Measuring Power Losses in Electric Motors and Inverters

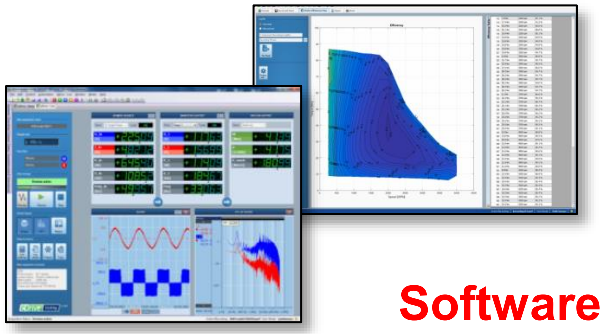
Learn more at
https://www.hbm.com/eDrive

PUBLIC

Agenda

1. Introduction
2. Inverter losses
3. Motor Losses
4. Measurement Uncertainty

Acquisition



Software

Sensors

Losses

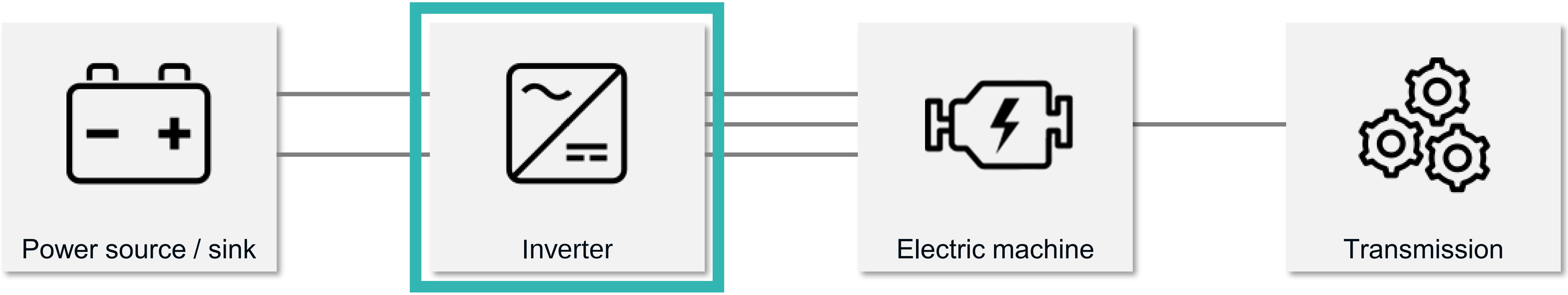
- Each component has losses in energy between states
- Losses create heat
- Losses decrease range
- Losses result in increased weight/volume
- Characterize losses so we can:
  - Understand them
  - Mitigate them
  - Manage them

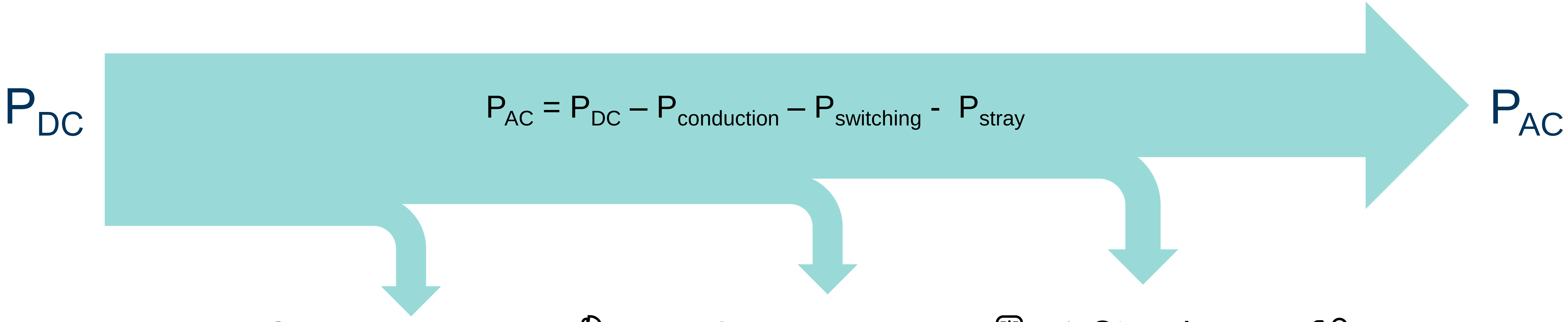
Heat

Vehicle Range

Weight & Volume

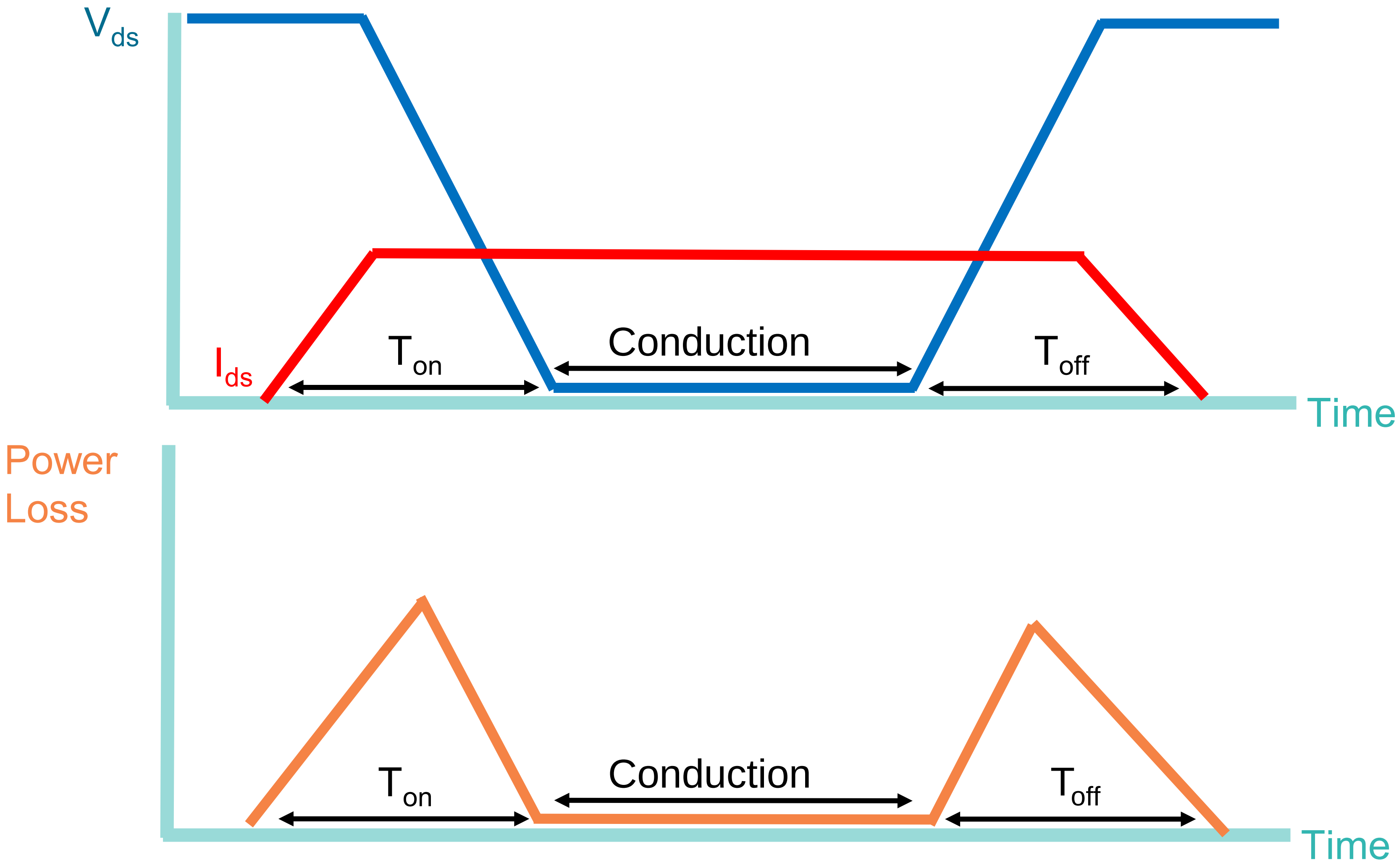
Inverter Losses





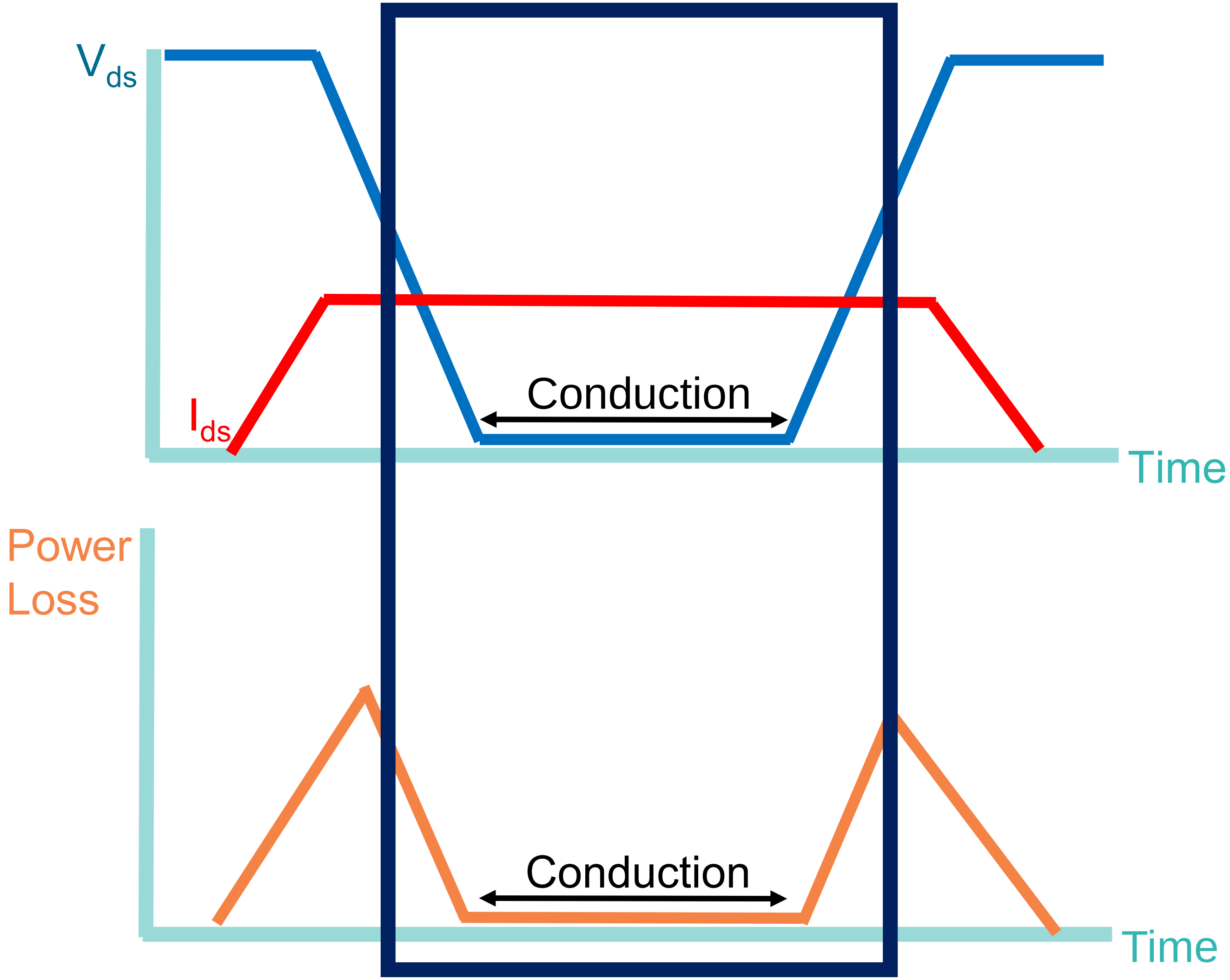
- Conduction Losses
  - Resistance of the switch
  - Resistance of the connections
- Switching Losses
  - Turn on losses
  - Turn off
- Stray Losses
  - off state
  - support circuits

Inverter Switch operation



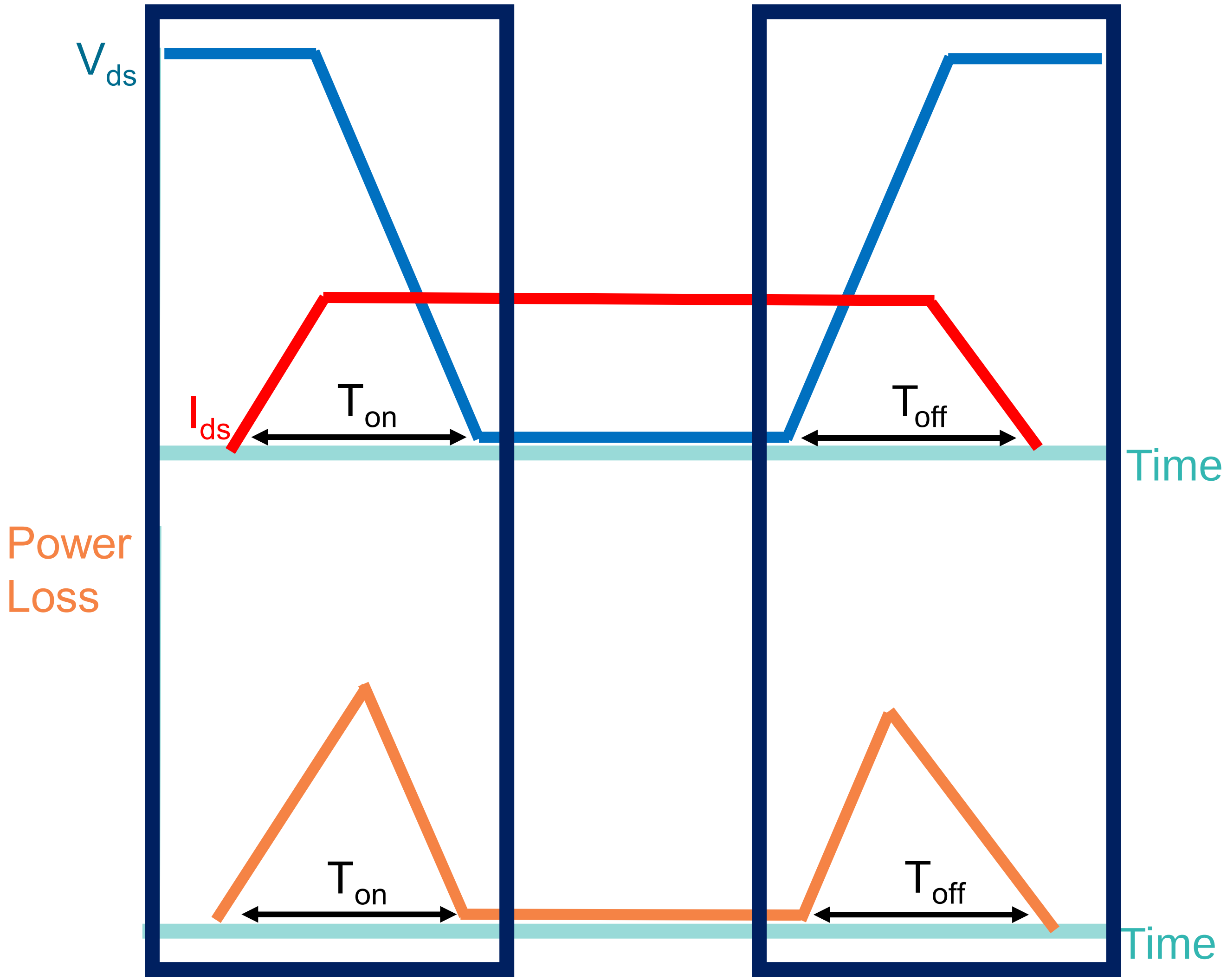
Conduction Losses

- Switch has an “on resistance”
- Power loss = $I^2R_{switchOn} = I_{ds}*V_{ds}$
- Number of switches
- Resistance is a function of temperature
- Other resistances in the circuit will cause losses
- Key to Measurement
  - Time aligned electric & mechanical
  - Calculations
  - Accuracy



Switching losses

- $P = f^*(E_{on} + E_{off}) = I_{ds}{}^*V_{ds}$
  - Frequency = f
  - Energy loss on/off
- Losses increase with frequency
- Losses increase with turn on/off time
  - T_{rise}
  - T_{fall}
- Key to Measurement
  - High speed
  - Differential
  - Recorded data



Inverter Loss Measurement

- Accurately measure DC in & AC out ⚖
- Estimate On resistance with TC and equation 🧮
  - Calculate losses
  - Time aligned temperatures
- Measure P_{on} & P_{off} with differential measurement across switch
  - Scope card @ 250MS/s

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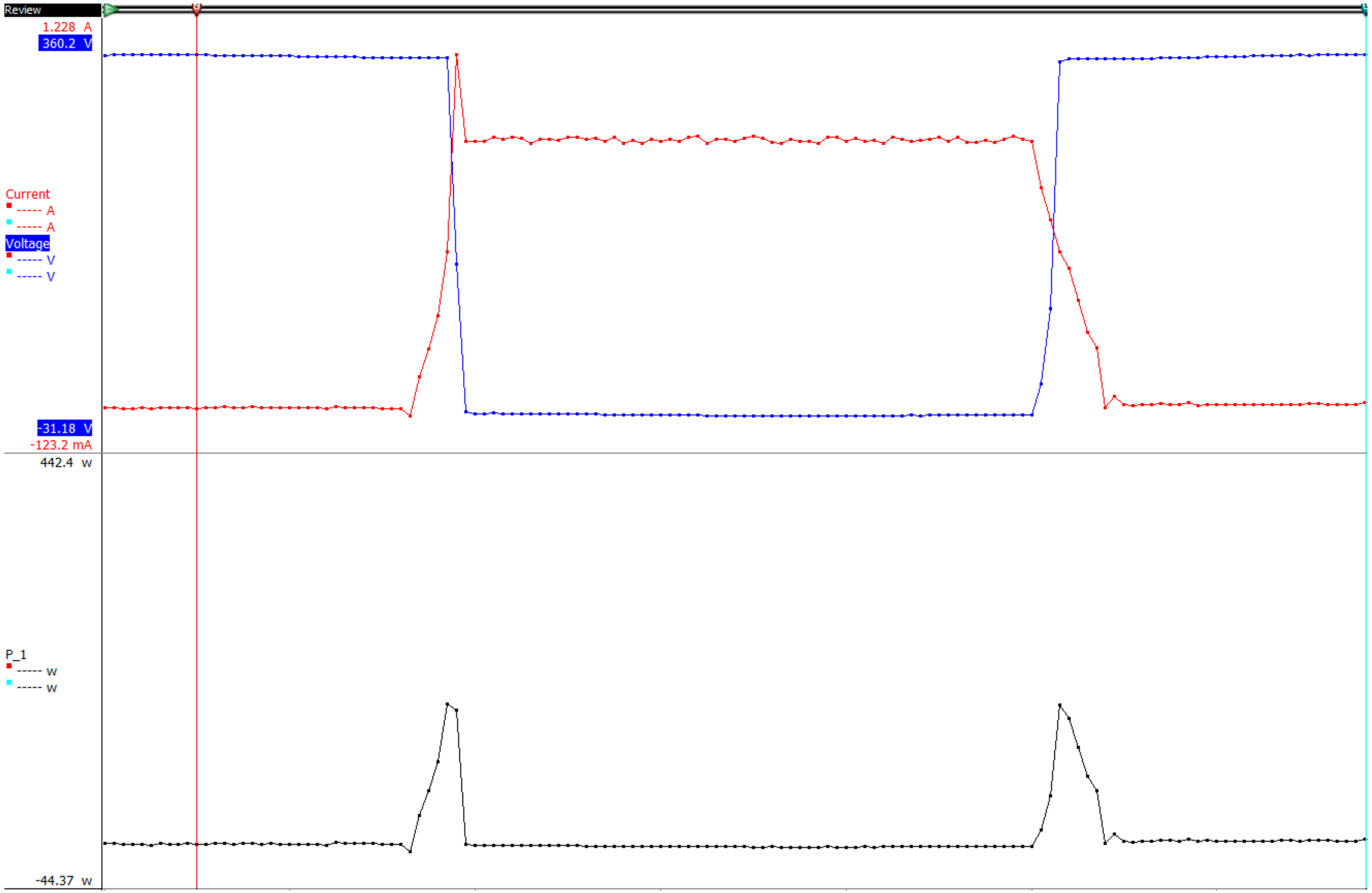
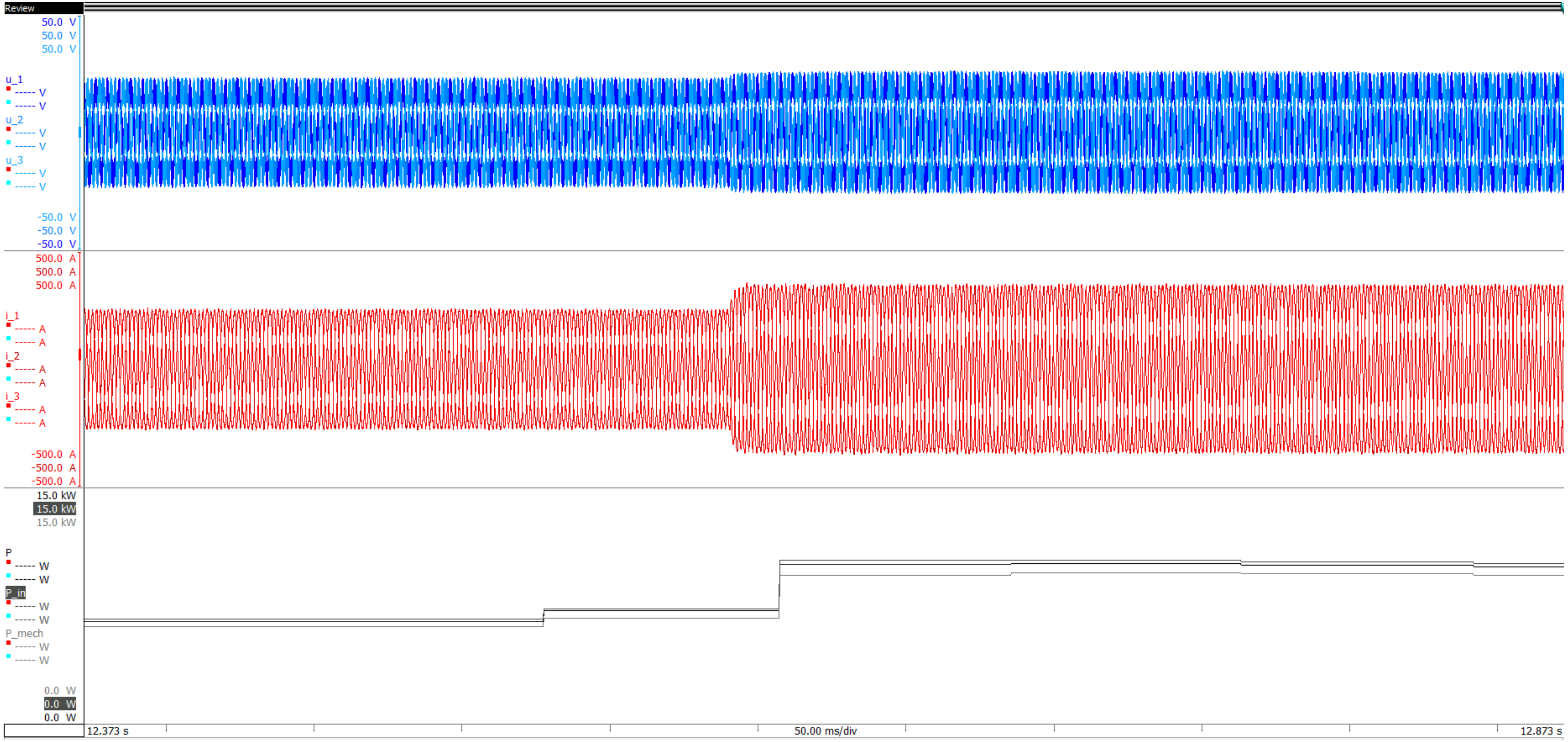
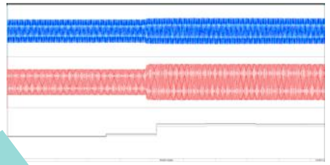
Inverter Switch On and Off Example

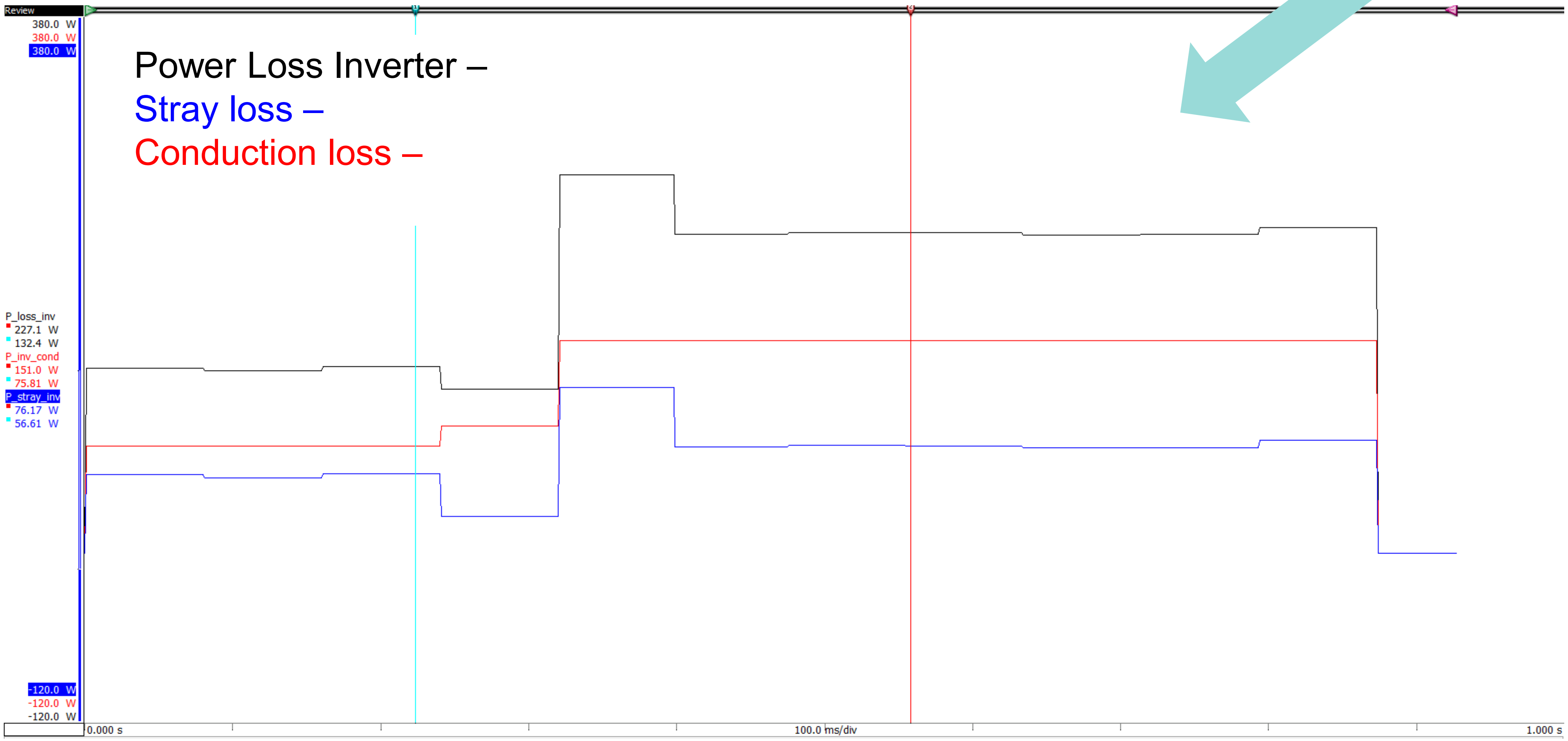


Real Example – Load Step



Inverter Losses





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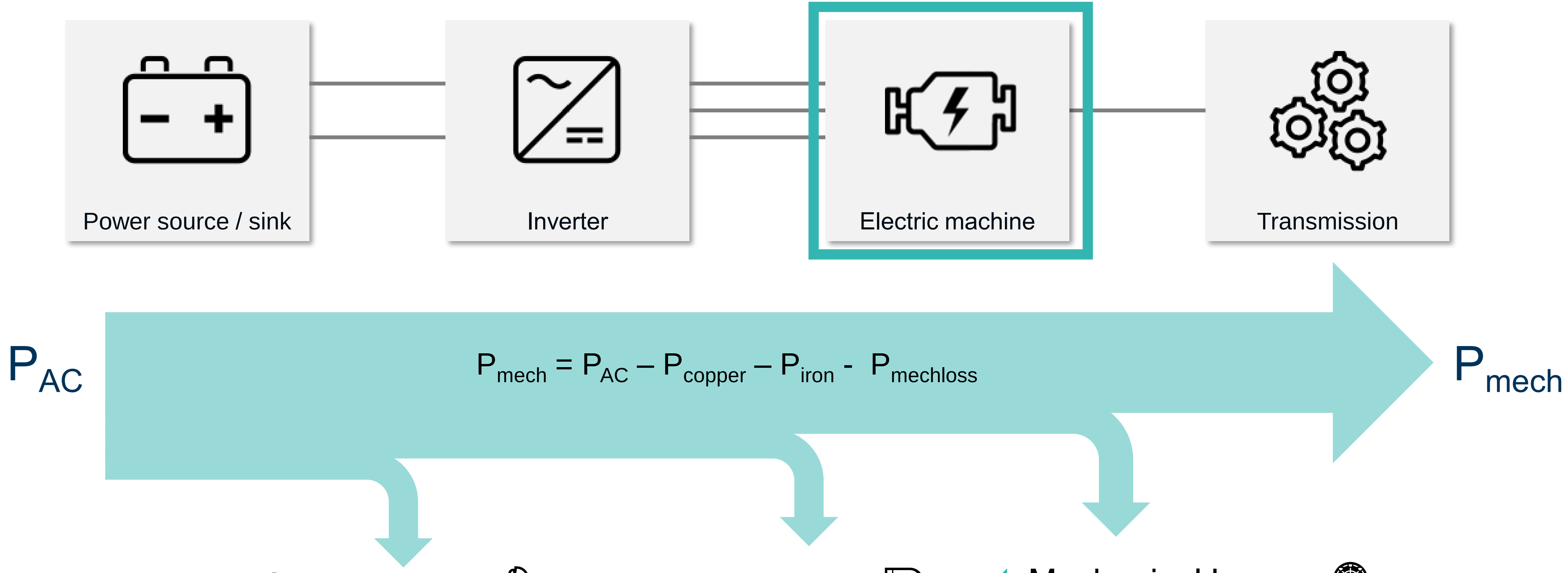
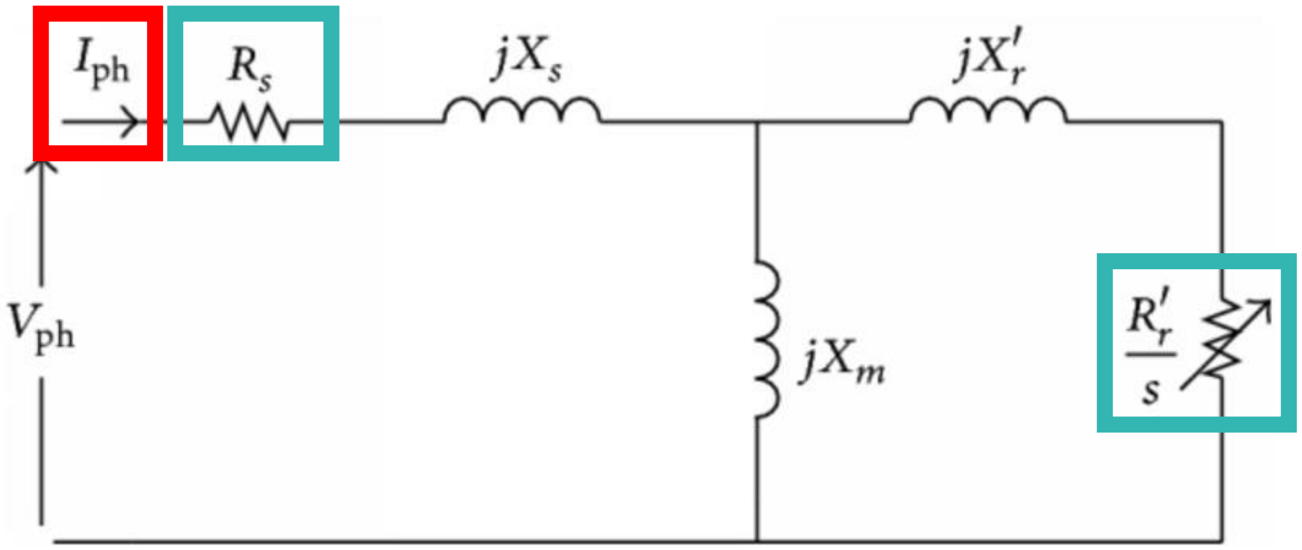
Motor Losses



- Copper Losses
  - Resistive
  - Skin effect
- Iron Losses
  - Eddy currents
  - Hysteresis
- Mechanical Losses
  - Friction
  - Windage

Copper Losses - Resistive

- Losses due to resistance of the motor windings 🔥
- $P_{copper} = I_{ph}^2 * R_{windings}$
- Temperature dependent 🌡
  - $R_{winding} = R_0*(1+\alpha*(T-T_0))$
  - Temp 📈 → Ω 📈
  - Can be reduced by cooling 🚒
- Measured with phase current and temperatures 📏
- Key to Measurement
  - Time aligned electric & mechanical
  - Custom sensors and calculations
  - Accuracy



Motor Circuit equation highlighting the resistive element

Copper Losses - Skin Effect

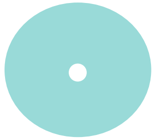
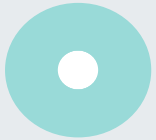
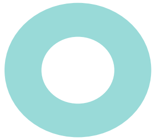
- AC frequency makes the conductor look smaller

- $R_{ac} = R_{dc} * k * \sqrt{f}$
  - K = gauge factor
  - F = frequency in MHz

- Effects high fundamentals and switching frequencies

- Taken into effect with resistance used in the copper loss equation

- Key to Measurement
  - Custom equations
  - Custom sensors
  - accuracy

Frequency	Skin Depth	Graphic
5 Hz	29.7 mm	
50 Hz	9.38 mm	
500 Hz	2.97 mm	
5 kHz	.938 mm	
50 kHz	.297 mm	

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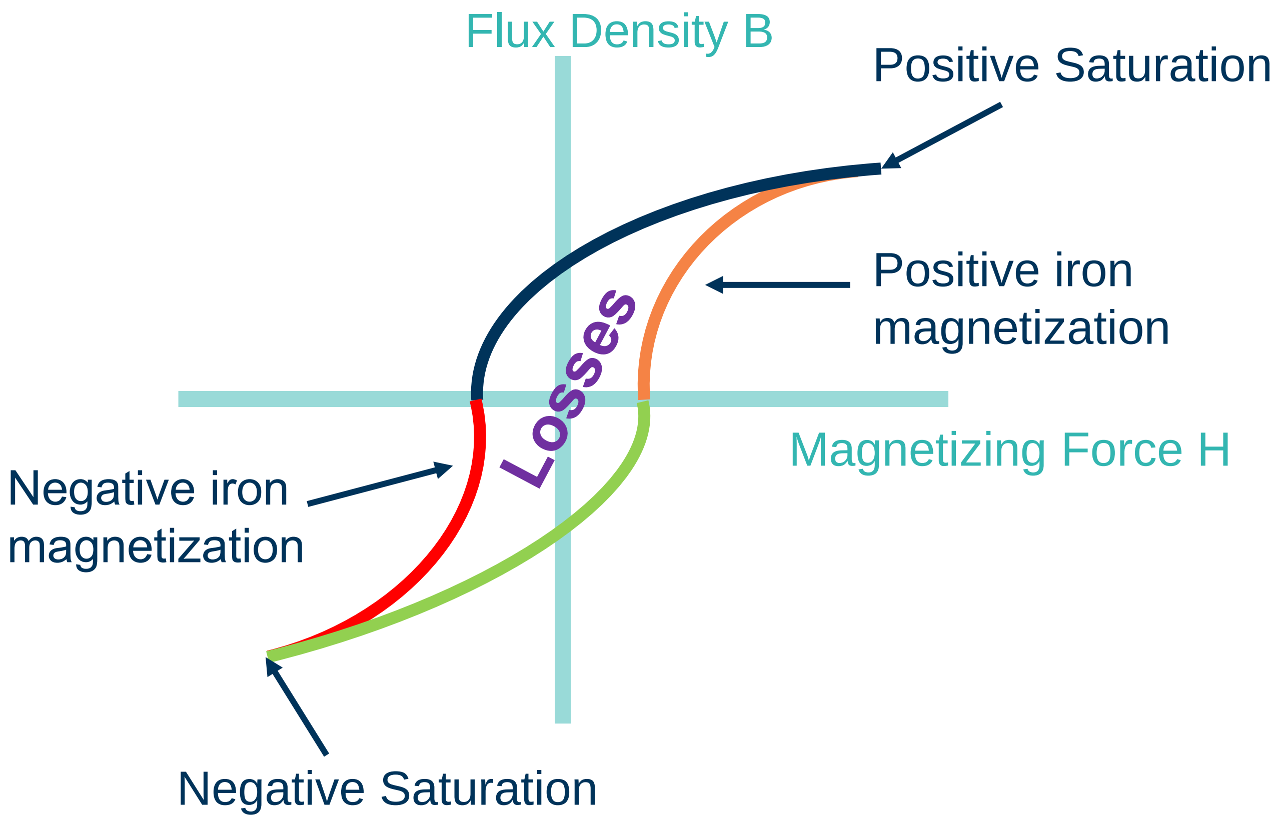
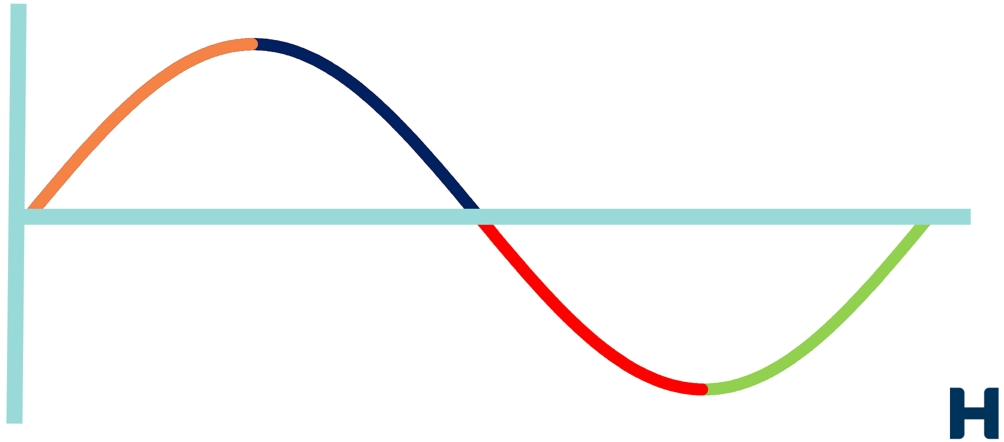
Iron Losses - Hysteresis

- Magnetizing iron requires energy 🧲
- Losses happen every sine wave 🌊
  - Property of the iron & permeability ⚓
- $P_b = \eta * f * V * B_{max}^n$
  - η – Steinmetz hysteresis coefficient (material property)
  - n - Steinmetz exponent (material property)
  - V – Volume
  - f – Frequency
  - B – Max flux density
- Key to Measurement
  - Data to understand variables → Sensitivity
  - Accuracy
  - Custom Calculations
  - Time aligned electric & mechanical





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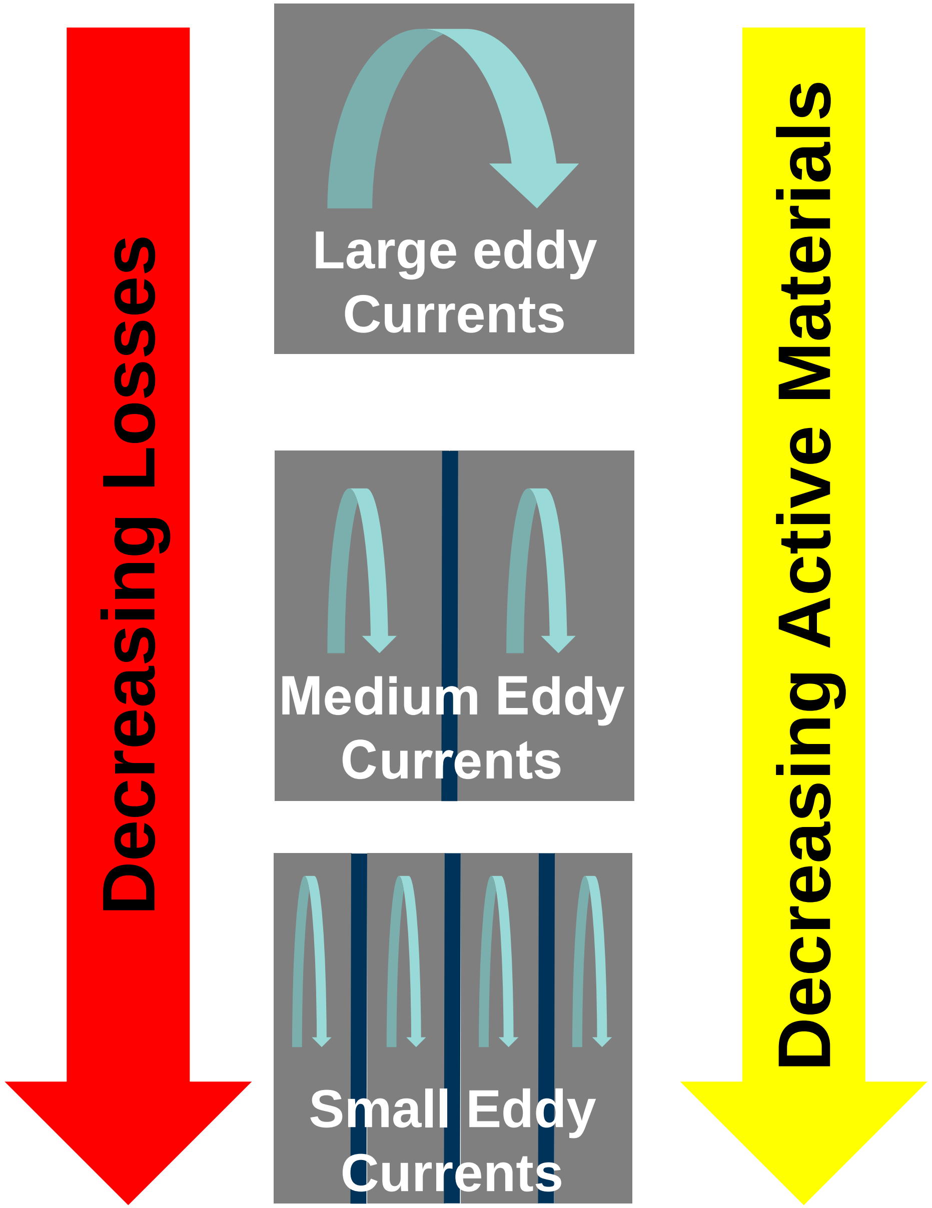
Iron Losses - Eddy Currents

- Faraday's law states *"any change in the environment of a coil of wire will cause a voltage to be induced in the coil, regardless of how the magnetic change is produced"*
  - The magnetism of the flux will self induce EMF
  - Current will flow in the core → losses
  - Thinner laminations have a higher resistance

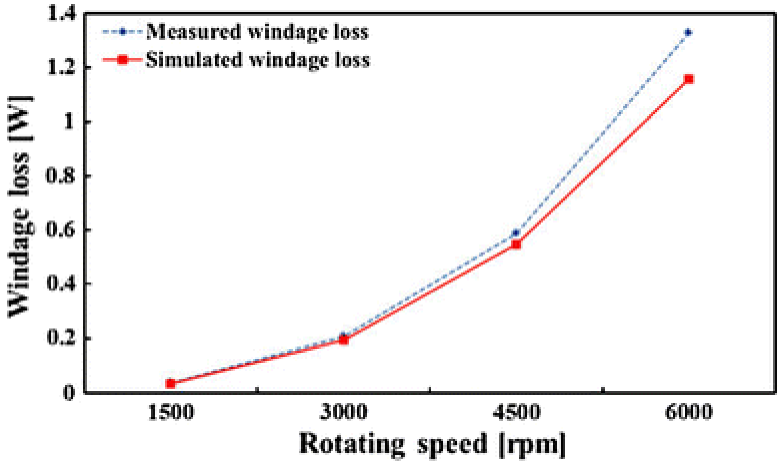
- $P_e = K_e * B_{max}^2 * f^2 * t^2 * V$
  - K_e – eddy current constant
  - B - Max flux density
  - f – frequency
  - t – Thickness
  - V – Volume

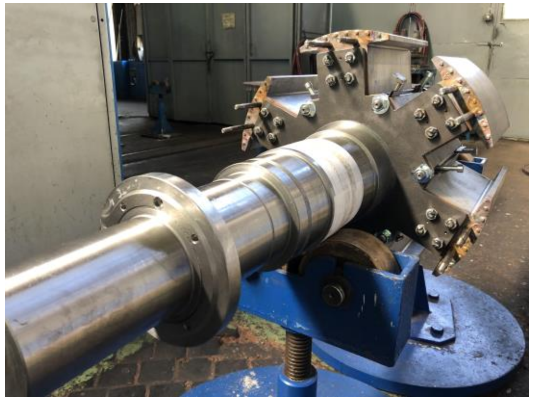
- Key to Measurement
  - Data to understand variables → Sensitivity
  - Accuracy
  - Custom Calculations

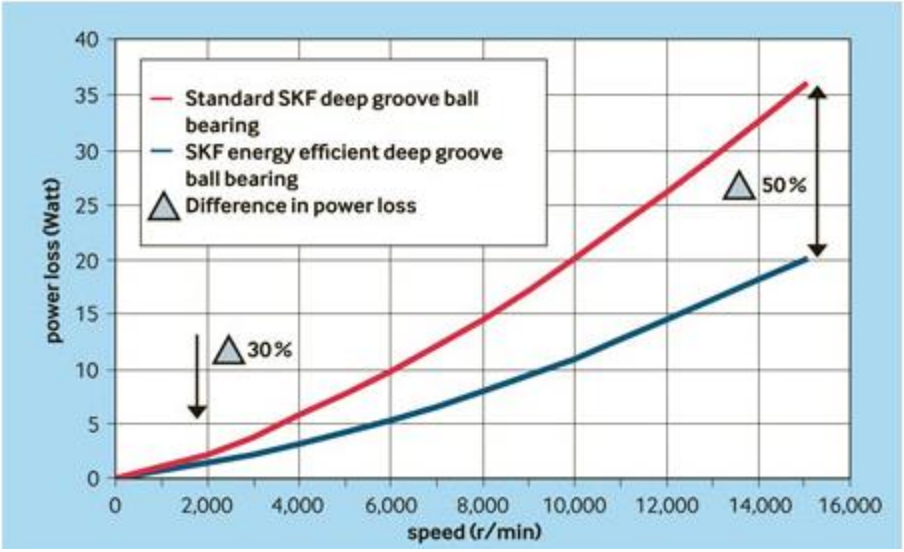


Mechanical losses

- Internal windage
- Bearing Friction
- Misalignment
- Keys to measurement
  - Accuracy
  - Custom sensors







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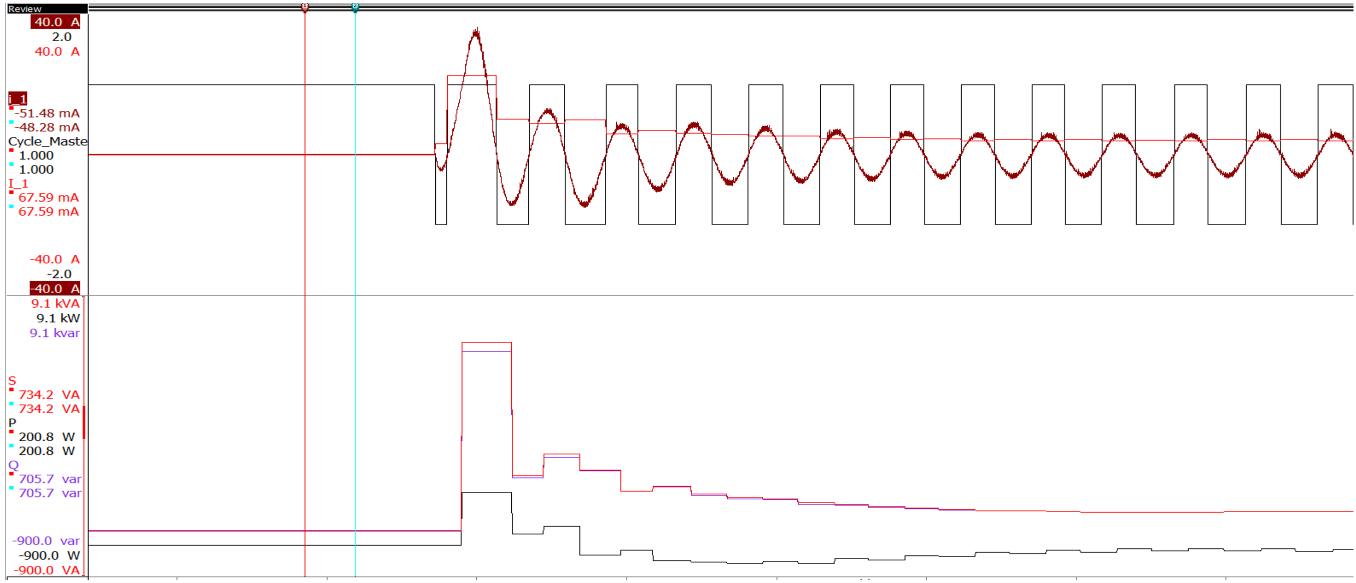
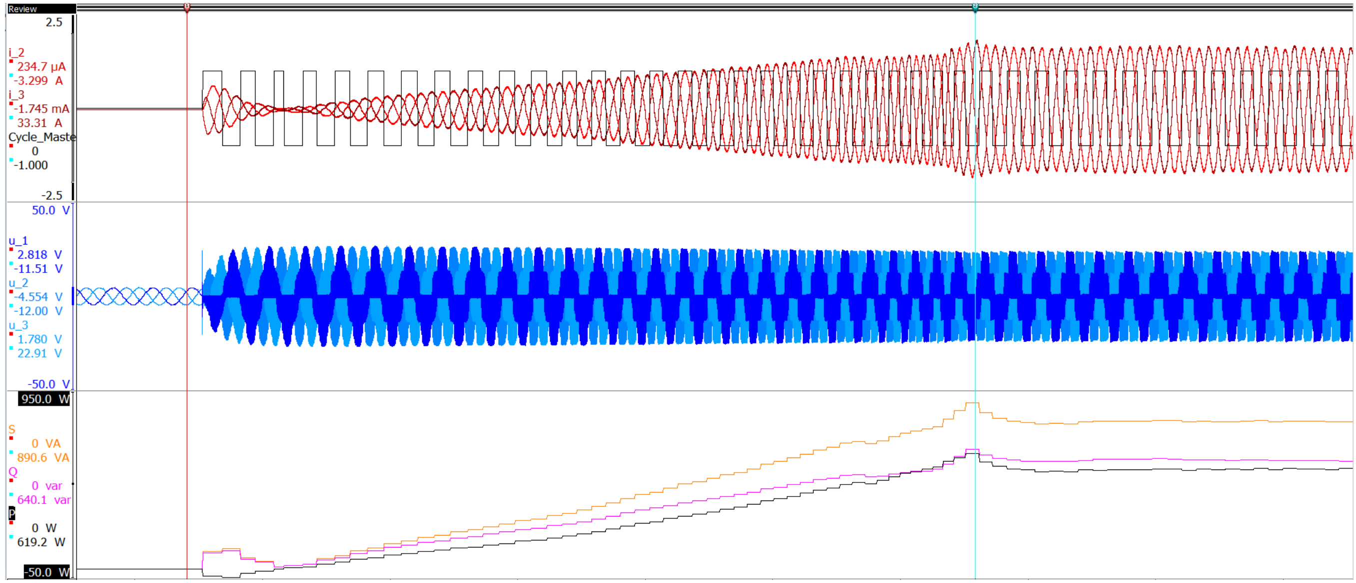
Dynamic Losses

- Load changes will result in magnetizing currents that are greater than normal operation

- Inrush currents happen even with variable frequency excitation

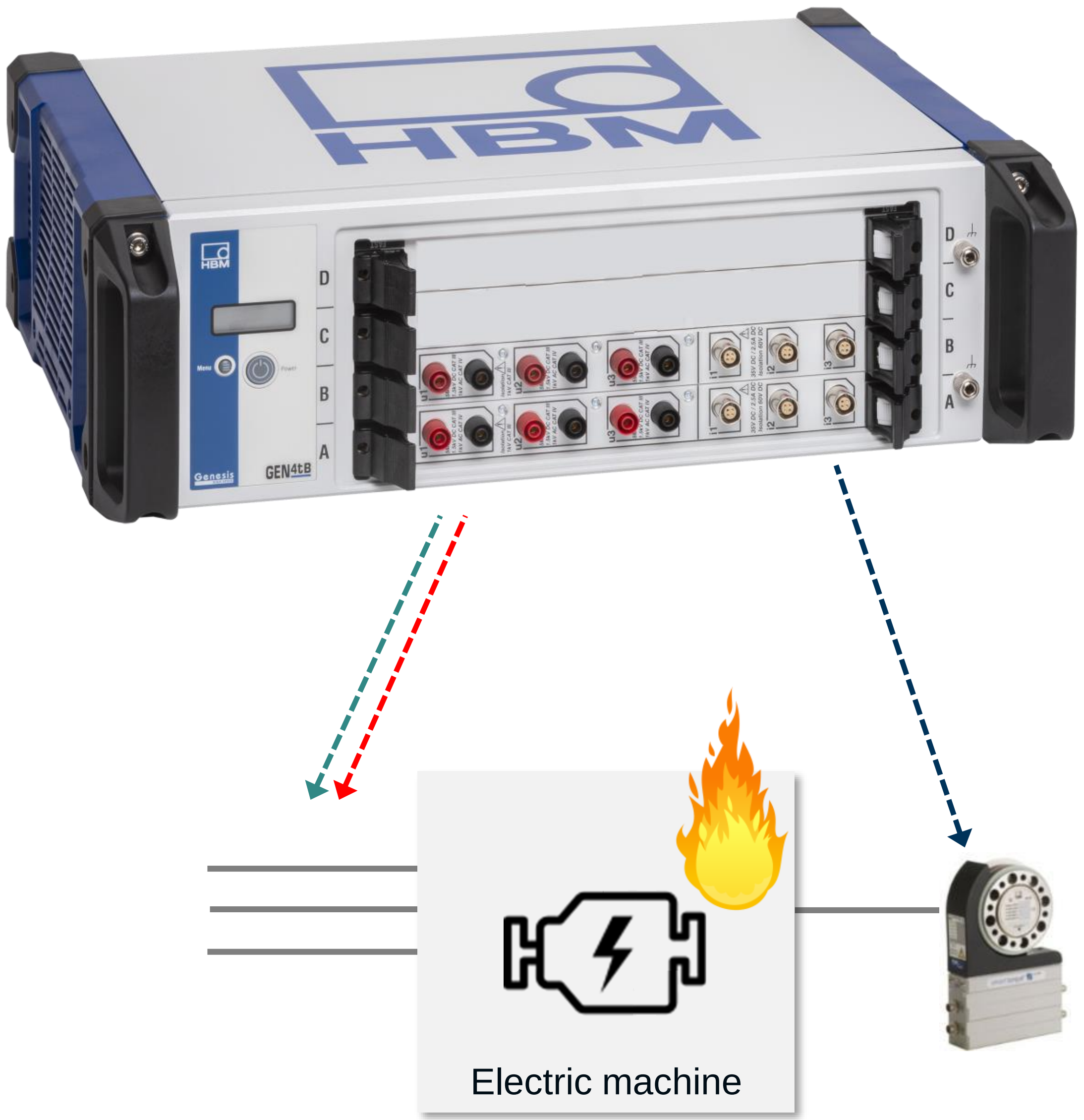
- Key to Measurement
  - Real time cycle detection
  - Time alignment – Electric and Mech





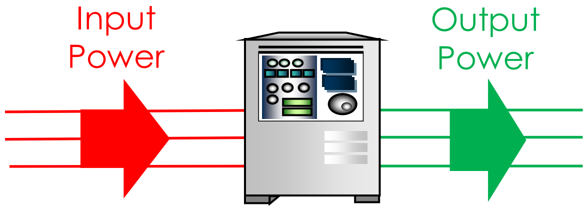
Motor Loss Measurement

- Accurately measure AC in & Mechanical out ⚖️
- Measure copper/iron losses thermocouples and equations 🧮
- Measure mechanical losses with equation or a curve based on measurement



Measurement Uncertainty

Measuring Power Losses → A Differential Problem



- 500 kW inverter
- 95% efficiency

			Measurement chain error @ 1%			Measurement chain error @ 0,1%	
	"Truth"		Measured	Error		Measured	Error
Input	500 kW		500 kW +/- 5 kW	1%		500 kW +/- 0.5 kW	0,1%
Output	475 kW		475 kW +/- 4.75 kW	1%		475 kW +/- 0.475 kW	0,1%
Losses	25 kW		25 kW +/- 9.75 kW	39,0%		25 kW +/- 0.975 kW	3,9%
Conduction	5 kW		5kW +/- 9.75 kW	😲		5 kW +/- .975 kW	19.5%

If you want to achieve **reasonable measurements** for derived values like **Power Loss** you need the **most accurate measurement** you can get

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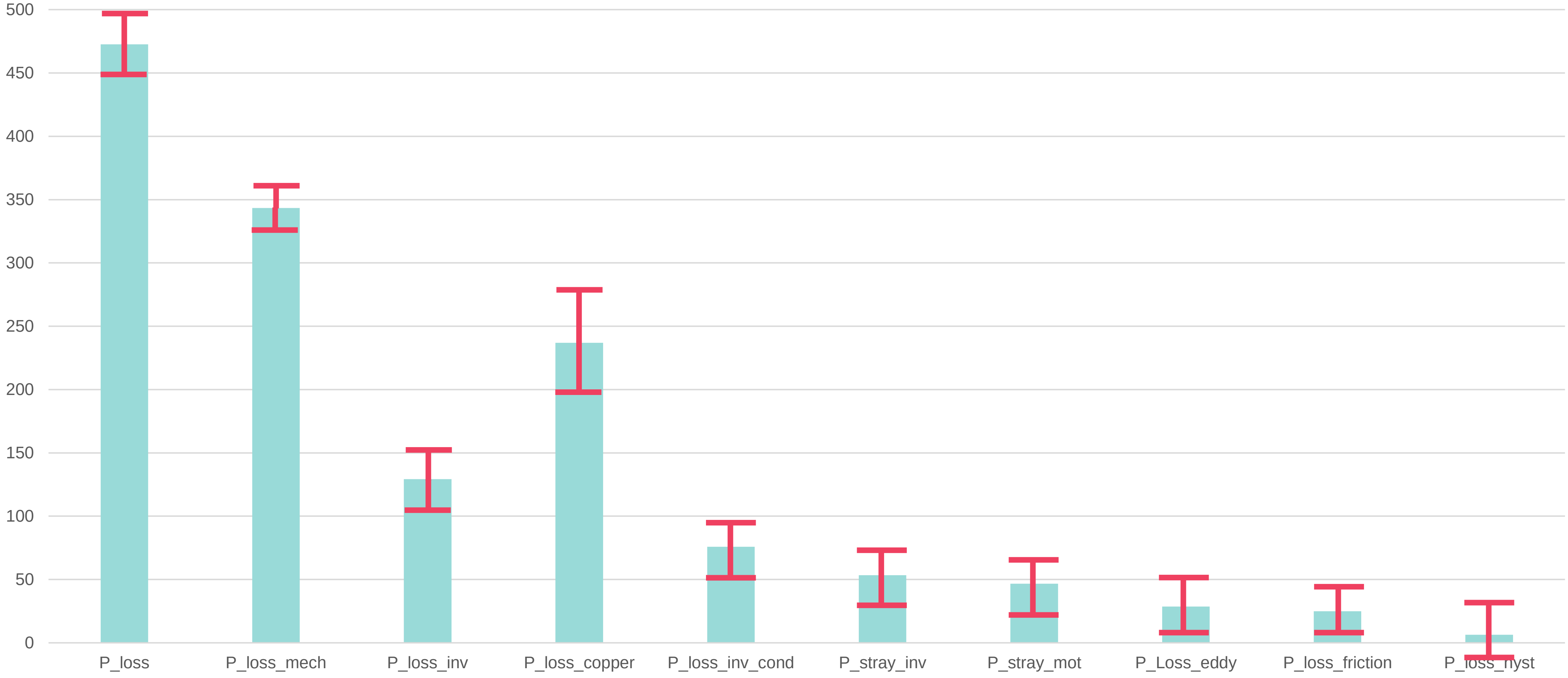
Measurement Uncertainty and Losses



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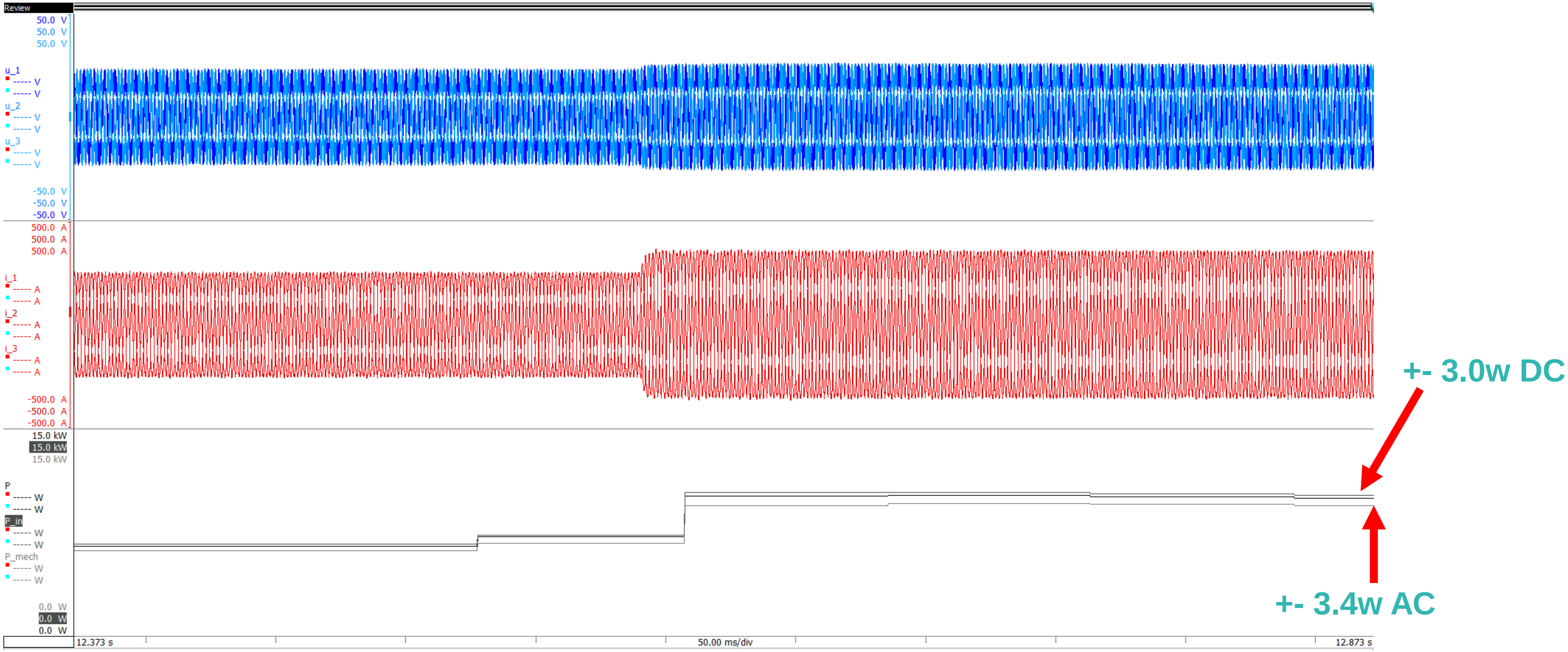
Real Example – Load Step



Measurements of raw signals

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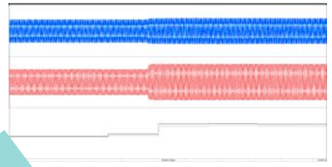
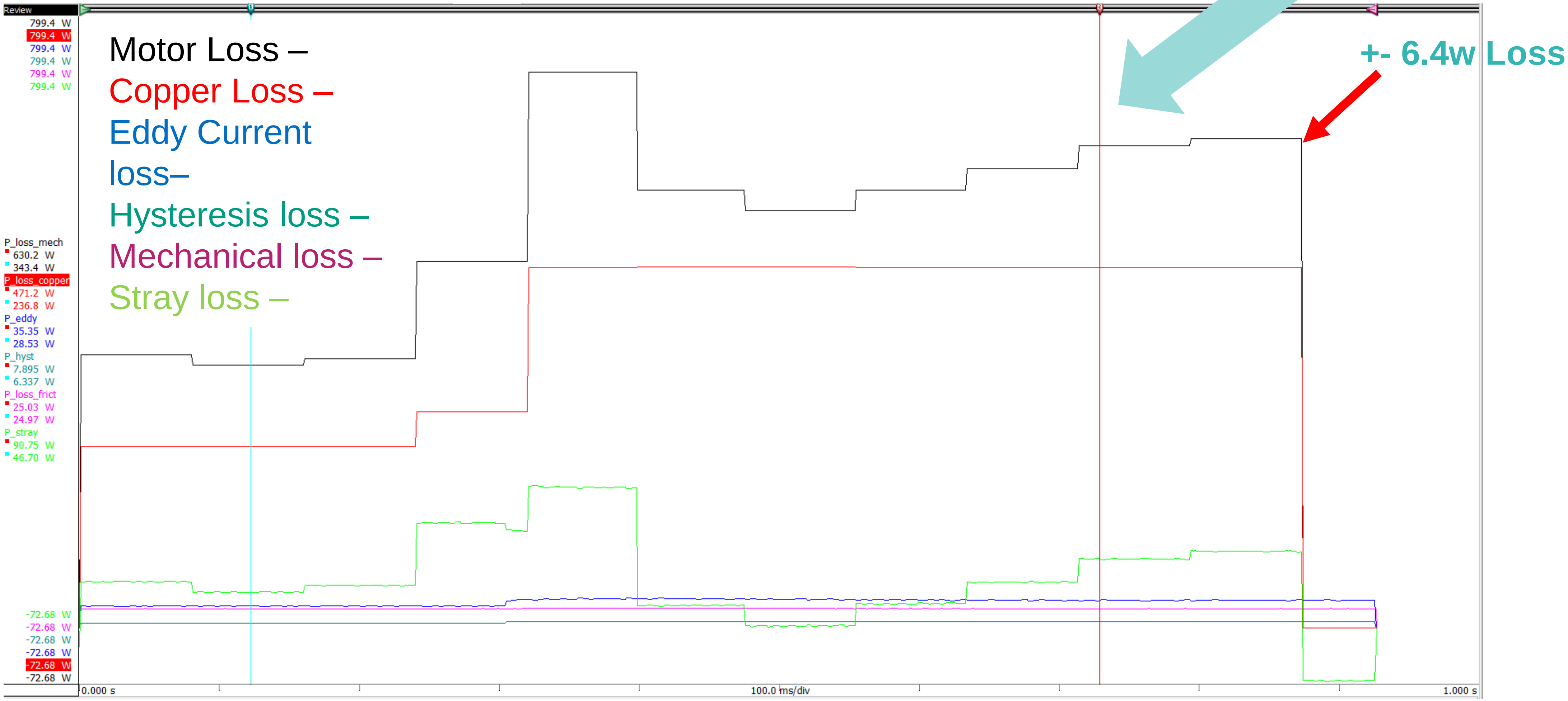
Example of Motor Losses





High accuracy measurement gives you ability to trust values

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eDrive Value

- Simple data collection of electro-mechanical signals

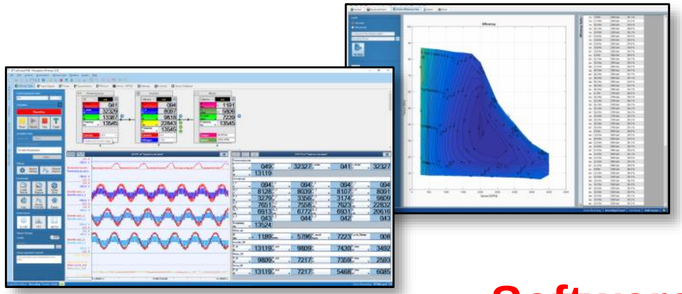
- Fast and accurate Power Meausrements
  - **Lowest Measurement Uncertainty (MU)**
  - **Lowest MU across the frequency range**
  - **Lowest Torque MU**

- Custom Equations

- Recorded Data
  - Recorded data will allow you to refine models in post process with 1 test

- Local Support & Training

Acquisition



Software

Sensors

Thank You - Questions?

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