An introduction to Electric Power Measurement

TIPS, TRICKS, AND CARE

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EPT

Agenda

1. Measuring the basics, voltage and current input methods
2. Sampling rate and fundamental power
3. Averaging in power calculations
4. Dynamic power measurement
5. Get to know existing and brand-new HBK solutions for (electrical) power measurement

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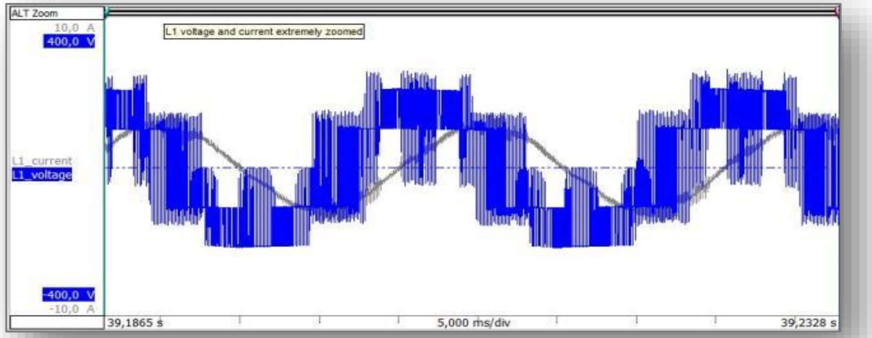
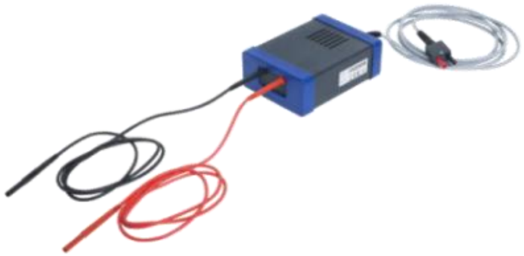
Measuring the basics
voltage and current input methods

Our theoretical Device Under Test today

Voltage measurements at different voltage levels





- **Direct voltage inputs up to +/- 1500 V DC**
  - 0.015% + 0.02% accuracy
  - Phase to phase or phase to (artificial) star
- **5 kV differential probe**
  - 0.1% accuracy
  - Certified and always USER safe
- *Higher voltages up to 20 kV including isolation ->Fiber optical isolated front ends paired with HV dividers*

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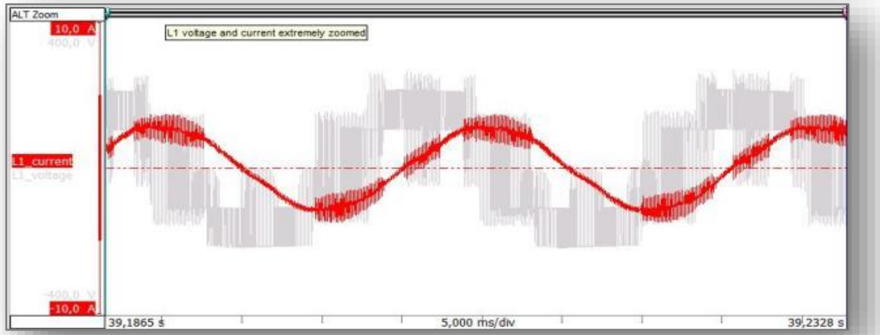
Current measurement methods



Zero-Flux Current transformer

- High accuracy and medium bandwidth
- Some effort in installation (circuit needs to be opened)
- Connected using burden resistors

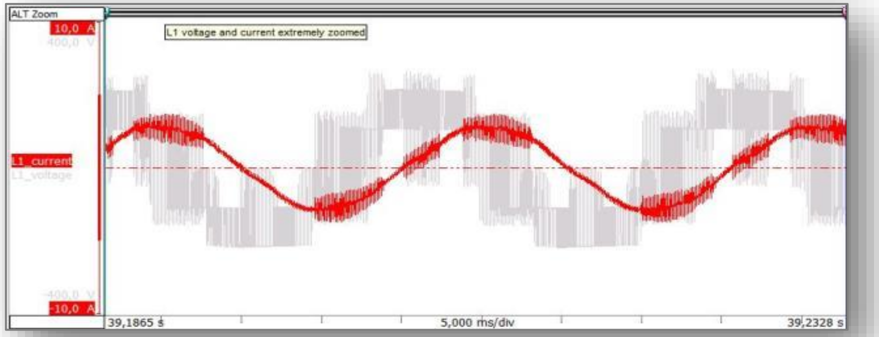
Current clamps or Rogowski coils

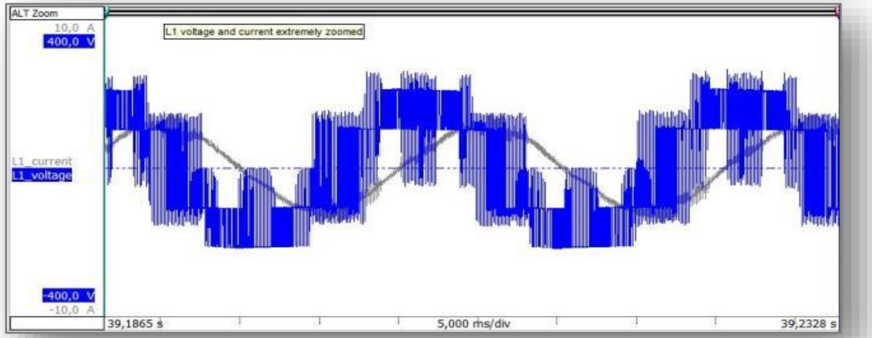
- Low accuracy and high bandwidth
- Rogowski coils -> AC only
- Easy to install

Sampling rate and fundamental power

Sampling Rate

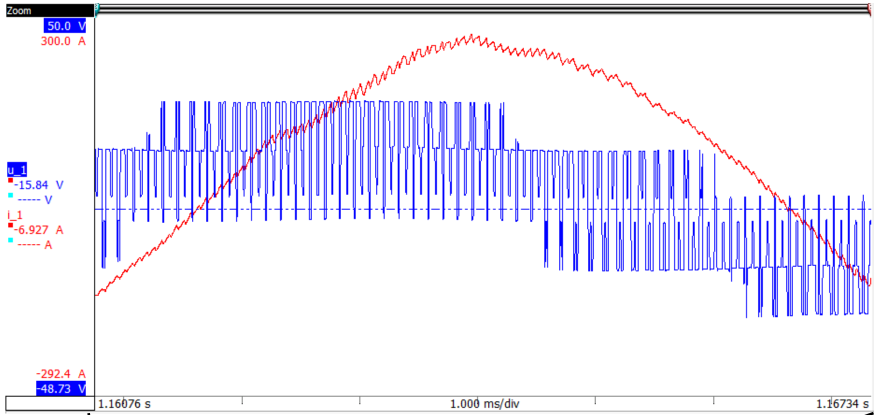
- Fundamental matters for useful power
- Current sensor bandwidth as limiting factor
- Catching rise time→ Not for power measurement
- If we do want to catch the switching behavior of the inverter components, sample rates >100MS/s



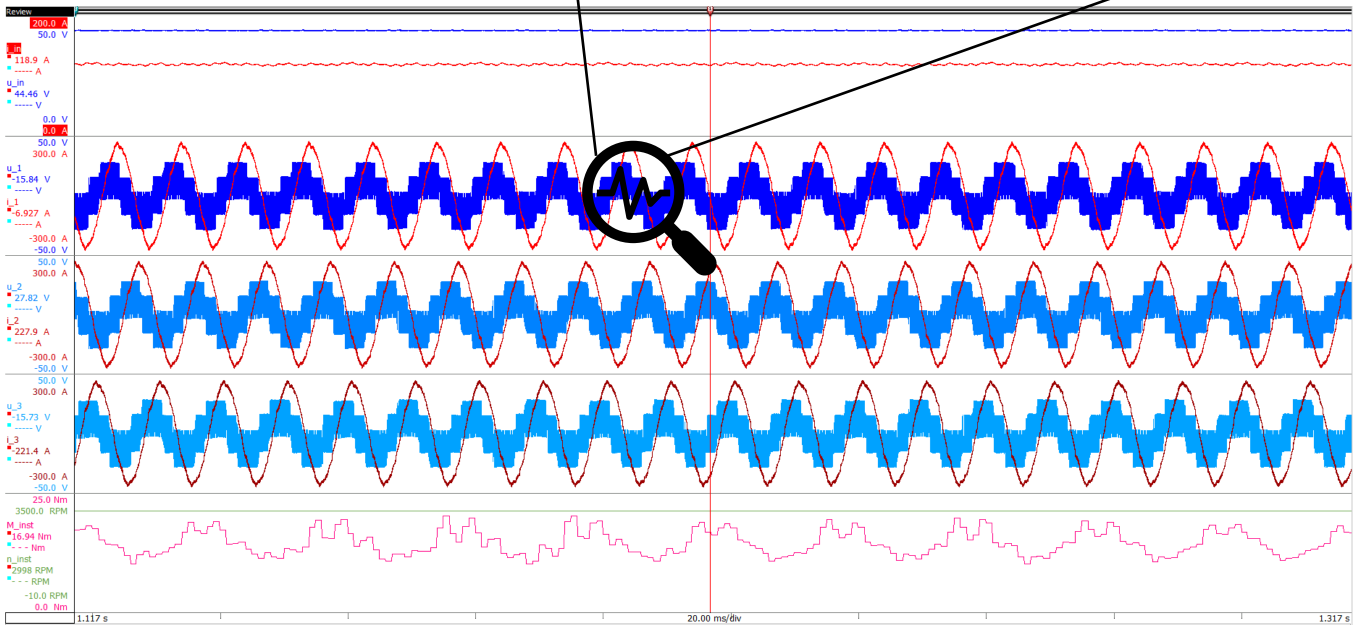


From measured signals to results

Could the inverter cause a challenge?



- DC Battery Voltage & Current
- Three Phase inverter Voltage & Current
- These are our inputs for the electric power calculations
- Simple multiplication?



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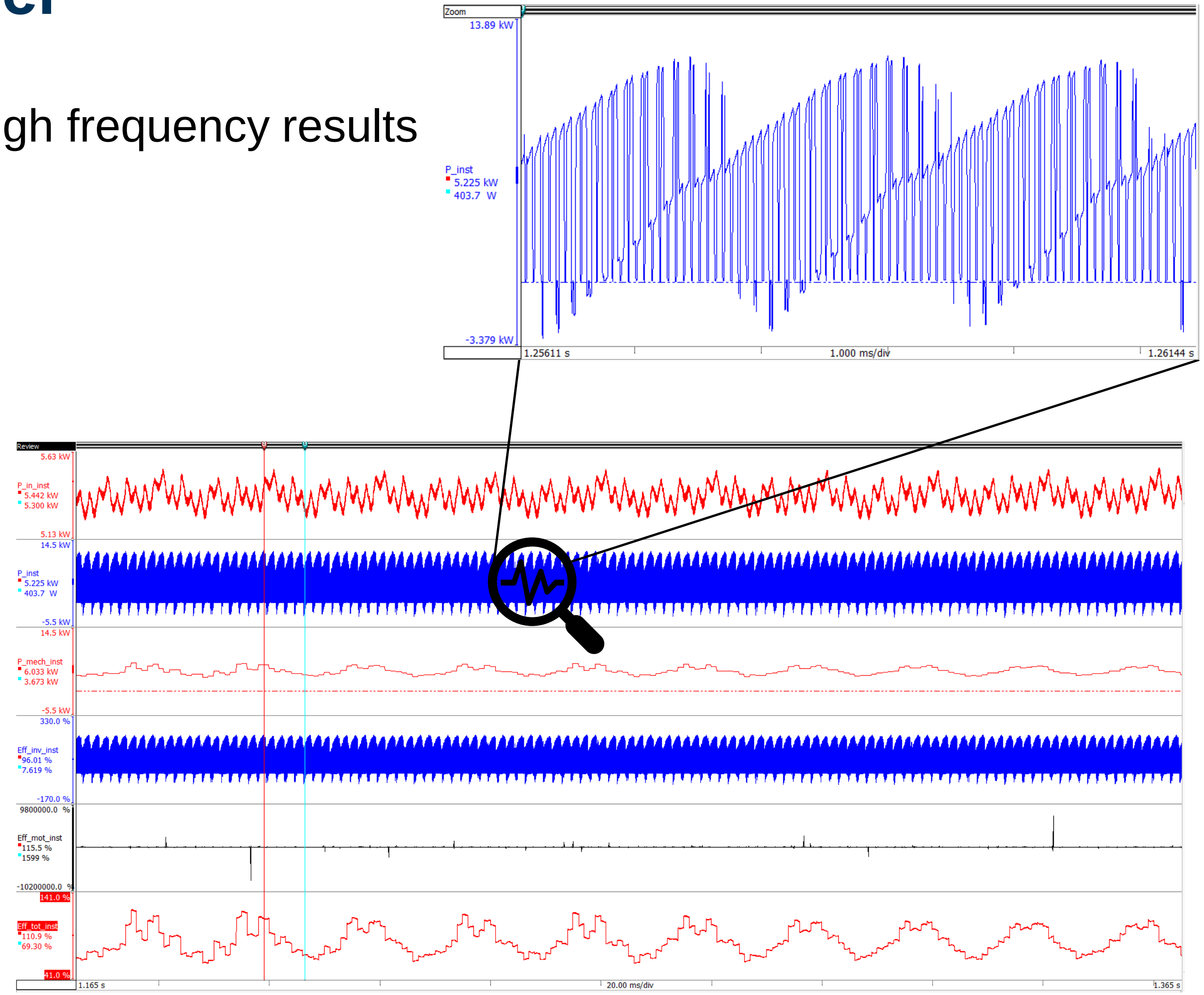
Calculating “Instant” Power

- Point by point multiplication gives high frequency results
- “Instant power” is not useful
  - No steady values
  - Positive to negative power swings
  - Power swings at inverter frequency
    - 3 phase power
    - DC power



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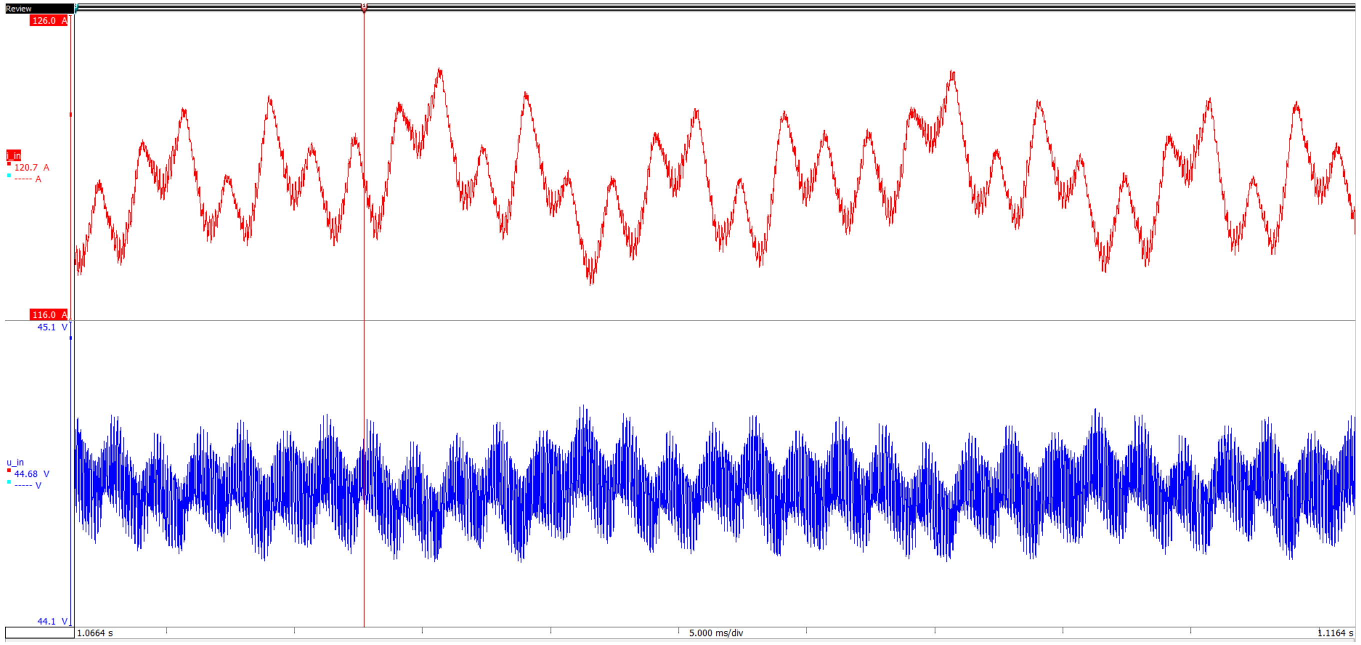
DC Inverter input – Not true DC

- AC from inverter is coupled to the DC from the battery or source
- High frequency content because of inverter switching
- How to average this?
  - Filter?
  - RMS?
  - Mean?
- How to calculate power?



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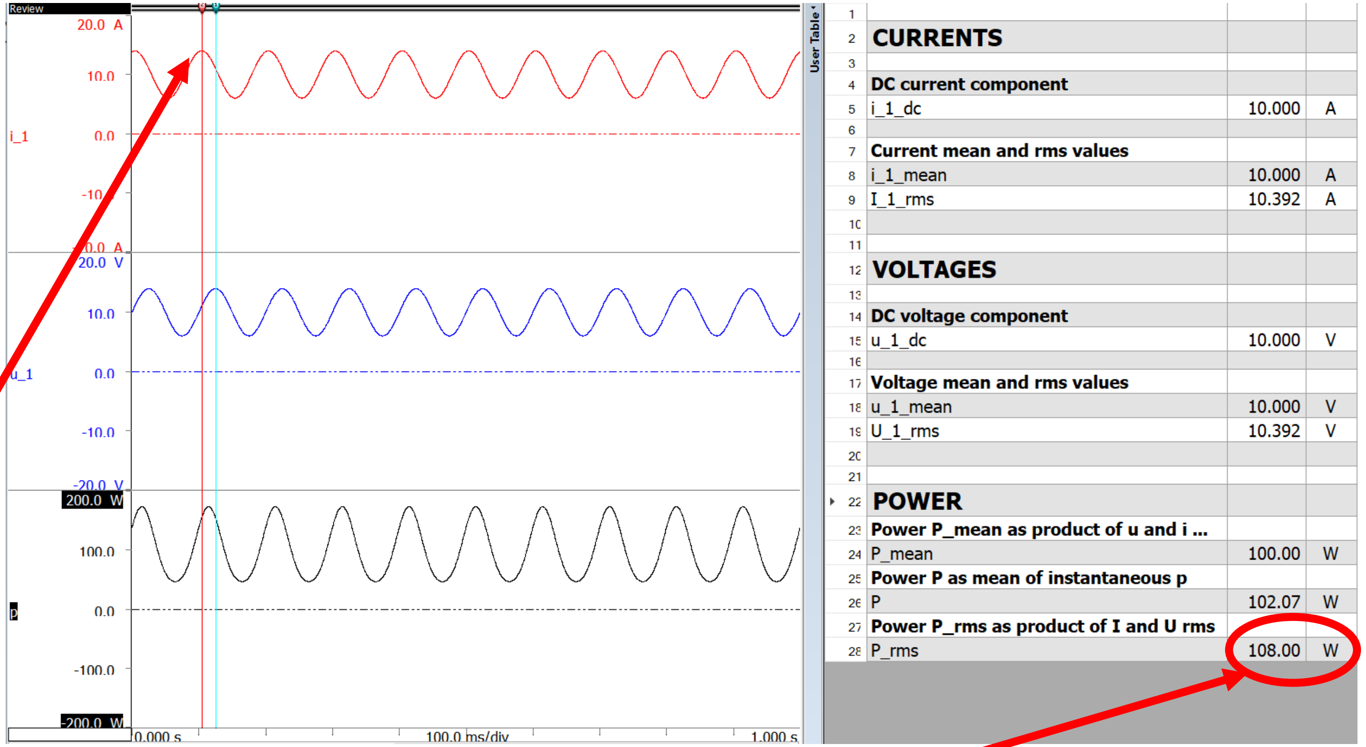
Calculating DC Average and DC Power

- 4A AC added to a 10A DC gives a good example of why we need to measure correctly

- Average voltage and current
  - Mean → averages the AC out of the value if the average is periodic
  - **RMS → includes the AC value**

Phase offset of AC components



1			
2	CURRENTS		
3			
4	DC current component		
5	i_1_dc	10.000	A
6			
7	Current mean and rms values		
8	i_1_mean	10.000	A
9	I_1_rms	10.392	A
10			
11			
12	VOLTAGES		
13			
14	DC voltage component		
15	u_1_dc	10.000	V
16			
17	Voltage mean and rms values		
18	u_1_mean	10.000	V
19	U_1_rms	10.392	V
20			
21			
22	POWER		
23	Power P_mean as product of u and i ...		
24	P_mean	100.00	W
25	Power P as mean of instantaneous p		
26	P	102.07	W
27	Power P_rms as product of I and U rms		
28	P_rms	108.00	W

- Power
  - u_mean*i_mean → No AC accounted for in power
  - U_RMS*I_RMS → No Phase accounted for in power
  - **Mean(u_1*i_1) → Correct Power for correct period**

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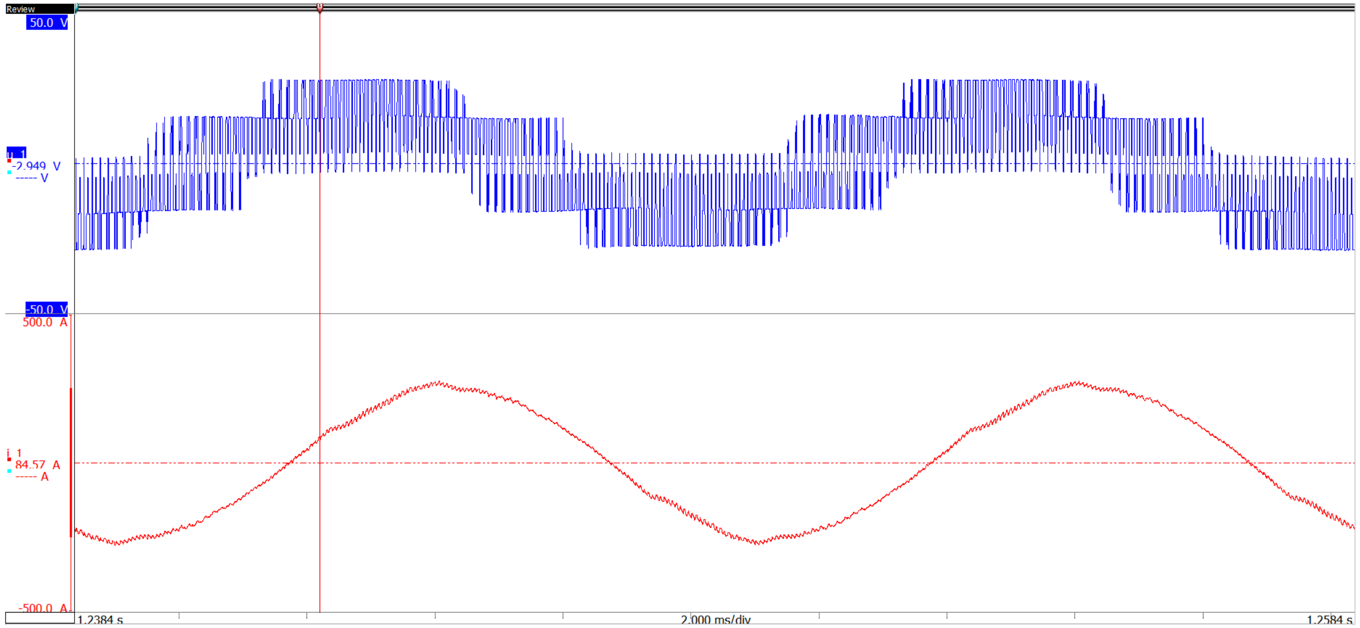
AC Inverter output – phase shifted and distorted signals

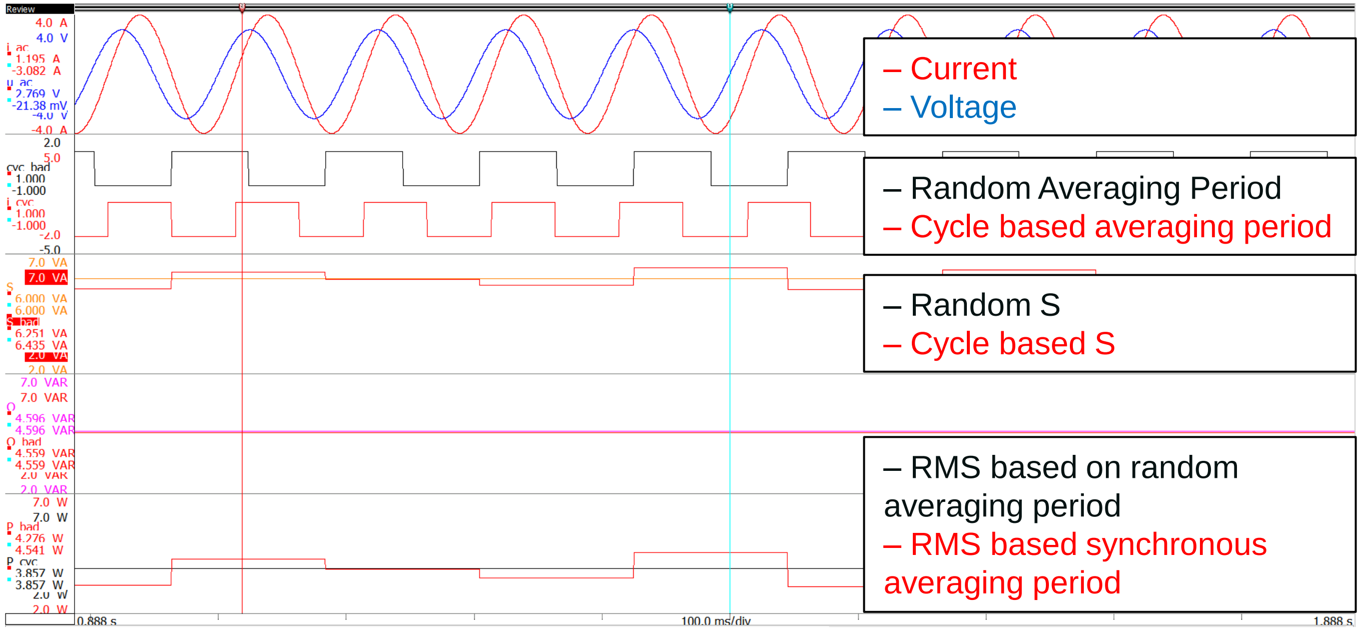
- PWM driven inverter has high frequency switches creating a sinusoidal voltage
- Current is a result of this high frequency sinusoidal voltage
- Considerations:
  - Phase shift between Voltage and Current
  - Reactive and apparent power
  - RMS Period



Calculating Real Power

- RMS Voltage * RMS current does not give real power
  - Phase offset needs to be accounted for
  - Real Power P = Mean(voltage*current)
  - Apparent Power S = Vrms* Irms
  - Reactive Power Q = sqrt(S^2-P^2)
    - Averaging basis also effects angle measurement

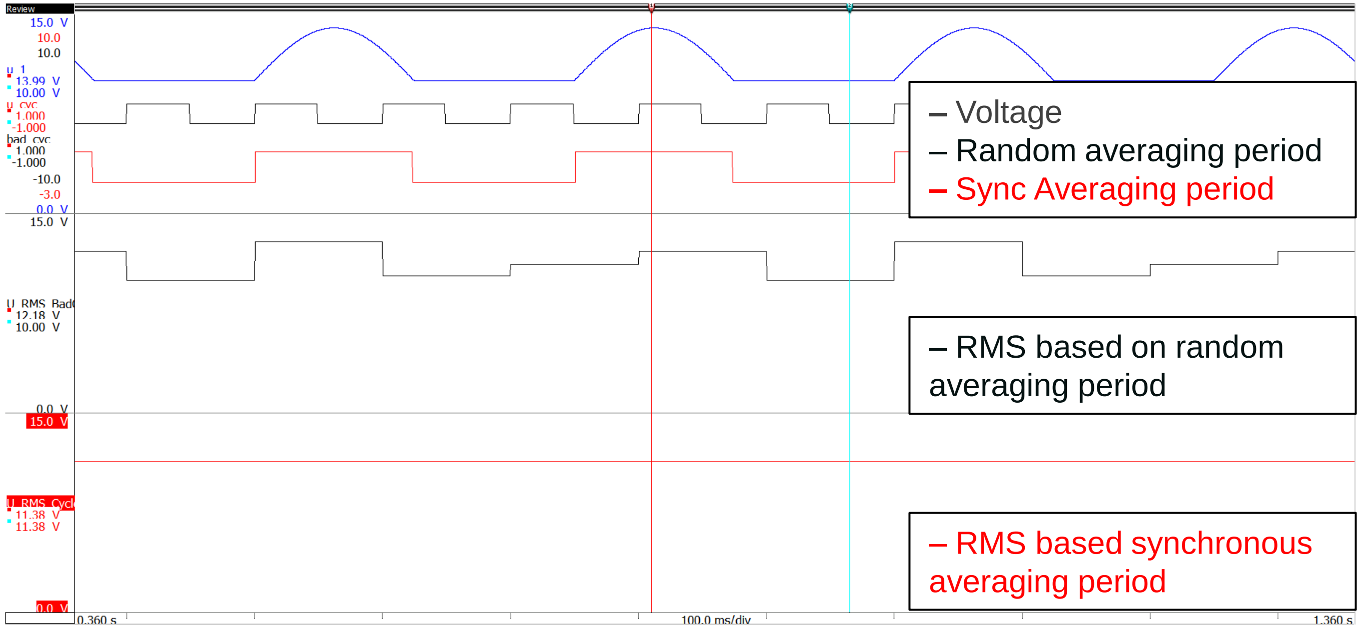
- **Calculation also based on cycle period**



averaging in power calculations

Averaging Period Matters

- Voltage with an asymmetrical ripple
- A random averaging period (**Black**) will give an RMS/average with an asymmetric signal
  - **Black** RMS bouncing around depending on average period
- A cycle based averaging period (**RED**) is used to capture the whole asymmetric event
  - **Red** RMS measurement is constant



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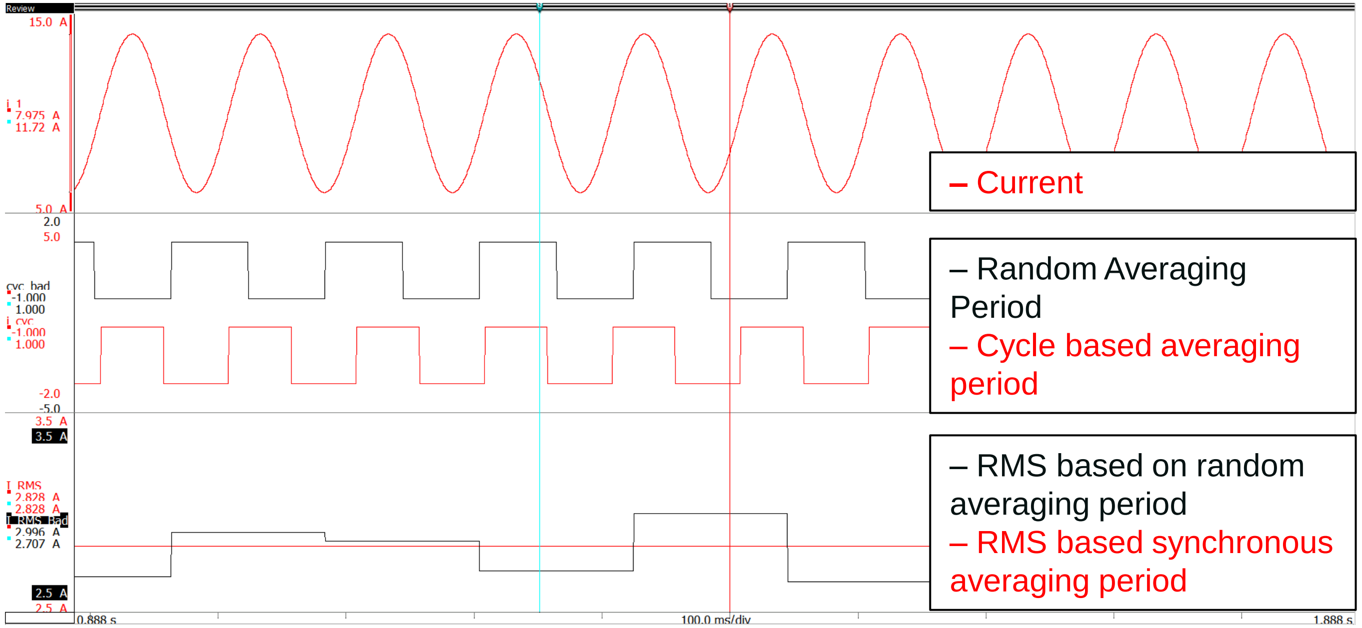
RMS → Periods matter

- Characterize AC signals with RMS calculation

- RMS calculation can be done on any
  - Random
  - Rotational
  - Cycle based

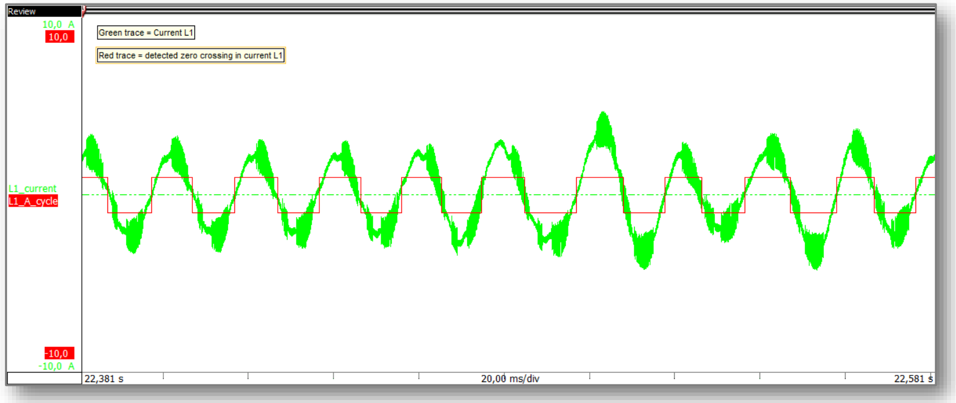
- Not all time basis will give a correct output
  - Only Cycle based or increments of cycle based give a proper output

- RMS shown for **Cycle based** and **Random calculation** periods

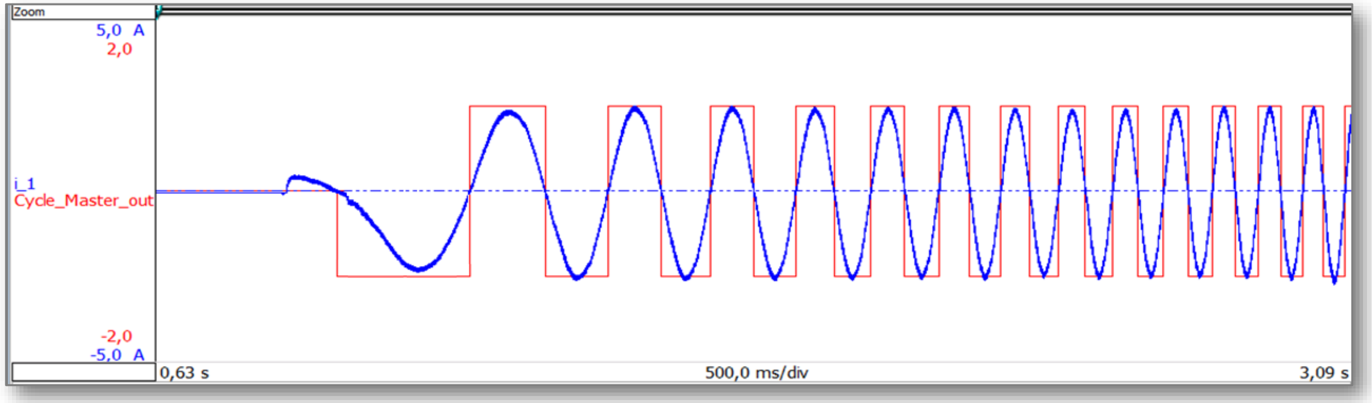


eDrive: Cycle detection – the key to correct power readings

- Conventional power analyzers use “Analog” PLL-based cycle detection
  - Problem: This only works in steady state load conditions
- The HBM eDrive system detects the cycles in real time using advanced digital algorithms
  - Then the power calculations are executed over a half cycle (or any multiple of this).
  - This delivers all cycle and thus accurate power results also in dynamic load changes



Current trace used for Cycle detection (green)
and resulting “CycleMaster” trace (red)



eDrive Cycle detection working during machine startup
at rapidly changing fundamental frequencies

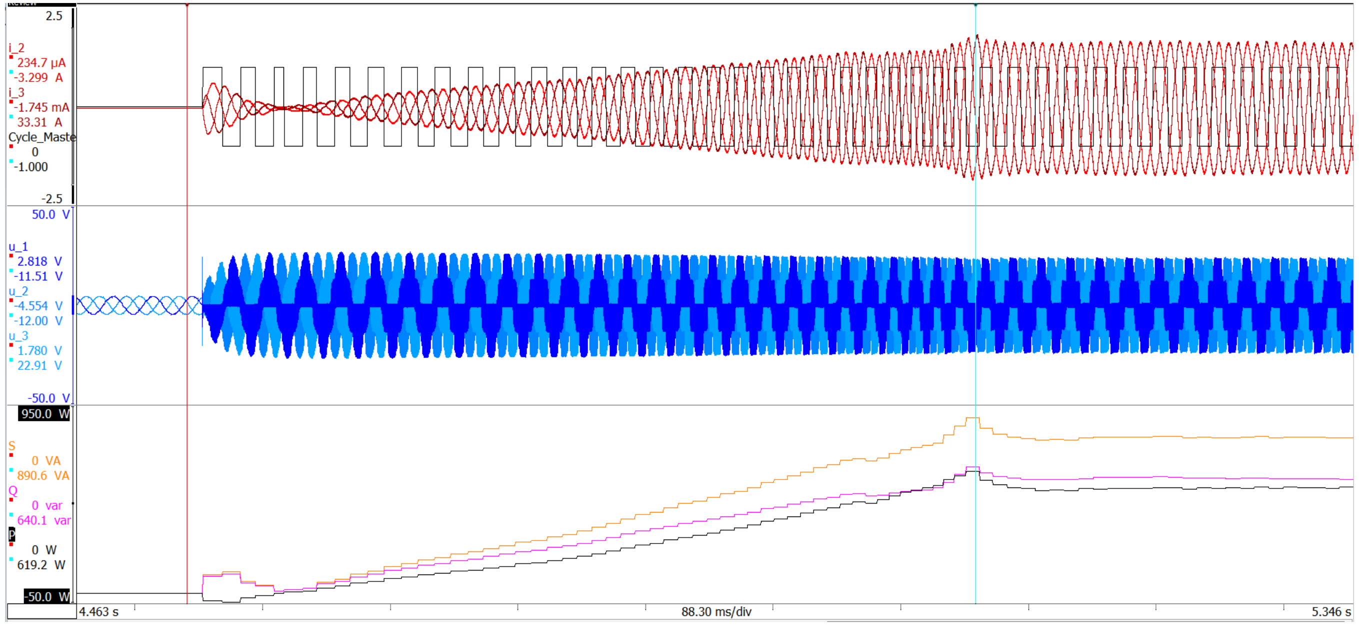
Dynamic power measurement

Half Cycle Measurement is The Fastest Power Measurement

- The figure shows a start of an electric vehicle and its dynamic power

- A single half cycle can be used to calculate power
  - Half cycle measurement can be used for dynamic tests
  - Requires an algorithm that tracks the cycle period (Current frequency)

Scooter acceleration from 0 speed showing a ramp from 0 to full power.
Top – Three phase currents (red) and cycle detect (black)
Middle – Three phase voltages (blue). Note back emf and PWM operation
Bottom – Apparent power (orange), reactive power (purple) and real power (black)



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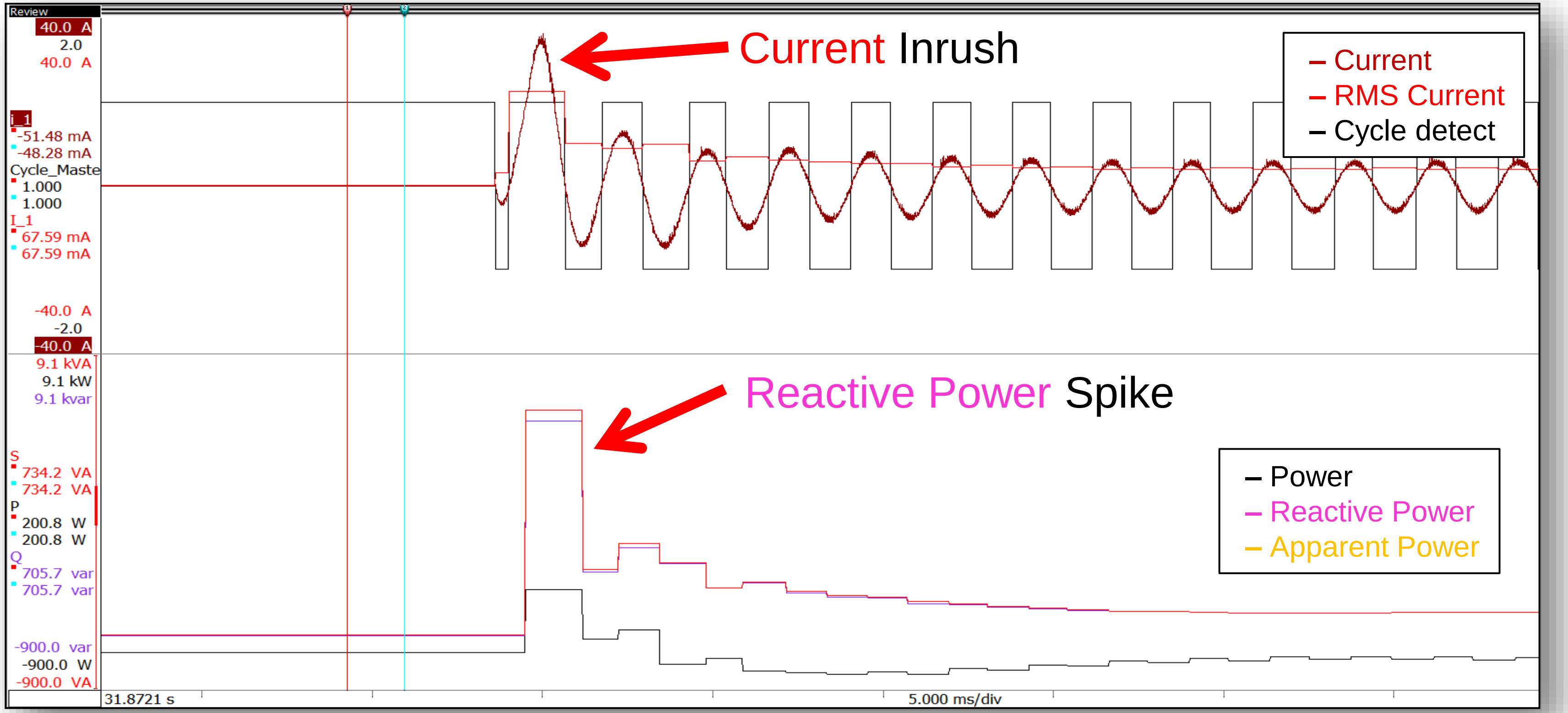
Importance of Dynamic Power Measurement

- At machine start, stop, or change of state there are losses associated with state change
- Example of an inverter started induction machine
- Large reactive power during the transient resulting in inefficiency
- Dynamic power measurements needed to understand actual efficiency during use



Current suddenly applied to an electric motor and associated power, reactive power, and apparent power for this dynamic load change

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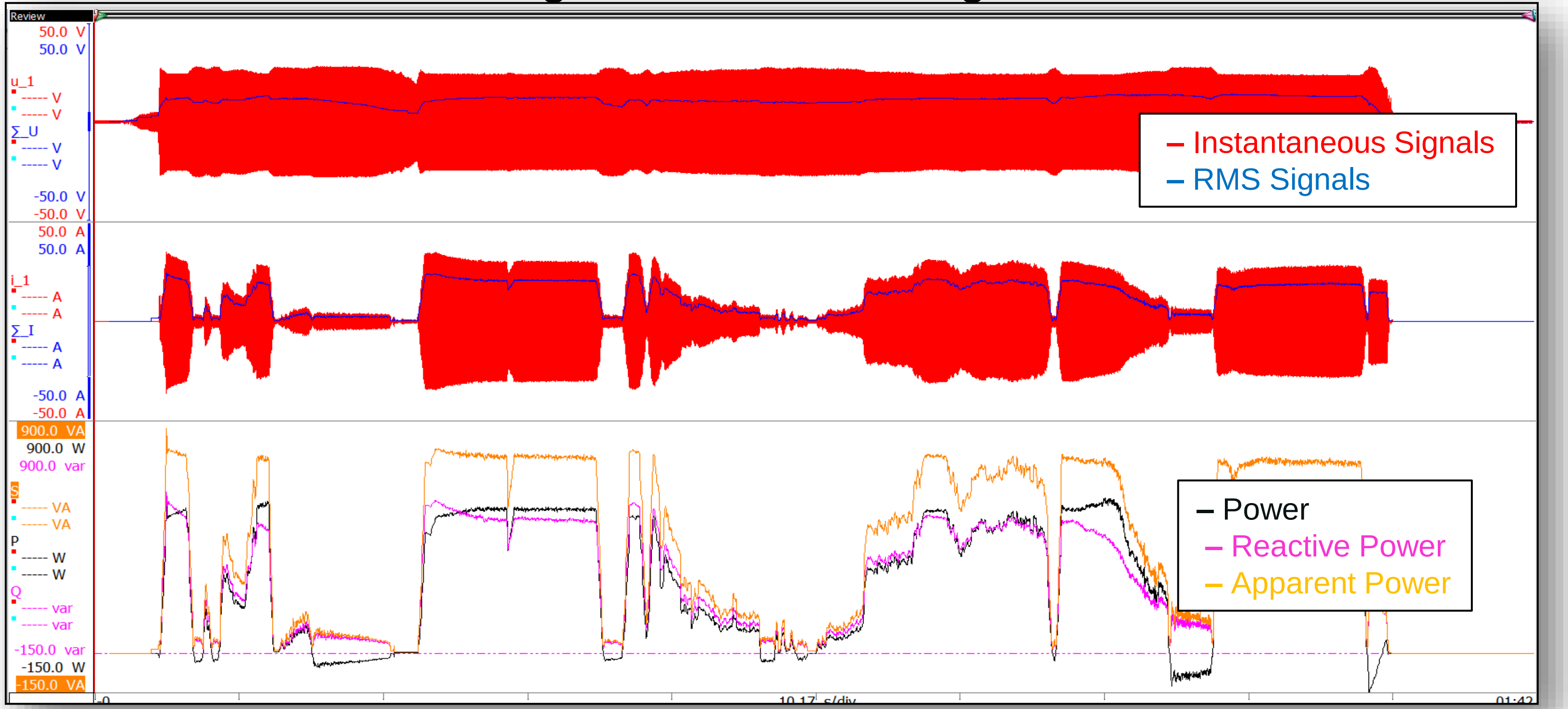
Real World Load Test Dynamics

- Increased losses in dynamic situations makes drive cycle testing necessary
- Testing the system the way a user will do this; this gives accurate range estimations
- Cycle based power analyzer can accurately measure dynamic power
- Understand control behavior to disturbances
- Dynamic power is needed to optimize the machine controller



Dynamic signals from laps around a track on an electric scooter. Including: starts, stops, coasts, uphills and downhills

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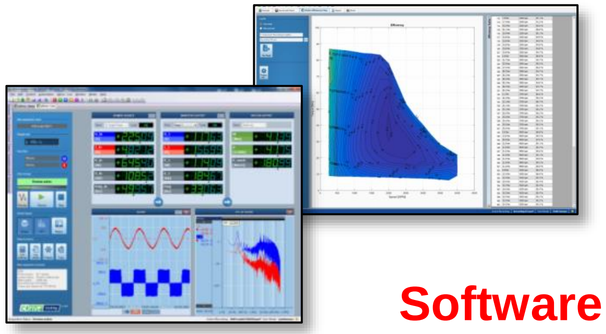
Get to know existing and brand-new HBK solutions for (electrical) power measurement

eDrive Value

- Simple data collection of electro-mechanical signals
- Fast and accurate efficiency measurements
- Future proof testing capabilities
- Auditable testing
  - Stored data
  - Public equations
- Feedback to control systems

Acquisition



Software

Sensors

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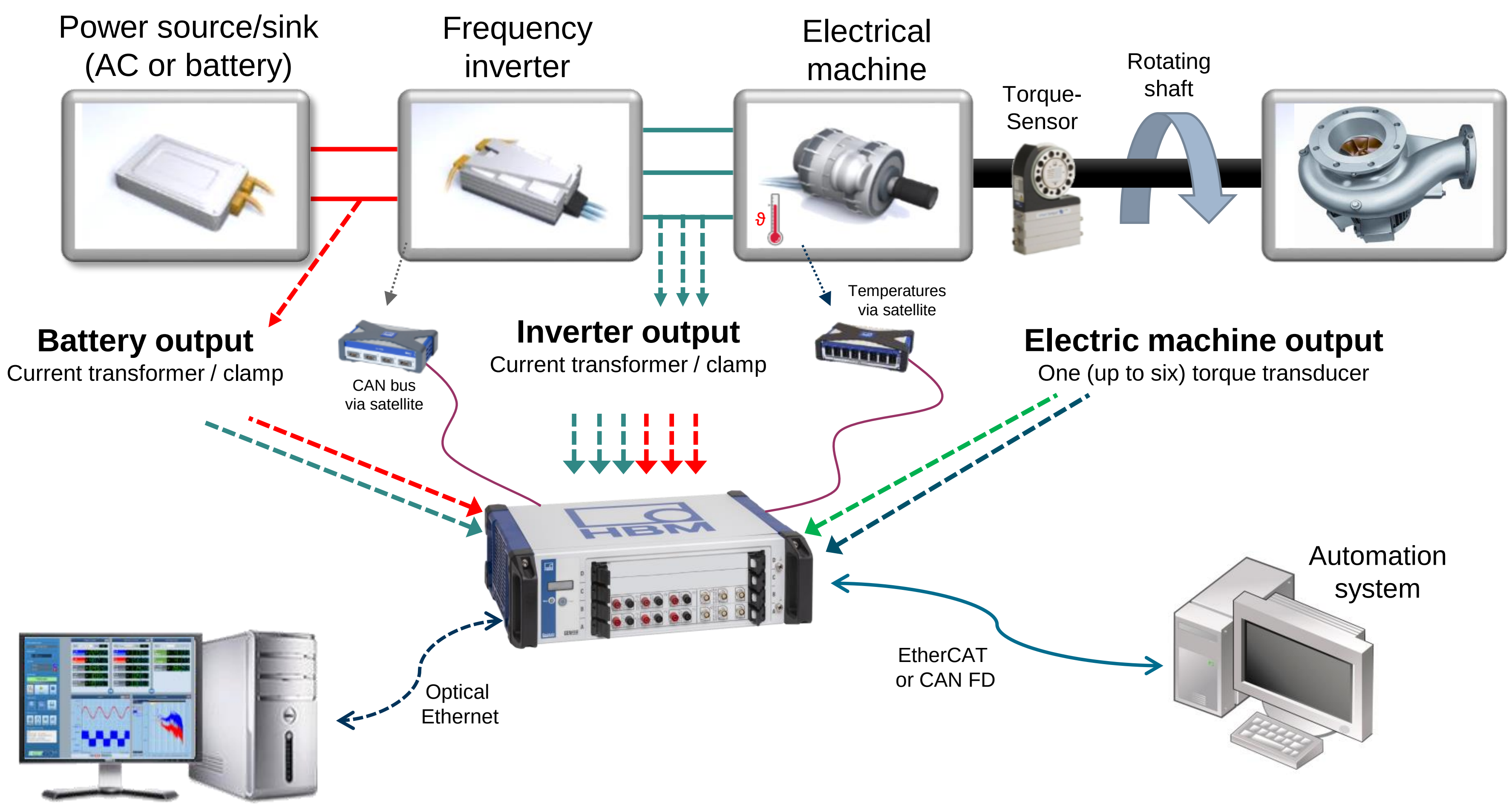
Simple Measurement Chain - Electric & Mechanical Signals

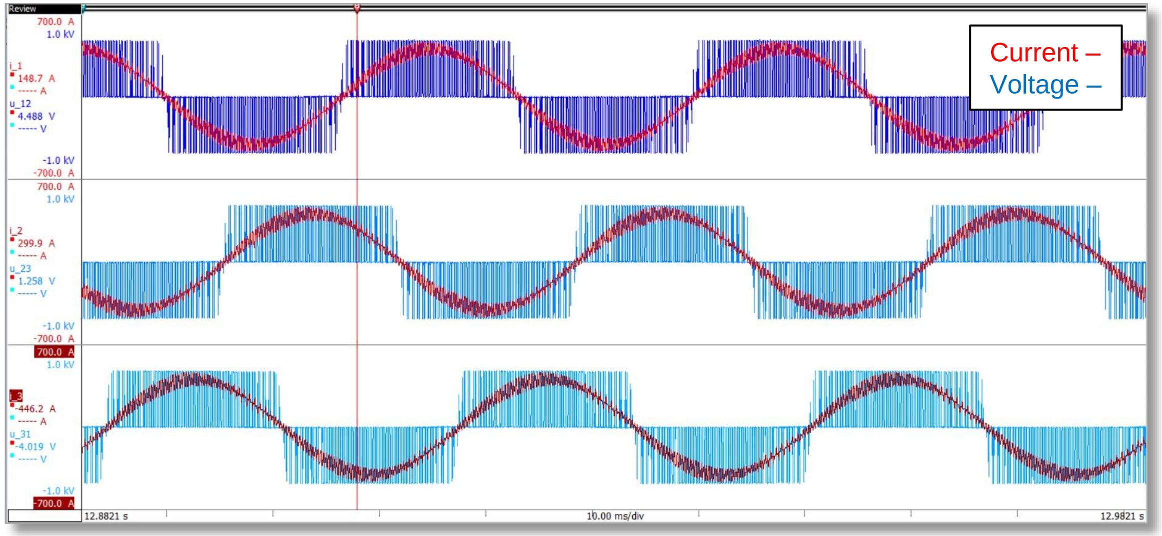
Measurements taken with <u>one system:</u>

- Voltages & Currents
- Accelerometers
- Microphones
- Torque & Speed
- Temperatures
- CAN
- Pressure
- Flow
- Force
- **Calculations for Power & Efficiency**



Auditable Testing – All data recorded & public equations

- eDrive stores all signals
  to hard disk at 2 MS/s per channel
- Calculated power results
  have the data to support them
- 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.

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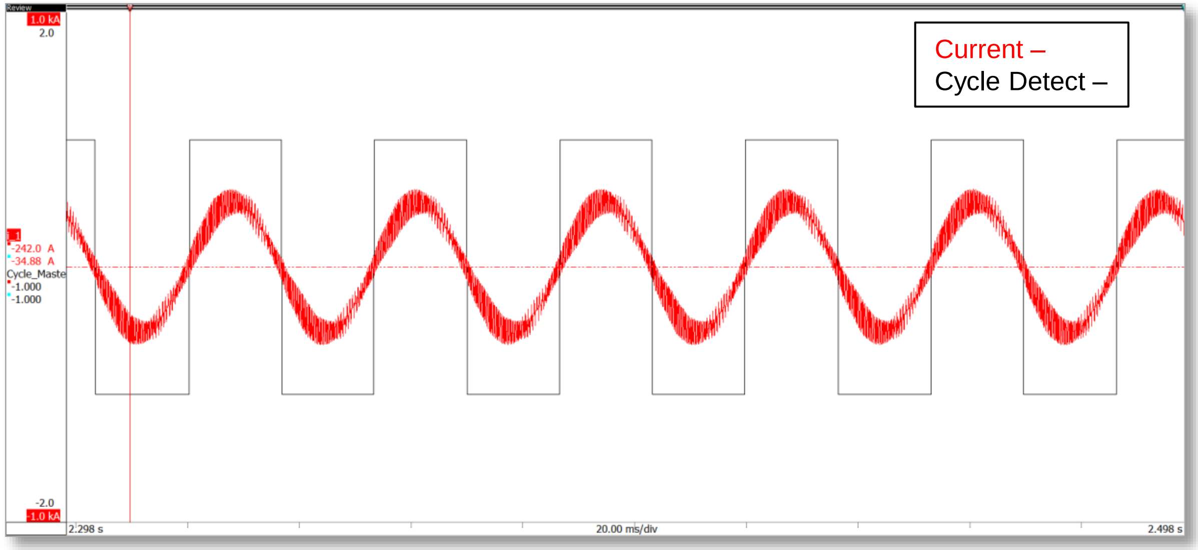
Fast and Accurate - Power is Calculated on a ½ Cycle Basis

- To compute any power result the “cycles” of the signals are needed
- The eDrive hardware detects the cycles using advanced digital algorithms in a DSP
- RMS values, power, efficiency, and advanced calculations are done on the cycle basis
  - Allows for dynamic testing
- Accuracy 0.015% +0.02%
  - And Auto Range



Current and cycle detect for a single phase of a 3-phase system.
This highlights the cycle detect identifying ½ cycles for calculation.

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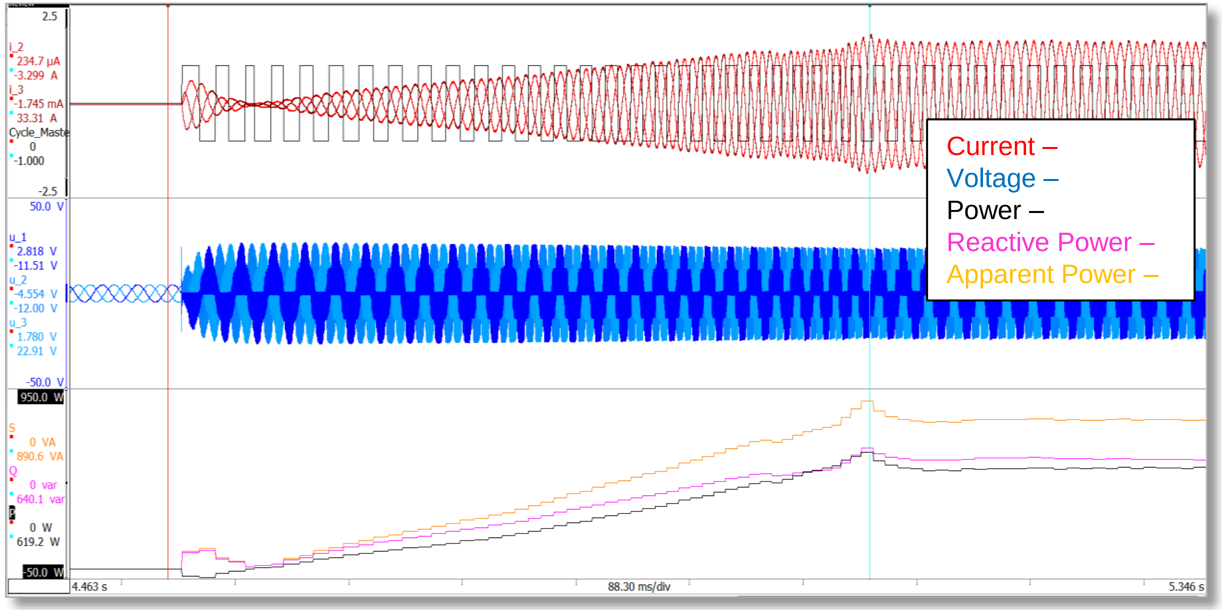
Dynamic Testing with Cycle Detect

- Transient power measurements allows to dynamically measure efficiency
- Cycle detect allows measurement of signals as frequency is changing
- Dynamic testing allows to characterize real world scenarios
- Measure power accurately during frequency changes



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

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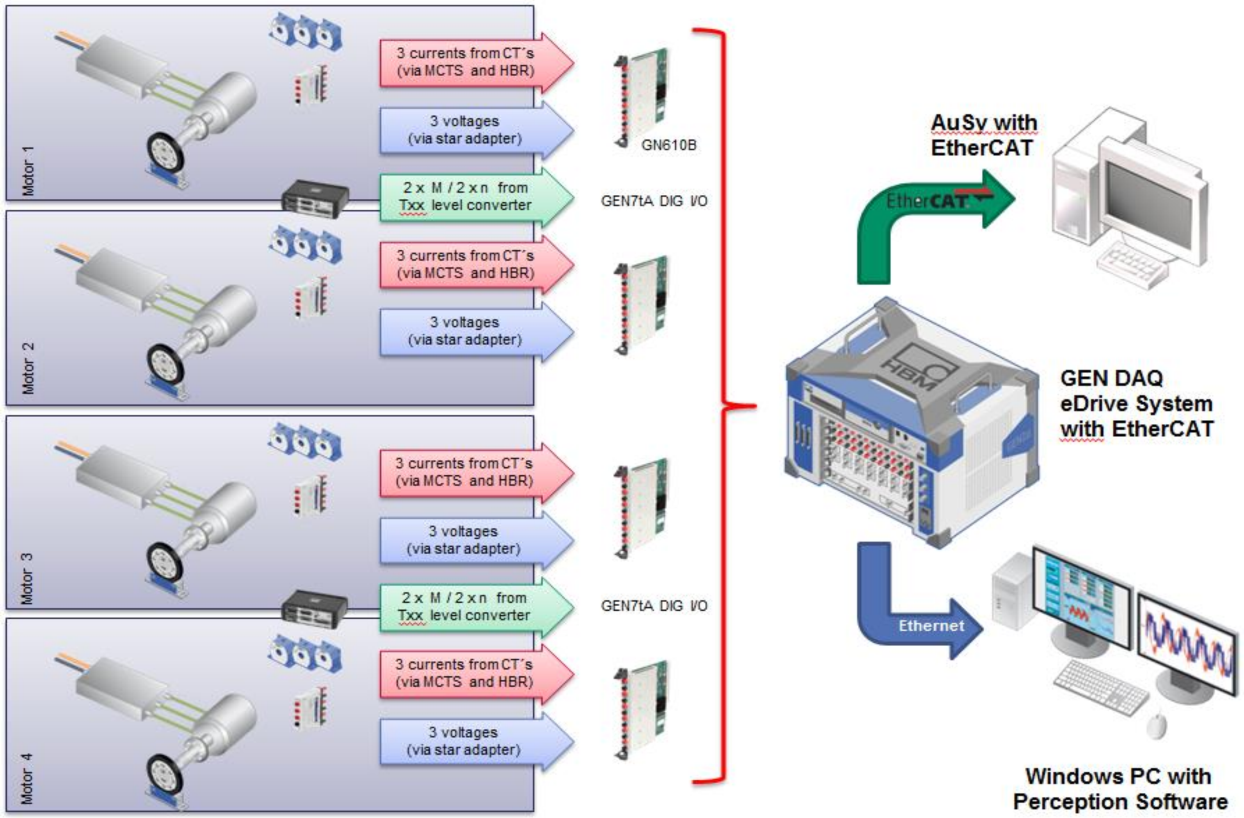
Future Proof - Expandable to Fit Any Test

- Continuous recording
  for as many signals as you need
- Up to 51 electrical power measurements
- Up to 6 torques and speeds
- Hundreds of mechanical measurements
- Hundreds of temperatures
  and CAN measurements
- Any combinations of these



Four wheel motor measurement with one system

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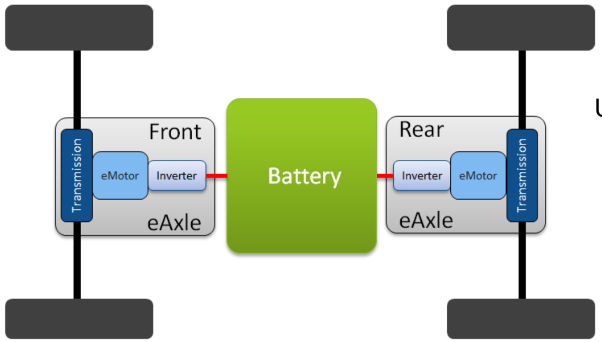
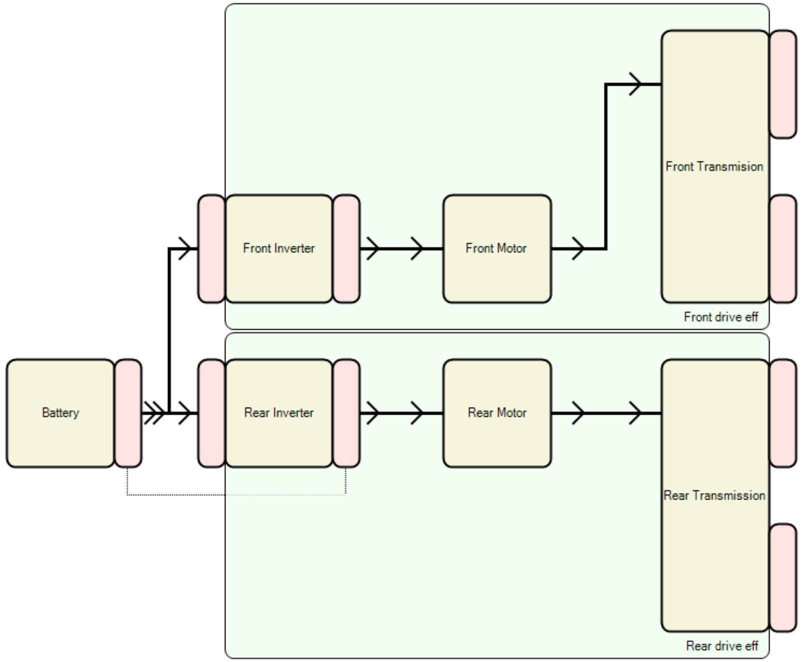
ePower software – Custom Power Display

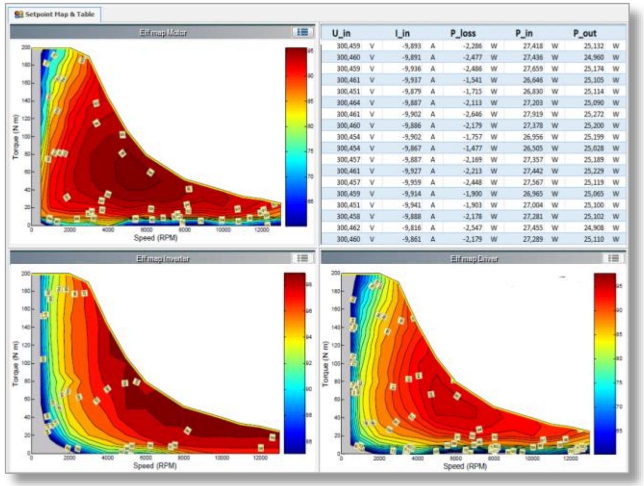
- Map the power analyzer to your powertrain



User Defined Power Flow & Power Measurements



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



- Live efficiency map plotting

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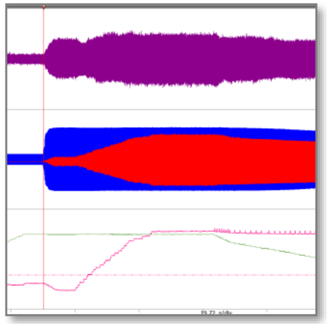
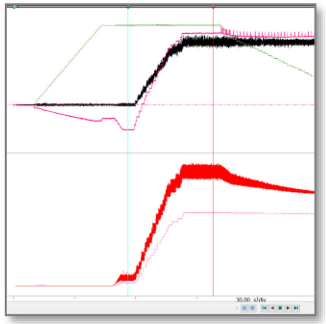
Future Proof – Many Applications and Analysis with One System

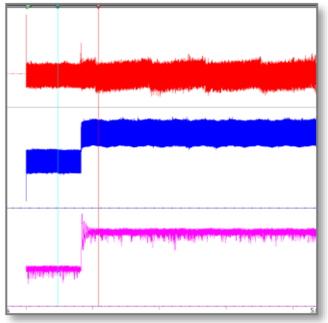
Vibration Analysis



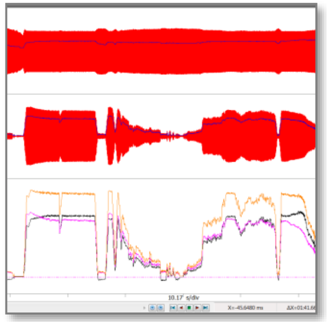
CAN Bus Correlation



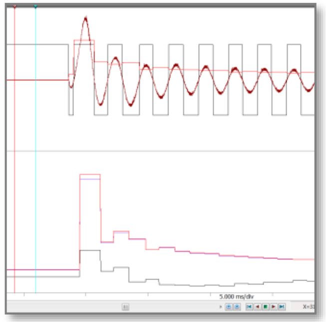
Live dq0 Transformation



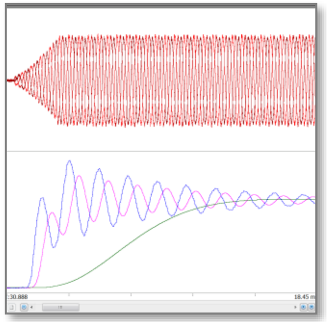
Drive Cycle Analysis



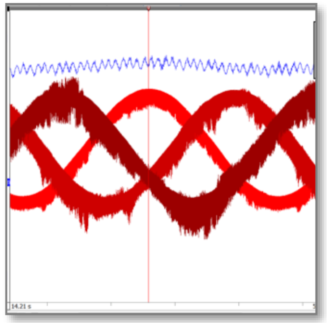
Dynamic Power



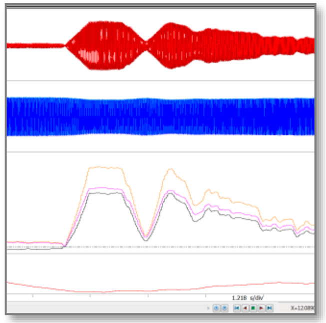
Transient Torque



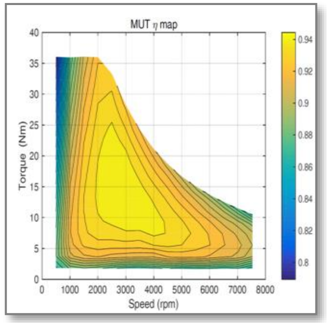
Torque Ripple



In Vehicle Measurement



Live Efficiency Plots



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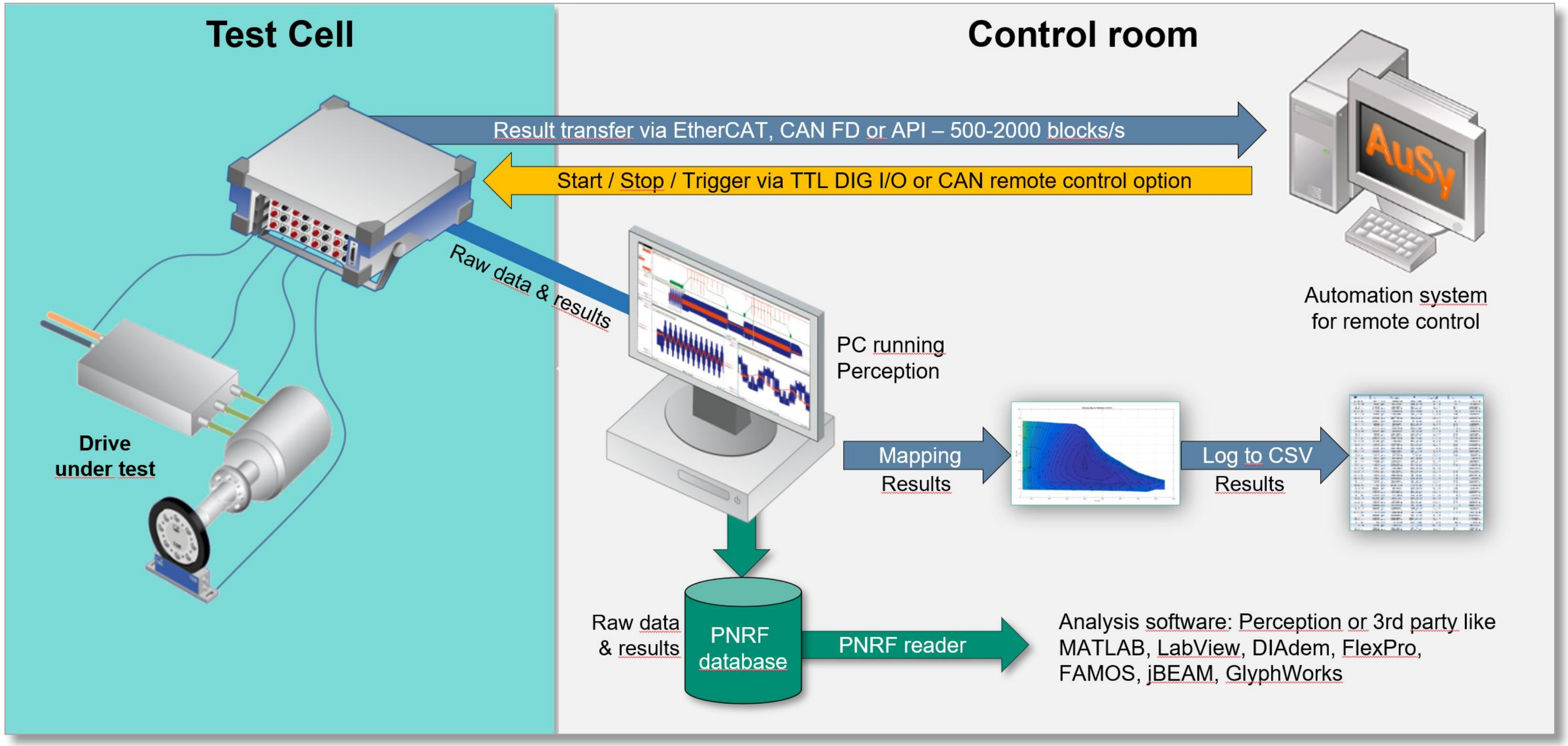
Feedback to Automation Systems - Integration Tools

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



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