METU EE462 Utilization of Electric Energy

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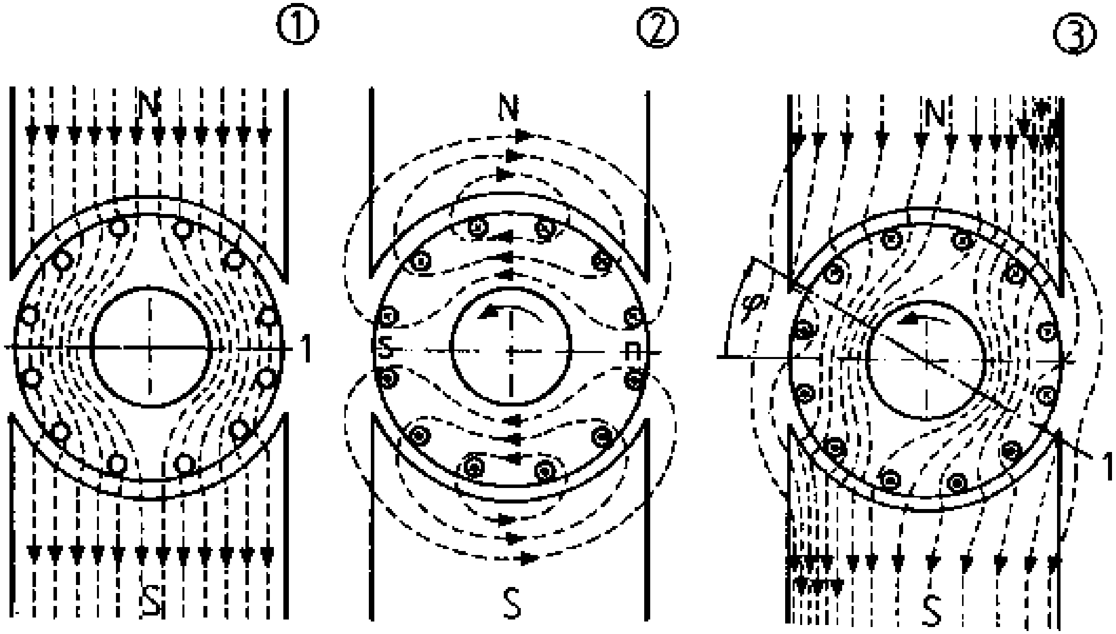
Content

DC machine drives

- Armature reaction
- Series wound DC machine & universal machine
- Operating limits of separately excited DC machines
- Dynamic behavior

Armature Reaction



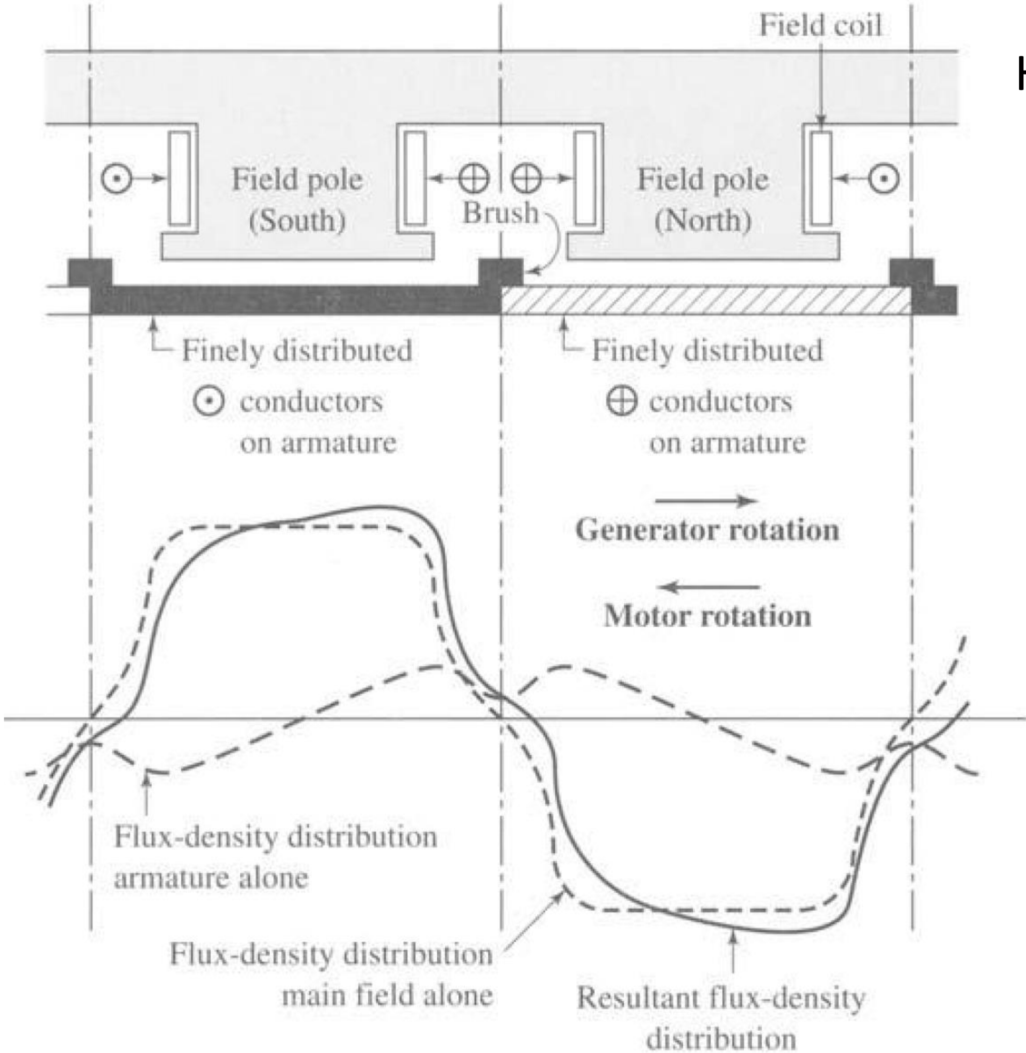
1. Magnetic field created by field winding
2. Magnetic field created by armature currents
3. Resultant magnetic field

Armature reaction will be there whenever we have armature current and it will change with the amount of the current. At open circuit, we do not have armature reaction.

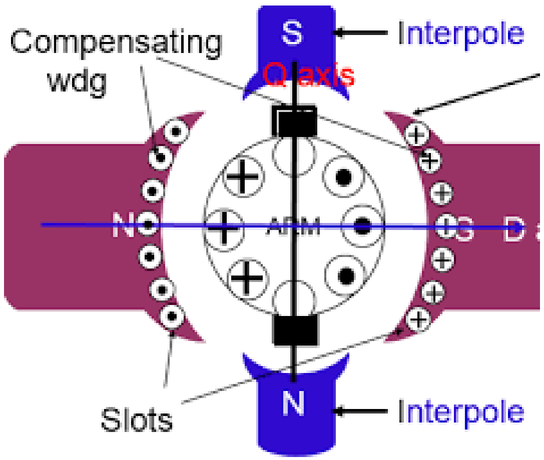
How is that going to affect characteristics of the DC machine?

- Machine constant decreases
- Commutation occurs at non-zero coil voltage.

Armature Reaction



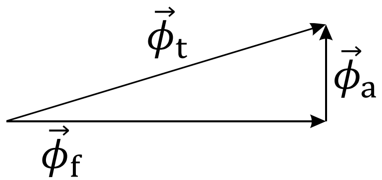
How can we compensate this?

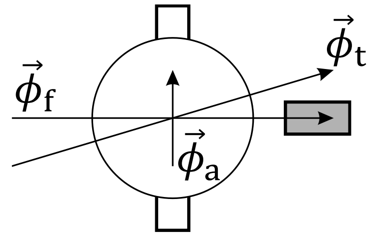


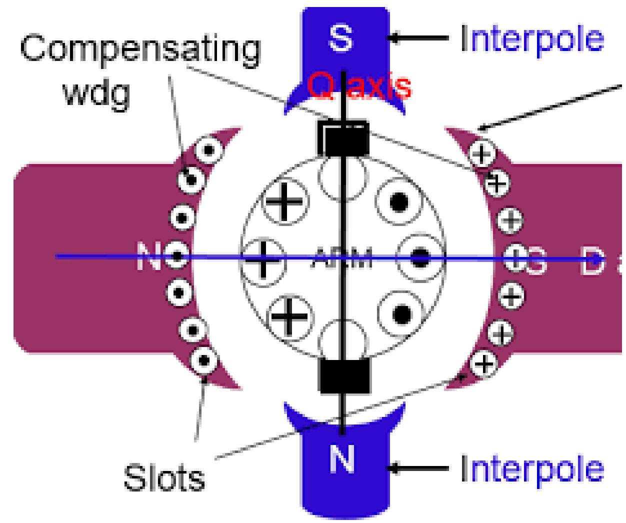
To avoid armature reaction, we insert compensating windings or interpoles.

Armature Reaction

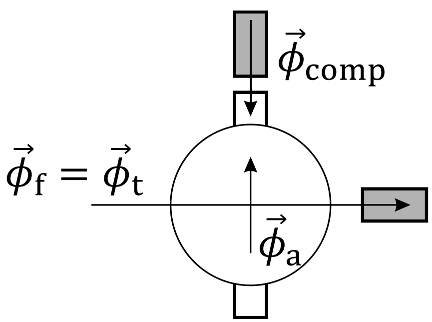
Space vector diagram:







With compensation winding:



$\vec{\phi}_f$: Field flux linkage

$\vec{\phi}_a$: Armature flux linkage

$\vec{\phi}_t$: Total flux linkage

$\vec{\phi}_{comp}$: Compensation flux linkage

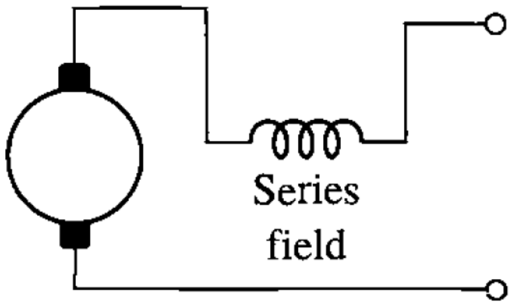
Compensating windings or interpole are required to avoid phase shift and a magnitude change of the flux. A flux change due to armature current indicates a change of magnetic stored energy indicating a large inductance. A major advantage of compensation winding is that armature has a smaller inductance.

Interpole winding: Sparking during compensation is decreased.

Compensation winding: Compensate the field of the armature winding.

Armature current flows through these windings and each of them produces a field opposing armature field.

Series Wound DC Machine



Field winding is connected series to armature:

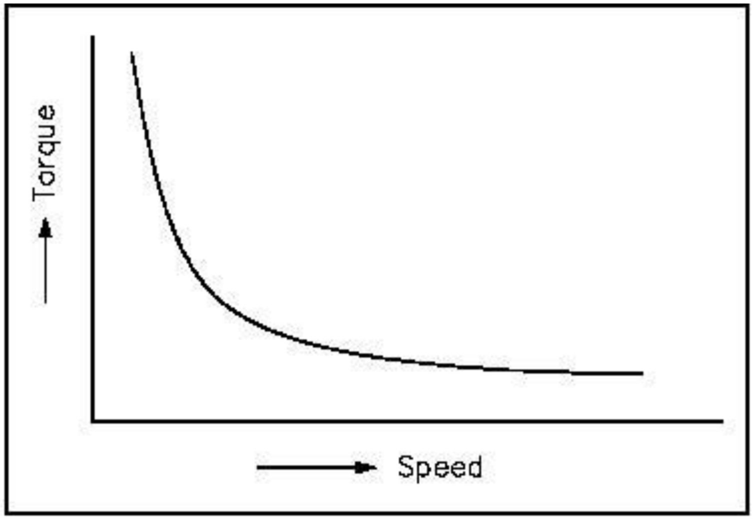
$I_a = I_f$

$V_t = (R_f + R_a) I_a + E_a$ (motoring)

$T_e = K_a \phi I_a$ where $\phi = K_f I_f = K_f I_a \Rightarrow T_e = K_a K_f I_a^2$

$E_a = K_a K_f I_a \omega_m$

=> $V_t = (R_f + R_a) I_a + K_a K_f I_a \omega_m$



High starting torque, so a series motor is suitable for cranes, electric trains and other applications require large starting torque.

Never run a DC series motor at no load (very low torque output)!

Series Wound DC Machine

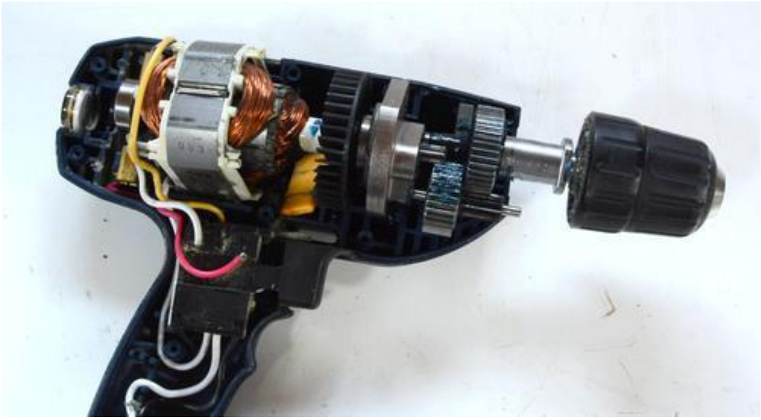
What happens if we supply a series excited DC motor with AC current?

Can we create a non-zero torque?

$T_e = K_a K_f I_a^2$

Since torque is related to square of the current, even with a sinusoidal excitation we get a net positive torque!

This kind of machines are called **universal machines**. Meaning that we can universally use them either with DC or AC supply.



How do Universal Motors work ?

Universal motor

Speed Control of DC Motors

What are your options, if you want to change the operating point?

- Vary the terminal voltage (V_t)
- Vary Field Current (I_f) (and hence flux)
- Vary Both

Armature Voltage Control

- Speed Control over a wide range
- Commonly used

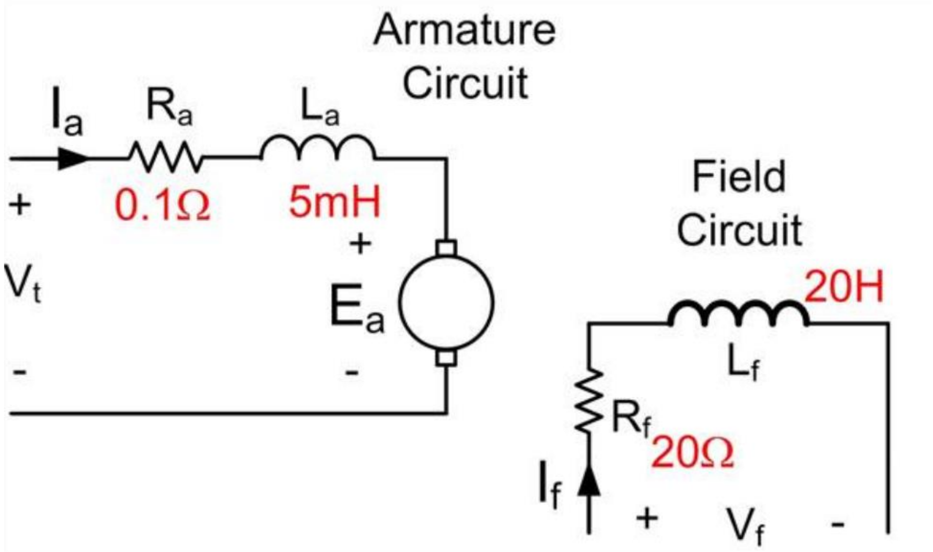
Field Current Control

An external resistor or variable voltage supply

- Usually used to achieve higher speeds -->Decrease I_f (Flux weakening)
- Speed control over a narrow range

Field Current Control

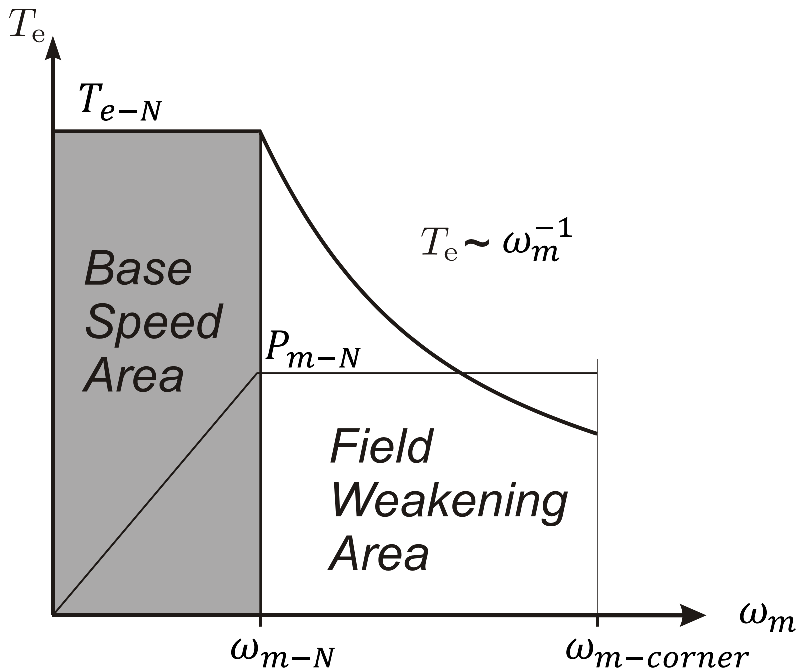
Which one is larger L_a or L_f?



$\tau_a = 50\ ms$ $\qquad$ $\tau_f = 1\ s$

Field current is easier to control due to low current values, but has a much higher electrical time constant -> slow response

Operating Limits



Can we operate beyond these limits?

	Overload capacity (with reference to P_N and n_N) for			
	motors without compensation		motors with compensation	
	Torque M_{max}/M_N	Current I_{max}/I_N	Torque M_{max}/M_N	Current I_{max}/I_N
15 s	1.6	~ 1.85	1.8	~ 1.85
5 s	1.8	~ 2.2	2.0	~ 2.1

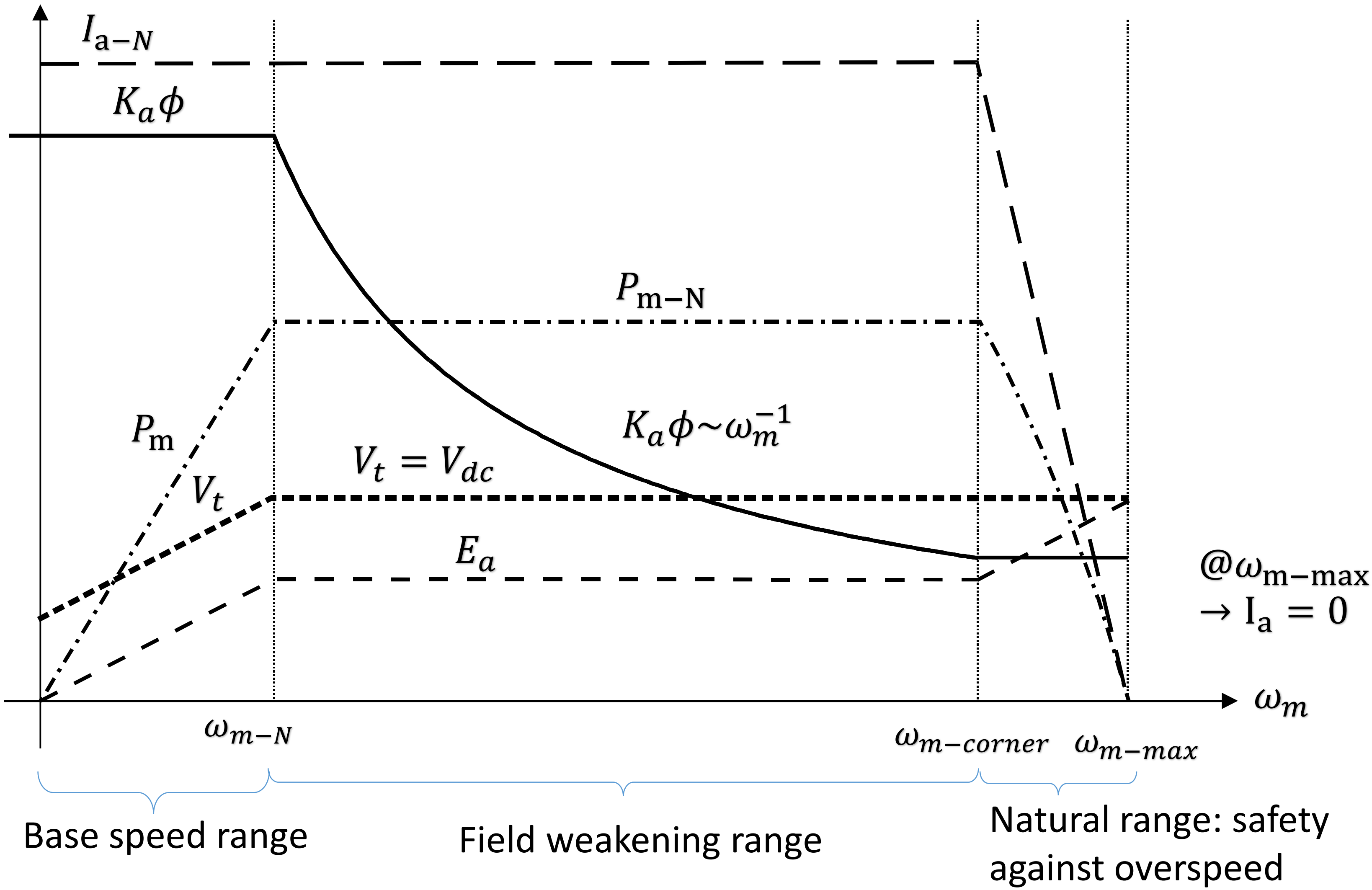
It is possible to achieve higher drive performance by exploiting overloading capacity

Base speed	Field weakening
- $K_a\phi$: constant	- $K_a\phi$: variable
- $T_e = T_{e-N}$: constant	- T_e: variable
- V_t: variable	- $V_t = V_{dc}$: constant
- P_m: variable	- $P_m = P_{m-N}$: constant

Subscript N stands for nominal, it can be also called rated value.

- V_t is limited (due to the rectifier, dc-link and insulation safety)
- $T_e \sim I_a$ and $\omega_m \sim E_a$
- $\omega_{m-N} \sim V_{dc}$
- To further increase ω_m the field has to be weakend ($\omega_m = \frac{E_a}{K_a\phi}$)
- $P_m = T_e\omega_m$

Operating Limits (Seperately Excited DC Machine)



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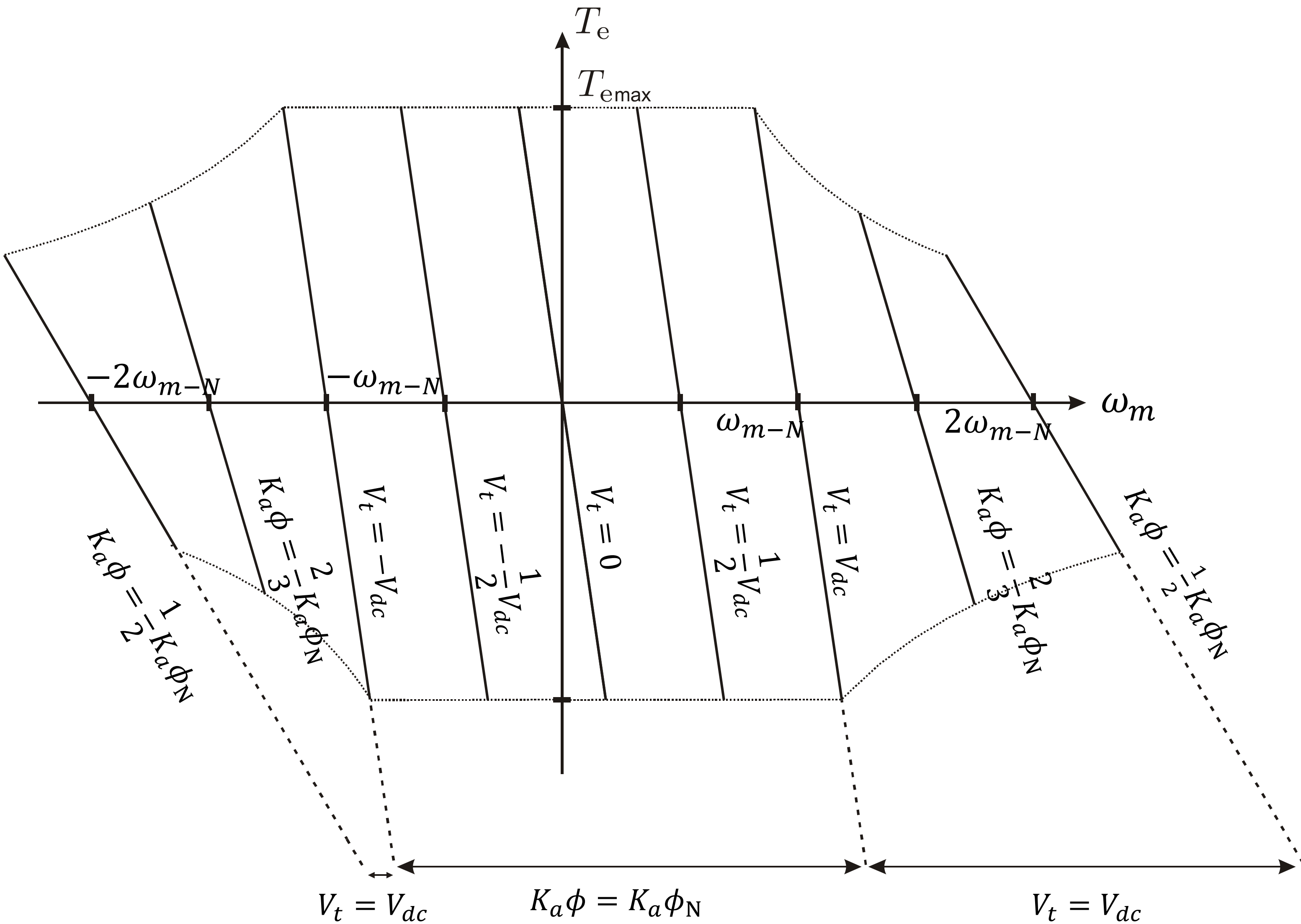


Dynamic Behavior

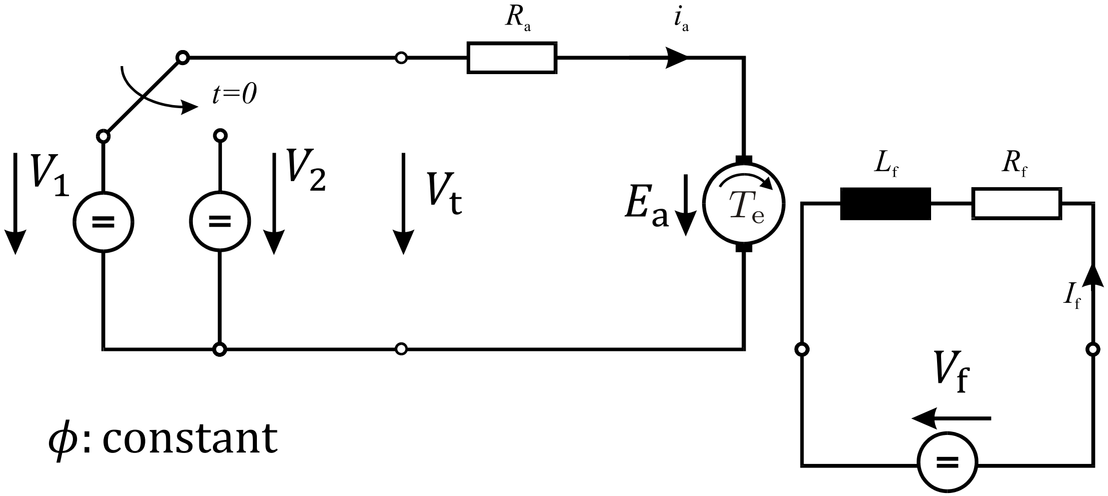
Assumptions:

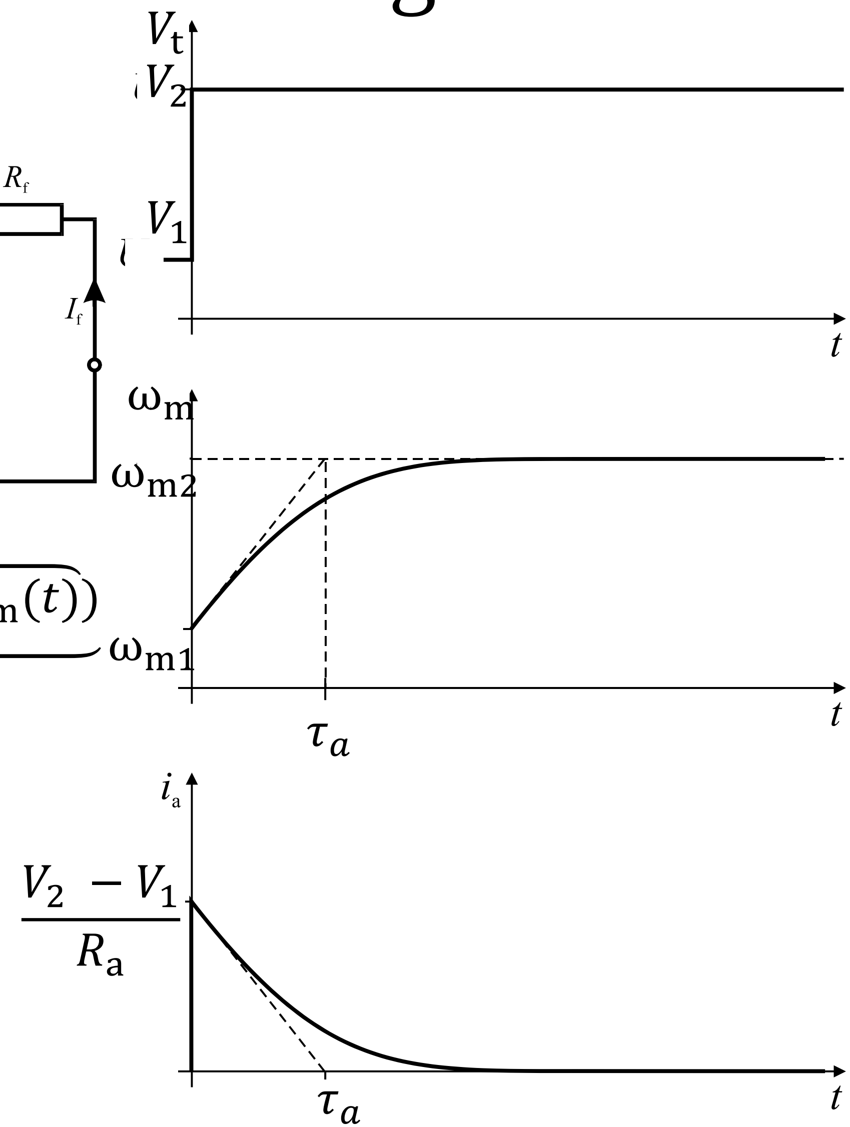
- Electrical time constants are much lower than mechanical time constants.
- Armature time constant is neglected, $L_a = 0$.
- No-load operation.

We are going to analyze and compare two dynamic responses:

1. Acceleration at constant voltage
2. Acceleration at constant current (torque)

1. Acceleration at Constant Voltage





ϕ: constant

$$\frac{\mathrm{d}\omega_\mathrm{m}(t)}{\mathrm{d}t} = \frac{1}{J}\underbrace{K_a\phi i_\mathrm{a}(t)}_{T_\mathrm{e}(t)} = \frac{1}{J}K_a\phi\underbrace{\frac{1}{R_\mathrm{a}}(V_\mathrm{t}(t) - \overbrace{K_a\phi\omega_\mathrm{m}(t)}^{E_a})}_{i_\mathrm{a}(t)}$$

$$\Rightarrow\ \frac{\omega_\mathrm{m}(s)}{V_t(s)} = \frac{\frac{1}{K_a\phi}}{\underbrace{\frac{JR_\mathrm{a}}{K_a^2\phi^2}}_{=\tau_a}\cdot s + 1}$$

$$\omega_\mathrm{m}(t) = \omega_\mathrm{m2} - (\omega_\mathrm{m2} - \omega_\mathrm{m1})\cdot \mathrm{e}^{-\frac{t}{\tau_a}}$$

$$i_\mathrm{a}(t) = \frac{V_2 - V_1}{R_\mathrm{a}}\cdot \mathrm{e}^{-\frac{t}{\tau_a}}$$

1. Acceleration at Constant Voltage

Change of the kinetic energy:

$$\Delta W_{\mathrm{kin}} = \frac{J}{2}(\omega_{\mathrm{m2}}^2 - \omega_{\mathrm{m1}}^2)$$

Injected electrical energy:

$$\Delta W_{el} = \int_{t(\omega_{\mathrm{m1}})}^{t(\omega_{\mathrm{m2}})} V_2 i_{\mathrm{a}}(t)\,\mathrm{d}t = \int_{\omega_{\mathrm{m1}}}^{\omega_{\mathrm{m2}}} J \underbrace{\frac{V_2}{K_a \phi}}_{\omega_{\mathrm{m2}}}\,\mathrm{d}\omega_{\mathrm{m}}$$

$$= J\omega_{\mathrm{m2}}(\omega_{\mathrm{m2}} - \omega_{\mathrm{m1}})$$

Loss energy (converted to thermal energy in $\boldsymbol{R}_{\mathbf{a}}$):

$$\Delta W_{\mathrm{loss}} = \Delta W_{\mathrm{el}} - \Delta W_{\mathrm{kin}} = \frac{J}{2}\left(\omega_{\mathrm{m2}} - \omega_{\mathrm{m1}}\right)^2$$

1. Acceleration at Constant Current (Torque)

$$\frac{\mathrm{d}\omega_{\mathrm{m}}(t)}{\mathrm{d}t} = \frac{T_{\mathrm{e}}}{J} = \frac{K_a\phi \cdot I_{\mathrm{a}}}{J}$$

$$\omega_{\mathrm{m}}(t) = \int \frac{R_{\mathrm{a}} I_{\mathrm{a}}}{K_a\phi}\frac{1}{\tau_a}\mathrm{d}t = \frac{R_{\mathrm{a}} I_{\mathrm{a}}}{K_a\phi}\frac{t}{\tau_a} + \omega_{\mathrm{m1}}$$

$$v_{\mathrm{t}}(t) = K_a\phi\omega_{\mathrm{m}}(t) + R_{\mathrm{a}} I_{\mathrm{a}}$$

$$= \underbrace{K_a\phi\omega_{\mathrm{m1}}}_{e_{\mathrm{a}}(\omega_{\mathrm{m1}})} + \underbrace{R_{\mathrm{a}} I_{\mathrm{a}}\frac{t}{\tau_a}}_{u_{\mathrm{e}}(t)} + \underbrace{R_{\mathrm{a}} I_{\mathrm{a}}}_{\text{voltage to drive } I_{\mathrm{a}}}$$

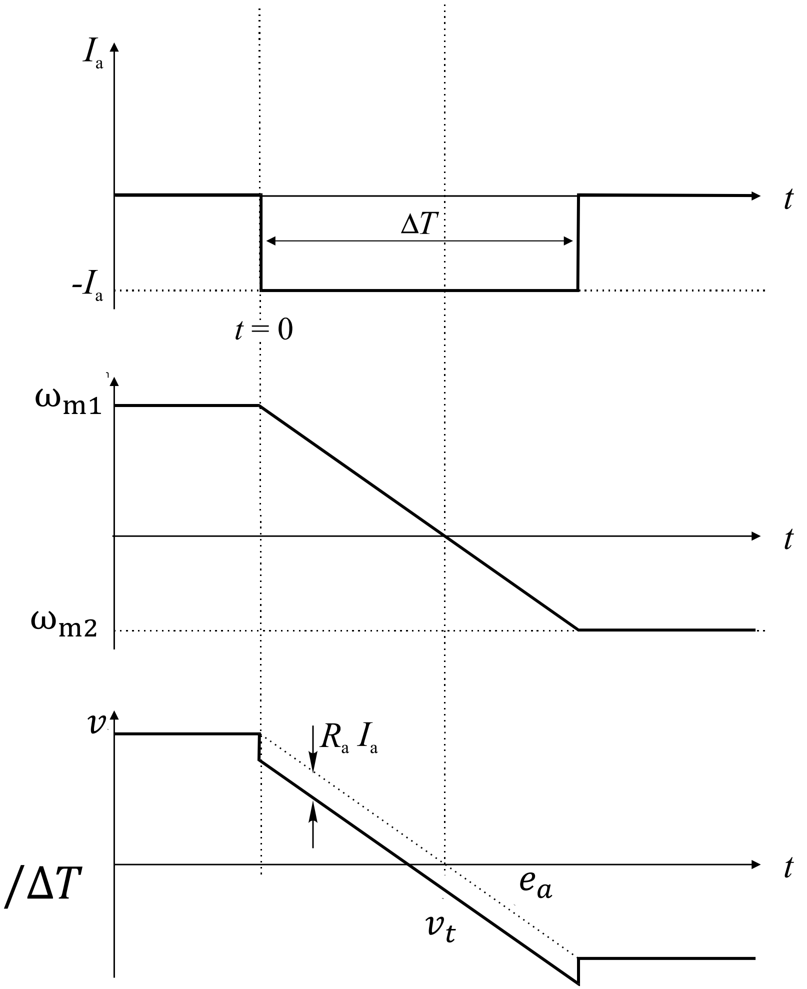
Injected electrical energy:

$$\Delta W_{\mathrm{el}} = \int_{\omega_{\mathrm{m1}}}^{\omega_{\mathrm{m2}}} (K_a\phi\omega_{\mathrm{m}} + R_{\mathrm{a}} I_{\mathrm{a}}) \frac{J}{K_a\phi}\,\mathrm{d}\omega_{\mathrm{m}}$$

$$= \frac{J}{2}(\omega_{\mathrm{m2}}^2 - \omega_{\mathrm{m1}}^2) + J\frac{R_{\mathrm{a}} I_{\mathrm{a}}}{K_a\phi}(\omega_{\mathrm{m2}} - \omega_{\mathrm{m1}})$$

Loss energy:

$$\Delta W_{\mathrm{loss}} = J\frac{R_{\mathrm{a}} I_{\mathrm{a}}}{K_a\phi}(\omega_{\mathrm{m2}} - \omega_{\mathrm{m1}}) = J(\omega_{\mathrm{m2}} - \omega_{\mathrm{m1}})^2\tau_a/\Delta T$$



Armature current and voltage represented for a speed reversal process

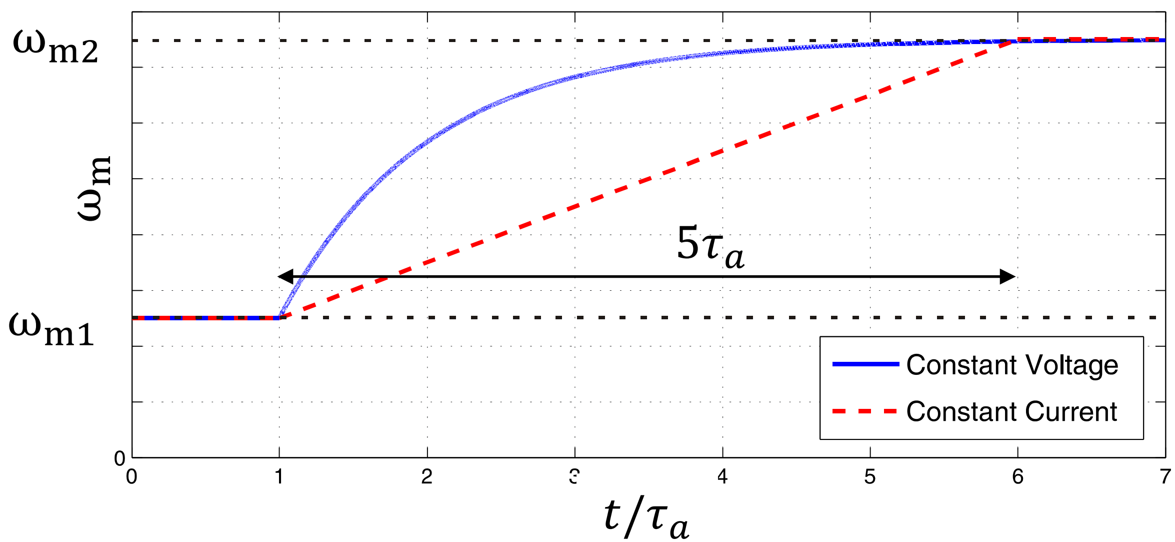
Dynamic Behavior

Assume speed change in $5\tau_a$ with current control:

Voltage Control: $\omega_m(t) = \omega_{m2} - (\omega_{m2} - \omega_{m1})\ e^{-\frac{t}{\tau_a}}$ with $\omega_m(5\tau_a) \approx \omega_{m2}$

Current Control: $\omega_m(t) = \omega_{m1} + \frac{R_a I_a}{k\psi_f}\frac{t}{\tau_a}$ with $I_a = \frac{K_a\phi}{R_a}(\omega_{m2} - \omega_{m1})\frac{\tau_a}{5\tau_a}$

Operation Mode	ΔW_{kin}	ΔW_{loss} (voltage control)	ΔW_{loss} (current control)
Start: $0 \rightarrow \omega_m$	$\frac{1}{2}J\omega_m^2$	$\frac{1}{2}J\omega_m^2$	$\frac{1}{5}J\omega_m^2$
Reverse: $+\omega_m \rightarrow -\omega_m$	0	$2J\omega_m^2$	$\frac{4}{5}J\omega_m^2$



- Speed change with low loss can be realized by controlling current (torque). Therefore, dc machines are generally operated with current control.

Discussion:

Materials used in DC machines

What kind of magnetic material is used in rotor and stator cores?