THE EUROPEAN SCHOOL ON MAGNETISM

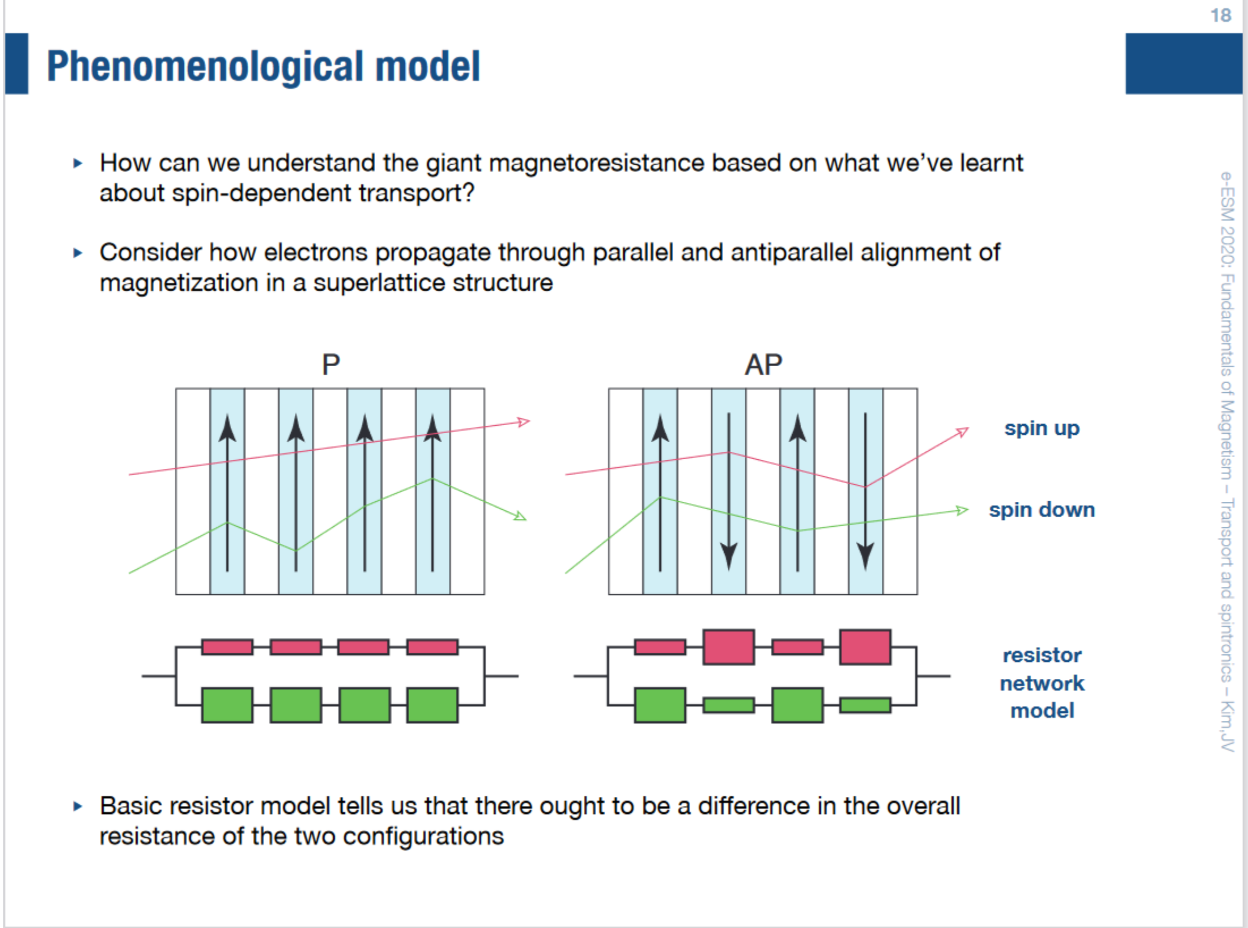
MAGNETIC ENERGY AND CIRCUITS

R&D and Large Volume Production of Electrical Drives Systems

AE Group; Industrieweg 78; 5145PW Waalwijk; The Netherlands ; www.ae-grp.nl; info@ae-grp.nl

BACKGROUND MATERIAL

- Resistor network….
  - It is actually an electrical equivalent circuit
- Lecture 1
  - Explanation of magnetic equivalent circuit
  - Energy from electrical via magnetic to electrical, while producing torque
  - Some basics about flux (or better said equipotential contours)



PERSONAL INFO

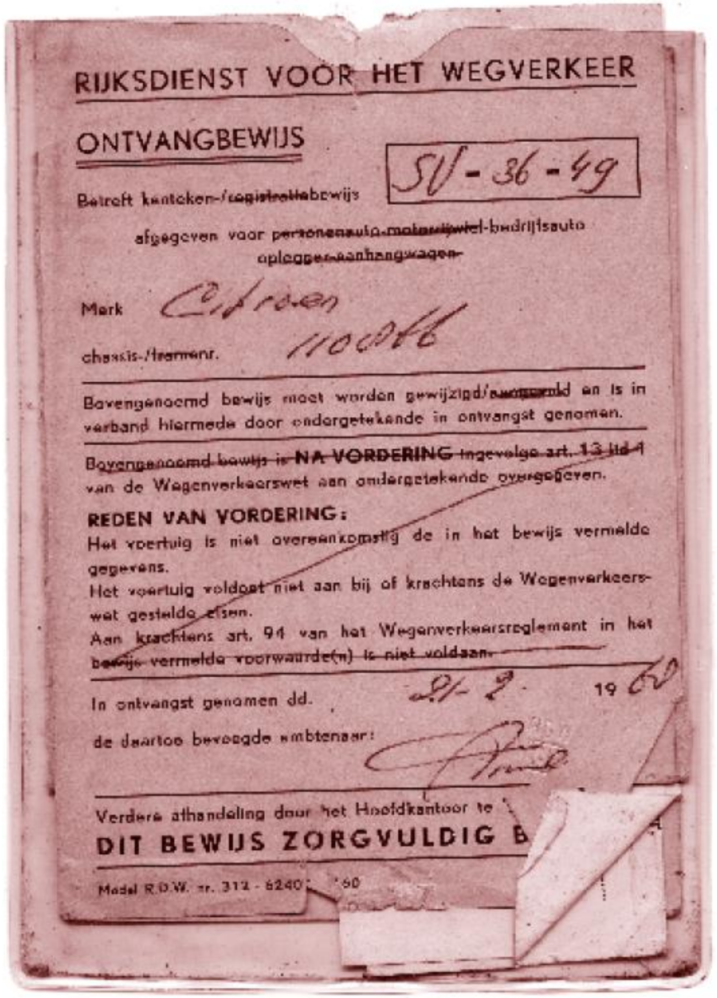
- Johan Paulides
  - Johannes Jacobus Hubertus Paulides
  - Owner of the AE Group; Industrieweg 78; 5145PW Waalwijk; www.ae-grp.nl; info@ae-grp.nl

Family owned businessman, third generation. Established in 1938.

MPhil and PhD in electric machine and drives group from Sheffield, a large and highly ranked university group on electrical drives in the world. Followed by 12.5 years in various roles at Eindhoven University of Technology, subject more sustainable society (includes automotive).

Owner of AE Group a number of companies related to design and manufacturing of electrical drives. Author of more than 150 papers and numerous patents, organizer and invited speaker at a variety of conferences related to electrical machines and drives, from medical, robotics to automotive topics.

80+ YEARS EXPERIENCE - FIRST VEHICLE CONVERSION (1968)


RIJKSDIENST VOOR HET WEGVERKEER

ONTVANGBEWIJS

SV-36-49

Betreft kenteken-/~~registratie~~bewijs

afgegeven voor ~~personenauto-motorrijwiel~~-bedrijfsauto ~~oplegger-aanhangwagen~~

Merk Citroen

chassis-/~~framen~~r. 110066

Bovengenoemd bewijs moet worden gewijzigd/~~vernieuwd~~ en is in verband hiermede door ondergetekende in ontvangst genomen.

~~Bovengenoemd bewijs is NA VORDERING ingevolge art. 13 lid 1 van de Wegenverkeerswet aan ondergetekende overgegeven.~~

~~REDEN VAN VORDERING:~~

~~Het voertuig is niet overeenkomstig de in het bewijs vermelde gegevens.~~

~~Het voertuig voldoet niet aan bij of krachtens de Wegenverkeerswet gestelde eisen.~~

~~Aan krachtens art. 91 van het Wegenverkeersreglement in het bewijs vermelde voorwaarde(n) is niet voldaan.~~

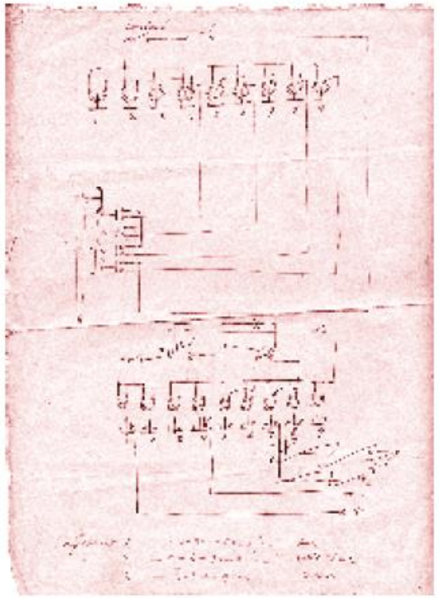
In ontvangst genomen dd. 21-2 1960

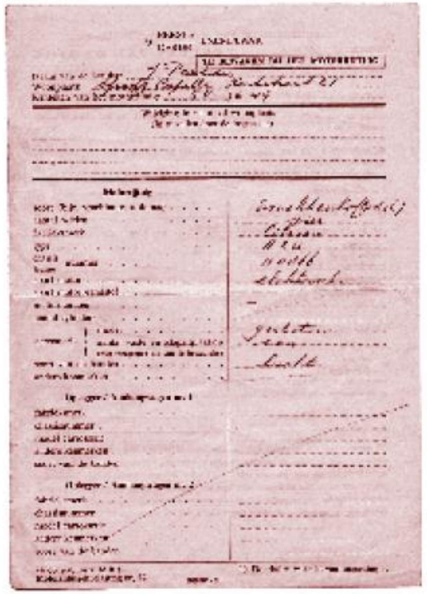
de daartoe bevoegde ambtenaar:

Verdere afhandeling door het Hoofdkantoor te

DIT BEWIJS ZORGVULDIG B

Model R.D.W. nr. 312 - 6240 - '60





Elektrische auto

Op dit moment is er een steeds grotere commerciële vraag naar zuinige hybride voertuigen (b.v. Toyota Prius, Honda Civic, etc.), maar al in de zeventiger jaren reed er in Sprang-Capelle een omgebouwde Citroen met een 48VDC motor. Hierin waren vier vrachtwagen accu's ingebouwd welke allemaal in parallel (12VDC), serie-parallel (24VDC) of in serie (48VDC) geschakeld konden worden d.m.v. start relais. Deze werden ingeschakeld door een driestanden gaspedaal. Ook de versnellingsbak was nog aanwezig, daardoor er vooraf gekozen kon worden hoe snel men wilde rijden (max 70km/uur) al kostte dat dan wel actieradius.

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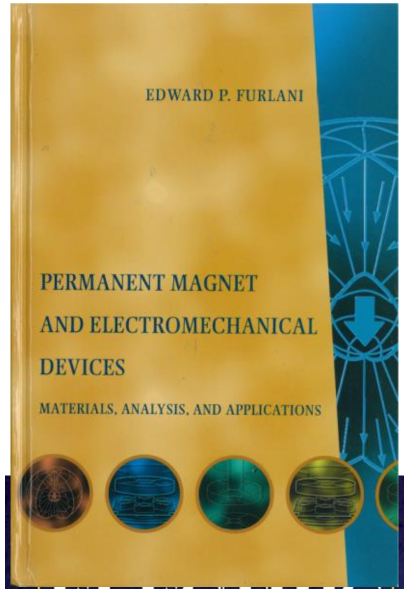
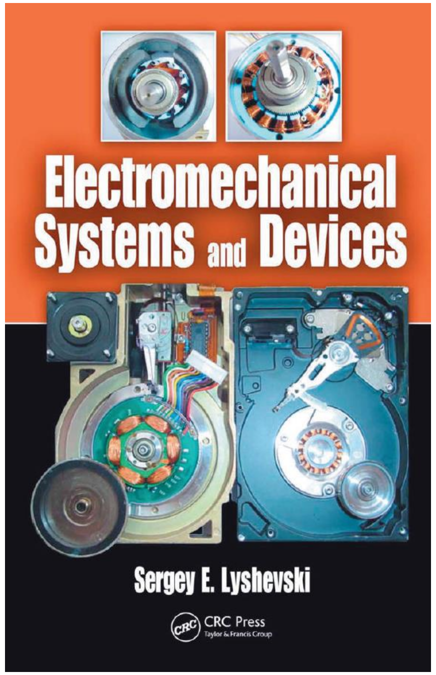
E-MACHINES R&D AND PRODUCTION

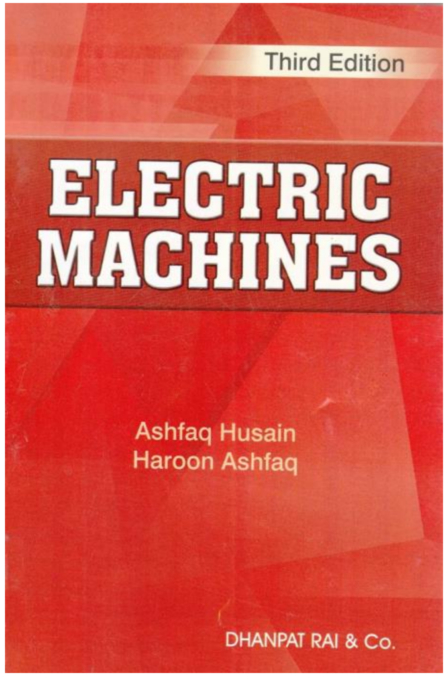
USED MATERIAL

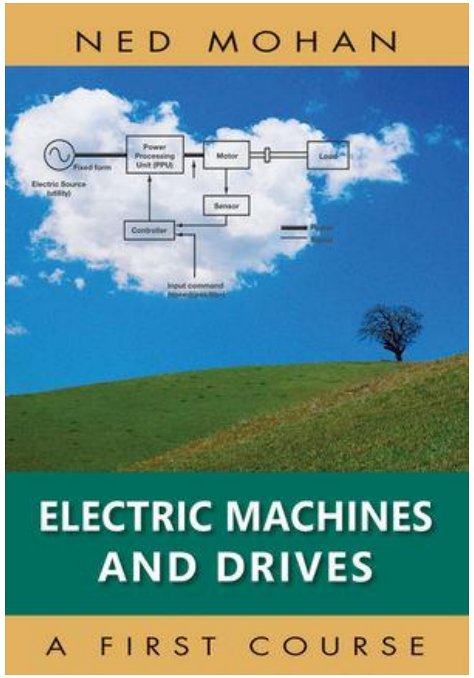
Various slides: Yang Tang, Helm Jansen, and others
All from Eindhoven University of Technology

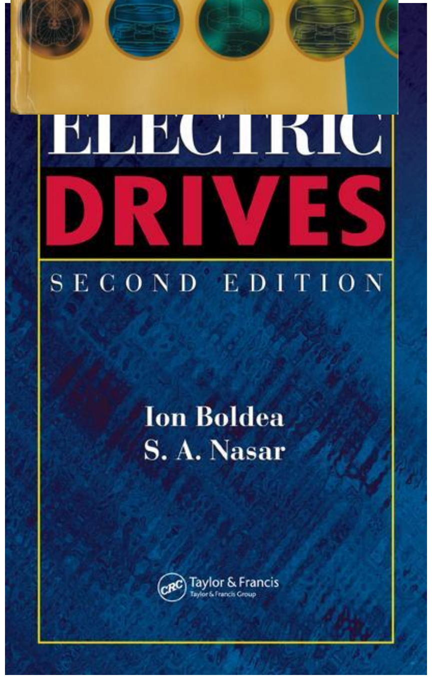
ISBN 0122699513











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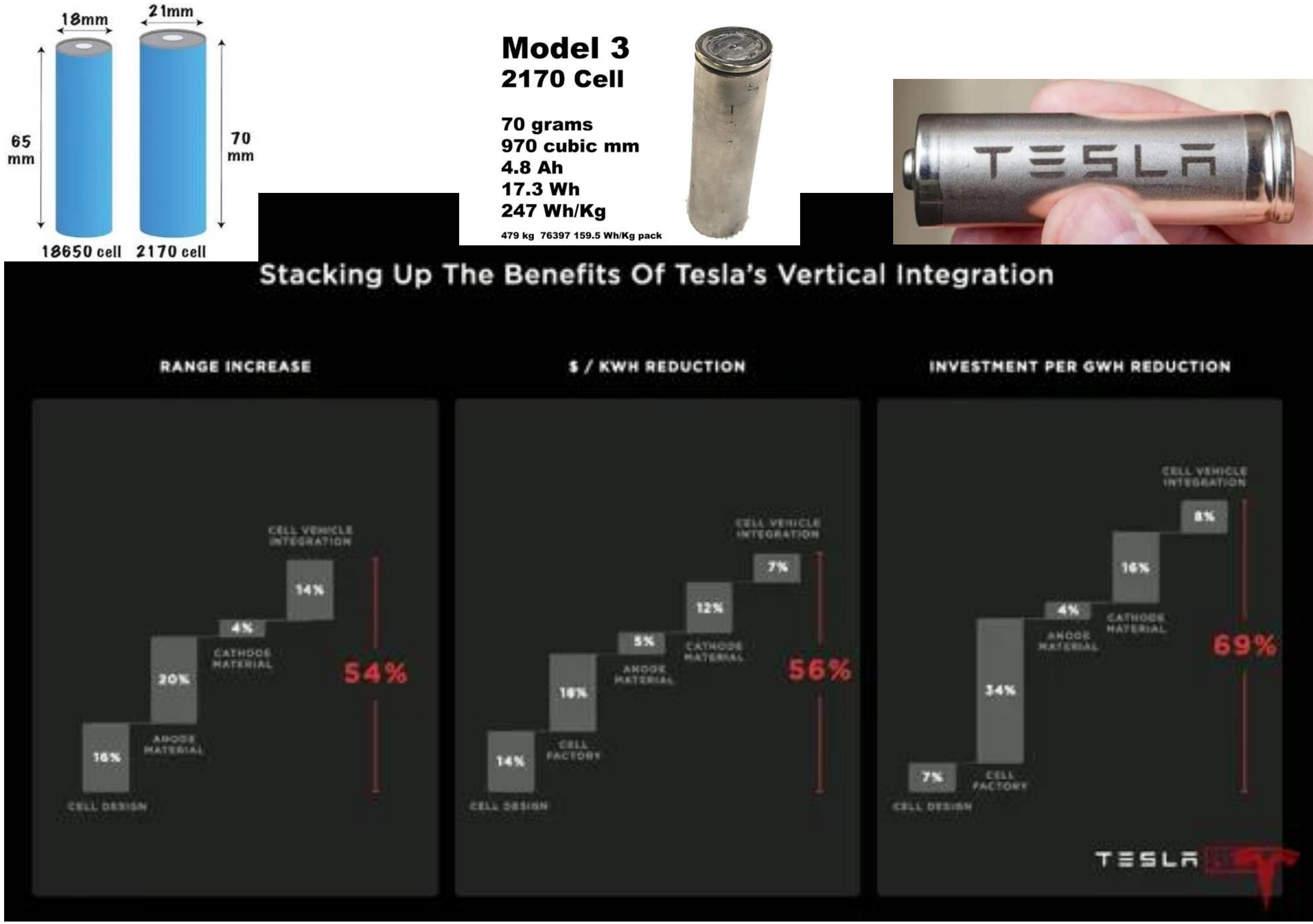
NOT NEW - 1907 – EV MARKET SHARE 30%

ELECTRIC MOBILITY IS NOW ALL AROUND (LONGEST RANGE VEHICLES)

BATTERIES ARE TO DATE (THE) KEY FOR ALL ELECTRIC MOBILITY

What to expect 2022 to 2023

- Especially for small mass and volume critical vehicles
- 250 Wh/kg to 400 Wh/kg
- 5x more capacity per cell
- 6x more power output from 4680 cell (diameter 46 mm, length 80 mm instead of 2170 cell, 21 mm diameter, length 70 mm)
- Costs per kWh "tank content" reduced with 50%



BATTERIES ARE TO DATE (THE) KEY FOR ALL ELECTRIC MOBILITY

BATTERIES ARE TO DATE (THE) KEY FOR ALL ELECTRIC MOBILITY

BATTERIES SWAPPING OR CHARGING

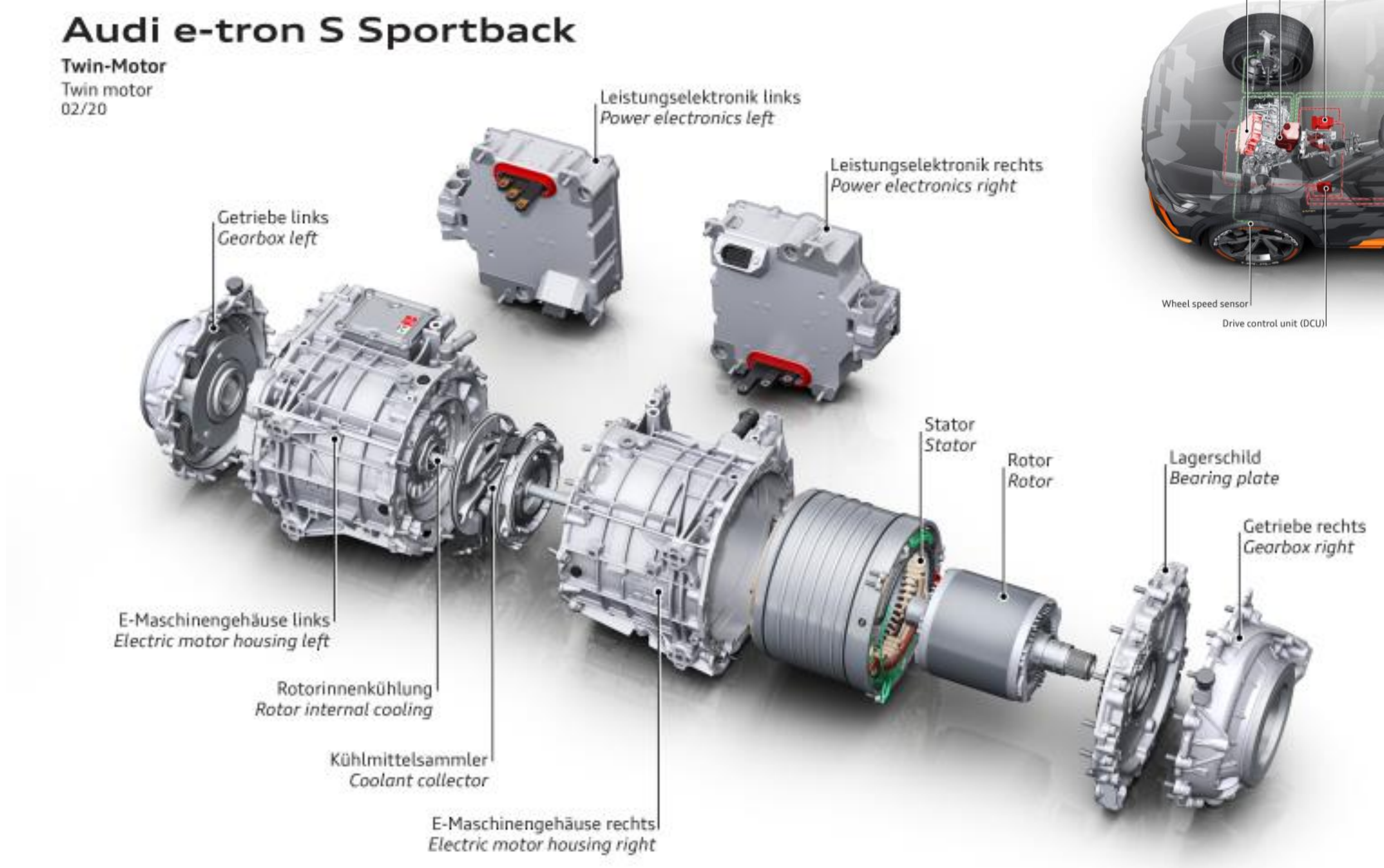
FUTURE CHARGING INFRASTRUCTURE … IS THIS THE FUTURE…

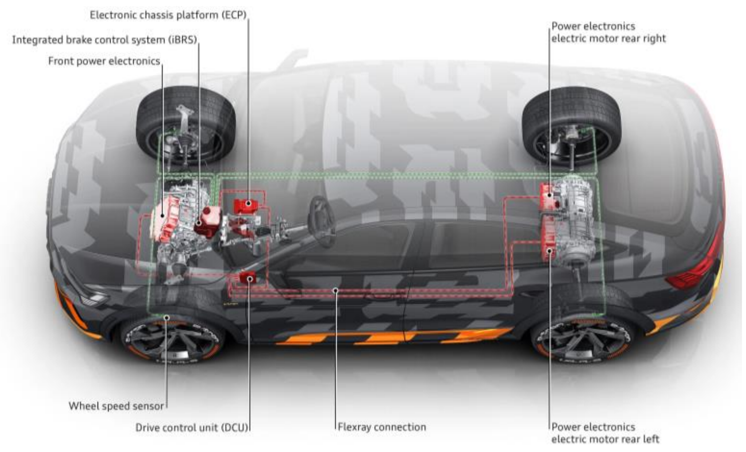
ON ROAD CHARGING... LIKE TRAINS

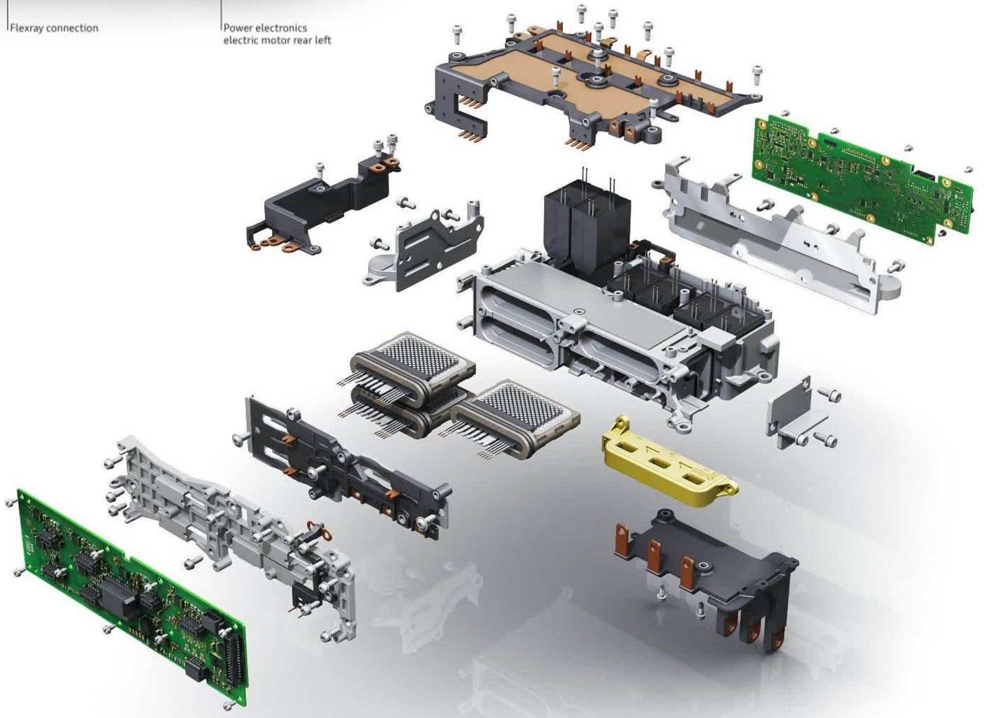
CHARGING WILL BE KEY FOR FUTURE CITIES

ELECTRIC POWERTRAIN WITH MAGNETIC COMPONENTS

ELECTRIC DRIVE (POWERTRAIN) WITH MAGNETIC COMPONENTS







ELECTRIC DRIVE (POWERTRAIN) WITH MAGNETIC COMPONENTS

- ✓ High torque
- ✓ Wide speed range
- ✓ Light, robust, cheap

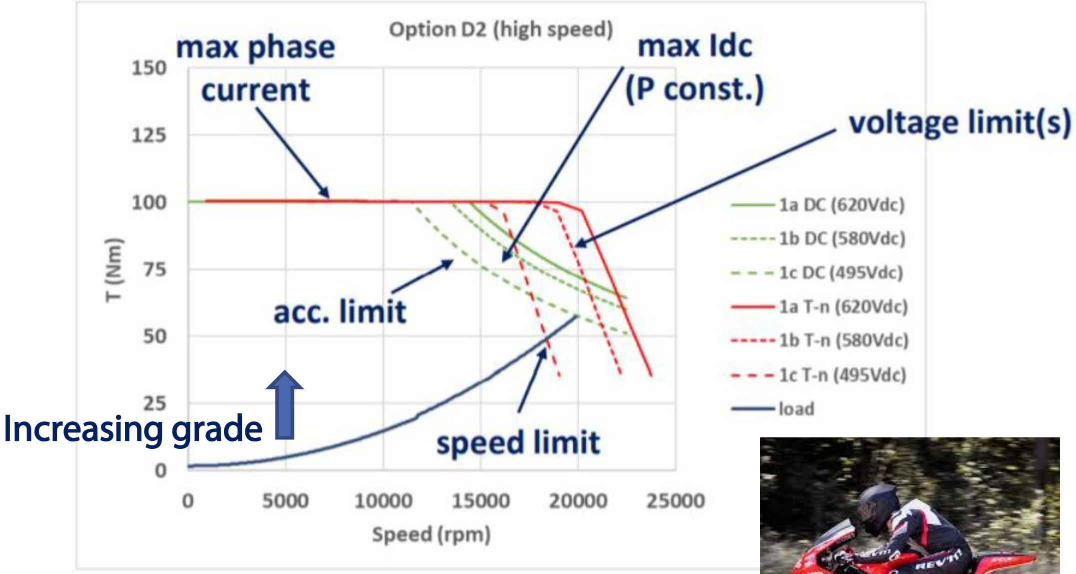
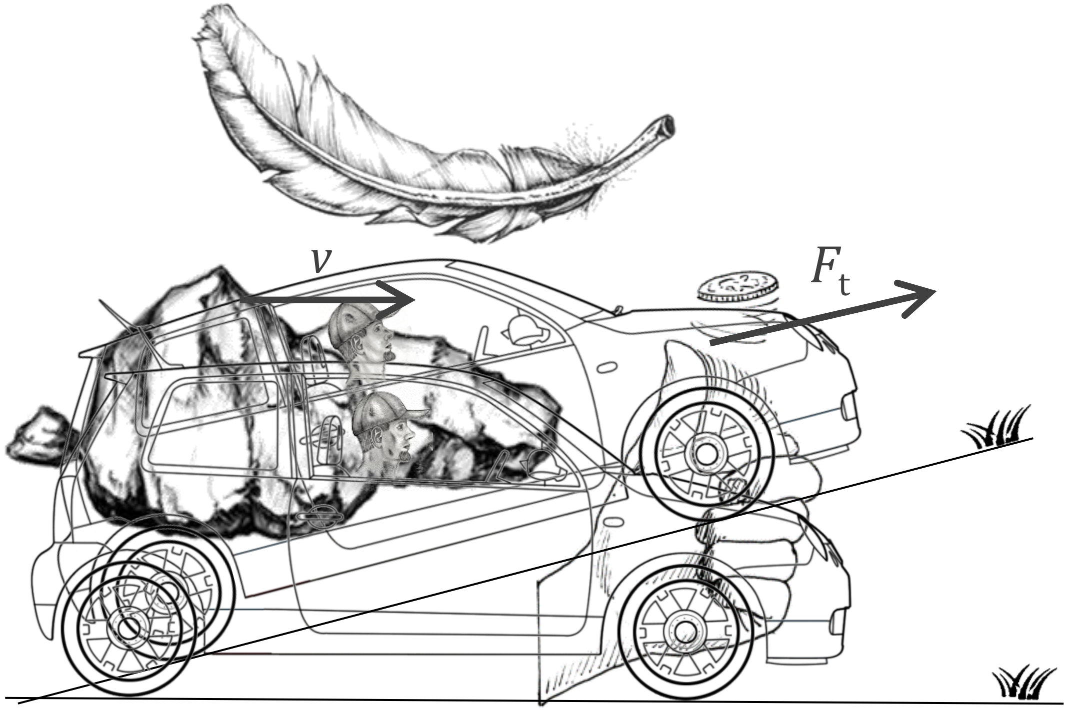
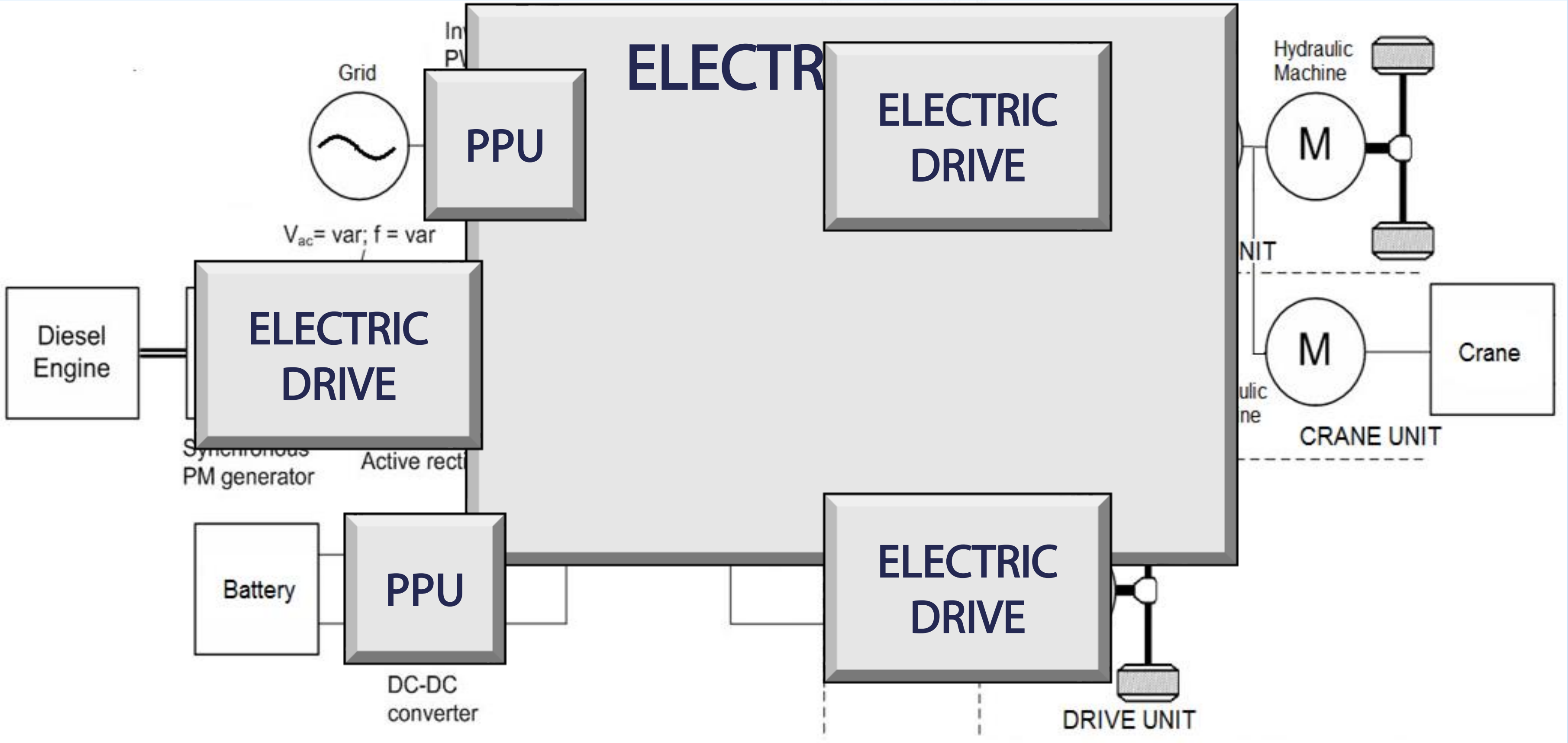


Figure 1: expected motor behavior

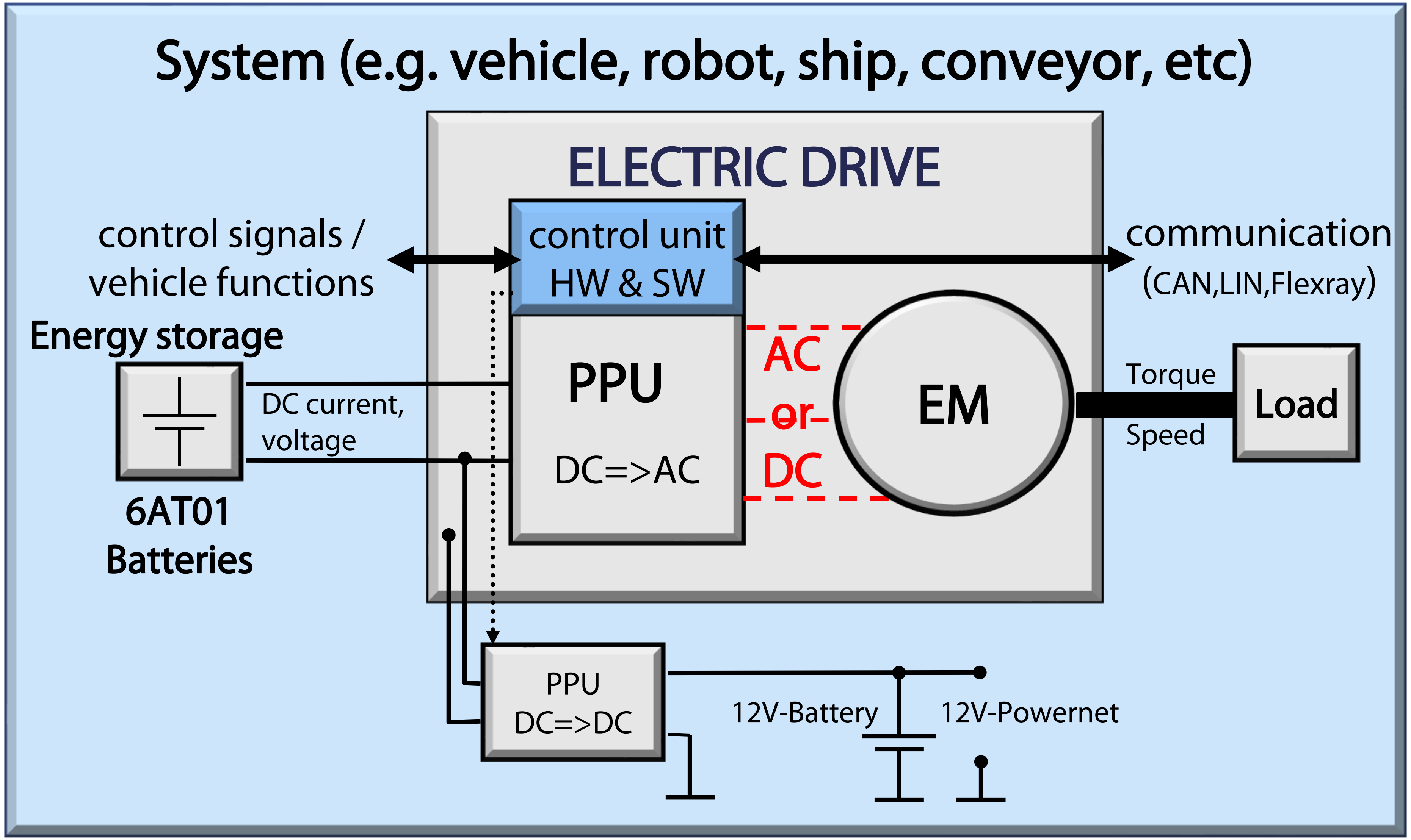


ELECTROMAGNETISM IN ROTATING EQUIPMENT

Powertrain (e.g. vehicle, robot, ship, conveyor, etc)



ADJUSTABLE/VARIABLE SPEED DRIVES



3-PHASE AC CURRENT AND SINGLE PHASE EQUIVALENT

Conditions:

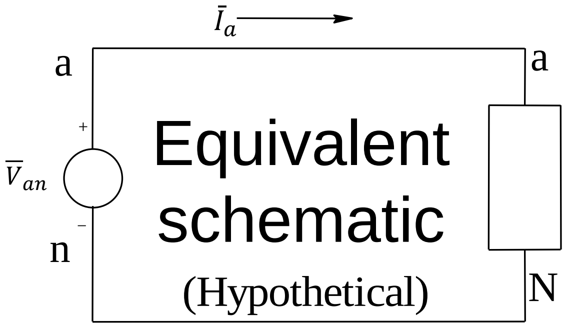
- Balanced set of source voltages,
- Equal impedances in each of the phases.

$$\bar{I}_a = \frac{\bar{V}_{an}}{|Z_L|} = \frac{\hat{V}_s}{|Z_L|}\angle -\varphi$$

$$\bar{I}_b = \frac{\bar{V}_{bn}}{|Z_L|} = \frac{\hat{V}_s}{|Z_L|}\angle -\frac{2\pi}{3} - \varphi$$

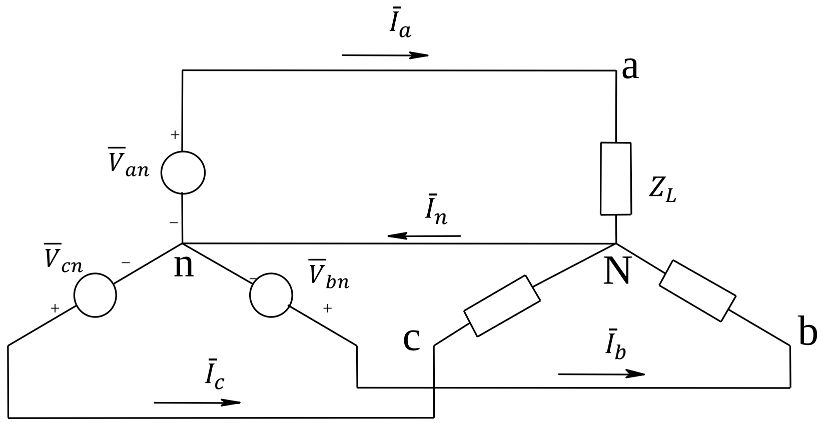
$$\bar{I}_c = \frac{\bar{V}_{cn}}{|Z_L|} = \frac{\hat{V}_s}{|Z_L|}\angle -\frac{4\pi}{3} - \varphi$$

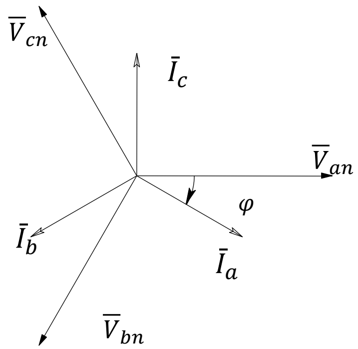
$$\bar{I}_n = (\bar{I}_a + \bar{I}_a + \bar{I}_c) = 0 \Rightarrow i_n(t) = [i_a(t) + i_b(t) + i_c(t)] = 0$$



Result:

Source neutral "n" and load neutral "N" are at the same potential.

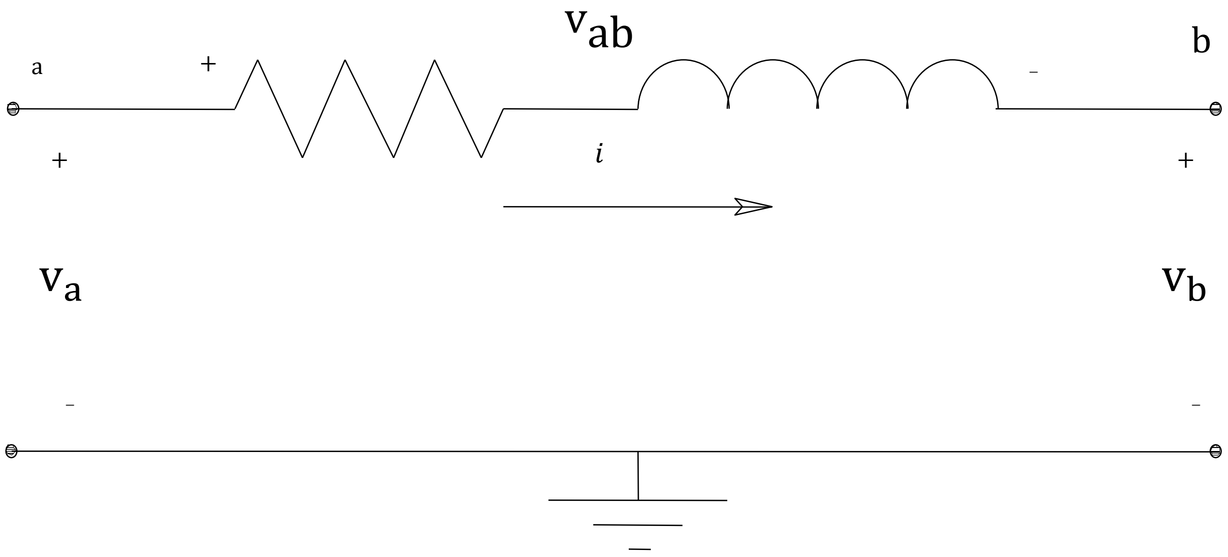




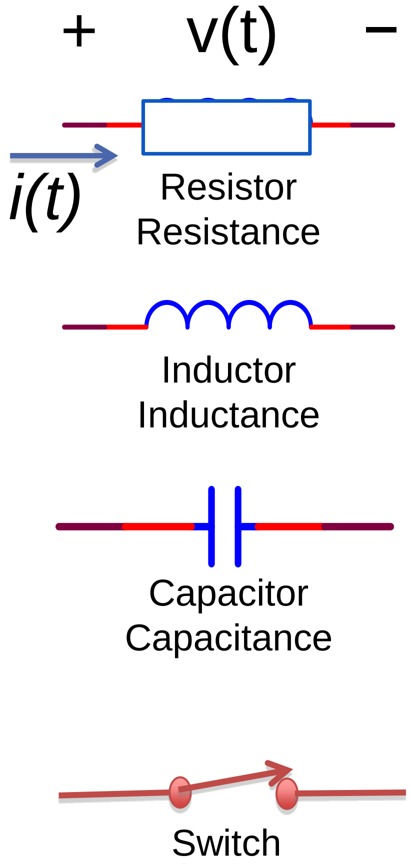
ADJUSTABLE/VARIABLE SPEED DRIVES

- SI Units
- Lower case v and i for instantaneous quantities
- Upper case V and I for average and rms
- Voltage and current subscripts
- Voltage polarities and current directions

1. Know sinusoidal waveforms.
2. AC circuit analysis deals with phasors and impedances
3. Do you know CIVIL ?
4. Instantaneous Power



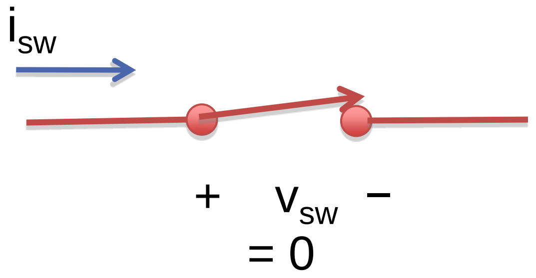
ELECTRICAL NETWORK ELEMENTS



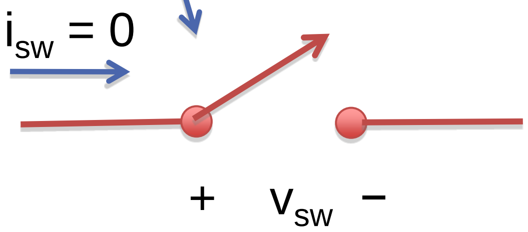
Time	Phasors	Network characteristics
$v(t) = R \cdot i(t)$	$\bar{V} = R \cdot \bar{I}$	$\bar{V} \neq 0 \quad \bar{I} \neq 0 \quad P \neq 0$
$v(t) = L \cdot \dfrac{di(t)}{dt}$	$\bar{V} = jX_L\bar{I} = j\omega L\bar{I}$	$\bar{V} = 0 \quad \bar{I} \neq 0 \quad P = 0$
$i(t) = C \cdot \dfrac{dv(t)}{dt}$	$\bar{V} = -X_C\bar{I} = j\dfrac{1}{\omega C}\bar{I}$	$\bar{V} \neq 0 \quad \bar{I} = 0 \quad P = 0$
$v(t)\begin{cases} 0 \\ v(t) \end{cases}$ $i(t)\begin{cases} 0 \\ i(t) \end{cases}$	$\bar{V}\begin{cases} 0 \\ \bar{V} \end{cases}$ $\bar{I}\begin{cases} 0 \\ \bar{I} \end{cases}$	$\bar{V} \neq 0 \quad \bar{I} \neq 0 \quad P = 0$

ELECTRICAL NETWORK ELEMENTS

Power semiconductor devices ⟷ ***Power switches***

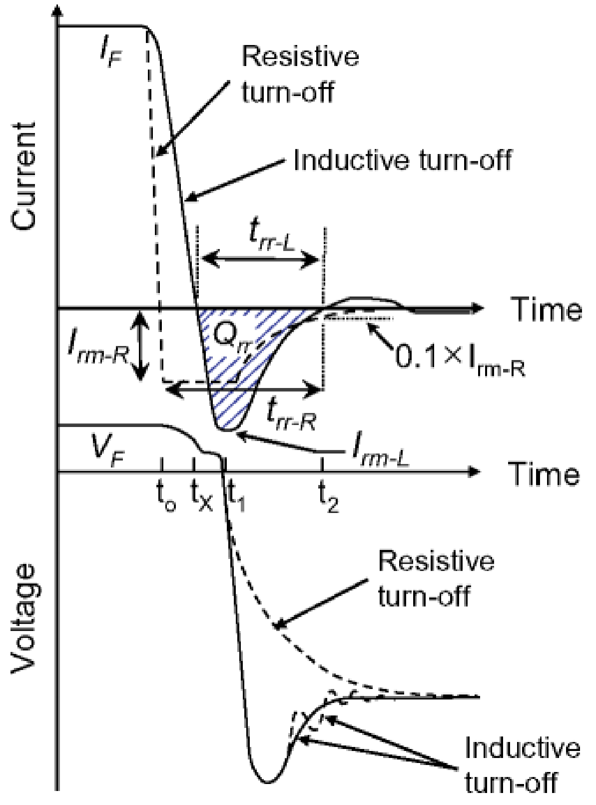


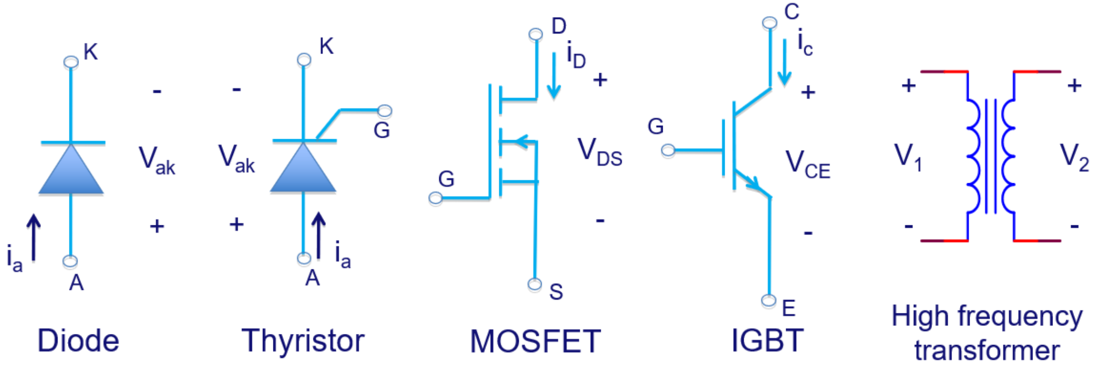
ON or OFF



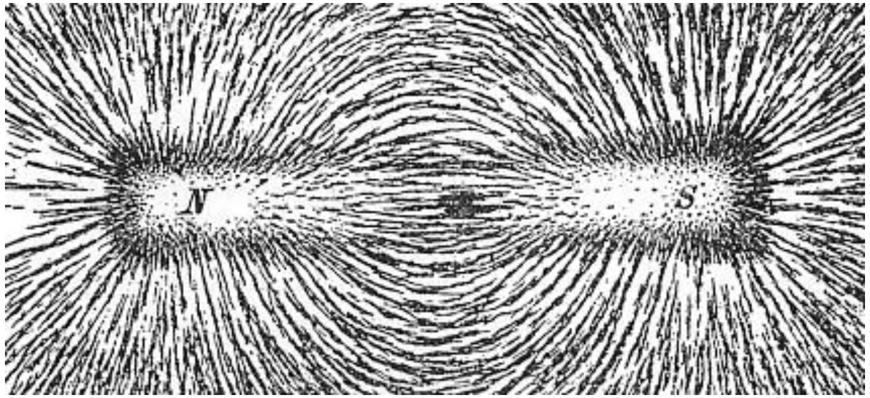
$$P_{loss} = v_{sw} \times i_{sw} = 0$$

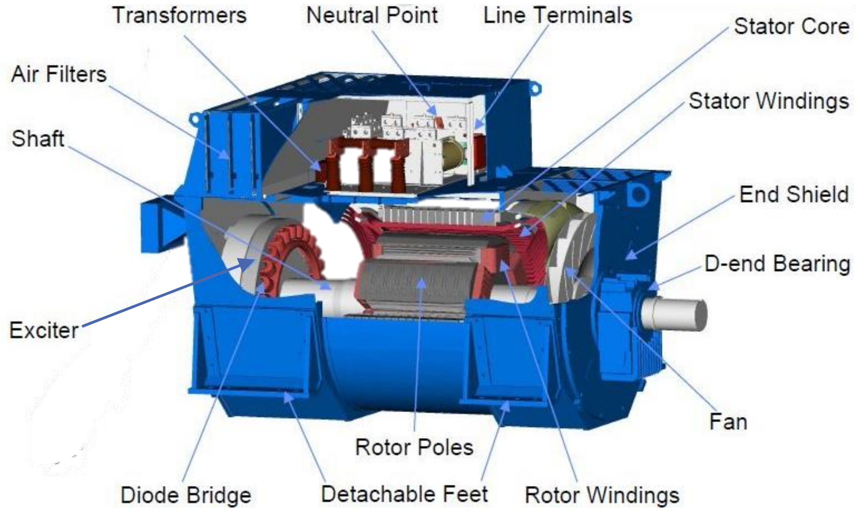
Losses ideally ZERO !



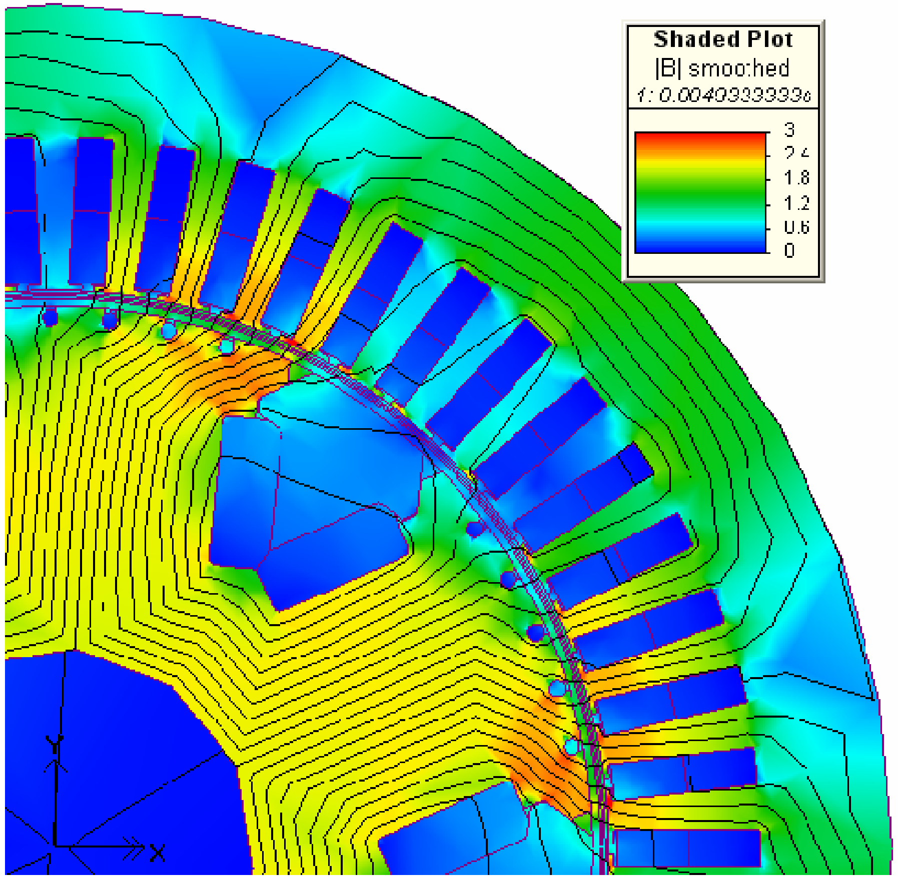


ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

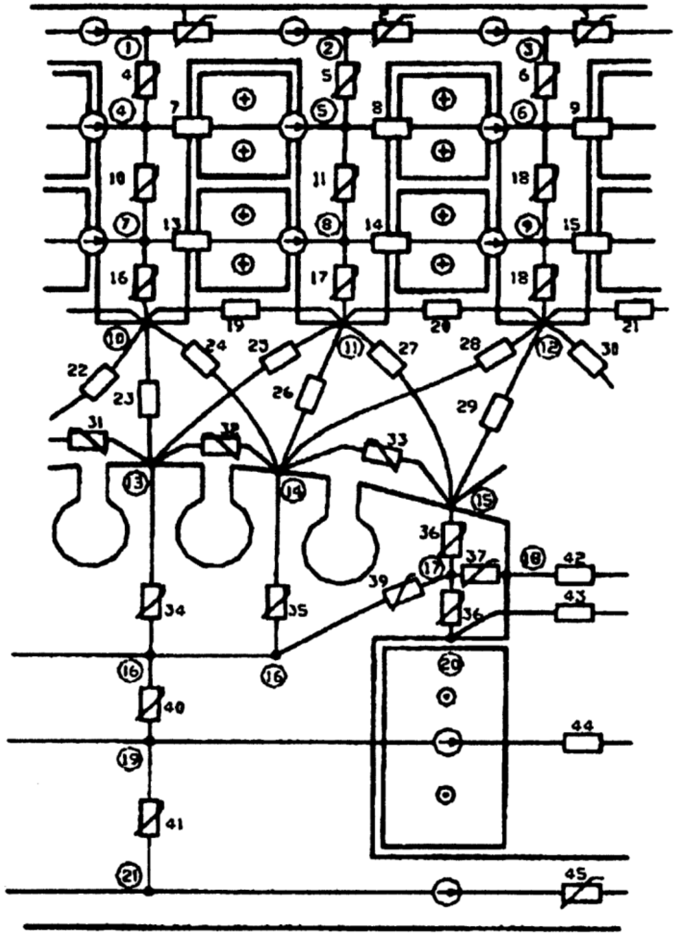




Synchronous Generator



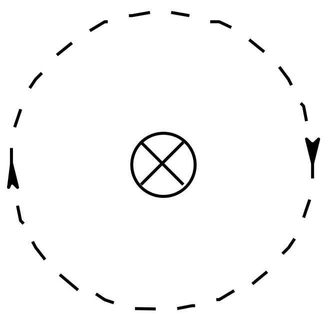
2D cross-section with “Flux lines”

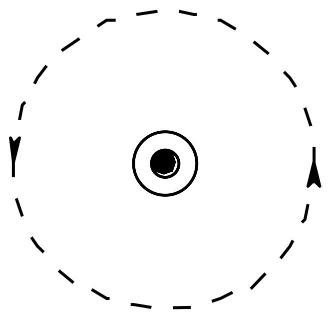


Magnetic Equivalent Circuit

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Magnetic field, *H*, produced by current carrying conductor



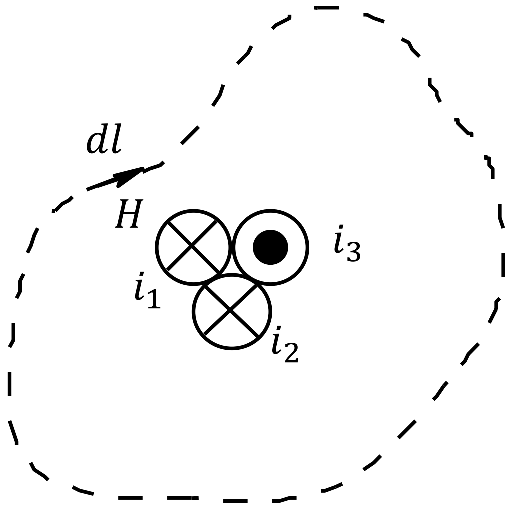


Ampere's Law

$$\oint_{closedpath} Hd\ell = \sum i \qquad (5\text{-}1)$$

Scalar *H* is the component of the vector in the direction of the length dl along the closed path.

H has the units of $\left[\frac{A}{m}\right]$



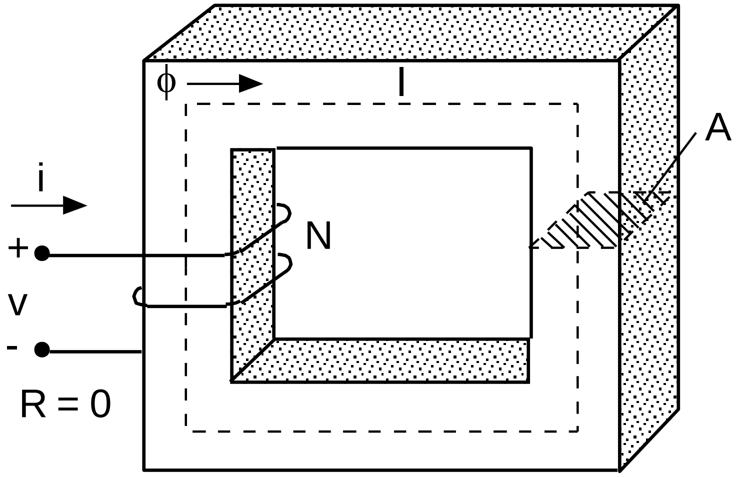
Magnetic field and Ampere's law

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

- Energy an Important Unit :
  - Theoretically energy can be converted from electrical form to magnetic form and vice versa with 100% efficiency
  - The electrical energy supplied to a lossless coil as the current increases must be equal to the energy stored in the magnetic field of the ferromagnetic core

$$i \xrightarrow{\times\left(\frac{N}{l_m}\right)} H_m \xrightarrow{\times(\mu_m)} B_m \xrightarrow{\times(A_m)} \varphi_m \xrightarrow{\times(N)} \lambda_m \xrightarrow{-\frac{d}{dt}} e$$

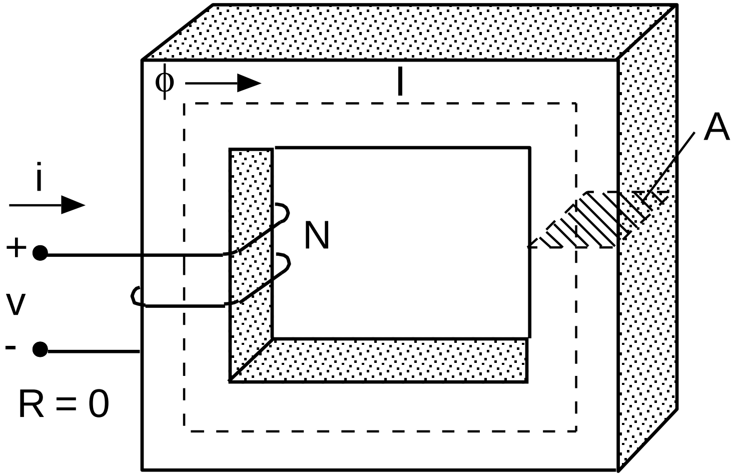
$$\times L_m = \frac{N^2}{\frac{l_m}{\mu_m A_m}}$$

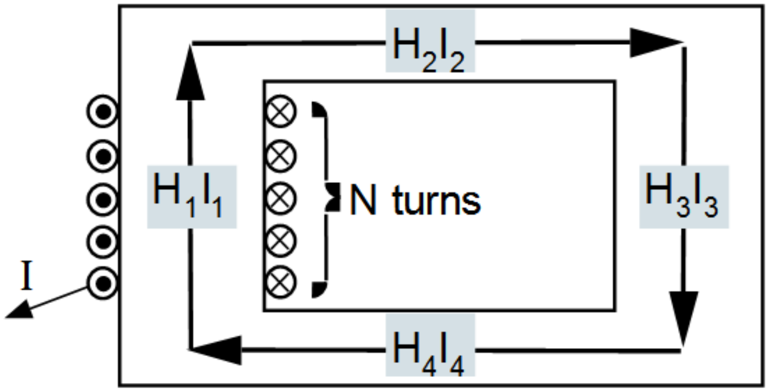


ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Isomorphism between electric and magnetic circuits

Electric circuits	Magnetic circuits
Current I	Magnetic flux φ_m
Voltage V	MMF F
Resistance R_e	Reluctance $\mathfrak{R}_m$





ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

1. Magnetic equivalent circuits (MEC) are sometimes used to model devices composed from highly permeable materials, e.g., ferromagnetic core

2. Magnetic flux is confined to the highly permeable material $\Rightarrow$ flux paths (tubes) can be "easily" identified

3. Air gap flux paths have to be approximated, i.e., the fringing effect has to be considered

4. Leakage paths have to be approximated

5. A-priori knowledge ("expert" understanding) of the magnetic flux distribution is necessary in order to define any Magnetic Equivalent Circuit !!!

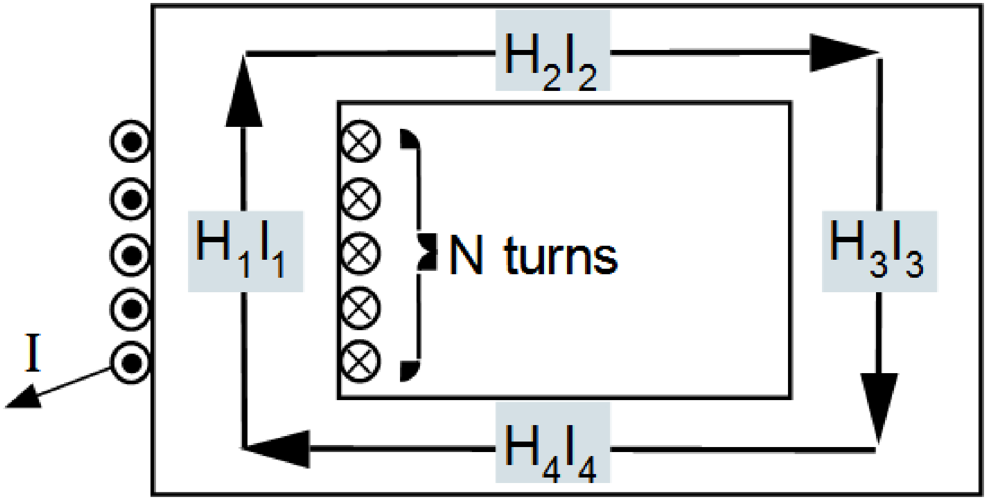
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

$$\oint_{closedpath} H d\ell = \sum i \qquad (5\text{-}1)$$

$$i \xrightarrow{\times\left(\frac{N}{l_m}\right)} H_m \xrightarrow{\times(\mu_m)} B_m \xrightarrow{\times(A_m)} \varphi_m \xrightarrow{\times(N)} \lambda_m \xrightarrow{-\frac{d}{dt}} e$$

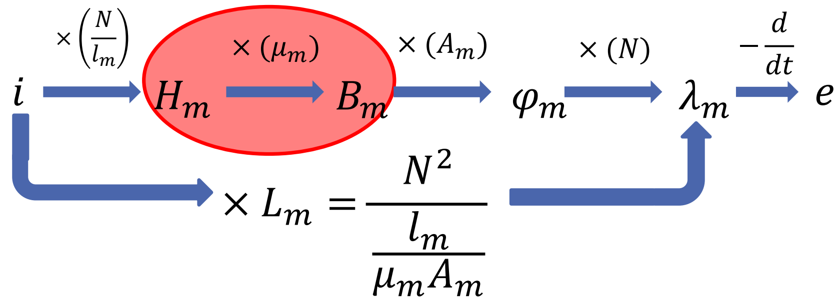
$$i \xrightarrow{\times L_m = \frac{N^2}{\frac{l_m}{\mu_m A_m}}} \lambda_m$$

$$\sum_k H_k l_k = \sum_k \mathcal{F}_k \quad = \quad \int_C \mathbf{H} \cdot d\mathbf{l} = H_1 l_1 + H_2 l_2 + H_3 l_3 + H_4 l_4 = N_1 I_1 = \mathcal{F}_1$$



ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

For a given H-field, the density of flux lines, called the flux density B, depends on the permeability μ of the material on which this H-field is acting.



Units of flux density B: $\frac{Weber}{meter^2}\left[\frac{Wb}{m^2}\right]$ or $Tesla\ [T]$

In air: $B = \mu_o H$ $\qquad \mu_o = 4\pi \times 10^{-7}\left[\frac{henries}{m}\right]$ or $\left[\frac{H}{m}\right]$ (5-3)

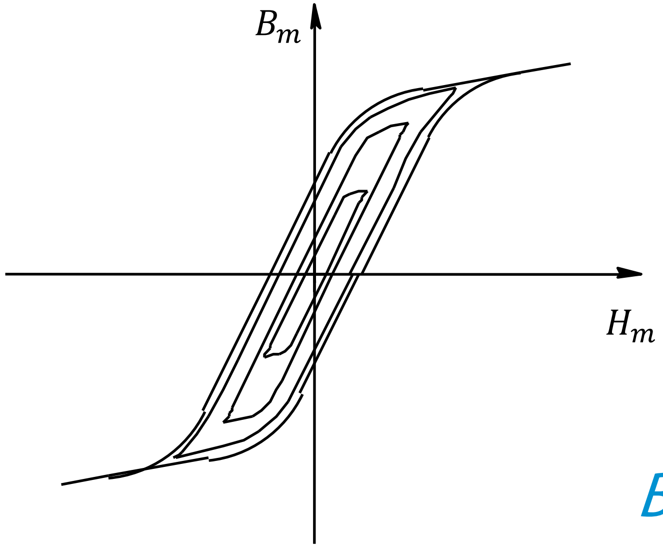
where μ_o is the permeability of air or free space.

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

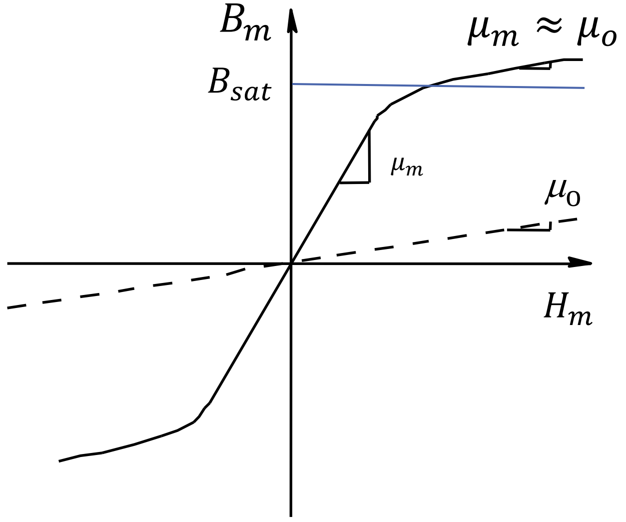
High magnetic permeability $$B_m = \mu_m H_m = \mu_r \mu_o H_m$$

Required B can be achieved with much lower values of H field than in the air => lower ampere-turns required

Multi valued nonlinear behavior



Joining the peaks of hysteresis loops

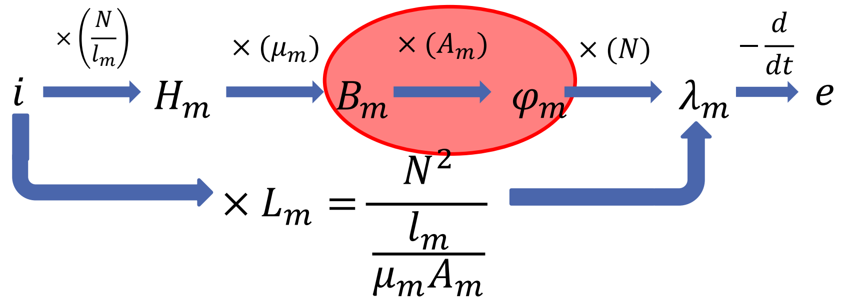


B_{sat} ~ 1.8 – 2.2 T

Drop of the permeability

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Magnetic flux lines form closed paths.
Area Am in a plane perpendicular to the direction of the flux lines.
Uniform H_m, hence uniform B_m over A_m:



$$B_m = \mu_m H_m = \mu_m \frac{Ni}{\ell_m} \quad (5\text{-}5)$$

$$\varphi_m = B_m A_m \quad (5\text{-}6)$$

$$\therefore \varphi_m = A_m \left(\mu_m \frac{Ni}{\ell_m}\right) = \frac{Ni}{\left(\frac{\ell_m}{\mu_m A_m}\right)} = \frac{F}{\Re_m} \quad (5\text{-}7)$$

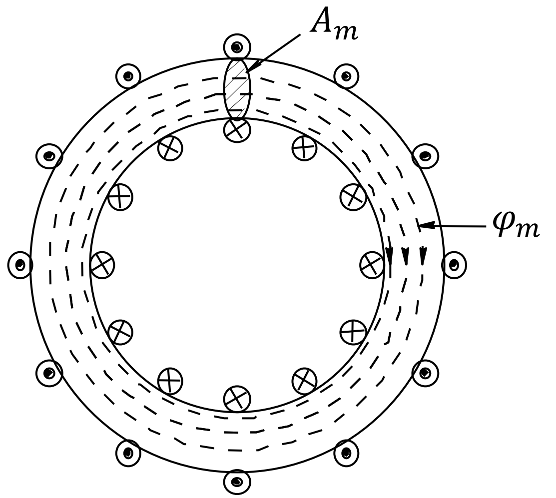


Fig. 5.4 Toroid with flux

Reluctance: $\Re_m = \frac{\ell_m}{\mu_m A_m}\left[\frac{A}{Wb}\right]$ (5-8)

MMF: $F = Ni$ ⟷ Ohm's law: $I = \frac{V}{R_e}$

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Flux linkage

If all turns N of a coil are linked with the same flux φ_m ,
then the coil has a flux linkage λ_m , where

$$\lambda_m = N\varphi_m \qquad (5\text{-}9)$$

$$i \xrightarrow{\times\left(\frac{N}{l_m}\right)} H_m \xrightarrow{\times(\mu_m)} B_m \xrightarrow{\times(A_m)} \varphi_m \xrightarrow{\times(N)} \lambda_m \xrightarrow{-\frac{d}{dt}} e$$

$$i \longrightarrow \times L_m = \frac{N^2}{\frac{l_m}{\mu_m A_m}} \longrightarrow \lambda_m$$

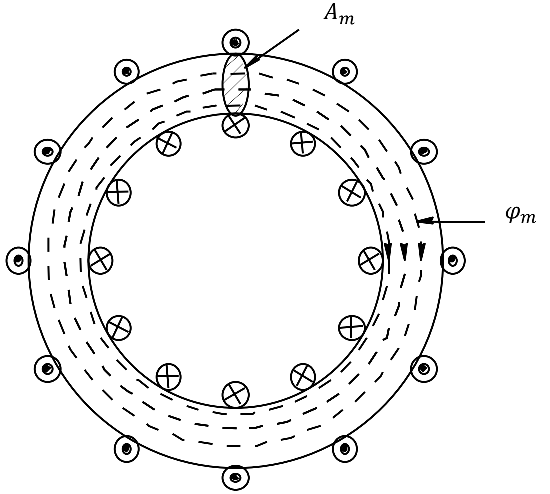
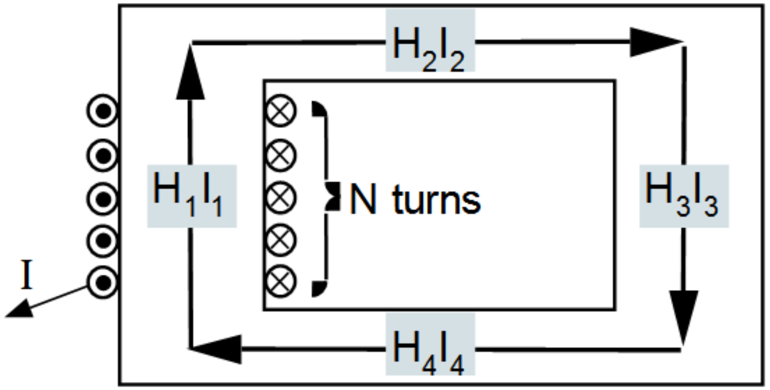


Fig. 5.4 Toroid with flux φ_m

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



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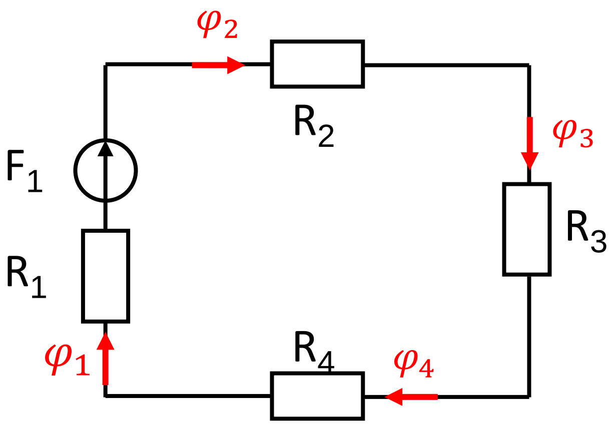


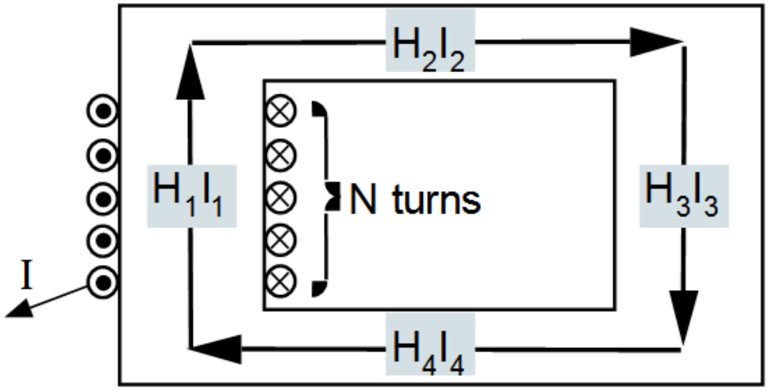
$$\sum_m H_m l_m = \sum_m \mathcal{F}_m \Rightarrow \sum_m \Phi_m \mathcal{R}_m = \sum_m \mathcal{F}_m$$

$$\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi$$

conservation of magnetic flux

$$\varphi \sum_m \mathcal{R}_m = \mathcal{F}_1 \Rightarrow \varphi = \frac{\mathcal{F}_1}{\sum_m \mathcal{R}_m}$$

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



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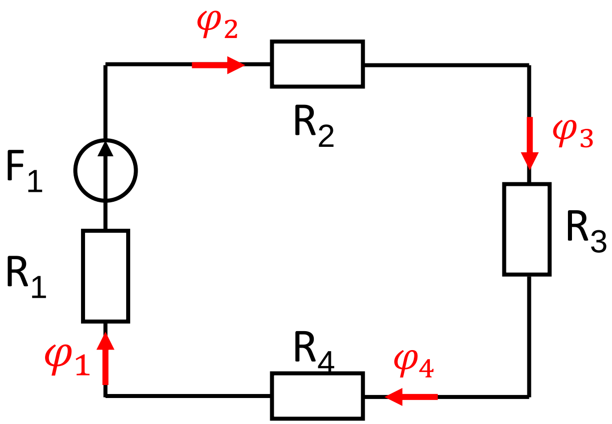


$$\varphi \sum_m \mathcal{R}_m = \mathcal{F}_1 \Rightarrow \varphi = \frac{\mathcal{F}_1}{\sum_m \mathcal{R}_m}$$

$$\mathcal{R}_m = \oint_{C_m} \frac{dl}{\mu_m A_m} \Rightarrow \mathcal{R}_m = \frac{l_m}{\mu_m A_m} \text{ if } A_m \text{ constant}$$

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

The flux linkage λ_m of the coil is related to the i current by a parameter defined as the inductance L_m

$$i \xrightarrow{\times\left(\frac{N}{l_m}\right)} H_m \xrightarrow{\times(\mu_m)} B_m \xrightarrow{\times(A_m)} \varphi_m \xrightarrow{\times(N)} \lambda_m \xrightarrow{-\frac{d}{dt}} e$$

$$i \xrightarrow{\times L_m = \frac{N^2}{\frac{l_m}{\mu_m A_m}}} \lambda_m$$

$$\lambda_m = L_m i \tag{5-19}$$

$$L_m = \frac{\lambda_m}{i} = \left(\frac{N}{l_m}\right)\mu_m A_m N = \frac{N^2}{\left(\frac{l_m}{\mu_m A_m}\right)} = \frac{N^2}{\Re} \tag{5-20}$$

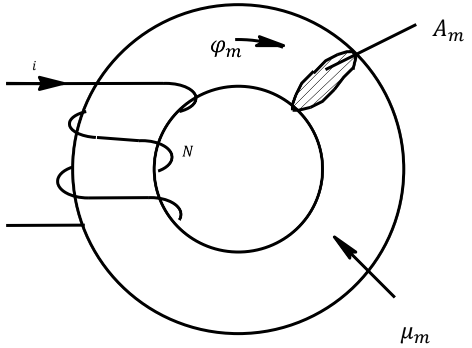


Figure 5-6 Coil inductance

For linear magnetic conditions the inductance is constant and depends only on the magnetic circuit.

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Energy in an inductor is stored in its magnetic field.

(5-21)

$$W_m = \frac{1}{2} L_m i^2 [J]$$

Assuming a structure without air gap (Fig. 5-6a)

(5-22a)

$$W_m = \frac{1}{2} \frac{N^2}{\frac{l_m}{\mu_m A_m}} (H_m l_m / N)^2 = \frac{1}{2} \frac{(H_m l_m)^2}{\frac{l_m}{\mu_m A_m}} = \frac{1}{2} \frac{B_m^2}{\mu_m} \underbrace{A_m l_m}_{\text{volume}} \; [J]$$

The energy density in the core is

(5-22b)

$$w_m = \frac{W_m}{\text{volume}} = \frac{1}{2} \frac{B_m^2}{\mu_m} \left[\frac{J}{m^3}\right]$$

The energy density in any medium is

$$w = \frac{1}{2} \frac{B^2}{\mu} \left[\frac{J}{m^3}\right]$$ (5-23)

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

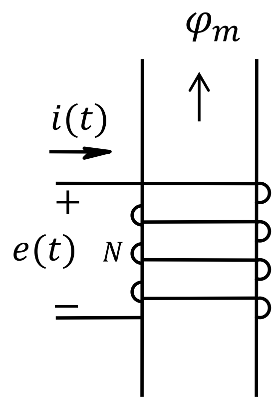
- Induced voltage $$e = -\frac{d\lambda}{dt} = -N\frac{d\varphi}{dt}$$

$$i \xrightarrow{\times\left(\frac{N}{l_m}\right)} H_m \xrightarrow{\times(\mu_m)} B_m \xrightarrow{\times(A_m)} \varphi_m \xrightarrow{\times(N)} \lambda_m \xrightarrow{-\frac{d}{dt}} e$$

$$i \longrightarrow \times\, L_m = \frac{N^2}{\frac{l_m}{\mu_m A_m}} \longrightarrow \lambda_m$$

- Current direction is into positive polarity voltage $\rightarrow$ flux direction

- Lenz's law: Polarity of induced voltage



When current and flux directions are consistent: A current as indicated would create a flux as indicated => voltage should be labeled positive where the current enters the coil.

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

The relationships between the electrical quantity φ and i the magnetic quantities H, B, λ and are valid under dc (static) conditions, as well as at any instant when these quantities are varying with time.

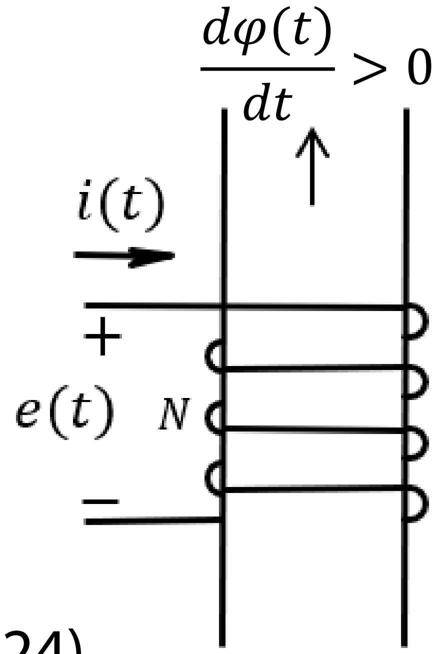


Figure 5-8

Faraday's law:
A coil of N turns linked by a changing magnetic flux φ has a voltage e induced behind the terminals of that coil with a magnitude:

$$e = \frac{d}{dt}\lambda(t) = N\frac{d}{dt}\varphi(t) \quad (5\text{-}24)$$

The voltage e induced in a coil by a changing flux is of such polarity that if a current could flow as a result of that induced voltage, the flux established by that current would oppose the causing or original flux change **(Lenz's rule)**.

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Relating e(t), $\varphi(t)$ and i(t): coil in sinusoidal steady state

$$\varphi(t) = \hat{\varphi}\ \sin(\omega t)$$

$$e(t) = N\frac{d\varphi}{dt} = N\hat{\varphi}\omega\ \cos\ \omega t$$

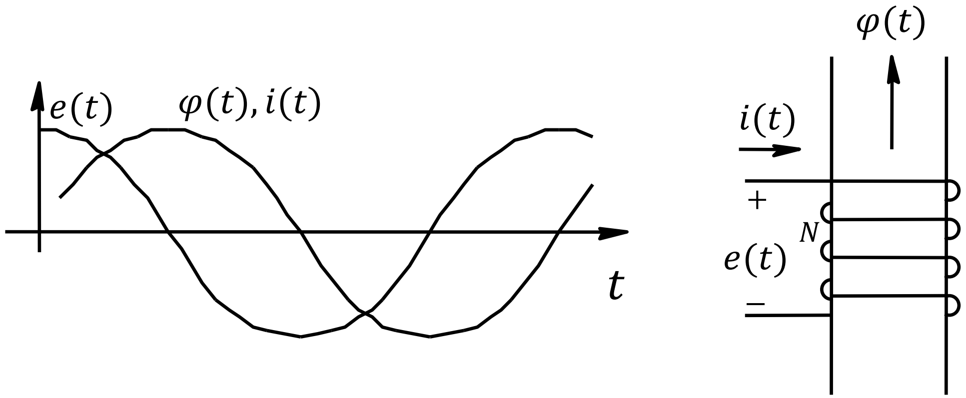


Figure 5-10 Voltage, current, and flux

Relating $e(t), \varphi(t)$, and $i(t)$ ➡ $L = \frac{\lambda}{i} = \frac{N\varphi}{i}$

$$\left.\begin{aligned} &\Rightarrow i(t) = \frac{N}{L}\varphi(t) \\ &\& \ e(t) = N\frac{d\varphi(t)}{dt} \end{aligned}\right\} \Rightarrow e(t) = L\frac{di(t)}{dt} \qquad (5\text{-}28)$$

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Objective: establish B_g in ℓ_g by controlling i

$$H_m\ell_m + H_g\ell_g = Ni \quad (5\text{-}10)$$

$$B_m = \mu_m H_m \,,\; B_g = \mu_o H_g \quad (5\text{-}11)$$

$$\frac{B_m}{\mu_m}\ell_m + \frac{B_g}{\mu_o}\ell_g = Ni \quad (5\text{-}12)$$

$$\phi_m = A_m B_m = A_g B_g \quad (5\text{-}13)$$

$$B_m = \frac{\phi_m}{A_m} \; B_g = \frac{\phi_m}{A_g} \quad (5\text{-}14)$$

$$A_g = (w + \ell_g)(d + \ell_g) \quad (5\text{-}15)$$ account for fringing

$$\varphi_m\Big(\underbrace{\frac{\ell_m}{A_m\mu_m}}_{\mathfrak{R}_m} + \underbrace{\frac{\ell_g}{A_g\mu_o}}_{\mathfrak{R}_g}\Big) = Ni \quad (5\text{-}16)$$

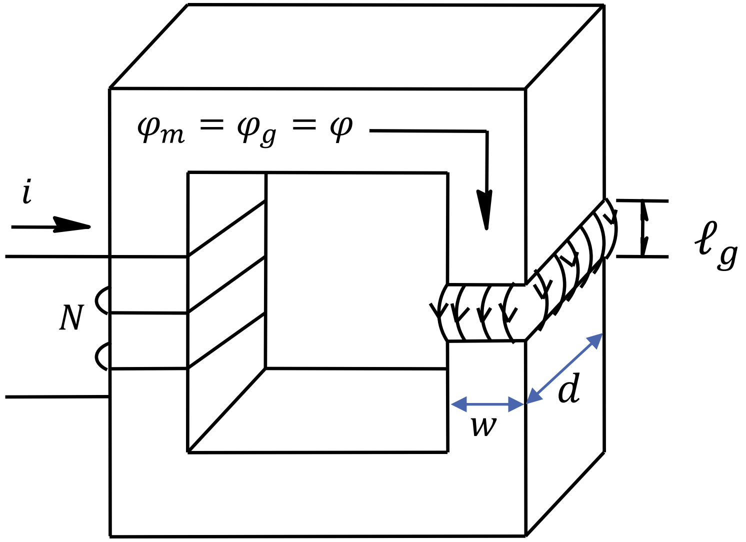


Figure 5-5 Magnetic structure with air gap

$$\mathfrak{R} = \mathfrak{R}_m + \mathfrak{R}_g \quad (5\text{-}17)$$

$$\varphi_m = \frac{F}{\mathfrak{R}} \quad (5\text{-}18)$$

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

Negligible leakage current: $\sigma_{e_{\mathrm{Cu}}} \approx 10^{20} \sigma_{e_{\mathrm{air}}}$

Not-negligible leakage flux: $\mu_{\mathrm{magn.mat.}} \approx 10^{4} \mu_{o}$

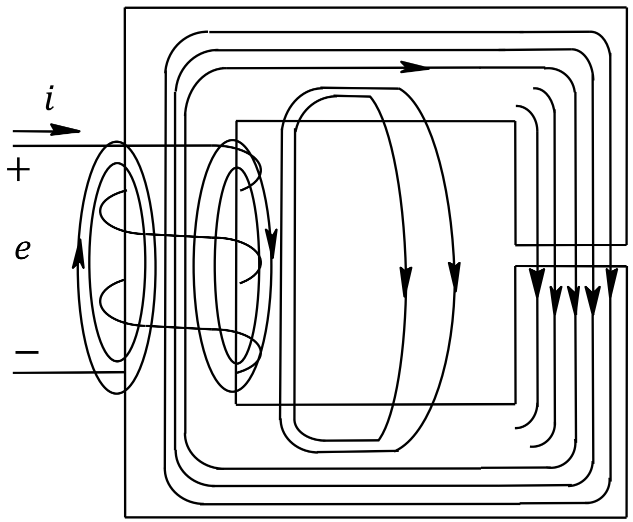
Approximations

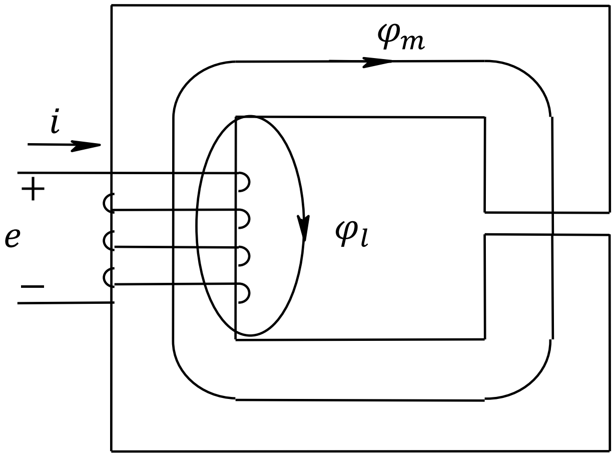
The total flux φ is divided in two parts:

The magnetic flux φ_m , completely confined to the core and linking all N turns;

The leakage flux φ_ℓ, partially in the air and also linking all N turns.

$$\varphi = \varphi_m + \varphi_\ell \qquad (5\text{-}29)$$





ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

$$\varphi = \varphi_m + \varphi_\ell \qquad (5\text{-}29)$$

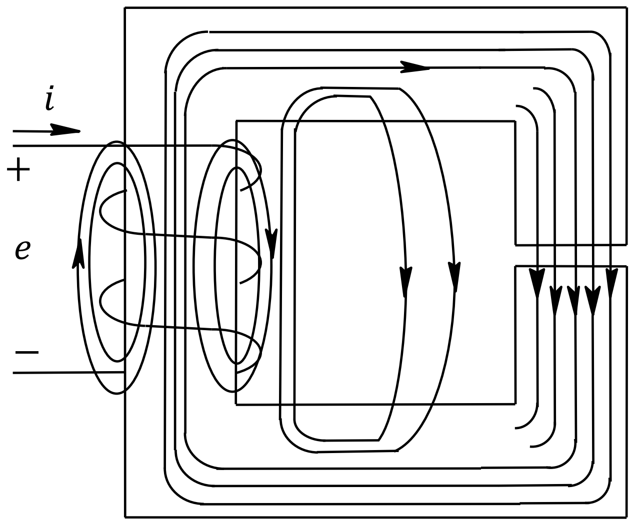
$$\lambda = N\varphi = \underbrace{N\varphi_m}_{\lambda_m} + \underbrace{N\varphi_\ell}_{\lambda_\ell} \qquad (5\text{-}30)$$

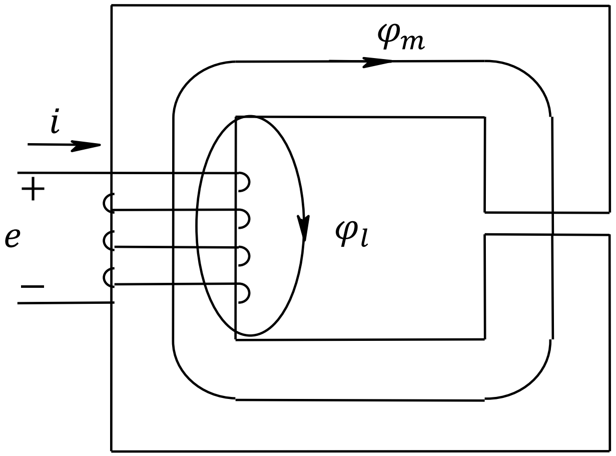
$$\frac{\lambda}{i} = \frac{\lambda_m}{i} + \frac{\lambda_\ell}{i} \qquad (5\text{-}31)$$

$$L_{self} = L_m + L_\ell \qquad (5\text{-}32)$$

$$\lambda = L_{self}\, i = L_m i + L_\ell i \qquad (5\text{-}33)$$

Total inductance or self-inductance L_{self} is sum of magnetizing inductance L_m due to φ_m , and leakage inductance L_ℓ due to φ_ℓ .





ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

From Faraday's law:

$$e = \underbrace{L_m \frac{di}{dt}}_{e_m} + \underbrace{L_\ell \frac{di}{dt}}_{e_\ell} = e_m + L_\ell \frac{di}{dt} \qquad (5\text{-}34)$$

The voltage drop due to the leakage flux can be shown separately, so that the voltage induced in the coil is solely due to the magnetizing flux.

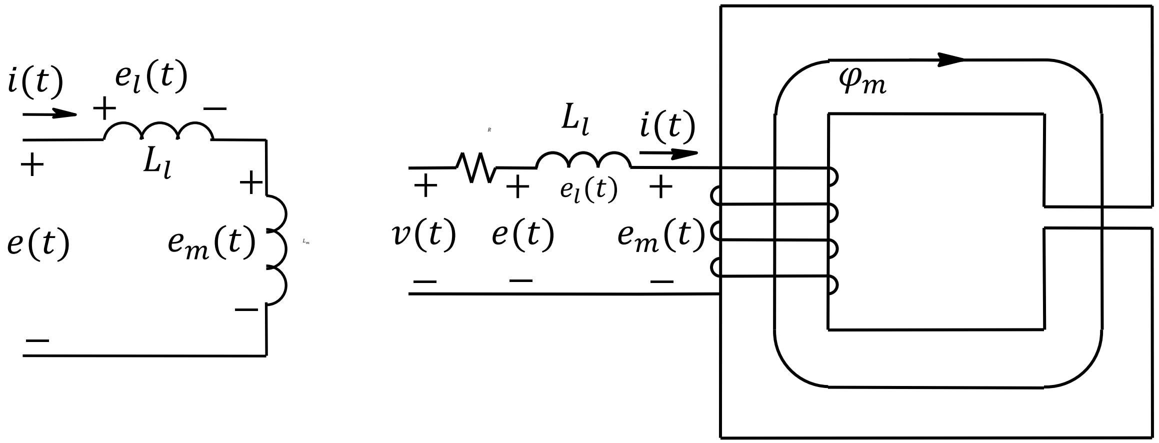


Figure 5-12 (a) Circuit representation; (b) leakage inductance separated from the core

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

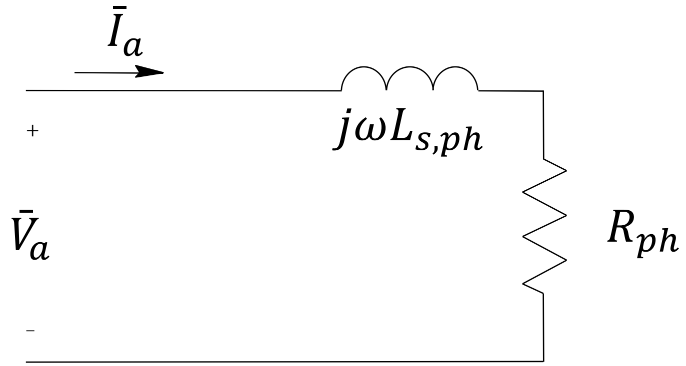
- Most magnetic circuits consist of multiple coils.
- In such circuits, the flux established by the current in one coil partially links the other coil or coils.
- This phenomenon can mathematically be described by means of mutual inductances.

Concentrated

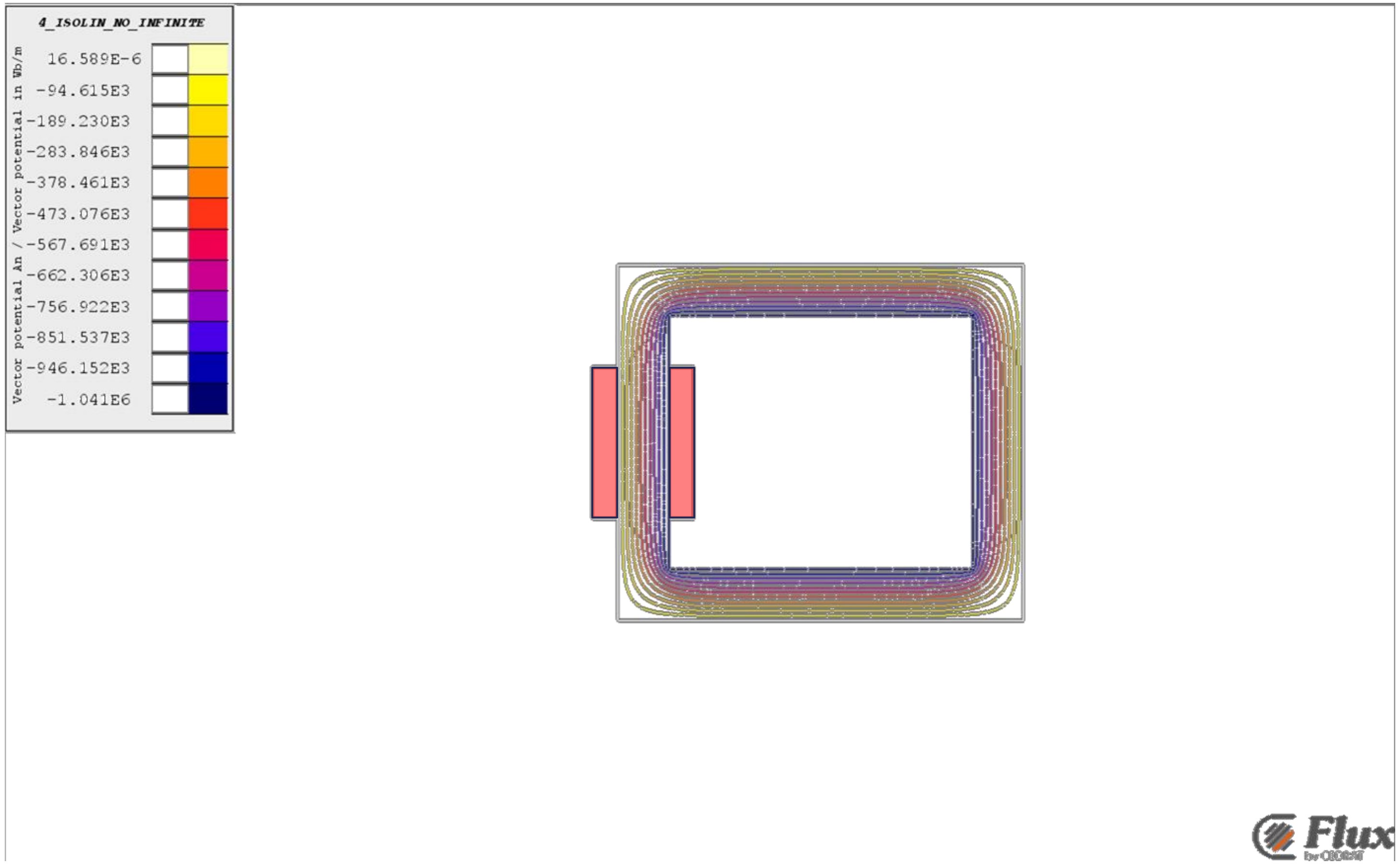
Distributed

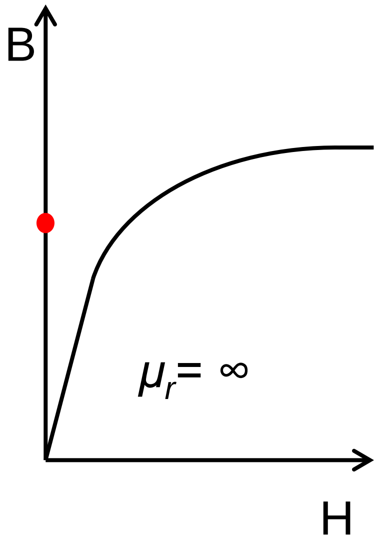
What you need to know is Synchronous inductance:

$$L_{s,ph} = L_{ph} + M_{ph}$$

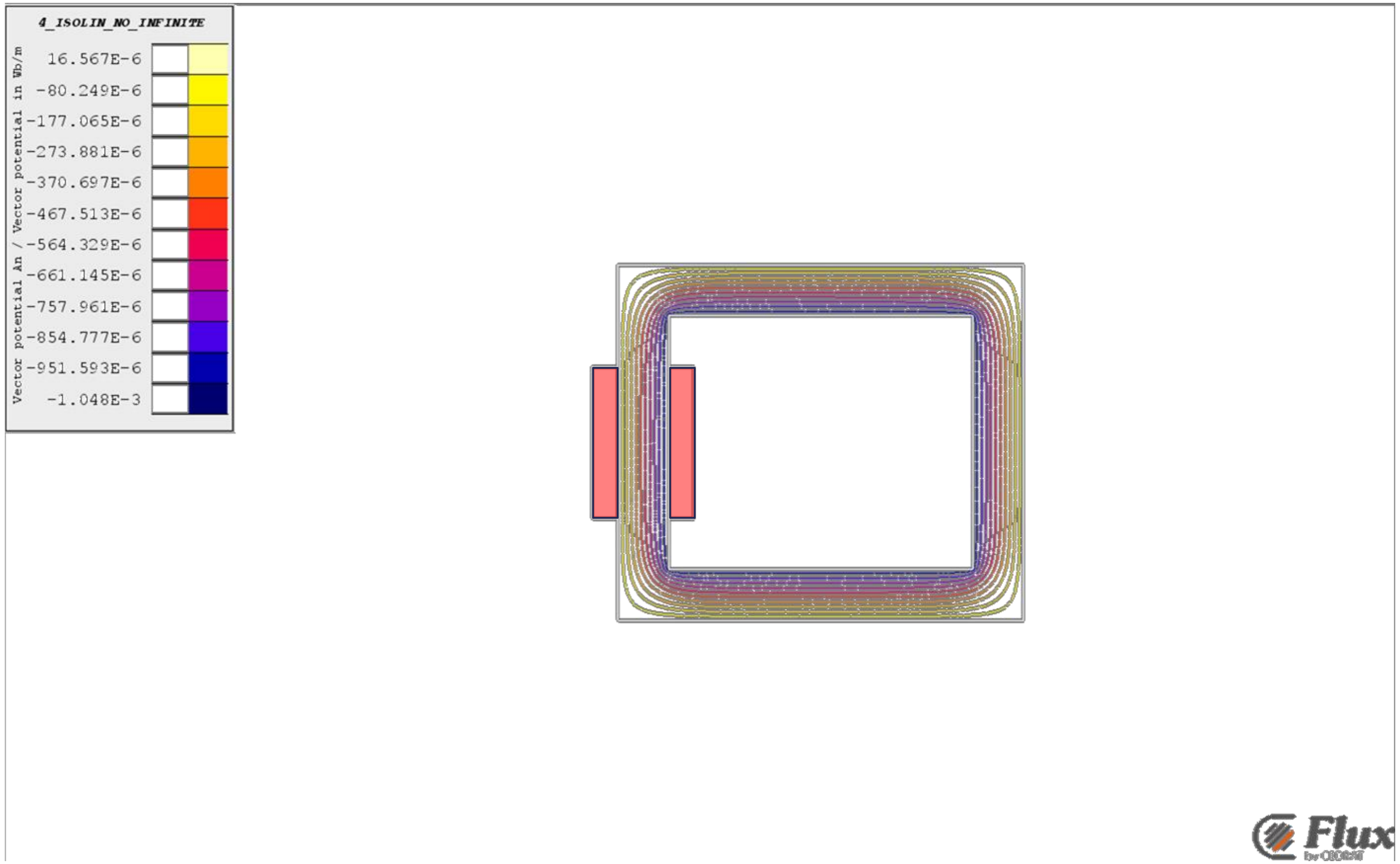


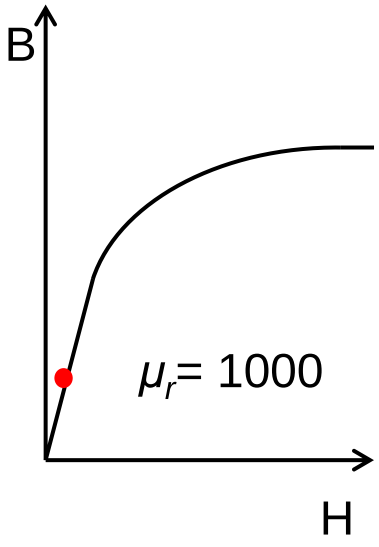
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



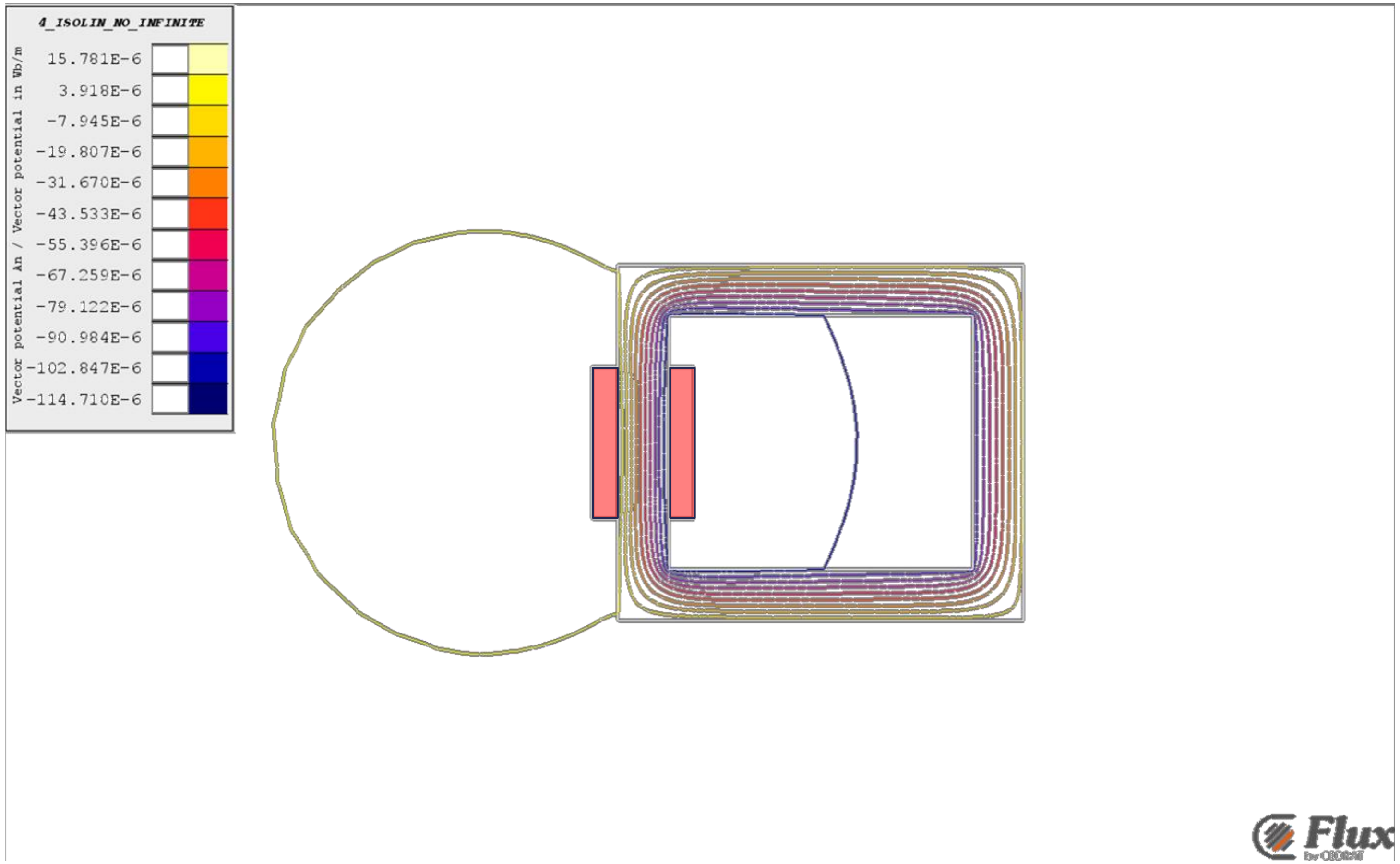


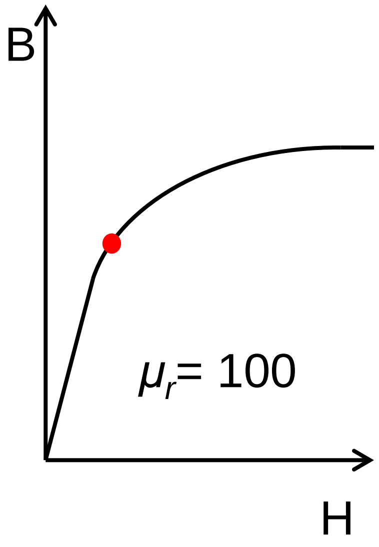
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



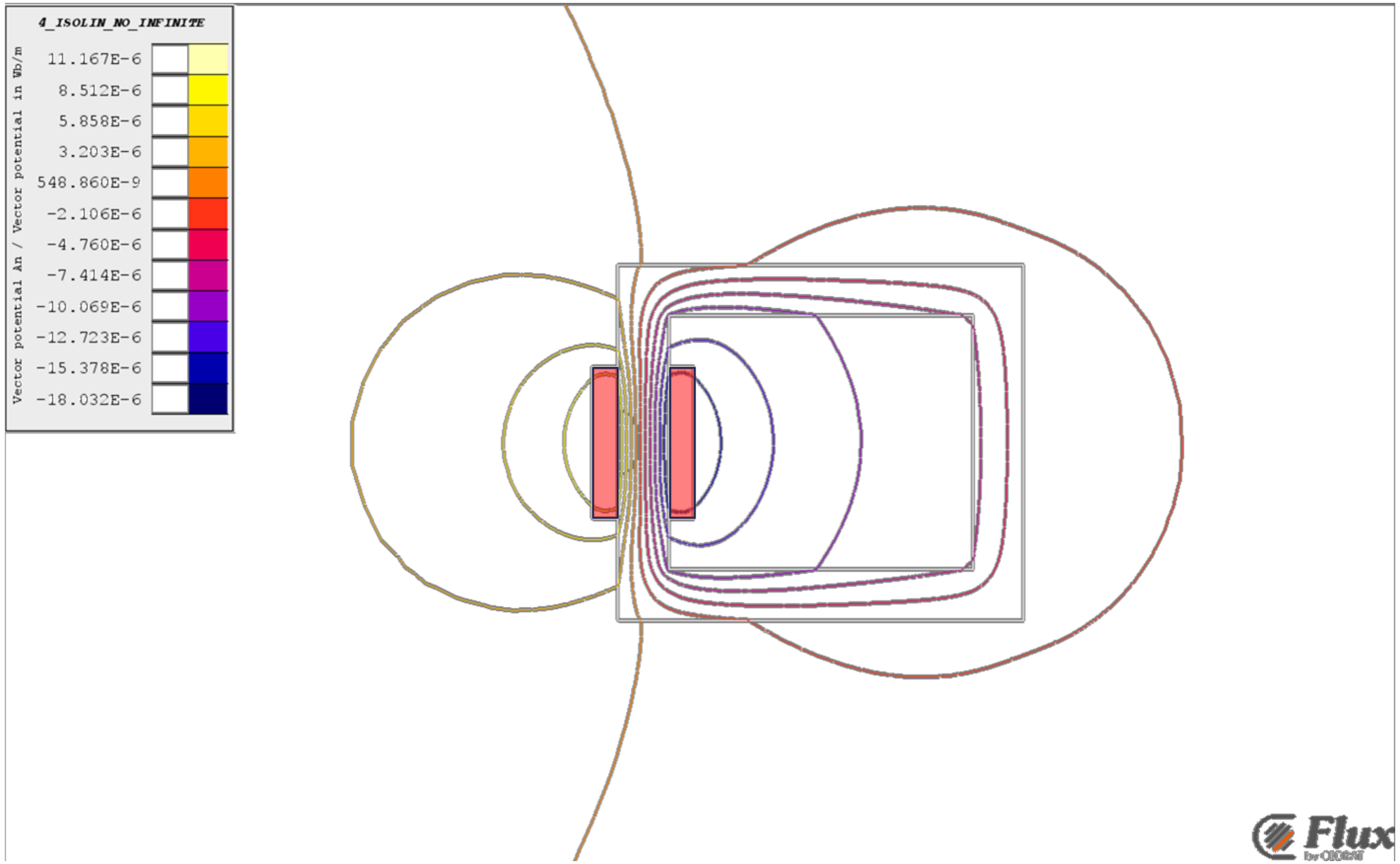


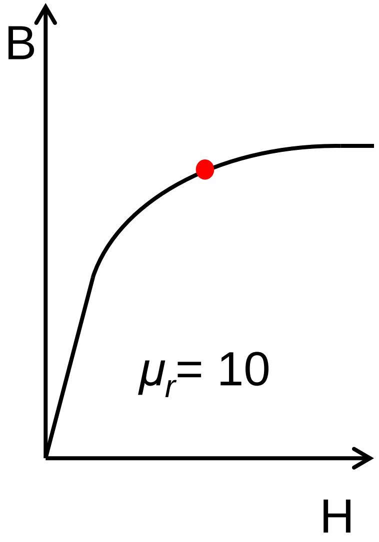
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



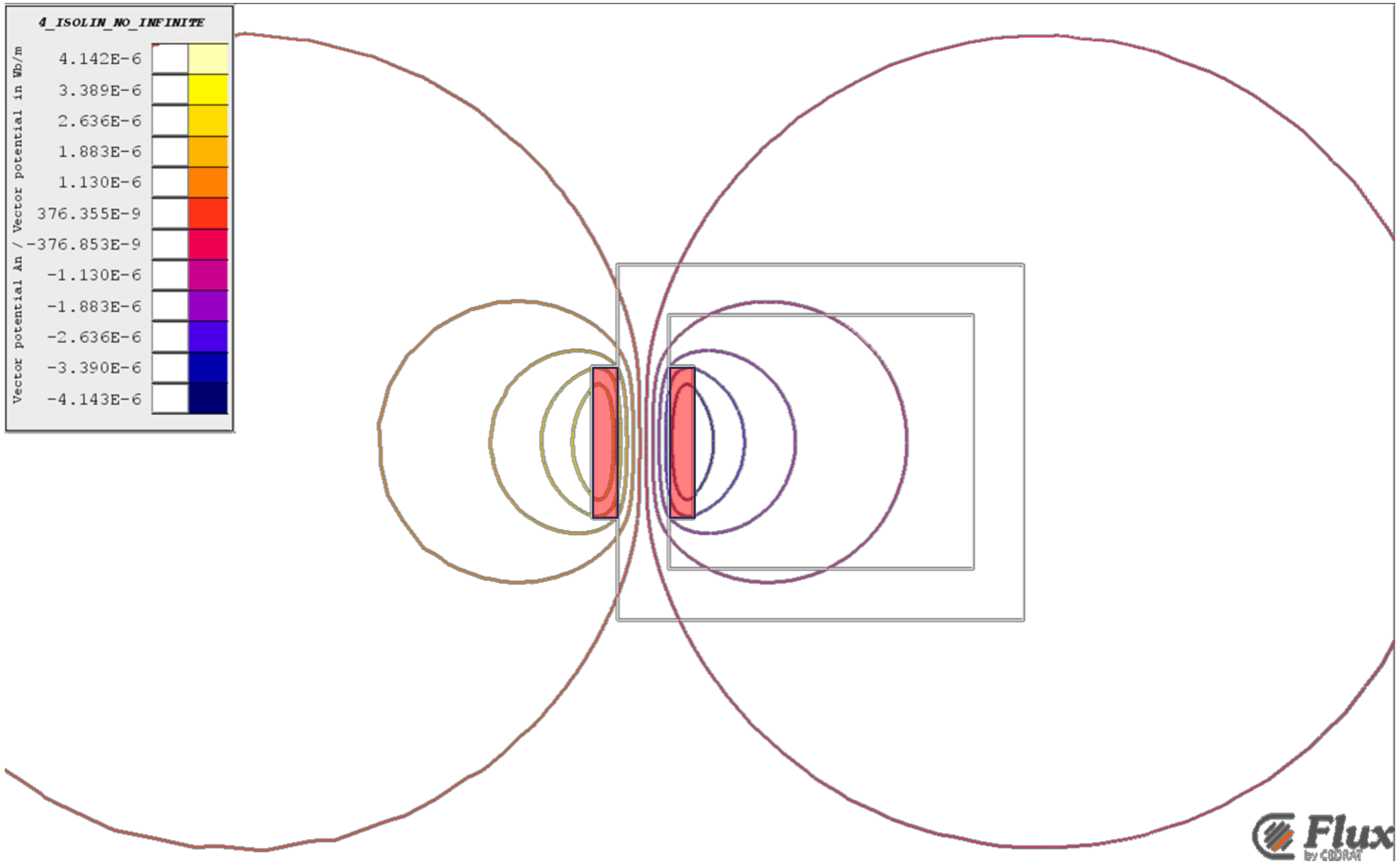


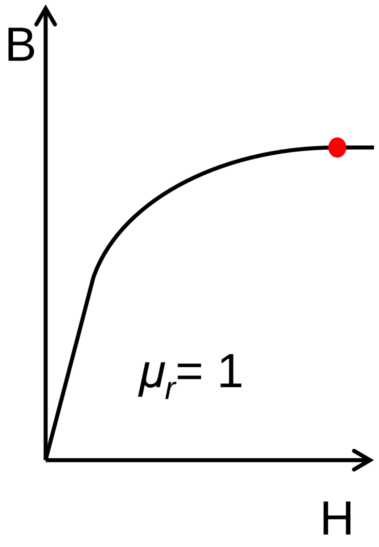
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)





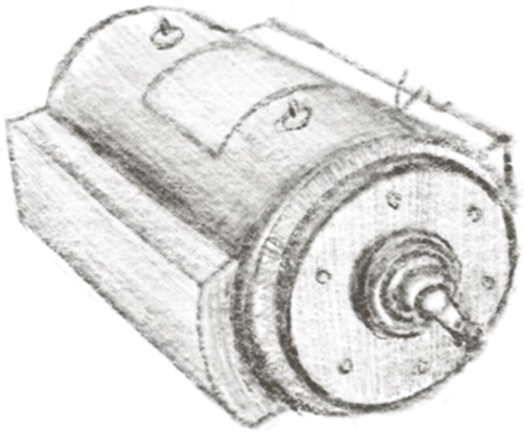
ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)

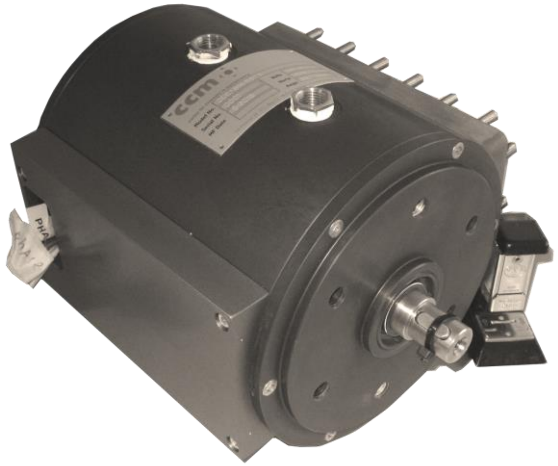


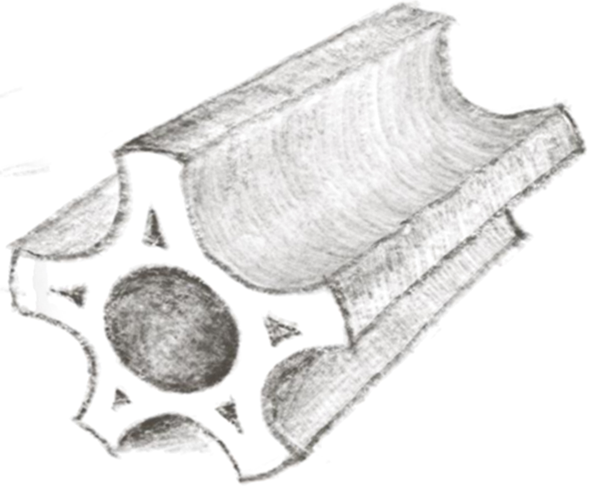


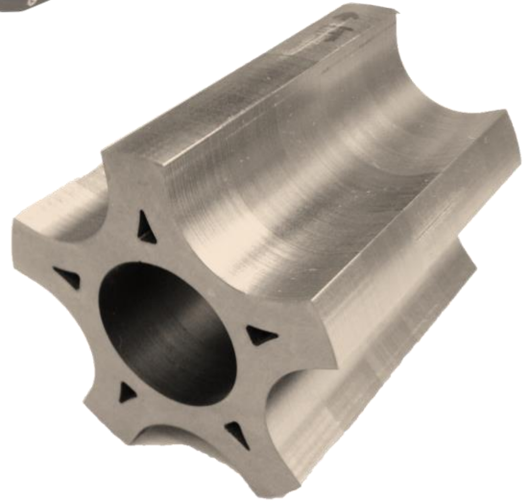
ELECTRICAL MACHINE EXAMPLE WITHOUT PERMANENT MAGNETS >>

ELECTRICAL NETWORK: MAGNETIC EQUIVALENT CIRCUIT (MEC)



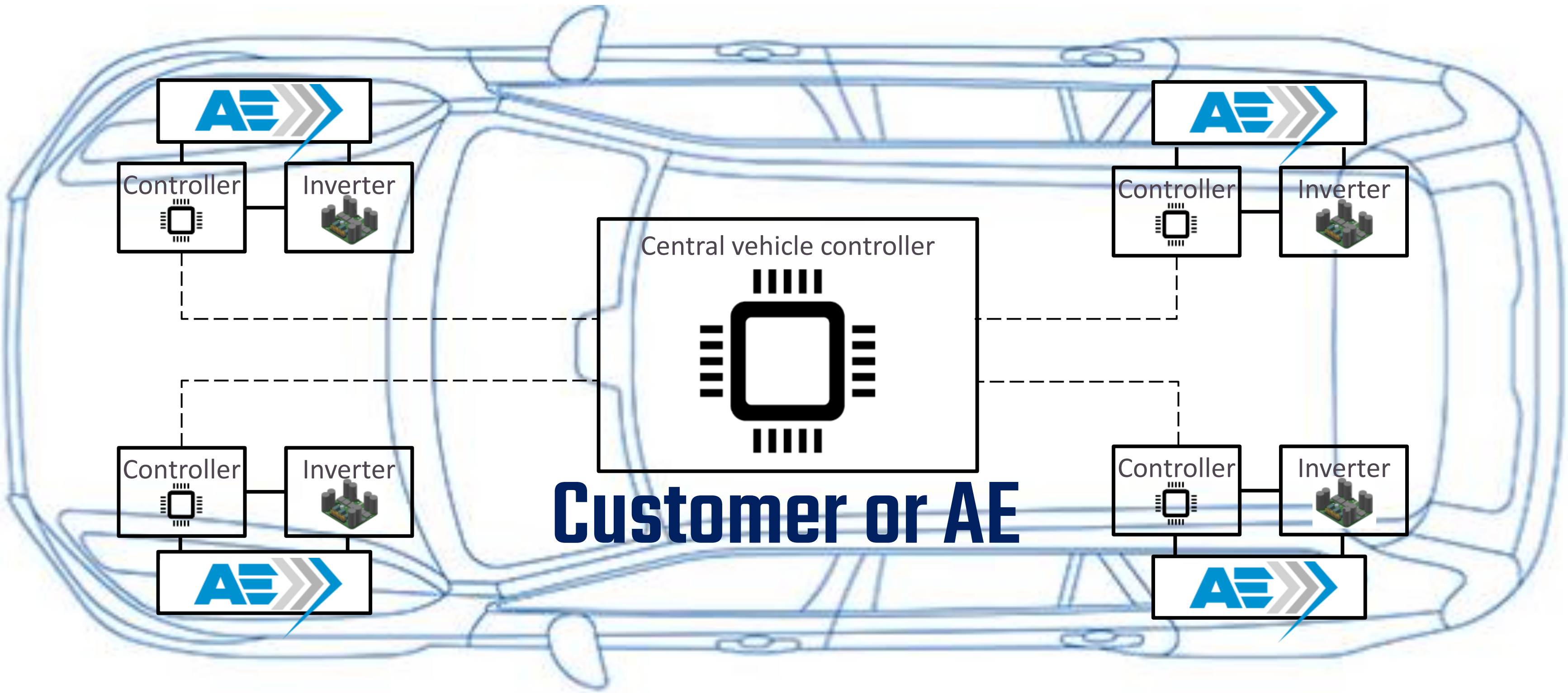






ELECTROMAGNETIC ACTIVE SUSPENSION >>

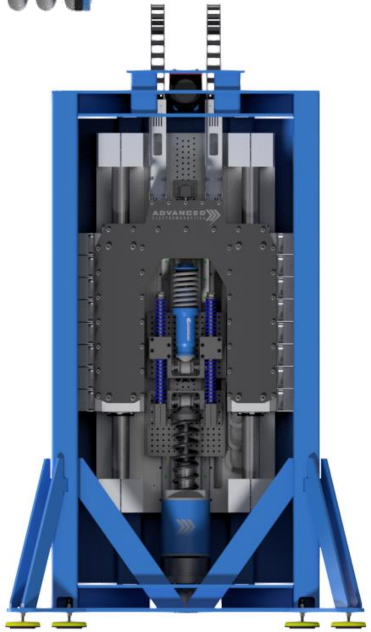
WHAT DOES AE SUSPENSION OFFER



WHAT DOES AE SUSPENSION OFFER

- **Active suspension strut**
  - Electric actuator
  - Drive (controller and inverter)

- **Test rig**
  - Dedicated high bandwidth Quarter Car test system



- **Concept Demonstration Vehicle**
  - Retrofit of existing vehicle with full active suspension

AE-Suspension

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>> Motion By Innovation

Thank You, Danke, Bedankt, Merci

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