Indirekte Wirkungsgradbestimmung bei Permanentmagnet-Synchronmaschinen – Methodik und Anwendungsgebiete

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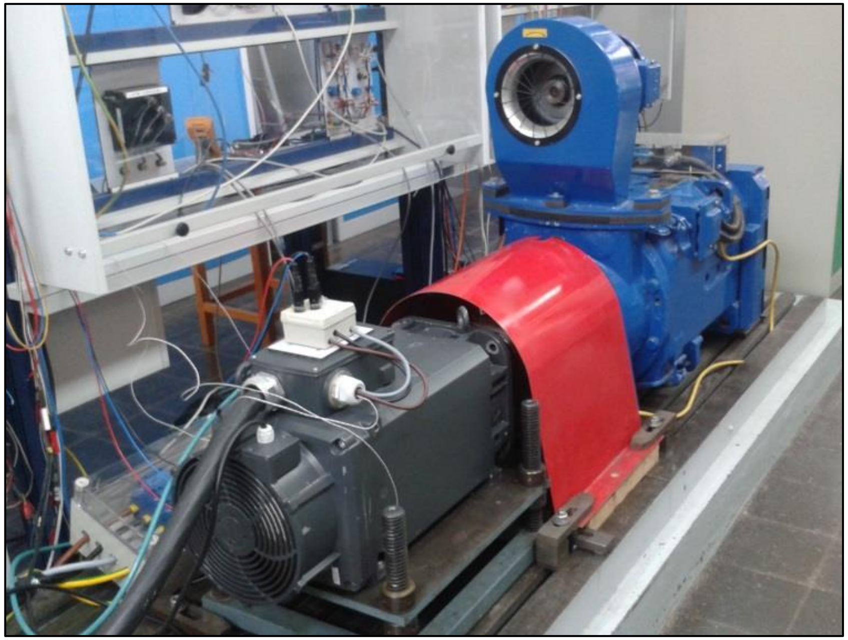

Prüfstand zur Wirkungsgradbestimmung

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Introduction
Motivation

- Large electrical machines: Usually high efficiency
- Two general efficiency determination techniques: Direct vs. indirect

- Example for **direct** determination: $\eta = 95\ \%$, $\epsilon = 0.2\ \%$

$$\eta_{\mathrm{meas}} = \frac{P_{\mathrm{out,meas}}}{P_{\mathrm{in,meas}}} = \frac{P_{\mathrm{out}} \cdot (1+\epsilon)}{P_{\mathrm{in}} \cdot (1-\epsilon)} = \eta \cdot \frac{1+\epsilon}{1-\epsilon} = 0.95 \cdot \frac{1.002}{0.998} = 95.38\ \%$$

- Problem: $\eta > 95\ \%$: Very high measurement accuracy ϵ needed

- Solution: Summation of losses P_{d} from separate single loss measurements
- Example for **indirect** determination of efficiency via $P_{\mathrm{out,meas}} = P_{\mathrm{in,meas}} - P_{\mathrm{d,meas}}$

$$\eta_{\mathrm{meas}} = \frac{P_{\mathrm{in,meas}} - P_{\mathrm{d,meas}}}{P_{\mathrm{in,meas}}} = 1 - \frac{P_{\mathrm{d}}}{P_{\mathrm{in}}} \cdot \frac{1-\epsilon}{1+\epsilon} = 95.02\ \% \approx 95\ \% = \eta$$

- Is this technique applicable for permanent-magnet synchronous machines?

Introduction
Initial situation

- Indirect efficiency determination methods
  - State of the art for large electrical machines with an efficiency $> 95\ \%$
  - Usually lower measurement uncertainty than direct measurement
- Industry standard for permanent magnet synchronous machines:
  Only direct efficiency determination

- Alternative indirect method proposed in 2014
- In coordination with DKE/K 311 committee (Rotating electrical mach.)
- TU Darmstadt / PTB Braunschweig: Method tested on six different PM machines with $P_\mathrm{N} = 7.5\ ...\ 160\ \mathrm{kW}$

Introduction
IEC efficiency measurement: Status quo

Fundamental losses

IEC 60034-2-1
Standard methods for determining losses and efficiency from tests

IEC 60034-2-2
Specific test methods for determining separate losses of large machines

- Induction machines
- Synchronous machines
- DC machines

- Method A: Input-Output
- Method B, C: Summation of losses
- Method D...G: *additional*

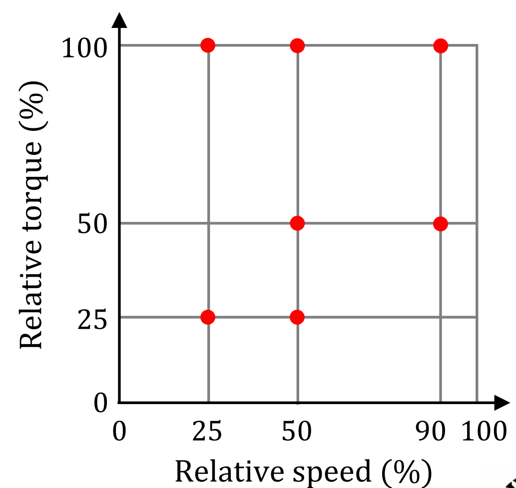
- No-load losses
- Load-dependent losses
- Excitation losses

especially for $P > 2$ MW

Converter-fed motors

IEC 60034-2-3
Specific test methods for converter-fed AC motors

- Additional losses due to current harmonics
- Operation points at variable speed operation



Introduction
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Converter-fed motors

IEC 60034-2-3
Specific test methods for converter-fed AC motors

Induction machines

Synchronous machines

DC machines

Method A: Input-Output

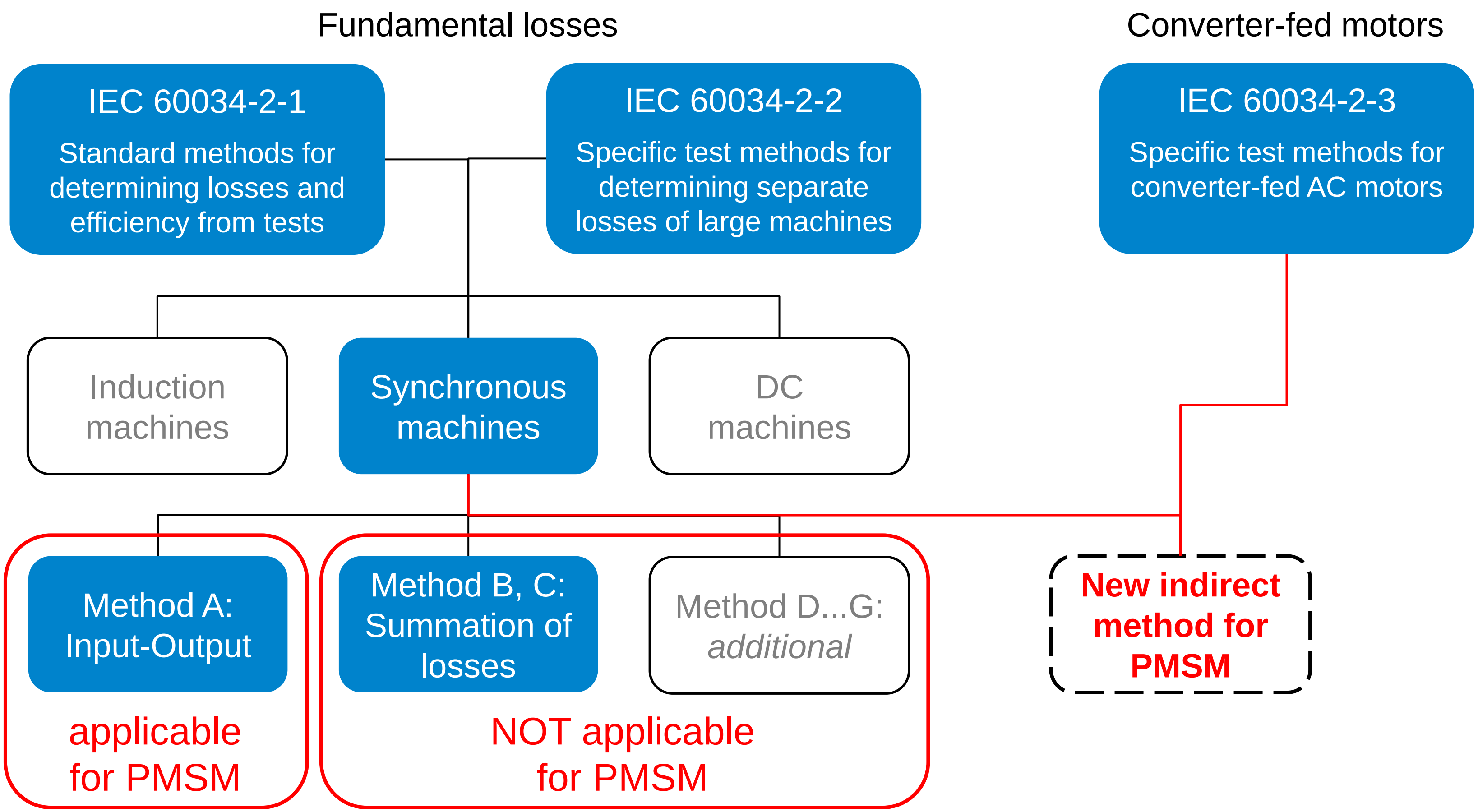
applicable for PMSM

Method B, C: Summation of losses

Method D...G: *additional*

NOT applicable for PMSM

Introduction
IEC efficiency measurement: Future



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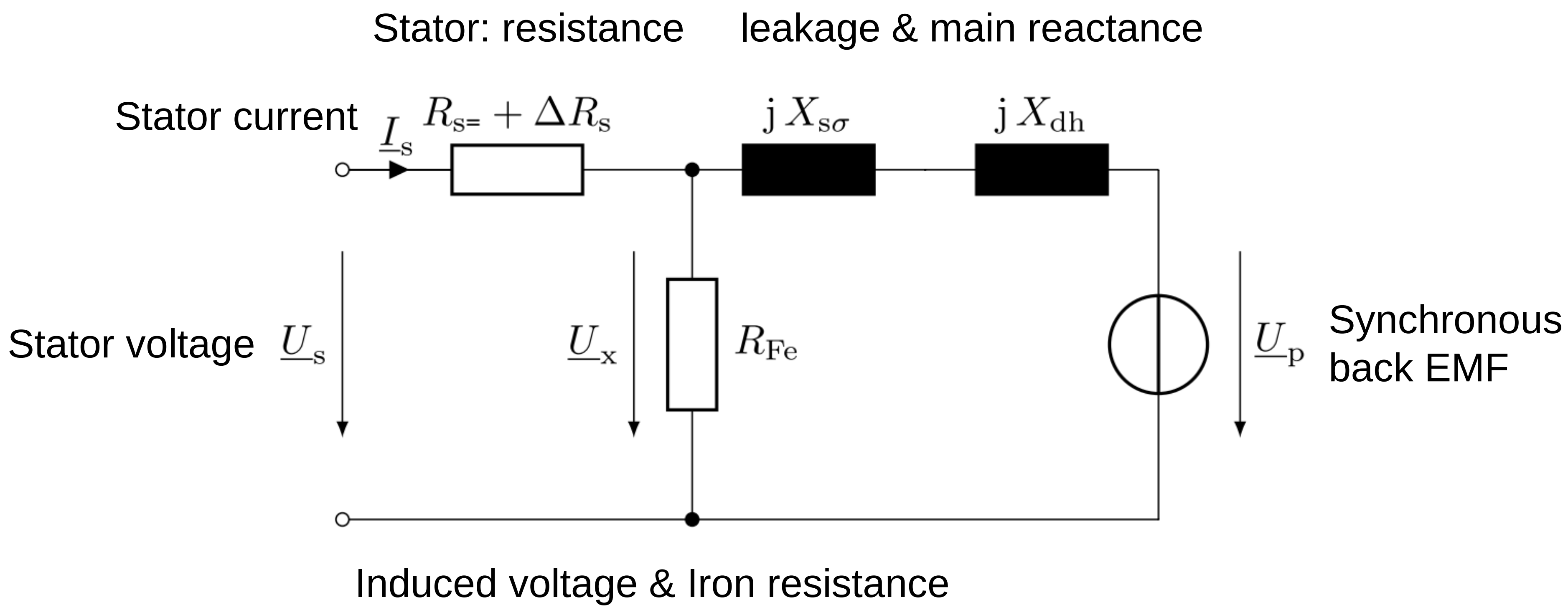
Indirect efficiency determination of PMSM
Equivalent circuit of a PMSM



Indirect efficiency determination of PMSM
Model for separation of losses

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A) Voltage-depending losses:

- Iron losses P_{Fe} ← Generator/motor no-load experiment at variable speed ($\sim U_{\mathrm{x}}^{2}$)
- Additional stator and rotor losses due to converter harmonics (order k) $P_{\mathrm{e,in,0,ad}}$ *

B) Current-depending losses $P_{\mathrm{Cu}\sim}$ ($\sim I_{s}^{2}$):

- I²R losses in the stator winding $P_{\mathrm{Cu=}}$
- Additional stator-side losses $P_{\mathrm{ad,1,s}}$ / ΔR_{s}

} Removed rotor experiment with sinusoidal feeding

- Additional rotor-side losses $P_{\mathrm{ad,1,r}}$ NOT considered

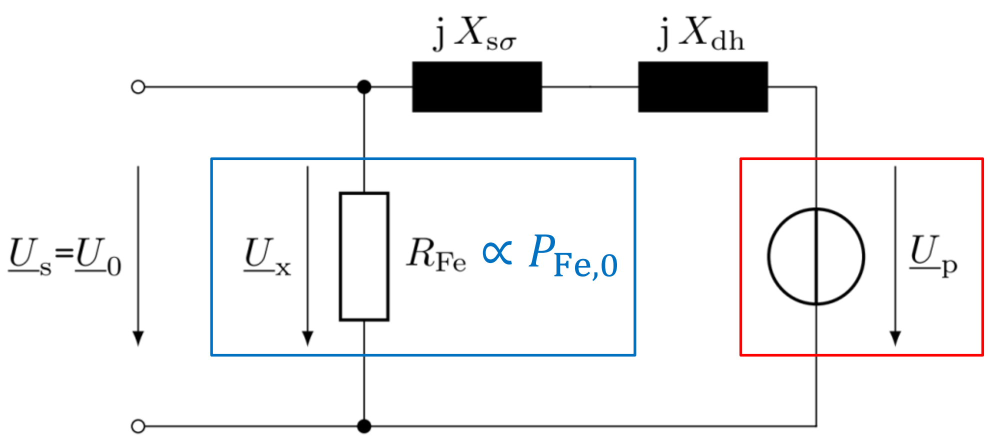
C) Friction and windage losses P_{fw}

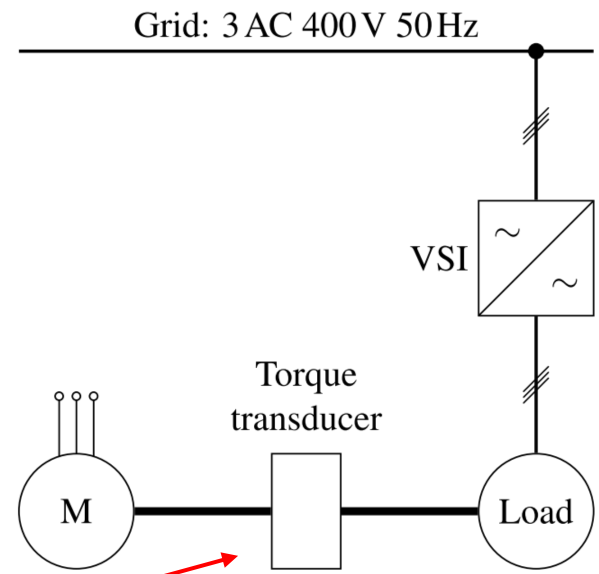
I. During manufacturing process, for correction of iron losses under load: No-load experiment with non-magnetized rotor

II. At assembled machine: Measurement with magnetized rotor and correction of iron losses under load with calculated P_{fw}

* also addressed in IEC 60034-2-3

Indirect efficiency determination of PMSM
A.1) Generator no-load test at variable speed



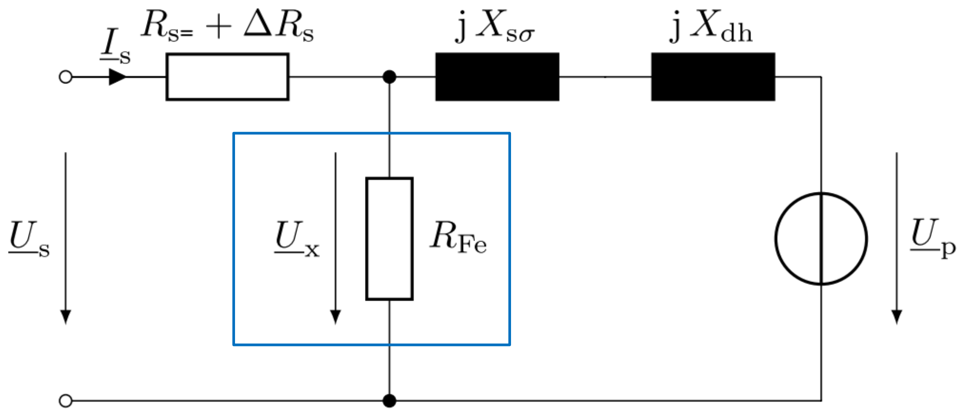


- Test machine (“M”) is driven by auxiliary machine (“Load”)
- No-load voltage $U_0 = U_x \approx$ Back EMF U_p
- Measured input shaft power $P_{m,in,0} = 2\pi \cdot n \cdot M_0$
  - Iron losses $P_{Fe,0}$ (+ additional losses e.g. magnet losses)
  - Friction and windage losses P_{fw}
- Determination of friction and windage losses P_{fw} C) with a non-magnetized rotor or less accurate via calculation

Indirect efficiency determination of PMSM
A.1) Re-calculated iron losses at load

Correction of iron losses with U_{x}:

$$P_{\mathrm{Fe}} \approx P_{\mathrm{Fe,0}} \cdot \left(\frac{U_{\mathrm{x}}}{U_0}\right)^2$$



$$\underline{U}_{\mathrm{x}} = \underline{U}_s - (R_{\mathrm{s=}} + \Delta R_{\mathrm{s}}) \cdot \underline{I}_s$$

Indirect efficiency determination of PMSM
A.2) Additional losses due to inverter feeding

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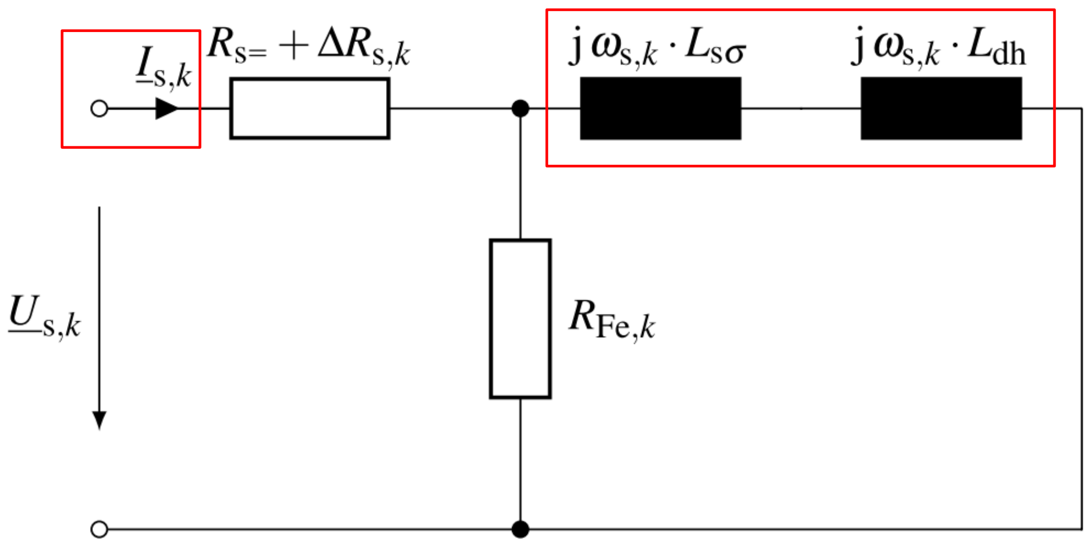
- Voltage harmonics $U_{s,k}$ (frequency: $k \cdot f_s$) → current harmonics $I_{s,k}$ in the stator winding

→ Additional fast rotating air-gap field waves

→ Additional stator & rotor losses

Equivalent circuit per phase for harmonic $k > 1$:



$$\boxed{I_{s,k} \approx \frac{U_{s,k}}{\omega_{s,k} \cdot L_d}}$$

$$R_{Fe,k} \gg \omega_{s,k} \cdot L_d$$

$$L_d = L_{dh} + L_{s\sigma}$$

Indirect efficiency determination of PMSM

A.2) Additional losses due to inverter feeding

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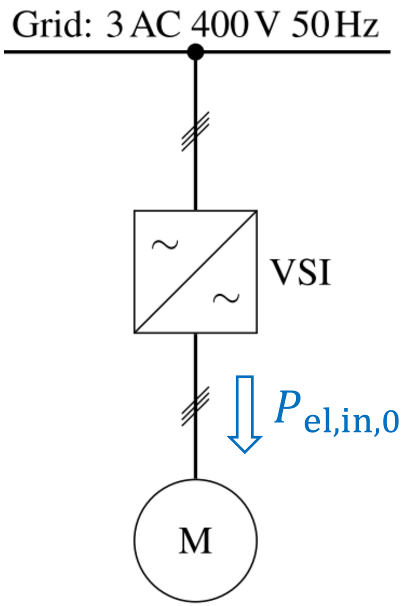
- In addition to generator no-load:

→ Motor no-load operation at the inverter (VSI)

- Separation of el. input power $P_{\mathrm{el,in,0}}$
  - fundamental input power $P_{\mathrm{el,in,0,1}} \approx P_{\mathrm{m,in,0}}$ (generator)
  - harmonic input power $P_{\mathrm{el,in,0,ad}} = P_{\mathrm{el,in,0}} - P_{\mathrm{el,in,0,1}}$

- Assumption: Independency of the additional losses on the actual current value

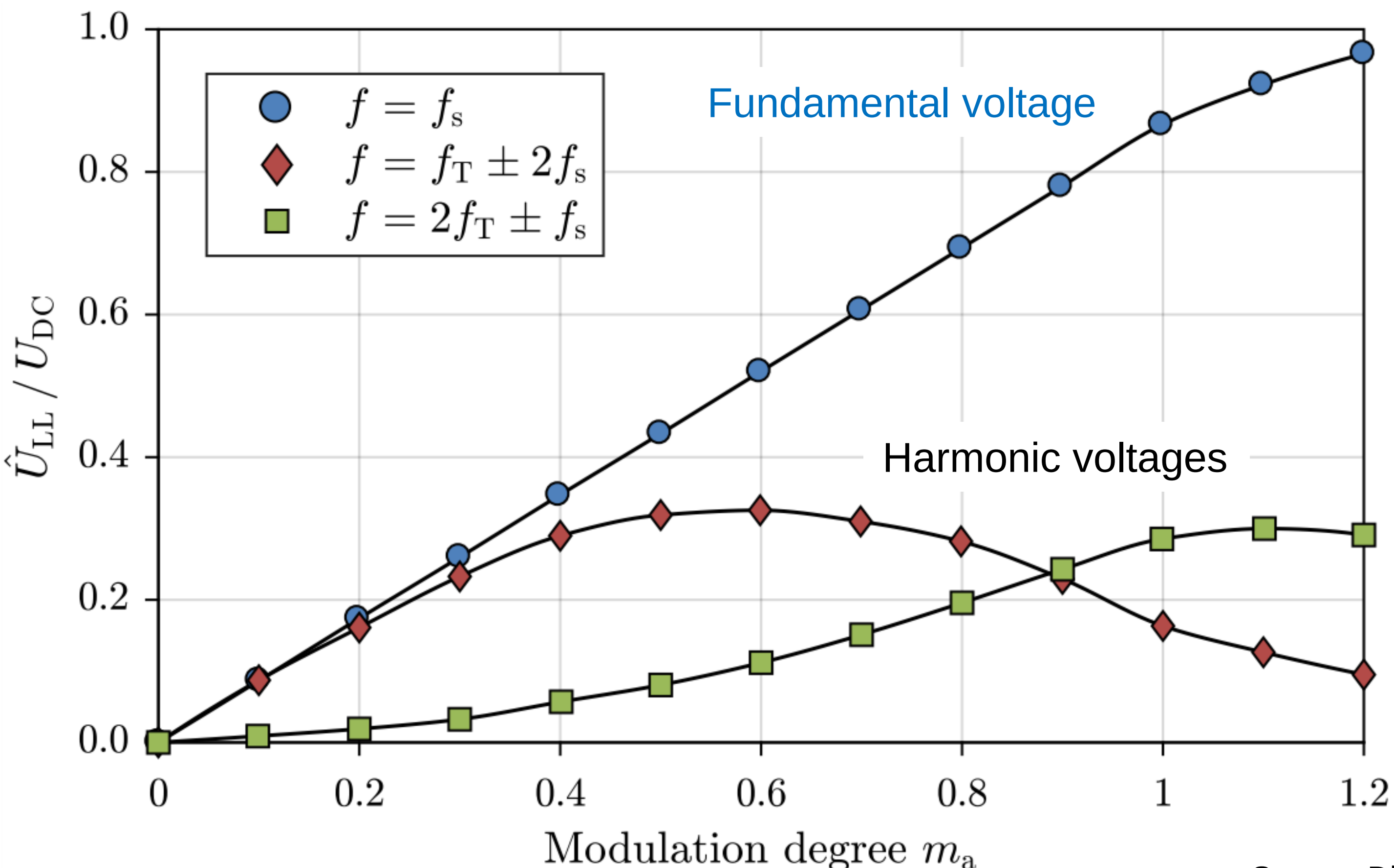
- But: Dependency on inverter modulation degree, therefore on the (no-load) voltage



Indirect efficiency determination of PMSM

A.2) Additional losses due to inverter feeding

Calculated fundamental and harmonic voltage amplitudes at PWM with $f_\mathrm{T}/f_\mathrm{s} = 15$



$$m_\mathrm{a} = \frac{\hat{U}_{LL}}{(\sqrt{3}/2 \cdot U_\mathrm{DC})}$$

Maximum of additional losses expected at $m_\mathrm{a} \approx 0.6 \dots 0.8$

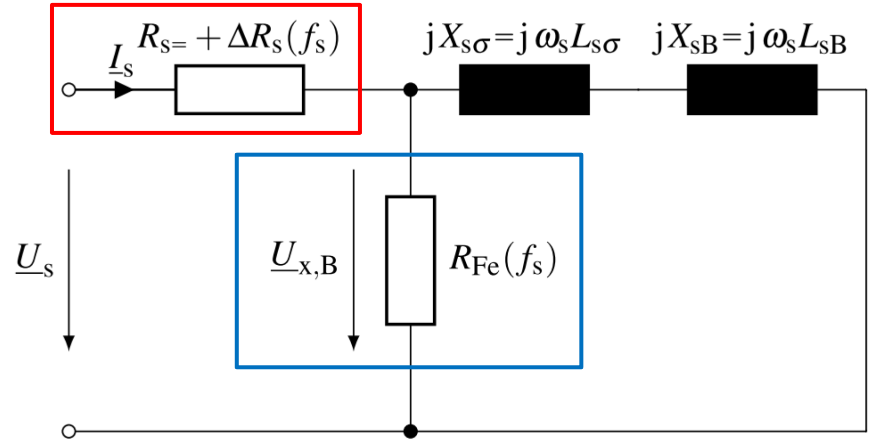
Source: Diss. T. Lu, 2004

Indirect efficiency determination of PMSM
B) Removed rotor test

Sinusoidal feeding: Variable current amplitude and frequency

Measured electrical input power:

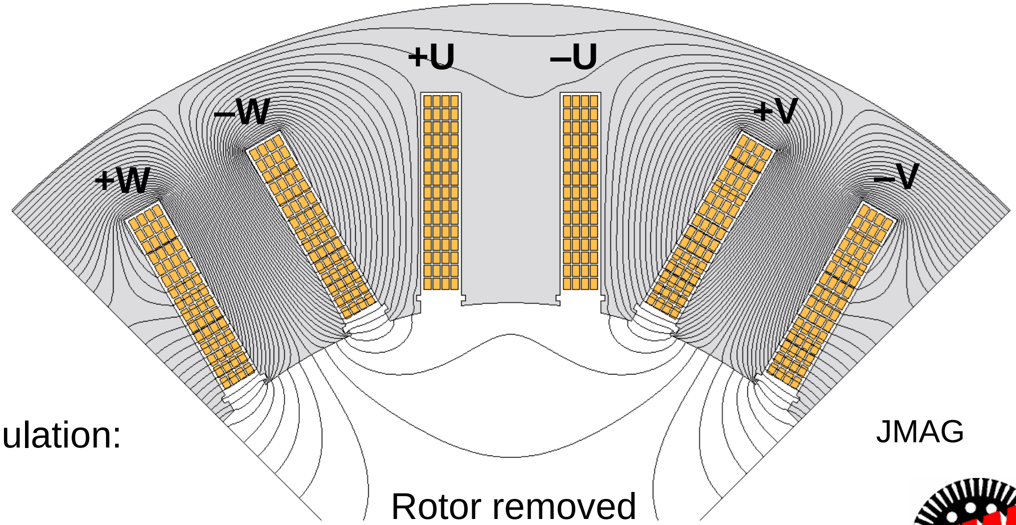
$$P_{\mathrm{el,in,B}} = P_{\mathrm{Cu=}} + \Delta P_{\mathrm{Cu}} + P_{\mathrm{Fe,B}}$$
$$= P_{\mathrm{Cu\sim}} + P_{\mathrm{Fe,B}}$$



The (small) iron losses $P_{\mathrm{Fe,B}}$ are determined from the no-load losses:

$$P_{\mathrm{Fe,B}} \approx P_{\mathrm{Fe,0}} \cdot \left(\frac{U_{\mathrm{x,B}}}{U_0}\right)^2$$

Example, 2D FE simulation:



JMAG

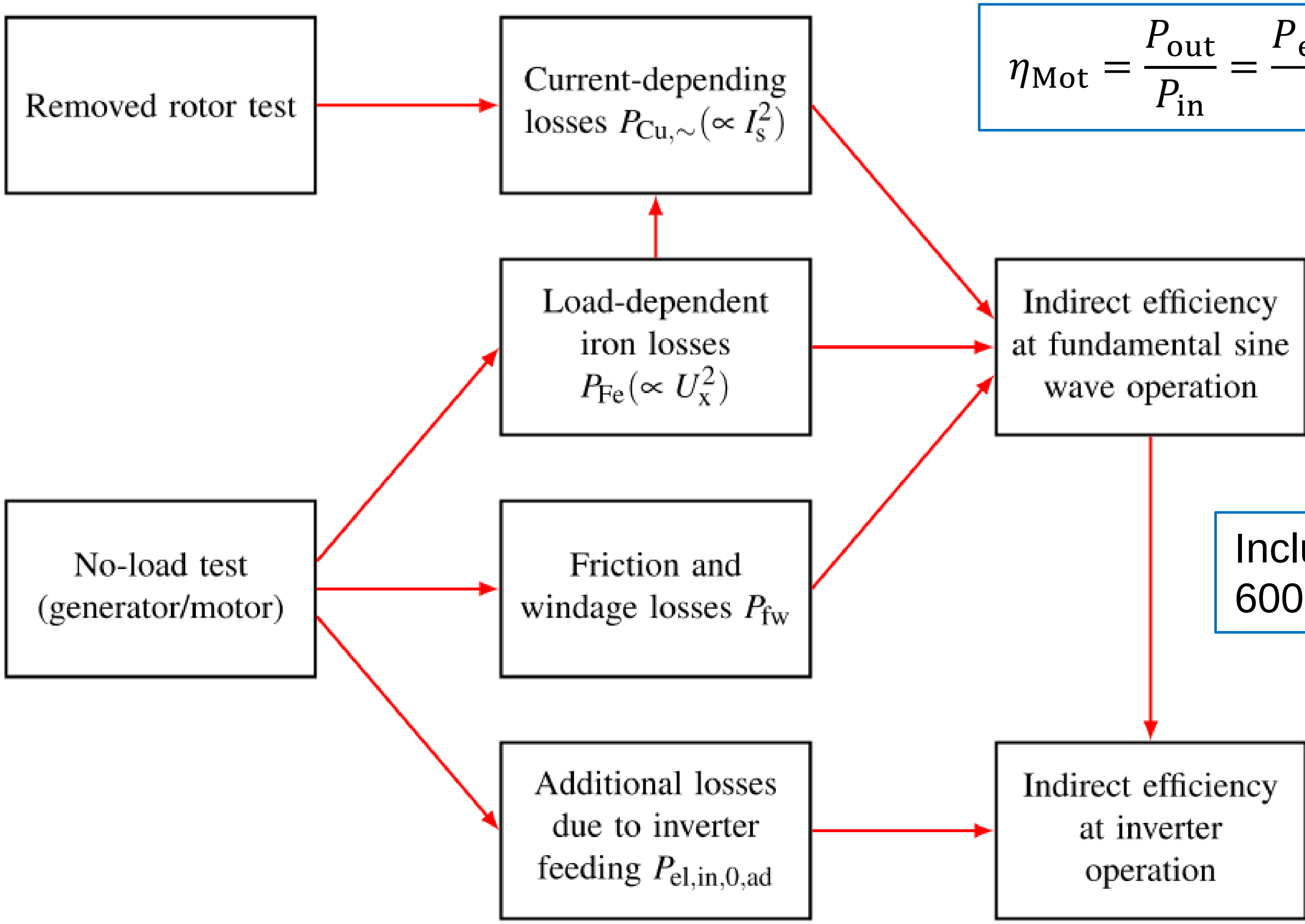
Indirect efficiency determination of PMSM
Efficiency at load operation

- Stator current $I_{s,1}$ and voltage $U_{s,1}$ at an arbitrary (fundamental) power factor $\cos\varphi_{s,1}$
- $P_{el,1} = 3U_{s,1}I_{s,1}\cos\varphi_{s,1}$, $\quad P_{Cu\sim} = f(f_s, I_s)$, $\quad P_{Fe} = f(U_x)$, $\quad P_{e,in,0,ad} = f(U_0)$

	Fundamental sine wave	Inverter operation
Generator operation	$\eta_{Gen} = \dfrac{P_{el,1}}{P_{e,1} + P_{Cu\sim} + P_{Fe} + P_{fw}}$	$\eta_{Gen} = \dfrac{P_{el,1}}{P_{el,1} + P_{Cu\sim} + P_{Fe} + P_{fw} + P_{e,in,0,ad}}$
Motor operation	$\eta_{Mot} = \dfrac{P_{el,1} - P_{Cu\sim} - P_{Fe} - P_{fw}}{P_{el,1}}$	$\eta_{Mot} = \dfrac{P_{el,1} - P_{Cu\sim} - P_{Fe} - P_{fw}}{P_{el,1} + P_{e,in,0,ad}}$

Indirect efficiency determination of PMSM
Flowchart of concept

$$\eta_{\mathrm{Mot}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{P_{\mathrm{el,1}} - P_{\mathrm{Cu}\sim} - P_{\mathrm{Fe}} - P_{\mathrm{fw}}}{P_{\mathrm{el,1}} + P_{\mathrm{el,in,0,ad}}}$$

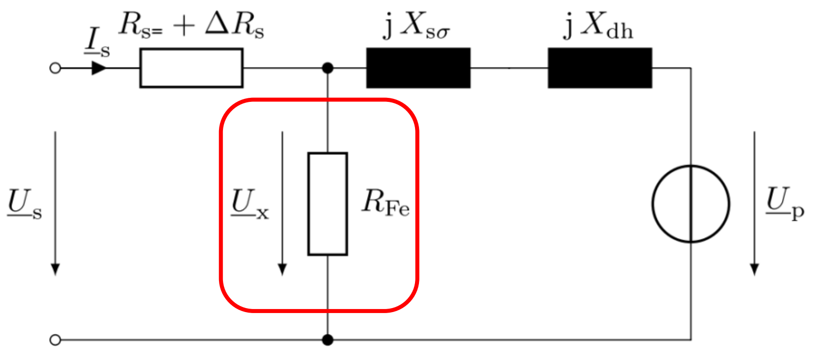


Inclusion into IEC standard 60034-2-X in progress

Indirect efficiency determination of PMSM
Summary: Assumptions

- Iron losses at load P_{Fe} are considered with induced voltage U_{x} from the measured no-load iron losses $P_{\mathrm{Fe,0}}$ and the no-load voltage U_0:

$$P_{\mathrm{Fe}} \approx P_{\mathrm{Fe,0}} \cdot (U_{\mathrm{x}}/U_0)^2$$



E.g. generator no-load measurement: $P_{\mathrm{Fe,0}} = P_{\mathrm{m,in,0}} - \mathrm{P_{fw}}$

- Additional rotor-side losses at sinusoidal voltage supply due to stator field space harmonics $P_{\mathrm{ad,1,r}}$ NOT considered (e.g. with distributed integer-slot winding rotor eddy current losses usually small)
- Current ripple and hence additional losses due to converter feeding assumed to be load-independent

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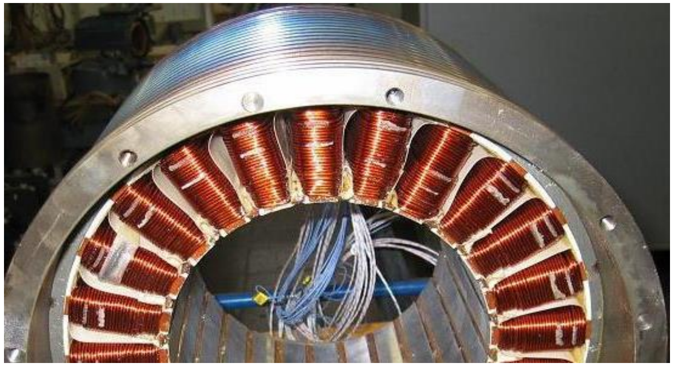
Measurements
Test machine parameters

	M1	M2	M5	M4	M3	„M6“ (PTB)
Rated power	45 kW	45 kW	160 kW	84 kW	90 kW	7.5 kW
Number of poles	16	16	12	8	6	4
Stator winding	fractional-slot	fractional-slot	fractional-slot	integer-slot	integer-slot	integer-slot
	tooth-coil	tooth-coil	distributed	distributed	distributed	distributed
Rotor magnets	surface-mounted	buried	buried	surface-mounted	surface-mounted	surface-mounted
Cooling system	water jacket	water jacket	water jacket	external fan	shaft-mounted fan	shaft-mounted fan
Simulation?	✓	✓		✓	✓	

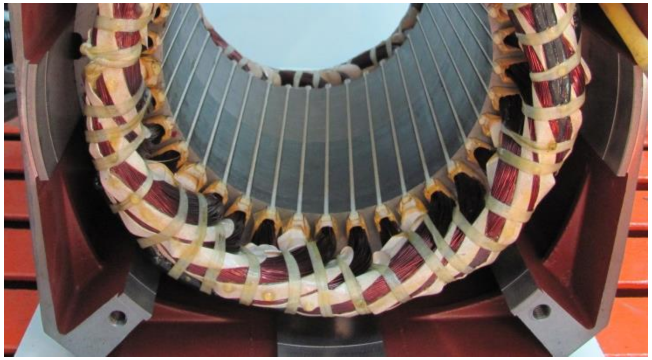
Measurements

Four of five test machines at EW, TU Darmstadt

M1: Double-layer winding, 16 poles, 45 kW



M3: Single-layer winding, 6 poles, 90 kW

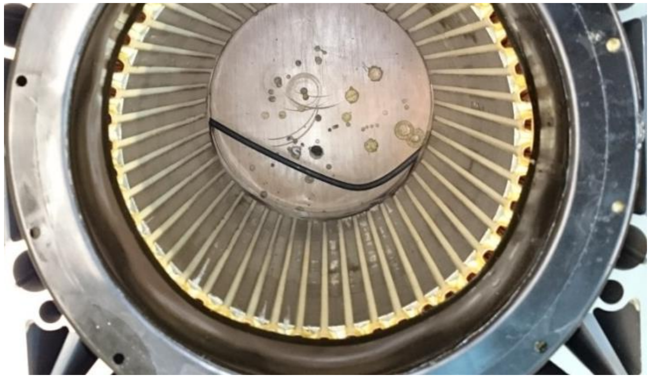


Tooth-coil, fractional slot

Distributed, integer slot

M2: Single-layer winding, 16 poles, 45 kW

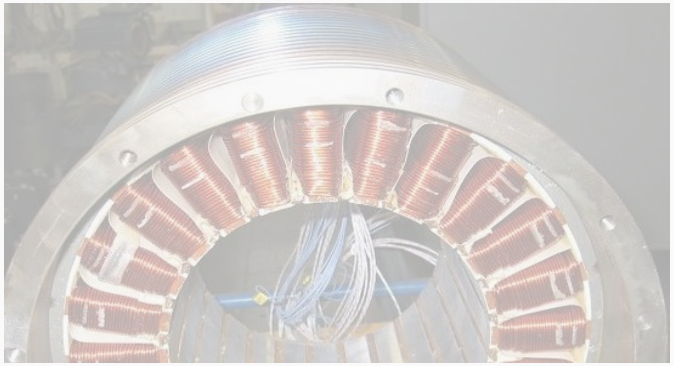
M4: Single-layer winding, 8 poles, 84 kW



Measurements

Four of five test machines at EW, TU Darmstadt

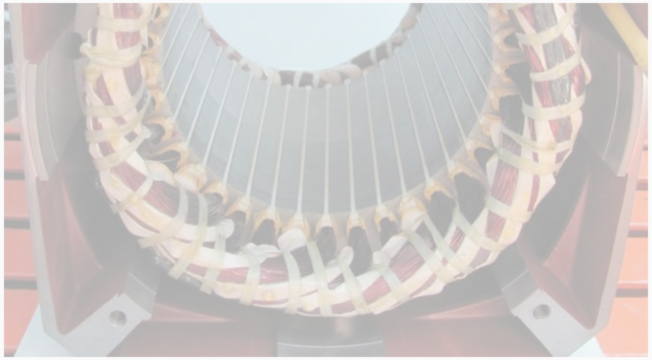
M1: Double-layer winding, 16 poles, 45 kW



Tooth-coil, fractional slot

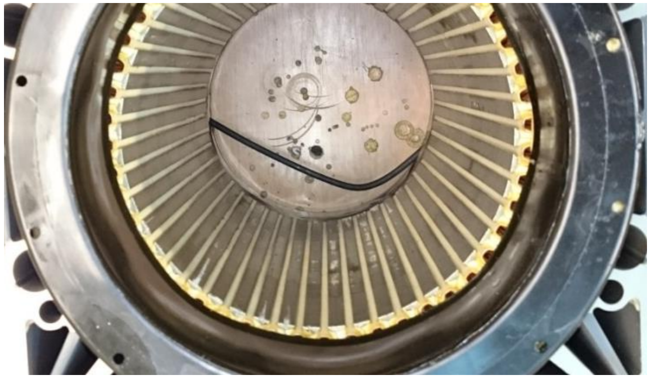
M2: Single-layer winding, 16 poles, 45 kW

M3: Single-layer winding, 6 poles, 90 kW



Distributed, integer slot

M4: Single-layer winding, 8 poles, 84 kW



Measurements

Example: Setup at the test bench

DC load machine

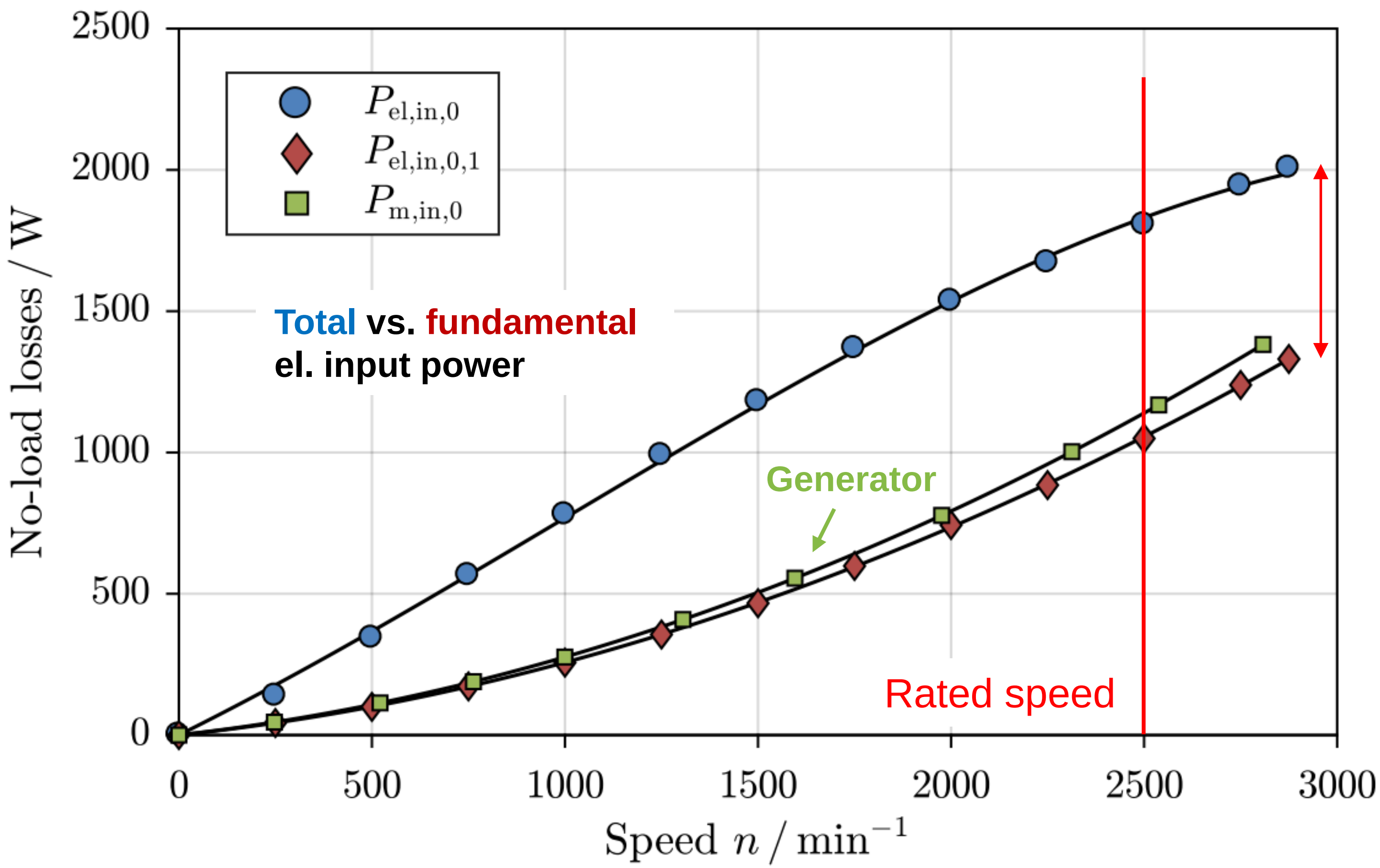
Torque and speed measurement below the red hood

External fan

Test machine M4

Measurement results of test machine M4

A.1) Motor vs. generator no-load operation

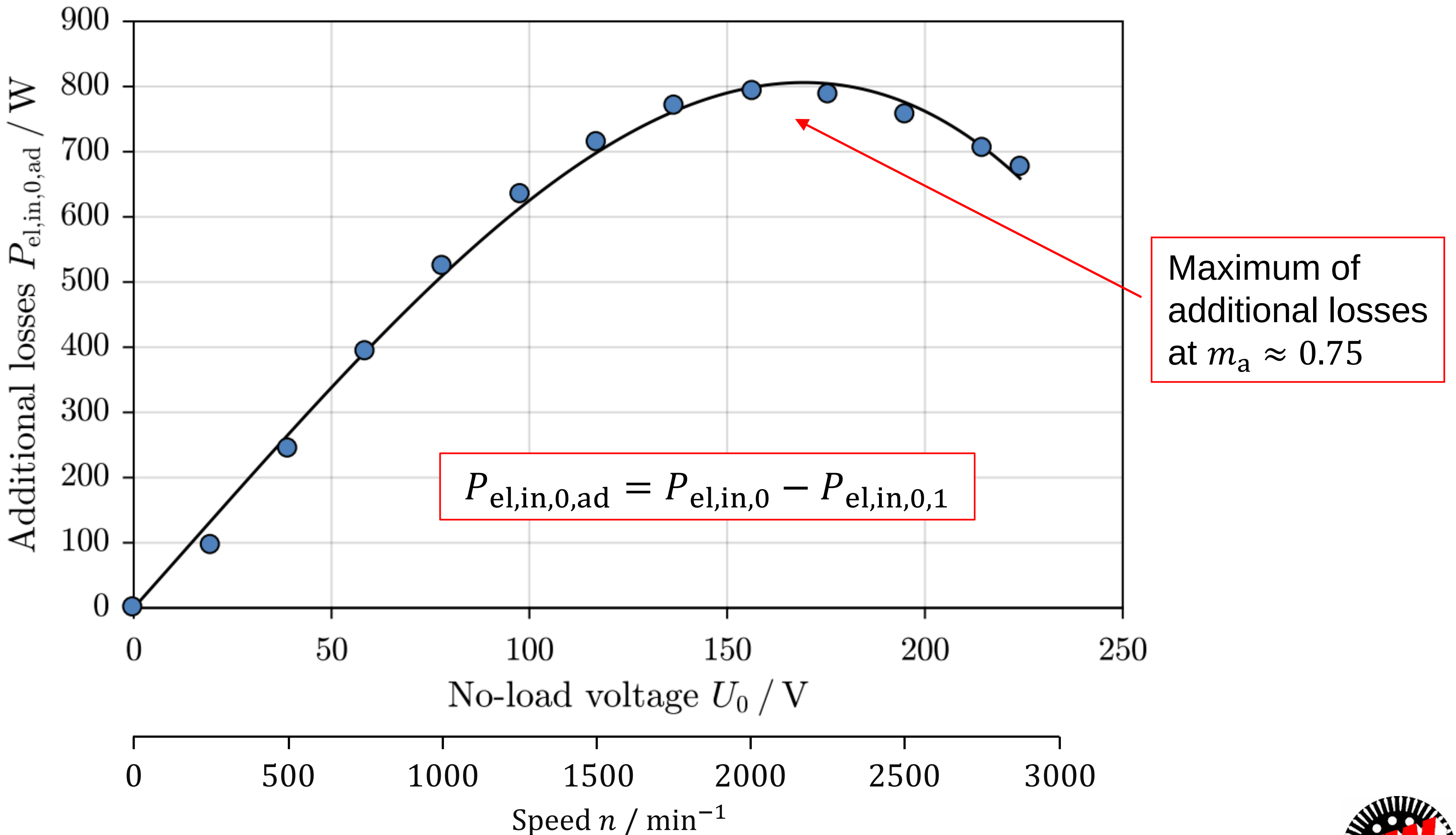


Additional losses due to inverter feeding
Switching frequency $4\ \mathrm{kHz}$

Fundamental input power ≈ mechanical power of generator test

Measurement results of test machine M4

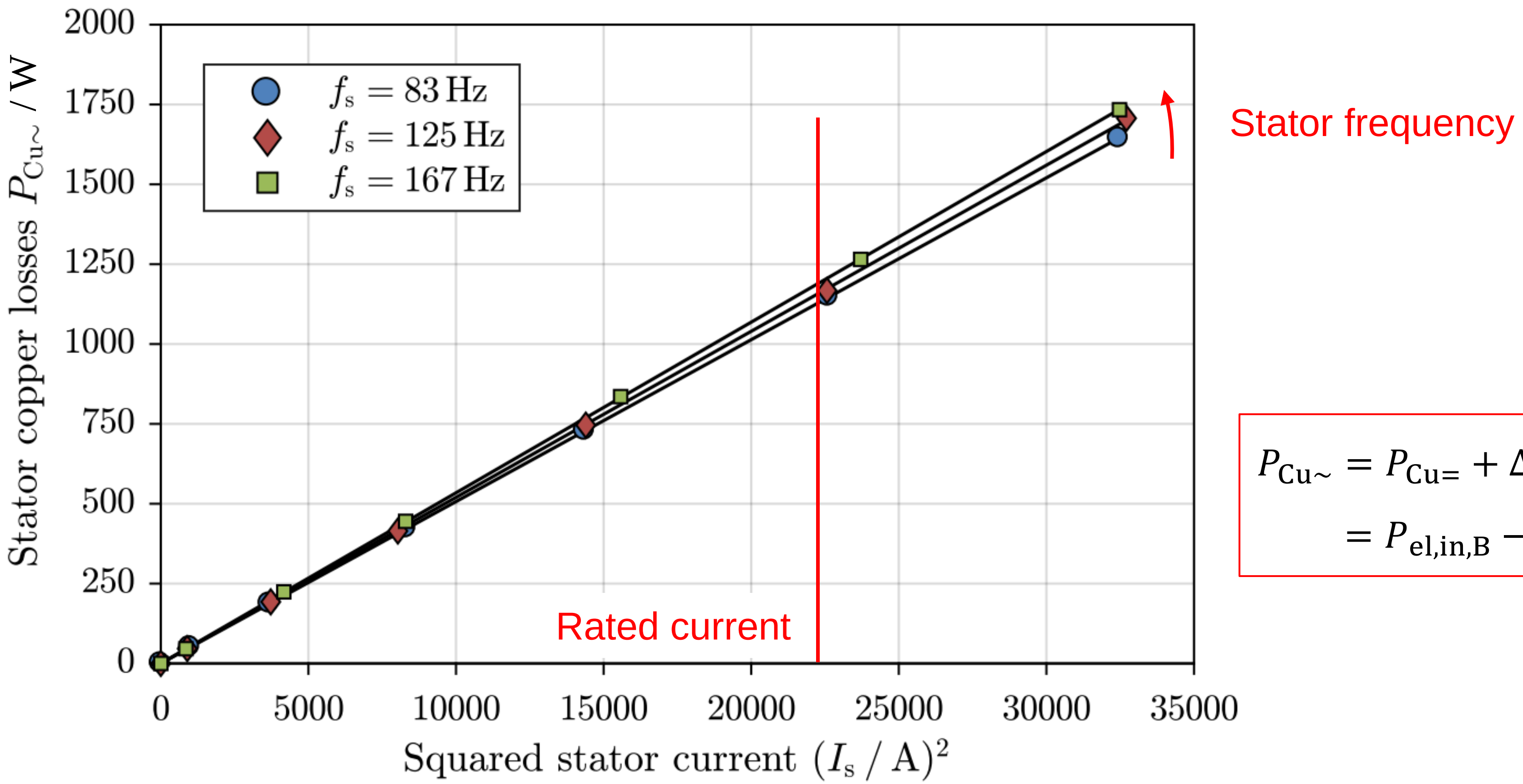
A.2) Additional no-load losses $P_{e,in,0,ad}$



Measurement results of test machine M4

B) Additional stator losses at sinusoidal feeding

Removed rotor test: Higher frequency → higher additional losses ΔP_{Cu}, but small absolute difference due to round wires

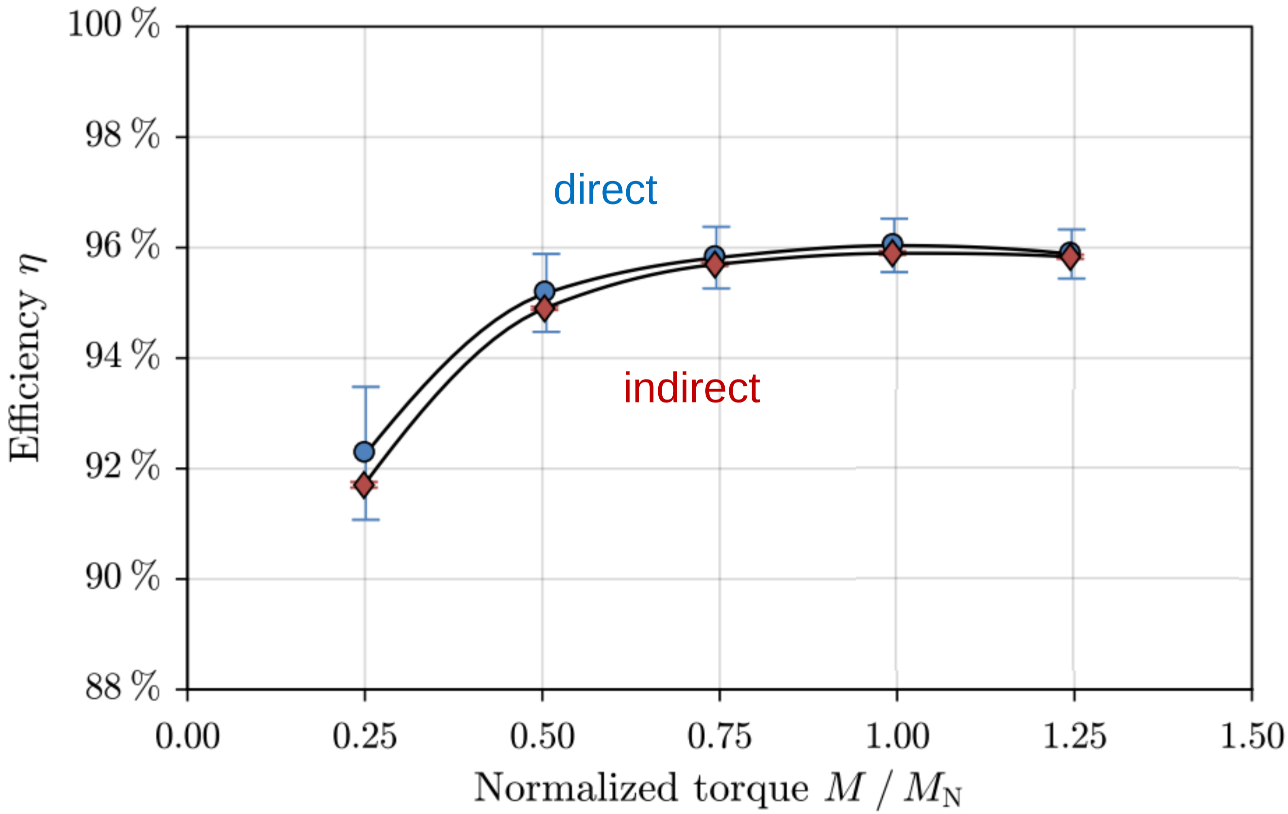


$$P_{\mathrm{Cu}\sim} = P_{\mathrm{Cu}=} + \Delta P_{\mathrm{Cu}}$$
$$= P_{\mathrm{el,in,B}} - P_{\mathrm{Fe,B}}$$

Measurement results of test machine M4

Efficiency at inverter operation

Motor operation at rated speed $n = 2500\ \mathrm{min}^{-1}$

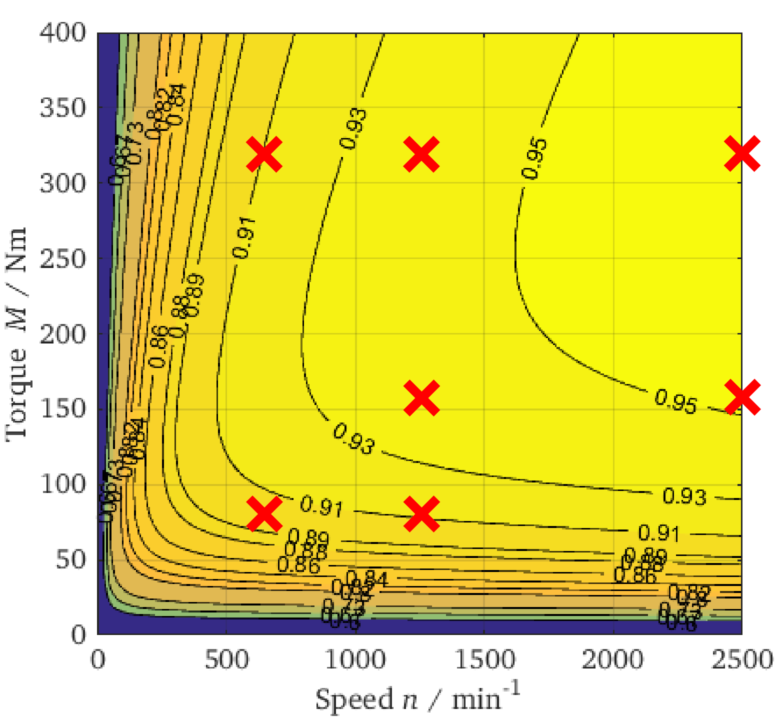


$M_N = 320\ \mathrm{Nm}$ $\quad$ $P_N = 84\ \mathrm{kW}$

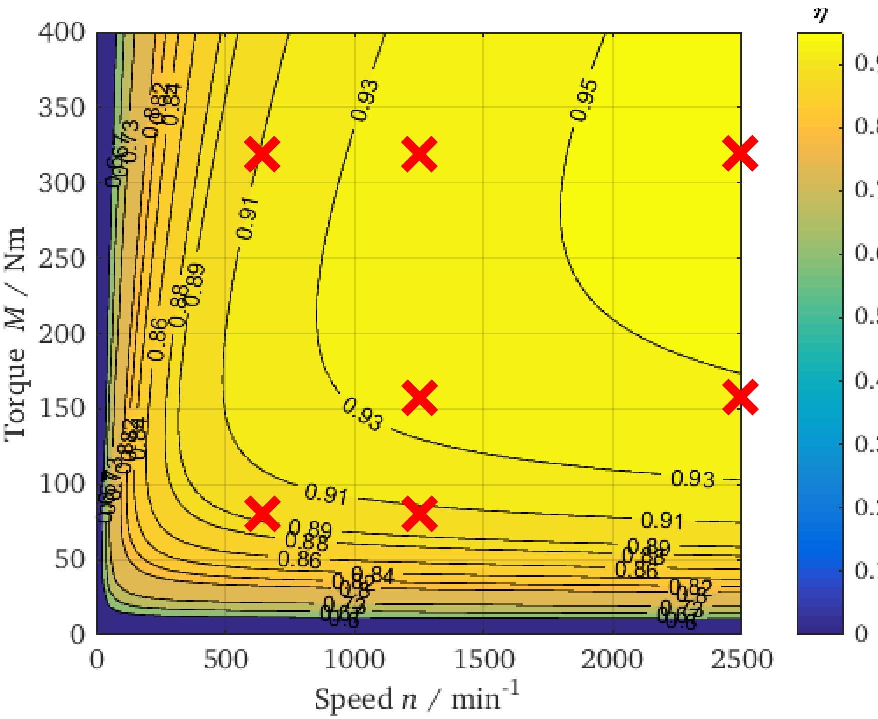
Measurement results of test machine M4
Efficiency at inverter operation

Interpolated efficiency map* at motor operation (7 interpolation points)

Direct:



Indirect:



* Interpolation procedure similar to IEC 60034-2-3

Measurements
Efficiency of further test machines

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	M1	M2	M5	M4	M3	„M6“ (PTB)
Rated power	45 kW	45 kW	160 kW	84 kW	90 kW	7.5 kW
Number of poles	16	16	12	8	6	4
Stator winding	fractional-slot	fractional-slot	fractional-slot	integer-slot	integer-slot	integer-slot
	tooth-coil	tooth-coil	distributed	distributed	distributed	distributed
Rotor magnets	surface-mounted	buried	buried	surface-mounted	surface-mounted	surface-mounted
Cooling system	water jacket	water jacket	water jacket	external fan	shaft-mounted fan	shaft-mounted fan

Measured efficiency at inverter operation (motor, $67\ \%\ n_{\mathrm{N}} = 1000\ \mathrm{min}^{-1}$)

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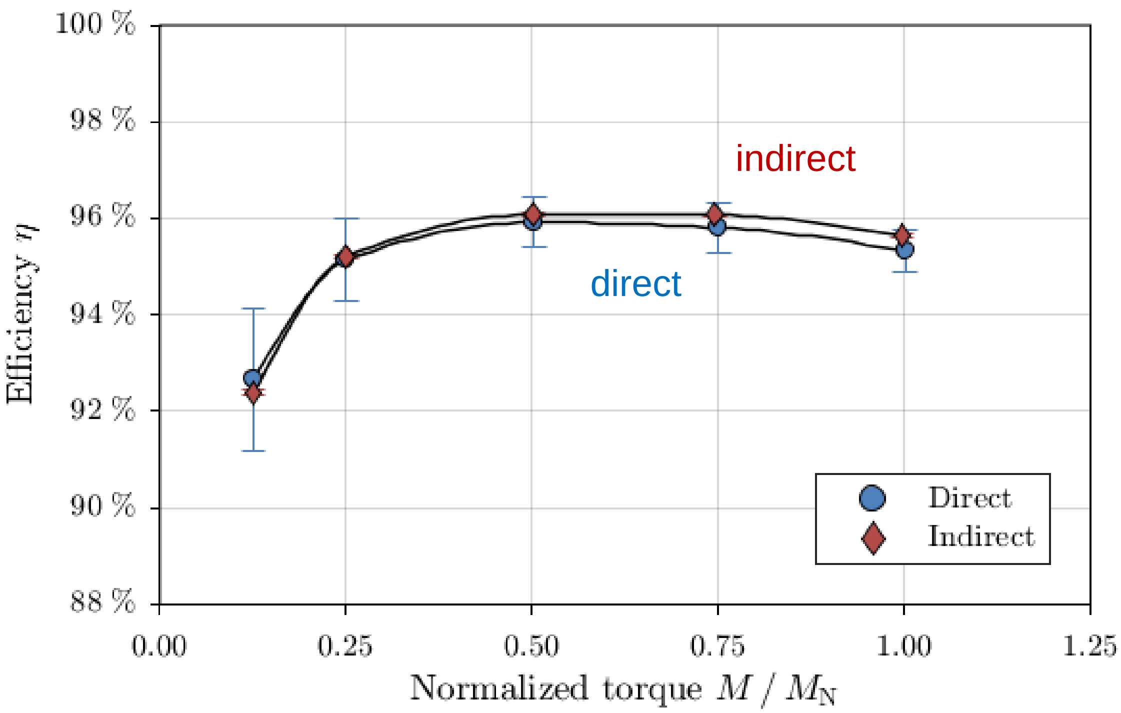
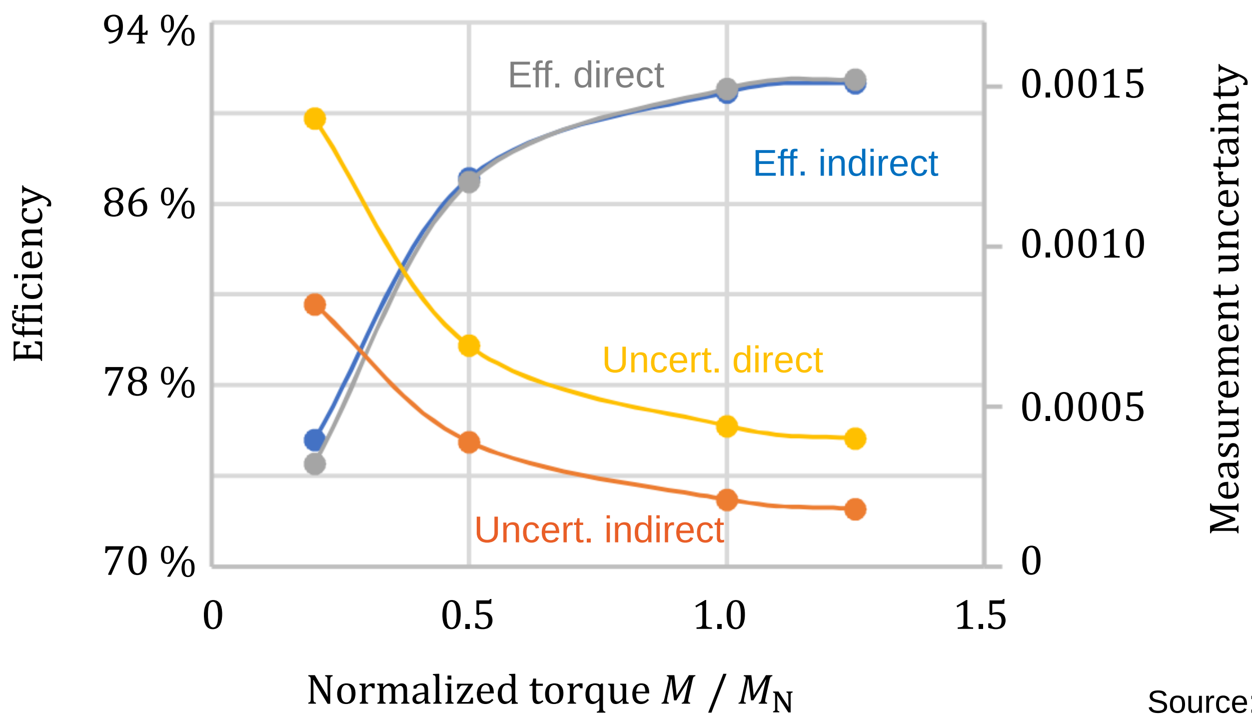
Test machine M5 (160 kW, 12 poles, distributed winding, water-jacket cooling)



Measured friction and windage losses (non-magnetized rotor): $P_{\mathrm{fw}} = 292\ \mathrm{W}$

Indirect vs. direct efficiency at the National Metrology Institute of Germany (PTB)

PMSM with distributed winding and surface-mounted rotor magnets,
$P_N = 7.5\ \mathrm{kW}, n_N = 1500\ \mathrm{min}^{-1}$



Source: Yogal, Lehrmann, Henke; ICEM 2018

Measured friction and windage losses: $P_{fw} = 54\ \mathrm{W}$

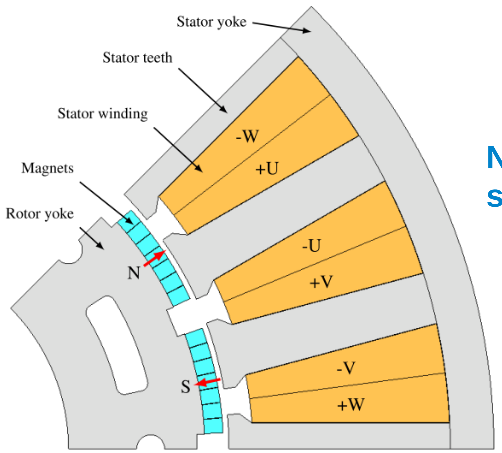
Numerical check

Test machines M1 … M4

	M1	M2	M5	M4	M3	„M6“ (PTB)
Rated power	45 kW	45 kW	160 kW	84 kW	90 kW	7.5 kW
Number of poles	16	16	12	8	6	4
Stator winding	fractional-slot	fractional-slot	fractional-slot	integer-slot	integer-slot	integer-slot
	tooth-coil	tooth-coil	distributed	distributed	distributed	distributed
Rotor magnets	surface-mounted	buried	buried	surface-mounted	surface-mounted	surface-mounted
Cooling system	water jacket	water jacket	water jacket	external fan	shaft-mounted fan	shaft-mounted fan

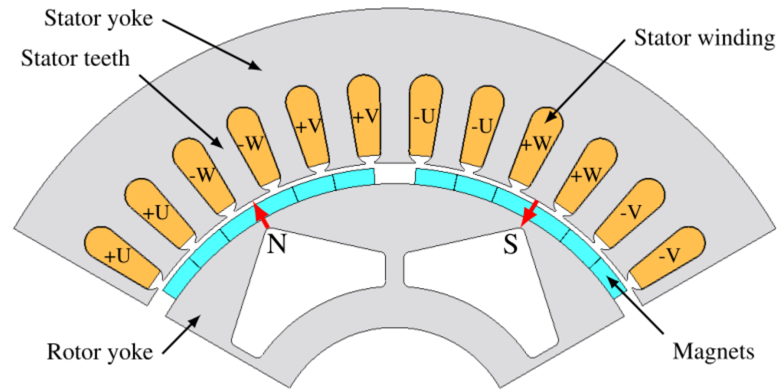
FE models for numerical check
Test machines M1 … M4

M1: Double-layer winding, 16 poles, 45 kW



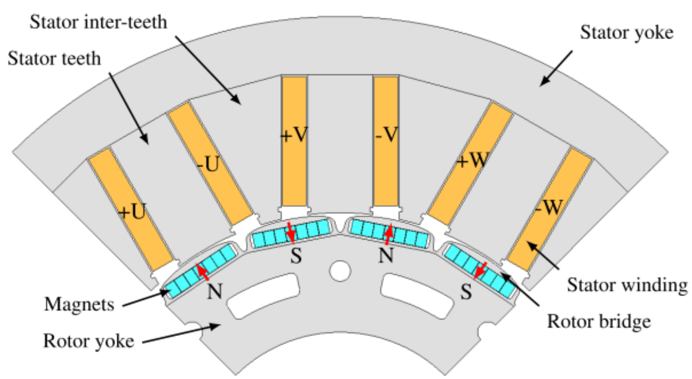
No sub-harmonic stator field wave

M3: Single-layer winding, 6 poles, 90 kW

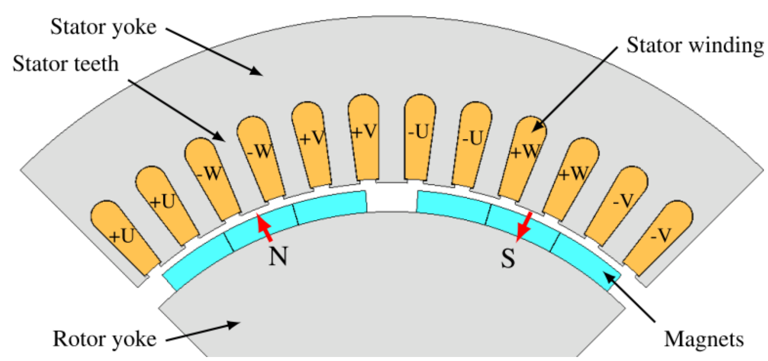


M2: Single-layer winding, 16 poles, 45 kW

One sub-harmonic stator field wave



M4: Single-layer winding, 8 poles, 84 kW

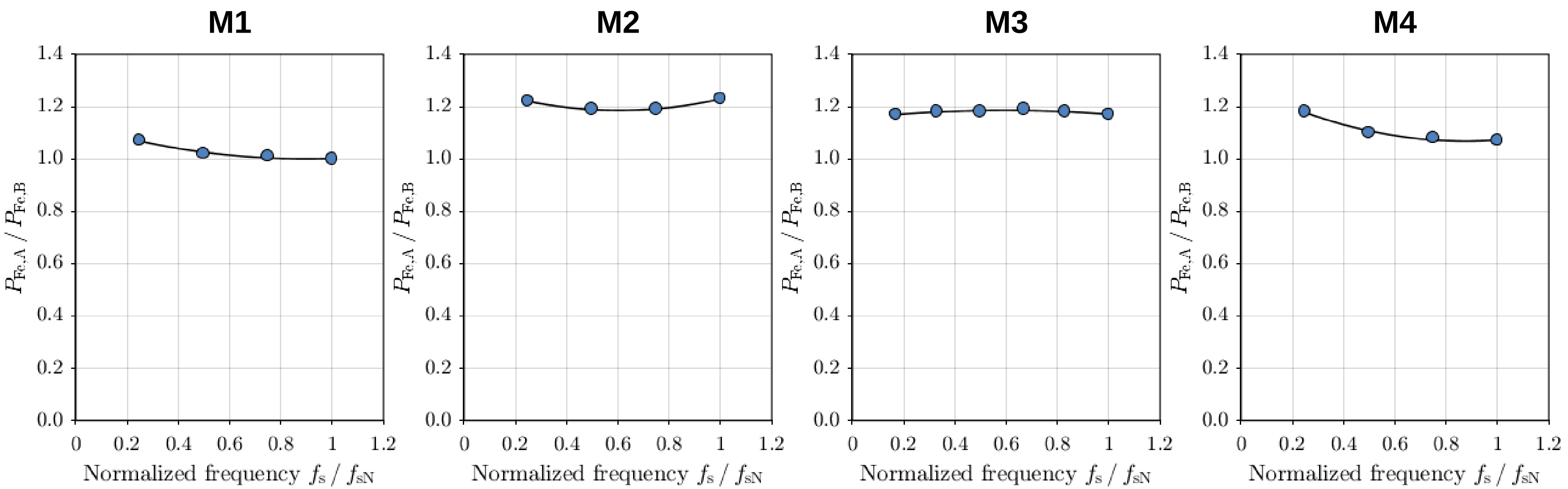


Software: JMAG Designer

Check of formula for load dependence of iron losses with numerical simulation (‘sim’, JMAG 2D)

Example: Motor rated torque at variable speed

A: Formula: $P_{\mathrm{Fe,A}} = P_{\mathrm{Fe,0,sim}} \cdot \left(\frac{U_{\mathrm{x,sim}}}{U_{0,\mathrm{sim}}}\right)^2$ vs. B: Numerical check: $P_{\mathrm{Fe,B}} = P_{\mathrm{Fe,sim}}$



f_{s}	33.3 Hz ... 133.3 Hz	33.3 Hz ... 133.3 Hz	25 Hz ... 150 Hz	41.7 Hz ... 167.7 Hz
$\frac{P_{\mathrm{Fe,sim}}}{P_{\mathrm{e,in,sim}}}$	7 % ... 33 %	8 % ... 35 %	10 % ... 48 %	11 % ... 42 %

→ Between 2 % and 25 % over-estimated iron losses at rated torque operation

Simulated vs. measured efficiency
(motor, $n_\mathrm{N} = 2500\ \mathrm{min}^{-1}$, fundamental sine wave operation)

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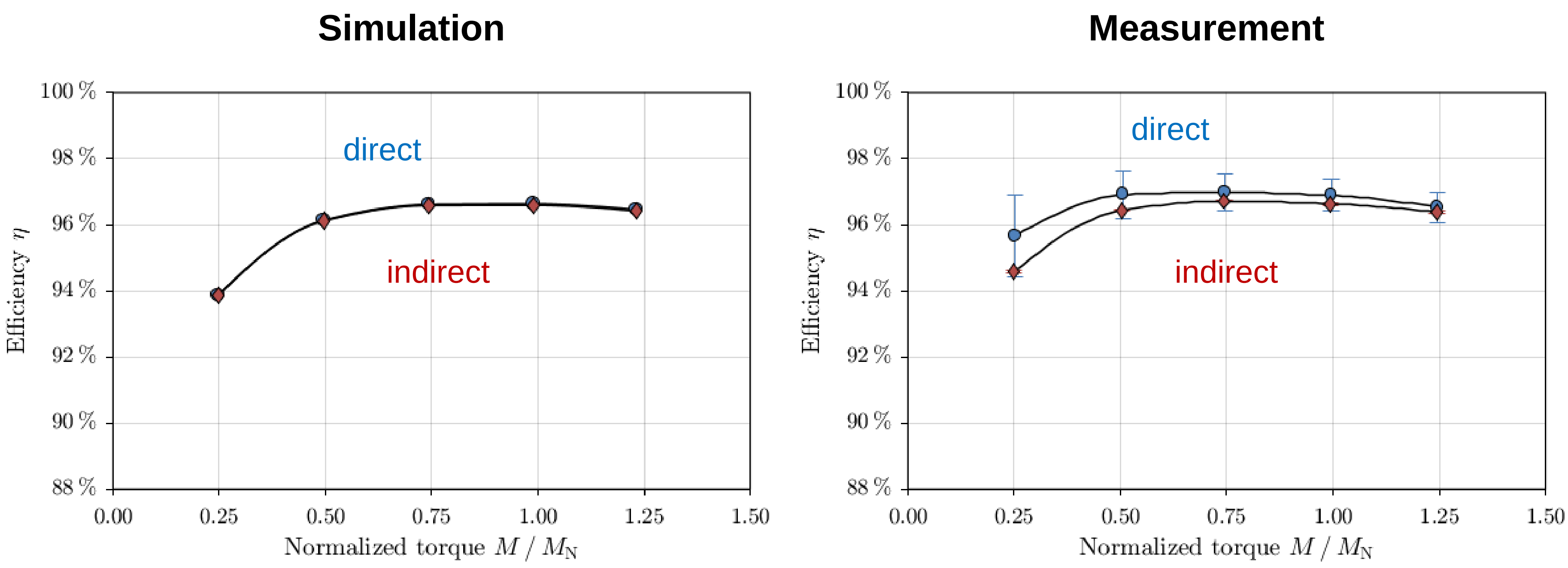
Test machine M4 (84 kW, distributed winding, external fan)

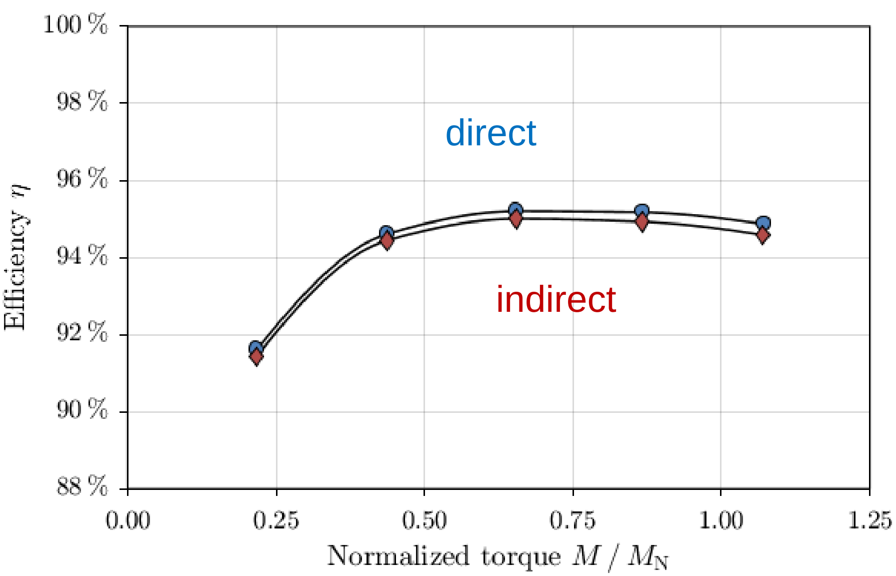


Small calculated friction and windage losses without fan: $P_\mathrm{fw} = 16\ \mathrm{W}$
(External fan losses not considered)

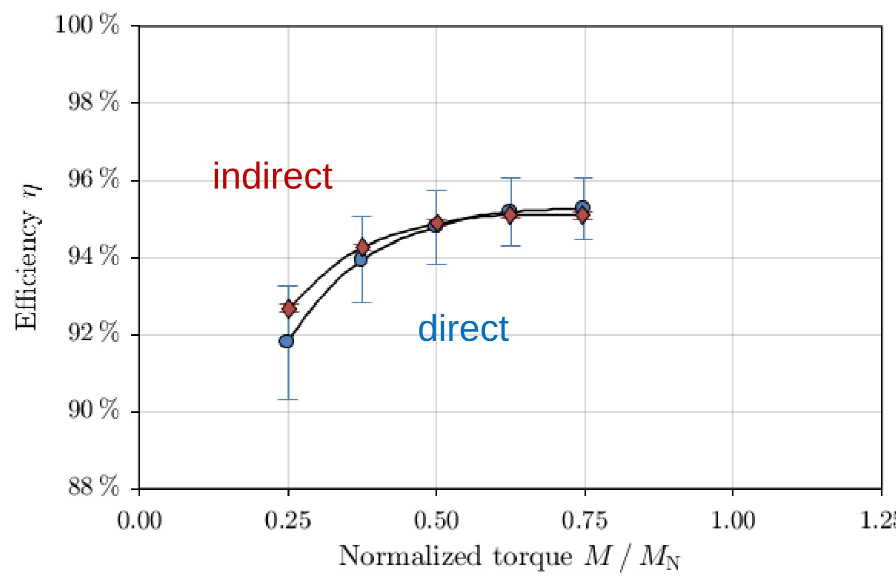
Simulated vs. measured efficiency
(motor, $n_\mathrm{N}/2 = 1500\ \mathrm{min}^{-1}$, fundamental sine wave operation)

Test machine M3 (90 kW, distributed winding, shaft-mounted fan)

Simulation



Measurement



Calculated friction and windage losses with fan:

$P_\mathrm{fw} = 20 \cdot r_\mathrm{ro} \cdot (l_\mathrm{Fe} + 0.15) \cdot (2\pi \cdot r_\mathrm{ro} \cdot n)^2$

n_N / 2: $P_\mathrm{fw} = 143$ W

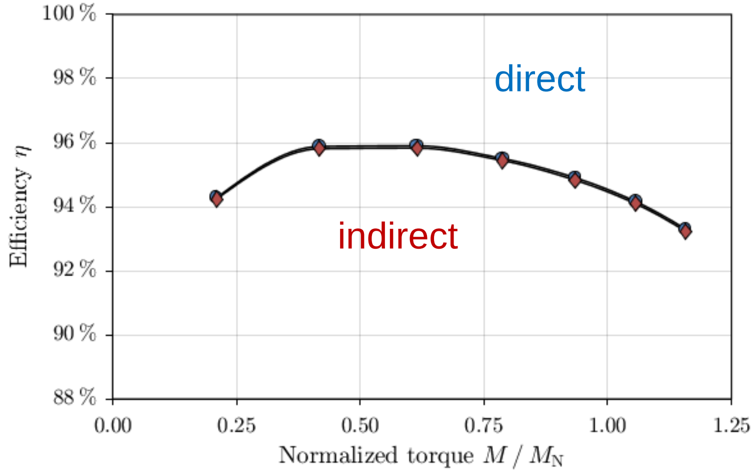
n_N: $P_\mathrm{fw} = 573$ W

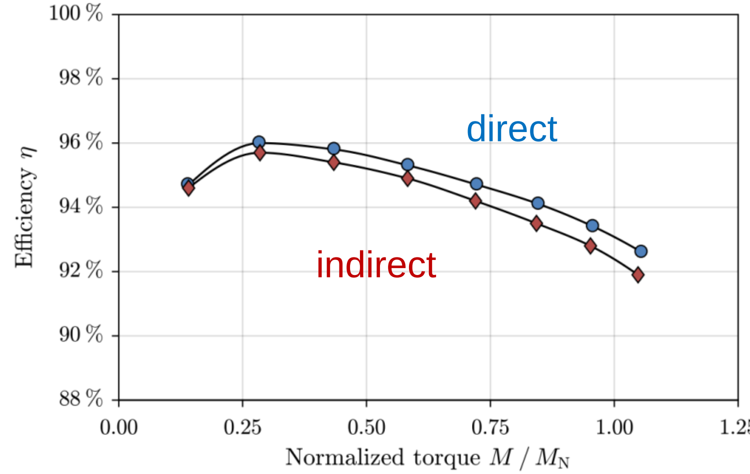
Worst case: Special motors with tooth-coil winding Simulated vs. measured efficiency (motor, $n_{\mathrm{N}} = 1000\ \mathrm{min}^{-1}$, fundamental sine wave operation, water-jacket cooling)

M1 (double-layer tooth-coil)
No sub-harmonic stator field wave

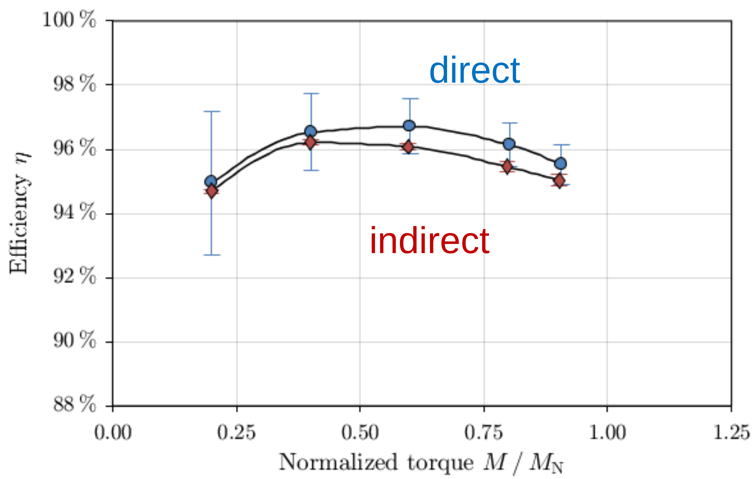
M2 (single-layer tooth-coil)
One sub-harmonic stator field wave

Sim.





Meas.



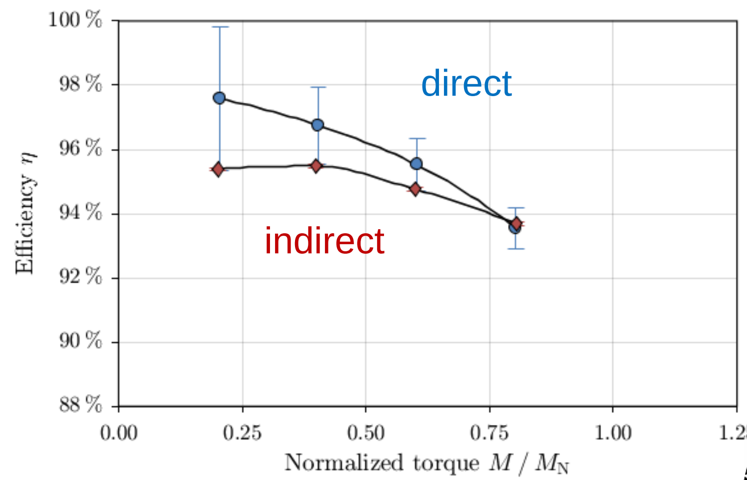


Table of contents

Summary

- Concept for efficiency determination of permanent magnet synchronous machines by summation of losses
- Comparison of indirect/direct measurements and finite element simulations
- Good accordance for machines with distributed winding
- Acceptable accordance for special machines with fractional-slot winding and stator field wave sub-harmonics

→ Inclusion into IEC standard 60034-2-X in progress

Recent publications

TU Darmstadt, Institute EW:

- B. Deusinger, M. Lehr and A. Binder, "Determination of efficiency of permanent magnet synchronous machines from summation of losses," *2014 Int. Symp. Power Electron., Electr. Drives, Automation and Motion (SPEEDAM)*, Ischia, 2014, pp. 619-624
- B. Deusinger, A. Binder, “Indirect efficiency determination of permanent magnet synchronous machines for sine wave and inverter operation”, in *9th Int. Conf. Energy Efficiency in Motor Drive Syst. (EEMODS)*, Helsinki, 2015
- B. Deusinger, A. Binder, “Quantitative analysis and finite element modeling for indirect efficiency determination of permanent magnet machines”, in *10th Int. Conf. Energy Efficiency in Motor Drive Syst. (EEMODS)*, Rome, 2017
- B. Deusinger, A. Binder, “Update on the indirect efficiency determination of permanent-magnet synchronous machine”, in *10th Int. Motor Summit for Energy Efficiency powered by Impact Energy*, 2020

National Metrology Institute of Germany (PTB) and TU Braunschweig:

- N. Yogal, C. Lehrmann and M. Henke, "Determination of the Measurement Uncertainty of Direct and Indirect Efficiency Measurement Methods in Permanent Magnet Synchronous Machines“, *2018 XIII Int. Conf. Electr. Mach. (ICEM)*, Alexandroupoli, 2018, pp. 1149-1156
- N. Yogal, C. Lehrmann and M. Henke, "Magnetic loss measurement of surface-mounted permanent magnet synchronous machines used in explosive environments“, in *J. Eng.*, vol. 2019, no. 17, pp. 3760-3765, 6 2019
- C. Lehrmann, “Wirkungsgradmessung permanentmagneterregter Synchronmaschinen – Ein Überblick unter den Aspekten der Messunsicherheit“, in *17. Technischer Tag der VEM*, Wernigerode, 2019

Danke für Ihre Aufmerksamkeit!

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