Karlsruhe Institute of Technology

Institute of Electrical Engineering (ETI)
Hybrid Electric Vehicles
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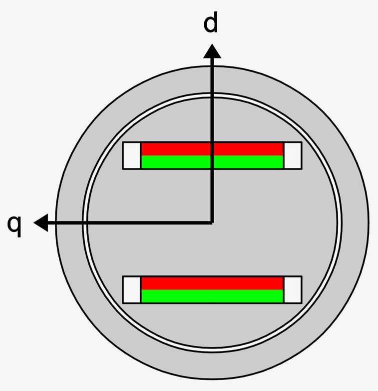
Hybrid Electric Vehicles

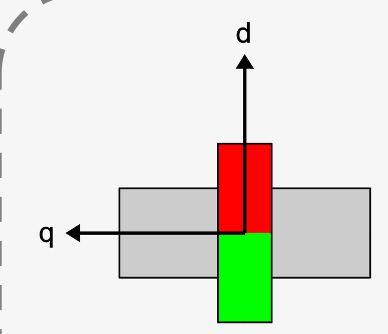
Theoretical Analysis of Synchronous Machines with Displaced Reluctance Axis

Patrick Winzer, Martin Doppelbauer

Conventional IPMSM

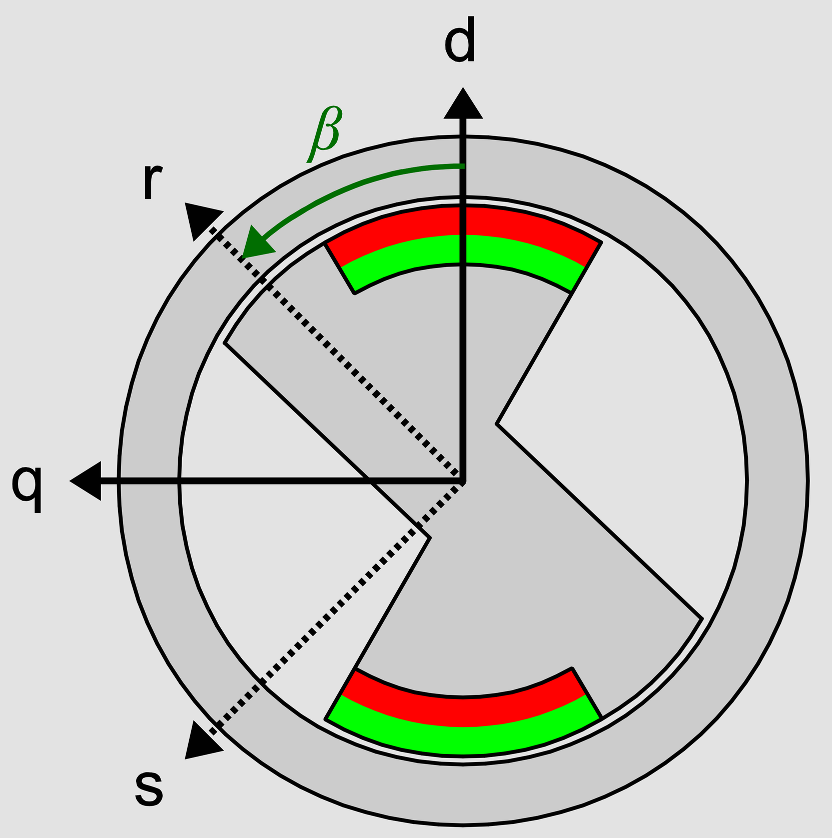


example geometry

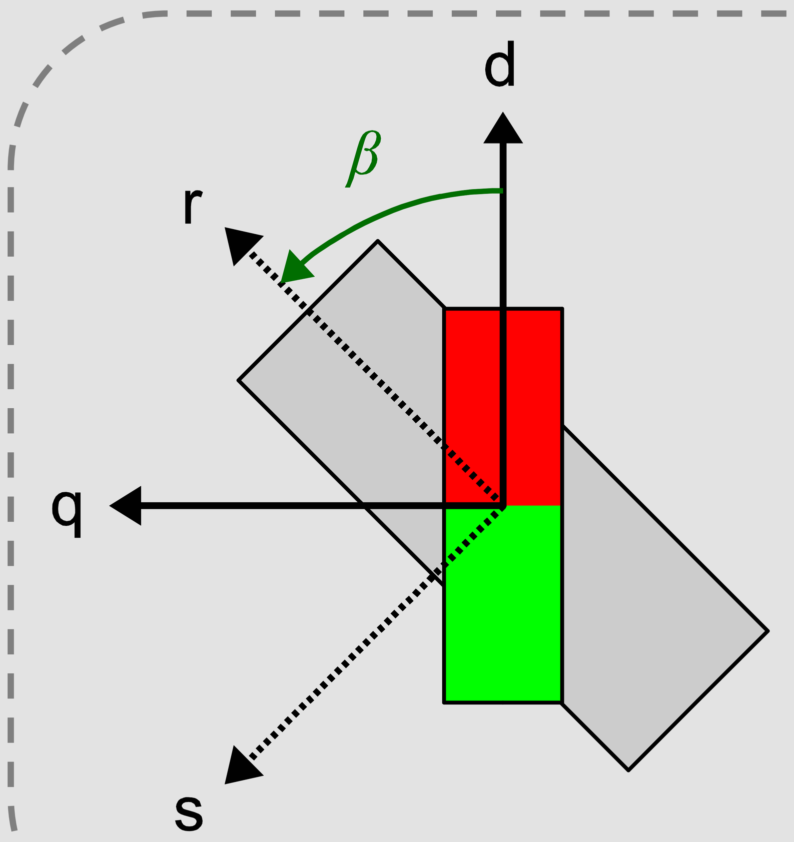


simplified model

PMSM with Displaced Reluctance Axis (Magnetically Asymmetric)

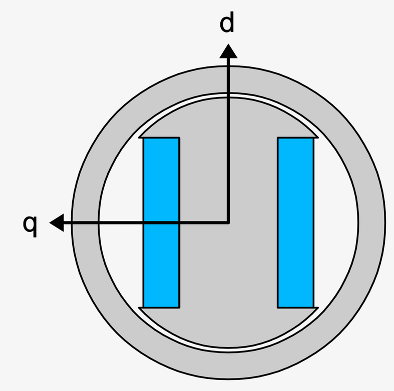


example geometry

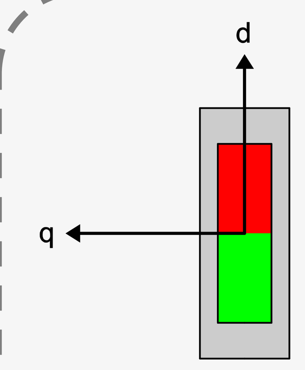


simplified model

Conventional EESM



example geometry



simplified model

Unified Theory

Assumptions

- no losses (no stator resistance)
- iron is linear (no saturation)
- no harmonics (no torque ripple)
- current feeding

Description

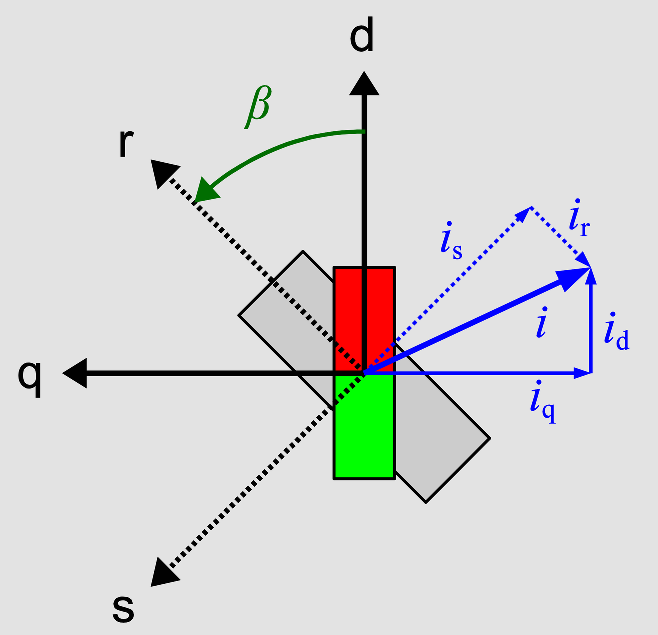
- normalized PM flux linkage: ψ_{PM}
- saliency (ratio of inductances): $\zeta = \frac{l_r}{l_s}$
- displacement angle (d→r): β

Special Cases

- conventional IPMSM: $\beta = 90°$
- conventional EESM: $\beta = 0°$

Transformation

$$i_\mathrm{r} = i_\mathrm{d} \cdot \cos\beta + i_\mathrm{q} \cdot \sin\beta$$
$$i_\mathrm{s} = -i_\mathrm{d} \cdot \sin\beta + i_\mathrm{q} \cdot \cos\beta$$



Normalized Machine Model

$i_\mathrm{r}, i_\mathrm{s}, n$ → $\zeta, \psi_{\mathrm{PM}}, \beta$ → $\psi_\mathrm{r}, \psi_\mathrm{s}, u_\mathrm{r}, u_\mathrm{s}, t, p$

input quantities | parameters | output quantities

resulting electrical quantities

$$\psi_\mathrm{r} = \psi_{\mathrm{PM}} \cdot \cos\beta + l_\mathrm{r} \cdot i_\mathrm{r} \qquad u_\mathrm{r} = -n\psi_\mathrm{s}$$
$$\psi_\mathrm{s} = -\psi_{\mathrm{PM}} \cdot \sin\beta + \zeta^{-1} l_\mathrm{r} \cdot i_\mathrm{s} \qquad u_\mathrm{s} = n\psi_\mathrm{r}$$

l_r is a function of ψ_{PM}, ζ and β

resulting mechanical quantities

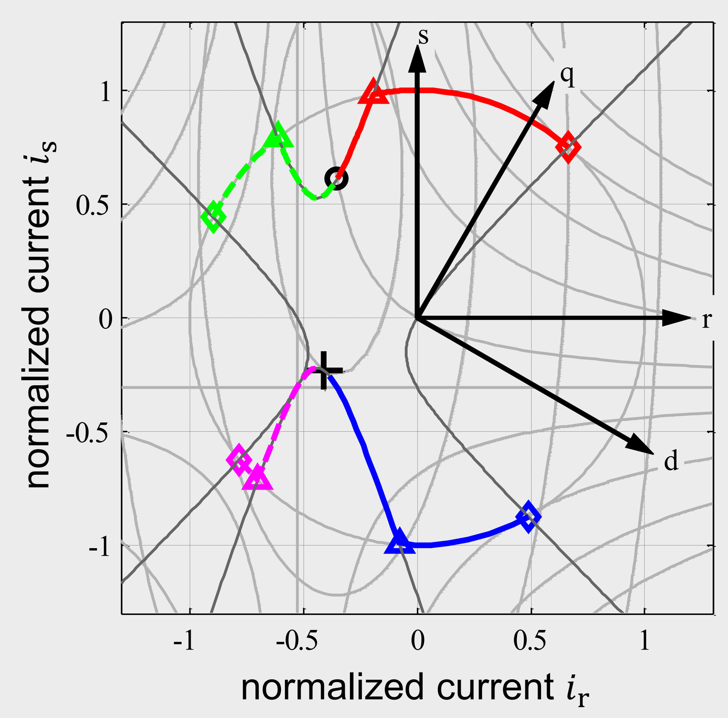
$$t = \psi_{\mathrm{PM}}(i_\mathrm{s}\cos\beta + i_\mathrm{r}\sin\beta) + l_\mathrm{r}(1-\zeta^{-1}) i_\mathrm{r} i_\mathrm{s} \qquad p = t \cdot n$$

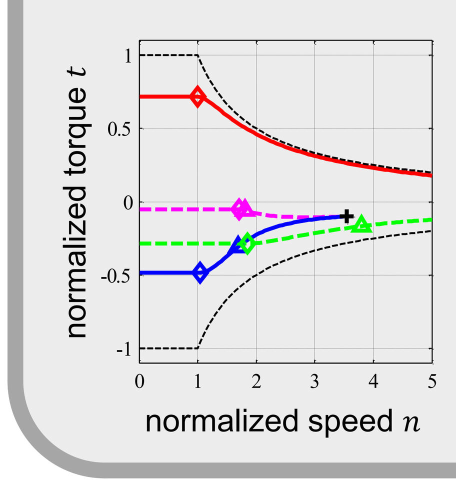
constraints:

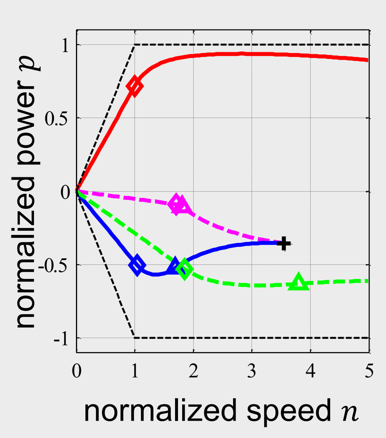
$$u = \sqrt{u_\mathrm{r}^2 + u_\mathrm{s}^2} \le 1 \qquad i = \sqrt{i_\mathrm{r}^2 + i_\mathrm{s}^2} \le 1$$

Control Strategies

example machine with $\psi_{\mathrm{PM}} = 0.4$, $\zeta = 3$, $\beta = 30°$

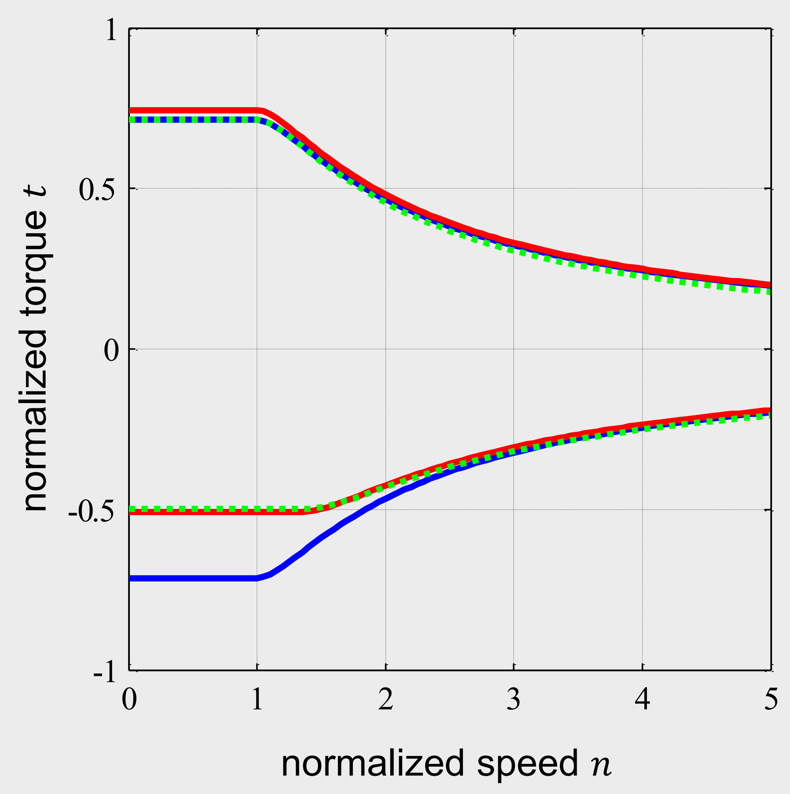






Machine Design I: t-Curves

advantages through variation of the displacement angle β



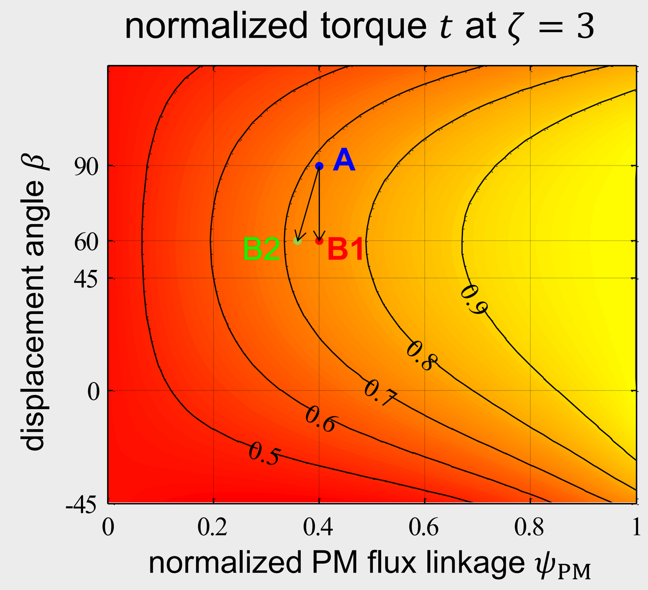
A: initial machine design:
$\psi_{\mathrm{PM}} = 0.4$, $\zeta = 3$, $\beta = 90° \rightarrow t = 0.71$

B1: improved performance:
$\psi_{\mathrm{PM}} = 0.4$, $\zeta = 3$, $\beta = 60° \rightarrow \boldsymbol{t = 0.74}$

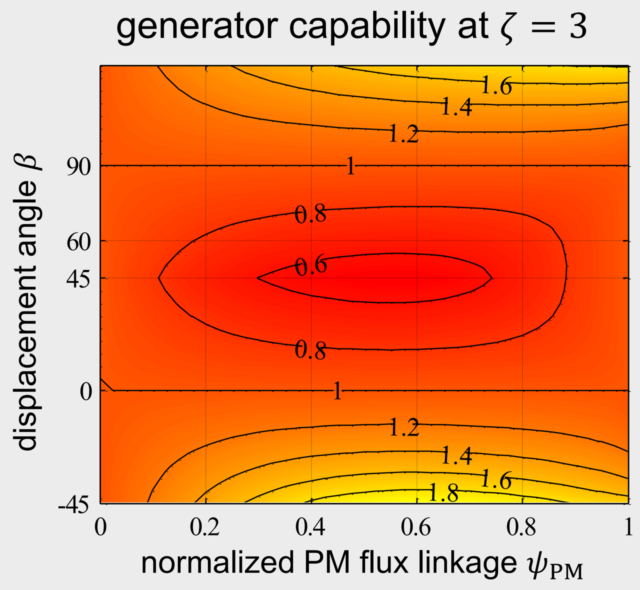
B2: reduced PM material, equal torque:
$\boldsymbol{\psi_{PM} = 0.35}$, $\zeta = 3$, $\beta = 60° \rightarrow t = 0.71$

Machine Design II: Parameter Planes

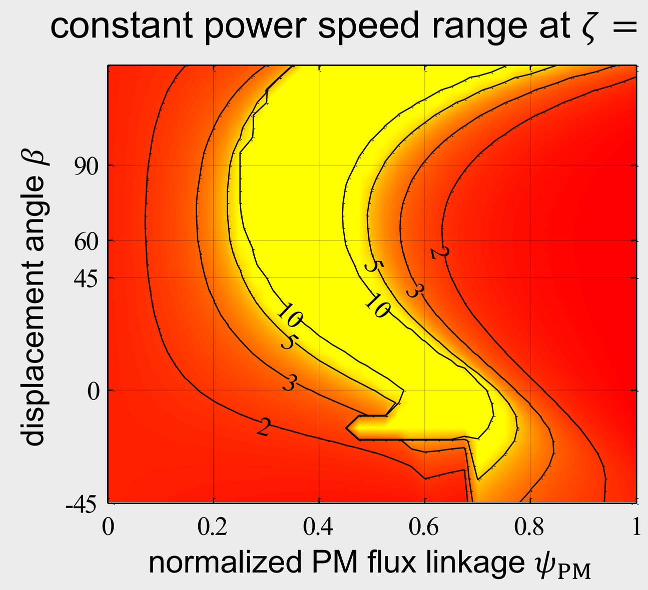
normalized torque t at $\zeta = 3$



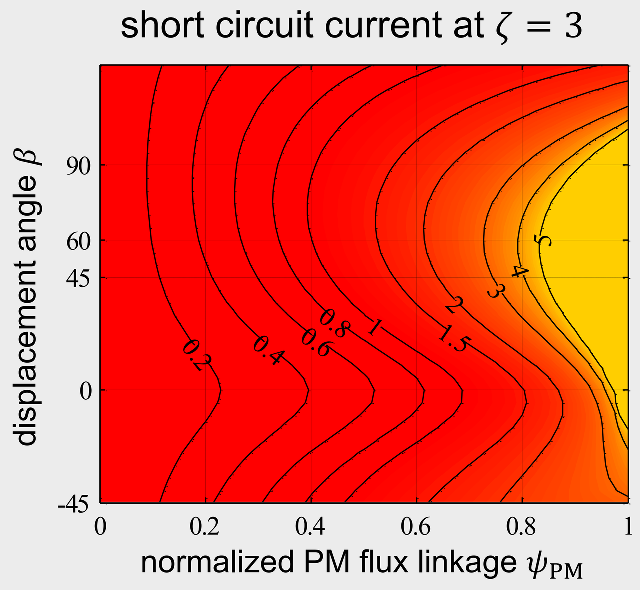
generator capability at $\zeta = 3$



constant power speed range at $\zeta = 3$



short circuit current at $\zeta = 3$



Conclusion

- **unified theory** of synchronous machines with displaced reluctance axis, dependent on **only three parameters**
- derivation of optimal torque **control strategies**
- further degree of freedom for **machine design**:
  - optimization of cost (e.g. case B1: **11.4% less PM material** for equal torque)
  - optimization of performance (e.g. case B2: **4.3% more torque** using the same amount of PM)