$$\boxed{SR = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%}$$

w_{nl} is the no-load speed of the motor in **rad/s**
w_{fl} is the full-load (*rated load*) speed of the motor in **rad/s**
n_{nl} is the no-load speed of the motor in **rev/min**
n_{fl} is the full-load (*rated load*) speed of the motor in **rev/min**

Types of DC Motors

- DC motors are driven from a **DC power supply**.
- Unless otherwise specified, the **input voltage** to a DC motor is assumed to be **constant**, because that assumption simplifies the analysis of motors and makes the comparison easy between different types of DC motors.
- There are **five major types** of DC motors in general use:
  - Separately excited DC motor
  - Shunt DC motor
  - Permanent-magnet DC motor
  - Series DC motor
  - Compounded DC motor
    - *Cumulatively compounded DC motor*
    - *Differentially compounded DC motor*
- Each of these types will be analyzed in detail in this Chapter.

The Equivalent Circuit of a DC Motor



The Equivalent Circuit of a DC Motor

- The **internal generated voltage (*armature voltage*)** of a DC machine is given by the equation

$$\boxed{E_A = K\phi\omega}$$

- The **induced torque** developed by the DC machine is given by

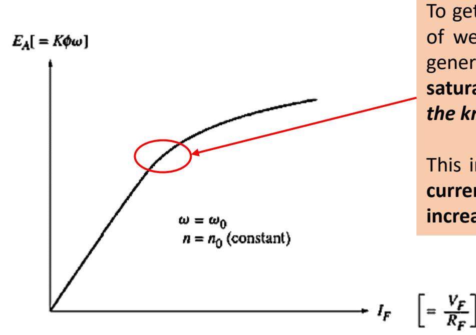
$$\boxed{\tau_{ind} = K\phi I_A}$$

where;

K is the machine constant
Ø is the flux generated in the stator by either field circuit or permanent magnets in Wb
w is the speed of the rotor (or *shaft*) in rad/s
$\boldsymbol{I_A}$ is the armature current in Amperes (A)

The Magnetization Curve of a DC Machine

- How is the **internal generated voltage (*armature voltage*)** related to the **field current I_F** in the machine?



To get the **maximum possible power** per pound of weight out of a machine, most motors and generators are designed to operate **near the saturation point** on the magnetization curve (***at the knee of the curve***).

This implies that a **fairly large increase in field current** is often necessary **to get a small increase in E_A** when operation is **near full load**.

The magnetization curve of a dc machine expressed as a plot of E_A versus I_F for a fixed speed of w_0 or n_0

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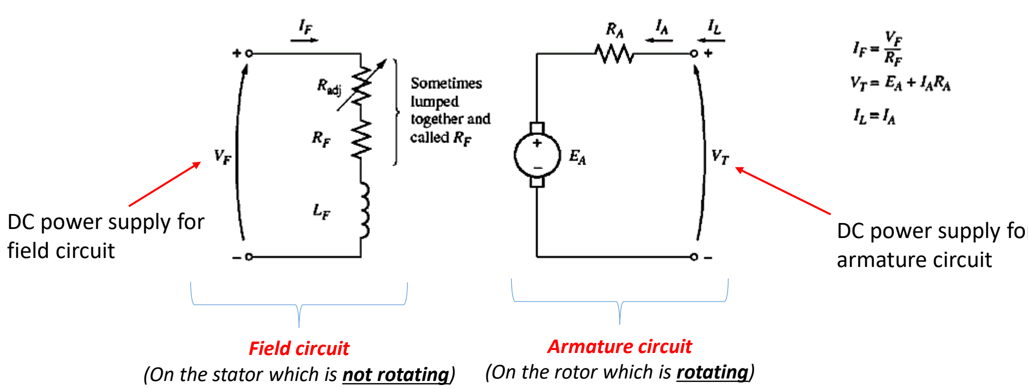
Separately Excited DC Motor

- A **separately excited DC motor** is a motor whose **field circuit** is supplied from **a separate DC power supply**.



$I_F = \frac{V_F}{R_F}$

$V_T = E_A + I_A R_A$

$I_L = I_A$

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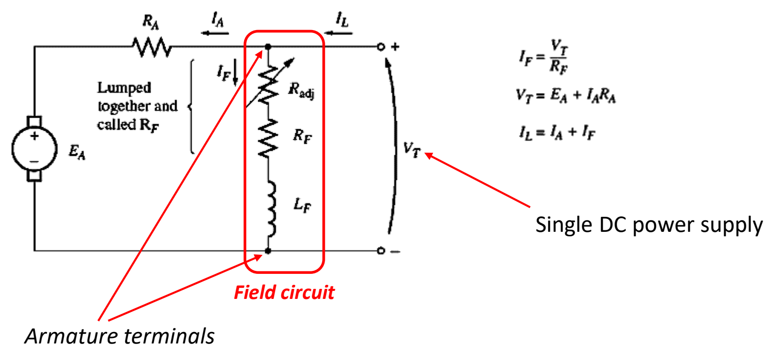
Shunt DC Motor

- A **shunt DC motor** is a motor whose **field circuit** gets its power **directly** **across the armature terminals.**
- The analysis principles of a **separately excited DC motor** and **shunt DC motor** is **same**.



Terminal Characteristic of a Shunt DC Motor

- A **terminal characteristic** of a **machine** is a plot of the **machine's output quantities** versus each other.
- For a **motor**, the output quantities are **output (*shaft*) torque** and **speed**.
- So, the **terminal characteristic** of a motor is a **plot** of its **output torque** versus **speed**.

  - **How does a shunt DC motor respond to a load?**
    - Suppose that the **load** on the shaft of a shunt DC motor is **increased**.
    - Then the load torque "***Tload***" will exceed the induced torque "***Tind***" in the machine, and the motor will start to **slow down**.
    - When the motor **slows down**, its **internal generated voltage** **drops** ($E_A = K\emptyset w$).
    - So the **armature current** in the motor $I_A = (V_T - E_A)/R_A$ increases.
    - As the **armature current** **rises**, the **induced torque** in the motor **increases** ($Tind = K\emptyset I_A$)
    - Finally the **induced torque** will be **equal** the **load torque** at a **lower** **mechanical speed of rotation**.

Terminal Characteristic of a Shunt DC Motor

- The **output characteristic** of a **shunt DC motor** can be derived from the **induced voltage** and **torque equations** of the motor and Kirchhoff's Voltage Law (KVL).

- KVL equation for a **shunt DC motor** is

$$V_T = E_A + I_A R_A$$

- Since,

$$E_A = K\phi\omega,$$

$$V_T = K\phi\omega + I_A R_A$$

- Since,

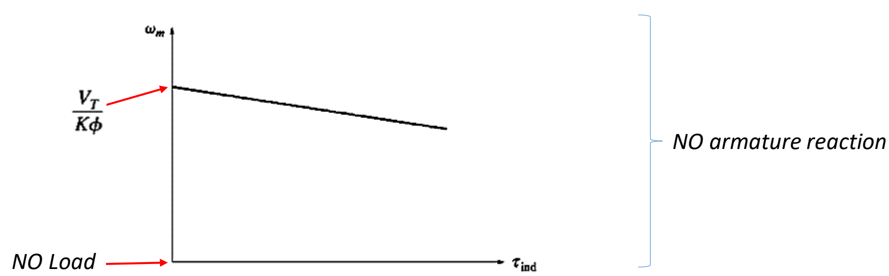
$$\tau_{\text{ind}} = K\phi I_A \Rightarrow I_A = \frac{\tau_{\text{ind}}}{K\phi}$$

$$V_T = K\phi\omega + \frac{\tau_{\text{ind}}}{K\phi} R_A \Rightarrow \boxed{\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{\text{ind}}}$$

Terminal Characteristic of a Shunt DC Motor

$$\boxed{\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{\text{ind}}}$$

- This equation is just a **straight line** with a **negative slope**.
- The resulting ***torque-speed characteristic*** of a **shunt DC motor** is shown in the figure.



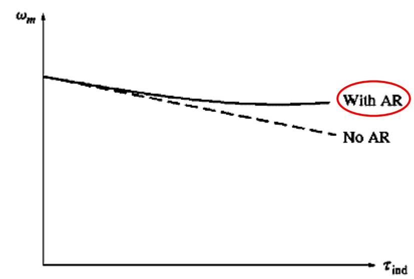
Torque-speed characteristic of a shunt DC motor (also separately excited DC motor) with compensating windings to eliminate armature reaction

Terminal Characteristic of a Shunt DC Motor under Armature Reaction

- If a motor has **armature reaction**, then when the **load** increases, the **flux-weakening effects** **reduce** **its flux**.
- When the **flux** **reduces**, the **speed of the motor** **increases**. (*See the speed equation given below*)
- The **terminal characteristic** of a **shunt DC motor** with **armature reaction** is shown in the figure.

$$\phi \downarrow \quad \Rightarrow \quad \boxed{\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{\text{ind}}}$$

- If a motor has **compensating windings**, there will be **no flux-weakening problems** in the machine, and the **flux** in the machine will be **constant** (***independent of load***). So the **terminal characteristic** becomes **linear** (*See the figure*)

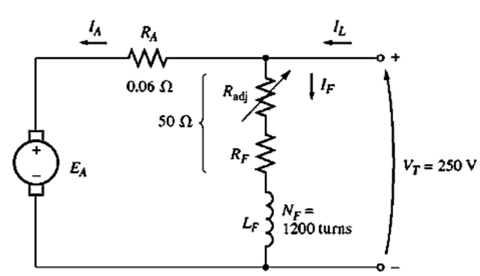


Torque-speed characteristic of the motor with armature reaction.

Example:

A **50-hp**, **250-V**, **1200 r/min** dc shunt motor **with compensating windings** (**armature reaction is ignored**) has an armature resistance (*including the brushes, compensating windings, and interpoles*) of **0.06 Ω**. Its field circuit has a total resistance Radj + RF of **50 Ω**, which produces a **no-load speed** of **1200 r/min**. There are **1200 turns per pole** on the shunt field winding (*See the figure*).

(a) Find the speed of this motor when its input current is **100 A**.
(b) Find the speed of this motor when its input current is **200 A**.
(c) Find the speed of this motor when its input current is **300 A**.
(d) Plot the **torque-speed characteristic** of this motor.



Example:

(a) If $I_L = 100$ A, then the armature current in the motor is

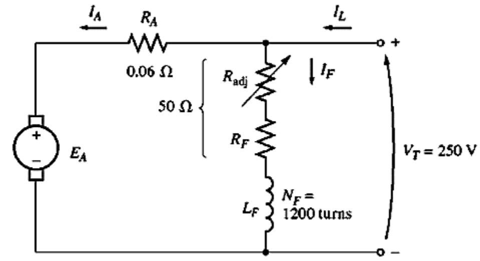
$$I_A = I_L - I_F = I_L - \frac{V_T}{R_F}$$
$$= 100\text{ A} - \frac{250\text{ V}}{50\ \Omega} = 95\text{ A}$$

Therefore, E_A at this load will be

$$E_A = V_T - I_A R_A$$
$$= 250\text{ V} - (95\text{ A})(0.06\ \Omega) = 244.3\text{ V}$$

The resulting speed of the motor is

$$n_2 = \frac{E_{A2}}{E_{A1}} n_1 = \frac{244.3\text{ V}}{250\text{ V}} 1200\text{ r/min} = 1173\text{ r/min}$$



Example:

(b) If $I_L = 200$ A, then the armature current in the motor is

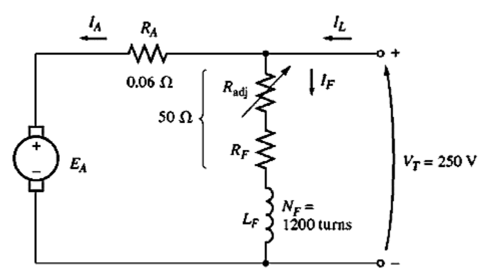
$$I_A = 200\text{ A} - \frac{250\text{ V}}{50\ \Omega} = 195\text{ A}$$

Therefore, E_A at this load will be

$$E_A = V_T - I_A R_A$$
$$= 250\text{ V} - (195\text{ A})(0.06\ \Omega) = 238.3\text{ V}$$

The resulting speed of the motor is

$$n_2 = \frac{E_{A2}}{E_{A1}} n_1 = \frac{238.3\text{ V}}{250\text{ V}} 1200\text{ r/min} = 1144\text{ r/min}$$



Example:

(c) If $I_L = 300$ A, then the armature current in the motor is

$$I_A = I_L - I_F = I_L - \frac{V_T}{R_F}$$

$$= 300\text{ A} - \frac{250\text{ V}}{50\ \Omega} = 295\text{ A}$$

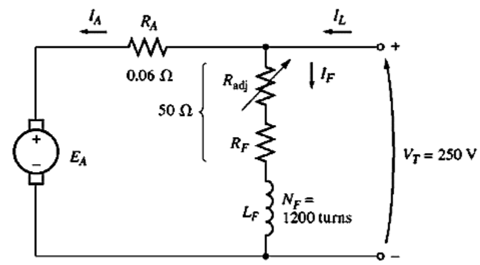
Therefore, E_A at this load will be

$$E_A = V_T - I_A R_A$$

$$= 250\text{ V} - (295\text{ A})(0.06\ \Omega) = 232.3\text{ V}$$

The resulting speed of the motor is

$$n_2 = \frac{E_{A2}}{E_{A1}} n_1 = \frac{232.3\text{ V}}{250\text{ V}} 1200\text{ r/min} = 1115\text{ r/min}$$



Example:

(d) To plot the output characteristic of this motor, it is necessary to find the torque corresponding to each value of speed. At no load, the induced torque τ_{ind} is clearly zero. The induced torque for any other load can be found from the fact that power converted in a dc motor is

$$\boxed{P_{conv} = E_A I_A = \tau_{ind}\omega}$$

From this equation, the induced torque in a motor is

$$\tau_{ind} = \frac{E_A I_A}{\omega}$$

Therefore, the induced torque when $I_L = 100$ A is

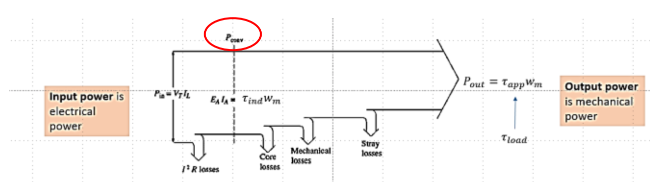
$$\tau_{ind} = \frac{(244.3\text{ V})(95\text{ A})}{(1173\text{ r/min})(1\text{ min/60s})(2\pi\text{ rad/r})} = 190\text{ N}\bullet\text{m}$$

The induced torque when $I_L = 200$ A is

$$\tau_{ind} = \frac{(238.3\text{ V})(95\text{ A})}{(1144\text{ r/min})(1\text{ min/60s})(2\pi\text{ rad/r})} = 388\text{ N}\bullet\text{m}$$

The induced torque when $I_L = 300$ A is

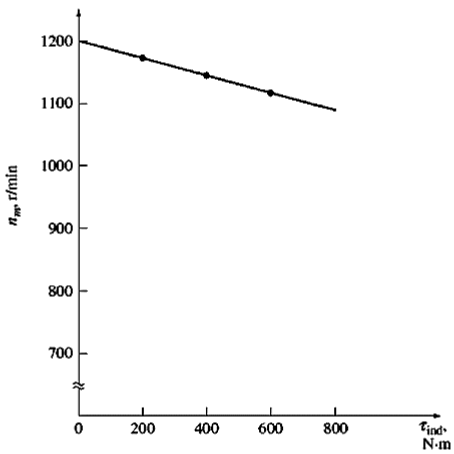
$$\tau_{ind} = \frac{(232.3\text{ V})(295\text{ A})}{(1115\text{ r/min})(1\text{ min/60s})(2\pi\text{ rad/r})} = 587\text{ N}\bullet\text{m}$$

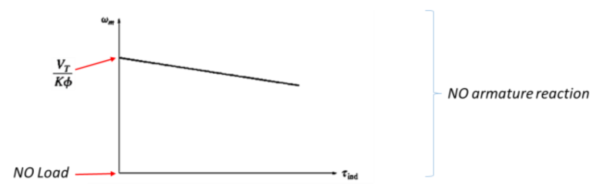


Power-flow diagram for DC motor

Example:

- The resulting **torque-speed characteristic** for this **shunt DC motor** is plotted in the figure below:

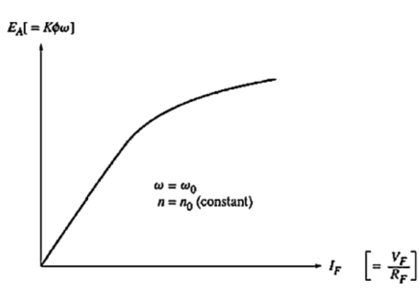




Theoretical torque-speed characteristic for a shunt DC motor

Nonlinear Analysis of a Shunt DC Motor

- The relationship between **field current (*or flux*)** and **internal generated voltage** of a DC machine is **nonlinear** as shown in the figure.
- So the **nonlinear magnetization curve** should be used in the analysis of DC machines if **accurate solution is expected**.



The magnetization curve of a dc machine expressed as a plot of E_A versus I_F for a fixed speed of w_0 or n_0

Nonlinear Analysis of a Shunt DC Motor

- Another important point is that if **compensating windings** are **<u>not used</u>** then the **effect of armature reaction <u>must be</u> taken into consideration**.

- So if a DC machine has **armature reaction**, its **flux** will be **<u>reduced</u>** when the **load** is **<u>increased.</u>**
- (*See "–" minus sign in the equation below*).

- The **total magnetomotive force (MMF)** in a **shunt DC motor** is the **field circuit magnetomotive force minus** the **magnetomotive force due to armature reaction**, given by the following equation:

$$\underbrace{\mathcal{F}_{\text{net}}}_{\textit{Total MMF}} = \overbrace{N_F I_F}^{\textit{Field circuit MMF}} - \underbrace{\mathcal{F}_{\text{AR}}}_{\textit{MMF due to armature reaction}}$$

The ***effective field current*** is found as

$$\boxed{I_F^* = I_F - \frac{\mathcal{F}_{\text{AR}}}{N_F}}$$

Effective field current is **<u>not available</u>** in the machine and **<u>can not be measured</u>** directly. It is only **hypothetical**.

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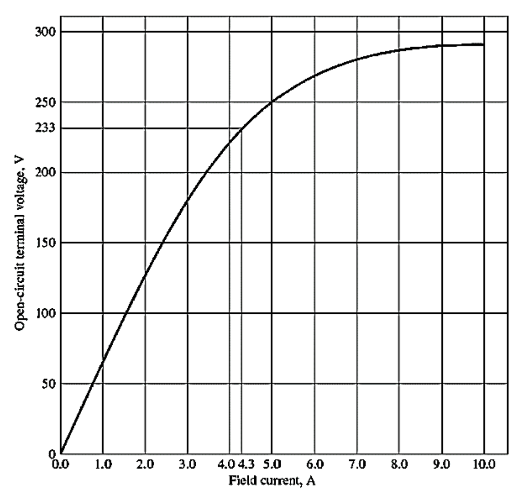
Example:

A **50-hp**, **250-V**, **1200 r/min** dc shunt motor **without compensating windings** has an armature resistance (including the brushes and interpoles) of **0.06 Ω**. Its field circuit has a total resistance RF + Radj of **50 Ω**, which produces a **no-load speed of 1200 r/min**. There are **1200 turns per pole** on the shunt field winding, and the **armature reaction** produces a **demagnetizing magnetomotive force of 840 A.turns** at a **load current** of **200 A**. The magnetization curve of this machine is shown in the figure.



(a) Find the speed of this motor when its input current is **200 A**.

(b) This motor is essentially identical to the one in previous example except for the absence of compensating windings. How does its speed compare to that of the previous motor at a load current of **200 A**?

(c) Calculate and plot the **torque-speed characteristic** for this motor.

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Solution

(a) If $I_L = 200$ A, then the armature current of the motor is

$$I_A = I_L - I_F = I_L - \frac{V_T}{R_F}$$
$$= 200\text{ A} - \frac{250\text{ V}}{50\ \Omega} = 195\text{ A}$$

Therefore, the internal generated voltage of the machine is

$$E_A = V_T - I_A R_A$$
$$= 250\text{ V} - (195\text{ A})(0.06\ \Omega) = 238.3\text{ V}$$

At $I_L = 200$ A, the demagnetizing magnetomotive force due to armature reaction is 840 A • turns, so the effective shunt field current of the motor is

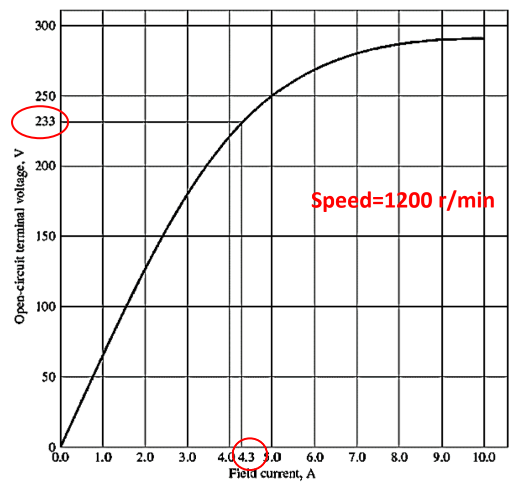
$$I_F^* = I_F - \frac{\mathscr{F}_{AR}}{N_F} \qquad (9\text{–}12)$$
$$= 5.0\text{ A} - \frac{840\text{ A} \cdot \text{turns}}{1200\text{ turns}} = 4.3\text{ A}$$

From the magnetization curve, this effective field current would produce an internal generated voltage E_{A0} of 233 V at a speed n_0 of 1200 r/min.

We know that the internal generated voltage E_{A0} would be 233 V at a speed of 1200 r/min. Since the actual internal generated voltage E_A is 238.3 V, the actual operating speed of the motor must be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \qquad (9\text{–}13)$$

$$n = \frac{E_A}{E_{A0}} n_0 = \frac{238.3\text{ V}}{233\text{ V}}(1200\text{ r/min}) = 1227\text{ r/min}$$



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Example:

(b) At 200 A of load in Example 9–1, the motor's speed was $n = 1144$ r/min. In this example, the motor's speed is 1227 r/min. *Notice that the speed of the motor with armature reaction is higher than the speed of the motor with no armature reaction*. This relative increase in speed is due to the flux weakening in the machine with armature reaction.

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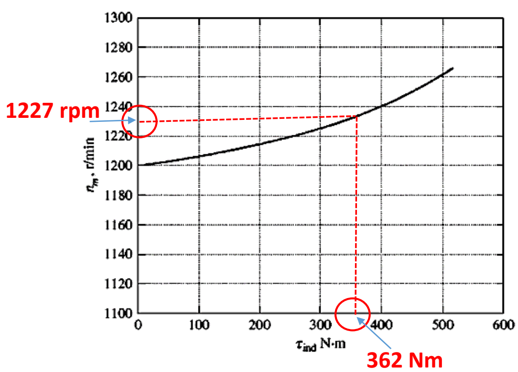
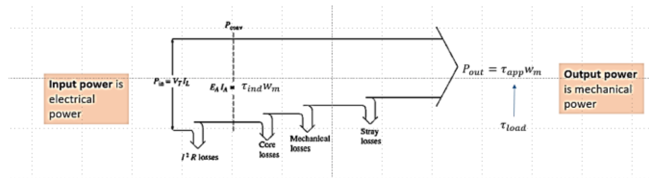
Example:

(c) To derive the torque–speed characteristic of this motor, we must calculate the torque and speed for many different conditions of load. Unfortunately, the demagnetizing armature reaction magnetomotive force is only given for one condition of load (200 A). Since no additional information is available, we will assume that the strength of $\mathcal{F}_{AR}$ varies linearly with load current.





Power-flow diagram for DC motor

Let's find a point on this curve:
What is **Tind=?** at **IL=200 A** ?
We know that **Ea=238.3 V** when IL=**200 A**.
So Ea.Ia = Tind.wm ➔
Tind = (238.3*195)/(2*pi*1227/60)=**362 Nm**
Now we know that **at this torque**, rotor speed is **1227 rpm**

The torque--speed characteristic of the motor with armature reaction

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Speed Control Of Shunt DC Motor

- We frequently need **speed control** of shunt DC motors in industry.
- But how can be the speed of a shunt DC motor controlled ?
- There are **three speed control methods** (*two common methods and one less common method*):

1) Adjusting the **field resistance R_F** (*and thus the field flux*)
2) Adjusting the **armature voltage V_T**

common methods

3) Inserting a **resistor in series** with the **armature circuit**

Less common method

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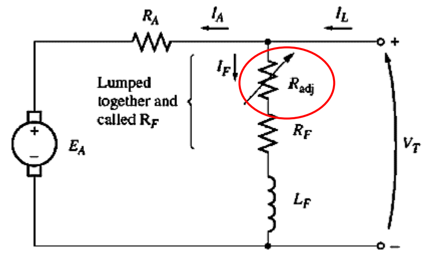
Speed Control Of Shunt DC Motor

Adjusting Field Resistance:

- If the **field resistance is increased**, then the **field current decreases**
- When the **field current decreases**, the **flux of the machine also decreases**
- A **decrease in flux causes** an **instantaneous decrease** in the **internal generated voltage** (**$E_A = K\phi w$**), which causes an **increase in the machine's armature current**:

$$I_A\uparrow = \frac{V_T - E_A\downarrow}{R_A}$$



$$I_F = \frac{V_T}{R_F}$$
$$V_T = E_A + I_A R_A$$
$$I_L = I_A + I_F$$

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Speed Control Of Shunt DC Motor

Adjusting Field Resistance:

- However, the **induced torque** is given as:

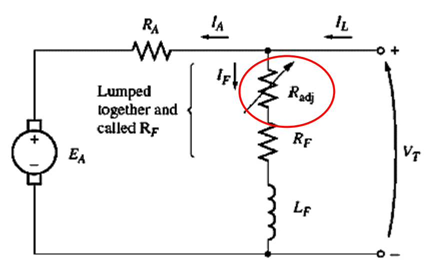
$$\tau_{\text{ind}} = K\phi I_A$$

- So does **induced torque** ***increase*** or ***decrease*** ?

$$?\ \uparrow\downarrow\ \tau_{\text{ind}} = K\phi\downarrow I_A\uparrow$$

Armature current increases

Flux decreases



$$I_F = \frac{V_T}{R_F}$$
$$V_T = E_A + I_A R_A$$
$$I_L = I_A + I_F$$

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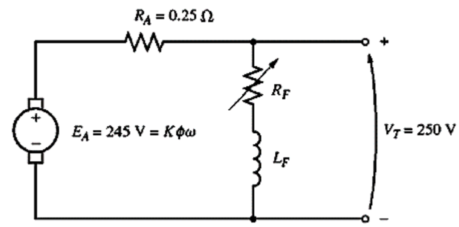
Speed Control Of Shunt DC Motor

Adjusting Field Resistance:

- To answer this question, refer to the figure.
- Now let's ask what happens to this motor ***if there is a 1 percent decrease in flux?***
- If the **flux** **decreases** by **1 percent**, then **EA** must **decrease** by **1 percent** too, because of the following equation:



A 250-V shunt DC motor with typical values of EA and RA.

$$E_A = K\phi\omega$$

$$E_{A2} = 0.99\ E_{A1} = 0.99(245\ \text{V}) = 242.55\ \text{V}$$

$$I_A = (250\ \text{V} - 245\ \text{V})/0.25\ \Omega = 20\ \text{A}.$$

*Armature current **before** adjusting field resistance*

The armature current must then rise to

$$I_A = \frac{250\ \text{V} - 242.55\ \text{V}}{0.25\ \Omega} = 29.8\ \text{A}$$

*Armature current **after** adjusting field resistance*

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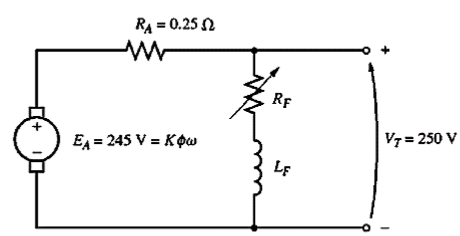
Speed Control Of Shunt DC Motor

Adjusting Field Resistance:

- Thus a **1 percent decrease** in **flux** produced a **49 percent increase** in **armature current**

$I_A = 20A$ *(Armature current **before** adjusting field resistance)*

$I_A = 29.8A$ *(Armature current **after** adjusting field resistance)*



A 250-V shunt DC motor with typical values of EA and RA.

So if we return to our main question, the **increase** in **armature current** predominates over the **decrease** in **flux**, and hence the **induced torque** **rises** as **field resistance** **increases**

$$\boxed{\tau_{ind} = K\overset{\downarrow}{\phi}\overset{\Uparrow}{I_A}}$$

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Speed Control Of Shunt DC Motor

Adjusting Field Resistance:

- When the **induced torque** begins to **increase**, it becomes **greater** than the **load torque** (**Tind > Tload**) and the **motor speeds up**.
- However, as the **motor speeds up**, the **internal generated voltage EA** rises, causing **armature current to fall**.

$$\downarrow I_A = \frac{V_T - E_A \uparrow}{R_A}$$

- As **armature current falls**, the **induced torque falls** too, and finally **induced torque** again **equals load torque** but at a **higher steady-state speed** than the case **before increasing field resistance**.
- Naturally, **decreasing field resistance** would **reverse** the whole process, and the **speed of the motor would drop**

$R_F \uparrow \quad speed \uparrow$

$R_F \downarrow \quad speed \downarrow$

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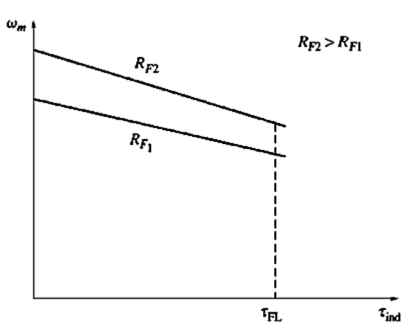
Speed Control Of Shunt DC Motor

Adjusting Field Resistance:



The effect of field resistance speed control on a shunt motor's torque-speed characteristic

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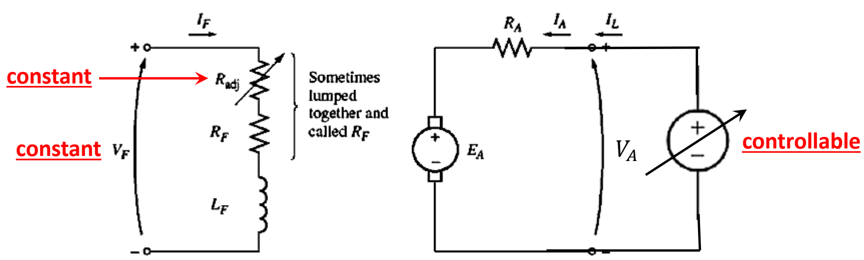
Speed Control Of Shunt DC Motor

Adjusting Armature Voltage:

- In this method, the **armature voltage** is **<u>changed</u>**.
- But, **field voltage** is **<u>constant</u>** (*not changed)*.



Armature voltage control of a separately excited DC motor

Speed Control Of Shunt DC Motor

Adjusting Armature Voltage:

- If **armature voltage** is <u>increased</u>, then the **armature current** <u>increases</u>:

$$\uparrow [I_A = (V_A\uparrow - E_A)/R_A]$$

- As **armature current** <u>increases</u>, then **induced torque** <u>increases</u>:

$$\uparrow \tau_{\text{ind}} = K\phi I_A\uparrow$$

- When **induced torque** <u>becomes</u> greater than **load torque**, then **motor speed** <u>increases</u>:
- But, as the **motor speed (*w*)** <u>increases</u>, the **internal generated voltage** <u>increases</u>:

$$\uparrow E_A(= K\phi\omega\uparrow)$$

- When the **internal generated voltage** <u>increases</u>, then **armature current** <u>decreases</u>:

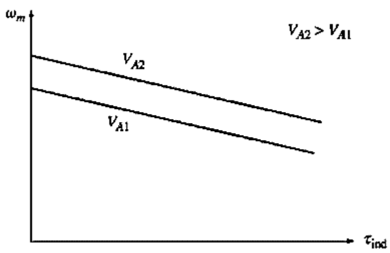
$$\downarrow I_A [= (V_A \quad -\uparrow E_A)/R_A]$$

- When the **armature current** <u>decreases</u>, then the **induced torque** <u>decreases until</u> **(*<u>Tind=Tload</u>*) <u>at a</u> <u>higher speed</u>**:

$$\downarrow \tau_{\text{ind}} = K\phi I_A\downarrow$$

Speed Control Of Shunt DC Motor

Adjusting Armature Voltage:



The effect of armature voltage speed control on torque-speed characteristic of a separately excited DC motor.

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Speed Control Of Shunt DC Motor

Inserting A Resistor In Series With The Armature Circuit:

- If a **resistor (R_{extra})** is inserted **<u>in series</u>** with the **armature circuit**, **armature current** **<u>decreases</u>**:

$$I_A = \frac{V_A - E_A}{R_A + R_{extra}}$$

- When the **armature current** **<u>decreases</u>**, then the **induced torque** **<u>decreases</u>**:

$$\tau_{\text{ind}} = K\phi I_A$$

- When the **induced torque** **<u>decreases</u>**, then the **speed of the motor** **<u>decreases.</u>**
- But when the **speed** **<u>decreases</u>**, then the **internal generated voltage** **<u>decreases:</u>**

$$E_A (= K\phi\omega$$

- When the **internal generated voltage** **<u>decreases,</u>** the **armature current** **<u>increases</u>**:

$$I_A = \frac{V_A - E_A}{R_A + R_{extra}}$$

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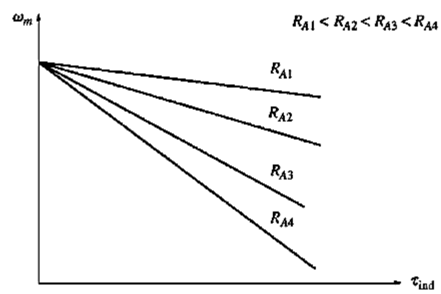
Speed Control Of Shunt DC Motor

Inserting A Resistor In Series With The Armature Circuit:

- Now, the **armature current** is **both** **decreasing** and **increasing**; so which one is **dominant** over the other one?
- The **decreasing effect** is more **stronger** than the other and hence the **motor slows down** after **adding resistance**.
- However, this speed control method is **not very effective**.
- Because, the **loss** in the **inserted resistor** is **very large**.
- For this reason, **this method is rarely used**.



The effect of armature resistance speed control on a shunt motor's torque-speed characteristic

Speed Control Of Shunt DC Motor

- **Can we use two methods together ?**

- **Adjusting field resistance** is very **effective** for the **speeds** which are **higher** than **base speed of the motor**.
- **Adjusting armature voltage** is very **effective** for the **speeds** which are **lower** than **base speed of the motor**.

Adjusting Field Resistance:

$\boxed{R_{adj(min)} \leq R_{adj} \leq R_{adj(max)}}$

- If $R_{adj} = R_{adj(min)} \Rightarrow I_F = I_{F(max)} \Rightarrow \emptyset = \emptyset_{(max)} \Rightarrow \text{w} = w_{(min)}$

We **cannot** **increase** **field current** so much because field windings can be **damaged**

- If $R_{adj} = R_{adj(max)} \Rightarrow I_F = I_{F(min)} \Rightarrow \emptyset = \emptyset_{(min)} \Rightarrow \text{w} = w_{(max)}$

There is **no problem** here because, **field current** can be **decreased** safely.

CONCLUSION→ **Adjusting field resistance** is very **effective** to **increase** **motor speed** (***higher than rated speed***) !

Speed Control Of Shunt DC Motor

- **Can we use two methods together ?**

- **Adjusting field resistance** is very **effective** for the **speeds** which are **higher** than **base speed of the motor**.
- **Adjusting armature voltage** is very **effective** for the **speeds** which are **lower** than **base speed of the motor**.

Adjusting Armature Voltage:

$\boxed{V_{A(min)} \leq V_A \leq V_{A(max)}}$

- If $V_A = V_{A(max)} \Rightarrow w = w_{(max)}$

We **cannot increase armature voltage** so much because of the **voltage rating** of the motor, since **insulation problems can occur !**

- If $V_A = V_{A(min)} \Rightarrow w = w_{(min)}$

There is **no problem** here because, **armature voltage** can be **decreased** safely.

CONCLUSION→ Adjusting armature voltage is very **effective** to **decrease motor speed** (***lower than rated speed***) !

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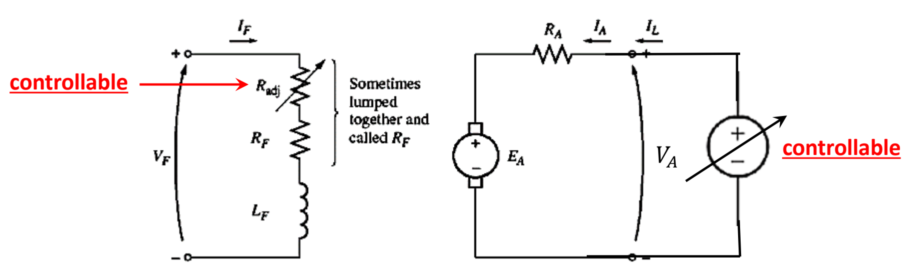
Speed Control Of Shunt DC Motor

- By **combining** these **two speed-control techniques**, it is possible to get a **very wide range** of **speed variations** for a motor.
- These **two speed-control techniques** can be successfully applied to both **shunt** and **separately excited DC motors**.



Adjusting field resistance *can be applied to* *increase* *motor speed, higher than rated speed*

Adjusting armature voltage *can be applied to* *decrease* *motor speed, lower than rated speed*

Speed control of the DC motor using the combination of two speed control methods

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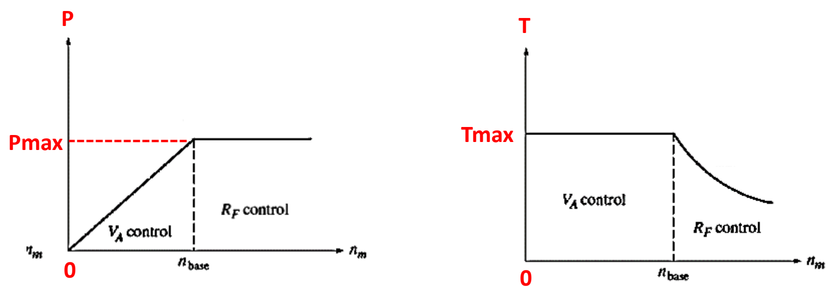
Speed Control Of Shunt DC Motor

Safe ranges of operation of two speed-control methods:



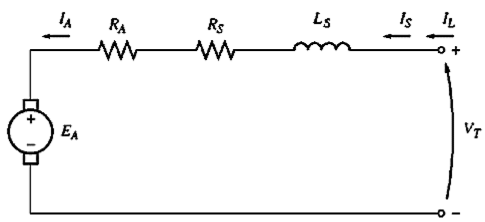
Power and torque limits of the combination of two speed-control methods

Self-study

- Solve Example 9.3 at page 555 from Chapman
- Solve Example 9.4 at page 558 from Chapman

Series DC Motor

- A **series DC motor** is a DC motor whose **field windings** is **connected in series** with the **armature circuit**.
- The **series field winding** generally consists of a **relatively few turns**.
- The important feature of the **series DC motor** is that **the flux is directly proportional to the armature current.**
- The equivalent circuit of a series DC motor is shown in the figure.



$$I_A = I_S = I_L$$
$$V_T = E_A + I_A (R_A + R_S)$$

The equivalent circuit of a series dc motor

Series DC Motor

- The Kirchhoff's Voltage Law equation for a **series DC motor** is given as:

$$V_T = E_A + I_A(R_A + R_S)$$

- The **induced torque** in a **series DC motor** is given as:

$$\tau_{\text{ind}} = K\phi I_A$$

- The **flux** in this machine is **directly proportional** to its **armature current** until saturation;

$$\phi = cI_A$$

- So the induced torque can be written as:

$$\tau_{\text{ind}} = K\phi I_A = KcI_A^2$$

- The result is that the **torque** in the motor is **proportional to the square** of its **armature current**

Series DC Motor

$$\tau_{\mathrm{ind}} = K\phi I_A = KcI_A^2$$

- As a result of the above relationship, we understand that a **series DC motor** gives **more torque per ampere** than any other DC motor.
- Therefore **series DC motors** are used in applications requiring **very high torques**.
- Examples of such applications are the **starter motors** in cars, elevator motors, tractor motors in locomotives, cranes, and forklifts.

Source: https://www.quora.com/

4KW 48V Series Wound DC Traction Electric Motor

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Series DC Motor

Quick Details

Place of Origin:	Shandong, China (Mainland)	Brand Name:	SUPER	Model Number:	ZC4-48B
Motor:	Brush	Voltage:	verious	Certification:	CE
Size & Diameter:	170mm-242mm	Excited Type:	Series or separately	Insulation Class:	F
Duty System:	S2-60min	Protection Class:	IP20	Type:	DC Motor
Use:	Electric Car				

Mode	Rated Power (Kw)	Rated Volt (V)	Rated Amp (A)	Rated Speed (r/min)	Duty	Protection Class
ZC2.2-48	2.2	48	57	2000	S2 60min	IP20
ZC2.2-48	2.2	48	57	2500		
ZC2.2-48	2.2	48	57	2800		
ZC2.2-60	2.2	60	46	3300		
ZC3-48	3	48	78	1500		
ZC3-48	3	48	78	2000		
ZC3-48	3	48	78	2500		
ZC3-48	3	48	78	2800		
ZC3-48	3	48	78	3200		
ZC3-48	3	48	78	3500		
ZC3-60	3	60	63	2000		
ZC3-60	3	60	63	2800		
ZC3-60	3	60	63	3500		
ZC3-72	3	72	52	3500		
ZC3.5-48	3.5	48	91	2800		
ZC3.5-60	3.5	60	73	2800		
ZC3.5-72	3.5	72	61	2800		
ZC4-48	4	48	104	1500		
ZC4-48	4	48	104	2000		
ZC4-48	4	48	104	2500		
ZC4-48	4	48	104	2800		
ZC4-48	4	48	104	3200		
ZC4-48	4	48	104	3500		

IP First number – Protection against solid objects

- **0** – No special protection
- **1** – Protected against solid objects up to 50 mm, e.g. accidental touch by persons hands.
- **2** – Protected against solid objects up to 12 mm, e.g. persons fingers.
- **3** – Protected against solid objects over 2.5 mm (tools and wires).
- **4** – Protected against solid objects over 1 mm (tools, wires, and small wires).
- **5** – Protected against dust limited ingress (no harmful deposit).
- **6** – Totally protected against dust.

IP Second number – Protection against liquids

- **0** – No protection.
- **1** – Protection against vertically falling drops of water e.g. condensation.
- **2** – Protection against direct sprays of water up to 15o from the vertical.
- **3** – Protected against direct sprays of water up to 60o from the vertical.
- **4** – Protection against water sprayed from all directions – limited ingress permitted.
- **5** – Protected against low pressure jets of water from all directions – limited ingress.

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Terminal Characteristic of a Series DC Motor

- To determine the **terminal characteristic** of a **series DC motor**, an analysis will be based on the assumption of a **linear magnetization curve**.
- So we can think that the **flux** in the machine is **directly proportional** to the **armature current**:

$$\phi = cI_A$$

- The **saturation effect** can be considered by performing a **graphical analysis**.
- The **KVL equation** for a **series DC motor** is given as:

$$V_T = E_A + I_A(R_A + R_S)$$

- The **induced torque** equation of a **series DC motor** can be rewritten as:

$$\tau_{\text{ind}} = K\phi I_A = KcI_A^2 \quad \Rightarrow \quad I_A = \sqrt{\frac{\tau_{\text{ind}}}{Kc}}$$

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Terminal Characteristic of a Series DC Motor

- Also, we remember that the **armature voltage equation** is

$$E_A = K\phi\omega$$

- Substituting the **last two equations** into the KVL equation yields:

$$V_T = \underbrace{E_A}_{E_A = K\phi\omega} + I_A(R_A + R_S) \qquad I_A = \sqrt{\frac{\tau_{\text{ind}}}{Kc}}$$

$$V_T = K\phi\omega + \sqrt{\frac{\tau_{\text{ind}}}{Kc}}(R_A + R_S)$$

- If the **flux** is eliminated from the above equation then the **terminal characteristic** equation can be derived.

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Terminal Characteristic of a Series DC Motor

- Notice that

$$I_A = \frac{\phi}{c}$$

- And the **induced torque** equation can be rewritten as

$$\tau_{\text{ind}} = K\phi I_A \quad \Rightarrow \quad \tau_{\text{ind}} = \frac{K}{c}\phi^2$$

- Therefore, the **flux** in the motor can be rewritten as

$$\phi = \sqrt{\frac{c}{K}}\sqrt{\tau_{\text{ind}}}$$

- Substituting this **flux equation** into the following equation:

$$V_T = K\phi\omega + \sqrt{\frac{\tau_{\text{ind}}}{Kc}}(R_A + R_S) \quad \Rightarrow \quad \boxed{V_T = K\sqrt{\frac{c}{K}}\sqrt{\tau_{\text{ind}}}\,\omega + \sqrt{\frac{\tau_{\text{ind}}}{Kc}}(R_A + R_S)}$$

$$\phi = \sqrt{\frac{c}{K}}\sqrt{\tau_{\text{ind}}}$$

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Terminal Characteristic of a Series DC Motor

$$\boxed{V_T = K\sqrt{\frac{c}{K}}\sqrt{\tau_{\text{ind}}}\,\omega + \sqrt{\frac{\tau_{\text{ind}}}{Kc}}(R_A + R_S)}$$

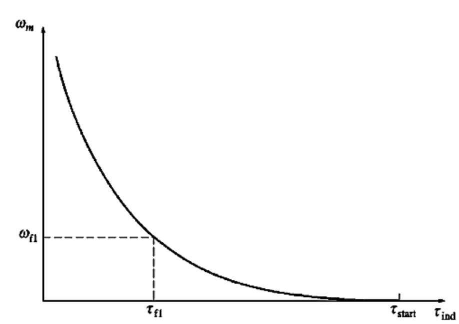
- If the above equation is solved for **speed (w)**:

$$\sqrt{Kc}\sqrt{\tau_{\text{ind}}}\,\omega = V_T - \frac{R_A + R_S}{\sqrt{Kc}}\sqrt{\tau_{\text{ind}}}$$

$$\omega = \frac{V_T}{\sqrt{Kc}\sqrt{\tau_{\text{ind}}}} - \frac{R_A + R_S}{Kc}$$

- The resulting **torque-speed relationship** of a **series DC motor** is given as:

$$\boxed{\omega = \frac{V_T}{\sqrt{Kc}}\frac{1}{\sqrt{\tau_{\text{ind}}}} - \frac{R_A + R_S}{Kc}}$$



The torque-speed characteristic of a series dc motor

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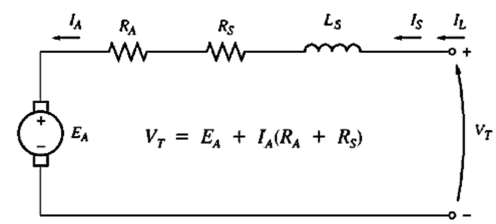
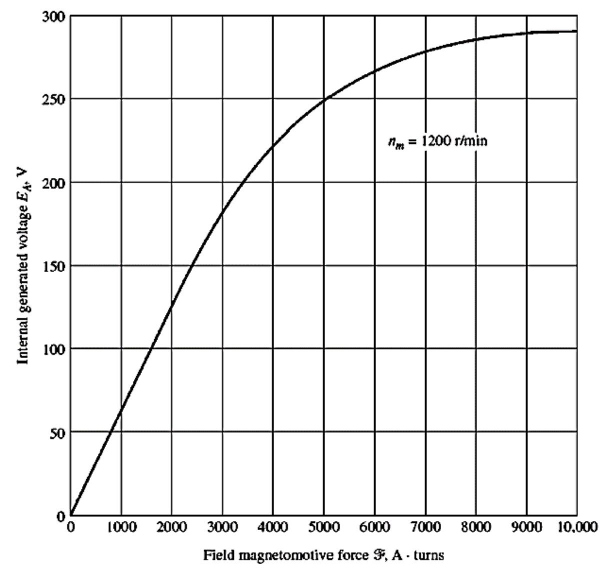
Example:

Example: The figure shows a **250-V series dc motor** with compensating windings and a total series resistance **RA + Rs of 0.08 Ω**. The series field consists of **25 turns per pole**, with the magnetization curve also shown.

(a) Find the speed and induced torque of this motor for when its armature current is **50 A**.
(b) Calculate and plot the torque-speed characteristic for this motor.



The equivalent circuit of a series dc motor



The magnetization curve

Example:

For $I_A = 50$ A,

$$E_A = V_T - I_A(R_A + R_S) = 250 \text{ V} - (50\text{A})(0.08\ \Omega) = 246 \text{ V}$$

Since $I_A = I_F = 50$ A, the magnetomotive force is

$$\mathscr{F} = NI = (25 \text{ turns})(50 \text{ A}) = 1250 \text{ A} \cdot \text{turns}$$

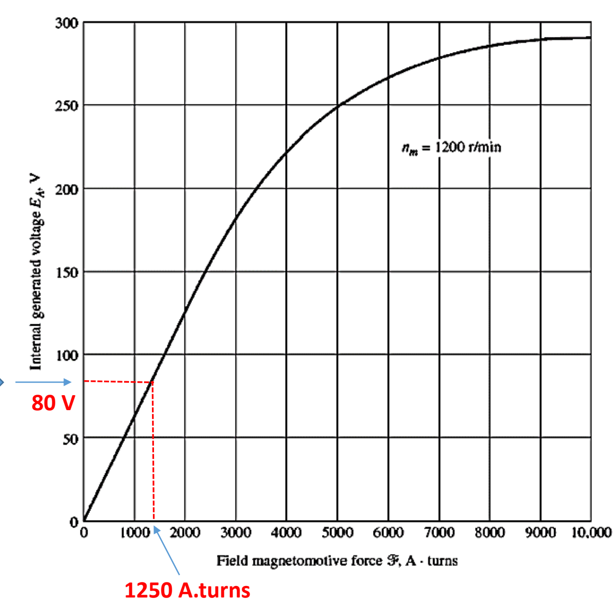
From the magnetization curve at $\mathscr{F} = 1250$ A • turns, $E_{A0} = 80$ V.

$$n = \frac{E_A}{E_{A0}} n_0$$

$$= \frac{246 \text{ V}}{80 \text{ V}}\ 1200 = 3690 \text{ r/min}$$

$$\tau_{\text{ind}} = \frac{E_A I_A}{\omega}$$

$$= \frac{(246 \text{ V})(50 \text{ A})}{(3690 \text{ r/min})(1 \text{ min}/60 \text{ s})(2\pi \text{ rad/r})} = 31.8 \text{ N} \cdot \text{m}$$



Example:

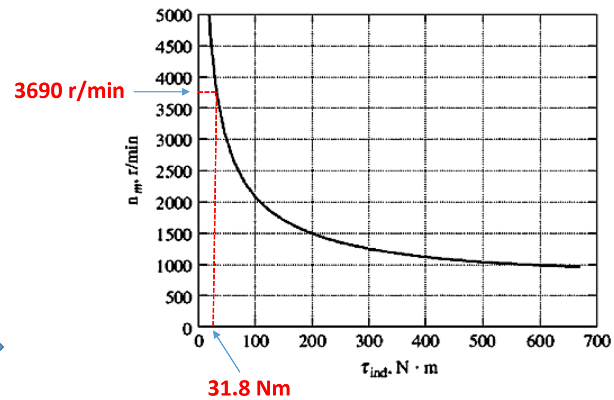
$$n = \frac{E_A}{E_{A0}} n_0$$

$$= \frac{246\text{ V}}{80\text{ V}}\, 120\text{ r/min} = 3690\text{ r/min}$$

$$\tau_{\text{ind}} = \frac{E_A I_A}{\omega}$$

$$= \frac{(246\text{ V})(50\text{ A})}{(3690\text{ r/min})(1\text{ min}/60\text{ s})(2\pi\text{ rad/r})} = 31.8\text{ N} \cdot \text{m}$$

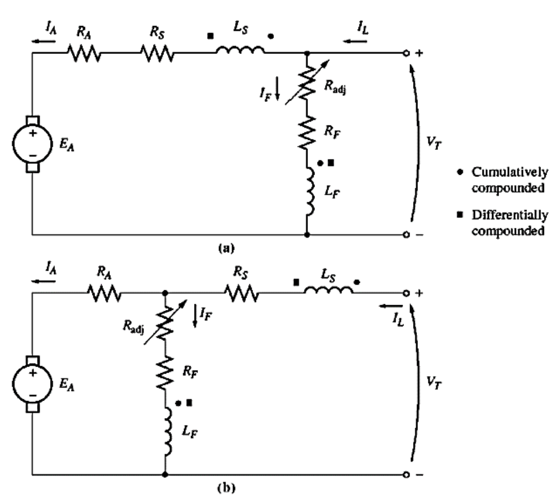
Many points (*torque-speed*) must be found to draw a complete torque-speed characteristic like this curve



The torque-speed characteristic of the series dc motor in Example

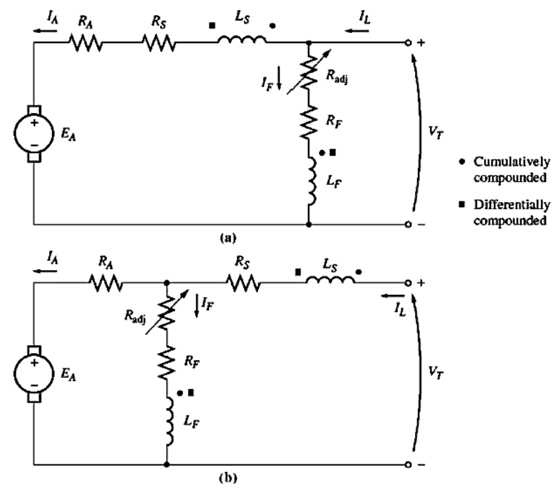
Compounded DC Motor

- A **compounded DC motor** is a DC motor with **both** a **shunt** and a **series** field windings as shown in figure.
- We can say that a **compounded DC motor** is the combination of both a **shunt DC motor** and a **series DC motor**.
- The **dots** that appear on the two field coils have the same meaning as the dots on a **transformer**:
- **Current flowing into** a **dot** produces a **positive MMF**.
- If **current flows into** the **dots** on **both field coils**, the two MMFs are added to produce a **larger total MMF**.
- This situation is known as "*cumulative compounding*".
- This type of motors are called as "***Cumulatively Compounded DC Motors***".



Compounded DC Motor

- **Current leaving** a **dot** produces a **negative MMF**.
- If **one current flows into** the **dot** on **one field coil** and the **other current leaves** a **dot** on the **other field coil**, the **resulting MMF** is obtained by **subtracting** one MMF from the other.
- This situation is known as "***differential compounding***".
- This type of motors are called as "***Differentially Compounded DC Motors***".



Compounded DC Motor

- The Kirchhoff's Voltage Law equation for a **compounded DC motor** is given as:

$$V_T = E_A + I_A(R_A + R_S)$$

- The currents in the **compounded DC motor** are shown to be:

$$I_A = I_L - I_F$$

$$I_F = \frac{V_T}{R_F}$$

- The **net MMF** and the **effective shunt field current** in the **compounded DC motor** are given by

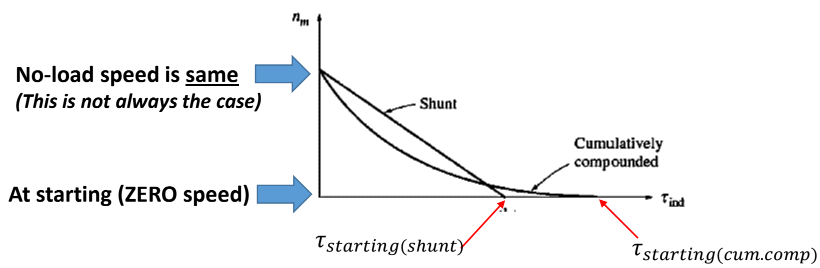
$$\boxed{\mathscr{F}_{\text{net}} = \mathscr{F}_F \pm \mathscr{F}_{\text{SE}} - \mathscr{F}_{\text{AR}}}$$

$$\boxed{I_F^* = I_F \pm \frac{N_{SE}}{N_F} I_A - \frac{\mathscr{F}_{\text{AR}}}{N_F}}$$

- **Positive sign** is associated with a **cumulatively compounded DC motor**
- **Negative sign** is associated with a **differentially compounded DC motor**

Torque-Speed Characteristic of a Cumulatively Compounded DC Motor

- The **cumulatively compounded DC motor** has a **higher** **starting torque** than a **shunt DC motor**:
- Because, there is **more flux** in a compounded DC motor during starting.
- Since both **shunt** and **series** **field windings** generate **MMF with the same polarity** and they are **added**
- This is an **advantage** of the **compounded DC motor** over **shunt DC motor** **during starting**.



$$\tau_{cum.comp.\_starting} > \tau_{shunt\_starting}$$

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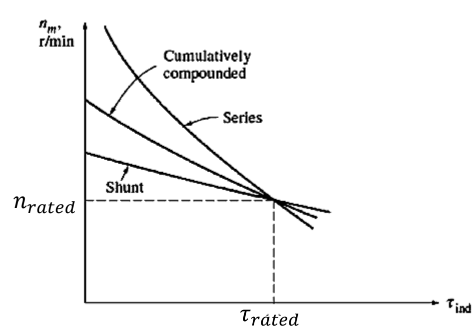
Torque-Speed Characteristic of a Cumulatively Compounded DC Motor

- The **cumulatively compounded DC motor** combines the **advantages** of **shunt** and **series DC motors**.
- At **light loads**, the series field has a very small effect, so the motor behaves **approximately** as a **shunt DC motor**.
- As **the load gets very large**, the **series flux** becomes quite important and the **torque-speed curve** begins to look like a **series DC motor's characteristic**.
- **Cumulatively compounded DC motor** has generally **higher torque** than a **shunt DC motor**.
- The **shunt filed winding** in the **cumulatively compounded DC motor** allows to make the **speed control possible**.



The torque-speed characteristic of a cumulatively compounded DC motor compared to series and shunt motors with the same full-load rating

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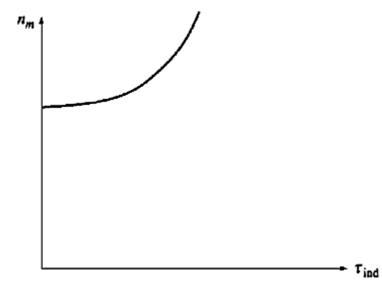
Torque-Speed Characteristic of a Differentially Compounded DC Motor

- In a **differentially compounded DC motor**, the **shunt MMF** and **series MMF force** **subtract** from each other.
- This means that as the **load** on the motor **increases**, **armature current increases** and *the* **flux** *in the motor* **decreases**.
- But as the **flux decreases**, the **speed of the motor increases**.
- This **speed increase** causes another **increase in load**, which further **increases armature current**, further **decreasing** the **flux**, and **increasing** the **speed** again.
- The result is that **differentially compounded DC motor** becomes **unstable** and tends to **run away**
- Because of this situation, **differentially compounded DC motor** is **unsuitable** for any application.



The torque-speed characteristic of a differentially compounded DC motor

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Self-study

- Solve Example 9.6 at page 571 from Chapman

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Speed Control in the Cumulatively Compounded DC Motor

- The techniques available for the **control of speed** in a **cumulatively compounded DC motor** are the **same** as those available for a **shunt DC motor**.

- There are **three speed control methods** (*two common methods and one less common method*):

1) Adjusting the **field resistance R_F** (*and thus the field flux*)
2) Adjusting the **armature voltage V_T**

common methods

3) Inserting a **resistor in series** with the **armature circuit**

Less common method

DC Motor Starters

- In order for a **DC motor** to function properly on the job, it must have **some special control and protection equipment** associated with it. The purposes of this equipment are:

  - To **protect** the motor against damage due to **short circuits** in the equipment.
  - To **protect** the motor against damage from **long-term overloads.**
  - To **protect** the motor against damage from **excessive starting currents.**
  - To **provide** a convenient manner in which to control the **operating speed of the motor.**

DC Motor Starters

- **At starting conditions**, the DC motor is not turning, and so **armature voltage (EA)** is **ZERO**.
- Since the **internal resistance** of a DC motor is generally **very low**, a **very high current** flows during **starting**.
- **DC motor starters** are used **to limit** the **very high starting current** of DC motors.

For example, for a **50-hp** motor if **RA=0.06 Ω** and **VT=250V**:

$I_{starting}$ = (VT-EA) / RA = (250V-0V) / 0.06 = **4167 A**

I_{rated} = (50*746)/250 = **149.2**

Then; $\frac{I_{starting}}{I_{rated}} \approx 28$

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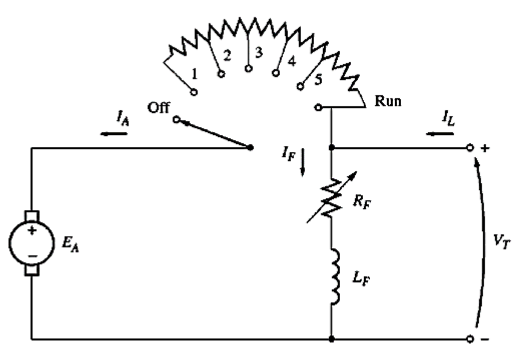
DC Motor Starters

- A **solution** to the problem of **excess current during starting** is to **insert** a **starting resistor in series with the armature** **to limit the current flow** until the motor reaches rated operating conditions.



A DC motor starter

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Self-study

- Solve Example 9.7 at page 575 from Chapman

Introduction to DC Generators

- **DC generators** are **DC machines** used as **generators**.
- There is **no real difference** between a **generator** and a **motor** except **for the direction of power flow**.
- There are **five major** types of **DC generators**, classified according to the manner in which their **field flux** is produced:
  - **Separately excited DC generator:**
  The field flux is derived from a **separate power source** independent of the generator itself.

  - **Shunt DC generator:**
  The field flux is derived by connecting the field circuit **directly across the terminals** of the generator.

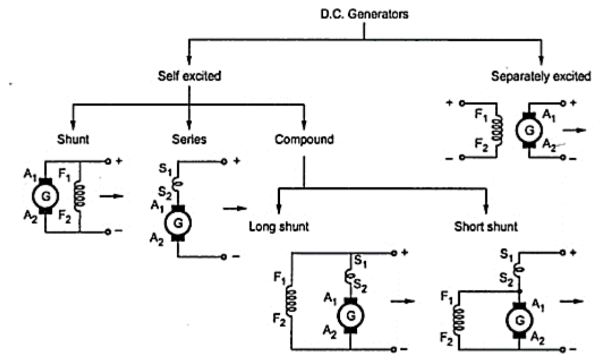
  - **Series DC generator:**
  The field flux is produced by connecting the field circuit **in series with the armature** of the generator.

  - **Cumulatively compounded DC generator:**
  Both a shunt and a series field are present, and their effects are **additive**.

  - **Differentially compounded DC generator:**
  Both a shunt and a series fie ld are present, but their effects are **subtractive** .

Introduction to DC Generators

- **DC generators** are **quite rare** in modern power systems.
- Even for DC power systems such as those in automobiles now use **AC generators plus rectifiers** to produce **DC power**.



Source: https://electricalshouters.com/types-of-dc-generators/

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Introduction to DC Generators

- The **terminal characteristics** of DC generators is the plot of **output voltage** *versus* **output current**.
- So, **DC generators** are compared by their **terminal characteristics**, **power ratings**, **efficiencies** and **voltage regulations**.
- **Voltage regulation (VR)** of a **DC generator** is defined as:

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

V_{nl} is the **no-load** terminal voltage of the DC generator
V_{fl} is the **full-load** (*rated-load*) terminal voltage of the DC generator

- A **positive voltage regulation** means a **drooping** terminal characteristic
- A **Negative voltage regulation** means a **rising** terminal characteristic

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Introduction to DC Generators

- All generators are driven by a **source of mechanical power**, which is usually called "**prime mover**" of the generator.
- A **prime mover** for a **DC generator** may be a **steam turbine**, a **diesel engine**, or even an **electric motor**.
- Since the **speed of the prime mover** affects the **output voltage of a generator**, and since prime movers can **vary widely** in their **speed characteristics**, it is good to compare the voltage regulation and output characteristics of different generators, assuming **constant speed** **prime movers**.
- Throughout this section, a DC generator's speed will be **assumed to be constant** unless a specific statement is made to the contrary.

steam turbine

diesel engine

electric motor

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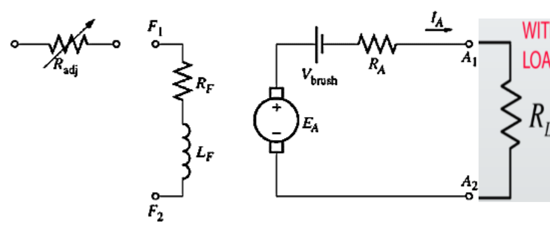
Separately Excited DC Generator

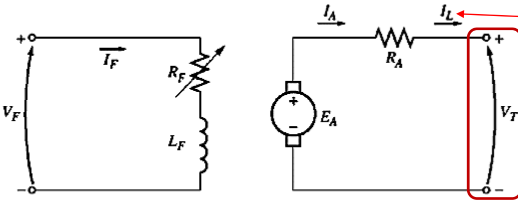
- A **separately excited DC generator** is a generator whose **field current** is supplied by a **separate** **external DC power source**.



The equivalent circuit of a separately excited DC generator

separate **external DC power source**

$I_L = I_A$
$V_T = E_A - I_A R_A$
$I_F = \frac{V_F}{R_F}$



Note that the direction of current is **outgoing** **(opposite of a DC motor)**

Terminal of generator (***Load is connected here***)

Simplified equivalent circuit of a separately excited DC generator

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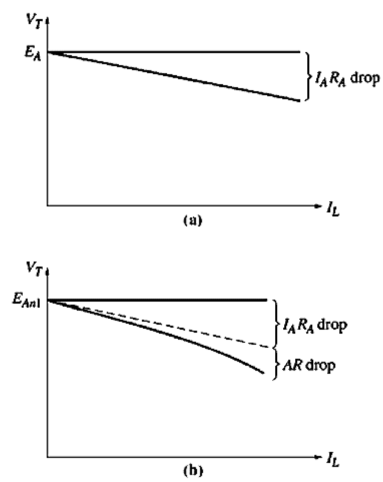
Terminal Characteristic of a Separately Excited DC Generator

$\boxed{V_T = E_A - I_A R_A}$ ⇒

Armature reaction effect **decreases** the **flux** in the machine, so; ⇒

$\emptyset \downarrow \quad E_A \downarrow \quad V_T \downarrow$



Armature Reaction is **ignored**

(Compensating Windings are **active**)

Armature Reaction is **active**

(Compensating Windings are **not used**)

The terminal characteristic of a separately excited DC generator

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Control of Terminal Voltage of a Separately Excited DC Generator

- Since **armature resistance (RA)** is **constant** and the **armature current (IA)** is dependent on the **magnitude of the load** on the generator, we need to control **armature voltage (EA)** in order **to control the terminal voltage (VT)** of a **separately excited DC generator**:

$\boxed{V_T = E_A - I_A R_A}$

$E_A \downarrow \Rightarrow V_T \downarrow$

$E_A \uparrow \Rightarrow V_T \uparrow$

$E_A = K\emptyset w$ ⇒

So we have **two possibilities** to control EA (**flux** and **speed**): Since, previously we assume that the **speed of the prime movers do not change so widely** (***assumed to be constant***), the only effective way to **control EA** is **to change flux** in the generator

$R_F \uparrow \Rightarrow I_F \downarrow \Rightarrow \emptyset \downarrow \Rightarrow E_A \downarrow$

$R_F \downarrow \Rightarrow I_F \uparrow \Rightarrow \emptyset \uparrow \Rightarrow E_A \uparrow$

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Nonlinear Analysis of a Separately Excited DC Generator

- **Nonlinear analysis** covers (*as in case of DC motors*)
  - The **magnetization curve** (non-linear relationship between **armature voltage (EA)** and **field current (IF)**)
  - In addition, if a machine has **armature reaction**, its flux will be reduced with each increase in load, causing **armature voltage (EA)** to decrease.
- The only way to **accurately** **determine the output voltage** in a **DC generator** **with armature reaction** is to make graphical analysis.
- The **total MMF** in a **separately excited DC generator** **with armature reaction** is given as:

$$\mathscr{F}_{\text{net}} = N_F I_F - \mathscr{F}_{\text{AR}}$$

- If the above equation is divided to ***NF*** for both sides:

$$I_F^* = I_F - \frac{\mathscr{F}_{\text{AR}}}{N_F}$$

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Nonlinear Analysis of a Separately Excited DC Generator

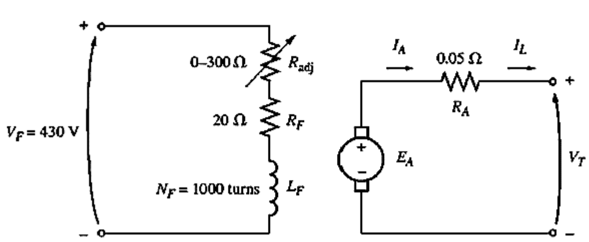
Example:

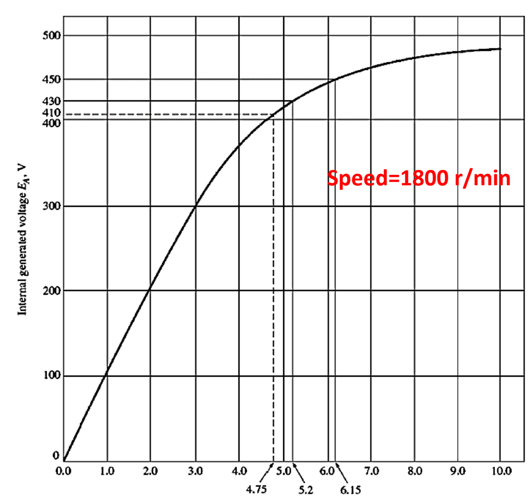
A separately excited DC generator is rated at **172 kW** @ **430 V**, **400 A** and **1800 r/min**. This machine has the following parameters:

$R_A = 0.05\ \Omega$ $\quad V_F = 430\text{ V}$

$R_F = 20\ \Omega$ $\quad N_F = 1000$ turns per pole

$R_{\text{adj}} = 0$ to $300\ \Omega$





Note: When the field current is zero, E_A is about 3 V.

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Nonlinear Analysis of a Separately Excited DC Generator

Example:

(a) If the variable resistor R_{adj} in this generator's field circuit is adjusted to 63 Ω and the generator's prime mover is driving it at 1600 r/min, what is this generator's no-load terminal voltage?

(b) What would its voltage be if a 360-A load were connected to its terminals? Assume that the generator has compensating windings.

(c) What would its voltage be if a 360-A load were connected to its terminals but the generator does not have compensating windings? Assume that its armature reaction at this load is 450 A • turns.

(d) What adjustment could be made to the generator to restore its terminal voltage to the value found in part *a*?

(e) How much field current would be needed to restore the terminal voltage to its no-load value? (Assume that the machine has compensating windings.) What is the required value for the resistor R_{adj} to accomplish this?

Nonlinear Analysis of a Separately Excited DC Generator

Example:

Solution

(a) If the generator's total field circuit resistance is

$$R_F + R_{adj} = 83\ \Omega$$

then the field current in the machine is

$$I_F = \frac{V_F}{R_F} = \frac{430\ \text{V}}{83\ \Omega} = 5.2\ \text{A}$$

From the machine's magnetization curve, this much current would produce a voltage $E_{A0} = 430$ V at a speed of 1800 r/min. Since this generator is actually turning at $n_m = 1600$ r/min, its internal generated voltage E_A will be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

The magnetization curve for the generator in Example 9–9.

$$E_A = \frac{1600\ \text{r/min}}{1800\ \text{r/min}} 430\ \text{V} = 382\ \text{V}$$

Since $V_T = E_A$ at no-load conditions, the output voltage of the generator is $V_T =$ 382 V.

Nonlinear Analysis of a Separately Excited DC Generator

Example:

(b) If a 360-A load were connected to this generator's terminals, the terminal voltage of the generator would be

$$V_T = E_A - I_A R_A = 382\text{ V} - (360\text{ A})(0.05\ \Omega) = 364\text{ V}$$

(c) If a 360-A load were connected to this generator's terminals and the generator had 450 A • turns of armature reaction, the effective field current would be

$$I_F^* = I_F - \frac{\mathscr{F}_{AR}}{N_F} = 5.2\text{ A} - \frac{450\text{ A • turns}}{1000\text{ turns}} = 4.75\text{ A}$$

From the magnetization curve, $E_{A0} = 410$ V, so the internal generated voltage at 1600 r/min would be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

$$E_A = \frac{1600\text{ r/min}}{1800\text{ r/min}} 410\text{ V} = 364\text{ V}$$

Therefore, the terminal voltage of the generator would be

$$V_T = E_A - I_A R_A = 364\text{ V} - (360\text{ A})(0.05\ \Omega) = 346\text{ V}$$

It is lower than before due to the armature reaction.

Nonlinear Analysis of a Separately Excited DC Generator

Example:

(d) The voltage at the terminals of the generator has fallen, so to restore it to its original value, the voltage of the generator must be increased. This requires an increase in E_A, which implies that R_{adj} must be decreased to increase the field current of the generator.

(e) For the terminal voltage to go back up to 382 V, the required value of E_A is

$$E_A = V_T + I_A R_A = 382\text{ V} + (360\text{ A})(0.05\ \Omega) = 400\text{ V}$$

To get a voltage E_A of 400 V at $n_m = 1600$ r/min, the equivalent voltage at 1800 r/min would be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

$$E_{A0} = \frac{1800\text{ r/min}}{1600\text{ r/min}} 400\text{ V} = 450\text{ V}$$

From the magnetization curve, this voltage would require a field current of $I_F =$ 6.15 A. The field circuit resistance would have to be

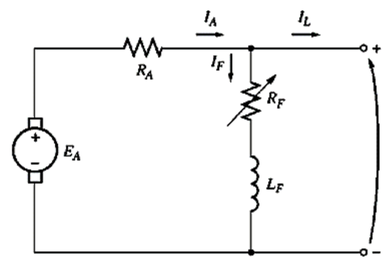
$$R_F + R_{adj} = \frac{V_F}{I_F}$$

$$20\ \Omega + R_{adj} = \frac{430\text{ V}}{6.15\text{ A}} = 69.9\ \Omega$$

$$R_{adj} = 49.9\ \Omega \sim 50\ \Omega$$

Shunt DC Generator

- A **shunt DC generator** is a **DC generator** that supplies its **own field current** by having its field **connected directly across the terminals of the machine**.
- **Shunt DC generator** has an **advantage** over the separately excited DC generator in that **no external power supply** is required for the field circuit.
- But there is a question: If the generator supplies its own field current, how does it get the **initial field flux** to start **when it is first turned on**?



$I_A = I_F + I_L$
$V_T = E_A - I_A R_A$
$I_F = \frac{V_T}{R_F}$

The simplified equivalent circuit of a shunt DC generator

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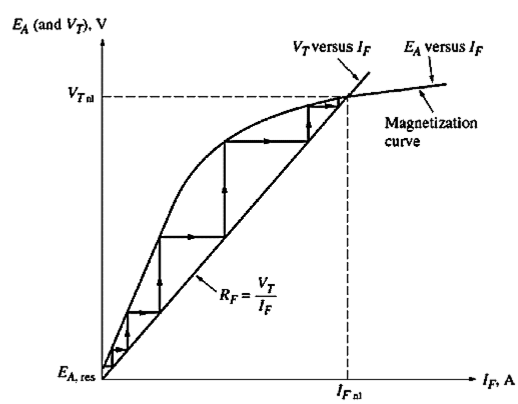
Voltage Buildup Mechanism in a Shunt DC Generator

- The **voltage buildup** in a **DC generator** depends on the presence of a **residual flux ($\emptyset_{res}$)** in the poles of the generator.
- When a generator **first** starts to turn, an **internal voltage** will be generated by means of **residual flux**:

$\boxed{E_A = K\phi_{res}\omega}$

(This voltage is normally very small 1-2 Volt)

- If residual flux **does not exist** in the DC generator than we have to **disconnect the field from the armature circuit** and **connect it directly** to an **external DC power source** such as a **battery**.
- This method is known as "**flashing the field**".



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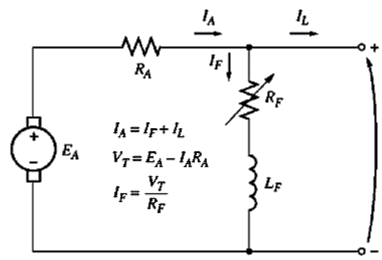
Terminal Characteristic of a Shunt DC Generator

- The **terminal characteristic** of a **shunt DC generator** differs from that of a **separately excited DC generator**, because the **amount of field current** in the machine **depends on** its **terminal voltage**.
- Assume that we start the DC machine without any load.
- Now as the **load** on the generator is increased, **line current** and **armature current** **increases**:

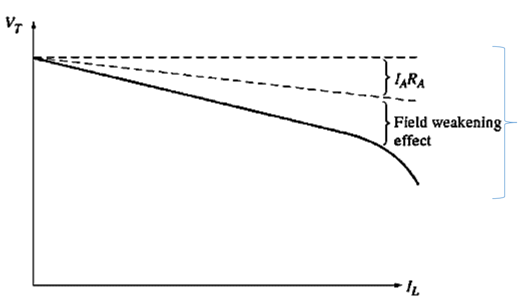
LOAD $\uparrow$ $I_L \uparrow$ $I_A \uparrow$ $R_A I_A \uparrow$ $V_T \downarrow = E_A - R_A I_A \uparrow$

- As **VT** **decreases**, **field current** and hence **flux** also **decreases**
- The **decrease** in **flux** **decreases** **armature voltage EA** and hence **VT** is **again** **decreased** by **flux reduction**.



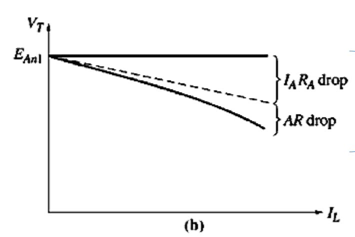
The simplified equivalent circuit of a shunt DC generator

Terminal Characteristic of a Shunt DC Generator



Voltage drop is BIG

The terminal characteristic of a ***shunt DC generator***



Voltage drop is SMALL

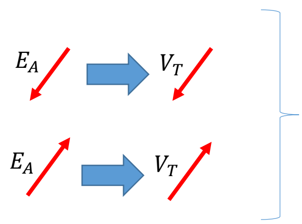
The terminal characteristic of a ***separately excited DC generator***

Voltage regulation of a **shunt DC generator** is **bigger** than the **voltage regulation** of a **separately excited DC generator**.

Voltage Control for a Shunt DC Generator

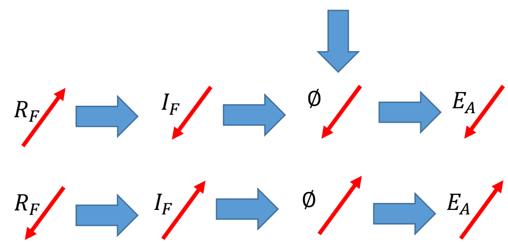
- The **voltage control** technique of a **shunt DC generator** is **same** as that of a **separately excited DC generator** in principle.

$$\boxed{V_T = E_A - I_A R_A}$$



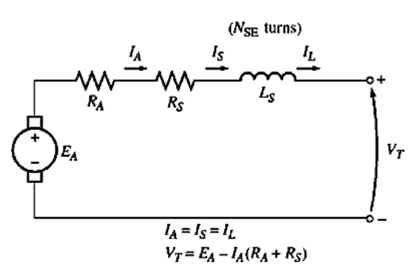
$$E_A = K\emptyset w$$

So we have two possibilities to control EA (**flux** and **speed**): Since, previously we assume that the **speed of the prime movers do not change so widely** (***assumed to be constant***), the only way to **control EA** is **to change flux** in the generator



The Series DC Generator

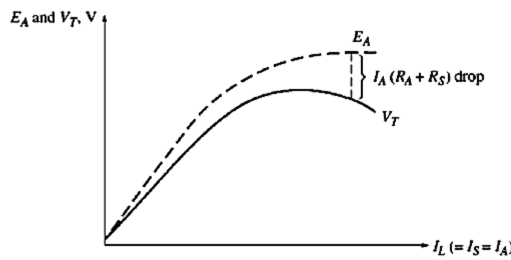
- A **series DC generator** is a **DC generator** whose **field** is connected **in series** with **its armature**.
- Since the **armature** has ***much* higher current** than that of **shunt field**, the **series field circuit** will have **only a very few turns of wire** to generate a sufficient amount of **MMF = Ns*Is**.
- The wire in **series field circuit** will be **much thicker** than the wire in a **shunt field circuit** **because of high current** .



The simplified equivalent circuit of a series DC generator

The Terminal Characteristic of a Series DC Generator

- At **No-load**, there is **no line current** and hence **no field current**; as a result **armature voltage** will be **very small** (*Because of any residual flux*)
- As the **load** is **increased**, **line current** and hence **field current rises**, so **armature voltage rises rapidly**.
- **Armature voltage** is always **greater** than **terminal voltage** because of the **voltage drop ➔ (RA + Rs).IA**.
- After a while, the machine approaches **saturation**, and **armature voltage** becomes **approximately constant**.
- After the **saturation point**, **voltage drop effect** becomes **very strong** and the **terminal voltage drops very fast**.

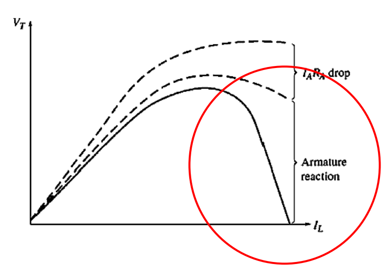


Terminal characteristic for a series DC generator

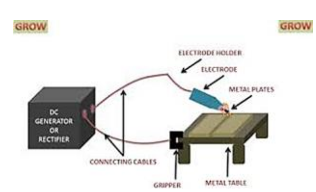
$$\boxed{V_T = E_A - I_A(R_A + R_S)}$$

The Terminal Characteristic of a Series DC Generator

- If **armature reaction** is **active** in the **series DC generator**, a **too much increase in load** will greatly **reduce** the **terminal voltage**, even approaching to **zero very fast**.
- **Series DC generators** are used **only** in a few specialized applications, such as **arc welding**.
- In **arc welding**, a **large armature reaction** is required as the one shown in the figure.
- Notice that when the **welding electrodes make contact** with each other before welding begins, a **very large current flows**.
- As the **operator separates** the **welding electrodes**, there is a **very steep rise in the generator 's voltage**, while the current remains high. This voltage ensures that **a welding arc is maintained** through the air between the electrodes.

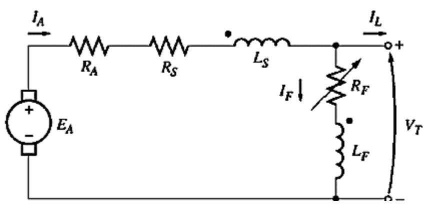


*A series DC generator terminal characteristic with **large armature reaction effects***



The Cumulatively Compounded DC Generator

- A **cumulatively compounded DC generator** is a **DC generator** with both **series** and **shunt fields**, connected so that the **MMF** from the two fields are **added** with each other.

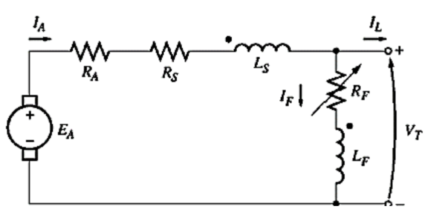


*The equivalent circuit of a cumulatively compounded DC generator with a **long-shunt connection***

The **dots** that appear on the two field coils have the same meaning as the dots on a transformer: Current flowing into a dot produces a **positive magnetomotive force**.

Long-shunt connection means that the **shunt field winding** is connected **in parallel** to the series combination of **armature** and **the series field winding**.

The Cumulatively Compounded DC Generator



*The equivalent circuit of a cumulatively compounded DC generator with a **long-shunt connection***

Long-shunt connection means that the **shunt field winding** is connected **in parallel** to the series combination of **armature** and **the series field winding**.

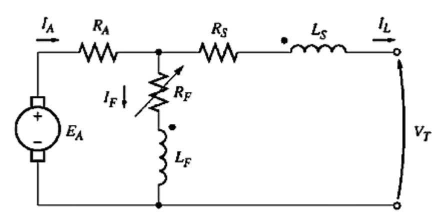
$$\boxed{I_A = I_F + I_L} \qquad \boxed{I_F = \frac{V_T}{R_F}}$$

$$\boxed{V_T = E_A - I_A(R_A + R_S)}$$

$$\boxed{\mathcal{F}_{net} = \mathcal{F}_F + \mathcal{F}_{SE} - \mathcal{F}_{AR}}$$

$$N_F I_F^* = N_F I_F + N_{SE} I_A - \mathcal{F}_{AR}$$

$$\boxed{I_F^* = I_F + \frac{N_{SE}}{N_F} I_A - \frac{\mathcal{F}_{AR}}{N_F}}$$



*The equivalent circuit of a cumulatively compounded DC generator with a **short-shunt connection***

Short-shunt connection means that the **shunt field winding** is only connected **in parallel** to the **armature**.

$$\boxed{I_A = I_F + I_L}$$

$$V_T = E_A - R_S I_A - R_S I_L$$

$$I_F = \frac{E_A - R_S I_A}{R_F}$$

$$\boxed{\mathcal{F}_{net} = \mathcal{F}_F + \mathcal{F}_{SE} - \mathcal{F}_{AR}}$$

$$N_F I_F^* = N_F I_F + N_{SE} I_L - \mathcal{F}_{AR}$$

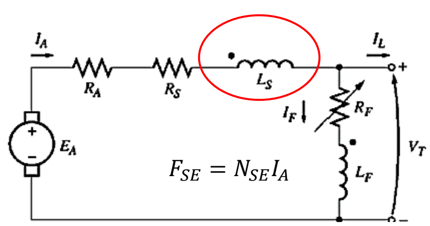
$$\boxed{I_F^* = I_F + \frac{N_{SE}}{N_F} I_L - \frac{\mathcal{F}_{AR}}{N_F}}$$

The Terminal Characteristic of a Cumulatively Compounded DC Generator

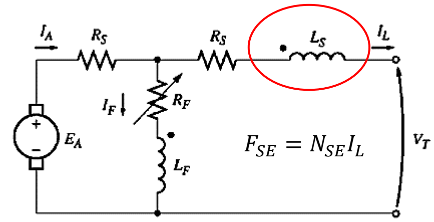
- Suppose that the **load** on the **cumulatively compounded DC generator** is increased.
- Then as the **load** **increases**, the **load (*line*) current** and **armature current** **increases too**.
- As **armature current** **increases** the **voltage drop** also **increases** and hence **terminal voltage** **decreases**:

$\boxed{V_T = E_A - I_A(R_A + R_S)}$ **(*long-shunt connection*)** **or** $V_T = E_A - R_S I_A - R_S I_L$ **(short-*shunt connection*)**

- Also as the **armature current** and **load current** **increases**, the **MMF** of the **series winding** also **increases**:



*The equivalent circuit of a cumulatively compounded DC generator with a **long-shunt connection***



*The equivalent circuit of a cumulatively compounded DC generator with a **short-shunt connection***

- The **increase** in **MMF of series winding** **increases** the **total MMF** in the machine and hence **EA** **increases**.
- As **EA** **increases**, **terminal voltage** tends to **increase** as well.

The Terminal Characteristic of a Cumulatively Compounded DC Generator

- So which effect is more stronger than another ?

V_T **or** V_T

- The answer depends on how much is the **MMF of the series field winding** **strong** or the **number of turns** **(N_{SE})** in the **series field winding** !

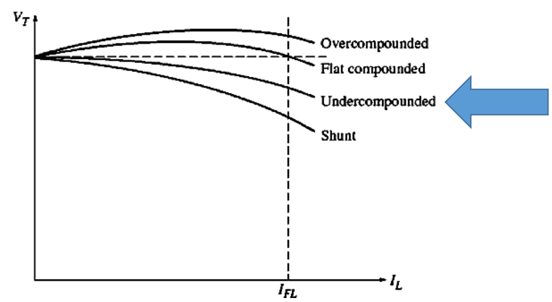
- **Three cases** will be considered:
  - **UNDER-COMPOUNDED CASE:** N_{SE} is **small** (There are a **few number of turns** in series field winding)
  - **FLAT-COMPOUNDED CASE:** N_{SE} is **larger** (There are **more number of turns** in series field winding)
  - **OVER-COMPOUNDED CASE:** N_{SE} is **much larger** (There are **much more number of turns** in series field winding)

The Terminal Characteristic of a Cumulatively Compounded DC Generator

- <u>**UNDER-COMPOUNDED CASE:**</u> N_{SE} is <u>**small**</u> (There are a <u>**few number of turns**</u> in series field winding)
  - In this case, **voltage drop** effect is <u>**much stronger**</u> than the **flux-strengthening effect**.
  - So **VT** <u>**decreases**</u> as **load** <u>**increases**</u>:

$LOAD \nearrow \quad V_T \swarrow$

The terminal characteristic is <u>**above**</u> the shunt DC generator terminal characteristics, since there is <u>**much flux**</u> in the compounded DC generator.



Terminal characteristics of cumulatively compounded DC generators for different number of turns in series field winding

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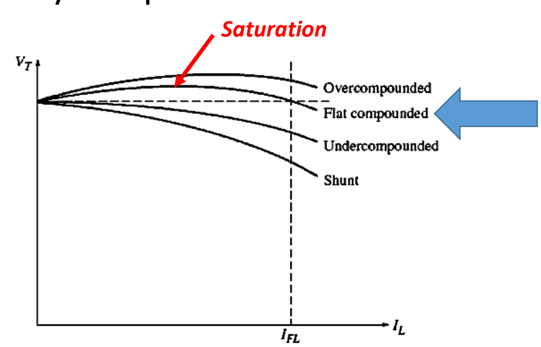
The Terminal Characteristic of a Cumulatively Compounded DC Generator

- <u>**FLAT-COMPOUNDED CASE:**</u> N_{SE} is <u>**larger**</u> (There are <u>**more number of turns**</u> in series field winding)
  - At first, the **flux-strengthening effect** <u>**wins**</u>, and the **terminal voltage** <u>**rises**</u> with the **load**.

$LOAD \nearrow \quad V_T \nearrow$ ***(Before Saturation)***

  - However, as the load continues to increase, **magnetic saturation** <u>**occurs**</u>, and after this point, the **resistive voltage drop** becomes <u>**stronger**</u> than the **flux increase effect**.
  - Then, the **terminal voltage** <u>**begins to fall**</u> as **load** <u>**increases**</u>.

$LOAD \nearrow \quad V_T \swarrow$ ***(After Saturation)***



Terminal characteristics of cumulatively compounded DC generators for different number of turns in series field winding

For Flat-Compounded DC generators:

VT at <u>**no load**</u> is **equal** to ***VT*** at <u>**full load**</u>

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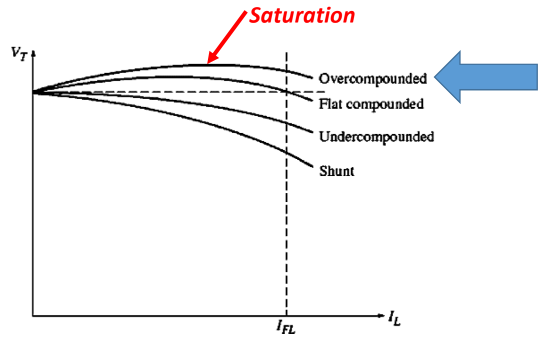
The Terminal Characteristic of a Cumulatively Compounded DC Generator

- **<u>OVER-COMPOUNDED CASE:</u>** N_{SE} is <u>much larger</u> (There are a **<u>much more number of turns</u>** in series field winding)
- This case is like **Flat-Compounded case**, but the **flux-strengthening effect** <u>predominates</u> **for a longer time** before the resistive drop takes over.
- At first, the **flux-strengthening effect** <u>**wins**</u>, and the **terminal voltage** <u>**rises**</u> with the **load**.

$LOAD \nearrow$ $\quad V_T \nearrow$ ***(Before Saturation)***

- After **saturation is reached**, the **resistive drop** becomes <u>**stronger**</u> than the **flux increase effect**.
- Then, the **terminal voltage** <u>**begins to fall**</u> as **load** <u>**increases**</u>.

$LOAD \nearrow$ $\quad V_T \swarrow$ ***(After Saturation)***



Terminal characteristics of cumulatively compounded DC generators for different number of turns in series field winding

For Over-Compounded DC generators:

VT at <u>**no load**</u> is **smaller than** to ***VT*** at <u>**full load**</u>

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Voltage Control of Cumulatively Compounded DC Generators

- The techniques available for controlling the terminal voltage of a **cumulatively compounded DC generator** are <u>**exactly the same**</u> as the techniques for controlling the terminal voltage of a **shunt DC generator**:

1) <u>Change the speed of rotation</u>:

$E_A = K\emptyset w \Rightarrow w \nearrow \Rightarrow E_A \nearrow \Rightarrow V_T \nearrow$

$E_A = K\emptyset w \Rightarrow w \swarrow \Rightarrow E_A \swarrow \Rightarrow V_T \swarrow$

2) <u>Change the field current</u>:

$R_F \nearrow \Rightarrow I_F \swarrow \Rightarrow \emptyset \swarrow \Rightarrow E_A \swarrow \Rightarrow V_T \swarrow$

$R_F \swarrow \Rightarrow I_F \nearrow \Rightarrow \emptyset \nearrow \Rightarrow E_A \nearrow \Rightarrow V_T \nearrow$

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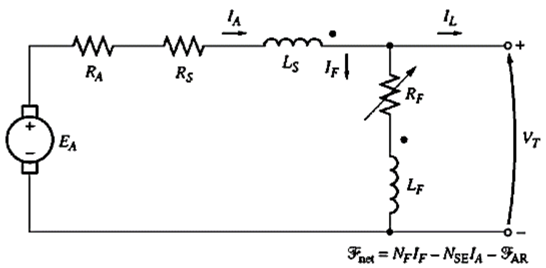
The Differentially Compounded DC Generator

- A **differentially compounded DC generator** is a **DC generator** with both shunt and series fields, but this time their **MMFs** **<u>subtract</u>** from each other.

- Like the **cumulatively compounded DC generator**, the **differentially compounded DC generator** can be connected in either **long-shunt** or **short-shunt** fashion.



$I_A = I_L + I_F$

$I_F = \dfrac{V_T}{R_F}$

$V_T = E_A - I_A(R_A + R_S)$

$$\boxed{\mathscr{F}_{net} = \mathscr{F}_F - \mathscr{F}_{SE} - \mathscr{F}_{AR}}$$

$$\boxed{\mathscr{F}_{net} = N_F I_F - N_{SE} I_A - \mathscr{F}_{AR}}$$

$$\boxed{I_F^* = I_F - \frac{N_{SE}}{N_F} I_A - \frac{\mathscr{F}_{AR}}{N_F}}$$

*The equivalent circuit of a differentially compounded DC generator with a **long-shunt connection***

The Terminal Characteristic of a Differentially Compounded DC Generator

- In the **differentially compounded DC generator**, the **voltage drop** and **flux-strengthening effect** were both present in the machine as in case of cumulatively compounded DC generator.

- But these **two effects** **<u>act</u>** in the **<u>same direction</u>**.

  - As **armature current (or LOAD)** **<u>increases</u>**, **voltage drop** **<u>increases</u>** as well. This will tend to **<u>decrease</u>** **terminal voltage**.

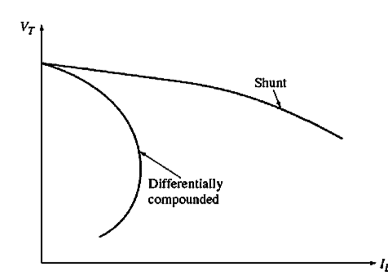
$LOAD \nearrow \qquad V_T \swarrow$

  - As armature current increases, the series MMF reduces the total MMF in the generator.

$\swarrow (\breve{\mathscr{F}}_{tot} = N_F I_F - N_{SE} I_A \uparrow),$

  - A **<u>decrease</u>** in **total MMF** and hence **total flux**, **<u>decreases</u>** also **terminal voltage**.

$F_{TOT} \swarrow \qquad V_T \swarrow$



The terminal characteristic of a differentially compounded DC generator

Self-study

- Solve **all problems** of Chapter 4 from Chapman

Review Questions

1) What is the speed regulation of a dc motor?
2) How can the speed of a shunt dc motor be controlled? Explain in detail.
3) What is the practical difference between a separately excited and a shunt dc motor?
4) What effect does armature reaction have on the torque-speed characteristic of a shunt dc motor? Can the effects of armature reaction be serious? What can be done to remedy this problem?
5) What are the desirable characteristics of the permanent magnets in PMDC machines?
6) What are the principal characteristics of a series dc motor? What are its uses?
7) What are the characteristics of a cumulatively compounded dc motor?
8) What are the problems associated with a differentially compounded dc motor?
9) What happens in a shunt dc motor if its field circuit opens while it is running?
10) Why is a starting resistor used in dc motor circuits?
11) How can a dc starting resistor be cut out of a motor's armature circuit at just the right time during starting?
12) What is the purpose of a field loss relay?
13) What types of protective features are included in typical solid-state dc motor drives? How do they work?
14) How can the direction of rotation of a separately excited dc motor be reversed?
15) How can the direction of rotation of a shunt dc motor be reversed?
16) How can the direction of rotation of a series dc motor be re versed?
17) Name and describe the features of the fi ve types of generators covered in this chapter.
18) How does the voltage buildup occur in a shunt dc generator during starting?
19) What could cause voltage buildup on starting to fail to occur? How can this problem be remedied?
20) How does armature react ion affect the output voltage in a separate ly excited dc generator?
21) What causes the extraordinarily fast voltage drop with increasing load in a differentially compounded dc generator?

END OF CHAPTER 4

DC MOTORS AND GENERATORS