Hybrid vehicles - Concepts and Future Developments

Kay HAMEYER, Thomas FINKEN
Institute of Electrical Machines, RWTH Aachen University

Sigrid JACOBS, Marc DE WULF, Patrick GOES
ArcelorMittal

Contents

- overview: hybrid systems
  - functionality, configuration, advantages and disadvantages
- overview: typically used electrical machines
  - advantages and disadvantages, evaluation
  - choice of the used electrical machine type
  - different types of PMSM
- the issue of losses
  - iron losses
  - losses in permanent magnets
- steel requirements in HEV

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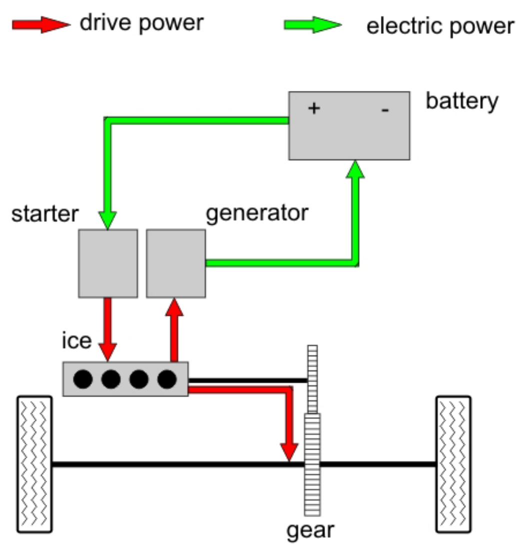
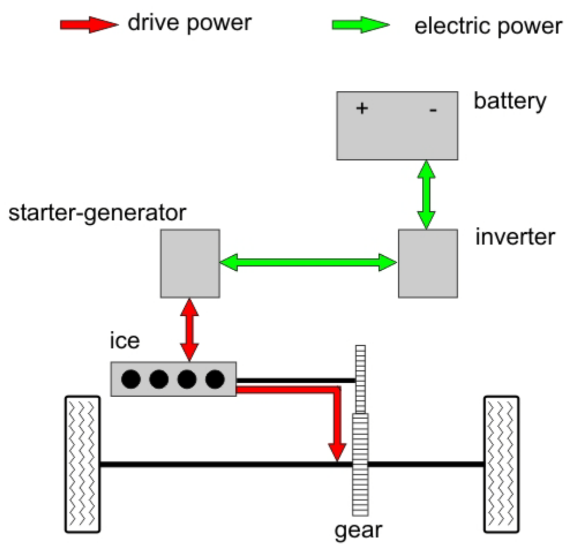
Overview: hybrid systems

conventional system



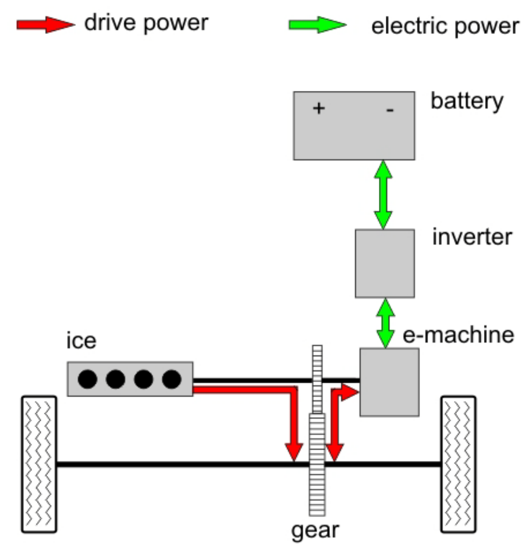
- starter (DC-machine; 1-2.5 kW) starts ICE
- generator (Lundell, clawpole-alternator; 1-3kW) power supply for electrical equipment, charges battery

micro hybrid system



- starter-generator combines starting and power supply operation (2-3 kW)
- functionality:
  - fast start/stop of ICE
  - generator operation

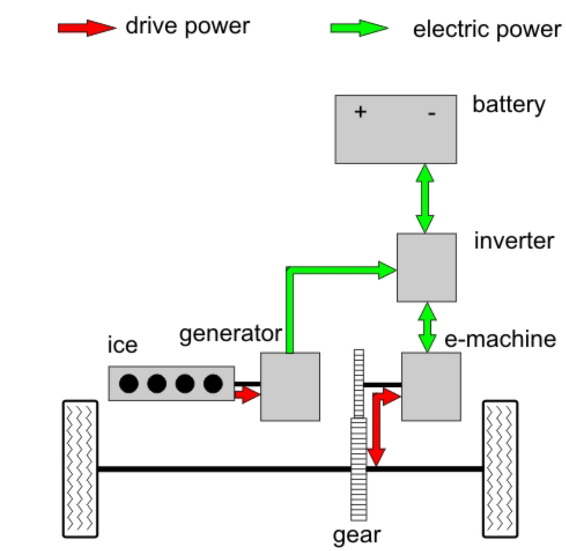
mild hybrid system



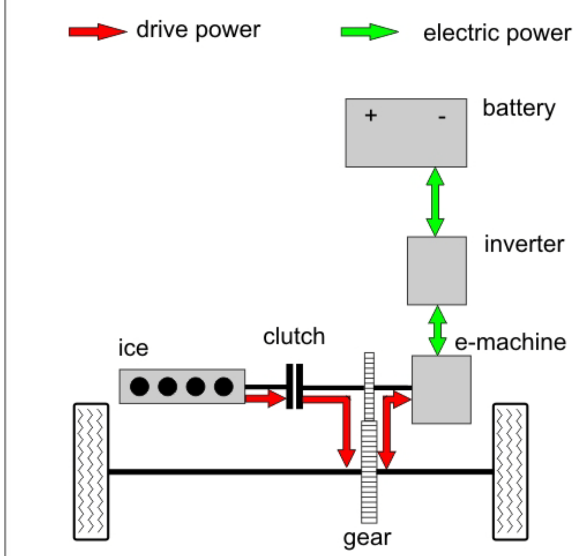
- electrical machine (10-15 kW) integrated in the drivetrain
- functionality
  - start/stop
  - generator operation
  - boost operation
  - recuperation

Overview: hybrid systems

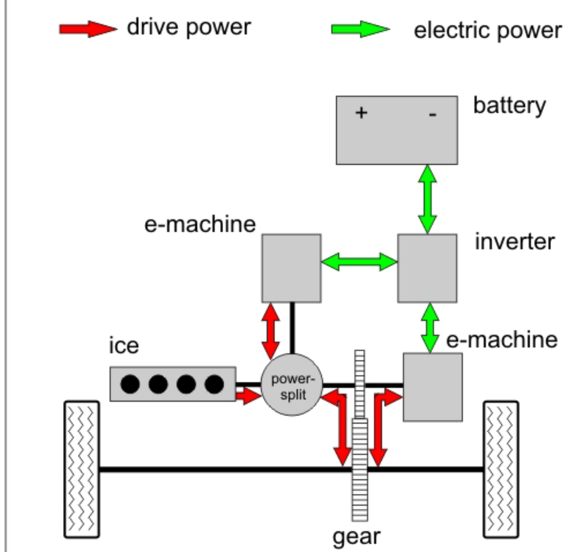
series hybrid system



parallel hybrid system



series parallel hybrid system / power split



Series hybrid system:

+ ICE in optimal operating point
+ drive without ICE is possible
  → „zero emission“
+ good weight arrangement is possible, due to separate arrangement of the machines and the engine
- several transformations of energy
  → lower overall efficiency

Parallel hybrid system:

- ICE mechanically connected to the wheels
  → gear
+ less transformations of energy
  → better overall efficiency than series system
+ “down-sizing” of the ICE is possible
+ four operating points available:
  • electrical traction
  • ICE-traction
  • ICE-traction + charging of battery
  • electrical- and ICE-traction („boost” at peak load)

Series parallel hybrid system / power split:

+ continuous combination of series and parallel hybrid system
  → overall efficiency like parallel hybrid system
+ “down-sizing” is possible
  → less frictional losses
  → better overall efficiency
- no conventional drivetrain (planetary gear), more complicated

Overview: hybrid systems

most widely applied concepts are:

mild hybrid

- intermediate step between conventional and full hybrid system
- only small-power electrical machine (not rated for electrical traction)
- fuel save of about 10-15% (start/stop, recuperation)

parallel hybrid

- better overall efficiency than series system
- electrical traction, ICE-traction, ICE-traction + charging the battery, boost
- fuel save > 15%

power-split hybrid

- continuous combination of series and parallel hybrid system
- best fuel save > 20%

fuel-save capability depends on electrical power

→ the higher the hybridization the better the fuel save

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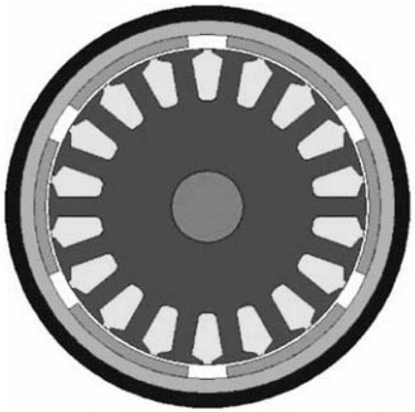
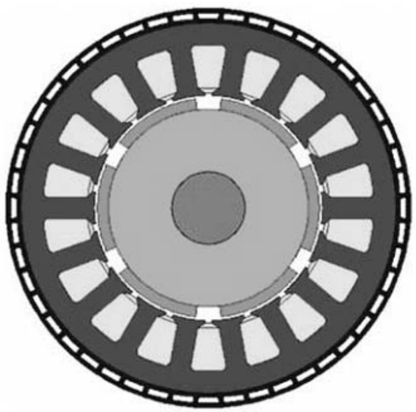
Overview: typically used machines

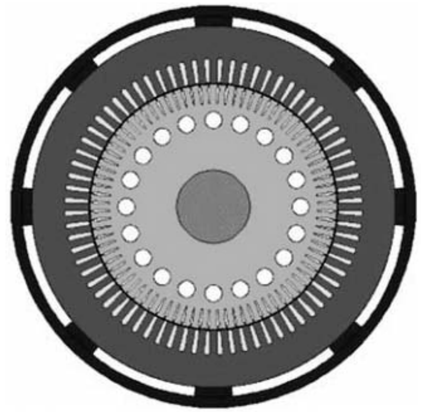
DC



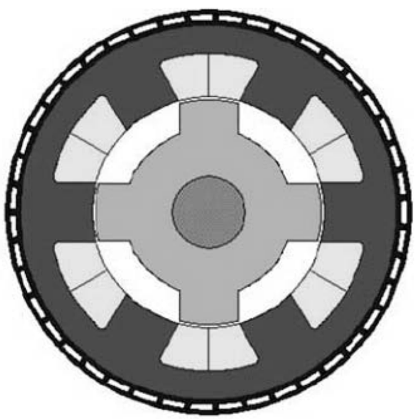
PMSM / BLDC



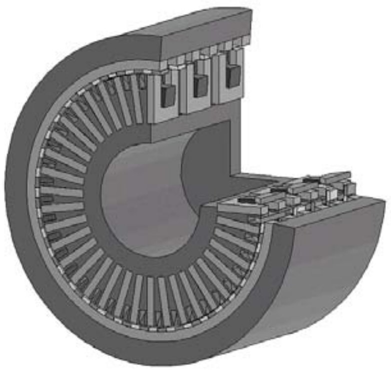
IM

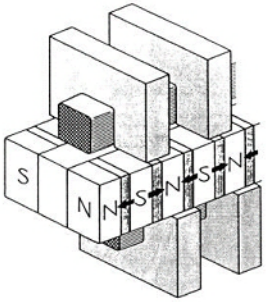


SRM



transverse-flux machine





Overview: typically used machines

HEV	driveline	HEV	driveline
PSA Peugot-Citroen / Berlingo Dynavolt (Frankreich) 	DC (1999, series)	VW / Touran Eco.Power II (Deutschland) 	PMSM (2006,parallel)
Holden / ECOmmodore (Australien) 	SRM (2002, parallel)	Mazda / Tribute (Japan) 	PMSM (2007, power split)
Nissan / Tino (Japan) 	PMSM (2000, parallel+CVT)	Renault / Kangoo (Frankreich) 	IM (2003, series)
Ford / Mariner (USA) 	PMSM (2006, power split)	Dodge,DaimlerChrysler / Durango (Deutschland/USA) 	IM (2007,TTR)
Toyota / Prius (Japan) 	PMSM (1997, power-split)	BMW / X5 (Deutschland) 	IM (2004, parallel)

Examples of hybrid vehicles:

- all configuration types are available on the market

- car producers use different motor types → they evaluate the concepts differently

- comparative analysis of all motor types is necessary to acquire a good understanding of the different concepts

Overview: typically used machines

	IM		SRM		PMSM / BLDC	
	motor	converter	motor	converter	motor	converter
efficiency	+	-	- / 0	0	+	+
reliability	+		0		-	
power density	-	-	0	0	+	+
torque ripple	+		-		0	
overload capicity	+		- / 0		0	
size	-		0 / +		+	
cost	+	-	0	0 / +	-	0 / +
max. revolution	0		+		-	
controler complexity		- / 0		+		- / 0

IEEE AES Systems Magazine

	DC	IM	PMSM	SRM
max. efficiency (%)	85-89	94-95	95-97	90
efficiency (load 10%) (%)	80-87	79-85	90-92	78-86
max. revolution (rpm)	4000-6000	9000-15000	4000-10000	15000
cost/torque ($/kW)	10	8-12	10-15	6-10
cost of controller	1	3.5	2.5	4.5
reliability	good	best	good	good

Nippon Steel Technical Report

	DC	IM	PMSM	SRM
power density	2,5	3,5	5	3,5
efficiency	2,5	3,5	5	3,5
controllability	5	5	4	3
reliability	3	5	4	5
technolocical maturity	5	5	4	4
cost	4	5	3	4

IEEE Transactions on Vehicular Technology

several published evaluations :

- some differences
- distinctive similarities

points: 1 (min) – 5 (max)

Comparative analysis: conclusion

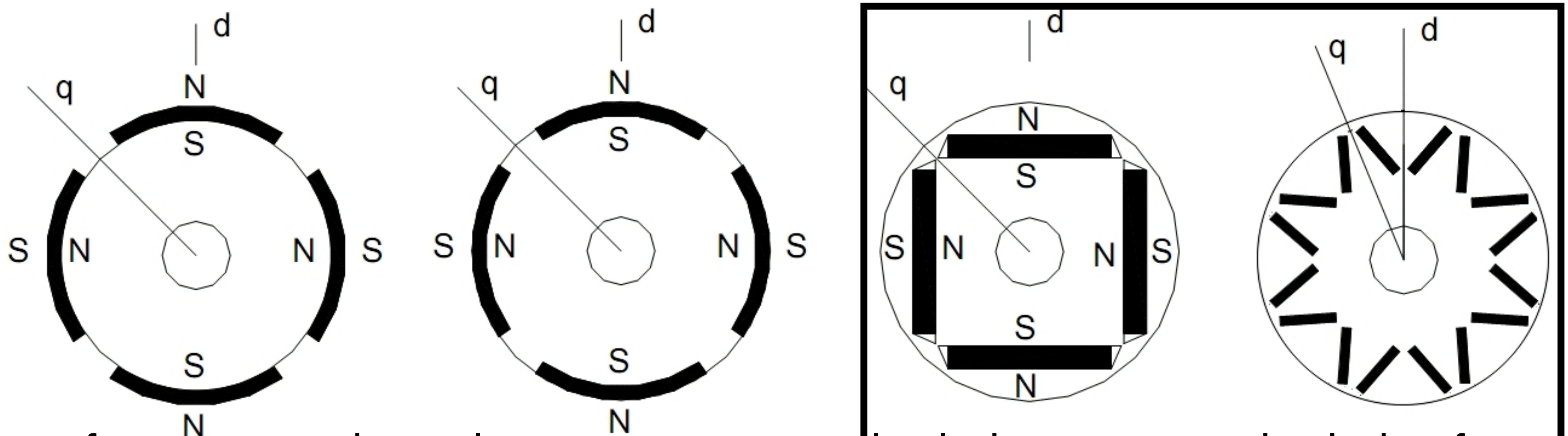
	DC	IM	PMSM	SRM	TFM
power density	- -	O	+ +	O	+ +
efficiency	-	+	+ +	O	
cost	+	+ +	-	+	- -
reliability	O	+ +	O	+	
technolocical maturity	+	+	O	O	
controllability, cost	++	O	+	O	

DC best and inexpensive controllability, bad efficiency and power density
IM inexpensive machine with best reliability
PMSM best efficiency and highest power density, but expensive
SRM good cost and reliability, but has not left prototype status yet (restricted use due to their noise and vibration)
TFM highest power density, but complex design → very expensive

The purpose of hybrid electrical vehicles is to save fuel
→ a high efficiency machine with less weight (high power density) is needed

➔ PMSM most suitable for HEV (mostly used machine type)

Overview: typically used machines

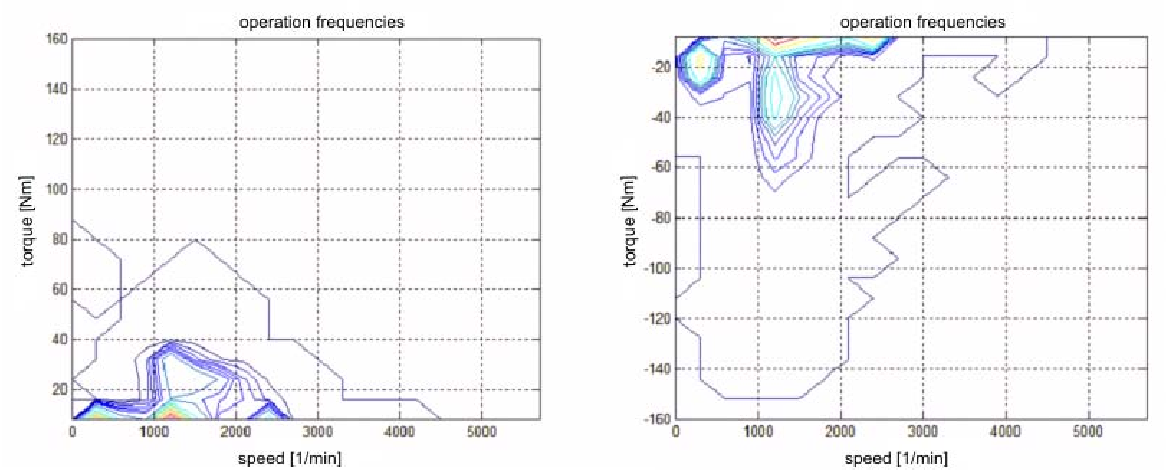


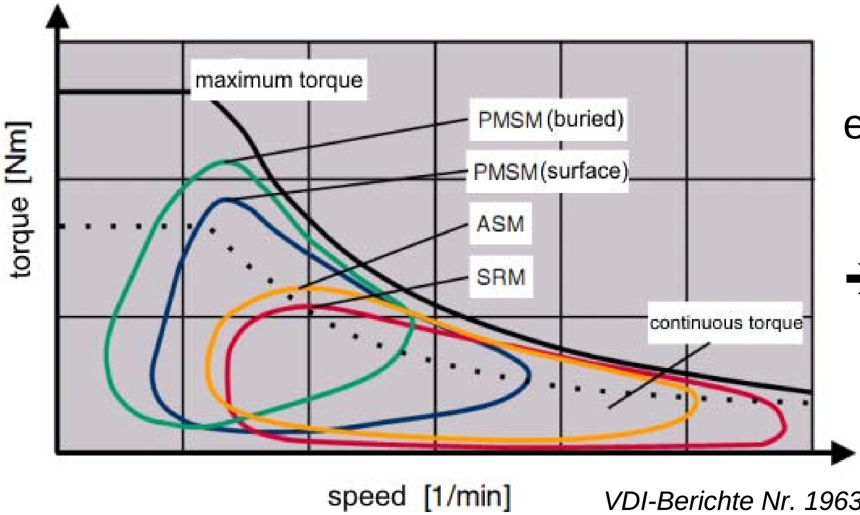
surface mounted — inset magnets — buried magnets — buried, v-form

advantages of buried magnets compared to surface mounted magnets :

- additional reluctance torque due to difference of reactance X_d and X_q
  → increased power factor, wider speed range
- less eddy-current losses in the magnets
- greater overload capability

The choice of motor type depends on the hybrid system
- hybridization (electrical power), installation space, ...
- frequency distribution of the machine's operation points (example of parallel hybrid)





exemplary efficiency map η>85%

➔ PMSM with buried magnets is the best choice in this case

VDI-Berichte Nr. 1963, 2006

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Iron losses in magnetic cores

- Field variation with time in magnetic materials
  → eddy currents → Joule losses
  → hysteresis losses

- Iron losses are reduced by
  → core lamination
  → material choice (soft magnetic)

- Iron losses are a 2[d] order term in the power balance of the system
  → neglected in the FE model
  → calculated by post-processing

Bertotti‘s general formula

$$P_{Fe} = P_h + P_{wb} + P_e$$

- Eddy current losses

$$P_{wb} = \frac{\pi^2 d^2 f^2}{6 \cdot \rho \cdot \rho_e} \int \left(\sum_{\upsilon=1}^{\infty} \upsilon^2 (B_{\upsilon,r}{}^2 + B_{\upsilon,t}{}^2) \right) \mathrm{d}V$$

- Hysteresis losses

$$P_h = \sigma_h \int \left([1 + c(r-1)] f (B_{\max}{}^2 + B_{\min}{}^2) \right) \mathrm{d}V \qquad c = \frac{B_{\min}}{B_{\max}}$$

- Excess losses

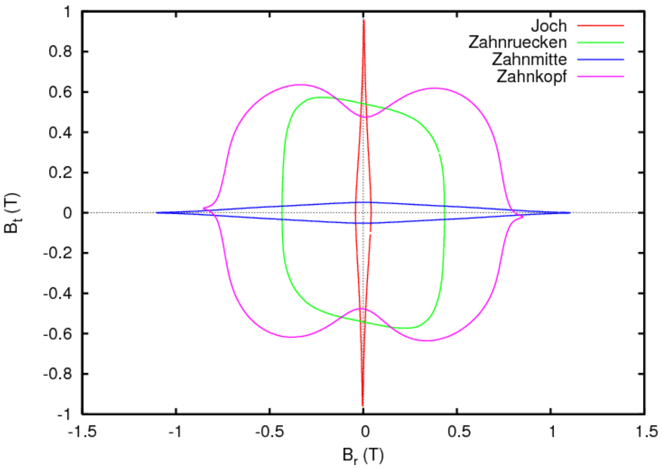
$$P_e = \sigma_e f^{1,5} \int \left(\sum_{\upsilon=1}^{\infty} \upsilon^{1,5} (B_{\upsilon,r}{}^{1,5} + B_{\upsilon,t}{}^{1,5}) \right) \mathrm{d}V$$

Improved model

- Correction for rotational hysteresis

$$P_h = \sigma_h \int \left([1 + c(r-1)] f (B_{\max}{}^2 + B_{\min}{}^2) \right) \mathrm{d}V$$

$$c = \frac{B_{\min}}{B_{\max}}$$



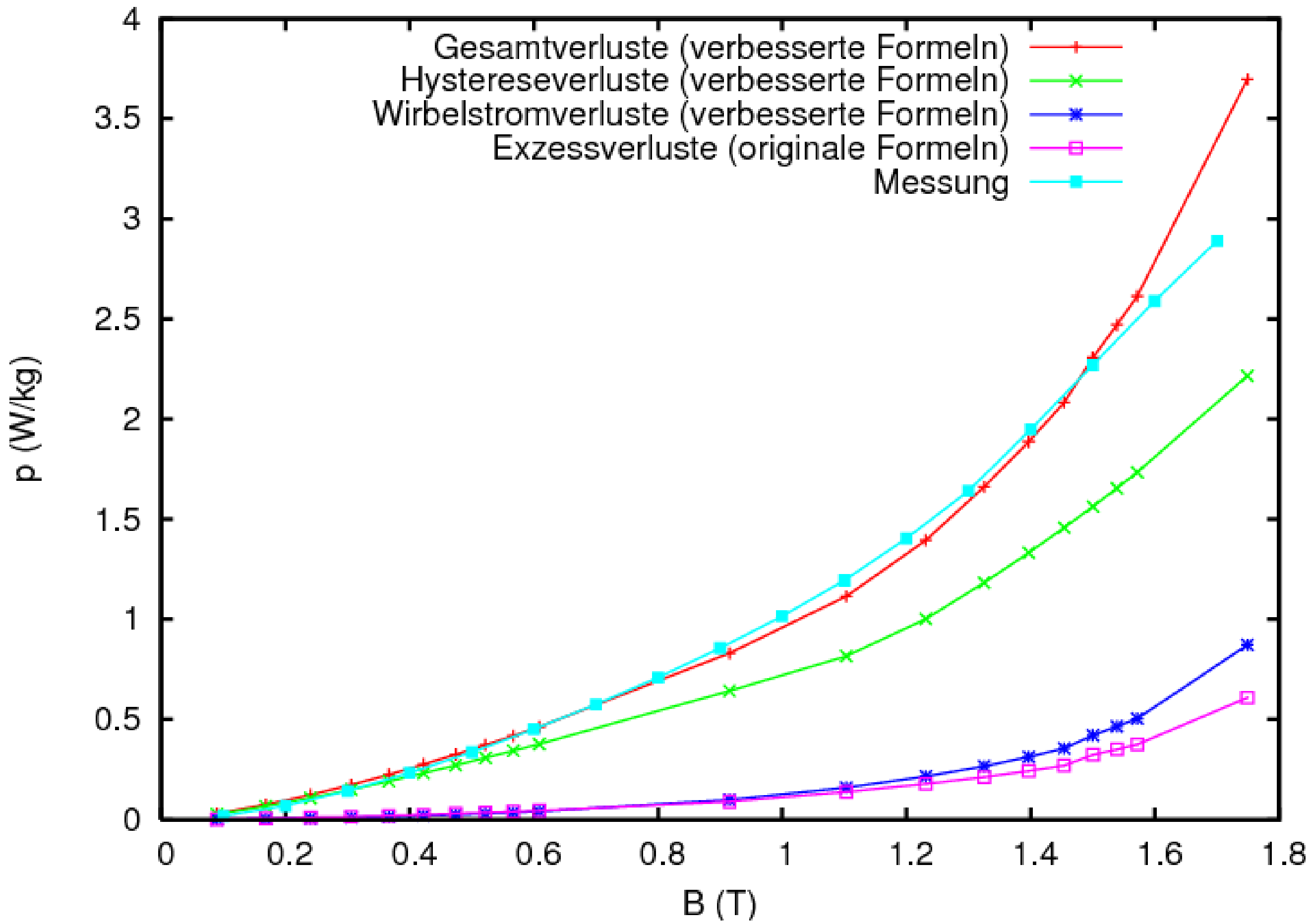
- Correction for skin effect in laminations

$$k_{wb} = \frac{\pi^2 d}{6\rho} \left[\frac{\frac{1}{m}\sinh(md) + \frac{2}{m}\sin(md)}{\cosh(md) + 2\cos(md)} \right]; \qquad k_{wb0} = \frac{\pi^2 d^2}{6\rho}$$

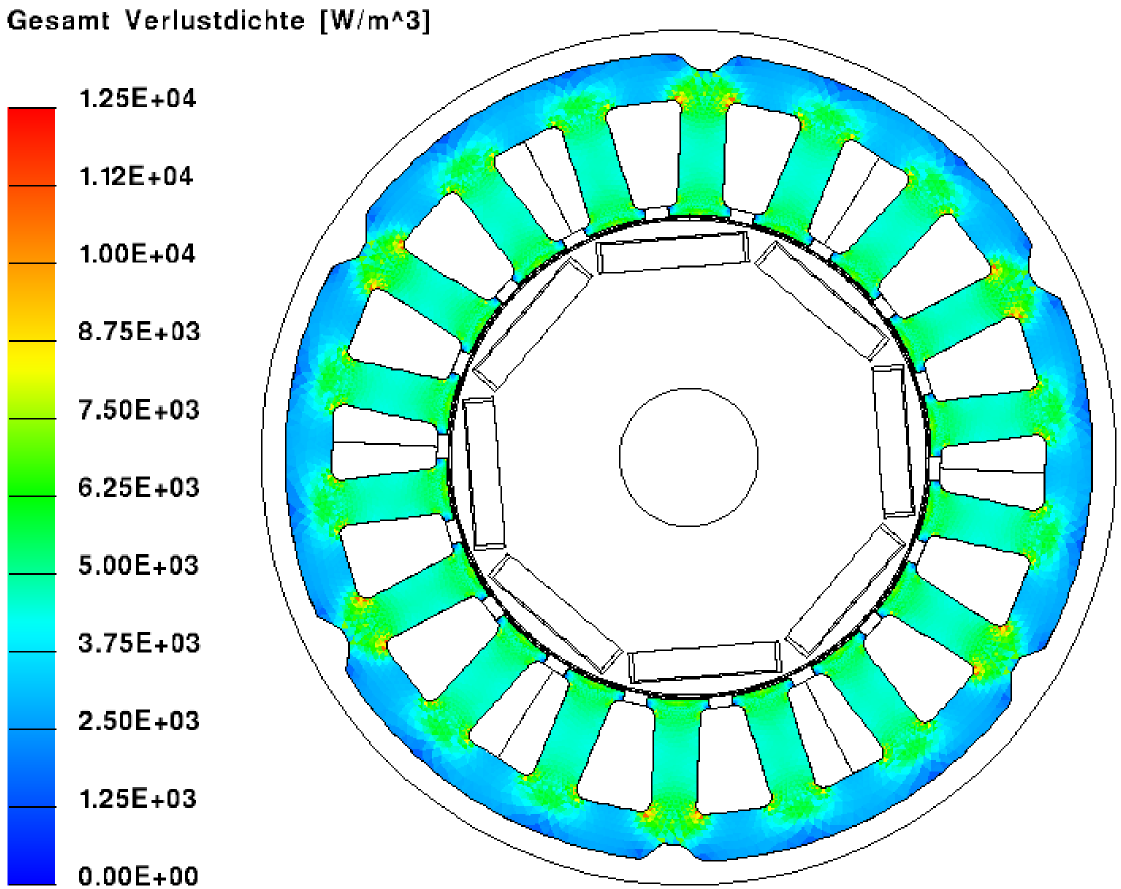
- Correction for hysteresis losses (2→α)

$$P_h = \sigma_h f (B_{\max}{}^{\alpha} + B_{\min}{}^{\alpha})$$

Match between measured losses
and the improved loss model based on Bertotti's formula



Typical iron loss distribution in the stator of a permanent magnet machine.



Losses in permanent magnets

- Plastic bonded and ferrite have a high resistivity
- Resistivity of sintered rare-earth magnets is much lower (typically 0.5-1.5µΩm vs 0.1µΩm for Fe)
- high energy density magnets are thus electrically conductive → Joule losses
- NdFeB magnets demagnetize at about 120 C (up to 200 C)
- Magnet losses can be reduced by segmentation

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steel requirements in HEV

- Hybrid Electrical Vehicles (HEV) are developed to *reduce fuel consumption*, they must assure a *sufficient travel range with a finite battery capacity*, due to the compact assembly and the near combustion engine, the additional *heat development should be as low as possible*
  → a good **efficiency** is required.

- With regard to the reduction of fuel consumption, the *weight of the machine must be as low as possible*,
  high output power at limited installation space is necessary
  → a high **power density** is required.

- The vehicle must assure a *good durability* and a *manageable maintenance*
  → a good **reliability** is required

- The vehicle must be *affordable compared to conventional motor vehicles*
  → inexpensive production, **costs** as low as possible

steel requirements in HEV

improvement of machine parameters and influence of magnetic material:

efficiency	PMSM: high iron loss (smaller copper loss due to less excitation current) → decrease **iron loss** IM: high copper loss (due to excitation current) → better **magnetization** decrease copper loss and total loss common: decreasing **thickness** suppress eddy current loss
reliability	increase **mechanical strength** (e.g. for buried magnets in PMSM) decrease **iron loss** to prevent heat deterioration
power density/ size	increase **magnetic permeability** (to increase torque) decrease **iron loss** to improve cooling demand and decrease the possible size
cost	improve the **punchability** (softer materials make rolling or punching operations easier and extend the life of punching dies)

Thank you for your attention.