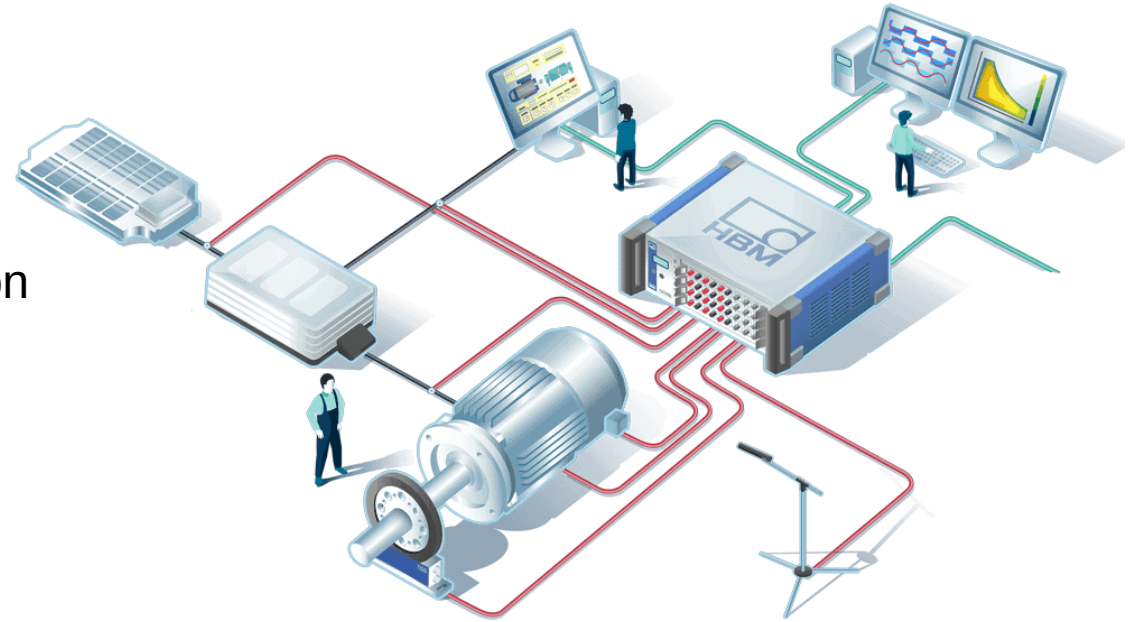
Tips for Selecting a Power Analyzer for Electric Drive Testing

PUBLIC

Agenda

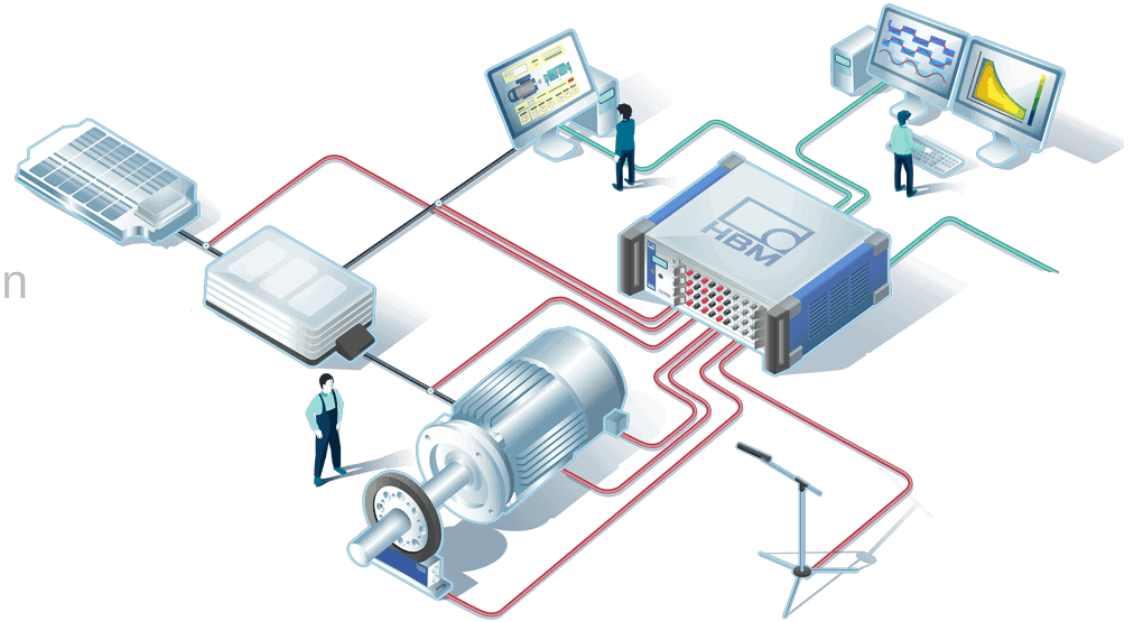
1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



HBK
HOTTINGER BRÜEL & KJÆR

Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information

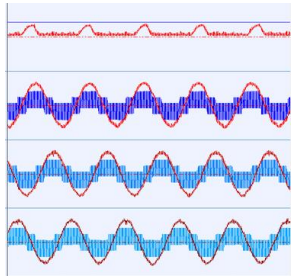


HBK
HOTTINGER BRÜEL & KJÆR

What is a Power Analyzer

- What is a Power Analyzer?
  - A test instrument for measuring the power flow in electrical systems
    - including power generation, consumption, loss, efficiency, etc.
  - Used in many applications, however, there's no universal solution to every power measurement challenge

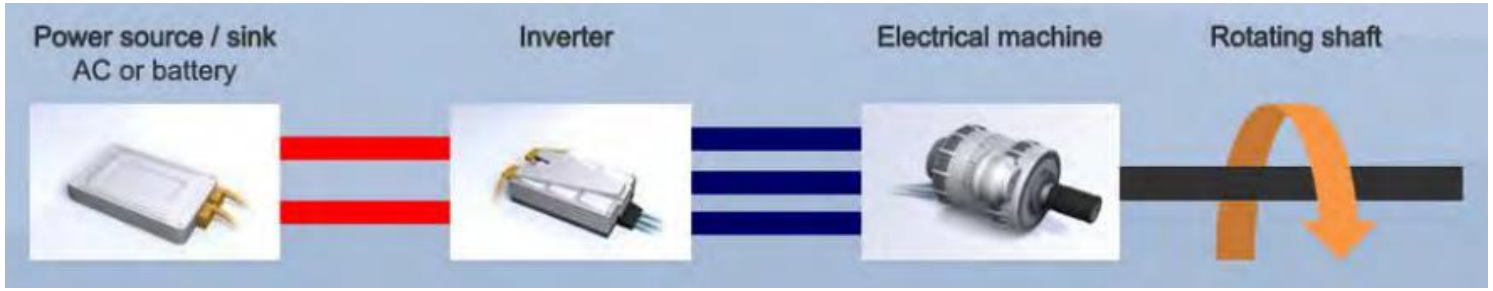
- Why Measure Power?
  - Improve efficiency and performance of products and services
  - Minimize loss and consumption resulting in reduce costs
  - Avoid downtime and revenue losses by determining the origin and type of power issues
  - Ensure safety of products and operators and comply with standards



- **To accomplish the tasks above**, one needs to measure, analyze and <u>gather as much information as possible and at the highest accuracy</u>, especially when improving efficiency

What is Electric Drive Testing

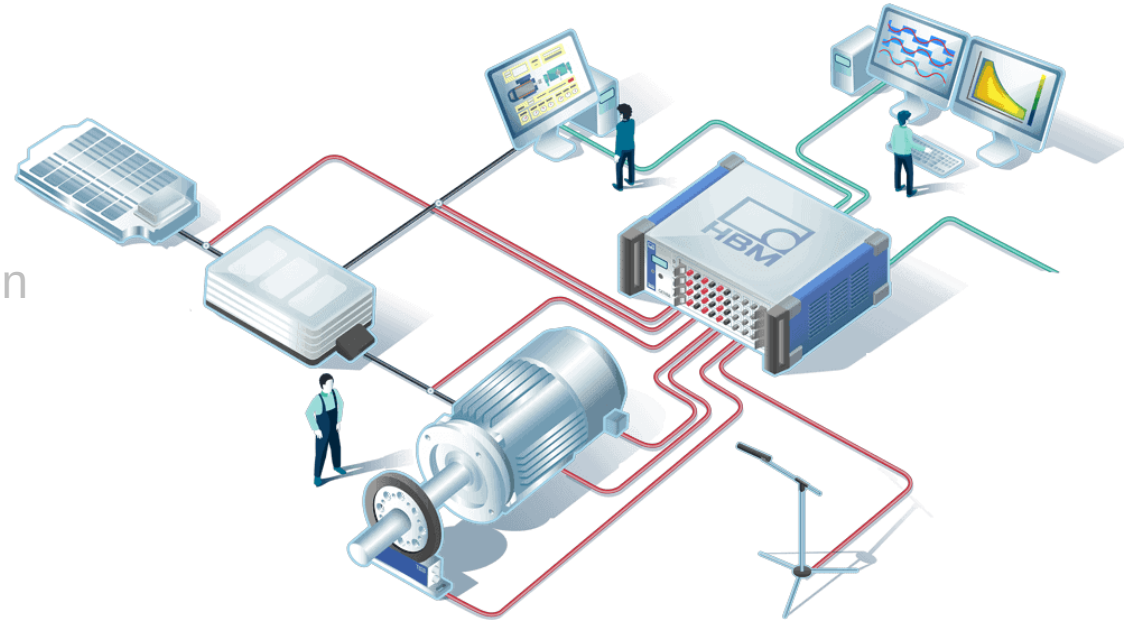
- Elements of an electric drive system …



  - **Power source** … often a battery or DC bus, sometimes AC
  - **Power converter** … often an inverter changing DC power to AC power
  - **Motor** … using AC power to convert electrical energy to mechanical power
- Electric Drive Testing goal? … to maximize efficiency across the entire drive system
- How? … by maximizing torque per amp for as many points as possible, by using clever battery, inverter and machine designs and implementing appropriate control techniques
- Again, **to accomplish the tasks above**, one needs to measure, analyze and <u>gather as much information as possible and at the highest accuracy</u>, especially when improving efficiency

Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



HBK
HOTTINGER BRÜEL & KJÆR

Tip # 1 – Accuracy

- Measurement accuracy is fundamental, why?
  - To optimize the performance of an electric inverter, motor or drivetrain
  - Minimizes measurement uncertainty
  - Offers reliable data to improve efficiency
- Select a power analyzer with the best…
  - Power accuracy
  - Torque and speed accuracy
    - Use a digital/frequency signal (for noise immunity), identify accuracy of the timer/counter
- Check the accuracy of any sensors to be used
  - Current sensors, voltage dividers, torque transducers, speed sensors, etc.

Tip # 1 – Accuracy – What Does The Spec Mean?

- No standard definition for electric power measurement accuracy
- Everyone defines their own method, often you may see one ‘banner spec’
  - For example, 0.03% accuracy or measurement error … 0.03% of what?
    - Voltage?
    - Current?
    - Power?
    - DC only or AC and at what frequency?
    - at what power factor?
    - at what input range?
    - with or without averaging?
    - with or without filtering?
    - Is accuracy a pass/fail (guaranteed) spec, or typical spec (not guaranteed)?
- These are questions to ask when reading a data sheet … read all the fine print

Tip # 1 – Power Accuracy – Data sheet Example

- Ideally power accuracy includes …
  - Banner spec
    - Reading error, often listed as gain error
    - Range error, often listed as offset error

GEN series
GN310B (GN311B)

Data sheet

3 channel power card
± 1500 V DC and ± 2 A

Special features

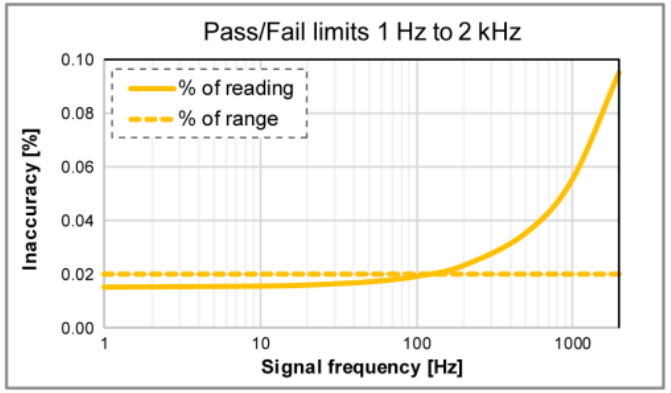
- Accuracy 0.015% of reading, 0.02% of range
- 3 power channels (U and I)
- 5 voltage ranges up to ± 1500 V DC
- 7 current ranges up to ± 2 A
- 2 Digital channels for torque and speed
- Real-time computations of RMS, P, S, Q, λ, η, cosφ, THD, i_alpha, i_ beta and more
- Full bandwidth power calculations
- Fundamental power calculations
- Phase matched anti-alias protection
- 1 ms latency real-time output
- 18 bit at 2 MS/s (200 kS/s) sample rate
- Triggering on real-time power results

Tip # 1 – Power Accuracy – Data sheet Example

- Ideally power accuracy includes …
  - Banner spec
    - Reading error, often listed as gain error
    - Range error, often listed as offset error
  - Detailed specs, pass/fail limits?
  - Formulas, tables, frequency plots
  - Over a variety of …
    - Power factors
    - Frequencies
    - Input ranges

Power Wideband Pass/Fail Limits

0.33 Ω shunt: ± 75 mA, ± 150 mA, ± 300 mA, ± 0.6 A and ± 1.2 A					
	DC	**1 Hz < f ≤ 25 kHz**	**25 kHz < f ≤ 100 kHz**	**100 kHz < f ≤ 200 kHz**	**200 kHz < f ≤ 500 kHz**
Reading error DC and all power factors	0.015%(1)	0.015% + (0.04 * kHz)%	1.015%	0.015% + (0.01 * kHz)%	2.015% + (0.04 * (kHz - 200))%
Range error DC	0.02% + 2.5 mW(2)	--	--	--	--
Range error 0.5 < power factor ≤ 1	--	0.02%	0.02%	0.02%	0.02%
Range error 0.01 ≤ power factor ≤ 0.5	--	0.04%	0.04%	0.04%	0.04%
0.1 Ω shunt: ± 1.0 A and ± 2.0 A					
	DC	**1 Hz < f ≤ 25 kHz**	**25 kHz < f ≤ 100 kHz**	**100 kHz < f ≤ 200 kHz**	**200 kHz < f ≤ 500 kHz**
Reading error DC and all power factors	0.02%	0.02% + (0.04 * kHz)%	1.02%	0.02% + (0.01 * kHz)%	2.02% + (0.04 * (kHz - 200))%
Range error DC	0.04% + 2.5 mW	--	--	--	--
Range error 0.01 ≤ power factor ≤ 1	--	0.04%	0.04%	0.04%	0.04%



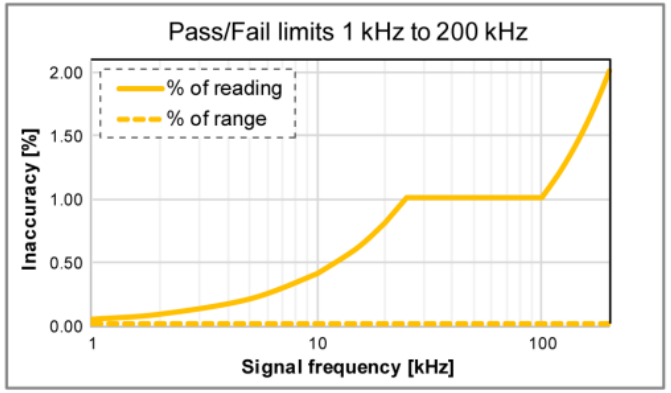


Figure 1.4: Power pass/fail limits (0.33 Ω shunt), Wideband and 0.5 ≤ Power Factor ≤ 1

(1) For ± 75 mA range, the DC Reading error is 0.02%

(2) For ± 75 mA range, the DC Range error is 0.04% + 2.5 mW

Tip # 1 – Power Accuracy – Data sheet Example

- Ideally power accuracy includes …
  - Banner spec
    - Reading error, often listed as gain error
    - Range error, often listed as offset error
  - Detailed specs, pass/fail limits?
  - Formulas, tables, frequency plots
  - Over a variety of …
    - Power factors
    - Frequencies
    - Input ranges
  - Measurement Uncertainty
    - Formulas

Power Measurement Uncertainty Examples

For DC Power the power range is defined from 0 W to maximum DC voltage * DC current.
For RMS power only when voltage and current sine waves are used without harmonic distortions, the maximum RMS power would be 0 to (Max DC voltage / V2) * (Max DC current / V2). However, in real world applications these signals have larges distortions, so maximum RMS power is harder to define.
Specification for both DC and RMS power therefore are all based on the power range calculated for DC signals. This creates a consistent spec, especially if both DC and RMS components exist in the same power signal to be measured.
As power calibration is a chain calibration, the individual voltage and current specifications can be excluded for power measurement uncertainty.

Comparing the same reading in two different power ranges		**Power range**	
400 W DC		**600 W**	**1200 W**
reading error	0.58 * 0.015% of reading	34.8 mW	34.8 mW
range error	0.58 * (0.02% of range + 2.5 mW)	71.05 mW	140.65 mW
Total error	$\sqrt{reading\_error^2 + range\_error^2}$	79.11 mW	144.89 mW
Uncertainty value (k=1)	`total error / reading * 100%`	**0.0198%**	**0.0362%**
250 W RMS at 10 kHz & power factor 1		**600 W**	**1200 W**
reading error	0.58 * (0.015 + (0.04 * kHz))% of reading	602 mW	602 mW
range error	0.58 * 0.02% of range	69.6 mW	139.2 mW
Total error	$\sqrt{reading\_error^2 + range\_error^2}$	606.0 mW	617.9 mW
Uncertainty value (k=1)	`total error / reading * 100%`	**0.242%**	**0.247%**

HBK HOTTINGER BRÜEL & KJÆR

Tip # 1 – Power Accuracy – Data sheet Example

- Ideally power accuracy includes …
  - Banner spec
    - Reading error, often listed as gain error
    - Range error, often listed as offset error
  - Identify if specs are pass/fail limits
  - Formulas, tables, frequency plots
  - Over a variety of …
    - Power factors
    - Frequencies
    - Input ranges
  - Measurement Uncertainty
    - Formulas and tables
    - Over a variety of ranges, frequencies

Power Pass/Fail Limit Overview: 0.33 Ω Shunt

(Wideband and 0.5 ≤ Power Factor ≤ 1).
All values are calculated using the power inaccuracy specifications. The listed value is the maximum inaccuracy that exist at the end of the frequency band. For more accurate values use the specified math in the power inaccuracy specification table.

Power ranges			Signal frequency (f)							
Voltage	Current	Power	DC	1 Hz < f ≤ 100 Hz	0.1 kHz < f ≤ 1 kHz	1 kHz < f ≤ 10 kHz	10 kHz < f ≤ 100 kHz	100 kHz < f ≤ 200 kHz	200 kHz < f ≤ 500 kHz	
± 1500 V DC [1060 V RMS]	± 1.2 A DC [0.84 A RMS]	1800 W	0.015% 0.020%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.6 A [0.42 A RMS]	900 W	0.015% 0.020%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.3 A [0.21 A RMS]	450 W	0.015% 0.021%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.15 A [0.10 A RMS]	225 W	0.015% 0.021%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.075 A [0.05 A RMS]	112.5 W	0.020% 0.041%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
± 1000 V DC [700 V RMS]	± 1.2 A DC [0.84 A RMS]	1200 W	0.015% 0.020%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.6 A [0.42 A RMS]	600 W	0.015% 0.020%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.3 A [0.21 A RMS]	300 W	0.015% 0.021%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.15 A [0.10 A RMS]	150 W	0.015% 0.022%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.075 A [0.05 A RMS]	75 W	0.020% 0.043%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
± 500 V DC [350 V RMS]	± 1.2 A DC [0.84 A RMS]	600 W	0.015% 0.020%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range
	± 0.6 A [0.42 A RMS]	300 W	0.015% 0.021%	0.019% 0.020%	0.055% 0.020%	0.415% 0.020%	1.015% 0.020%	2.015% 0.020%	14.015% 0.020%	reading range

HBK HOTTINGER BRÜEL & KJÆR

Tip # 1 – Timer/Torque/Speed Accuracy – Data sheet Example

Maximum Timer Inaccuracy

Timer accuracy is a tradeoff between update rate and minimum required accuracy. This table shows the relationships between measured signal frequency, selected measurement time (update rate) and timer accuracy. The inaccuracy distribution is to be considered rectangular.

Calculate the inaccuracy by using:

$$\text{Inaccuracy} = \pm\left(\frac{(\textit{signal frequency} * 50\ ns)}{\textit{INTEGER}(\ (\textit{signal frequency} - 1) * \textit{measurement time})}\right) * 100\%$$

Measure-ment	Higher signal frequencies: Signal frequency (2 MHz down to 10 kHz)									
	2 MHz	1 MHz	500 kHz	400 kHz	200 kHz	100 kHz	50 kHz	40 kHz	20 kHz	10 kHz
1 µs	±10.000%									
2 µs	±3.333%	±5.000%								
5 µs	±1.111%	±1.250%	±1.333%	±2.000%						
10 µs	±0.526%	±0.556%	±0.625%	±0.667%	±1.000%					
20 µs	±0.256%	±0.263%	±0.278%	±0.286%	±0.333%	±0.500%				
50 µs	±0.101%	±0.102%	±0.103%	±0.105%	±0.111%	±0.125%	±0.133%	±2.000%		
0.1 ms	±0.050%	±0.051%	±0.051%	±0.051%	±0.053%	±0.056%	±0.063%	±0.067%	±0.100%	
0.2 ms	±0.025%				±0.026%	±0.026%	±0.028%	±0.029%	±0.033%	±0.050%
0.5 ms	±0.010%					±0.010%	±0.010%	±0.0011%	±0.0011%	±0.0013%
1 ms	±0.0050%					±0.0051%	±0.0051%	±0.0051%	±0.0053%	±0.0056%
2 ms	±0.0025%								±0.0026%	±0.0026%
5 ms	±0.0010%									
10 ms	±0.0005%									
20 ms	±0.00025%									
50 ms	±0.00010%									
100 ms	±0.00005%									

Measure-ment	Lower signal frequencies: Signal frequency (40 Hz to 5 kHz)									
	5 kHz	4 kHz	2 kHz	1 kHz	500 Hz	400 Hz	200 Hz	100 Hz	50 Hz	40 Hz
0.5 ms	±0.0133%	±0.0200%								
1 ms	±0.0063%	±0.0067%	±0.0100%							
2 ms	±0.0028%	±0.0029%	±0.0033%	±0.0050%						
5 ms	±0.0010%	±0.0011%	±0.0011%	±0.0013%	±0.0013%	±0.0020%				
10 ms	±0.00051%	±0.00051%	±0.00053%	±0.00056%	±0.00063%	±0.00067%	±0.00100%			
20 ms	±0.00025%	±0.00025%	±0.00026%	±0.00026%	±0.00028%	±0.00029%	±0.00033%	±0.00050%		
50 ms	±0.00010%	±0.00010%	±0.00010%	±0.00010%	±0.00010%	±0.00011%	±0.00011%	±0.00130%	±0.00013%	±0.00020%
100 ms	±0.000050%	±0.000050%	±0.000050%	±0.000051%	±0.000051%	±0.000051%	±0.000053%	±0.000056%	±0.000063%	±0.000067%

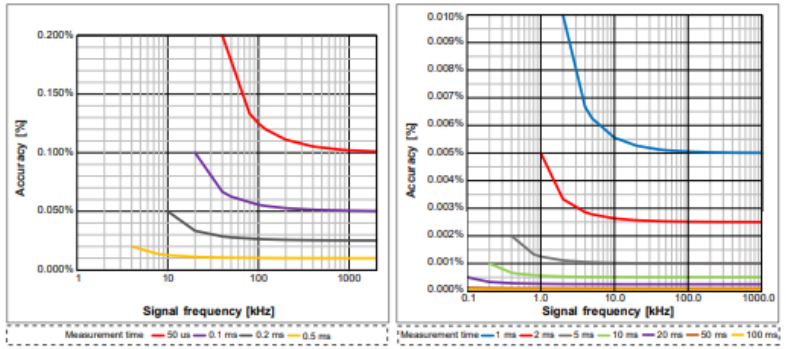


Figure 1.33: Maximum Timer Inaccuracy

Torque Measurement Uncertainty using Frequency Measurements

When using the Timer/Counter channels to measure torque, the measurement uncertainty introduced by the timer inaccuracies can be calculated using the following examples based on HBK T40 torque transducers.
The T40 torque transducer comes with 3 variants for frequency output: 10 kHz, 60 kHz or 240 kHz center frequency.
From the datasheets you can extract the minimum and maximum frequency output like table below.

T40 Variant	-Full Scale frequency output	+Full Scale frequency output
T40 - 10 kHz	5 kHz	15 kHz
T40 - 60 kHz	30 kHz	90 kHz
T40 - 240 kHz	120 kHz	360 kHz

Overlay these operating ranges on top of the timer inaccuracy plots of Figure 1.33 will result in Figure 1.34 (see below)

- Remains the step to balance the update rate (torque bandwidth) versus the torque accuracy required.
- Calculate the inaccuracy using the -Full Scale frequency output and desired measurement time.
- Using a minimum of 60 RPM the following inaccuracies are calculated.

Selected measurement time	Maximum inaccuracy: T40 - 240 kHZ	Maximum inaccuracy: T40 - 60 kHZ	Maximum inaccuracy: T40 - 10 kHZ
50 µs (left red curve)	0.1200%	0.1500%	Not possible
100 µs (left purple curve)	0.0546%	0.0750%	Not possible
500 µs (left orange curve)	0.0101%	0.0107%	0.0125%
1 ms (right blue curve)	0.0050%	0.0052%	0.0063%
2 ms (right red curve)	0.0025%	0.0025%	0.0028%
5 ms (right grey curve)	0.0010%	0.0010%	0.0010%

For K=1 (70% probability) use the specified rectangular distribution and the maximum inaccuracy numbers and calculate:
`Measurement uncertainty = Maximum inaccuracy * 0.58 (Conversion for rectangular distribution)`

Measurement uncertainty K=1 (About 70% probability)	Maximum inaccuracy: T40 - 240 kHZ	Maximum inaccuracy: T40 - 60 kHZ	Maximum inaccuracy: T40 - 10 kHZ
50 µs (left red curve)	0.0696%	0.0870%	Not possible
100 µs (left purple curve)	0.0316%	0.0435%	Not possible
500 µs (left orange curve)	0.0059%	0.0062%	0.00725%
1 ms (right blue curve)	0.0029%	0.0029%	0.00365%
2 ms (right red curve)	0.00145%	0.0015%	0.00162%
5 ms (right grey curve)	0.00058%	0.0006%	0.00058%

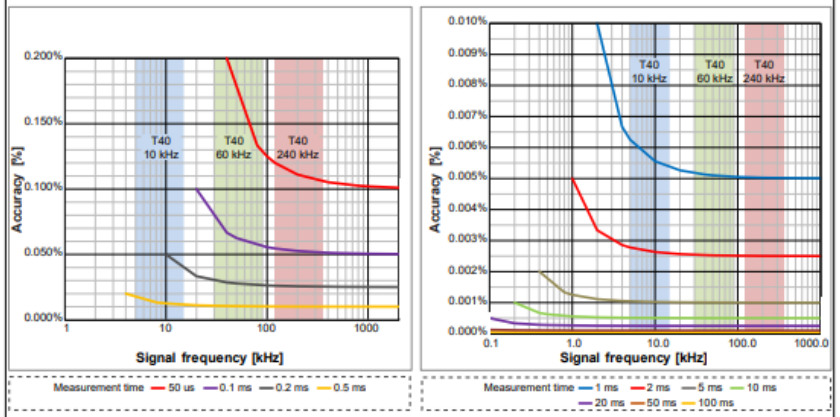


Figure 1.34: Torque operating range versus inaccuracy and measurement time

Speed (RPM) Measurement Uncertainty using Frequency Measurements

When using the Timer/Counter channels to measure speed (RPM), the measurement uncertainty introduced by the timer inaccuracies can be calculated using the following example.
In the datasheet of the speed sensor locate the specified number of pulse per rotation to calculate the frequency range of the sensor output:

`Minimum frequency = minimum RPM used during testing * number of pulse per rotation / 60 sec`
`Maximum frequency = maximum RPM used during testing * number of pulse per rotation / 60 sec`

Speed Sensor pulse per rotation	Frequency at 60 RPM	Frequency at 10 000 RPM	Frequency at 20 000 RPM
180	180 Hz	30 kHz	60 kHz
360	360 Hz	60 kHz	120 kHz
1024	1024 Hz	170.7 kHz	341.3 kHz

Overlay these operating ranges on top of the timer inaccuracy plots of Figure 1.33 will result in Figure 1.35 (see below)

- Remains the step to balance the update rate (angle position change updates per second) versus the RPM accuracy required.
- Using the graphs find the crossings of the overlayed operating frequencies with the measurement time curves.
- As examples the following crossings can be found in the graphs (at 60 RPM).

Selected measurement time	180 pulse sensor	360 pulse sensor	1024 pulse sensor
2 ms (red curve)	Can't record at 60 RPM	Can't record at 60 RPM	0.00256%
5 ms (grey curve)	Can't record at 60 RPM	0.0018%	0.0010%
10 ms (Green curve)	0.0009%	0.0006%	0.00051%

For K=1 (70% probability) use the specified rectangular distribution and the maximum inaccuracy numbers and calculate:
`Measurement uncertainty = Maximum inaccuracy * 0.58 (Conversion for rectangular distribution)`

Measurement uncertainty K=1 (About 70% probability)	180 pulse sensor	360 pulse sensor	1024 pulse sensor
2 ms (red curve)	Can't record at 60 RPM	Can't record at 60 RPM	0.00148%
5 ms (grey curve)	Can't record at 60 RPM	0.00104%	0.00059%
10 ms (Green curve)	0.00052%	0.00035%	0.00030%

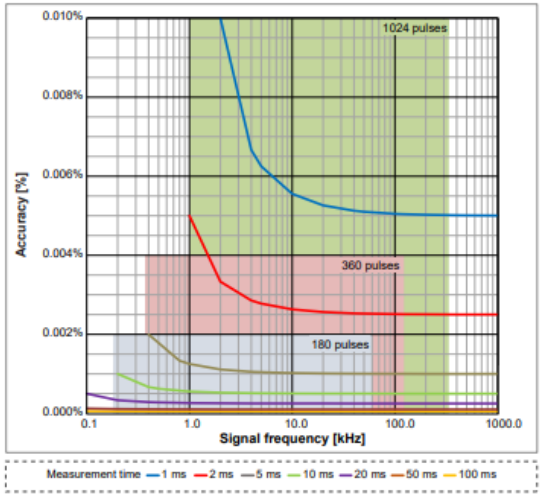
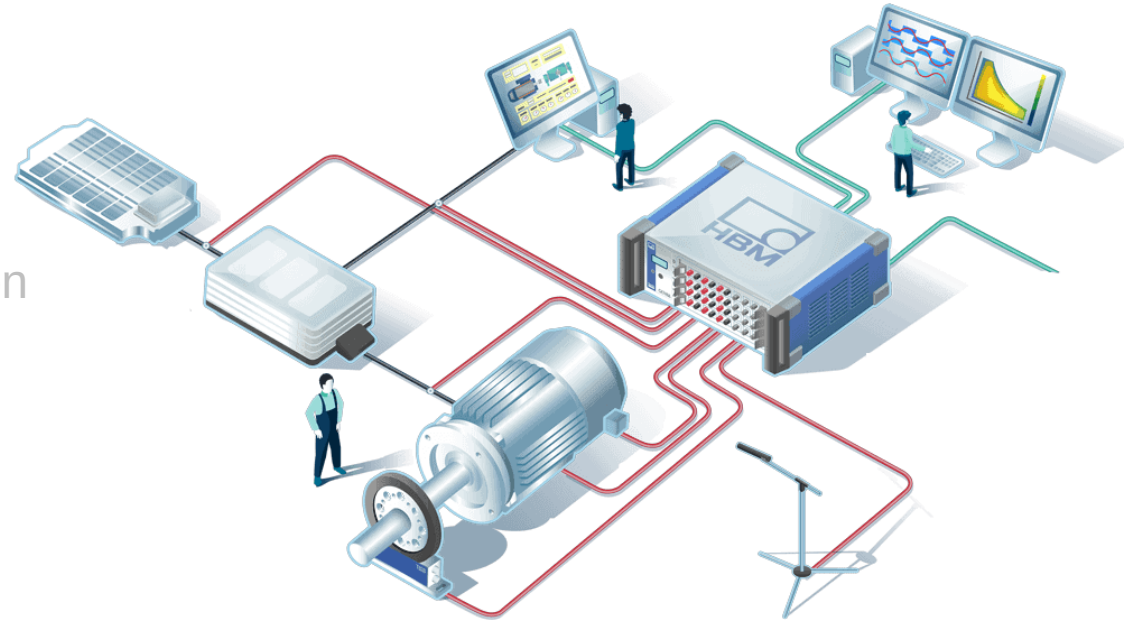


Figure 1.35: RPM sensor operating range versus inaccuracy and measurement time

Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



HBK HOTTINGER BRÜEL & KJÆR

Tip # 2 – Number and Type of Inputs – Modular Solution

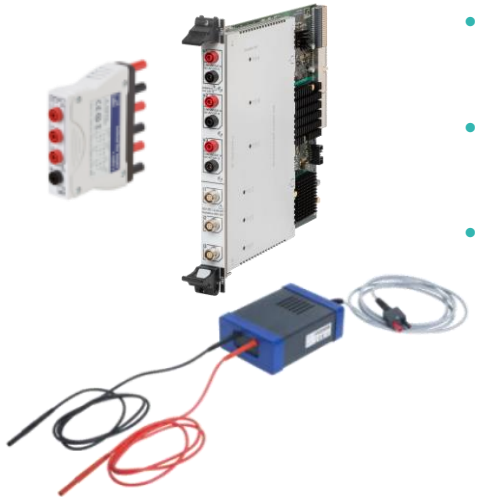
- Select a power analyzer that meets your needs …
  - **Today**
  - And can easily expand for **tomorrow**
- A modular solution allows for future expansion, for example ...
  - **Today** you may only have a one inverter driven application
    - 4+ power channels
    - 1 torque inputs
    - 1 speed inputs
  - **Tomorrow** you may have four-inverter driven wheels application
    - 13+ power channels
    - 4 torque inputs
    - 4 speed inputs
    - Just add three more 3 channel power cards that include 4 timer/counters each for torque and speed

7 slot modular power analyzer
(in 2, 4, 7, 17 slot configurations)

3 channel power card
for 3 voltages & 3 currents
with 4 timer/counters
for 2 torques & 2 speeds

Tip # 2 – Number and Type of Inputs

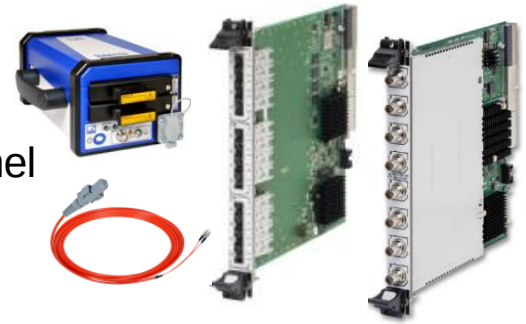
- Identify number of channels needed to record…
  - Power (card) – 3 power channels per card
    - Highest power **accuracy 0.015% reading + 0.02% range**
  - Voltage – up to +/-1500 V DC directly
    - 5 kV differential probe with 0.1% accuracy
    - Higher voltages up to 20 kV including isolation
  - Current
    - High accuracy medium bandwidth zero-flux current sensors
      - 50-2000 A, up to 1 MHz bandwidth, 0.01% accuracy to 5 kHz
    - Options for current probe, Rogowski coil however less accurate
  - Sample Rate and Bandwidth
    - 2 MS/s with 1 MHz bandwidth per channel @ 18 bit
    - Options for higher sample rates up to 250 MS/s per channel



- 3 Currents, 3 Voltages up to +/- 1500 V DC
- AUTO-Range to minimize Measurement Uncertainty
- 2 MS/s, 1 MHz bandwidth per channel @ 18 bit

Recommended for high accuracy

When bandwith is more important than accuracy or no room for a CT



HBK HOTTINGER BRÜEL & KJÆR

Tip # 2 – Number and Type of Inputs

- Additional channels needed to record…
- Multiple timer/counter Inputs for **Torque and speed**
  - Record frequency output for the highest signal fidelity
  - Up to 8 timer/counters needed for 4-wheel motor measurements
  - Up to 0.007% accuracy, highest in a torque sensor
  - Higher accuracy for higher efficiency measurements
  - **Temperature**
    - Standard thermocouples and RTDs
    - Temperature module insulated up to 1000 V
  - **Vibration / Microphone** inputs for NVH
  - **Strain** to measure multi-axis forces and moments
  - **CAN and CAN FD** for bus data
- High voltage, low noise, shielded cables

- Highest accuracy: 0.007% linearity
- Low latency speed measurement system, better for dq0 transformation

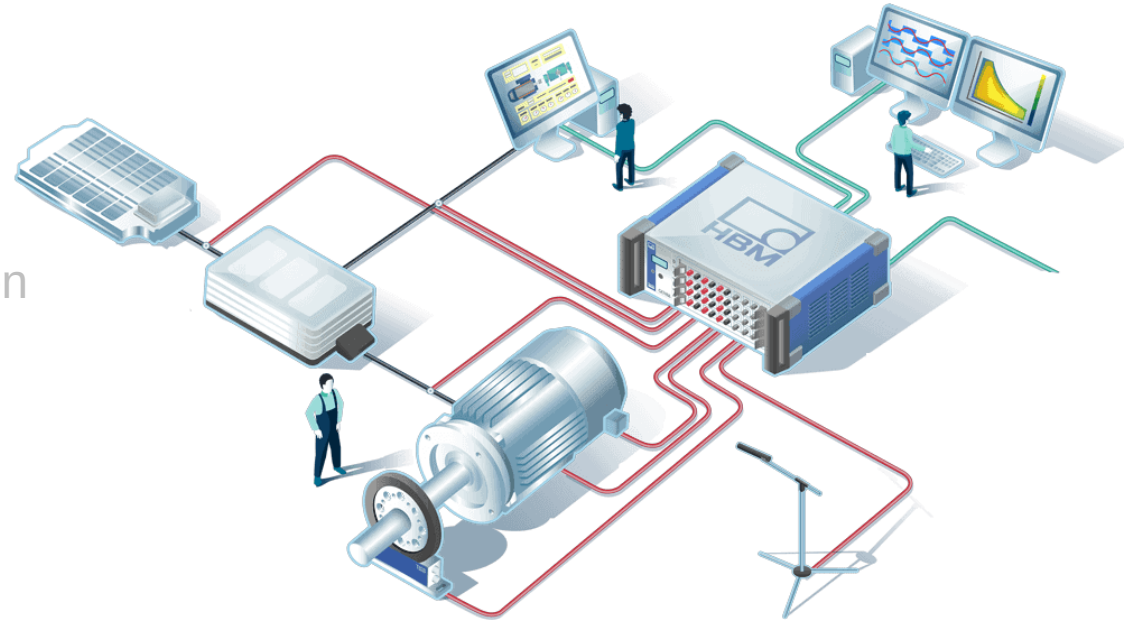
- Standard accuracy: 0.03% linearity
- Higher rpm up to 45,000

- K, J, T, B, E, N, R, S, C
- Isolation up to 2500 V transients

- Shielded 3-wire 1.5 kV cable
- 1500 V DC CAT III, 1000 V CAT IV

Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information

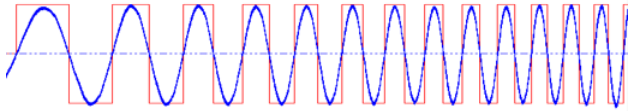


HBK HOTTINGER BRÜEL & KJÆR

Tip # 3 – Dynamic Power Measurements

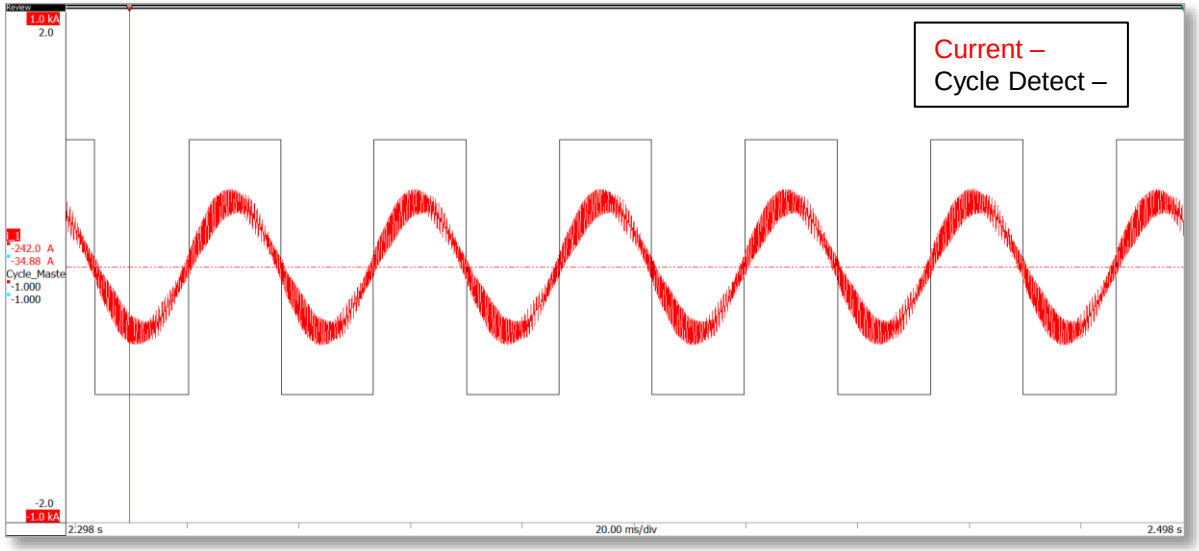
- A traditional power analyzer is a…
  - Static power analyzer
  - Designed to measure steady-state systems like the electric power grid
  - Uses “Analog” PLL-based cycle detection, only works in steady state load conditions
  - Measurements are not available during frequency changes

- To test variable speed drives, you need a …
  - Dynamic power analyzer
  - Designed to measure power during load steps, run-ups and run-downs
  - Ideally uses “Digital” cycle detection, i.e. searches zero crossing points of current
  - Measurements are available continuously even during dynamic load changes



Tip # 3 – Dynamic Power Measurements - Fast and Accurate

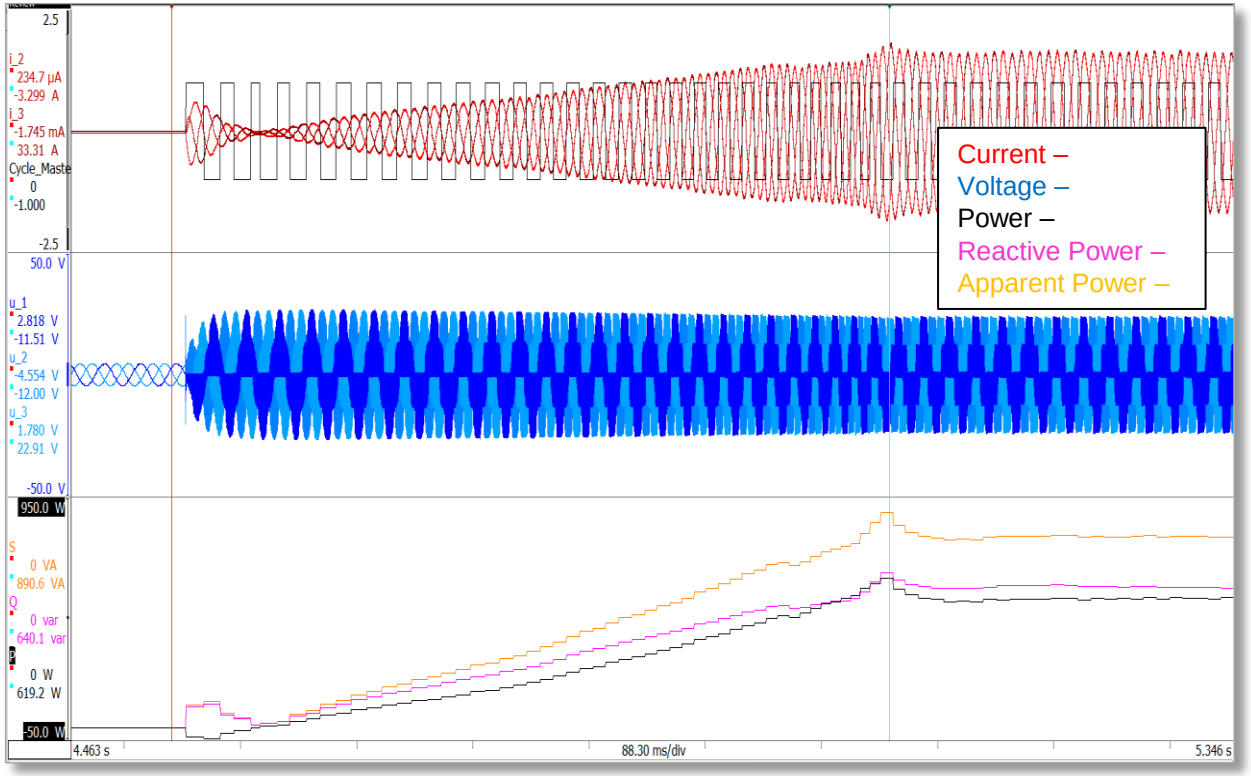
- To compute any power result accurately the “cycles” of the signals are needed
- Using advanced DSP algorithms…
  - Cycles can be detected in real-time
  - Even during load/frequency changes
- RMS, power, efficiency and advanced calculations can be done on a ½ cycle basis



Cycle detect on a single phase of current of a 3-phase system.
This highlights the cycle detect identifying ½ cycles for calculation.

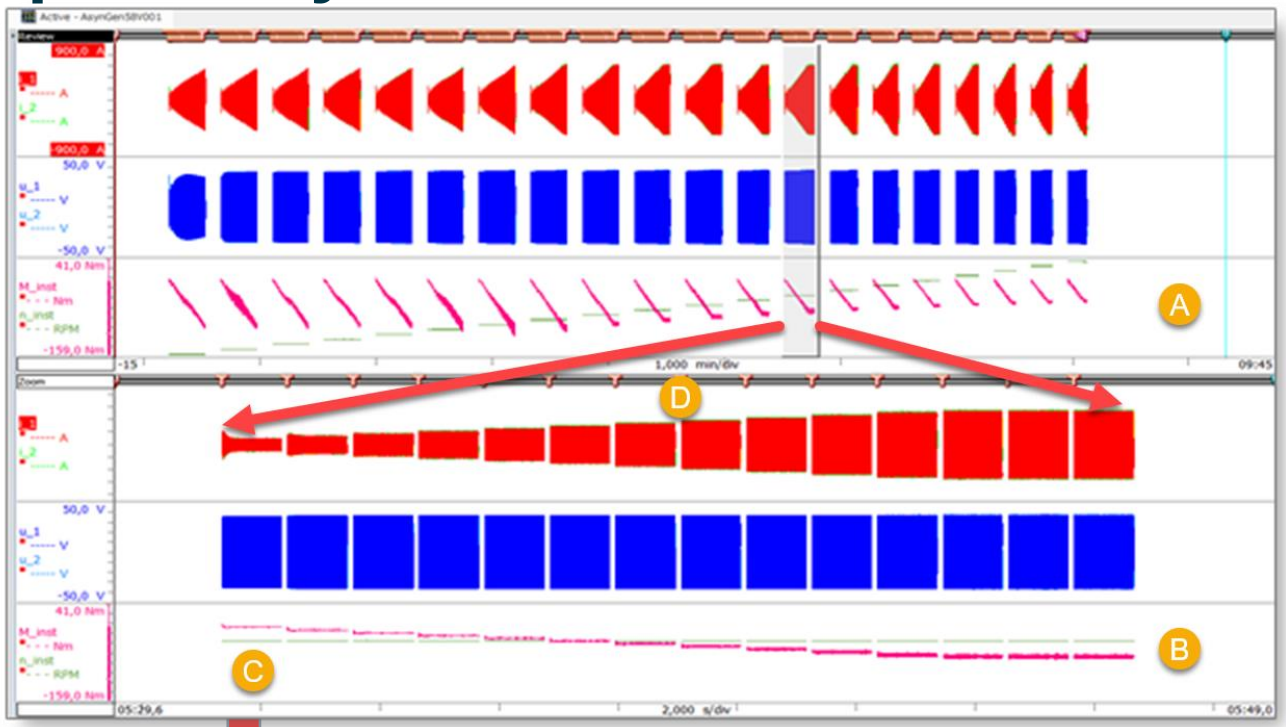
Tip # 3 – Dynamic Power Measurements – Using Cycle Detect

- Cycle detect enables measurements even as the fundamental frequency is changing
- Dynamic testing allows one to characterize real world scenarios
  - Accelerating and decelerating
  - Increase in load and decrease in load
- Measure electrical and mechanical power accurately on the same cycle
  - No more >1 efficiency results



Vehicle acceleration from 0 to full speed showing a ramp from 0 to full power.

Tip # 3 – Dynamic Power Measurements – Accelerated Efficiency Maps

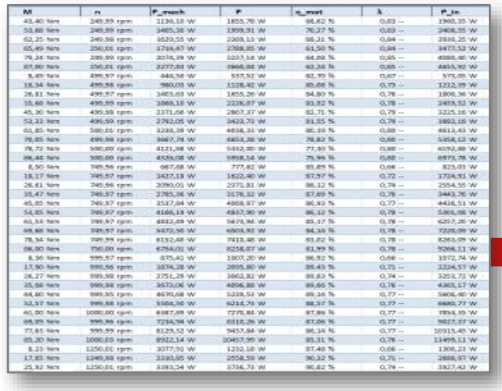


❶ Real time raw data storage

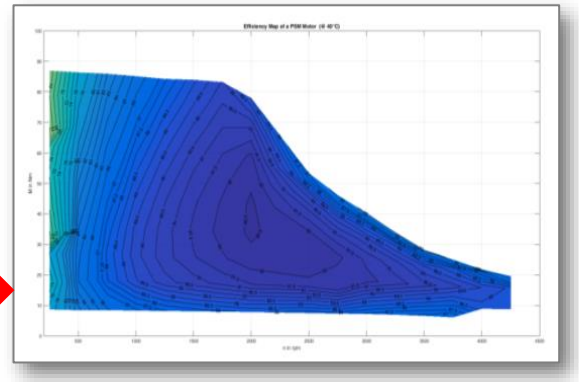
- Example: 280 set points
  - A. 20 different speed values
  - B. 14 different torque values
- Each set point:
  - C. 1 sec recording
  - D. 100 ms pause, then next torque step
    - After torque ramp,
    - a few secs pause, then next speed step

➲ **full test in about 8 minutes**

Typical analyzer may take 10X longer, 1.5-2 hours
~10 s to settle on changing frequency
Added wait time for motor to cool



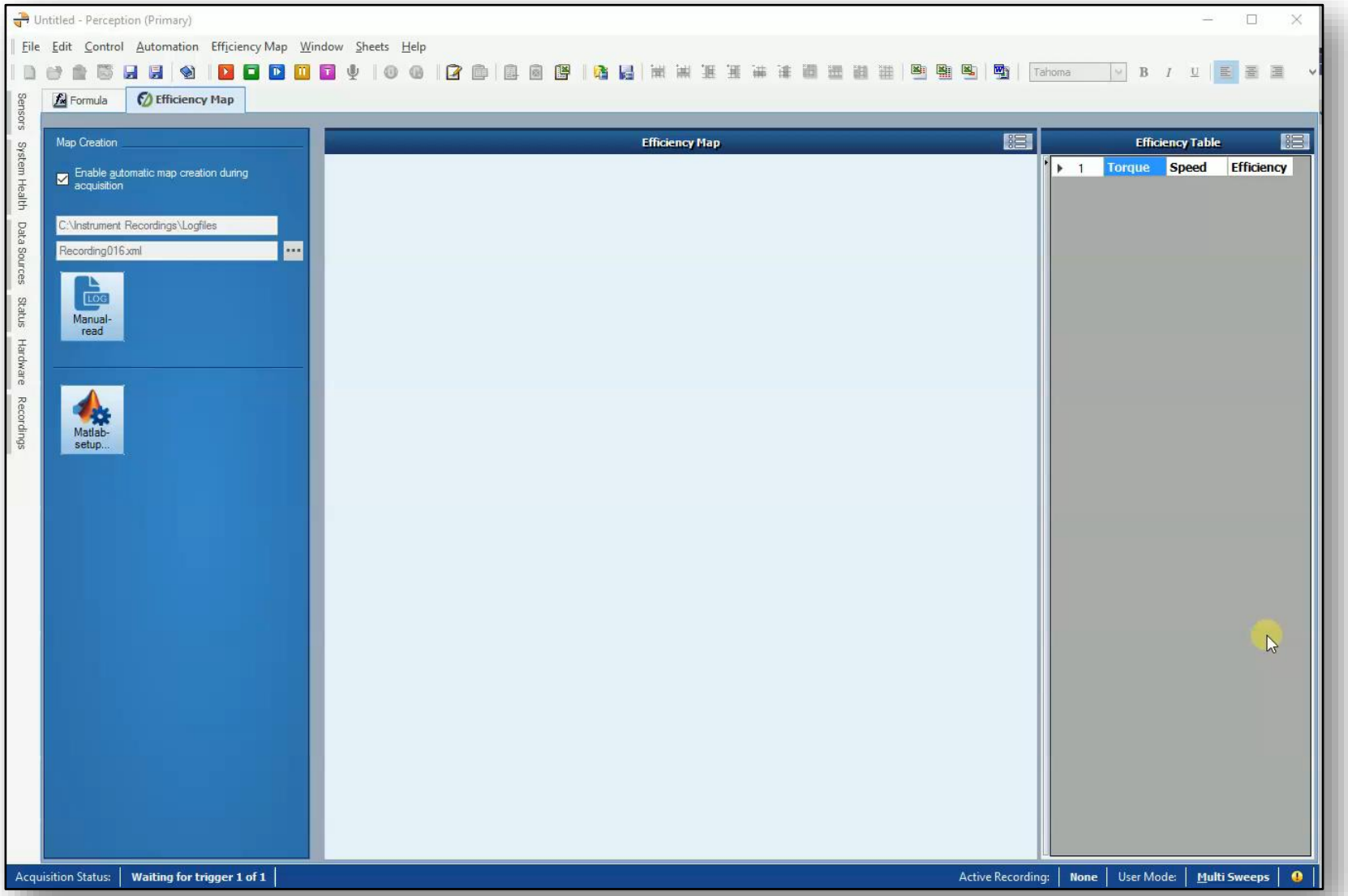
❷ A result table is created with P, P_mech, M, n, η values along with the corresponding motor efficiency map in real time



➲ **Complete mapping can be done in a few minutes**

HBK HOTTINGER BRÜEL & KJÆR

Tip # 3 – Dynamic Power Measurements – Accelerated Mapping

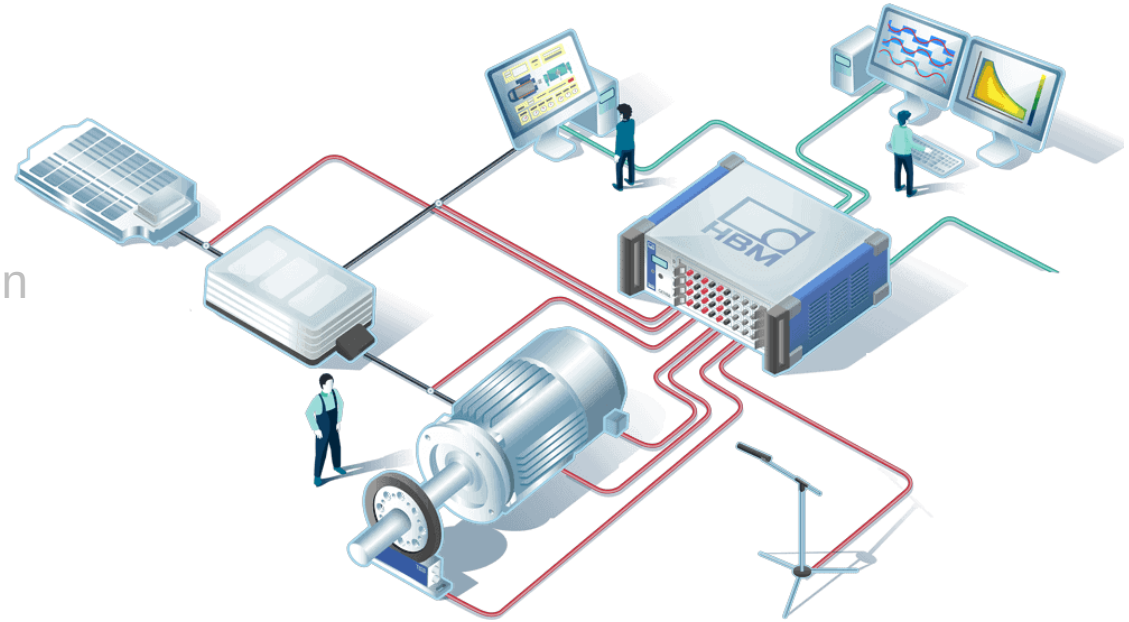


Example of Motor efficiency mapping done in real time

HBK HOTTINGER BRÜEL & KJÆR

Agenda

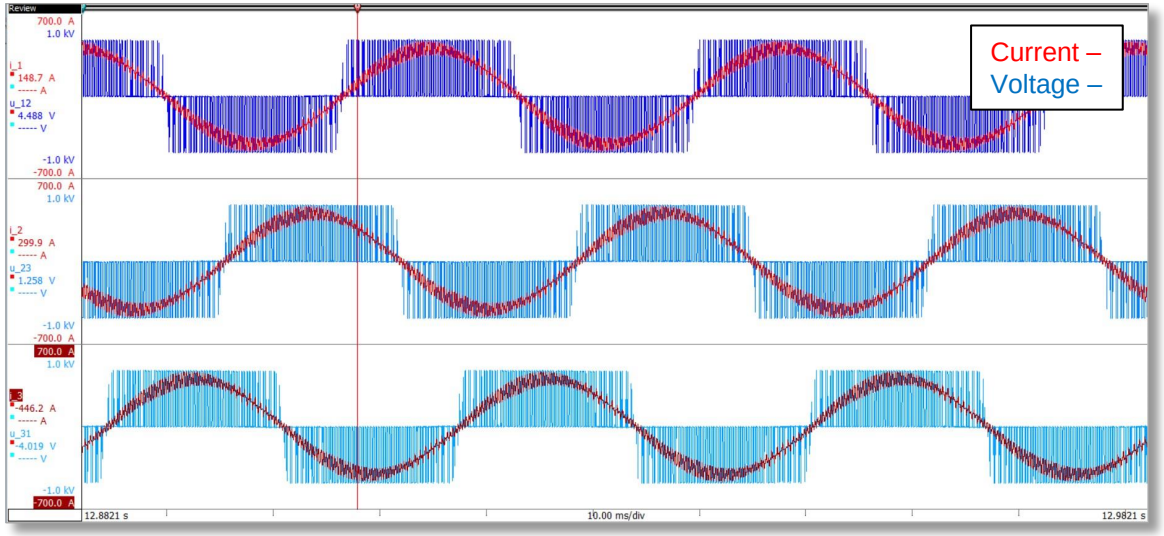
1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



HBK
HOTTINGER BRÜEL & KJÆR

Tip # 4 – Raw Data Storage and Analysis – Auditable Testing

- A power analyzer should store all raw signals ideally to a hard disk up to 2 MS/s per channel
- Calculated power results have the data to support them
  - Analyze data without having to run test again
  - Correlate tests to models
- Execute equations in real time to cut down post process time



Current and voltage for a 3-phase machine. Line to line voltage measurements are shown.

99	Cycle_Master_out	@CycleDetect (Cycle_source_out ; Cycle_level_out ; Cycle_hyst_out)
109	I_1	@CycleRMS (i_1 ; Cycle_count_out ; Cycle_Master_out)
110	I_2	@CycleRMS (i_2 ; Cycle_count_out ; Cycle_Master_out)
111	I_3	@CycleRMS (i_3 ; Cycle_count_out ; Cycle_Master_out)
117	U_1	@CycleRMS (u_1 ; Cycle_count_out ; Cycle_Master_out)
118	U_2	@CycleRMS (u_2 ; Cycle_count_out ; Cycle_Master_out)
119	U_3	@CycleRMS (u_3 ; Cycle_count_out ; Cycle_Master_out)

Power calculations done with public formulas. User formulas can be added.

Tip # 4 – Raw Data Storage and Analysis – Efficiency Formulas

Cycle detection

RMS of voltage and currrent per phase

Instantaneous power per phase

True power per phase and total

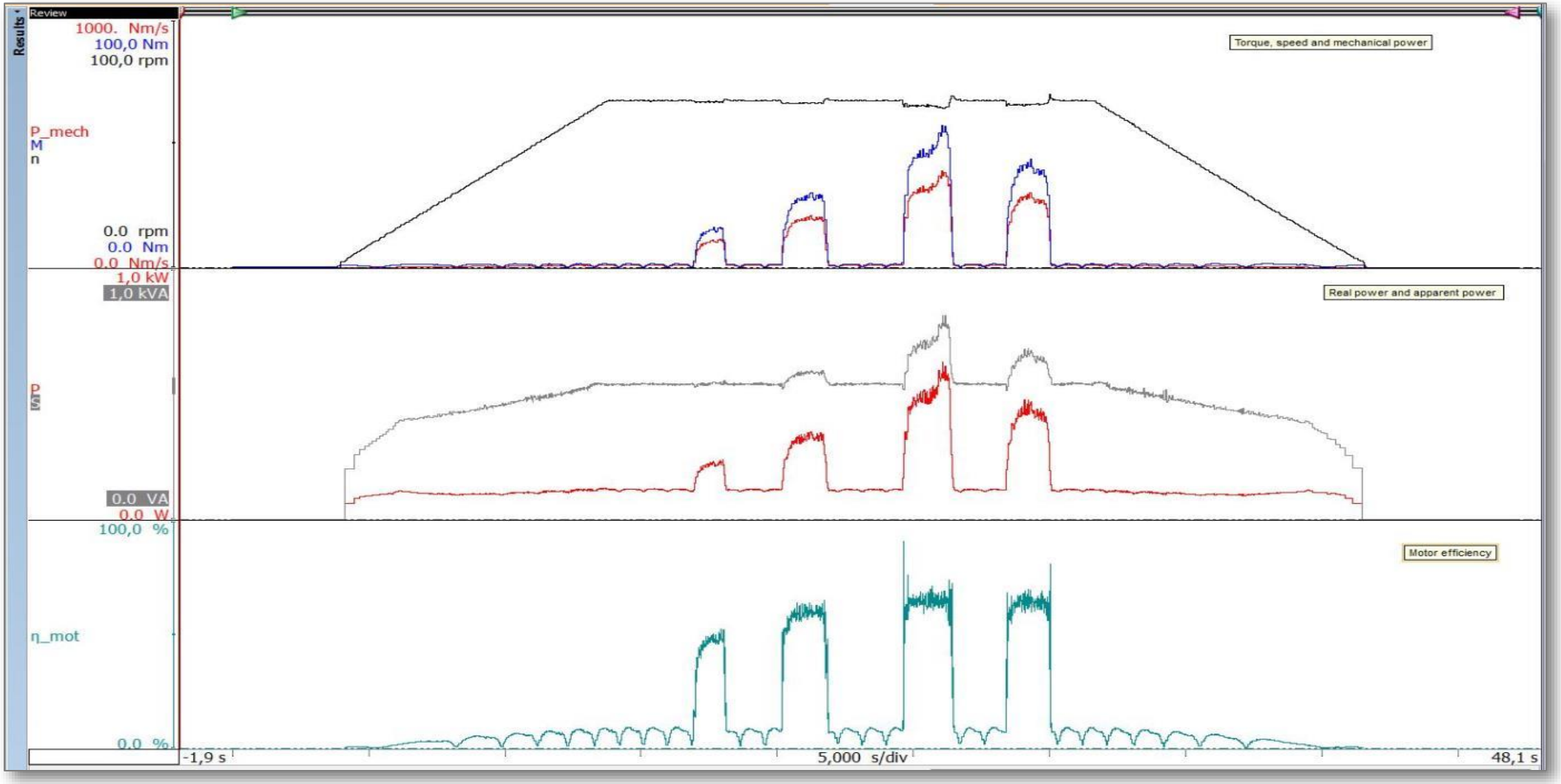
Mechanical power

Machine efficiency

99	Cycle_Master_out	@CycleDetect (Cycle_source_out ; Cycle_level_out ; Cycle_hyst_out)	
109	I_1	@CycleRMS (i_1 ; Cycle_count_out ; Cycle_Master_out)	
110	I_2	@CycleRMS (i_2 ; Cycle_count_out ; Cycle_Master_out)	
111	I_3	@CycleRMS (i_3 ; Cycle_count_out ; Cycle_Master_out)	
117	U_1	@CycleRMS (u_1 ; Cycle_count_out ; Cycle_Master_out)	
118	U_2	@CycleRMS (u_2 ; Cycle_count_out ; Cycle_Master_out)	
119	U_3	@CycleRMS (u_3 ; Cycle_count_out ; Cycle_Master_out)	
128	p_1	u_1 * i_1	W
129	p_2	u_2 * i_2	W
130	p_3	u_3 * i_3	W
132	P_1	@CycleMean (p_1 ; Cycle_count_out ; Cycle_Master_out)	W
133	P_2	@CycleMean (p_2 ; Cycle_count_out ; Cycle_Master_out)	W
134	P_3	@CycleMean (p_3 ; Cycle_count_out ; Cycle_Master_out)	W
135		The sum of the active power per phase gives the total active power	
136	P	P_1 + P_2 + P_3	W
196	P_mech	2 * Pi * n / 60 * M	Nm/s
257	η_mech	(P_mech / P) * 100	%

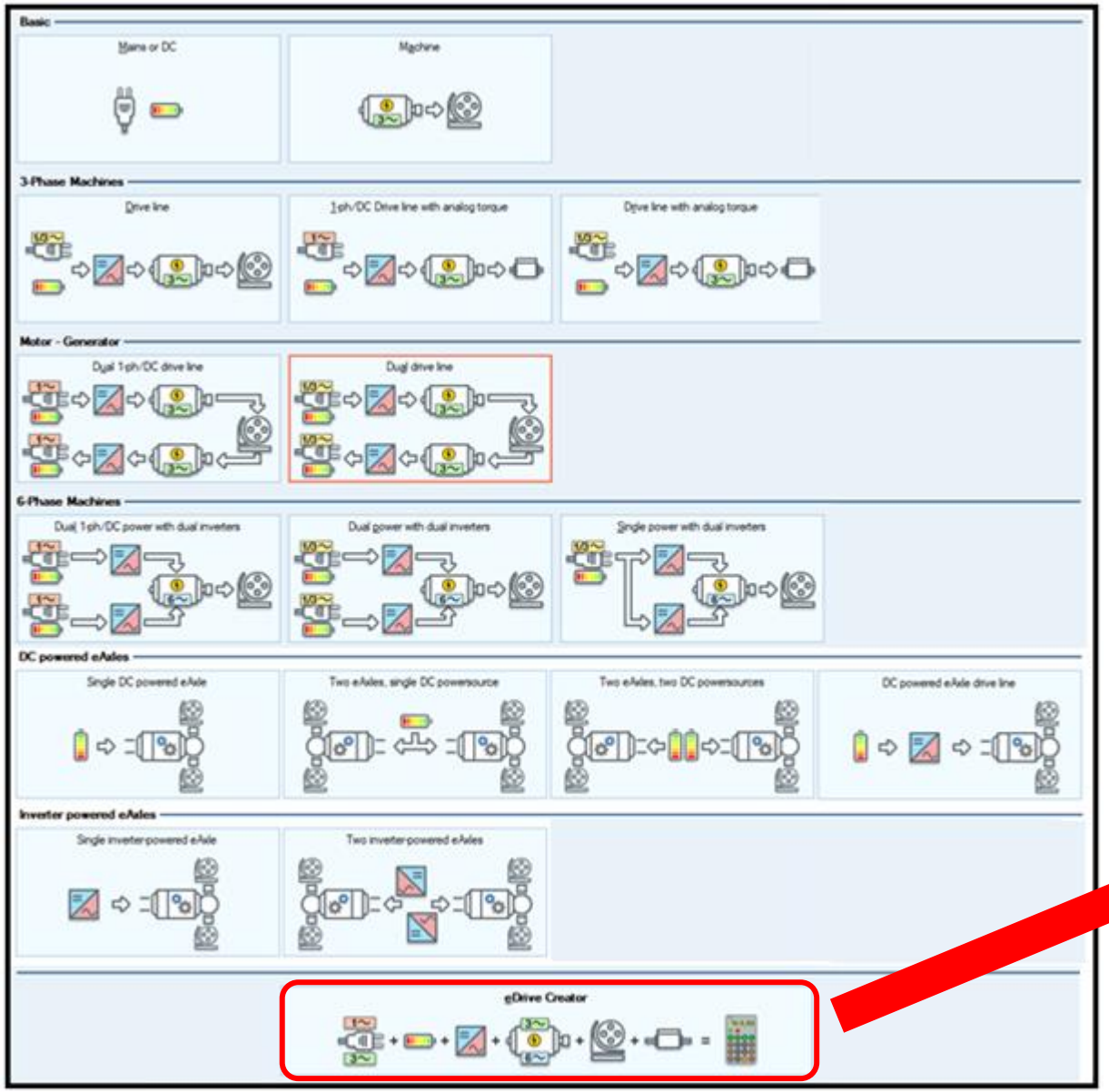
HBK HOTTINGER BRÜEL & KJÆR

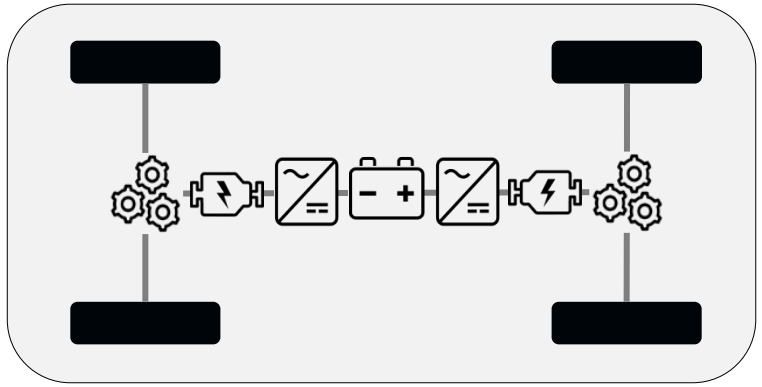
Tip # 4 – Raw Data Storage and Analysis – LIVE or for Review



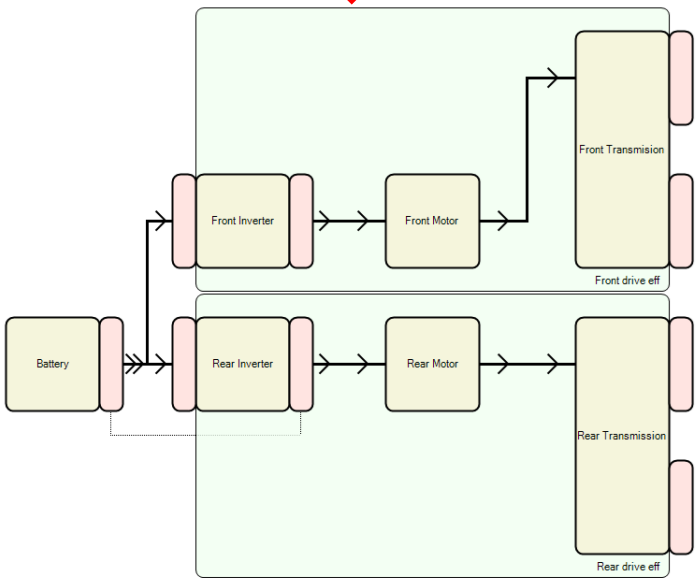
Shown are: Mechanical (P_mech, M, n), electrical (P, S), machine efficiency (η)

Tip # 4 – Raw Data Storage & Analysis – Preconfigured or Custom





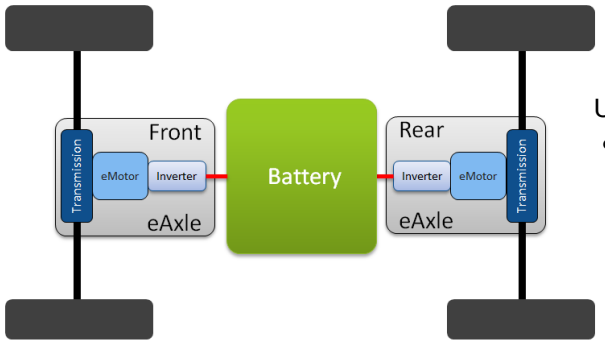
Your configuration



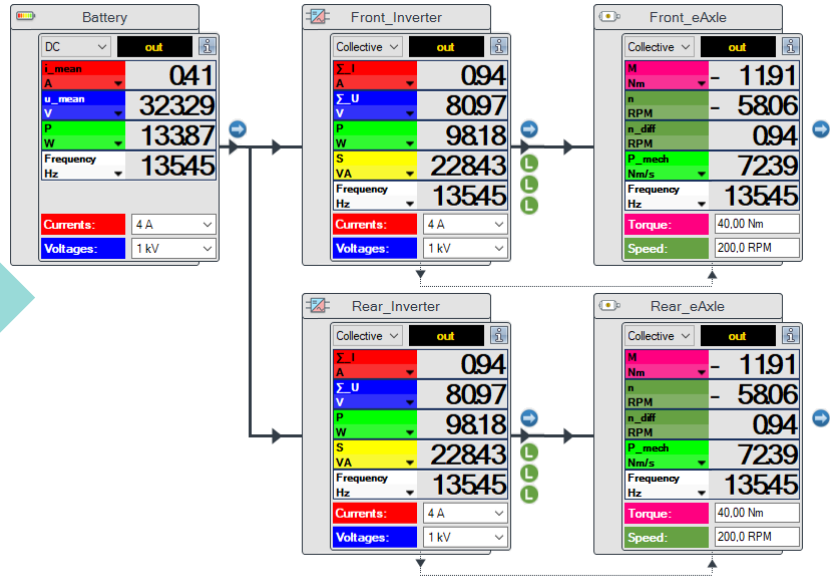
…and map your own configuration into the system

Tip # 4 – Raw Data Storage & Analysis – Custom Power Display

- Map the power analyzer to your powertrain

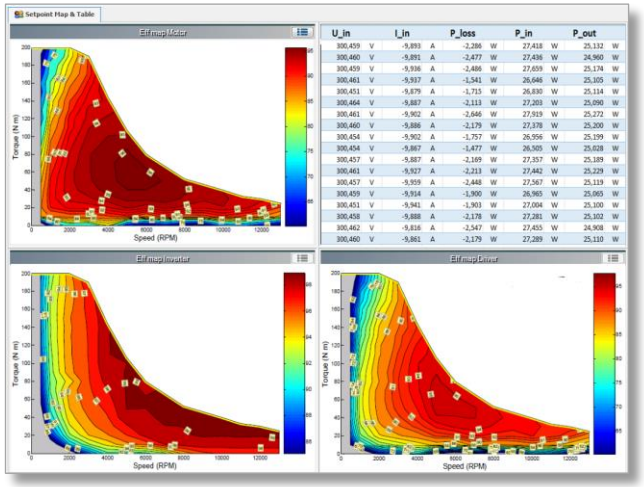


User Defined Power Flow & Power Measurements



- Graphical displays for users & management
  - Simplify setup
  - Simplify display

- Customize live efficiency map plotting
  - Efficiency of inverter, motor or entire drive train

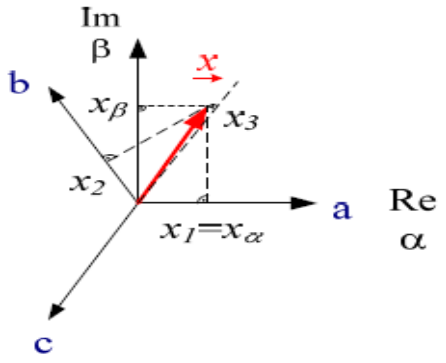


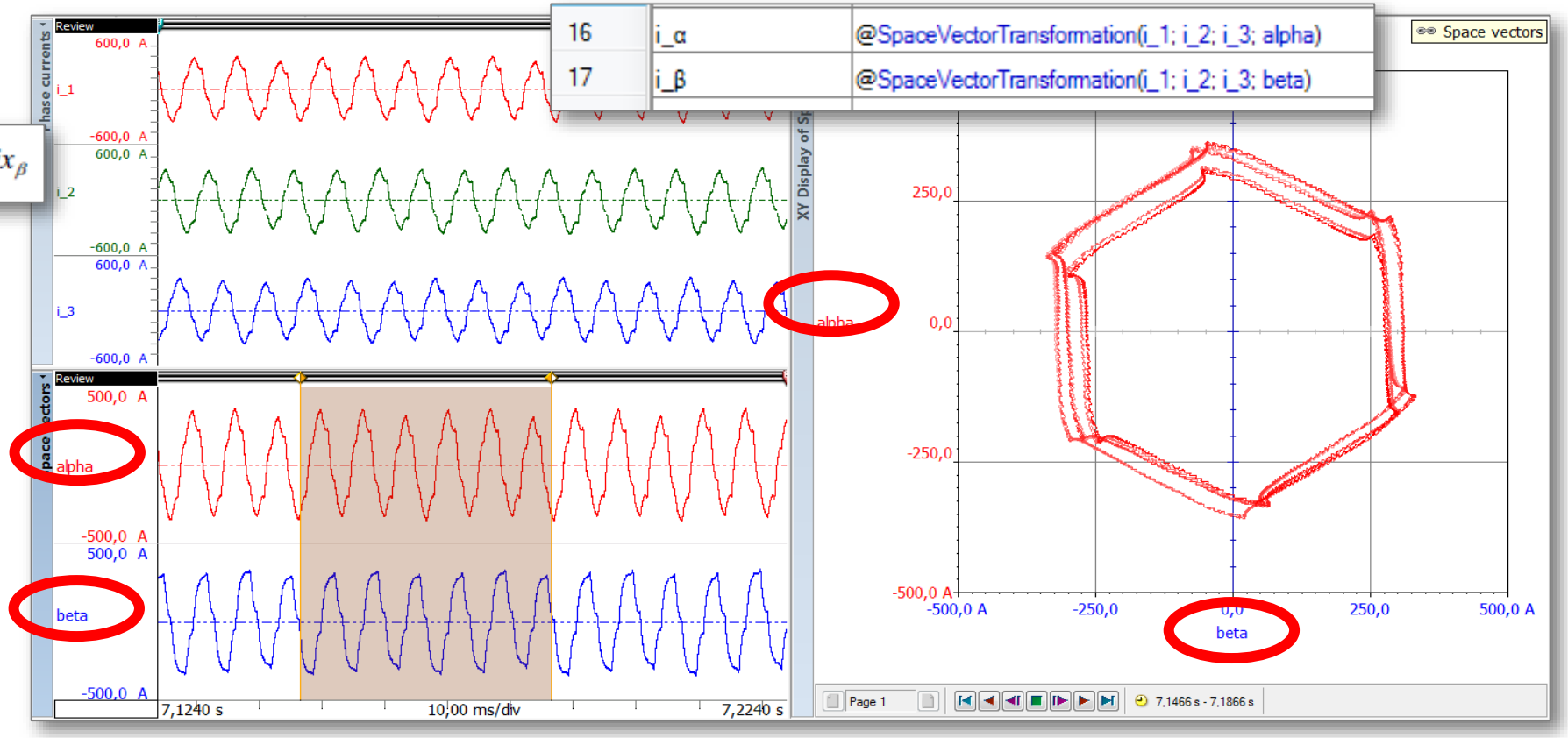
HBK HOTTINGER BRÜEL & KJÆR

Tip # 4 – Raw Data Storage & Analysis – Space Vector (Clarke) Transformation

The currents i_1, i_2, i_3 of a 3 phase system are represented with two linear independent vectors i_α , i_β.
One signal represents torque and the other represents magnetic flux.
Mathematical way to simplify motor models and control algorithms, easier to understand what is going on in the machine.

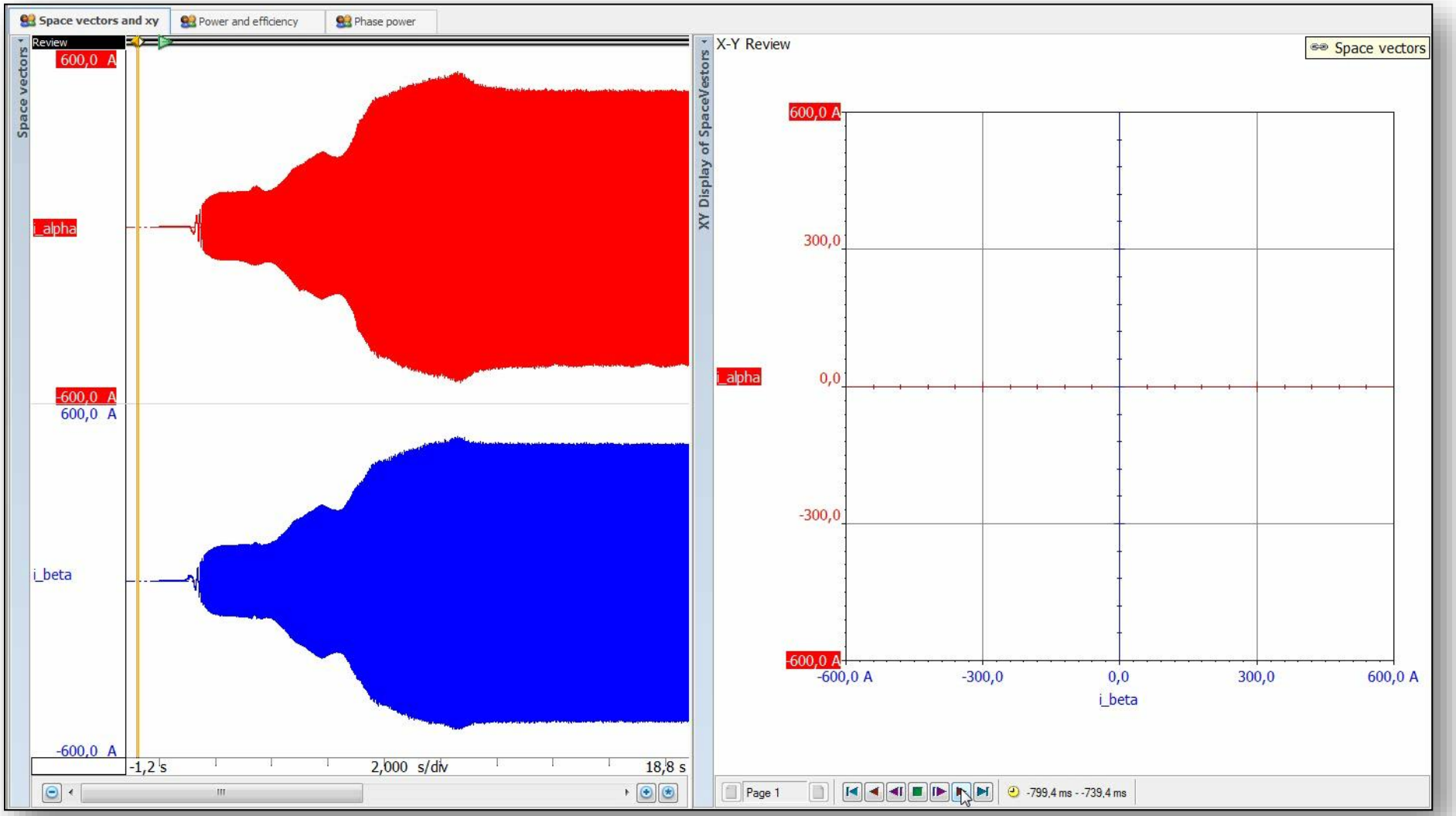
$$\vec{x}(t) = \frac{2}{3}\left(x_1(t) + \underline{a}\cdot x_2(t) + \underline{a}^2 \cdot x_3(t)\right) = x_\alpha + jx_\beta$$





i_α and i_β displayed as a x/y-plot to show system unbalance and control behaviour.

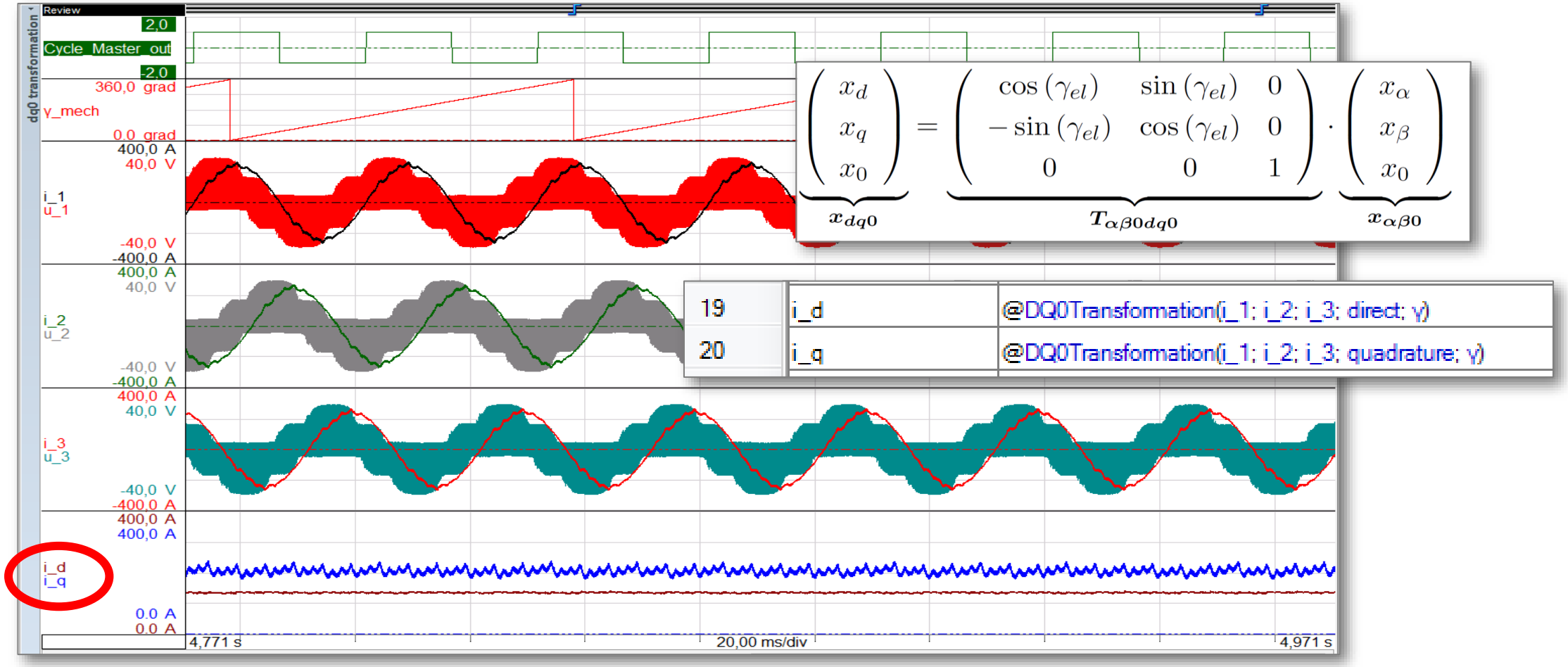
Tip # 4 – Raw Data Storage & Analysis – Space Vector Example



Space vectors during electric motor bike acceleration

Tip # 4 – Raw Data Storage & Analysis – dq0 (Park) Transformation

Here space vectors i_α, i_β are calculated and transformed into a rotational coordinate system using postion of the motor y_{mech}.

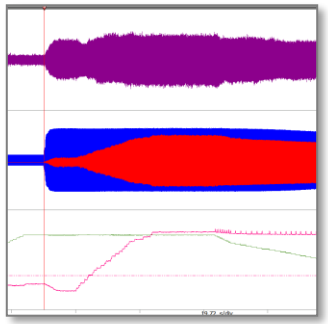


$$\underbrace{\begin{pmatrix} x_d \\ x_q \\ x_0 \end{pmatrix}}_{x_{dq0}} = \underbrace{\begin{pmatrix} \cos(\gamma_{el}) & \sin(\gamma_{el}) & 0 \\ -\sin(\gamma_{el}) & \cos(\gamma_{el}) & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{T_{\alpha\beta 0 dq0}} \cdot \underbrace{\begin{pmatrix} x_\alpha \\ x_\beta \\ x_0 \end{pmatrix}}_{x_{\alpha\beta 0}}$$

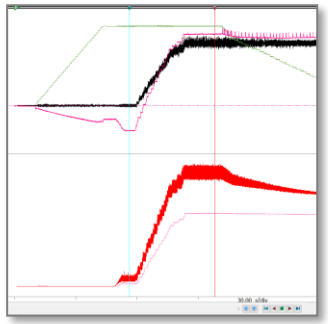
The resulting i_d, i_q currents are represent the current components for torque and magnetic flux. Thus control algorithms become much easier to verify.

Tip # 4 – Raw Data Storage & Analysis – Advanced Analysis

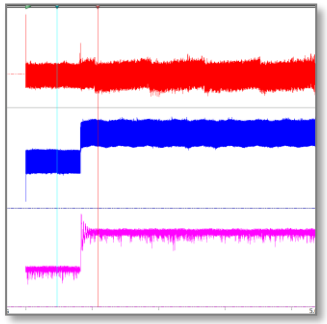
Vibration Analysis



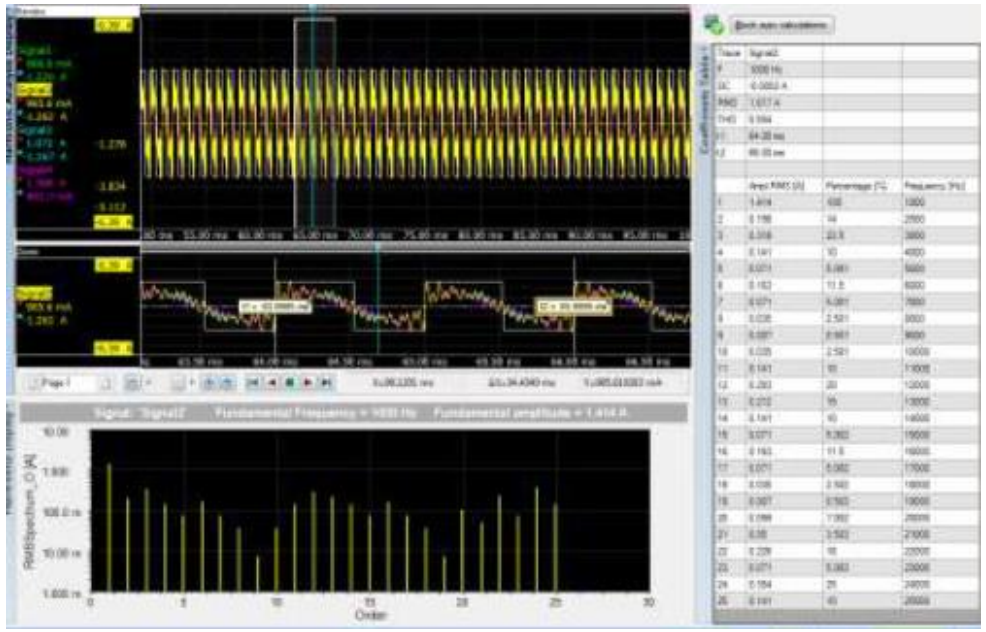
CAN Bus Correlation



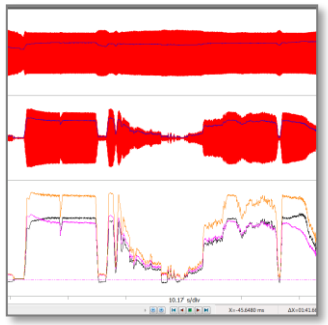
Live dq0 Transformation



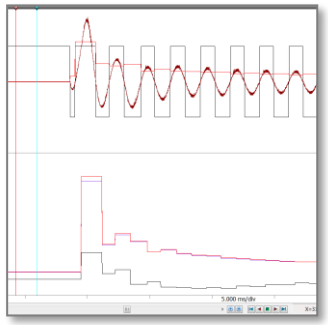
Harmonic Analysis



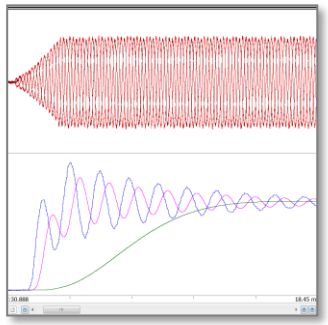
Drive Cycle Analysis



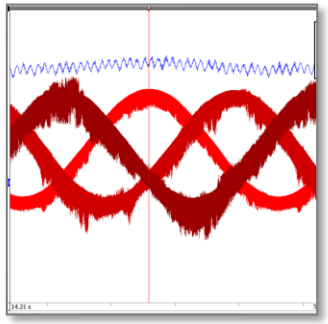
Dynamic Power



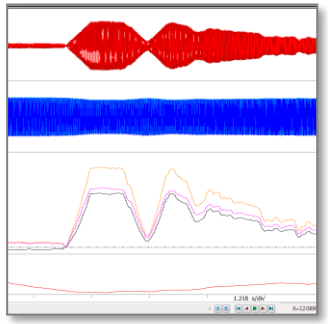
Transient Torque



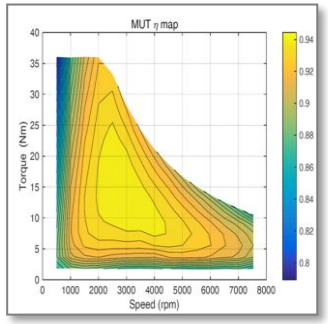
Torque Ripple



In Vehicle Measurement



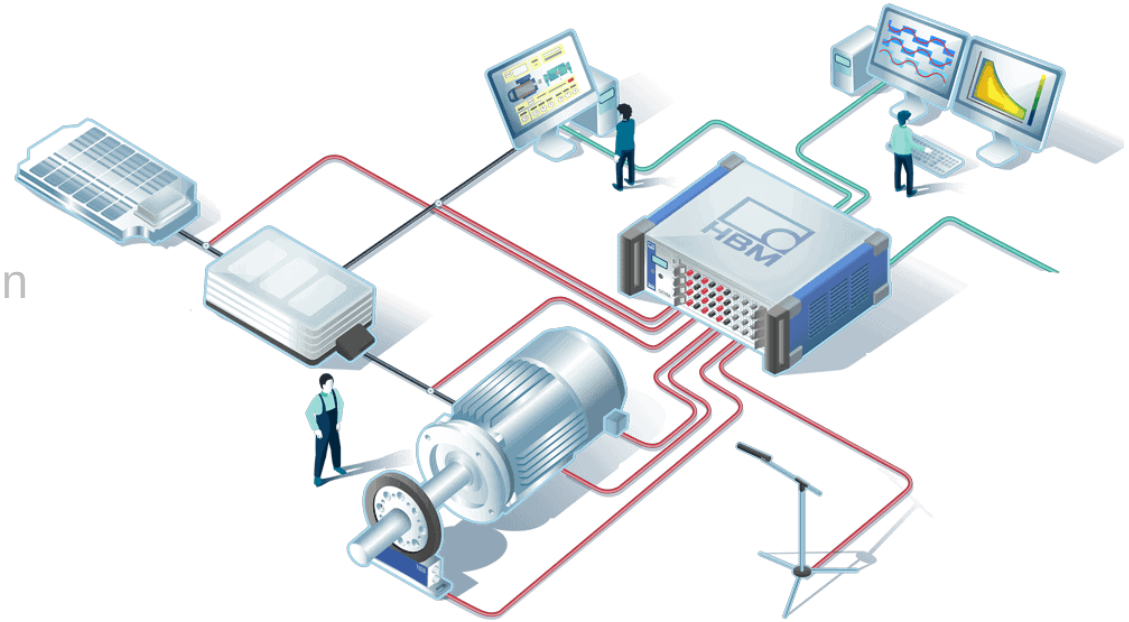
Live Efficiency Plots



HBK HOTTINGER BRÜEL & KJÆR

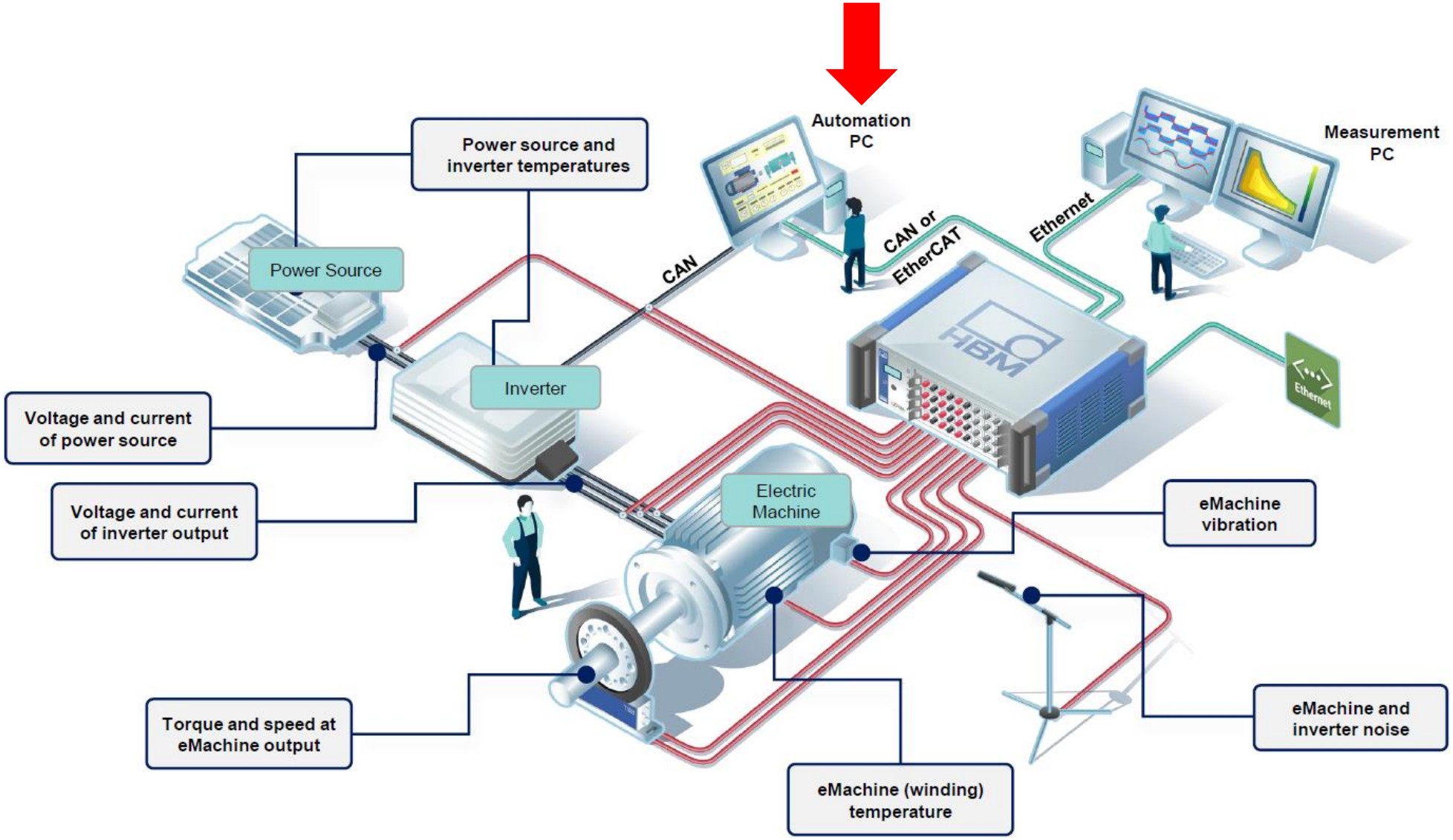
Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



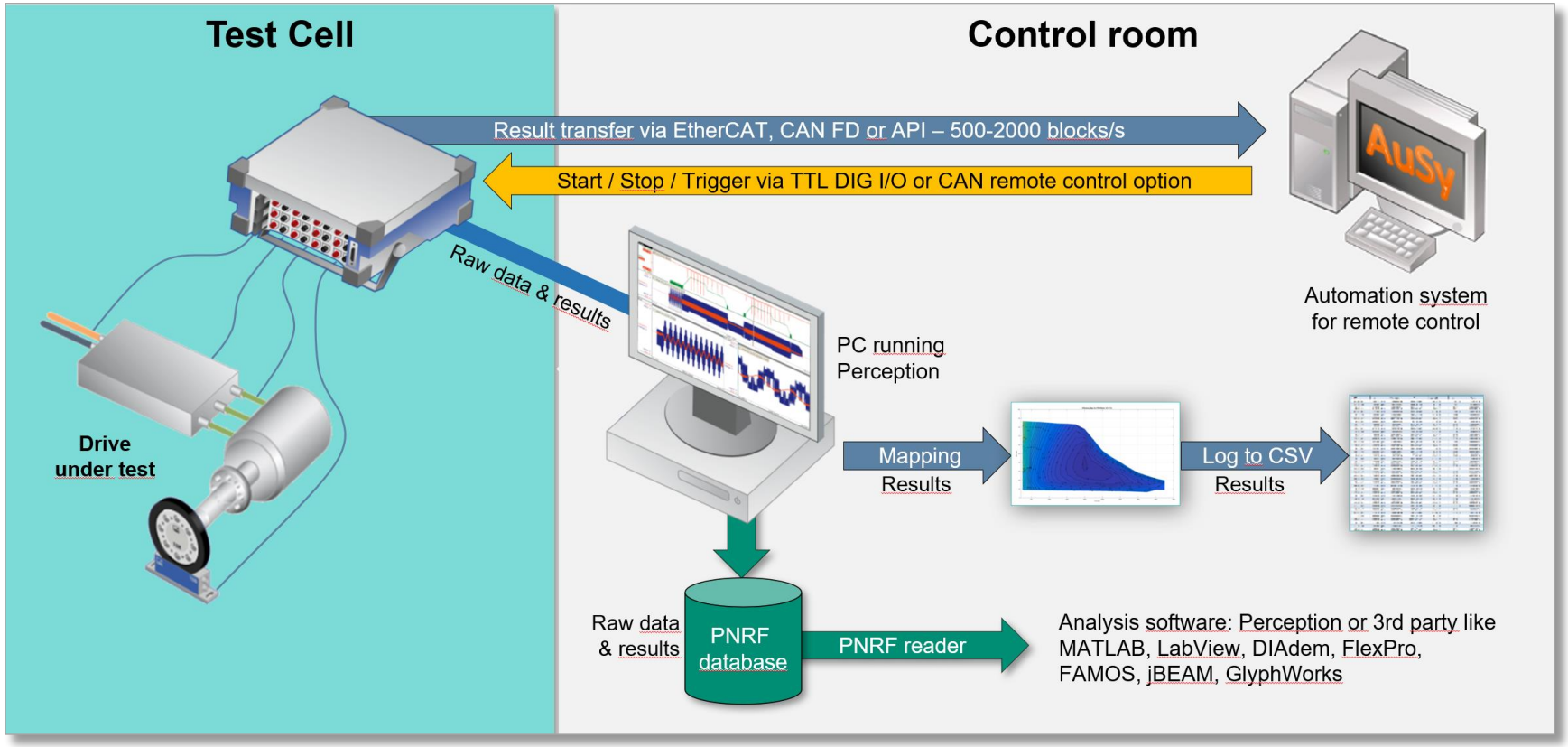
HBK
HOTTINGER BRÜEL & KJÆR

Tip # 5 – Real-time Results and Integration – Electric Power Train



Tip # 5 – Real-time Results and Integration – To Automation PC

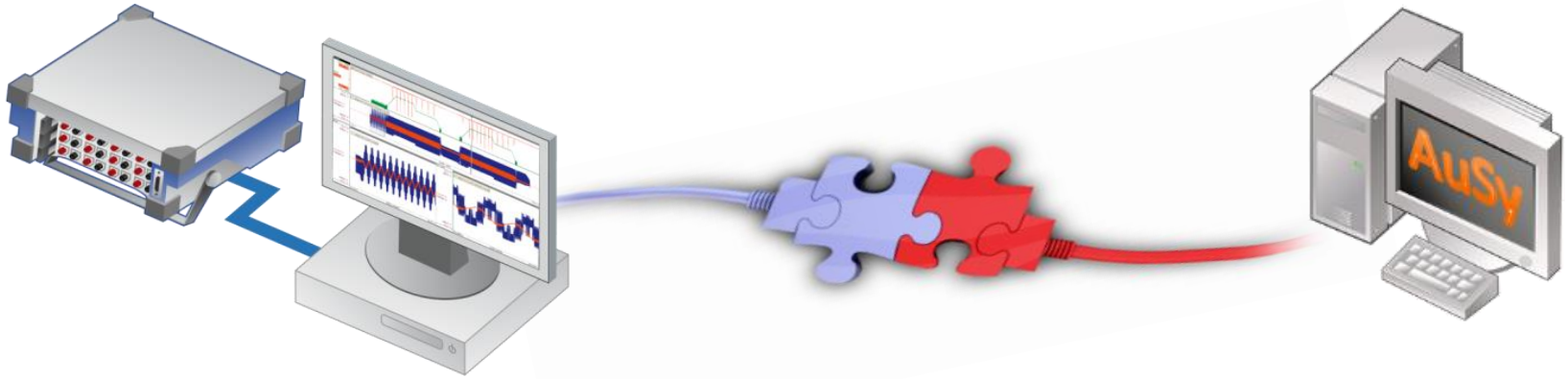
- Real Time Feedback
  - CAN 2.0 or FD
  - EtherCAT
  - API
- System Control
  - LabVIEW
  - .NET / C# / C++
  - Python
  - TTL signals



Tip # 5 – Real-time Results and Integration – Integration examples

HBM´s eDrive system

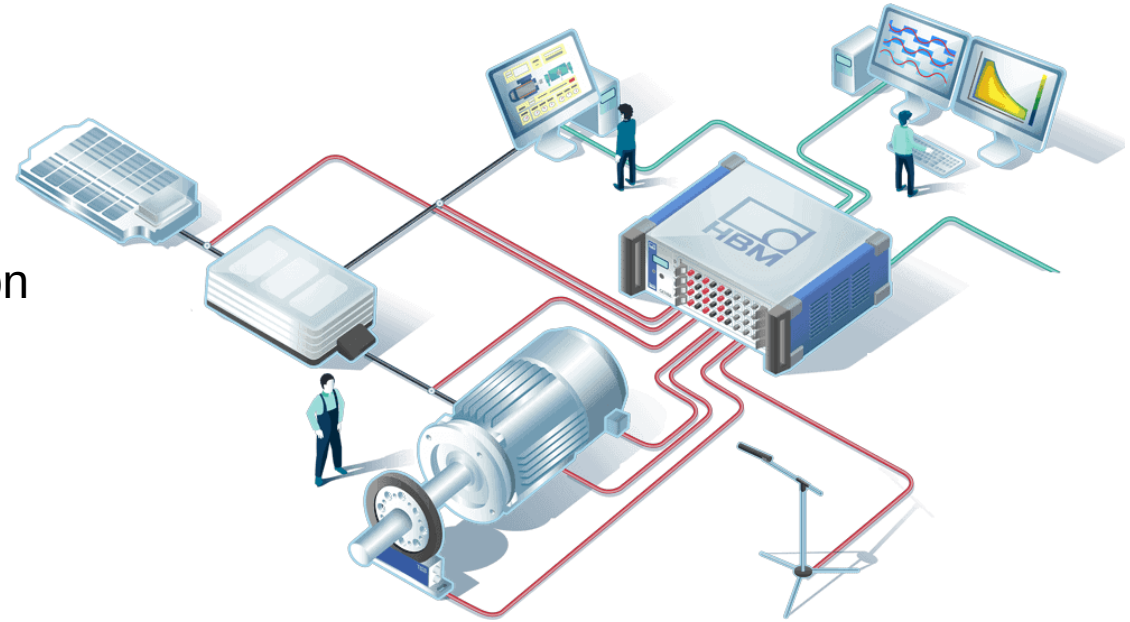
Automation system



System integrator	Automation system
Kristl & Seibt	Tornado
Kratzer	PAtools
National Instruments	LabView
AVL	PUMA
Siemens	CATS
National Instruments	Veristand / LabView RT
MAHA	MAHA RT
Intest	Inova
Horiba	Stars
FEV	morphee

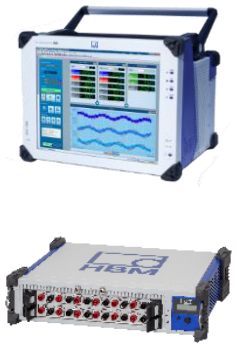
Agenda

1. What is a Power Analyzer and Electric Drive Testing
2. Selecting the right power analyzer for electric drive testing
   - Accuracy and Measurement Uncertainty
   - Number and Type of Inputs
   - Dynamic Power Measurements
   - Raw Data Storage and Analysis
   - Real-time Results and Integration
3. Conclusion
   - Where to get additional information



HBK
HOTTINGER BRÜEL & KJÆR

The HBM Power Analyzer - Designed for electric drive testing



Full range of future proof configurable **mainframes**

2 to 17 slots for Power Analyzer cards
Up to **51 power channels** (U&I)
Up to **12 torque & 12 speed sensors**
Fiber-optical remote control
SSD for local **raw data storage**

3 ch **Power analyzer card**

Power Accuracy 0.015% rd + 0.02% rg
3 voltage inputs +/- 1500 V DC
3 current inputs for CT´s or clamps
Sample rate 2 MS/s @ 18 bit resolution
On board DSP with **user programmable math**
Digital cycle detection for reliable results

Complete Power Analyzer Solution

High accuracy **torque and current transducer**

T12HP with **accuracy up to 0.007%**
Speed option with Reference pulse

Full **range of CT´s** 50A to 2000A
Slim line power supply

Accessories

EtherCAT/CAN FD for **real time data transfer**
CAN FD input for bus data
or Thermocouple modules
Vibration / Microphone inputs for NVH
Cards up to 250 MS/s
HV probes up to 20 kV
HV low noise cables

Conclusion

- Select a power analyzer for electric drive testing based on …
  - **Accuracy and measurement uncertainty**
    - The best accuracy offers reliable/credible data
    - Review power analyzer and sensor data sheets in detail, read the fine print
  - **Number and type of inputs**
    - A modular solution allows for future expansion
    - Review inputs for voltage, current, torque, speed, temperature, CAN, NVH
  - **Dynamic power measurements**
    - Digital cycle detection enables measurements during dynamic load changes
    - Digital cycle detection creates efficiency maps in minutes instead of hours
  - **Raw data storage and analysis**
    - Storing raw data saves costly lab time and offers quick validation and correlation
    - Advanced setup and analysis enables you to understand how to improve your system
  - **Real-time results and integration**
    - Real-time feedback and communication with a control PC makes test automation possible
    - A variety of communication methods and control options makes for a seamless integration

Additional Information

- HBK Electric Power Testing YouTube Channel
  - https://www.youtube.com/channel/UCRww1cDXwGmzacFSpBKpYdg
    - Videos on every electric power testing topic

- Electric Power Testing Knowledge Base
  - https://www.hbm.com/en/7381/electric-power-knowledge-base/
    - White papers
    - Customer application stories
    - Videos and tutorials

- Electric Drive Testing Solutions
  - www.hbm.com/edrive
  - https://www.hbm.com/en/8750/electric-power-testing/

Who is HBK?

HBM + Brüel & Kjær = HBK HOTTINGER BRÜEL & KJÆR

www.hbm.com

Test and measurement, fatigue and reliability analysis plus custom sensors

- **Sensors:** torque, force, pressure, displacement, load cells, custom, conventional and optical strain gauges
- **DAQ:** low and high speed and rugged
- **Power analyzers** for eDrive and eGrid
- **DAQ amplifiers** for industrial control
- **Analysis software** for fatigue, structural durability and reliability

www.bksv.com

Sound, noise and vibration plus NVH engineering services

- Sound and vibration **analyzers**
- **Sound level meters**
- **Software** for sound and vibration analysis for numerous applications
- **Vibration test systems**
- **Acoustic** end of line **test** systems
- **Microphones**
- **Accelerometers**

www.hbkworld.com

Complete integrated solutions for any test, from a single partner.

- HBK provides a complete portfolio of solutions including:
- **Engineering services**
- For you this means **shorter development cycles, optimized products and better decisions**.

Thank You - Questions?

Mike Hoyer
Applications Engineer
Mike.Hoyer@hbkworld.com
Technical Support: 1-800-578-4260

HBM Electric Power Testing

PUBLIC