ECE330: Power Circuits & Electromechanics

Lecture 17. Energy conversion cycles

Prof. Richard Y. Zhang
Univ. of Illinois at Urbana-Champaign
ryz@illinois.edu

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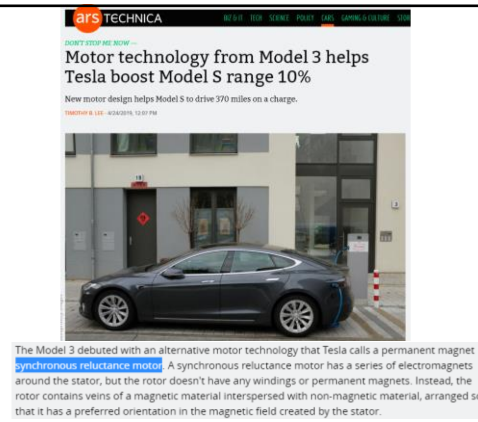
ars TECHNICA

DON'T STOP ME NOW —

Motor technology from Model 3 helps Tesla boost Model S range 10%

New motor design helps Model S to drive 370 miles on a charge.

TIMOTHY B. LEE - 4/24/2019, 12:07 PM

The Model 3 debuted with an alternative motor technology that Tesla calls a permanent magnet synchronous reluctance motor. A synchronous reluctance motor has a series of electromagnets around the stator, but the rotor doesn't have any windings or permanent magnets. Instead, the rotor contains veins of a magnetic material interspersed with non-magnetic material, arranged so that it has a preferred orientation in the magnetic field created by the stator.

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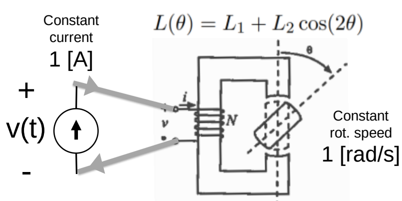
Last time: Rotating reluctance machine

$L(\theta) = L_1 + L_2 \cos(2\theta)$



Input $P_e = vi$ → Output $P_m = f\dfrac{\mathrm{d}x}{\mathrm{d}t}$

Stored energy

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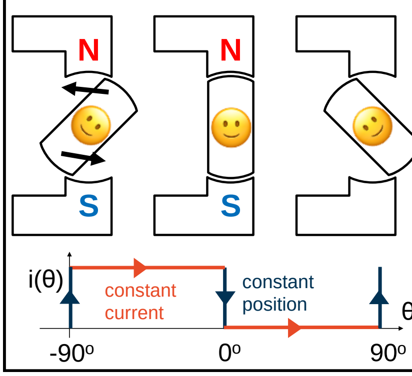
Last time: Switched reluctance system



Today: **How much power?**

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Line integral definition of energy

$$\mathrm{Energy}(\lambda_1, x_1) - \mathrm{Energy}(\lambda_0, x_0)$$
$$= \int_C \underline{F}(\underline{r}) \cdot \mathrm{d}\underline{r} = \int_C i(\lambda, x)\,\mathrm{d}\lambda + \int_C -f(\lambda, x)\,\mathrm{d}x$$

Path independent (via conservation)

Energy From Electrical

Energy From Mechanical

△ Path dependent

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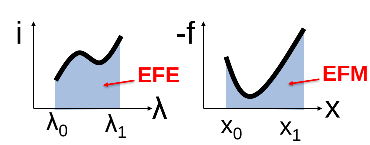
Trajectories and force diagrams

$$\mathrm{Energy}(\lambda_1, x_1) - \mathrm{Energy}(\lambda_0, x_0)$$
$$= \int_C \underline{F}(\underline{r}) \cdot \mathrm{d}\underline{r} = \int_C i(\lambda, x)\,\mathrm{d}\lambda + \int_C -f(\lambda, x)\,\mathrm{d}x$$

Monday:
1. Draw trajectory from description
2. Draw force diagrams from trajectory

Friday: Analyze electrical machines as a sequence of trajectories



ΔE = EFE + EFM

Function of start and end

Function of entire trajectory

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Today

- Example: Switched reluctance machine
- Example: Linear actuator

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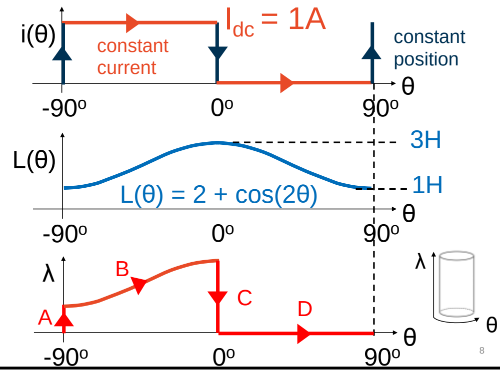
Reluctance machine conversion cycle



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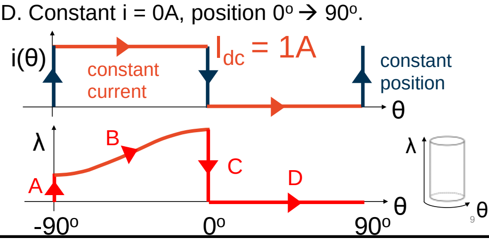
Reduction to EFE / EFM problem

L(θ) = 2 + cos(2θ). Find the EFE / EFM:

- A. Constant θ = -90º, current 0 → 1A.
- B. Constant i = 1A, position -90º → 0º.
- C. Constant θ = 0º, current 1A → 0A.
- D. Constant i = 0A, position 0º → 90º.



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Reduction to EFE / EFM problem

L(θ) = 2 + cos(2θ). Find the EFE / EFM:

A. Constant θ = -90º, current 0 → 1A.

L'(θ) = $\frac{\partial L}{\partial \theta}$ = – 2sin(2θ).

$\tau^e = \frac{\partial}{\partial \theta}\left\{\frac{1}{2}L(\theta)i^2\right\}$ = – i²sin(2θ).

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Reduction to EFE / EFM problem

L(θ) = 2 + cos(2θ). Find the EFE / EFM:

B. Constant i = 1A, position -90º → 0º.

L'(θ) = $\frac{\partial L}{\partial \theta}$ = – 2sin(2θ).

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Reduction to EFE / EFM problem

L(θ) = 2 + cos(2θ). Find the EFE / EFM:

C. Constant θ = 0º, current 1A → 0A.

L'(θ) = $\frac{\partial L}{\partial \theta}$ = – 2sin(2θ).

$\tau^e = \frac{\partial}{\partial \theta}\left\{\frac{1}{2}L(\theta)i^2\right\}$ = – i²sin(2θ).

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Reduction to EFE / EFM problem

L(θ) = 2 + cos(2θ). Find the EFE / EFM:

D. Constant i = 0A, position 0º → 90º.

L'(θ) = $\frac{\partial L}{\partial \theta}$ = – 2sin(2θ).

$\tau^e = \frac{\partial}{\partial \theta}\left\{\frac{1}{2}L(\theta)i^2\right\} = -i^2\sin(2\theta)$.

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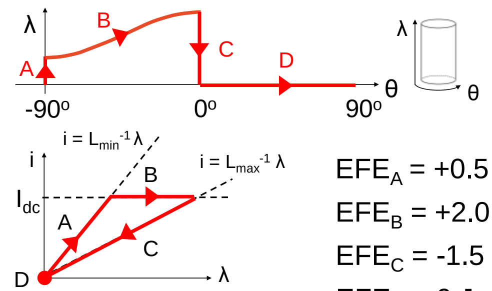
Reduction to EFE / EFM problem



L(θ) = 2 + cos(2θ) H

I_{dc} = 1 A

EFE_A = +0.5 J

EFE_B = +2.0 J

EFE_C = -1.5 J

EFE_D = 0 J

EFE_{ABCD} = +1 J

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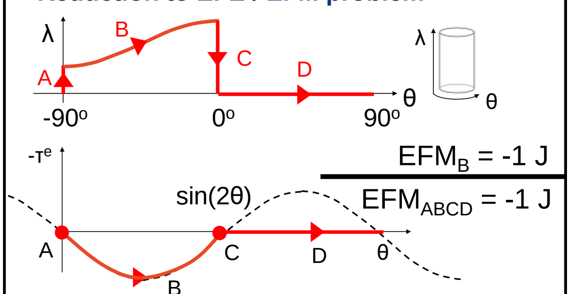
Reduction to EFE / EFM problem



EFM_B = -1 J

EFM_{ABCD} = -1 J

τ^e = – i^2sin(2θ) Nm

I_{dc} = 1 A

$EFE_{cycle} + EFM_{cycle} = 0$

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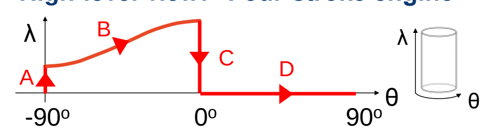
High-level view: "Four-stroke engine"



Input $P_e = vi$ → Output $P_m = f\frac{dx}{dt}$

Stored energy

	A	B	C	D
EFE [J]	+1/2 J	+2 J	-3/2 J	0
EFM [J]	0	-1 J	0	0

Av. power out = 1 J / half-cycle = **120 W @ 60 Hz**

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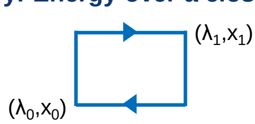
Summary: Energy over a closed loop



$$\text{Energy}(\lambda_1, x_1) - \text{Energy}(\lambda_1, x_1)$$

$$= \underbrace{\oint_C \underline{F}(\underline{r}) \cdot d\underline{r}}_{=0} = \underbrace{\oint_C i(\lambda, x)\, d\lambda}_{EFE|_{cycle}} + \underbrace{\oint_C -f(\lambda, x)\, dx}_{EFM|_{cycle}}$$

Motor elec → mech: $\text{EFE}|_{\text{cycle}} > 0, \quad \text{EFM}|_{\text{cycle}} < 0$

Generator mech → elec: $\text{EFE}|_{\text{cycle}} < 0, \quad \text{EFM}|_{\text{cycle}} > 0$

⚠ Positive = power input, negative = power output

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Today

- ~~Example: Switched reluctance machine~~
- Example: Linear actuator

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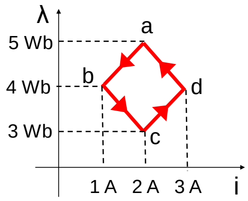
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



Game plan
- Get formula for energy
- Evaluate energy at each node
- For each path
  - ΔE = EFE + EFM
  - EFE = $\int i \, d\lambda$

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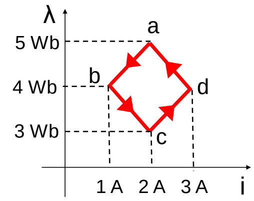
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



$E_a = 5J$, $E_b = 2J$, $E_c = 3J$, $E_d = 6J$

Game plan
- ~~Get formula for energy~~
- ~~Evaluate energy at each node~~
- For each path
  - ΔE = EFE + EFM
  - EFE = $\int i \, d\lambda$

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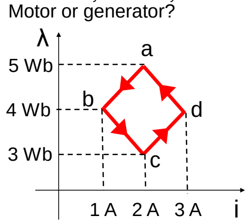
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



$E_a = 5J$, $E_b = 2J$, $E_c = 3J$, $E_d = 6J$

$EFE_{a\to b} = -1.5J$,
$EFM_{a\to b} = -1.5J$,

Game plan
- ~~Get formula for energy~~
- ~~Evaluate energy at each node~~
- For each path
  - ΔE = EFE + EFM
  - EFE = $\int i \, d\lambda$

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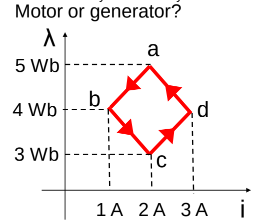
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



$E_a = 5J$, $E_b = 2J$, $E_c = 3J$, $E_d = 6J$

$EFE_{a\to b} = -1.5J$, $EFE_{b\to c} = -1.5J$,
$EFM_{a\to b} = -1.5J$, $EFM_{b\to c} = +2.5J$,

Game plan
- ~~Get formula for energy~~
- ~~Evaluate energy at each node~~
- For each path
  - ΔE = EFE + EFM
  - EFE = $\int i \, d\lambda$

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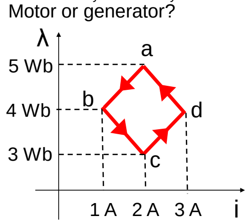
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



$E_a = 5J$, $E_b = 2J$, $E_c = 3J$, $E_d = 6J$

$EFE_{a\to b} = -1.5J$, $EFE_{b\to c} = -1.5J$, $EFE_{c\to d} = +2.5J$,
$EFM_{a\to b} = -1.5J$, $EFM_{b\to c} = +2.5J$, $EFM_{c\to d} = +0.5J$,

Game plan
- ~~Get formula for energy~~
- ~~Evaluate energy at each node~~
- For each path
  - ΔE = EFE + EFM
  - EFE = $\int i \, d\lambda$

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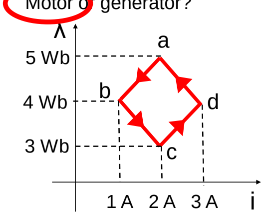
Linear actuator

$\lambda(i,x) = 5i/x$.
Find EFE_{cycle}, EFM_{cycle}.
Motor or generator?



$E_a = 5J$, $E_b = 2J$, $E_c = 3J$, $E_d = 6J$

$EFE_{a\to b} = -1.5J$, $EFE_{b\to c} = -1.5J$, $EFE_{c\to d} = +2.5J$,
$EFM_{a\to b} = -1.5J$, $EFM_{b\to c} = +2.5J$, $EFM_{c\to d} = +0.5J$,

Game plan
- ~~Get formula for energy~~
- ~~Evaluate energy at each node~~
- ~~For each path~~
  - ~~ΔE = EFE + EFM~~
  - ~~EFE = ∫ i dλ~~

$\mathbf{EFE_{cycle} = -1.5 -1.5 + 2.5 + 2.5 = +2\ J}$

$\mathbf{EFM_{cycle} = -1.5 +2.5 + 0.5 - 3.5 = -2\ J}$

$EFE_{d\to a} = +2.5J$,
$EFM_{d\to a} = -3.5J$,

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