Dynamic Power Measurement and Accelerated Efficiency Mapping

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HBK – Who we are

Brüel & Kjær

HBM

Complementary discipline expertise

Sound, noise and vibration + Reliability, durability, propulsion efficiency, electrical properties, weighing

Complementary domain expertise

Frequency domain + Time domain

Combined covering the complete measurement chain

Sensors I Data acquisition I Data preparation I Data evaluation I Engineering

HBK
HOTTINGER BRÜEL & KJÆR

As the product physics experts

We deliver valuable insights through three physical domains

MECHANICAL

SUB-DOMAINS

- Strain
- Load
- Torque
- Force
- Pressure
- Durability

EXAMPLES OF OUR TASKS

- Weighing bottles on a production line to ensure the correct amount
- Measuring the torque generated by an electric motor driving a hybrid vehicle
- Measuring the strain in an aircraft wing as it is tested for durability and ultimate load

SOUND & VIBRATION

SUB-DOMAINS

Noise
Sound quality
Sound power
Acoustics

Designing optimal car sound quality – inside/outside
Evaluating acoustics in new buildings
Improving cabin comfort in passenger aircraft
Ensuring mobile phone production sound quality
Vibration testing sattelites before launching into space

ELECTRICAL

SUB-DOMAINS

- Electrical signals
- Voltage
- Current
- Speed
- Temperature

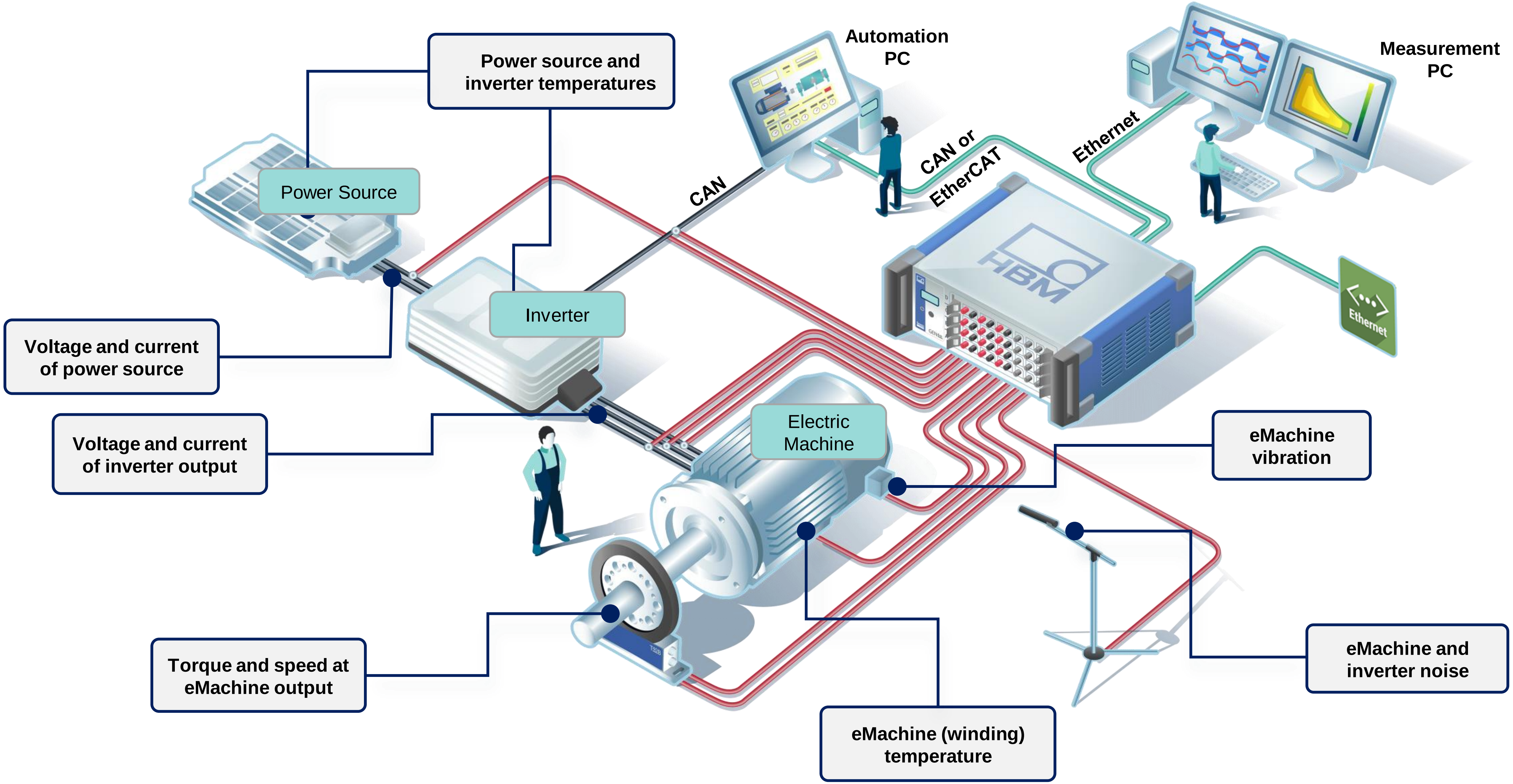
EXAMPLES OF OUR TASKS

- Testing inverters powering electric vehicles
- Checking the reliability of power grids
- Optimising performance and range of electric vehicle motors

Agenda

1. Electric power train
2. Conventional electric power calculation
3. Dynamic electric power approximation
4. Comparative measurements
5. Accelerated efficiency mapping
6. Conclusion

Electric Power Train



How to Measure Voltages and Currents

Recommendation for Power analysis [5,6]

- Voltages may be measured
  - against any arbitrary common reference potential r
  - Phase to phase with different reference phases
- Calculate phase to natural zero voltages $u_{v0}(t)$ before analyzing power quantities
- Measure the line currents
- Zero-sum quantities for power analysis

$\sum_{v=1}^{n} i_v(t) = 0$ $\sum_{v=1}^{n} u_{v0}(t) = 0$

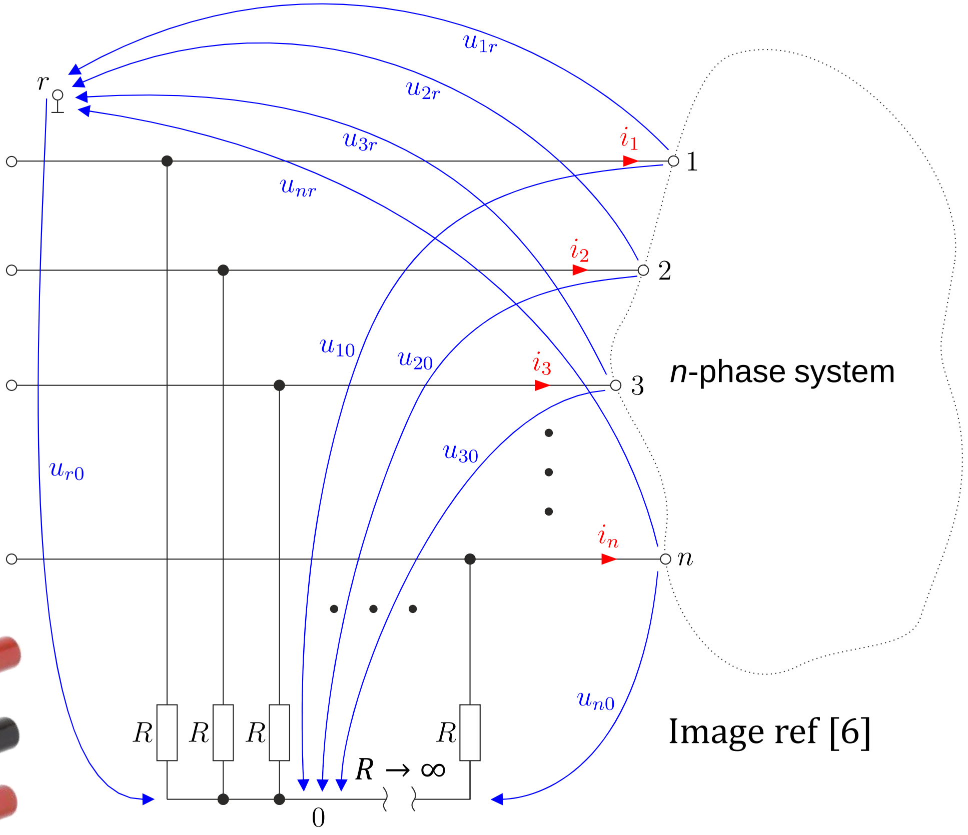
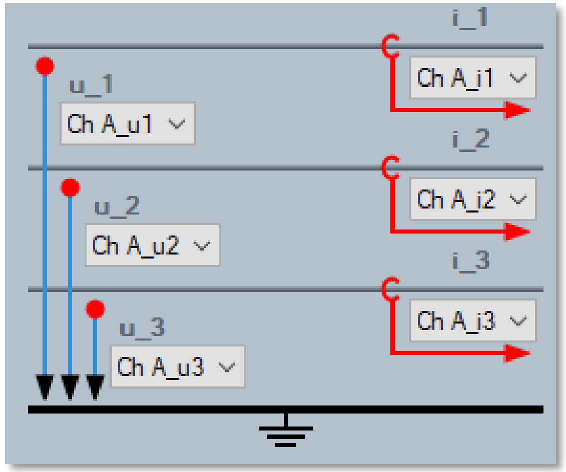


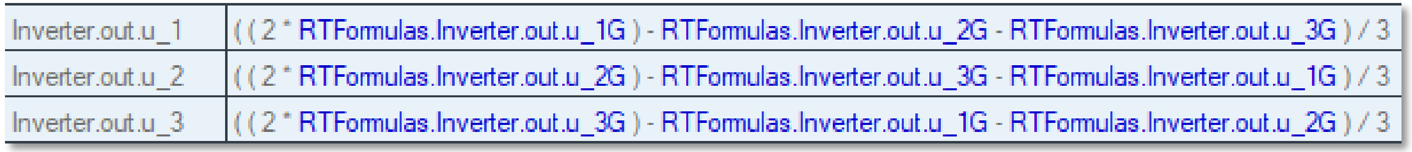
Image ref [6]

How to Measure Voltages and Currents

Phase to ground /

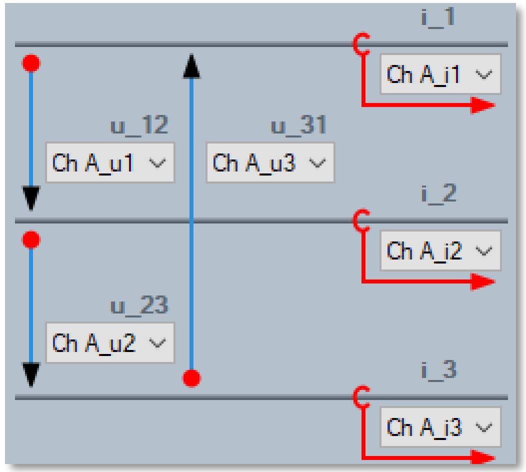
Phase to common arbitrary reference potential

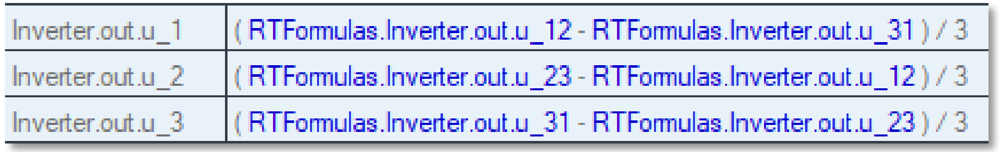




Inverter.out.u_1	((2 * RTFormulas.Inverter.out.u_1G) - RTFormulas.Inverter.out.u_2G - RTFormulas.Inverter.out.u_3G) / 3
Inverter.out.u_2	((2 * RTFormulas.Inverter.out.u_2G) - RTFormulas.Inverter.out.u_3G - RTFormulas.Inverter.out.u_1G) / 3
Inverter.out.u_3	((2 * RTFormulas.Inverter.out.u_3G) - RTFormulas.Inverter.out.u_1G - RTFormulas.Inverter.out.u_2G) / 3

Phase to phase

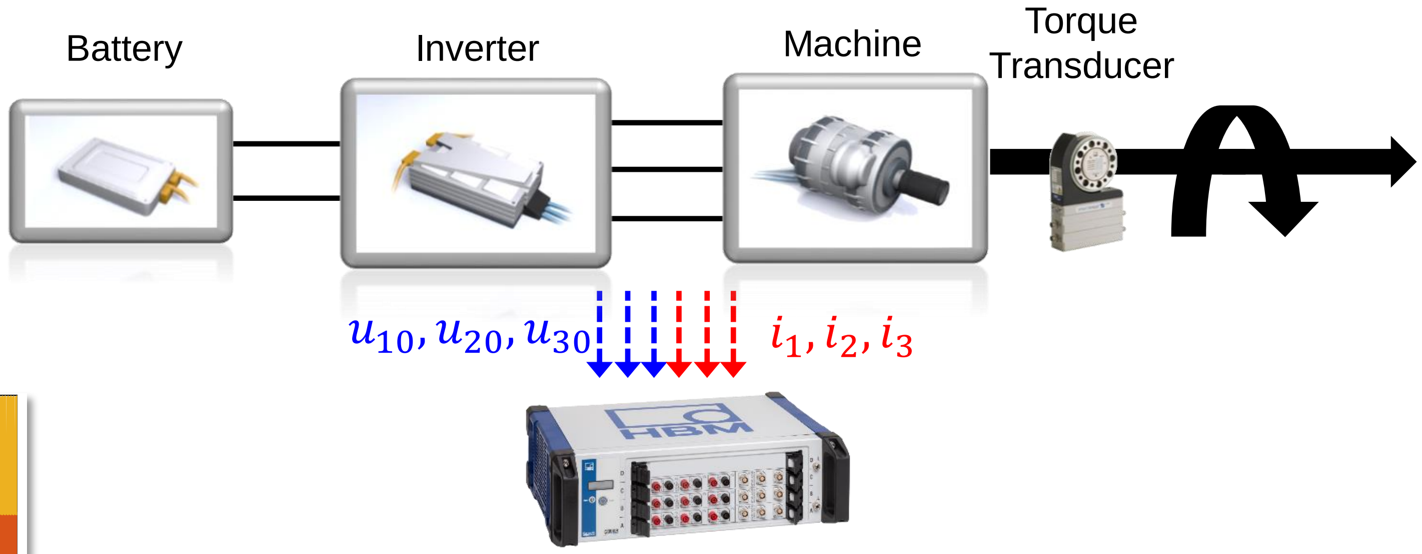


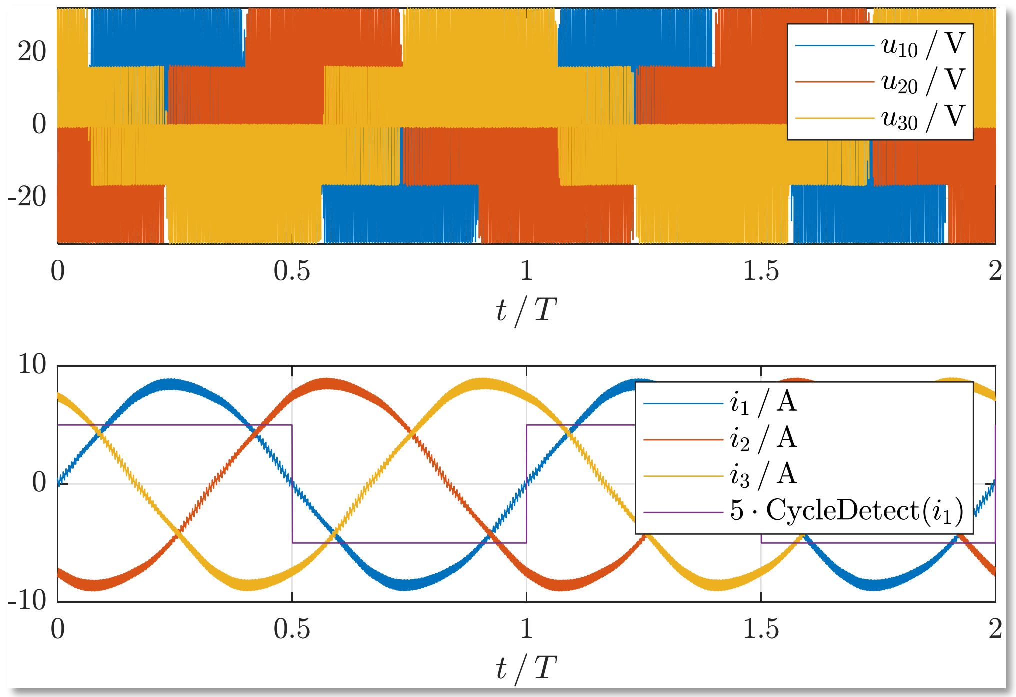


Inverter.out.u_1	(RTFormulas.Inverter.out.u_12 - RTFormulas.Inverter.out.u_31) / 3
Inverter.out.u_2	(RTFormulas.Inverter.out.u_23 - RTFormulas.Inverter.out.u_12) / 3
Inverter.out.u_3	(RTFormulas.Inverter.out.u_31 - RTFormulas.Inverter.out.u_23) / 3

Conventional Electric Power Calculation

- Input power of the machine
  1. Measurement of the line currents and voltages
  2. Detection of the fundamental cycle (based on smooth current waveform)





Cycle is the basis of all calculations related to the fundamental period, such as:

RMS values, active, reactive and apparent power

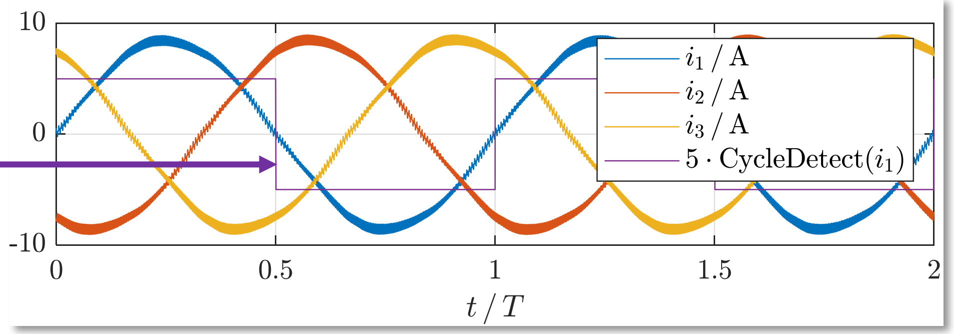
Conventional Electric Power Calculation

- Calculation of the **instantaneous power** [1-6]

$$p(t) = u_{10}(t)\cdot i_1(t) + u_{20}(t)\cdot i_2(t) + \cdots + u_{n0}(t)\cdot i_n(t)$$

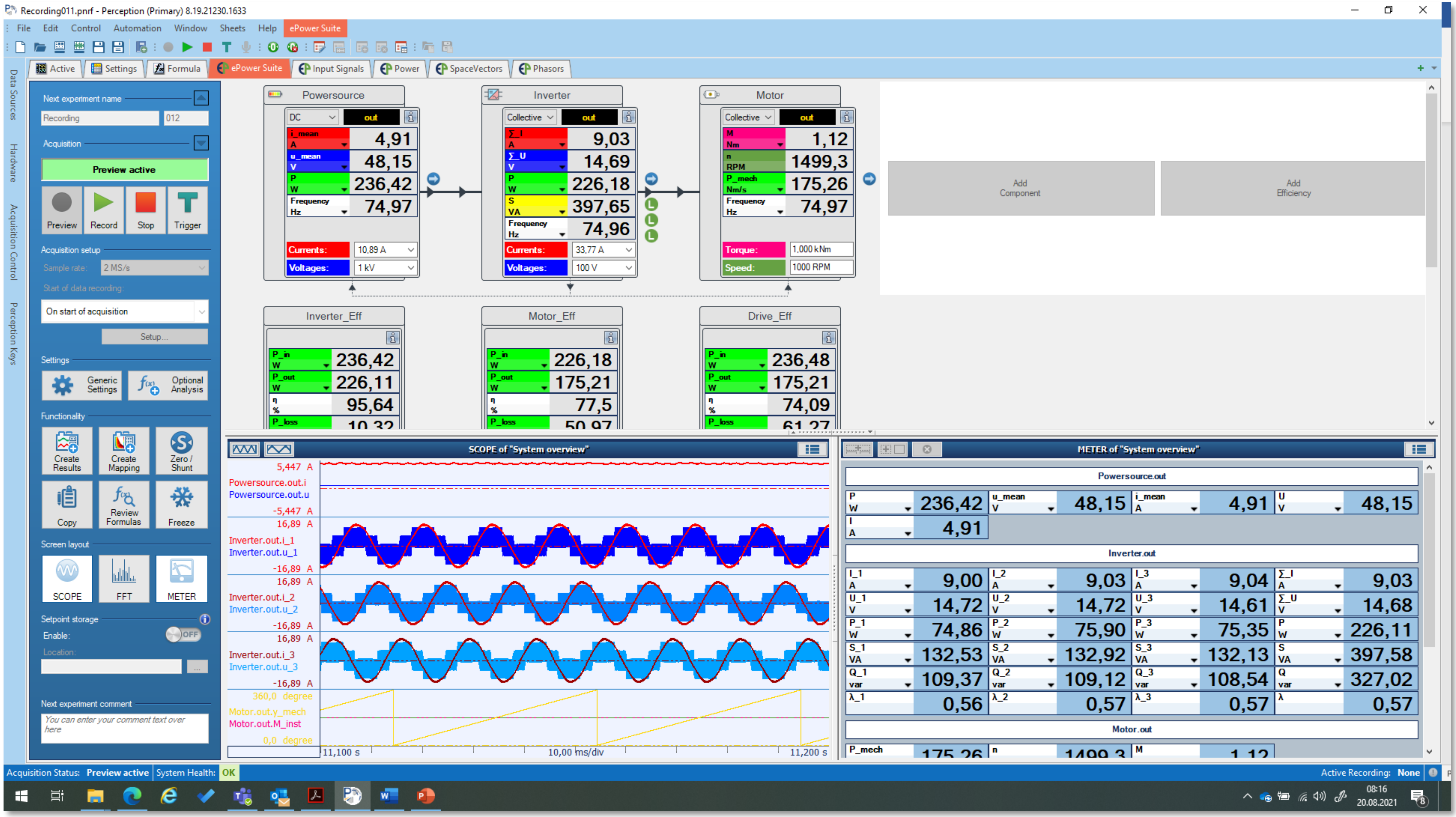
- Calculation of the **active power** as the **average** of the instantaneous power related to the **fundamental period** T [1-6] → fundamental period is defined by the previously determined cycle

$$P = \overline{p(t)}\Big|_T = \frac{1}{T}\cdot\int_T p(\tau)\,\mathrm{d}\tau$$



- Further cycle-based parameters, such as power quantities, RMS values, fundamentals, etc., may be implemented analogously

Configuration of the ePower Suite



Recording011.pnrf - Perception (Primary) 8.19.21230.1633

Next experiment name: Recording 012

Acquisition: Preview active

Acquisition setup

Sample rate: 2 MS/s

Start of data recording: On start of acquisition

Enable: OFF

Location:

Next experiment comment: *You can enter your comment text over here*

Powersource (DC, out)

- i_mean A: 4,91
- u_mean V: 48,15
- P W: 236,42
- Frequency Hz: 74,97
- Currents: 10,89 A
- Voltages: 1 kV

Inverter (Collective, out)

- Σ_I A: 9,03
- Σ_U V: 14,69
- P W: 226,18
- S VA: 397,65
- Frequency Hz: 74,96
- Currents: 33,77 A
- Voltages: 100 V

Motor (Collective, out)

- M Nm: 1,12
- n RPM: 1499,3
- P_mech Nm/s: 175,26
- Frequency Hz: 74,97
- Torque: 1,000 kNm
- Speed: 1000 RPM

Inverter_Eff

- P_in W: 236,42
- P_out W: 226,11
- η %: 95,64
- P_loss: 10,32

Motor_Eff

- P_in W: 226,18
- P_out W: 175,21
- η %: 77,5
- P_loss: 50,97

Drive_Eff

- P_in W: 236,48
- P_out W: 175,21
- η %: 74,09
- P_loss: 61,27

SCOPE of "System overview"

METER of "System overview"

Powersource.out							
P W	236,42	u_mean V	48,15	i_mean A	4,91	U V	48,15
I A	4,91						
Inverter.out							
I_1 A	9,00	I_2 A	9,03	I_3 A	9,04	Σ_I A	9,03
U_1 V	14,72	U_2 V	14,72	U_3 V	14,61	Σ_U V	14,68
P_1 W	74,86	P_2 W	75,90	P_3 W	75,35	P W	226,11
S_1 VA	132,53	S_2 VA	132,92	S_3 VA	132,13	S VA	397,58
Q_1 var	109,37	Q_2 var	109,12	Q_3 var	108,54	Q var	327,02
λ_1	0,56	λ_2	0,57	λ_3	0,57	λ	0,57
Motor.out							
P_mech	175,26	n	1499,3	M	1,12		

Acquisition Status: Preview active | System Health: OK | Active Recording: None

08:16 20.08.2021

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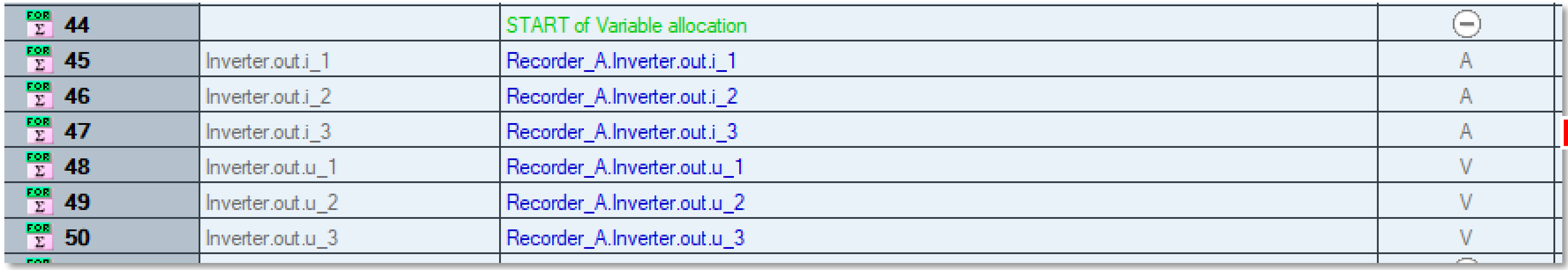
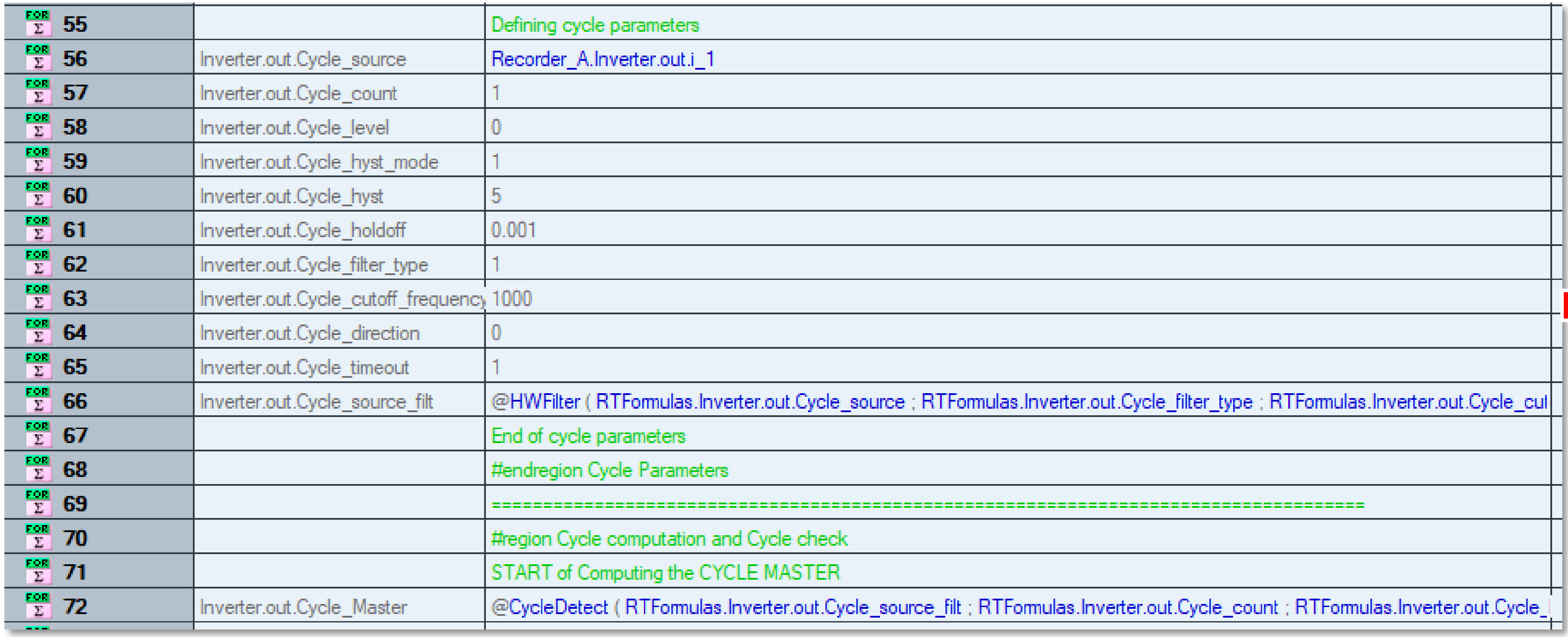
Automatically Created ePower Suite Formulas



44		START of Variable allocation	⊖
45	Inverter.out.i_1	Recorder_A.Inverter.out.i_1	A
46	Inverter.out.i_2	Recorder_A.Inverter.out.i_2	A
47	Inverter.out.i_3	Recorder_A.Inverter.out.i_3	A
48	Inverter.out.u_1	Recorder_A.Inverter.out.u_1	V
49	Inverter.out.u_2	Recorder_A.Inverter.out.u_2	V
50	Inverter.out.u_3	Recorder_A.Inverter.out.u_3	V

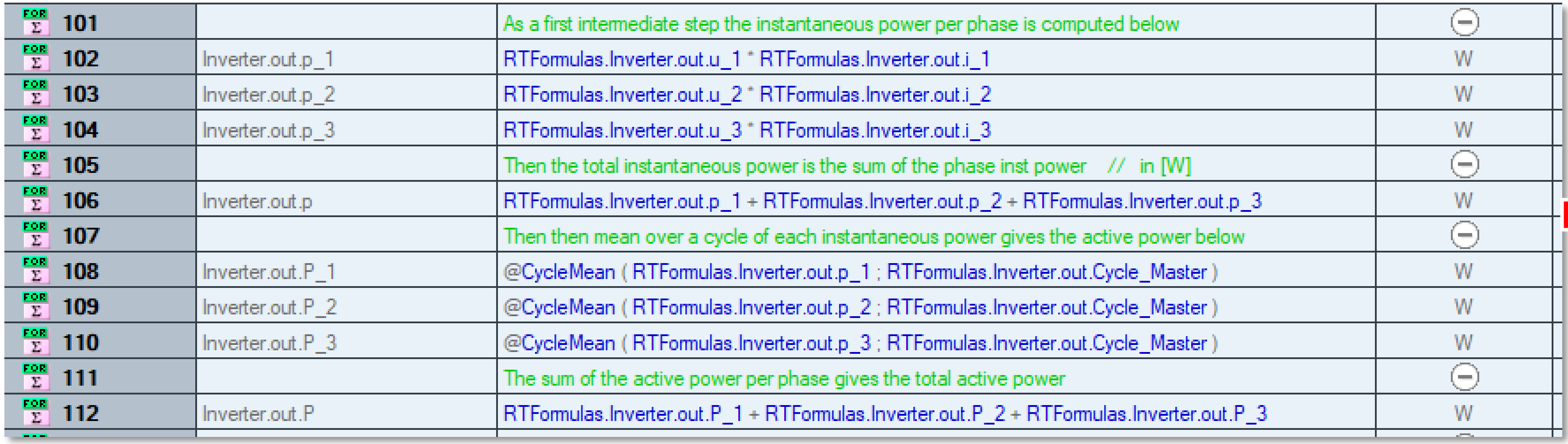
Allocation of measured phase quantities



55		Defining cycle parameters
56	Inverter.out.Cycle_source	Recorder_A.Inverter.out.i_1
57	Inverter.out.Cycle_count	1
58	Inverter.out.Cycle_level	0
59	Inverter.out.Cycle_hyst_mode	1
60	Inverter.out.Cycle_hyst	5
61	Inverter.out.Cycle_holdoff	0.001
62	Inverter.out.Cycle_filter_type	1
63	Inverter.out.Cycle_cutoff_frequency	1000
64	Inverter.out.Cycle_direction	0
65	Inverter.out.Cycle_timeout	1
66	Inverter.out.Cycle_source_filt	@HWFilter (RTFormulas.Inverter.out.Cycle_source ; RTFormulas.Inverter.out.Cycle_filter_type ; RTFormulas.Inverter.out.Cycle_cu
67		End of cycle parameters
68		#endregion Cycle Parameters
69		===
70		#region Cycle computation and Cycle check
71		START of Computing the CYCLE MASTER
72	Inverter.out.Cycle_Master	@CycleDetect (RTFormulas.Inverter.out.Cycle_source_filt ; RTFormulas.Inverter.out.Cycle_count ; RTFormulas.Inverter.out.Cycle_

Cycle detection

Automatically Created ePower Suite Formulas

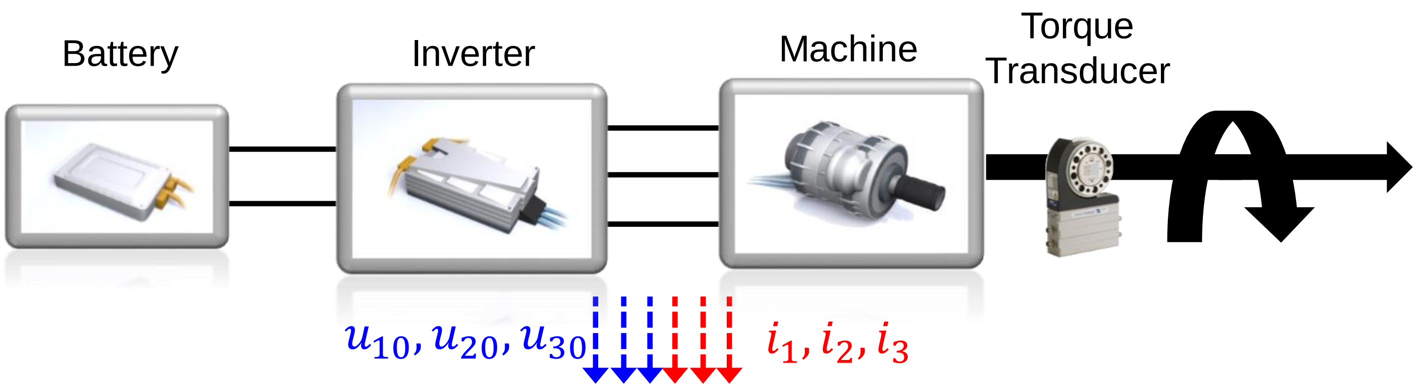


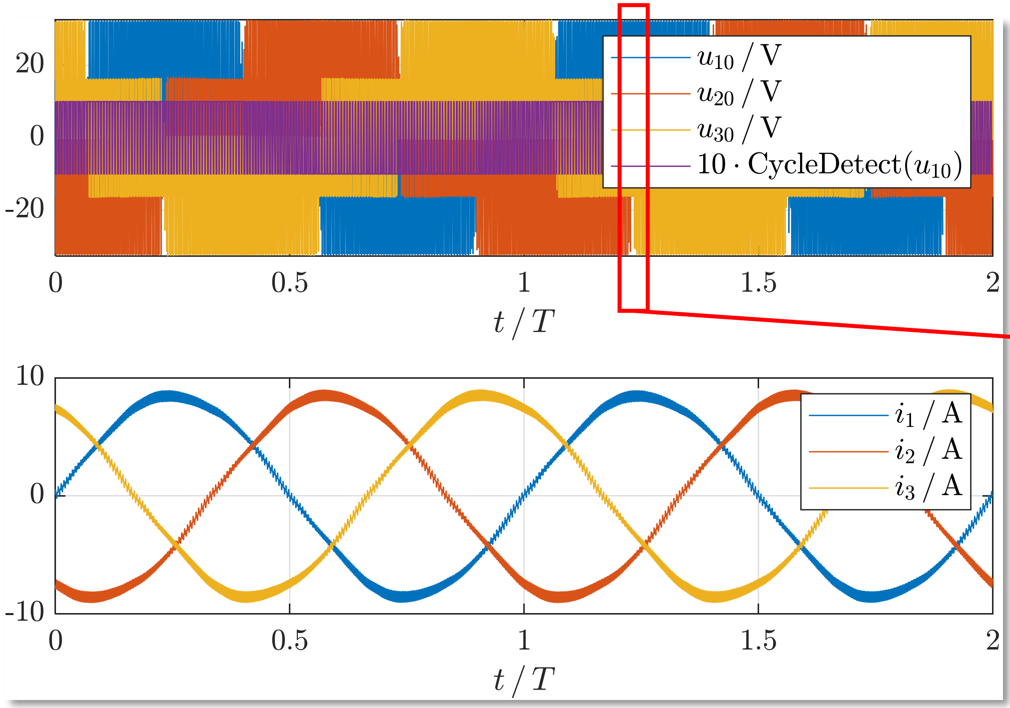
101		As a first intermediate step the instantaneous power per phase is computed below	⊖
102	Inverter.out.p_1	RTFormulas.Inverter.out.u_1 * RTFormulas.Inverter.out.i_1	W
103	Inverter.out.p_2	RTFormulas.Inverter.out.u_2 * RTFormulas.Inverter.out.i_2	W
104	Inverter.out.p_3	RTFormulas.Inverter.out.u_3 * RTFormulas.Inverter.out.i_3	W
105		Then the total instantaneous power is the sum of the phase inst power // in [W]	⊖
106	Inverter.out.p	RTFormulas.Inverter.out.p_1 + RTFormulas.Inverter.out.p_2 + RTFormulas.Inverter.out.p_3	W
107		Then then mean over a cycle of each instantaneous power gives the active power below	⊖
108	Inverter.out.P_1	@CycleMean (RTFormulas.Inverter.out.p_1 ; RTFormulas.Inverter.out.Cycle_Master)	W
109	Inverter.out.P_2	@CycleMean (RTFormulas.Inverter.out.p_2 ; RTFormulas.Inverter.out.Cycle_Master)	W
110	Inverter.out.P_3	@CycleMean (RTFormulas.Inverter.out.p_3 ; RTFormulas.Inverter.out.Cycle_Master)	W
111		The sum of the active power per phase gives the total active power	⊖
112	Inverter.out.P	RTFormulas.Inverter.out.P_1 + RTFormulas.Inverter.out.P_2 + RTFormulas.Inverter.out.P_3	W

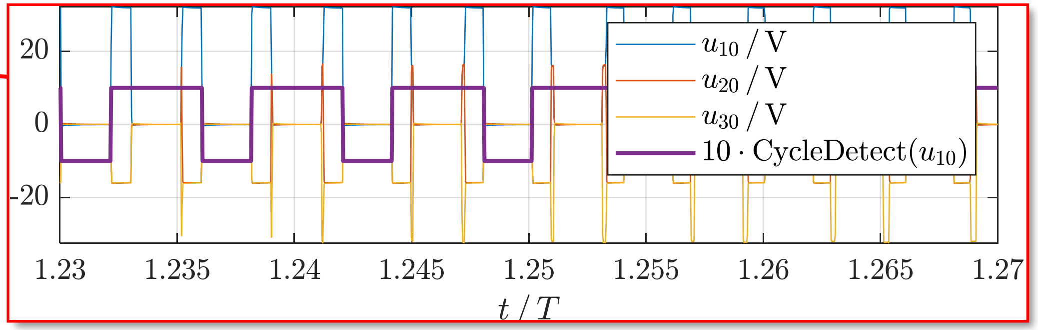
→ Power Calculation

Dynamic Electric Power Approximation

- Input power of the machine
  1. Measurement of the line currents and voltages
  2. Detection of the switching cycle (based on pulsed voltage waveform) [6,9]



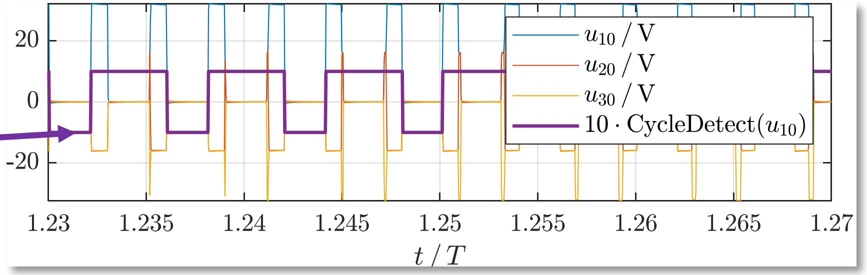




Dynamic Method to Estimate Electric Power

- Calculation of the **dynamic active power** as **average** of the instantaneous power related to the **switching period** T_s [6,9] → switching period is defined by the previously determined switching cycle

$$P_\mathrm{dyn} = \overline{p(t)}\Big|_{T_\mathrm{s}} = \frac{1}{T_\mathrm{s}} \cdot \int_{T_\mathrm{s}} p(\tau)\,\mathrm{d}\tau$$



- This method is applicable for numerous PWM-methods
  - Provides an **approximation of the conventional active power** definition during **steady state**
  - **Combines** the information of the **instantaneous power** $p(t)$ (during transients) and the **active power** P (during steady state) in a new dynamic active power definition P_dyn
  - The **quality of the approximation** becomes **better the larger** T **is compared to** T_s, i.e., $f_\mathrm{s} > f$, resp.
  - It can be mathematically proven that the dynamic active power and the conventional definition of active power are analytically identical, see[6],…
    1. … in the theoretical ideal case of infinitely high switching frequency
    2. … certain restrictions are observed when generating the PWM

Comparative measurements – startup of a PMSM

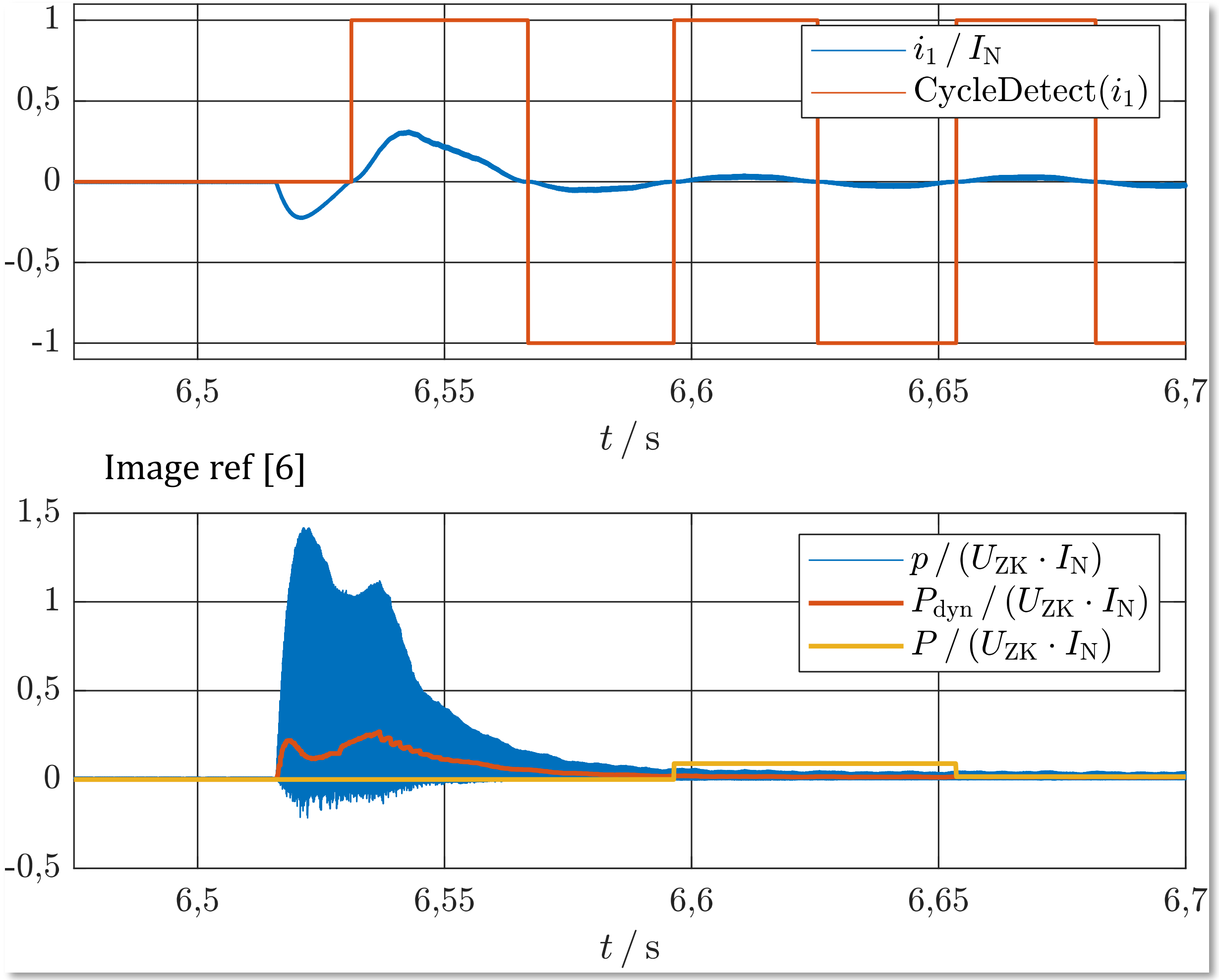


Image ref [6]

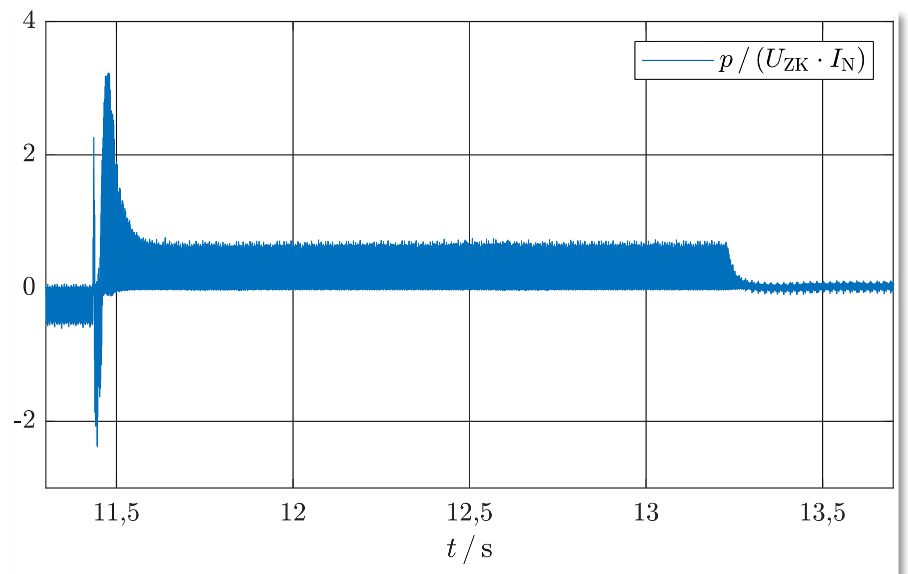
→ Drastically increased dynamic and update rate of active power information

- No load acceleration from standstill to constant speed
- Due to causality, the first value of P can only be calculated after the first fundamental cycle is completed

  → at this point, the startup is already finished
- P_{dyn} is delayed only by one inverter switching cycle

  → provides a representative dynamic average of inst. power

Transition between different steady state operating points



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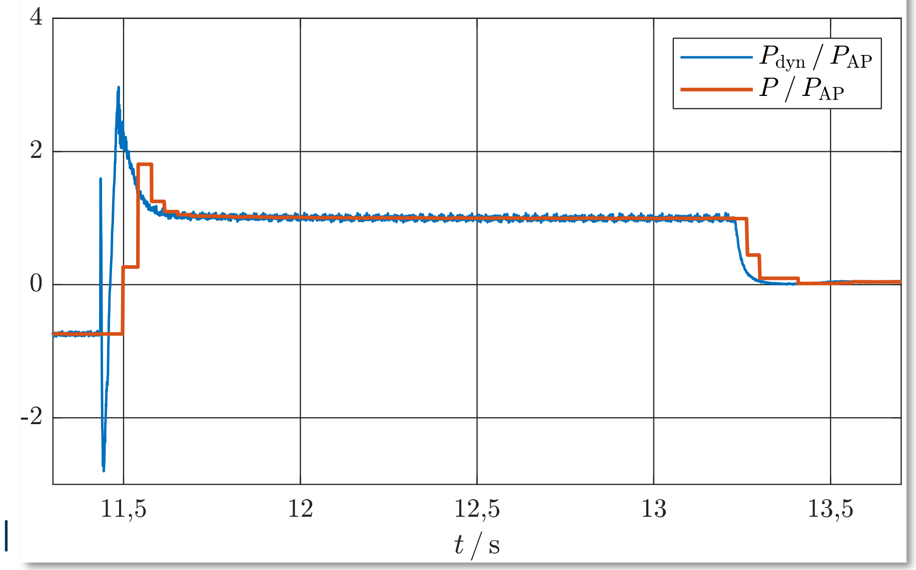

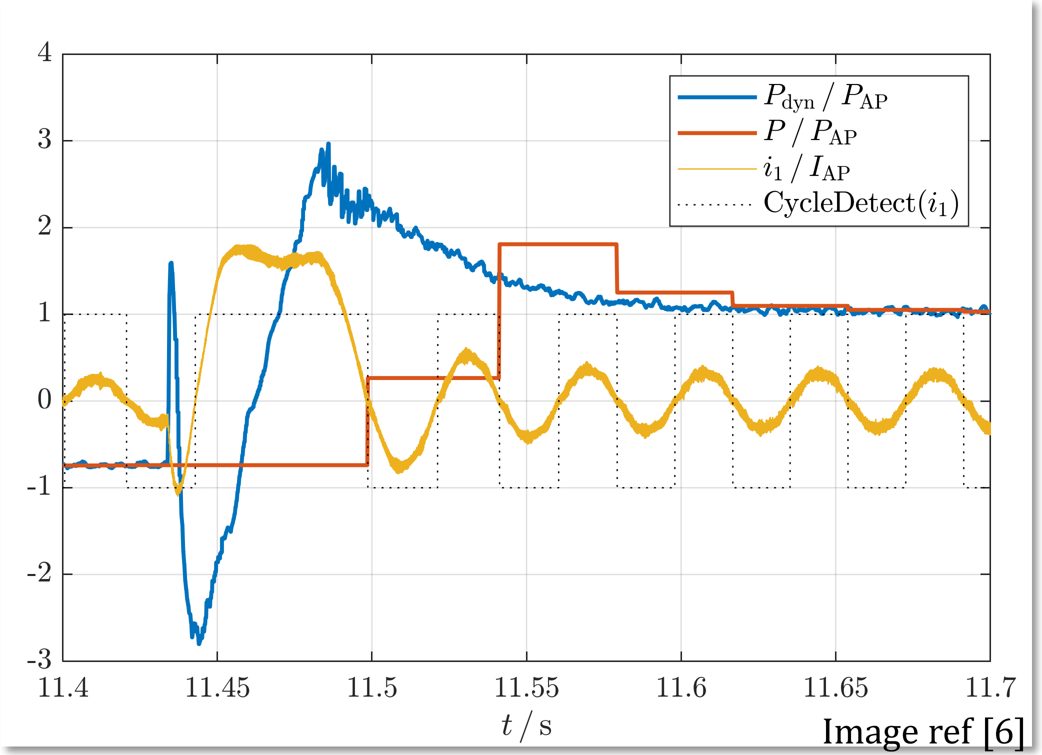

Image ref [6]

- P and P_{dyn} are very similar during steady state

  $f_s \approx 100 \cdot f$ for this measurement

- P_{dyn} provides significantly more dynamic information

→ Precise active power approximation during steady state

Dynamic Fundamental Quantities

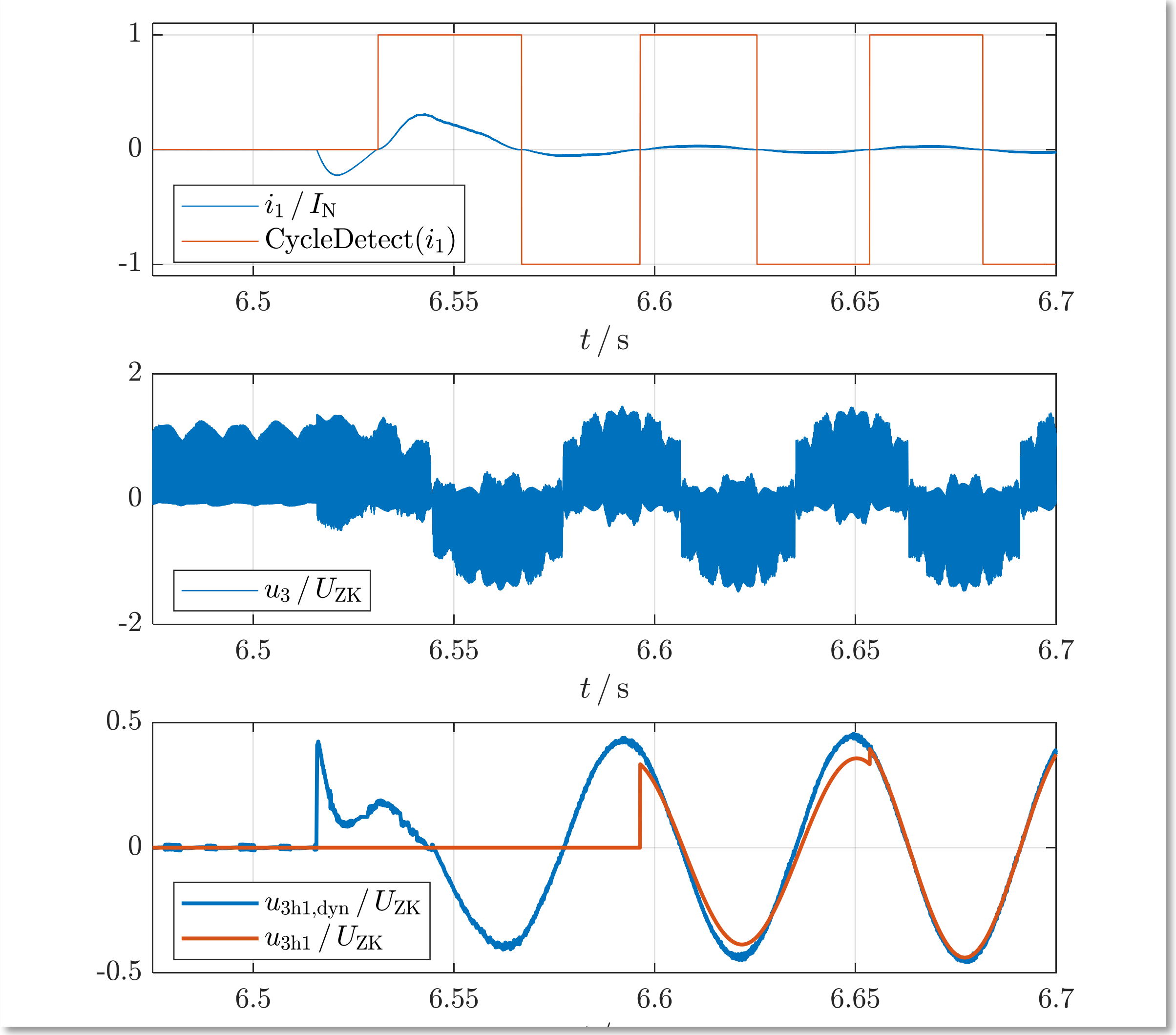

Image ref. [6]

- Switching cycle-based averaging of the inverter output voltages, with $\nu \in \{1,2,3\}$

$$u_{\nu r,\mathrm{h1dyn}} = \overline{u_{\nu r}(t)}\Big|_{T_\mathrm{s}} = \frac{1}{T_\mathrm{s}} \cdot \int_{T_\mathrm{s}} u_{\nu r}(\tau)\,\mathrm{d}\tau$$

- Subtraction of the zero-sequence voltage

$$u_{\nu,\mathrm{h1dyn}} = u_{\nu r,\mathrm{h1dyn}} - \sum_{\mu=1}^{3} u_{\nu r,\mathrm{h1dyn}}$$

→ Dynamic approximation of the fundamental waveforms

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Fundamental Space Vectors

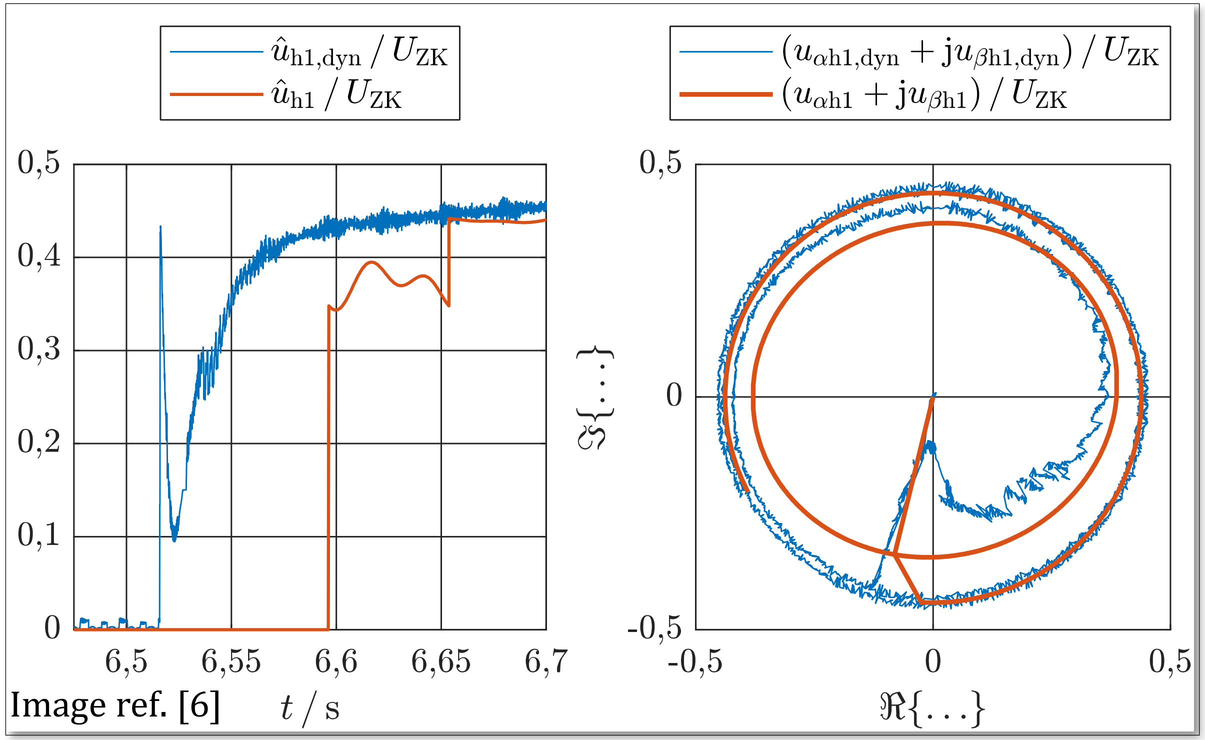

Image ref. [6]

- Applying the space vector transformation (Clark-transformation) [4]

$$\begin{pmatrix} u_{\alpha\mathrm{h1,dyn}} \\ u_{\beta\mathrm{h1,dyn}} \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{pmatrix} \cdot \begin{pmatrix} u_{1\mathrm{h1,dyn}} \\ u_{2\mathrm{h1,dyn}} \\ u_{3\mathrm{h1,dyn}} \end{pmatrix}$$

- Calculate the magnitude or phase angle of the space vector

$$\hat{u}_{\mathrm{h1,dyn}} = \sqrt{u_{\alpha\mathrm{h1,dyn}}^2 + u_{\beta\mathrm{h1,dyn}}^2}$$

$$\varphi_{\mathrm{h1,dyn}} = \mathrm{atan2}\left(u_{\alpha\mathrm{h1,dyn}}, u_{\beta\mathrm{h1,dyn}}\right)$$

→ Dynamic space vectors may be used to verify and assess the quality of the inverter control

→ Fundamental dq0-Transform (Park-Transform) can be calculated

Dynamic RMS Values

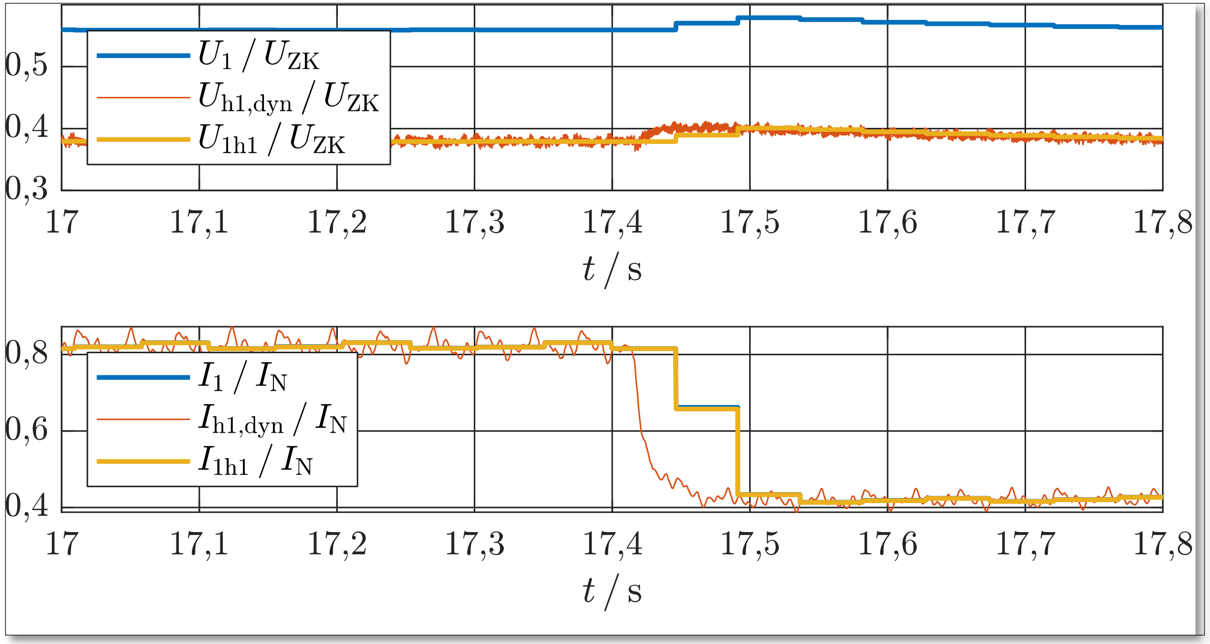

Image ref. [6]

- Assuming a balanced 3-phase system → RMS values are calculated from the approximated fundamental space vector magnitude

$$U_{\mathrm{h1,dyn}} = \frac{\hat{u}_{\mathrm{h1,dyn}}}{\sqrt{2}}$$

- Same procedure for the current

Dynamic RMS Values & Power Quantities

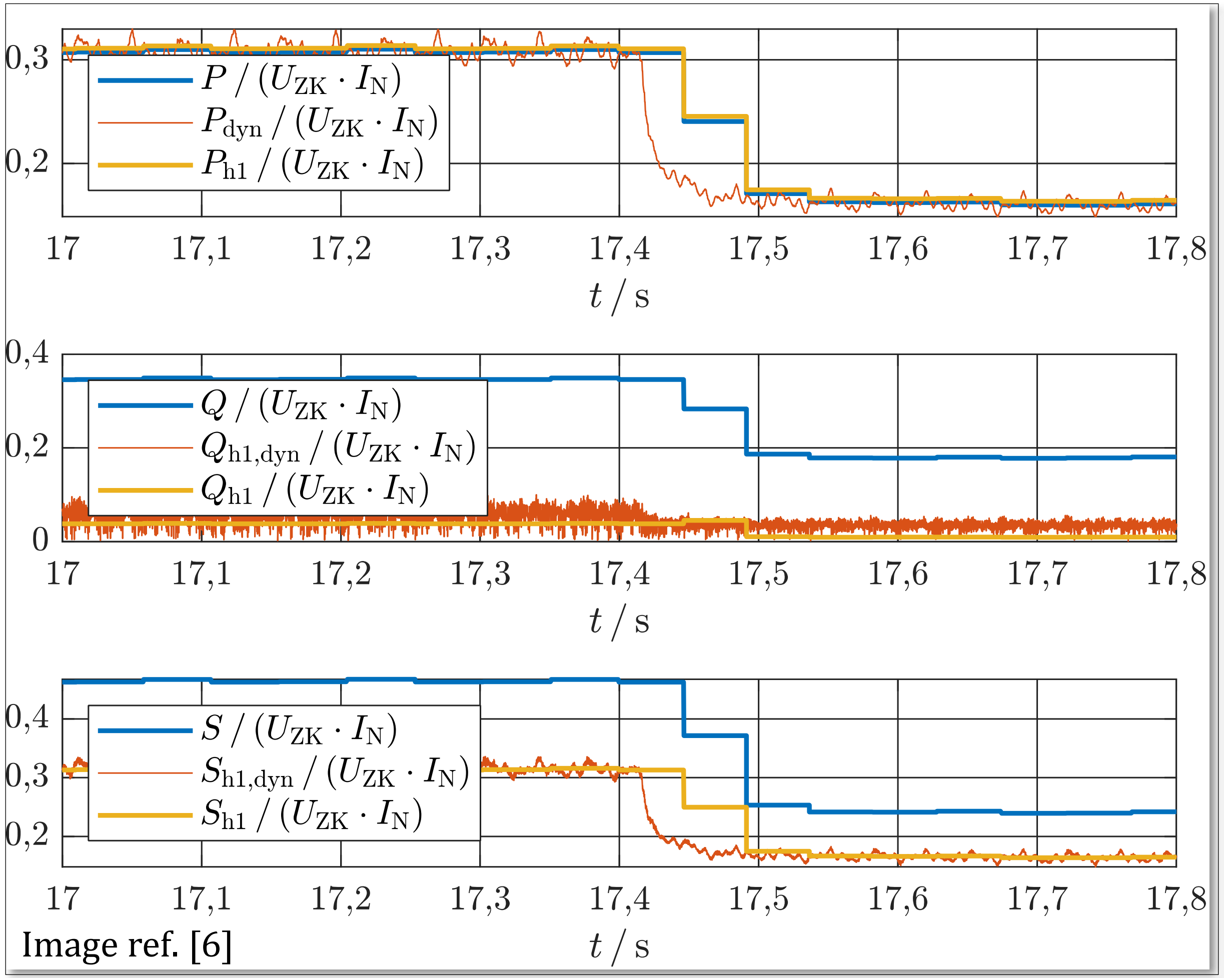

Image ref. [6]

- Dynamic (fundamental) active power

$$P_{\mathrm{dyn}} = \overline{p(t)}\Big|_{T_s} = \frac{1}{T_s} \cdot \int_{T_s} p(\tau)\, \mathrm{d}\tau$$

- Dynamic (fundamental) apparent power

$$S_{\mathrm{h1,dyn}} = 3 \cdot U_{\mathrm{h1,dyn}} \cdot I_{\mathrm{h1,dyn}}$$

- Dynamic (fundamental) reactive power

$$Q_{\mathrm{h1,dyn}} = \sqrt{S_{\mathrm{h1,dyn}}^2 - P_{\mathrm{dyn}}^2}$$

Accelerated Dynamic Efficiency Mapping

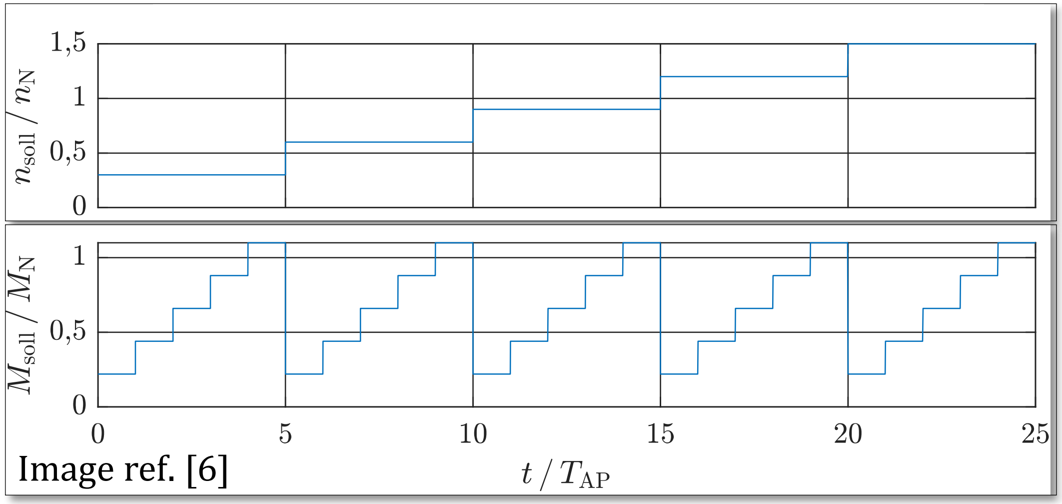

Image ref. [6]

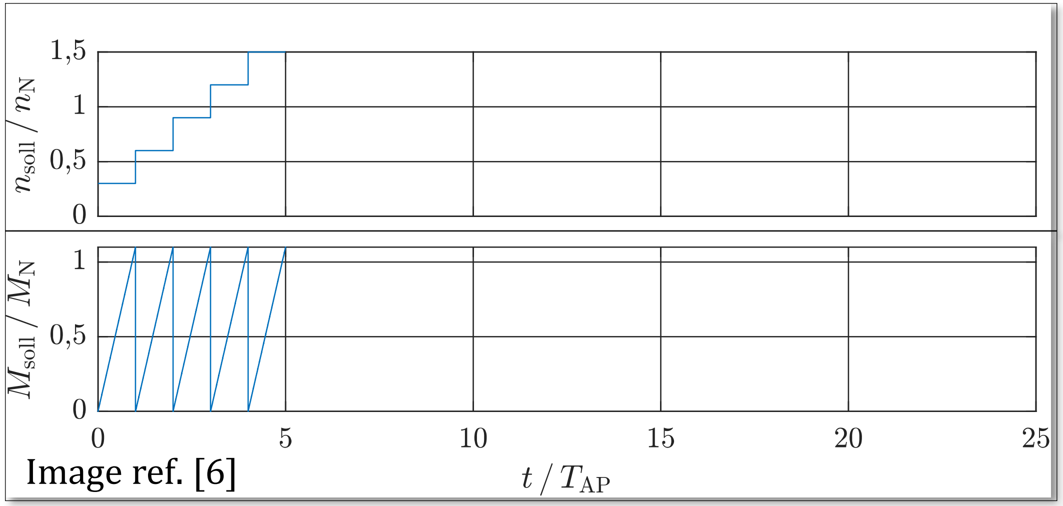

Image ref. [6]

Conventional method

- Steady state set-point values of speed and torque are driven sequentially
- Conventional active power and mechanical power are calculated based on the fundamental cycle
- Efficiency is calculated

Dynamic method

- Steady state state set-point values of speed are driven sequentially
- For each speed, the torque is ramped up continuously
- Active power and mechanical power are calculated based on the inverter switching cycle

Significant time savings!

Accelerated Dynamic Efficiency Diagram

Conventional Method

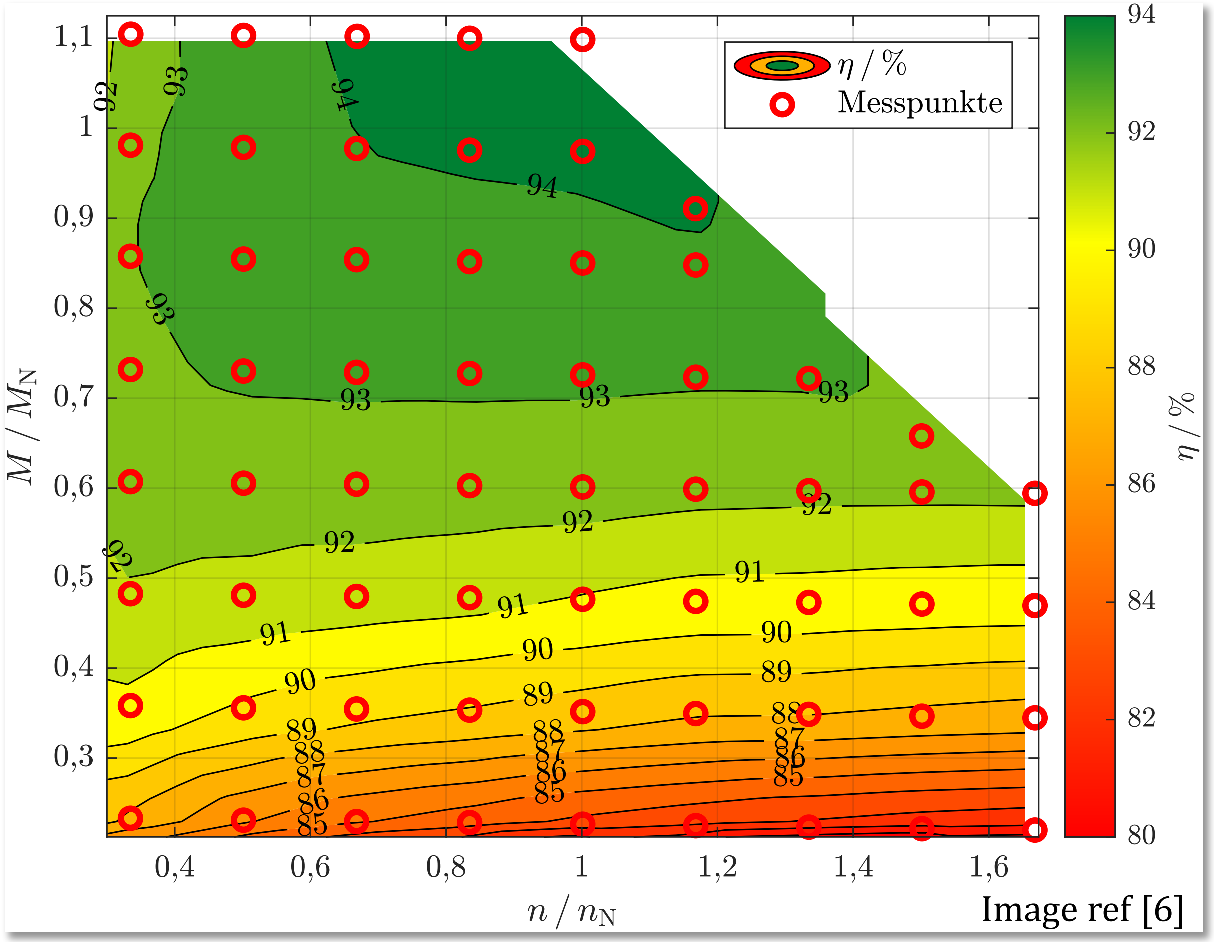

Image ref [6]

Dynamic Method

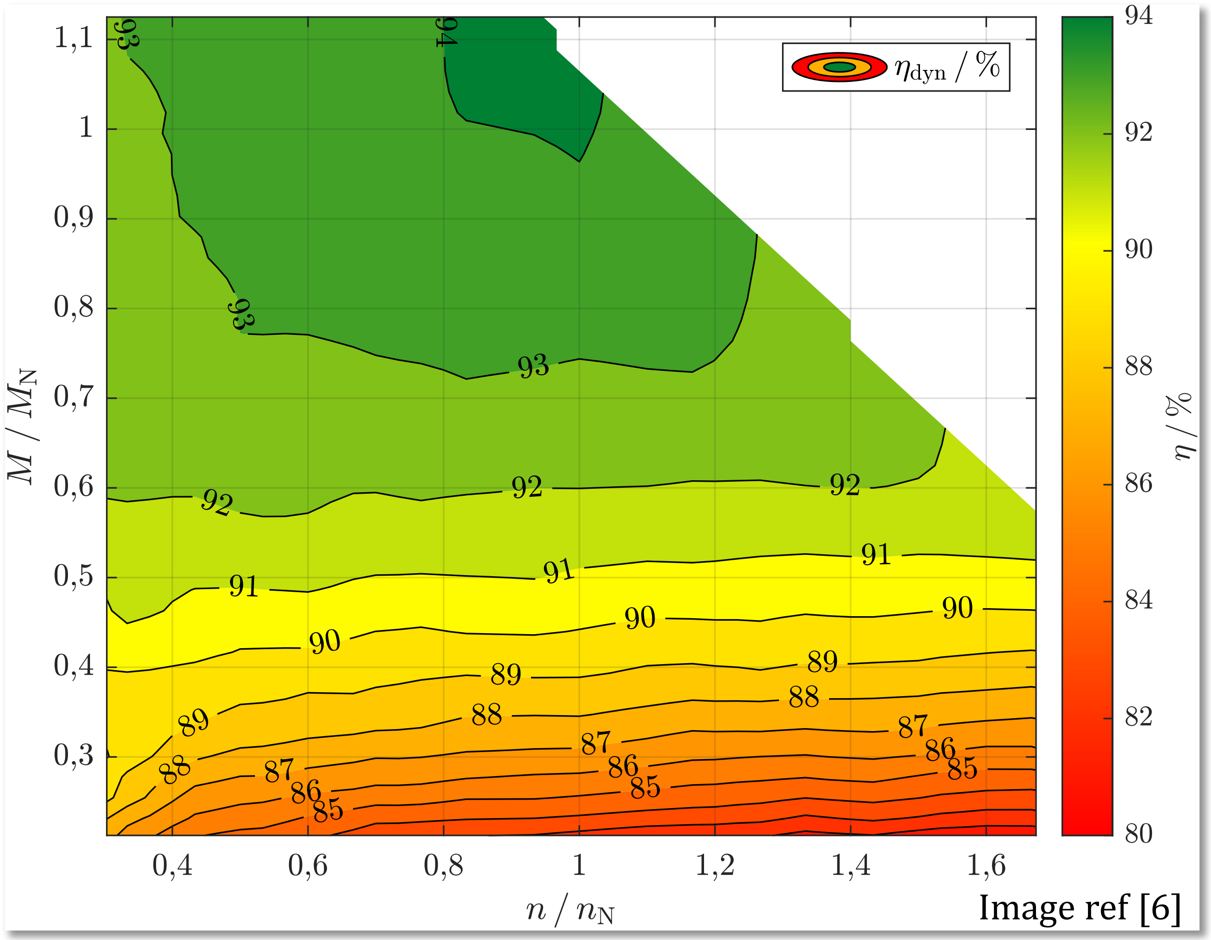

Image ref [6]

High level of similarity and enormously reduced measurement time

Accelerated Dynamic Efficiency Mapping

- Very small deviation between both methods

  → a small deviation from conventional method is inevitable

  → not suitable for the highest accuracy requirements, but:

- Accelerated measurement (time reduced to 10%)

  → Very suitable / cost efficient for end of line tests (pass/fail)

- Could also be evaluated during WLTP measurement

  → no additional efficiency measurement necessary

Deviation of Conventional and Dynamic Method

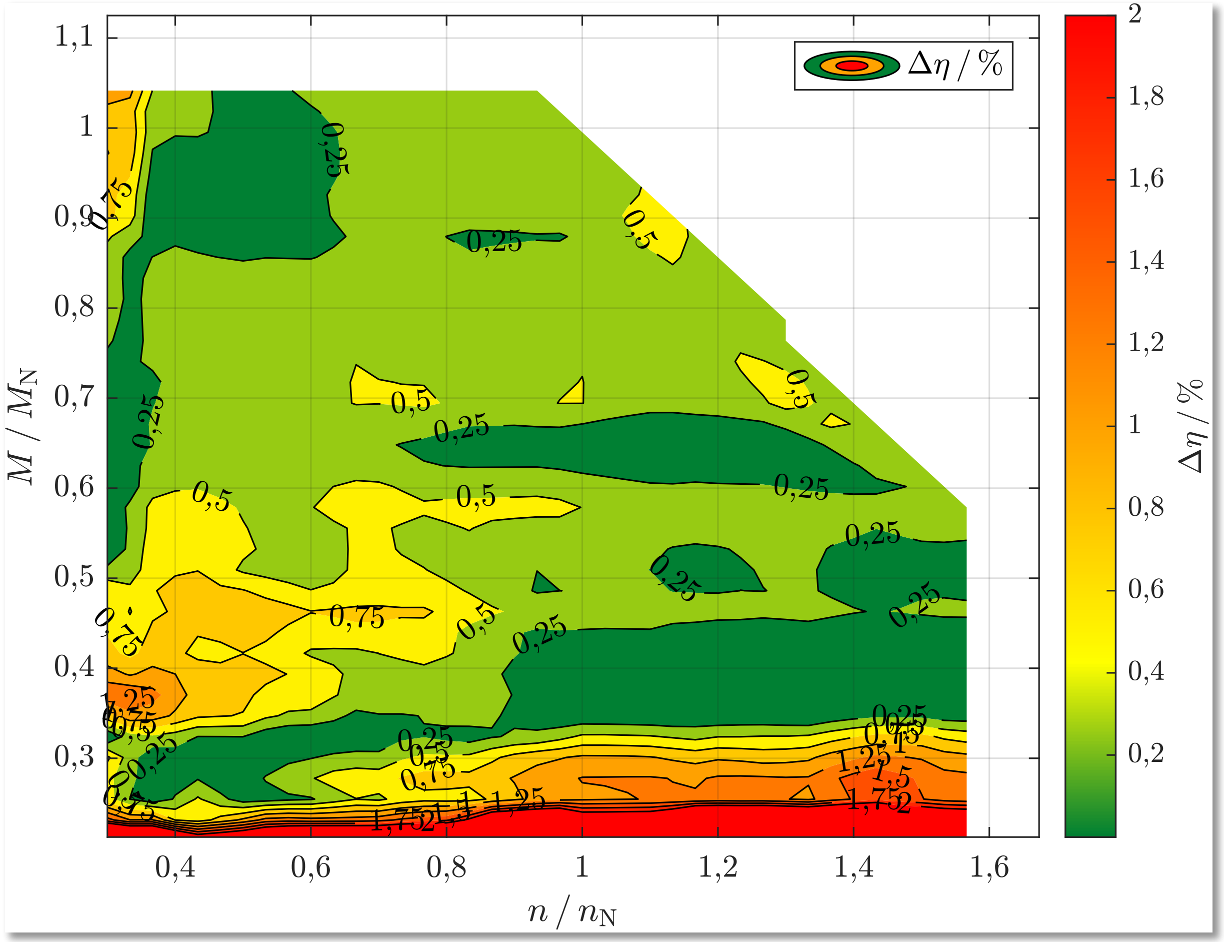

Image ref [6]

Summary

- Dynamic active power P_{dyn} was introduced as an additional new active power definition
- P_{dyn} combines the advantages of instantaneous power p and active power P in a new quantitiy
- Dynamic active power calculation method may be transfered to other cycle-based parameters, such as RMS, reactive power etc.
- P_{dyn} may be used to accelerated efficiency diagram measurements / save ressources and costs
- Efficiency mapping may be included in test procedures to be done anyhow (e.g., WLTP tests)
- Suitable method for real-time measurements fed back into control algorithms (power control on the inverter system, double-two level inverter [7], doubly-fed PM synchronous machine [8])

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Thank You

Questions?
Please don't hesitate to contact me…

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